Applications of Nanotechnology

in Space Developments and Systems

Technological Analysis

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Title Page: The image shows the concept of a nanosatellite envisioned by researchers at The Aerospace Corporation. *Image courtesy of The Aerospace Corporation (www.aero.org).*

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1 INTRODUCTION

Nanotechnology is regarded world-wide as one of the key technologies of the 21st Century. Nanotechnological products and processes hold an enormous economic potential for the markets of the future. The production of ever smaller, faster and more efficient products with acceptable price-to-performance ratio has become for many industrial branches an increasingly important success factor in the international competition. The technological competence in nanotechnology will be a compelling condition to compete successfully with better procedures and products on high technology markets in the future. Due to its interdisciplinary cross-section character, nanotechnology will affect broad application fields within the ranges of chemistry/materials, medicine/life sciences, electronics/information technology, environmental and energy engineering, automotive manufacturing as well as optics/analytics and precision engineering in various ways.

Also in space technology a high potential for nanotechnological applications is postulated. The increasing commercialisation of manned and unmanned space travel as well as ever more ambitious missions for the scientific investigation of the solar system and far space, require the development of more efficient, more economical and more resistant space technologies and systems in the future. Nanotechnology could contribute significantly to solutions and technological breakthroughs in this area (nano-spin-on).

Expected nanotechnology spin-on for space

In this context nanotechnological improvements of space technology and systems are to be considered both in a short to medium-term time scale as well as on a long-term basis in view of visionary applications of molecular nanotechnology, which might be realized- if at all- only in the distant future. Examples of such visionary applications of molecular nanotechnology in space are the terraforming of other planets through raw material extraction and material synthesis, the construction of a „space elevator“ by applying ultrastrong carbon nanotube materials or the extreme miniaturization and integration of space systems in the sense of a "flying chip".

Visionary applications

Meanwhile however, various applications of nanotechnology in space technology appear to be feasible in a short to medium-term time horizon, which could lead to major improvements in the area of lightweight and strong space structures, improved systems and components of energy production and storage, data processing and transmission, sensor technology as well as life support systems. Appropriate research and development projects have already been performed in particular by NASA for some years with substantial financial measures. In Germany and in Europe the situation is different. In the German and European space agencies nanotechnology is still regarded so far rather as a subordinated topic in

Short to medium term applications

Extensive nanotechnology activities of NASA

In Germany and Europe little contacts between space and nanotechnology communities the field of microtechnologies and R&D activities are rare. For the future, however, the ESA attaches a greater importance to nanotechnology, e.g. in the framework of the AURORA program, which is dedicated to the long term exploration of the solar system. Also the space industry pursues the area of nanotechnology with increasing awareness.

Expected space spin-off for nanotechnology

On the other side, space flight could be utilized for research and development in the field of nanotechnology as well. As an example the use of microgravity for investigations and optimizations of production processes for nanomaterials or nanostructures can be mentioned. Experiments in microgravity could supply relevant data regarding particle interactions or self-organization phenomena, which could be used for modelling and optimization of terrestrial process technologies in the range of nanotechnology. These examples represent potential space spin-offs for nanotechnology.

1.1 Settings of Tasks

The objective of the ANTARES study was the identification and evaluation of different applications of nanotechnological procedures and products in technology developments for space. The basis for the investigations was an adjustment of the working fields of nanotechnology competence centers in Germany and space technology requirements, which for example are mentioned in the "European space technology requirement document" of ESA[1].

In addidition, the utilization of space infrastructure as a research instrument (e.g. microgravity experiments) for nanotechnological developments should be identified and evaluated. Based on the results the R&D needs should be determined and in a further step, suggestions for research and development projects should be formulated in this area. As a further aspect the communication between the space and the nanotechnology communities should be intensified and improved as a basis for lasting cooperation relations.

1.2 Approach

1.2.1 Screening

In the first screening phase of the project, starting points for potential nano-spin-ons and nano-spin-offs were identified. To this end, Internet-, literature and patent searches were accomplished. The following sources were used:

- Literature data bases (Science Citation Index, AEROSPACE)[2]
- Patent data bases (WPINDEX, USPATFULL, EUROPATFULL)[2]

[1] ESTEC 1999
[2] STN services of FIZ Karlsruhe (http://stnweb.fiz-karlsruhe.de/)

- Project data bases (Funding catalogue of the BMBF[3], SBIR/STTR-Program of NASA and DoD)[4,5], CORDIS[6], ESA Microgravity Database[7], Microgravity Research Experiments (MICREX) Database[8]
- Proceedings of relevant workshops and conferences
- Internet searches and Internet news services in context with nanotechnology or space travel (z. B. www.atip.org, www.scicentral.com, www.stp-gateway.de, www.ivcon.com, nanotechweb.org, www.space-daily.com, www.space-future.com, www.spacenews-feed.co.uk, www.astronautix.com)

Beyond that, interviews with experts from the nanotechnology and space community were performed and the following meetings and conferences were visited:

- Spring Meeting of the German Industry for the utilization of the International Space Station on February 15th 2001 in Berlin
- Nanospace 2001, 4th International Conference on Integrated Nano/ Microtechnology for Space and Biomedical Applications, 13.-16. March 2001 in Galveston/Texas
- ISS-Forum 2001, 5.-7. June 2001 in Berlin
- NanoDe Innovations through Nanotechnology, BMBF-Congress 6.-7. May 2002 in Bonn
- Boeing Technology Summit, 14. Juni 2002 in Berlin
- Nanospace 2002, 5th International Conference on Integrated Nano/ Microtechnology for Space and Biomedical Applications, 24.-28. June 2002 in Galveston/Texas

In the next step, the identified nanotechnology spin-ons and spin-offs were correlated with future technological requirements and objectives in space technology. As sources for this, technological research programs of the ESA and NASA as well as the European Space Technology Requirement Document (ESTEC 1999) were consulted. Beyond that, an expert meeting with representatives of the German space industry was organized, which took place on 14.12.2001 in Duesseldorf. Representatives of the following space companies were involved:

Participating space companies

- Astrium
- EADS
- Kaiser-Threde
- MAN Technologie
- OHB System AG

3 http://oas.ip.kp.dlr.de/foekat/foekat/foekat
4 http://www.sbirsttr.com/
5 http://sbir.gsfc.nasa.gov
6 http://www.cordis.lu/fp5/projects.htm
7 http://www.esa.int/cgi-bin/mgdb
8 http://mgravity.itsc.uah.edu/microgravity/micrex/

As a result a matrix was derived, in which space technological requirements were correlated with possible activities of the nanotechnology competence centers in Germany (see chapter 5.1).

1.2.2 Evaluation

The results of the screening phase were summarized in a statement paper, that was sent to approx. 200 experts of the German nanotechnology and space communitiy with the request for evaluation and technical additions to the statement paper by answering an attached catalog of questions (s. appendix) dealing with the following topics:

- Links to their own research activities in the field of nanotechnology applications in space
- Potential research demand
- Potential obstacles for applications of nanotechnology in space
- Potential demand and obstacles concerning the use of space as a research instrument for nanotechnology

The return ratio of the questionnaires was approx. 27 %, which can be regarded as a satisfactory value in view of the very specialised topic. Altogether the statement paper was well accepted in the nanotechnology and space community. In addition, several further topics were specified, which were included in the investigations of this study.

An English translation of the statement paper was distributed to approx. 50 experts at international level (in particular to experts of the ESA and NASA). In the further course of the project a workshop with 40 participants of the nanotechnology and space community was accomplished, which took place on 04.06.2002 in the German Aerospace Center in Cologne. The objective of the workshop was to present and evaluate relevant aspects through invited experts and to discuss further research demands in this area. Based on the obtained interim results of the study an evaluation of the potential nanotechnology application in space was accomplished using the following criteria:

- Technology readiness
- Market potential for terrestrial application
- Contribution to space objectives
- Economic benefits for space
- Potential obstacles to application in space

The application possibilities of space infrastructure as a research instrument for nanotechnology were evaluated on the basis of a cost-benefit analysis. Finally, recommendations concerning the further treatment of the topic field were derived and further R&D needs were outlined.

2 R&D ACTIVITIES IN NANOTECHNOLOGY

Nanotechnology meanwhile is established as an individual field of public research and development programs in nearly all industrialized states. The public funding for nanotechnology, which has been increasing strongly worldwide in the last years, exceeded the sum of 1,5 billion $ in the year 2001. The leading nations with regard to public nanotechnology funding are Japan (approx. 650 million $ funds in 2002) and the USA (approx. 604 million $ in 2002) followed by Western Europe (approx. 400 million $ in 2002). Also other industrial countries particularly the Southeast Asiatic area (Taiwan, Singapore, South Korea, China) intensify their research efforts in the field of nanotechnology. Illustration 1 shows the world-wide development of public nanotechnology funding from 1997 to 2002. Remarkable is the strong rise in the section „other states", which relates to Australia, Canada, China, Eastern Europe, Russia, Israel, Korea, Singapore and Taiwan. The Western European funding, from which the portion of Germany constitutes approx. 50 %, was in 1997 approximately on the same level as Japan and the USA. This dropped back since then however. After only a small rise of the European funds in the year 2001 however, a substantial growth of up to approx. 441 million Euro is expected for the year 2002 (BMBF 2002).

Japan and USA leading with regard to public nanotechnology funding

Other industrialized countries are catching up

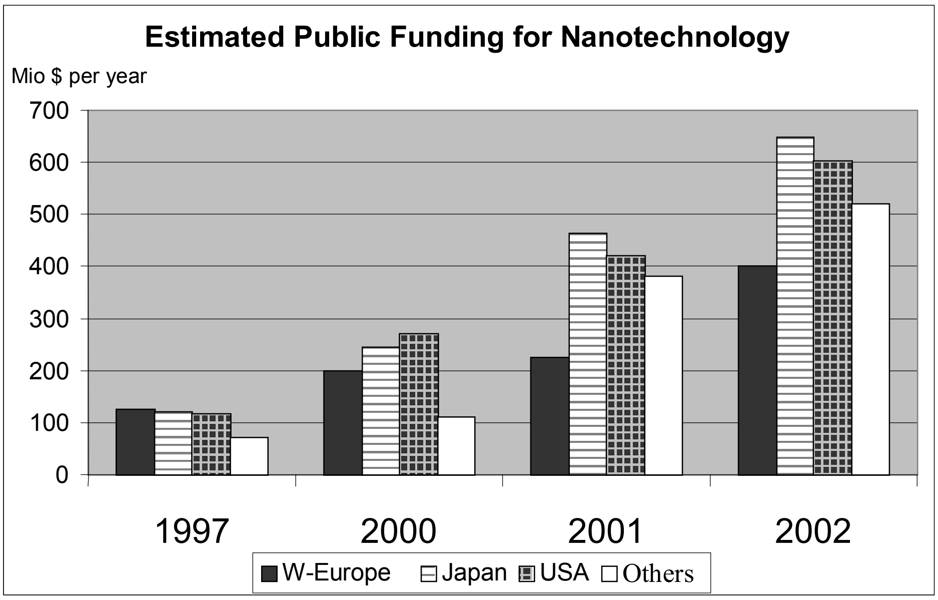


Illustration 1: Public Funding for Nanotechnology in Mio. $ per year (Source: Roco 2002, partly based on estimations)

2.1 R&D Landscape in Germany

2.1.1 Nanotechnology Funding of the BMBF

Nanotechnology competence centers of the Federal Ministry of Reseach and Education (BMBF)

Nanotechnology, which was undertaken as a research topic in Germany at the beginning of the nineties, is now extensively promoted as an interdisciplinary cross section technology by the Federal Ministry of Research and Education both in the range of the institutional as well as project funding. Nanotechnology funding received a distinct thrust by the establishment of nanotechnology competence centers in the year 1998 with the following fields of work:

- Production and use of lateral nanostructures
- Applications of nanostructures in the field of optoelectronics
- Functional ultra-thin films
- Functionality by means of chemistry
- Ultra-precise surface treatment
- Nanoanalytics

One objective of the competence centers is to bring together nanotechnology researchers and industrial users. In the entire network approx. 440 participants from universities, research institutes, large-scale enterprises, small and medium sized enterprises as well as financiers, consultants and asociations are presently linked together.

The network "NanoMat" at the research center Karlruhe was added to the list of the BMBF competence centers in 2001. Beyond that, a nanobiotechnology network (NanoBioNet, Saarbruecken) was established, composed of universities, research centers and industrial partners.[9] As a superordinate Internet platform, the Nanonet[10] was established by the BMBF, which provides links to the different competence centers (CC) and additional information.

[9] www.nanobionet.de
[10] www.nanonet.de

CC	Coordinator	Topics
Functional ultra-thin films	Fraunhofer-Institut für Werkstoff- und Strahl-technik IWS, Dresden Internet: www.nanotechnology.de	• Advanced CMOS • Innovative components • Biomolecular layers • Mechanical and protective layers • Ultrathin layers for optics and photonics • Nanoactuators and sensors (nanosystems)
Lateral nanostruc-tures	Advanced Microelectro-nic Center, Aachen Internet: www.nanoclub.de	• Magnetoelectronics • Ultraelectronics • Sub-100 nm CMOS • Self-Assembly • Lithography • Simulation, nanotools
Nano-Analytics	Institute for Applied Phy-sics University Hamburg Internet: www.nanoscience.de	• Scanning tunneling microscopy • Scanning force microscopy • Near-field optical microscopy • High resolution photoelectron spectroscopy • Electron microscopy • Secondary mass spectroscopy • Ion probe techniques
Functionali-ty by means of che-mistry	University Kaiserslautern Internet: www.cc-nanochem.de	• Medicine & pharmacy • Sensors & catalysis • Electronics • Power engineering • Surface treatment • Nanoparticles • Bulk & Composites
Nanostruc-tures in the field of Optoelec-tronics	Institute for Solid State Physics, TU Berlin Internet: www.nanop.de	• Quantum dot laser • VCSEL • Edge-/surface emitter • Photonic crystals
Ultra-precise surface treatment	Physikalisch-Technische Bundesanstalt, Braun-schweig Internet: www.upob.de	• Mechanical/chemical finishing • Ionbeam- and plasma methods • Optical methods • Characterization of surfaces • Optical and x-ray optical Layers • Ultraprecise 3D-structuring • Nanopositioning- and measuring systems
Nano-Materials (Network NanoMat)	Research Center Karlsru-he GmbH Internet: www.nanomat.de	• Design of nanomaterials • Surfaces and inner boundaries

Table 1: Nanotechnology Competence Centers of the BMBF (Source: www.nanonet.de)

2.1.2 Nanotechnology players and institutions

The main participants in the field of nanotechnology in Germany comprise university institutes, non-university institutes and enterprises. The institutional nanotechnology research outside the universities is concentrated on four large research councils in Germany:

Scientific nanotechnology institutions

- Wissensgemeinschaft G. W. Leibniz (WGL)
- Helmholtz Gemeinschaft deutscher Forschungszentren (HGF)
- Fraunhofer Gesellschaft (FhG)
- Max-Planck-Gesellschaft (MPG)

Based on the number of scientific publications in the area of the nanotechnology in the years 1991 to 1999, institutions of the above mentioned research councils, occupy the front places (see Hullmann 2001). A selection of institutions of the research councils, which are active in the area of nanotechnology, is shown in table 2.

Wissensgemeinschaft G. W. Leibniz (WGL)	Helmholtz Gemeinschaft deutscher Forschungszentren (HGF)
• Institute for New Materials, Saarbruecken	• Research Center Karlsruhe
• Institute for Solid State and Materials Research Dresden	• Research Center Juelich
• Institute for Surface Modification, Leipzig	• Hahn-Meitner-Institute, Berlin
• Institute for Polymer Research, Dresden	• GKSS- Research Center, Geesthacht
Max-Planck-Gesellschaft (MPG)	**Fraunhofer Gesellschaft (FhG)**
• Institute for Polymer Research, Mainz	• Institute Institute for Material and Beam Technology, Dresden
• Institute for Metal Research, Stuttgart	• Institute for Silicate Research, Würzburg
• Institute for Solid State Research, Stuttgart	• Institute for Biomedical Engineering, St. Ingbert
• Institute of Microstructure Physics, Halle	• Institute for Applied Solid States Physics, Freiburg

Table 2: Selected Institutions of WGL, HGF, MPG and FhG with research activities in the field of nanotechnology

Beyond that, the German Research Council (DFG) funds nanotechnology in the context of special research areas, e.g. molecular electronics. The institutional funding in the range of nanotechnology amounted to approx. 93 million Euro in Germany in the year 2001 (BMBF 2002).

Enterprises with nanotechnology activities

University institutes and public research institutions as well as several industrial enterprises belong to the main players within the range of nanotechnology in Germany. Regarding the patent applications, large chemical enterprises such as BASF, Bayer or Degussa hold leading positions, which are mainly focused on the production of nanostructured materials and surfaces.[11] In electronics Siemens and its subsidiary companies such as Infineon should be mentioned among others. Furthermore a multiplicity of start-up enterprises have meanwhile appeared, which are specialized in distinct fields of nanotechnology and often carry the prefix "nano" in the company name (e.g. Nano-X, ItN Nanovation, NanoSolution, NanoAnalytics, Nanotype).

2.2 International Activities

2.2.1 Europe

TOP Nano 21 initiative in the Switzerland

In many European countries, (e. g. Finland, France, Great Britain, the Netherlands, Spain, Sweden and Switzerland) as in Germany, special research programmes in the field of nanotechnology have been established. An example for a nanotechnology research initiative coordinated at national level is the Swiss program "TOP nano 21", aiming at the efficient transfer of technological inventions into products ready for the market and promoting joint projects of universities and partners from industry.

In France a strong linkage between micro- and nanotechnology exists

In France the conception of nanotechnology is based on a strong link to the micro world and/or micro system engineering, which is regarded as a direct predecessor of nanotechnology. In Grenoble the Minatec was established as a competence center for the promotion of innovations in the field of micro- and nanotechnologies. The "Centre National de la Search Scientifique" (CNRS) initiated a program for ultraprecise processing (Ultimatech) and is promoting nanotechnology in the framework of interdisciplinary progammes with an emphasis on material sciences. Beyond that, a national research network ("Réseau de Recherche en Micro et Nano Technologies") and the "French nanotechnology club" exist, which strive for the bundling of nanotechnology activities.

In Great Britain specific measures for nanotechnology promotion started with the establishment of the national initiative on Nanotechnology in the year 1988. Meanwhile, different funding programmes exist, e.g. in the context of Interdisciplinary Research Collaborations (IRC) in Nanotechnology and University Innovation Centres (UIC).

[11] see Hullmann 2001, p.168

On the European Union level in the 5th framework programme nanotechnological research projects were funded in different programmes (IST, GROWTH, QoL, etc.) with approx. 50 million € in the year 2001. In the 6th frame work programme nanotechnology funding will rise to annually at least 150 million €, whereby the emphasis will lie in the priority 3 ("nanotechnologies and nanosciences, knowledge based multifunctional material, new production processes and devices") and further in the priorities 1 and 2 ("genomics and biotechnology for health“ and „information society technologies") (BMBF 2002).

Extensive nanotechnology funding in the 6th frame work programme of the EU

2.2.2 USA

The USA occupy the second position regarding the public research funding in the range of nanotechnology scarcely behind Japan (see illustration 1, chapter 2). For the year 2003 a further substantial rise of nanotechnology funding summing up to 710 million $ was announced (IEEE 2002). In the USA the Nanotechnology Initiative was established in the year 2000 (NNI)[12], aiming at the promotion of nanotechnology as an urgent national task.

National Nanotechnology Initiative in the USA

The largest portion of funding is attributable to the National Science Foundation (NSF) as well as the ministries for defense (DOD) and for energy (DOE). Nanotechnology research centers were established in nearly all larger scientific-technological universities and partly also within the non-university range. In some research fields public-private partnerships exist e.g. the SEMATEC consortium within the field of micro/nano-electronics, which is supported by the DARPA and substantial factoring of industrial enterprises (see National Research Council 2002). Several US-American enterprises such as IBM, Hewlett-Packard or Motorola possess their own nanotechnological research centers, which are partly cooperating closely with universities. Beyond that, a multiplicity of smaller enterprises, which were founded e.g. in the context of the SBIR-programme of the Federal Government or other federal programmes, are specialised in distinct nanotechnology areas (e.g. Nanocor, Nanogene, Nanophase, Nanopore, Nanosphere, Nanowave etc.).

2.2.3 Japan and South East Asia

Japan has meanwhile the world-wide leading position in nationally funded nanotechnology research. Both in the application orientated and the basic research range, numerous nanotechnology research programmes were established. Two of the most important nanotechnology research institutions in Japan are the „Joint Research Center for Atom Technology (JRCAT)" and the „Institute for Physical and Chemical Research (RIKEN)“. As central core of the nanotechnology activities in Japan, the

[12] See also www.nano.gov

Nanotechnology Research Institute (NRI) of the National Institute Advanced Industrial Science and Technology (AIST) has meanwhile been founded. Furthermore, several industrial consortia especially in the range of nanoelectronics exist, which strive for bundled research efforts. The main activities in the nanotechnology field in Japan concentrate on material research as well as on metrology (measurement), production and simulation of nanostructures.

In Southeast Asia, particularly in South Korea, Taiwan, China and Singapore intensified activities in nanotechnology research should be likewise noticed. Significant funds are particularly invested in the establishment of an institutional infrastructure, e.g. in China (Nano Network of the Chinese Academy of Sciences), in Taiwan (Nanotechnology Center with emphasis in electronics and materials) and in Korea (Center for Science in Nanometerscale, Nano Bioelectronics & Systems Research Center).

3 NANOTECHNOLOGY ACTIVITIES IN SPACE

In view of the far-reaching innovation potential of nanotechnology and the world-wide boom in nanotechnology funding, the first objective of the ANTARES-study was to investigate, which nanotechnology activities can be determined within the space community. For this a screening of space specific nanotechnology activities was accomplished particularly in Germany, in Europe and in the USA. The basis for the stocktaking were literature-, data base-, and patent searches, research projects and programmes of DLR, ESA and NASA as well as interviews and workshops with experts of the space industry.

3.1 Literature analysis

Selection of databases for the literature analysis

As the first step, a database search was accomplished to determine space-specific nanotechnology research in the scientific literature. For this a search strategy was developed, making it possible to analyse space-relevant aspects of nanotechnology. Two data bases were selected, SCISEARCH (Science Citation Index) and AEROSPACE, which are accessible over the STN services of the information center Karlsruhe. The SCISEARCH data base comprises publications of different journals from the medical, scientific and engineering range and thus comprehensively covers the interdisciplinary field of nanotechnology. However the engineering specific range, in particular aerospace, is only incompletely represented in the SCISEARCH data base. So, as supplementing information, the data base AEROSPACE was searched, which is provided by the American Institute of Aeronautics and Astronautics (AIAA) and covers publications of all relevant ranges in aerospace from over 100 countries.

The search terms were selected in such a way that the topic fields nanotechnology and space are covered in sufficient completeness. As derived from publication analyses described in the literature (see e.g. European Parliament 2002, Hullmann 2001) and own preliminary investigations, relevant nanotechnology publications could extensively be captured with the search term "nano?" ("?" is a truncation character, which permits any further characters, e.g. nanoparticle, nanostructured, nanotubes, nanocrystals, nanowires, etc.). This procedure entails the advantage that the search words are found independent of the way of writing with or without a hyphen (e.g. nano-particle or nanoparticle). Since the topic nanotechnology is defined however relatively broad in particular in Germany, supplementing search terms were added, which indicate a relation to nanotechnology also without the prefix „nano“, e.g. "quantum dot", "quantum well", "fullerene" or also nanotechnologically improved components in the range of electronics and optoelectronics, like HEMT or VCSEL (see table 3).

However, some terms with the prefix "nano" were excluded, which are frequently used in scientific publications without a direct connection to nanotechnology, such as "nano-gram", "nano-second", "nano-meter" (e.g. as unit for wavelength data), "nano-gravity" or "nano-satellite". The term "nano-satellite" was used in a separate data base inquiry, since the topic nano-satellite can be assigned not directly to the nanotechnology but rather to the microsystem technology; but it nevertheless is a point of interest in the context of the ANTARES study. The space technology area was queried for practicable reasons only by using general terms such as "spacecraft", "space system", "satellite", "spaceflight", as the topic field was very broad and multilayered.

The search terms for nanotechnology, which resulted in most scores in linkage with space-relevant search terms in the selected data bases, are summarized in table 3. Based on the results, the database inquiry was accomplished for the publication and patent analysis (see tab. 4 and 5).

The development of the number of publications in context with space-relevant aspects of nanotechnology in the period from 1990 to 2001 is depicted in illustration 2. Here a different picture results for the two data bases used. In the thematically broad and interdisciplinary data base SCISEARCH, a clear rise in the number of relevant publications should be noted since beginning of the 90's, while in the aerospace specific data base AEROSPACE the number of publications has been clearly smaller and relatively constant in the time period. This shows that the topic nano-technology in context with space travel is taken up more frequently in a broad scientific context rather than within the classical aerospace technology ranges. An explanation for this among other things is the fact that the main approach of nanotechnology is the interdisciplinary linkage of biological, chemical and physical research. Nanotechnology research is predominantly still in the range of basic research and the application possibilities in space are at present more or less visionary. Therefore scientific publications of concrete applications within the aerospace range (as cited in the AEROSPACE data base) are rather rare.

Search Term	SCI-SEARCH	AERO-SPACE	USPAT-FULL	EURO-PATFULL	WP-INDEX	Sum
quantum well?	147	45	144	33	18	387
HEMT	23	60	153	69	26	331
nanotube?	1	4	157	4	2	168
nanoparticle?	10	4	66	2	3	85
nanocapsul?	0	0	80	2	0	82
fulleren?	33	9	28	8	1	79
single electron	23	8	34	4	1	70
nanostruct?	14	9	26	2	3	54
nanotech?	6	34	11	0	0	51
nanocrystal?	21	8	17	0	1	47
quantum dot?	26	5	9	3	1	44
magnetoresist?	1	11	28	2	1	43
VCSEL?	1	6	25	2	0	34
nanoscal?	7	2	23	1	1	34
SWCNT?	0	0	27	1	0	28
self assembl? monolayer?	2	1	20	4	0	27

Nanotechnology terms in scientific and patent publications mentioned in connection with space applications

Table 3: Number of hits for nanotechnology search terms in connection with space-relevant search terms in the databases used for the literature and patent analyses.

Search terms	Data base	Hits
(nano? or self assembl monolay? or HEMT or quant? dot? or quant? well? or magnetoresist? or VCSEL or SWCNT? or fulleren? or single electron) not nanometer? not nanogra? not nanosatel? not nanosec? not nano-sec?	SCISEARCH	135621
	AEROSPACE	11896
(nano? or self assembl monolay? or HEMT or quant? dot? or quant? well? or magnetoresist? or VCSEL or SWCNT? or fulleren? or single electron) not nanometer? not nanogra? not nanosatel? not nanosec? not nano-sec? and (spacecraft? or satellite? or spaceflight? or space system?)	SCISEARCH	414
	AEROSPACE	296
Nanosatellit? or nano-satellit?	SCISEARCH	17
	AEROSPACE	122

Less than 1% of nanotechnology search terms are mentioned in context with space relevant terms

Table 4: Database searches for analysis of space-relevant nanotechnology publications

Generally it should be stated that the topic space plays a rather subordinated role in the scientific literature in the field of nanotechnology. Less than one per cent of the nanotechnology publications, which are indicated in the data base SCISEARCH, have a textual connection with space technology (see table 4).

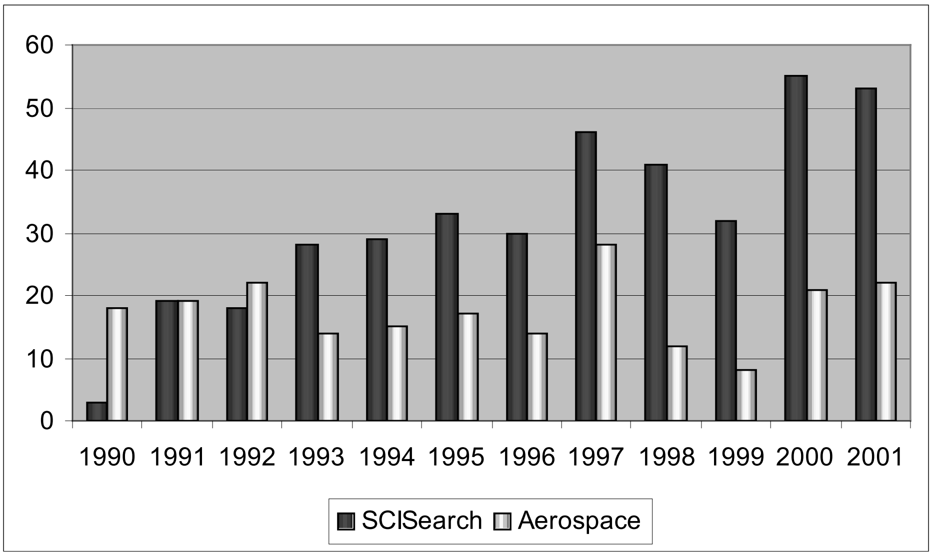


Illustration 2: Number of space-relevant nanotechnology publications from 1990 to 2001, for explanations see text above

The development of the number of publications containing the term "nano-satellite" shows that the topic was taken up in the scientific literature to a significant extent since 1995 with a substantial rise in the year 2000. In this case the number of relevant publications in the database AEROSPACE was significantly higher than in the data base SCISEARCH.

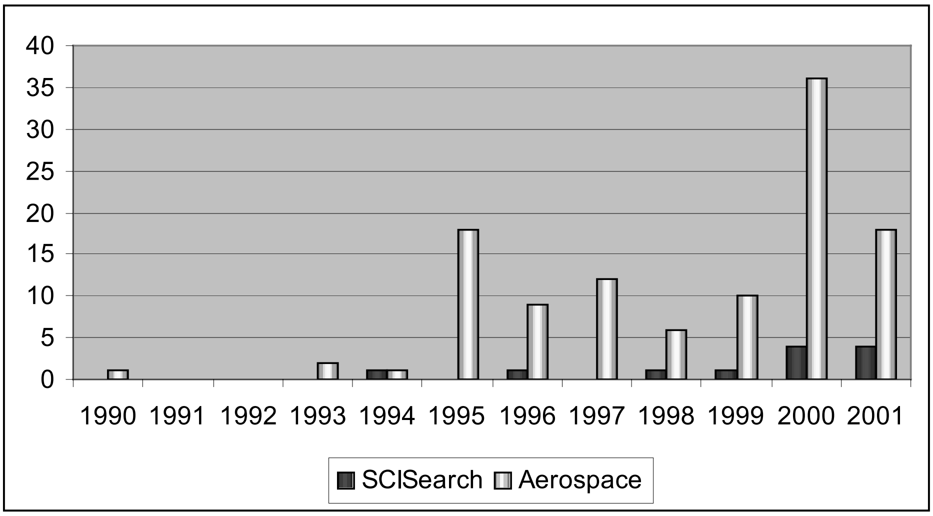


Illustration 3: Number of publications containing the search term „Nanosatellite" from 1990 to 2001, for explanations see text above

3.2 Patent analysis

Besides scientific publications about space-relevant nanotechnology developments also patent applications were of interest within the ANTARES study. Patent specifications contain first indications of the state of the art changing developments, of nascent markets as well as of changes in the competition. Interesting in this context is in particular the temporal development of patent publications, from which early indications of innovations and market changes can be derived. To be considered here is that the process from the patent application to the market readiness of the appropriate product could take up to seven years, depending on different factors, like the importance of the invention, the kind of industrial branch and the company size (see Haeusser 1984).

The patent analysis was accomplished both at international level and separately for the leading space-technology nation USA as well as for Europe. As data sources here, the data bases WPINDEX of the world patent office WIPO, USPATFULL of the US patent office USPTO as well as EUROPATFULL of the European patent office EPA were used. The two latter data bases have the advantage that full texts of the patent documents are searchable and thus contain more searchable information.

In order to analyze patent applications regarding space-relevant applications of nanotechnology, the following search strategies were applied:

- Search for nanotechnology applications within IPC (International Patent Classification) B64G (Cosmonautics; vehicles or equipment therefore)
- Search for space applications within IPC (International Patent Classification) B82 (Nanotechnology)[13]
- Search for terms in context with nanotechnology and space in all patent classes (see table 5)

For the patent analyses the same search terms were used as for the literature analysis (see 3.1). For the search without restriction of the patent classification, the group B41J ("Typewriters; Selective Printing mechanisms...") was excluded, because a multiplicity of hits resulted from the phrase “satellite drop", which designates a problem within ink jet printer technology and therefore has no relevance for space technology. The search strategies and their results are summarized in table 5.

The following results were achieved:

- Within the space technology classification (IPC B64G) nearly no patent applications relating to nanotechnology exist.
- Within the nanotechnology classification (IPC B82B) no patent ap-

[13] IPC B82 was introduced as patent classificaion in the year 2000

plication relating to space technology exist.

- In the remaining patent classifications a substantial number of documents should be registered, which deal with both aspects of nanotechnology and space.

Within space technology patent class there are few nanotechnology patents

In other patent classes a multiplicity of patents with an indirect relation to nanotechnology and space exists

No.	Search terms	Database	Hits
1	B64G/IC and (nano? or self assembl monolay? or HEMT or quant? dot? or quant? well? or magnetoresist? or VCSEL or SWCNT? or fulleren? or single electron) not nanometer? not nanogra? not nanosatel? not nanosec? not nano-sec?	WPINDEX	1
		USPATFULL	12
		EUROPATFULL	4
2	B82B/IC and (spacecraft? or satellite? or spaceflight? or space system?) not nanometer? not nanogra? not nanosatel? not nanosec? not nano-sec?	WPINDEX	0
		USPATFULL	0
		EUROPATFULL	0
3	(nano? or self assembl? monolayer? or HEMT or quantum dot? or quantum well? or magnetoresistiv? or VCSEL or SWCNT? or fulleren? or single electron) and (spacecraft? or satellite? or spaceflight? or space system?) not nanometer? not nanogra? not nanosatel? not nanosec? not nano-sec? not B41J/IC	WPINDEX	63
		USPATFULL	748
		EUROPATFULL	168
4	Nanosatel? or nano-satel?	WPINDEX	5
		USPATFULL	11
		EUROPATFULL	1

Table 5: Database searches for the patent analysis of space-relevant nanotechnology applications

Although a significant number of patent documents could be identified, in which both nanotechnology as well as space search terms appear (especially in the database USPATFULL), no accurate statement can be made about the kind of linkage of the two topics and their relevance for the patent application without further analyses. The fact that in the database WPINDEX, which contains more compressed information than the full text databases USPATFULL and EUROPATFULL, the number of hits is significantly smaller than in the other data bases, shows that the core content of the patent application often does not deal with space-relevant nanotechnology applications. Only a full text analysis reveals a significant number of patent documents containing both nanotechnology and space-relevant search terms. It should be mentioned that in this context patent applications in the USA are significantly higher than in Europe, which is a logical consequence of the fact, that the USA is the world leading space nation.

The temporal development of patent applications in the context of space and nanotechnology shows a remarkable increase in the last years in particular for the USA (see illustration 4). This indicates innovative developments within some fields of nanotechnology which may have implications for space technology in the future. To derive more concrete statements, it was analysed to which patent classification the identified patent documents can be assigned. Here the main classification (IPC Main index) of the patents was queried, which indicates, to which field of technology the innovation basically refers to. The analyses were performed only for the database USPATFULL of the US-American patent office, as by far the most hits were registrated in this database.

Significant increase of patents with an indirect relation to nanotechnology and space in the USA

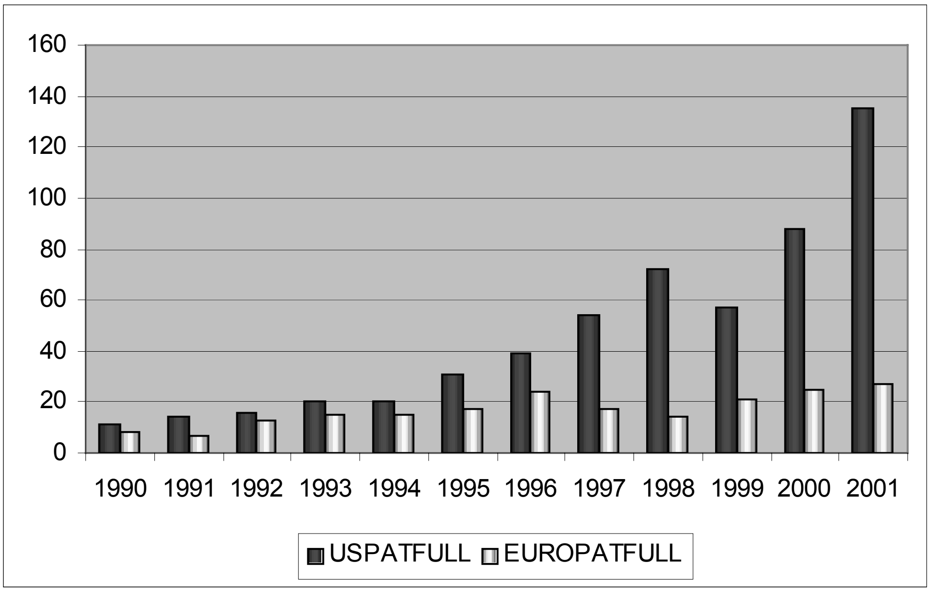
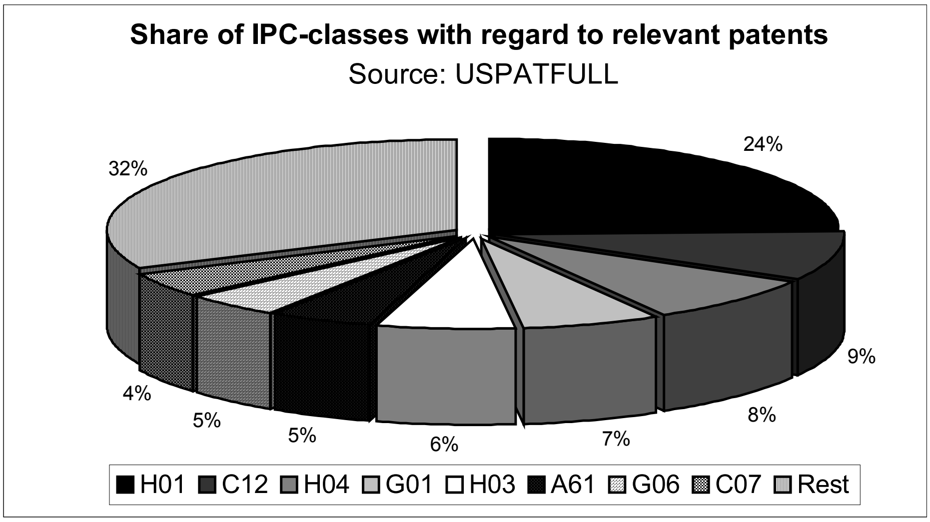


Illustration 4: Number of patent applications containing space and nanotechnology relevant search terms from 1990 to 2001. For further explanations see text above



H 01	BASIC ELECTRIC ELEMENTS
C 12	BIOCHEMISTRY
H 04	ELECTRIC COMMUNICATION TECHNIQUE
G 01	MEASURING; TESTING
H 03	BASIC ELECTRONIC CIRCUITRY
A 61	MEDICAL OR VETERINARY SCIENCE; HYGIENE
G 06	COMPUTING; CALCULATING; COUNTING
C 07	ORGANIC CHEMISTRY

Illustration 5: Breakdown of relevant patent applications with regard to IPC-classes

The relevant IPC-classes can be assigned roughly to the following technology fields:

- Electronics, Data Processing and Communication
- Biochemistry, Medicine
- Physical Measuring Techniques
- Chemistry, Materials

A further breakdown of patent classes to patent groups shows, that the following patent groups constitute a portion of over one per cent of the total number of identified patent documents (arranged according to descending hit frequency):

IPC-Group	Description
C 12 Q001-68	Measuring or testing processes involving enzymes or micro-organisms involving nucleic acids
H 01 L021-00	Processes or apparatus adapted for the manufacture or treatment of semiconductor or solid state devices or of parts thereof
C 07 H021-04	Compounds containing two or more mononucleotide units having separate phosphate or polyphosphate groups linked by saccharide radicals of nucleoside groups, e.g. nucleic acids
H 01 S003-19	Semiconductor lasers comprising PN junctions, e.g. hetero- or double- hetero-structures
H 04 B010-00	Transmission systems employing beams of corpuscular radiation, or electromagnetic waves other than radio waves, e.g. light, infra-red

Table 6: IPC-Groups of relevant patent documents with a portion of more than one per cent of the total number of identified patent documents (Source: USPATFULL)

From that analyses it can be derived that a significant number of patent applications in the context of space and nanotechnology can be assigned to the following topics:

- Satellite communication systems (semiconductors and optoelectronics for data communication)
- Biomedical testing procedures with application potential in manned and unmanned space flight

Here again it should be stated that the main application ranges of the identified patent documents lie outside space applications and that only a full text analysis of the patent documents reveals a relation to space and nanotechnology.

3.3 National activities

In the German space community nanotechnology is regarded rather as subordinated topic of microsystem technology

In Germany up to now there are few contacts between nanotechnology and the space community. The past efforts for the miniaturization of space systems and components should be assigned to the micro system technology. The micro system technology (MST) meanwhile has achieved a high market readiness and the worldmarket volume of MST products is estimated at approx. 40 bn $ according to a market study carried out in the year 2002 (NEXUS 2002).

The main application ranges of MST are information technology, biomedicine, automotive manufacturing and telecommunications. Space only represents a niche market for the MST due to the small quantities. Nevertheless intensified efforts for utilizing MST for space technology are made within the space community. Main objectives in this context are possible savings of weight and power consumption as well as a higher functionality. In Germany, activities in this field have been registered since the mid 90's, e.g. in the frame of the RAMES study of the DARA (DARA 1995), which examined and evaluated micro system technologies for the miniaturization of individual satellite modules as well as the application potential of nanosatellites. The RAMSES study however dealt only in a few aspects with Nanotechnology, e.g. the development of acceleration sensors based on nanoscale tunneling tips.[14] In the frame of the activities of the DLR research institutes, nano-technology is pursued so far rather in single aspects than systematically. Although meanwhile four DLR institutes have become members of the network of nanotechnology competence centers, concrete nanotechnology projects are rare. As examples for nanotechnology activities of DLR institutes the characterisation of ultra-precise surfaces under space conditions can be mentioned (project SESAM of the DLR Institute of Flight Guidance in Braunschweig, see section 5.6.2) as well as the application of nanomaterials and nanolayers for space technology (e.g. the development of nanostructured layers for heat-insulating in rocket engines, see section 5.3.2, or the use of aerogels as mould material for the investigation of solidification processes in metallic alloys[15]). Beyond that, some connecting points exist in the framework of nanotechnology projects funded by the BMBF (e.g. within the ranges quantum dot solar cells[16], quantum dot IR detectors or supercaps [17]). The Bavarian research foundation supports a joint project for the development of ceramic nanocomposites for high temperature rocket engines with participation of Astrium, further space companies and some nanotechnology research institutes. Furthermore, nanotechnology is promoted as a topic in the frame of the DLR activities relating to the (industry-close) utilization of the international space station. In this context a workshop was organized by the DLR in the year 2000, where both the use of the international space station as a research instrument for nanotechnology as well as applications of nanotechnology for space technology were discussed (DLR 2000). Also in the context of the ISS forum from 5.to 7. June 2001 in Berlin, nanotechnology was a topic.

RAMSES study of DARA in the mid 90's

Some connections to space applications in the frame of BMBF funded nanotechnology projects

[14] see RAMSES-Study, p.2.1-15 (DARA 1995)
[15] DLR Institute for Space Simulation, (http://www.kp.dlr.de/WB-RS/Erstarrung/web_dt/aerocast_dt.html)
[16] BMBF-Project: „Self-organized growth of Si/Ge Islands on Si for high efficient solar cells“ BMBF-FKZ 13N7869
[17] BMBF-Project: „Nanostructured thin layer electrodes for advanced supercaps“, BMBF-FKZ 03N3076A/2

3.4 Activities at European level

At European level, nanotechnology is so far understood by the space community similar to the German viewpoint, rather as a long-term subordinated topic of the micro system technology. The past quite extensive activities of the ESA aiming at the miniaturization of space systems, which is regarded as one of the priority goals within the space community, are to be assigned so far almost exclusively to the micro system technology range. Since 1995 the ESTEC organized three round-table meetings on "Micro/Nano Technologies for space", dealing with applications of the micro- (only partly nano-) technologies for space components and systems in the range of communication, energy production and storage, propulsion and scientific payload (ESTEC 1995, ESTEC 1997, ESTEC 2000). After the first phase of the MST activities performed by the ESA until the end of the 90's, where knowledge diffusion and first development steps were the main objectives, the demonstration and utilization of the MST in space shall be the primary goal in the next phase starting from 2001 (see Manhart 2001).

MST activities of ESA

In the AURORA programme of the ESA, which aims at developing a long-term strategy for the exploration of the solar system with manned and unmanned missions, nanotechnology however will have a stronger impact. This applies in particular to the range of material technologies, e.g. the evaluation of nanocrystalline materials, nanocomposites as well as biomimetic self-healing materials. Appropriate roadmaps and technological requirements for space aplications are in development at present.[18] A German participation in the AURORA programme however is not planned at present.

AURORA programme of ESA at present without German participation

3.5 Activities of NASA

In the USA, which spent approx. 600 million $ public funds on Nanotechnology in the year 2002 in the framework of the NNI, nanotechnology has substantially higher importance for space technology than in Europe. This for example is manifested through the fact that NASA had its own nanotechnology budget of 46 million $ in 2002. The nanotechnology research of NASA can be assigned to four main directions:

46 Mio. $ per year NASA funds for nanotechnology

- Materials (11 Mio. $, controlled by NASA Langley Laboratory)
- Electronics and data processing (15 Mio. $, controlled by NASA Ames Laboratory)
- Sensors and Components (10 Mio. $, controlled by NASA Jet Propulsion Laboratory)
- Basic research

[18] Personal communication of F. Ongaro (ESA) from 07.06.2002

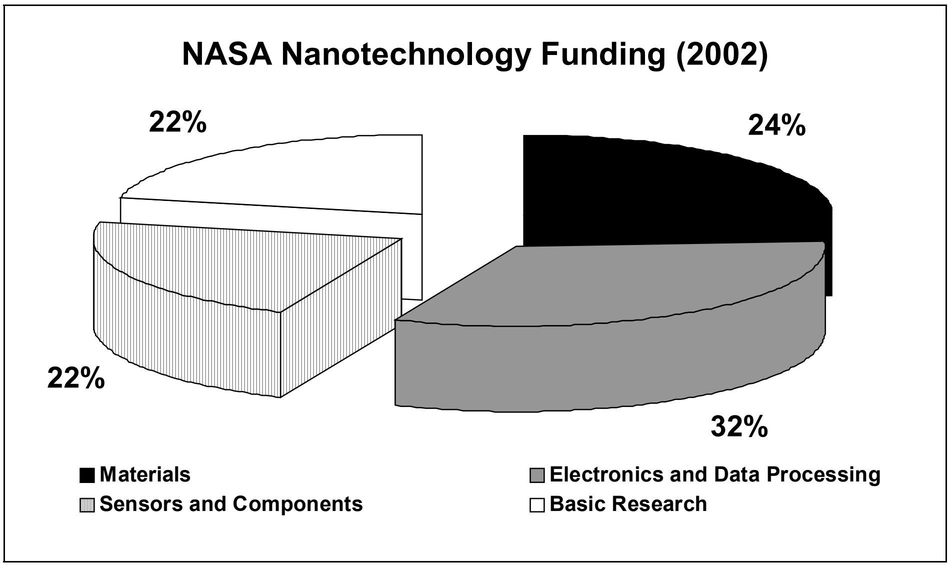


Illustration 6: Planned Distribution of 46 Mio. $ nanotechnology funds of the NASA in the year 2002 (Source: Roco 2001)

Long term nanotechnology objectives of NASA

Many of the nanotechnology objectives of NASA aim at a long-term time horizon and are more or less visionary at present. One main goal is a significant increase in spacecraft capabilities with simultaneous mass reduction and miniaturization, which can not be achieved with conventional technologies. A new era of robotic exploration of the solar system is to be proposed by application of nanotechnology among other technologies through the development of small economical spacecrafts with high autonomy and improved capabilities. Furthermore, nanotechnological diagnostics and therapy procedures will improve life support systems and an autonomous medical supply of astronauts which will pave the way for long-term and more complex manned space missions. Nanotechnological roadmaps of NASA reach up to 20 years into the future (see illustration 7).

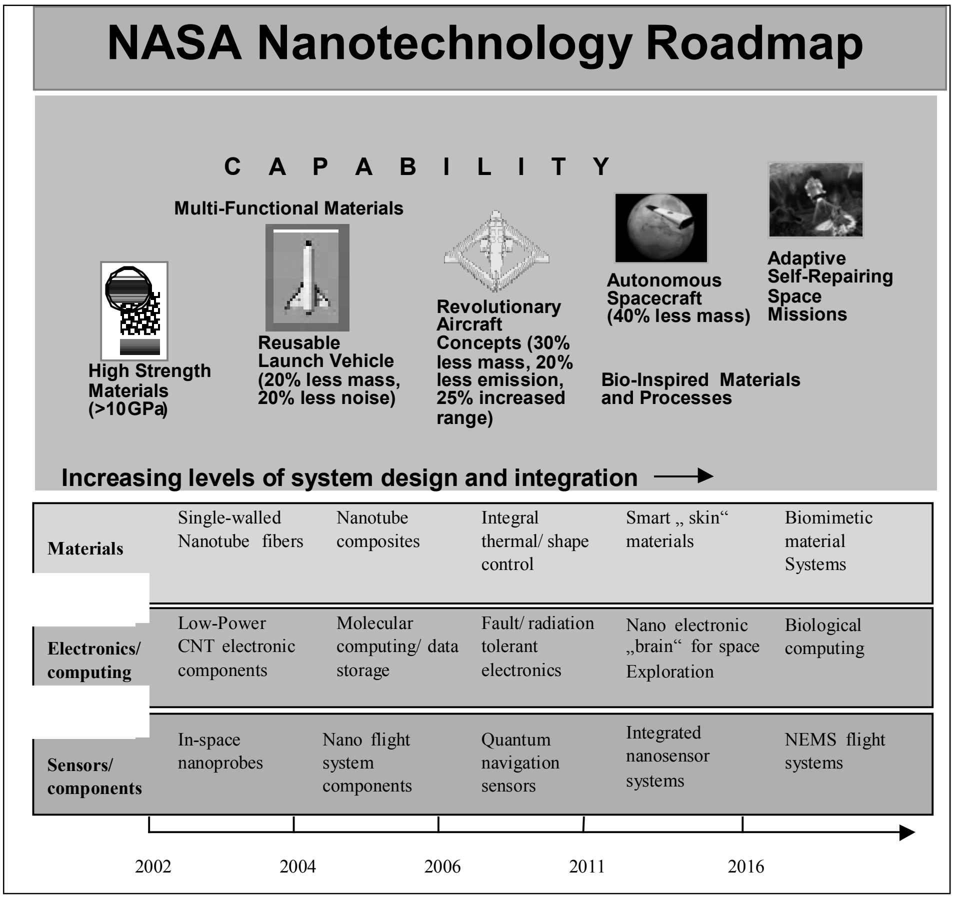


Illustration 7: NASA Nanotechnology Roadmap (Source: Center for Nanotechnology, NASA Ames Research Center 2001)[19]

The long-term nanotechnology research approaches of NASA, most of which are at present still in the range of basic research, are based predominantly on "Bottom up" strategies of the molecular nanotechnology. That is to be understood as the controlled building of materials and structures from molecular components by linkage of physical, chemical and biological principles. The control and technical utilization of molecular-biological functions and self assembly phenomena play an important role here. The vision of intelligent, adaptive and evolvable space systems as proposed by NASA scientists are based on the convergence of nanotechnological, biotechnological and information technological research fields (see illustration 8).

[19] (http://www.ipt.arc.nasa.gov)

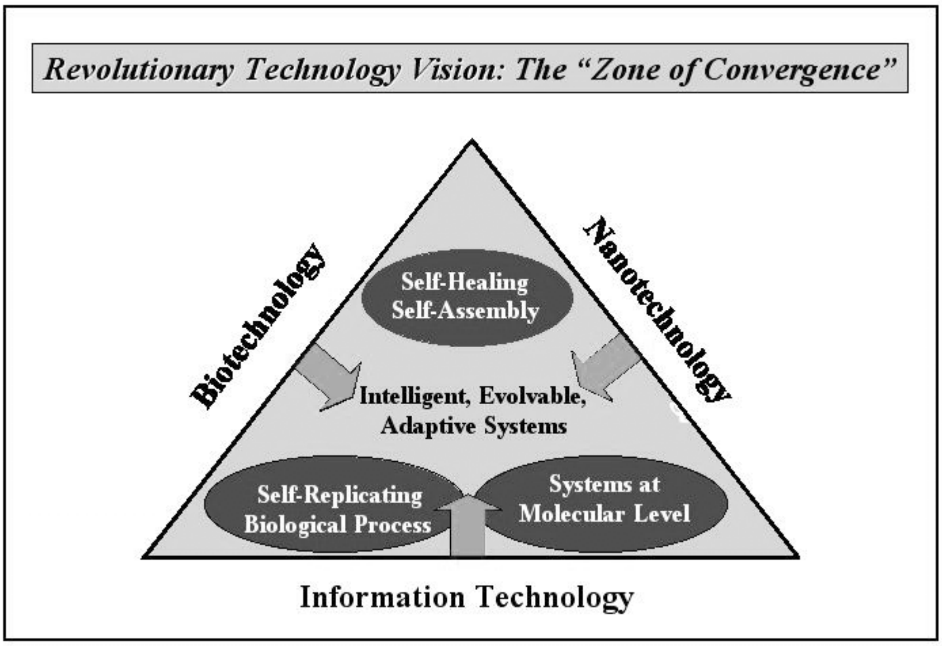


Illustration 8: Visionary technology developments by convergence of nanotechnology, biotechnology and information technology (Source: NASA 2001)

Main areas of NASA nanotechnology research are (see figure 9):

- Nanomaterials (high strength materials, materials with programmable, intrinsic sensing and compensating properties etc.)
- Nanoelectronics (data processing and communication systems with minimized energy consumption, highly integrated nanodevices for miniaturized space systems etc.)
- Biomolecular nanotechnology (Lab-on-a-chip-systems for biomedical and scientific in-situ detection, nanotechnological methods for diagnostic, therapy and autonomous self medication of astronauts etc.)

Critical Nanotechnology Products for NASA

Nanoengineered Materials

- High strength/mass, smart materials for aerospace vehicles and large space structures
- Materials with programmable optical/thermal/mechanical/other properties
- Materials for high-efficiency energy conversion and for low temperature coolers
- Materials with embedded sensing/compensating systems for reliability and safety

Nano Electronics

- Devices for ultra high capability, low-power computing & communication systems
- Low-power, integrable nano devices for miniature space systems
- Bio-inspired adaptable, self-healing systems for extended missions
- Quantum Devices and systems for ultrasensitive detection, analysis and communication

Biomolecular nanotechnology

- Bio-geo-chem lab-on-a-chip for in situ science and life detection
- Nanoscale sensing, assessment and therapeutics delivery for medical autonomy
- Molecule-to-organism bio process modeling, digital human and cybermedicine
- Tools for direct study of space-induced medical effects and countermeasures

Illustration 9: Main themes of NASA nanotechnology research (Source: NASA 2001)

An important element of the nanotechnology research of NASA is the use of materials and components, which are based on carbon nanotubes. For this, a multiplicity of potential applications is postulated within the range of structure materials, nanoelectronics, sensor technology and biomedicine (see NASA 2000), which are described in detail in chapter 5. NASA will co-operate in some areas with other organizations:

Numerous cooperations of NASA with other federal agencies and private companies

- Materials (DoD)
- Radiation-hard devices and materials (DoD)
- Biosensors, Lab-on-a-chip-Systems, environmental monitoring (DoE, DoD, NIH)
- Drug delivery, non-invasive health monitoring (NIH)
- Miniaturized space systems (DoD)
- Efficient energy generation and storage (DOE)

SBIR-Programme of NASA for short to medium term nanotechnology applications in space

Also in co-operation with enterprises, NASA forwards developments within the range of nanotechnology. Here in particular, the Small Business Innovation (SBIR-) programme of NASA should be mentioned, which promotes technology developments through small enterprises. This concerns predominantly application orientated research for a short to medium-term time horizon. This research deals in particular with applications of nanomaterials and -layers. Also in the frame of SBIR programmes of other US agencies, in particular the DoD, nanotechnological developments are promoted with relevance for the space sector.

4 REQUIREMENTS AND APPLICATION FIELDS FOR FUTURE SPACE SYTEMS

An important criterion for the exertion of potential nanotechnology applications in space is, to what extent these can make a contribution to the implemention of future requirements in space technologies and systems and to the realization of future missions in space travel.

4.1 Space technology demands

In the following, some substantial requirements for future space travel technologies and systems are summarized, which were defined by the European Space Agency (see ESTEC 1999, ESA 2001) and to which nanotechnology could contribute significant solutions.

4.1.1 Cost reduction

4.1.1.1 Space Transportation

The main starting point for the cost reduction in space travel are savings in space transportation by reduction of mass and volume of spacecrafts and payload. At present, the costs amount to approx. 10.000 to 20.000 €/kg for transport into the earth‘s orbit (Janovsky 2001). Therefore a high incentive results for the miniaturization of spacecraft, which is possible in principle both on the level of components and modules as well as whole spacecrafts. Regarding the miniaturization of complete space systems at present, so called „Nano“-satellites (m< 10 kg)[20] and even „Pico“-satellite (m< 1 kg) were examined, which possess as independent satellites among other things their own propulsion and control systems. The development of such satellites makes a progressive miniaturization of all subsystems and the supply of efficient and lightweight power supply systems necessary. The miniaturization of satellites however only makes sense if the payload can be miniaturizised without capability losses. This is for example not the case, if large antennas for observation or communicaton are necassary or large solar cell panels are needed for the power supply. As further critical factors concerning the miniaturization of the payload, a sufficient signal response of instruments, devices for the cryogenic cooling of detectors or the equipment for the on board data handling should be mentioned.[21] Nanosatellites are thus generally only suitable for special applications and missions. In the RAMES study (DARA 1995), as promising reference missions for nanosatellites, the detection of space debris or the measurement of the earth's magnetic field vector were

Miniaturization of satellites

„Nanosatellites"

Limitations of miniaturization

[20] The definition of nanosatellites with a mass range of 1 to 10 kg is not unequivocal, some sources refer to other mass ranges e. g. up to 20 kg, see Caceres 2001)

[21] see „Space Instrument Size Drivers“ NASA Instrument and Sensing Technology http://ranier.hq.nasa.gov/

proposed among other things. Up to the year 2000, more than 20 nanosatellites were launched worldwide primarily for universitary or military research purposes. Meanwhile, also first beginnings of a commercial use of nanosatellites appear, operating for example from carrier platforms in space (Caceres 2001). On a long-term time horizon the application of nanosatellite swarms and constellations, which form huge high-performance sensor networks as „virtual satellites“, seems to be very promising. The following tasks and application fields for nanosatelllite swarms can be mentioned:[22]

Swarms of nanosatellites for visionary space applications

- Simultaneous wide-area measurements for earth observation or planetary exploration
- Sensor networks distributed over large orbit segments, which form a huge "virtual" sensor (for example for 3-D photographs)
- Swarms of co-operating small satellites, which form giant optical or microwave based devices for observation and communication missions

The potential of micro-/nanosatellite swarms is the subject of current investigations in the space community and will gain importance in the future. The ESA at present is in the phase of preliminary studies and prepares calls for proposals on this topic.

Trend to ever heavier satellites is limited by technological and economical barriers

High demand for mass and energy savings in space

While the miniaturization of complete satellites is suitable only for special tasks, the reduction of weight and volume as well as energy-savings can generally be regarded as a priority objective for cost reduction in space. At present, however, a contrary development at least within the range of the telecommunications satellites occurs, where a trend to ever larger and heavier satellites can be observed. But in this context, more and more technical and financial borders arise from rarely manageable huge solar cell panels, problems with the heat dissipation of electronics as well as capacity bottlenecks of the carrier systems for space transportation. Therefore the need for lightweight, smaller and energy-saving space systems will grow in the future. Nanotechnology could contribute solutions in this context in many areas, e.g.:[23]

- Data processing and system control (highly integrated avionics, wireless data communication, sensors etc.)
- Energy generation and storage (e.g. solar cell and fuel cell technology)
- Structure and thermal control elements (lightweight materials, miniaturized cooling loops and heat exchangers)
- Propulsion (electric propulsion technologies, MEMS-propulsion technologies)

[22] personal communication Dr. Schlitt OHB-System AG, Bremen, March 2002
[23] see Creasey et al. 2001

Data processing and control systems are the main energy consumers in spacecrafts. The development of miniaturized energy saving electronics could therefore lead to mass-savings through secondary effects for other subsystems (e.g. energy production, structure, thermal control elements). Further mass savings are expected by wireless data communication and highly integrated electronics. Within the range of systems for energy production, storage and distribution, which constitute up to 30 % of the dry weight in today's satellites, a further mass reduction can be obtained not only by energy-saving electronics but also by an increased efficiency. Reduction of mass can also be achieved within the structure range. New construction techniques e.g. grid construction instead of conventional sandwich constructions could lead to mass savings up to 60 % according to estimations of the ESA (Creasey et al. 2001). As explained in more detail in chapter 5, nanotechnology in a mid to long term time scale could also contribute significantly to mass savings in spacecrafts by lightweight construction materials, high-efficient energy production and storage technologies as well as energy saving highly efficient electronic components.

On a mid to long term scale significant mass savings are expected by the use of nanotechnological components and materials

A further starting point for reduction of costs in space transportation is the development of re-usable space transport systems, which require among other things an advancement of re-entry technologies (e.g. reusable, high temperature-resistant components such as heat control surfaces and shields).

4.1.1.2 On-Board Autonomy

By increasing the on-board autonomy of spacecrafts, (e.g. autonomous attitude and orbit control, payload data processing, health monitoring of astronauts etc.) the operating costs for routine operations and fault corrections could also be lowered. This could be achieved by nanotechnologically improved information and communication technologies and sensor technology.

Cost reduction by increased on-board autonomy

4.1.1.3 COTS-Technologies

Further cost savings can be realized by using of COTS (Commercial off the Shelf) technologies. Cost-intensive technology developments, e.g. within the ranges of micro- or nanotechnology, are usually not feasible for the space sector due to budget restrictions. In these cases the space sector acts no longer as „technology pusher" but rather as a „technology follower“ which examines market-ready technologies regarding their suitability for space applications and adjusts them for the specific space conditions. For this, application-specific modifications as well as space qualification of the terrestrial components have to be performed, to guarantee the required reliability and durability under the extreme space

Space sector in the range of nanotechnology rather a „technology follower" than a „technology pusher" conditions (radiation, vacuum, mechanical impacts and vibrations, extreme temperature gradients etc.).

4.1.2 Increased capabilities

Improved capabilities of future space systems are a further substantial objective both for scientific and commercial applications. In context with possible applications of micro-/nanotechnologies, innovation task forces were established by the ESA dealing with the following topics:

- Improved communication performance
- Instruments and sensors breakthroughs
- Innovative components and materials
- Intelligent space systems operation

The objectives of these innovation task forces will be described in the following.

4.1.2.1 Improved communication performance

Within the range of satellite telecommunications the aim is a drastic increase of transmission capacity and efficiency, in order to supply broadband communication services especially for mobile users and to manage the increasing data flood within the range of scientific space missions. Main starting point for this is the use of higher frequency ranges not only in the EHF range of conventionally used radio-/microwaves, but also in the optical frequency range in particular in the near infrared (NIR). The transition of radiowaves with working frequencies of about 40 GHz to optical satellite communication with frequencies of approx. 193 THz in the NIR range would increase the transmission capacity by several orders of magnitude. Also regarding size-, weight- and energy-savings, optical data communication offers clear advantages. To realize the potential of optical data communication, optical intra- and inter-satellite links as well as intersystem connections to ground stations have to be established.

Optical data transmission for future satellite communication systems

Optical intersatellite links in space have already been successfully demonstrated by the SILEX terminal in the context of the ARTEMIS mission of the ESA (ESA 2001). The technological advancement of optical telecommunication systems is promoted by the DLR in the context of the LCT/MEDIS programme. One objective of the MEDIS mission is to demonstrate an optical inter-satellite link with a high data transmission rate between the European ISS module Columbus and a MEO satellite (Smutny et al. 2002). While optical intersatellite links thus have already been demonstrated, the realization of an "all optical" satellite communication still is far away. To be mentioned here for example is the transmission of optical signals from space to terrestrial ground stations, which is possible only with a cloudless sky due to light absorption in the atmosphere. This problem may be solved by a high redundancy of ground stations, sited on mountain summits in different regions, to increase the

Optical Intersatellite links demonstrated by ESA in the frame of the ARTEMIS-Mission probability of a functioning data-link (Bland Hawthorn et al. 2002). In addition the availability of space-qualified micro-optoelectronic components such as lasers, amplifiers and modulators has to be improved significantly.

4.1.2.2 Instruments and sensors breakthroughs

One focal point of the scientific and increasingly also commercial space applications is the earth observation. In this field improved instruments and sensors shall allow new applications in the future. Technological objectives to be mentioned in this context are (see Roederer 2001):

- a significant reduction of mass, ernergy consumption and costs of the instruments,
- improved detection methods in particular from geostationary orbit in the optical and microwave frequency range
- improved data communication and on-board data handling

Concrete technology developments are pursued e.g. for improved LIDAR systems (laser, new active components etc.), innovative optical sensor systems (micro-optical systems, camera-on-a-chip etc.) as well as for microwave sounding technologies from the GEO (antennas, front-end etc.). In this context the application of micro system technology will play a central role.

4.1.2.3 Innovative components and materials

The topic „innovative components and materials" deals in particular with:

- innovative methods for three-dimensional integration of electronic components in compact modules (3 D Stacking),
- wide-band-gap semiconductor components (e.g. SiC, GaN)
- evaluation of MEMS for space application[24]

WBG semiconductors for radiation hard electronics

In particular within the range of WBG semiconductors, nanotechnological processes for the production of electronic components such as transistors, diodes and lasers will be essential. Components from WBG materials possess better characteristics compared with conventional semiconductors (e.g. GaAs) like an increased breakdown voltage, a better thermal conductivity, a higher temperature working area and radiation hardness. Thus on the one hand smaller and more efficient electronic components for applications under harsh conditions, e.g. for electronics in the proximity of rocket engines, and on the other hand also improved opto-electronic components within the UV range will be possible.

[24] see Boetti et al. 2001

4.1.2.4 Intelligent space systems operation

In the frame of the Innovation Task Force „intelligent space system operations“ the following objectives are pursued:

- increased „system-intelligence“ (on-board autonomy, intelligent fault recognition and correction, increased fault tolerance and autonomy of the spacecraft crew etc.)
- remote controlled/ tele-present operations (user-interfaces for intelligent information and visualization systems, improved tele-manipulation systems, data capture and compression technologies etc.)
- suitable „End-to-end“-system architectures (for the autonomous operation of space systems e.g. for formation flights of satellite constellations, the monitoring of space transportation and reentry systems, the payload operations etc.)
- innovative space systems (miniaturized inspection probes for satellites or the ISS, innovative robotic systems for the exploration of space

The objectives aim at a long-term time horizon for future European space missions. Connecting factors to nanotechnology exist particularly in the development of high-performance and energy-saving data processors, storage and transmission as well as nanotechnological sensors.

One of the most important aspects for increased capabilities of space systems is an improved power supply, which is needed in particular within the range of telecommuncation satellites. For this on the one hand, high-efficient, lightweight and durable energy generation and storage systems (solar arrays, fuel cells, batteries and supercapacitors) must be made available and on the other hand the energy consumption of the space systems must be reduced by means of miniaturization. Since components of the energy generation, storage and distribution constitute at present up to 30 % of the mass of satellites, this would also contribute substantially to the cost savings by reduction of the launch mass (see chapter 4.1.1).

4.1.3 Lowering of mission risks

Nanomaterials and nanotechnologically improved sensors for more safety in future space systems

The costs of payload development for space missions and of the space transportation are usually very high, so that a reduced mission risk is given a high priority. An important objective is therefore an increased reliability and durability of space components and systems. This might be achieved for example by improved fault recognition and correction methods as well as an increased fault tolerance. Here nanomaterials with improved mechanical and possibly intrinsic fault recognition and self-healing properties as well as nanotechnologically improved sensors could supply a substantial contribution. A further possibility of lowering the risk of space missions is to increase the redundancy of space components and systems. For example, if the mission task would be distributed among a multiplicity of small satellites, the loss of one satellite would be far less serious than if only one satellite would be used, whereby its loss would usually cause the entire mission to fail. Beyond that the capability of the whole system could also be increased by a network of small co-operating satellites (see chapter 4.1.1). In this context miniaturized spacecrafts (nano-, pico-satellites, inspection probes, etc.) will play an important role in the future.

4.1.4 Innovative system concepts

A further objective within the range of the space technologies is the realization of new system conceptions for different targeted applications. For example, the following space systems are under discussion, which partly possess visionary character:

Visionary space systems based on nanotechnology applications

- Constellations and swarms of miniaturized satellites and probes („nano“-, „pico“-satellites, „flying chips“ etc.)
- Stratospheric platforms (aerostats and gliders) for altitudes up to 45 km to complement satellites in some specific applications
- Gossamer Spacecrafts (very large light and self-unfoldable space systems with integrated subsystems e.g. thinfilm solar cells or phased-array-antennas) with applications in telescopes, mirrors, antennnas, starcovering-structures for the detection of planets outside the solar system, solar sails, solar power plants in space (e.g. European Sail Tower or NASA Sun Tower)
- Inspection probes, controlled either by the ground station or the spacecraft crew, for maintenance and monitoring of the spacecraft (satellite, space stations etc.) and/or the exploration of space objects (planets, meteorites etc.)
- Space elevator (visionary conception, consisting of a cable, which has its center of gravity in geosynchronous orbit and is manufactured from ultra strength materials with extremely high strength-to-weight ratio, like for example carbon nanotubes exhibit on molecular level, (see chapter 5.2.1.2)

4.2 Space application fields

The implementation of nanotechnology for space applications will depend strongly on the development of commercial space activities and the realization of demanding scientific missions (e.g. manned Mars mission) in the future. Impulses could arise in particular from the commercial range, for which a substantial rise of the world market volume up to approx. 150 billion $ is prognosticated for the year 2005 (ISBC 2000, see chapter 5.8.4).[25]

[25] This figure seems to be overestimated with regard to the current market trend, in particular in the range of telecommunication satellites

The telecommunications sector will take the largest portion of the commercial sector with satellite-based broadband multimedia services (television, video conferences, Internet etc.) and mobile communication applications, followed by satellite navigation and positioning and earth observation (meteorology, geographical information services etc.).

In addition, within the scientific range, missions are discussed which can only be implemented with achievement of technological breakthroughs in the range of nanotechnology as well. In the following, the main tasks of the space application fields are summarized in the light of respective technology programmes of the ESA (ESTEC 1999) and the BMBF (BMBF 2001). These seven topic fields of space form the basis of the confrontation of space technology requirements with potential applications of nanotechnology as shown in chapter 5.1.

4.2.1 Earth observation

Satellite based earth observation for commercial and scientific applications

The earth observation serves both application orientated/commercial and scientific purposes. The application orientated earth observation covers uses within the ranges of meteorology and oceanography, environmental monitoring as well as safety-relevant clearing-up. Additionally, a stronger commercialization of earth observation services is aimed at, e.g. within the ranges of mapping for agriculture and forestry ("precision farming"), raw material exploration, land resource management and disaster monitoring. The scientific earth observation serves the fundamental investigation of atmospheric and biospherical processes, e.g. mechanisms and dynamics of the depletion of the stratospherical ozone layer or the anthropogenic influences on the global atmospheric warm up. The technological base for these earth observation services is formed by satellite based optical, infrared and radar detection systems (e.g. Terra-SAR, Rapid-Eye etc.).

4.2.2 Telecommunication

Satellite telecommunication to supplement terrestrial communication networks

In the field of telecommunications the emphasis is put on broadband multimedia applications and on mobile communication services. Satellite-based services supplement here the terrestrial communications network within some areas (in particular for thinly settled or difficultly accessible regions):

- GEO-systems for less interactive „asymmetric“ data communication (television, video-on-demand etc.)
- Networks of satellites in near-earth orbits for interactive highspeed applications (e.g. „Internet in the Sky“) by using optical intersatellite links
- Mobile satellite communication services (e.g. S-UMTS)

From a German view a focus is put on optical intersatellite links in the framework of the demonstration project COMED, serving to develop critical technologies and components with the goal of opening up new markets for the German space industry, ensuring its global competitivness and increasing the German market share of satellite components and subsystems significantly within five years (BMBF 2001).

4.2.3 Navigation and positioning

Planned European satellite navigation system GALILEO

Within navigation and positioning, the establishment of the civilian European satellite navigation system Galileo, is the priority objective of the ESA and the DLR, in order to become independent of nationally controlled systems. Here, a strong commitment from the private industrial sector is aimed at. Applications are expected particularly in the establishment of intelligent traffic-guidance-systems for safer, environmentally friendly and more efficient traffic management. Especially for sensitive application areas like automatic landing aids for airplanes, the reliable availability of a positioning system under European sovereignty will be a crucial safety factor for traffic (BMBF 2001).

4.2.4 Science and exploration

In the field of science exploration, the emphasis of ESA activities lies in the investigation of the solar system (in particular Mars and Mercury), astrophysics (especially the search for planets outside the solar system) and fundamental physics (e.g. detection of gravity waves). The exploration of space aims at a better understanding of origin, structure and development of the cosmos and at the same time of origin, conditions and future of our own existence. Observatories in earth orbits allow the observation of the universe and its objects within all ranges of the electromagnetic spectrum without interferences through the earth's atmosphere (multi-frequency astronomy with emphasis in the infrared and x-ray/ gamma range). In this context for example, the ESA will take part in the development of the Next Generation Space Telescope (NGST) in co-operation with NASA, which will be the successor of the Hubble space telescope. In the solar system the study of Mars is of special interest, in order to understand the development of earth similar planets and to draw conclusions for earth by "comparative planetology". Planned for the future, among other things is a Mars Sample Return Mission likewise in co-operation with NASA.

4.2.5 Manned spaceflight and microgravity

In the field of manned spaceflight the participation in the establishment and the utilization of the international space station is the most important goal for the ESA. The European contribution to ISS is in particular made with the completion and operation of the Columbus module and appropriate devices for microgravity research. In addition, the development of robotic systems and probes to support the operation of the ISS are planned by the ESA. As a visionary goal, a manned Mars mission under participation of the ESA is being discussed at present.

Microgravity research for the investigation of gravity dependent phenomena

In the frame of microgravity research the missing gravity force is used for experiments and developments in particular in the range of biology, medicine and material sciences. For this, apart from other manned and unmanned flight opportunities, the international space station is playing the most important role as the "laboratory in the universe". In the life sciences range, an improved understanding of the functions of organs and systems of the human body and their cooperating interactions regarding the adaption to microgravity conditions stands in the center of interest. Investigations for material sciences deal mainly with a detailed understandig of solidification processes as well as fundamental mechanisms of combustion processes. Investigations on three-dimensional colloidal plasmas (plasma crystals), a phase state which was unknown until a few years ago, will mainly examine basic aspects of plasma physics, but in the longer term also application-relevant aspects of industrial plasma processes. A goal in the microgravity research is to increase the participation of private companies by promoting application orientated research with own financial contributions from the participating enterprises. The microgravity research and in particular its potential use for nanotechnology is discussed in detail in chapter 6.

4.2.6 Generic technologies

The topic „general technologies for space travel systems“ covers technological requirements, which are generally aimed at standards for space systems (e.g. cost reduction, improved abilities etc.). These requirements were mainly described in section 4.1 already.

4.2.7 Space Transportation

A superordinate goal of the ESA in the frame of space transport is to secure a competitive and independent European access to space. With the core element of European space transportation activities, the ARIANE programme, the responsibility for the adjustment to the market requirements (e.g. lowering of production costs, increase of the mission flexibility, reliability and transportation capacity) should be transferred increasingly to the industry. A crucial goal for a future generation of space transporters is the significant lowering of transport costs. It is to be expected that this can be realized only with partially or completely re-usable systems. In the frame of the Future Launchers Preparatory Programme of the ESA, technologies for future re-usable space transporters are examined.

ESA investigates re-usable space launch systems

5 APPLICATION POTENTIALS OF NANOTECHNOLOGY IN SPACE

The identified potential applications of nanotechnology in space travel are hereafter described, which could in future contribute substantially to the space requirements and objectives described above. In accordance with setting of tasks, nano-applications are assigned to the appropriate activities of the nanotechnology competence centers in Germany:

- Functionality by means of chemistry (Nanochem)
- Functional ultra-thin films (Nanolayers)
- Applications of nanostructures in optoelectronics (NanOp)
- Production and use of lateral nanostructures
- Ultra-precise surface treatment (Ultraprecise Surfaces)
- Nanoanalytics

The topic areas nano-materials and nano-biotechnology are assigned to the competence center „Functionality by means of chemistry" (CC Nanochem) due to thematic proximity. The fields of activities of the competence centers are partly quite similar, so that a clear separation of the topic fields is not possible. In the following chapters content overlaps are therefore unavoidable. This applies in particular to the range of nanomaterials, since material aspects play a more or less important role in nearly all nanotechnological developments concerned.

In section 5.1 a confrontation of space-technological requirements and possible applications of nanotechnology is shown in the form of a matrix. The identified potential applications of nanotechnology are described in detail in the chapters 5.2 to 5.7 and summarized and evaluated in chapter 5.8.

5.1 Nanotechnology solutions for future space demands

Matrix of space technological requirements and potential nanotechnology applications

In order to get an overview of possible nanotechnology applications in space, space technological requirements are confronted with the working areas of the nanotechnology competence centers in table 7. The space application fields were classified according to the main topics of the "Technology requirement document" of the ESA (ESTEC 1999, see section 4.2).

Nano-Competence Centers (CC) → Space technologies ↓	Nanochem, Nanobio, Nanomat	Nanolayers	NanOp	Lateral Nanostructures	Ultraprecise Surfaces	Nanoanalytics
Earth Observation						
Microwave equipment and antenna technologies						
Components for Limb-Sounder and SAR (Amplifier, diodes, etc.)		√		√		
Optics/Optoelectronics						
Extremely high resolution optics, lightweight Optics, high integrated CCD	√			√	√	
High temperature IR sensors (QD), Microbolometer			√	√		
LIDAR-technologies						
Diode pump laser for solid state laser			√			
Telecommunications						
On-Board equipment technologies						
Components for data communication in the EHF-Band (SSPA, HEMT, HBT, etc.)	√	√		√		
Components for optical data communication, Intra- and Intersatellite links		√	√			
Antenna technologies (e.g. large, lightweight and unfoldable antennas)	√	√			√	
Navigation und Positioning						
On-Board equipment technologies						
Electronic components (e. g. SSPA)		√		√		
Science and Exploration						
In-situ instrument technologies						
Miniaturized instruments for geochemical analyses (e. g. AFM devices)						√
Aerogel for particle detection	√					
X-ray technologies						
Mirrors for X-ray astronomy		√			√	
Laser technologies						
Diode pump laser for ultrastable solid-state lasers (LISA-Mission)			√			
Optical technologies						
Lightweight IR-Optics, high integrated CCD (GAIA Mission)	√	√		√		

Nano-Competence Centers (CC) → Space technologies ↓	Nanochem, Nanobio, Nanomat	Nanolayers	NanOp	Lateral Nanostructures	Ultraprecise Surfaces	Nanoanalytics
Microwave equipment technologies						
Components for radar systems (MMIC, HEMT etc.)	√	√		√		
Manned spaceflight and microgravity						
Life support technologies						
Gas sensors, biochemical sensors, electronic nose	√			√		
Oxygen generation	√					
Waste water and exhaust air treatment	√					
Heat exchanger	√					
Biomedical monitoring of astronauts	√					√
Thermal protection technologies						
Improved thermal protection systems, hot structures and re-entry technologies for earth and mars atmosphere	√	√				
Robotics and automation						
Miniaturized sensors (mechanical, chemical, thermal, radiation etc.)	√	√		√		
Miniaturized and integrated electronics	√	√		√		
Generic technologies						
Structure technologies						
High strength lightweight materials for space structures (MMC, CNT, plastics etc.)	√					
Energy generation and storage						
High efficient solar cells (Multi junction III/V-semiconductor, QD, dye, polymer etc.)	√	√		√		
High efficient fuel cells (SOFC, PEM), hydrogen storage, batteries (Li-Ion, NiH_2), supercapacitors	√					
Thermal Control and Protection						
Miniaturized active control elements	√			√		
High temperature technologies for operations up to 2000 °C (ceramic composites)	√					
Thermal control layers (e.g. DLC)		√				
Propulsion technologies						
Solar sails (thin film technologies, multifunctional layers etc.)	√	√				

Nano-Competence Centers (CC) → Space technologies ↓	Nanochem, Nanobio, Nanomat	Nanolayers	NanOp	Lateral Nanostructures	Ultraprecise Surfaces	Nanoanalytics
AOCS technologies						
High integrated, miniaturized sensors (IR-earth sensor, startracker, gyroscope etc.)	√	√		√		
On-Board data processing and data communication						
Radiation hard microelectronics (e.g. MRAM, SOI, ASICs)		√		√		
Energy saving high performance data processing	√			√		
Mass storage	√	√		√		
Microwave Components for HF-range (transistors, MMIC, SAW-filters etc.)	√	√		√		
Components for broadband downlink (EHF-Band or optical)		√	√	√		
Optoelectronic components (optical couplers, laser, etc.)		√	√			
Space transportation						
Liquid propulsion systems						
Gas sensors for engine monitoring	√	√				
Improved turbopumps and lines	√					
Solid propulsion systems						
Materials for housings and nozzles (e. g. reinforced polymers)	√					
Improved propellants, non-chlorinated, (e. g. aluminum nanopowders)	√					
Materials, thermal protection						
Hot structures and thermal protection for reentry and rocket propulsion (ceramic fiber composites, gradient layers etc.)	√	√				

Table 7: Possible nanotechnology applications for future space technology demands

5.2 Nanochemistry, nanomaterials and nanobiotechnology

The spectrum of nanostructured materials reaches from inorganic and organic amorphous or crystalline nanoparticles over nanocolloids and suspensions up to nanostructured carbon compounds such as fullerenes and carbon nanotubes. In principle all substantial material classes, i.e. metals, semiconductors, glass and ceramics, polymers as well as composites can be produced with nanostructured configurations. By controlled synthesis of macroscopic bodies from atomic and molecular components, their optical, electronic, magnetic, catalytic or mechanical characteristics can be adjusted specifically. The understanding of the molecular principles for the production and application of new materials opens up possibilities for adjustable and smart materials, which can not be obtained with conventional methods. Due to the outstanding functional characteristics of nanostructured materials, which are mainly based on a large surface-to-volume-ratio and on quantum effects, numerous application potentials arise in space.

5.2.1 Materials for space structures

A range of applications of nanomaterials lies in the construction of spacecrafts and space structures due their improved mechanical characteristics (higher firmness and stability and concurrently a lower density) compared with conventional materials. Nanomaterials could in particular contribute to the reduction of the lift-off masses of spacecrafts leading to substantial cost savings and also ensure safer and more flexible space missions. In the context of space structures, different material classes should be taken into consideration.

5.2.1.1 Nanoparticle reinforced polymers

Nanoparticle for improved mechanical properties of polymers

The mechanical properties of polymers can be improved by dispersion of nanoparticles into the polymer matrix. As suitable nanoparticles e.g. silicates (in particular montmorillonite clay), POSS (Polyhedral Oligomeric Silesquioxanes) or also carbon nanotubes (CNT, see section 5.2.1.2) are considered. As polymer matrices for example epoxide, nylon, polyphenole or polyimide can be used. The reinforcement effect of the nanoparticles is usually based on chemical connections, whereby a network between nanoparticles and the polymer matrix is formed. Nanoparticle reinforced polymers can be formed and extruded like conventional polymers but possess however thermal and mechanical properties, which lie between those of organic polymers and inorganic ceramics. Due to its high mechanical firmness and resistance against heat and radiation, nanoparticle reinforced polymers have application potentials for various components in space, among other things as housings of solid-propellant rockets, as heat protection material in rocket nozzles, electrical isolations or fire protection applications. The development of nanoparticle reinforced polymers is promoted by NASA e.g. in the frame of the SBIR programme. First tests for the space qualification of nanoparticle reinforced polymers have already been accomplished by NASA at the exterior of the ISS. Also within the range of aviation, nanoparticle reinforced polymers are investigated intensively at present as lightweight structure materials for airplane bodies (Chen 2001, Rice 2001).

5.2.1.2 Carbon Nanotubes

Carbon nanotubes (CNT) with diameters of few nanometers as fullerene derivatives represent pure carbon compounds and occur in different modifications, e.g. single walled (SWCNT) or multi-walled (MWCNT). CNT possess unusual mechanical characteristics (on molecular level approx. 50 times stronger than steel and outstanding thermal and electrical conductivity). Due to their special properties, CNT possess numerous application potentials in space, among other things within the ranges of space structures, thermal control devices, sensor technology, electronics and biomedicine. A substantial part of the nanotechnology programme of NASA is based on the development and application of CNT based materials, sensors and electronics (see NASA 2000). In particular the huge potential for mass savings in space structures makes CNT very interesting for space applications. A further advantage of CNT composites is that the changes of the mechanical properties of the material can be indicated through changes of the electrical resistance and so possible damages could in principle be easily detected by simply monitoring the electric conductance of the material.

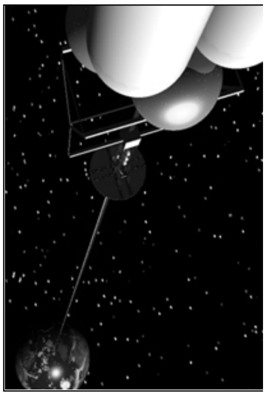


Illustration 10: Vision of a space elevator based on ultra-strong CNT materials

(Source: www.space.com)

If it should succeed in the future to manufacture favourable priced CNT with defined characteristics on industrial scale and to transfer the outstanding molecular properties into macroscopic materials, not only improved conventional spacecraft will be possible, but also space applications, which sound very visionary at present. Conceivable for example is a space elevator, consisting of a self-supporting CNT rope, which is connected from earth to a geostationary object in space (see illustration 10).

At present however, technical applications of CNT based materials for structures are still far away. This is on the one hand due to the very high price, particularly for SWCNT, which amounts to approx. 500 $ per gram depending on the purity and quality of the product. The high price is due to the fact that CNT can be produced so far only on a laboratory scale with quantities up to 100g per day through different gas-phase processes (flame synthesis, catalytic CVD, electrical arc discharge, laser ablation etc.) and require a complex cleaning procedure. On the other hand, also problems concerning the transfer of the molecular properties to macroscopic materials are still unsolved, e.g the dispersion of CNT in composite matrices or spinning of CNT to macroscopic fibers. A problem with the production of CNT composites, e.g. reinforced polymers, is the alignment and the adhesion of the CNT in the matrix. CNT tend here to agglomerate, so that the loading rate with CNT is limited to a little weight percentage. A solution could be the chemical modification of the CNT and the chemical binding to the polymer-matrix. Such investigations are accomplished at present by NASA and also in Germany for example by the technical university Hamburg-Harburg (Gojny et al. 2002). Only recently scientists of the university of Oklahoma and the university of Erlangen-Nuernberg succeeded in the synthesis of SWCNT/polymer composites with a sandwich structure containing about 50 % weight percentage of SWCNT. These composites exhibit a tensile strength of up to 325 MPa and are therefore six times stronger than conventional polymers (Mamedov et al. 2002). However this can not compete with the mechanical properties of conventional carbon fiber reinforced polymers, which exhibit tensile strengths over 2 GPa, and further technological breakthroughs should be made to exploit the potential of CNT for the production of ultralight, high-strength hybrid materials, which could be used for various structure applications in space.

CNT polymer composites with application potential in space structures

Another approach for synthesis of CNT materials is the spinning of CNT to macroscopic fibers. The spinability of CNT however is limited by the bad solubility in organic solvents. By dispersion of SWCNT in strong acids however fibers with a mostly uniform alignment and promising mechanical and electrical properties have already been achieved (Ericson et al. 2002). Recently Chinese researchers of the Tsinghua university succeded in the production of a 200 µm thick yarn from carbon nanotubes by dragging a bundle of CNT grown on a silicon substrate up to 30 cm length similarly to spinning silk (Jiang et al. 2002). If it should be possible in the future to weave such CNT fibers into macroscopic objects, numerous applications will arise also in space, e.g. in materials for electromagnetic radiation shielding or protection against mechanical impacts for space stations or astronaut suits).

Research efforts for the production of continous CNT fibers

While applications of CNT materials for structure applications are to be expected rather in a long-term time horizon, due to their high price and problems with the scalability of production processes, other applications of CNT such as fillers for electrical conductive polymer composites e.g. for antistatic insulating materials could be realized earlier. Such materials are developed among other things in the context of a SBIR project of NASA by the US-American companies Triton-Systems and Foster-Miller. In addition, a multiplicity of further space relevant applications of CNT is conceivable, for example in the sensor technology or molecular electronics, as described in more detail in the following sections.

Electric conducting CNT composites for electrostatic isolations

5.2.1.3 Metal-Matrix-Composites

Nanostructuring improves thermomechanical properties of MMC materials

By reinforcement of metals with ceramic fibers, in particular silicium carbide, but also alumium oxide or aluminum nitride, their thermomechanical properties can be improved. Such metal matrix composites (MMC), e.g. SiC in aluminum alloys or TiN in Ti/Al alloys, possess due to their high heat resistance, firmness, thermal conductivity, controllable thermal expansion and low density, a high potential for aerospace applications and are examined at present regarding the replacement of magnesium and aluminum in various structures of spacecrafts and aeroplanes. As it has been reported, the strength of MMC could be increased up to 25 % through nanostructuring and beyond that, superplasticity and a better resistance against material fatigue can be obtained in comparison to conventional MMC.[26] Nanostructured ceramic fibers can be manufactured for example by modified flame synthesis on a several kg per day scale.[27] Different research activities can be noticed in the frame of the SBIR-programme of NASA.

5.2.1.4 Nanocrystalline metals and alloys

The thermomechanical characteristics of metals and alloys can also be improved by controlling the nano-/microstructure of the materials. Melting points and sintering temperatures can be reduced up to 30 %, if the material is made of nanopowders. Another advantage is the easy formability of the materials through superplasticity. In a SBIR project of NASA, nano-crystalline aluminum alloys were developed for space applications by the company DWA Aluminum Composites in co-operation with different US-American aerospace companies. Such materials are investigated as alternatives for titanium in components of liquid rocket engines (e.g. lines and turbopumps), since they are lighter and less susceptible to embrittlement by hydrogen.

5.2.1.5 Nanostructured ceramics/ceramic nanopowders

Within ceramics a special focus lies on the production of controlled micro/nano-structured grain sizes. An objective is the improvement of thermomechanical properties, fracture toughness and formability ("superplasticity") of this brittle material class. In addition, the sintering temperatures and the consolidation time of ceramic materials can be reduced by applying nanopowders, which saves not only money but also allows new manufacturing techniques like coprocessing of ceramics and metals.[28] Ceramic nanopowders meanwhile can be manufactured with high chemical purity and adjustable powder grain size. Both gas or liquid phase processes are used for the production of ceramic nanopowders, for

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[26] personal communication 30.08.2001, Dr. J.C. Whithers, MER Corporation
[27] see http://www.argonide.com/alumina_fibers.html
[28] „Rapid Densification of Ceramic Monoliths and Composites“ press release of NASA-MSFC, October 1998

non-oxidic powders (e.g. Si_3N_4, SiC, TiCN) preferentially gas phase processes and for oxidic powders (e.g. Al_2O_3, SiO_2) also sol gel procedures.

For space application, nanostructured ceramic composites will play a role in particular as thermal and oxidative protection for fiber-reinforced construction materials (e.g. coating of carbon fiber materials with boron nitride, see section 5.2.2). Further application could arise in sensor technology, optoelectronics and for space structures. An interesting development is the production of high-strength transparent bulk ceramics. The Fraunhofer institute IKTS for example has developed a procedure for manufacturing sub µm structured corundum ceramics (Al_2O_3), which possess high firmness (600 - 900 MPa), scratch resistance and transparency (Krell 2002). A controlled grain growth during the sintering process makes it possible to avoid porosity to a large extent, which guarantees a dense texture and thus a high firmness. Applications in space may be seen within the range of transparent exterior surfaces and skins of spacecrafts or sensor windows.

High-strength transparent corundum ceramics

A further relevant topic are nanostructured gradient materials, in which the gradient can be adjusted both regarding thermomechanical or chemical properties. These materials could be used for example in the production of photonic structures in optical data communication or in the production of micromechanical and microelectronic components with a high degree of miniaturization. Problematic however is the shaping and compacting of nanoparticles to components. So most of conventional shaping techniques for ceramics cannot be applied economically with nanoparticles, since the ceramic fragment formation depends usually on the particle size and thus long process times must be taken into account. Solutions are offered here e.g. through the formation of nanoscale ceramic particles by means of electrophoretic deposition (EPD). The EPD process, in which particles are moved through a dispersion medium by an electrical field with a size independent speed and are deposited on a ceramic green body, allows a near net shaping of complex components.

Electrophoretic deposition of nanoparticles for the near-net-shaping of complex components

5.2.2 Thermal protection and control

5.2.2.1 Thermal protection

Due to the extreme conditions in space, thermal protection is an important topic. By improved thermal protection systems for re-usable spacecrafts the costs in space transportation could be lowered, and moreover, a higher mission flexibility and security in manned space travel could be obtained. In the range of thermal protection systems, in particular, ceramic materials for protective layers or fiber composites are important. Ceramic fiber composites for example can be used for re-usable, high temperature components such as nozzles or combustion chambers of rocket engines or heat shields of reentry space systems. Like past applications, such as:

- Substrate foils from oxide ceramics for reflector layers (e.g. internal multi-screen insulation, which was developed for the orbital glider HERMES on basis of a sol gel procedure)
- Formation of ceramic matrix from silicon-organic oligo- and polymer precursors for complex structures
- Nanopowder (SiC, Al_2O_3) as a matrix component
- Nanostructured ceramic fibers
- Fiber coatings with nanoscale texture

show, nanotechnology could be used favourably in the areas of thermal protection and hot structures for future reuseable space transportation systems (see Muehlratzer 2001). For a long-term exposition at temperatures above 1400 °C however, rather single-crystal oxide fibers are favored such as sapphire, while for a temperature range from 1100 to 1400 °C in particular siliconborcarbonitride ($SiBN_3C$)-fibres and oxygen-poor SiC fibers as well as high temperature stable interfaces are important (Sporn 2002).

Preceramic polymers for the production of nano-structured ceramic fiber composites

In Germany in this context, the joint project „ceramic fiber composites for high temperature engines in space" is promoted by the Bavarian research foundation with the participation of Astrium, four other companies and some scientific research institutions. Among other things oxidation protection procedures are to be developed by application of preceramic polymer precursors for carbon-based construction units. Thus the cooling effort should be reduced and the application temperature of the materials should be increased to maximum 2000 degrees Celsius.

Also nanostructured heat-insulating layers are suitable as thermal protection for combustion chambers in space propulsion systems. By means of PLD (pulse laser deposition) methods, nano-structured heat-insulating layers can be manufactured as interior coatings of combustion chamber components and be specifically adapted to the requirements (adhesion layers, sealing layers, active layers etc.). Appropriate heat-insulating layers on the basis of ZrO_2 have been developed in co-operation with FhG IWS, TU Dresden and Astrium and have been tested successfully under working conditions (Gawlitza 2002, see chapter 5.3.2).[29]

5.2.2.2 Thermal control

Thermal control of space systems is a further topic of high relevance. This concerns, among other things, the protection of sensitive electronics against large variations in temperature. This comprises for example an efficient radiation of electronic power dissipation, which in particular represents a problem within the miniaturization of satellites. Nano-

[29] IDW-news from 04.07.2002: „Keramische Faserverbundstoffe für bessere Raketenantriebe" (http://idw-online.de)

materials offer different approaches for an improved thermal monitoring of space travel systems. For example, nanostructured diamond-like carbon layers can improve thermal control systems of nanosatellites, since they possess approx. four times a higher thermal conductivity than copper (Rossoni et al. 1999). Beyond that, diamond-like-carbon layers offer also corrosion protection, e.g. against atomic oxygen and are stable in a wide temperature range (see section 5.3). Another approach for the thermal control of miniaturized satellites are MEMS-based micro cooling loops (Birur et al. 2001). Also magnetic fluids possess application potentials in thermal control systems. Magnetic fluids are concentrated, sedimentation-stable dispersions of ultrafine ferromagnetic particles in almost arbitrary dispersing mediums (carrier liquids). The agglomeration of the magnetic particles is prevented by a nm thick polymer coating. Due to the small dimension of the dispersed particles, magnetic fluids behave usually superparamagnetic. Average particle sizes are between 5 to 50 nm. From a technological point of view, magnetic fluids are of interest, because the pressure, the viscosity, the electrical and thermal conductivity can be controlled by external magnetic fields. Magnetic fluids at present are used mainly as sealing and damping media. In the future there might be applications in space technology in highly precise thermal control systems for miniaturized electronic components or as free-floating self-lubricating bearing for micromechanical components (IWGN 1999).

Magnetic fluids for a high precise temperature control of miniaturized electronic components

5.2.3 Energy generation and storage

Within the range of energy generation and storage nanomaterials, nanolayers and nanomembranes will find applications as improved electrodes and electrolytes in condensers (supercaps), batteries (e.g. Li ion batteries) and fuel cells as well as photosensitive materials for high-efficient solar cells (e.g. quantum dot solar cells).

5.2.3.1 Solar cells

The efficiency of energy conversion of solar energy into electric current can be increased significantly by application of nanomaterials. Beyond that, anti-reflecting coatings for solar cells and collectors can increase the light conversion efficiency. For applications in space however, clearly higher demands on solar cells must be fulfilled rather than for terrestrial applications. While due to the mass restrictions in space transportation a maximum efficiency is aimed at, even if expensive manufacturing processes and materials are to be accepted, an appropriate durability of the collectors under space conditions must also be ensured (radiation and corrosion resistance). At present the most efficient solar cells for space applications are based on III/V-semiconductors such as GaAs and InP. These cells are manufactured by heteroepitactical deposition on semiconductor substrates. By vertical alignment of two or more compounds

III/V compound semiconductor solar cells are the most efficient systems at present (junctions) with different gaps the energy output can be optimized (binary or multi junction cells). By means of optical concentrators the energy output can be increased additionally. At present the most efficient solar cells for space applications have a conversion efficiency of approx. 30 % and are manufactured for example by the US-American company Spectrolab.[30]

In principle conversion efficiencies of over 50 % appear possible with such compound semiconductor solar cells (Aroutiounian et al. 2001). In case of an optimal use of the solar spectrum even conversion efficiencies up to 66 % are theoretically conceivable, without using optical concentrators (Nozik 2001). Practically however, numerous obstacles thwart the realization of the theoretically possible conversion efficiencies, like for instance different lattice constants of the semiconductor materials, which lead to mechanical stress and defects in the crystal structure. At present however, there is still a substantial potential for further improvements of III/V semiconductor solar cells. For example the use of indium gallium nitride seems promising for solar cells. This material system has, as scientists of the Lawrence Berkeley National Laboratory recently discovered, an optimal gap range for the conversion of almost the entire solar spectrum and is very tolerant with regard to lattice mismatches (Wu et al. 2002).

Indium gallium nitride potentially is an optimal solar cell substrate

In Germany the development of III/V-semiconductor solar cells for space applications is promoted by the DLR and accomplished in a joint project with participation of the Fraunhofer Institute for Solar Energy Systems and the RWE Solar AG. The production of multi junction solar cells with MOCVD and MBE procedures requires process control on a nanoscale level. Disadvantages of III/V semiconductor solar cells are relatively high material costs and a complex process technology.

Quantum dots for the optimization of band gaps

Another starting point for the increase of the conversion efficiency of solar cells is the use of semiconductor quantum dots. By means of quantum dots, the band gaps can be adjusted specifically to convert also longer-wave light and thus increase the efficiency of the solar cells. These so called quantum dot solar cells are at present still subject to basic research. As material systems for QD solar cells III/V-semiconductors and other material combinations such as Si/Ge or Si/Be Te/Se are considered. In a BMBF joint project with participation of DaimlerChrysler QD solar cells, on the basis of selfstructured Ge-islands on Si substrates, are investigated at present. Potential advantages of these Si/Ge QD solar cells are:

- higher light absorption in particular in the infrared spectral region
- compatibility with standard silicon solar cell production (in contrast to III/V semiconductors)
- increase of the photo current at higher temperatures

[30] SpaceDaily news from 12.06.2000: „Spectrolab moves to next-generation Solarcell“ (www.spacedaily.com)

- improved radiation hardness compared with conventional solar cells

The present results show that the improved photoresponse within the IR range is overshadowed by a worse response in the visible and UV spectral region, so that altogether smaller efficiencies than with pure Si cells are obtained. However, still a potential exists for an improvement of the efficiency by an improved layer structure and parallel contacting of the QD solar cells (Presting 2002). The illustration 11 shows the schematic structure of a Si/Ge QD solar cell.

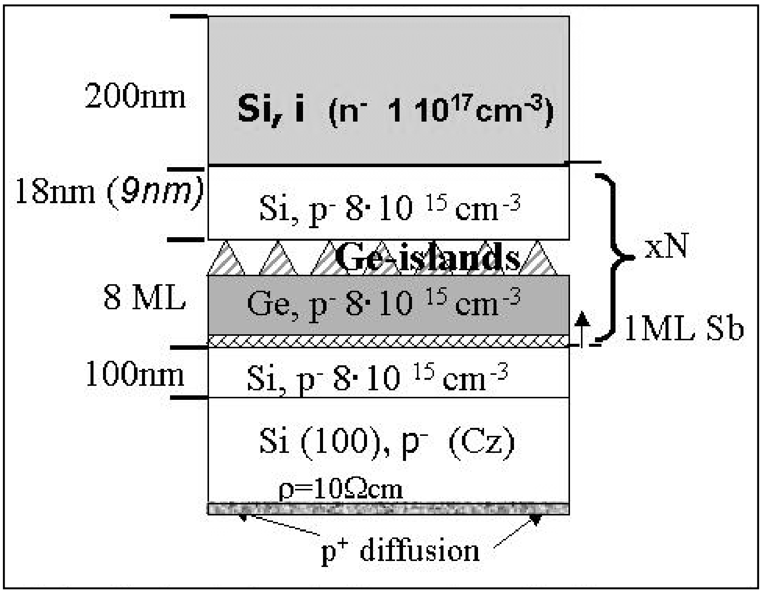

Illustration 11: Schematic structure of a Si/Ge QD solar cell with layers of Ge quantum dots in the active layer of the Si solar cell substrate (Source: Presting 2002)

Thin film solar cells on flexible, light substrates exhibit high potential for space applications

Further approaches for nanotechnology applications within the range of space solar cells are thin film solar cells, which have already been used for solar cell panels of satellites. Thin film solar cells for space applications are based for example on amorphous silicon or on $Cu(In)(Se,S)_2$-layers, which are attached to thin metal or polymer foils. For space applications in particular, thin film cells on polymer substrates are interesting due to their small weight and their flexibility. The US-American company United Solar develops for example amorphous silicon thin film cells on thin Kapton foils, which reach conversion efficiencies of 12 % under space conditions and also demonstrate a good radiation hardness.[31] The company Solarion in Leipzig/Germany has recently developed an ion beam process, which allows a cheap production of large area CIS thin film solar cells on Kapton foils (Lippold 2001). Such flexible large area thin film cells are interesting not only for satellites, but particularly for

[31] SpaceDaily news from 26.04.2000: „Energy ConversionDevices Wins Solar Cell Deal with Airforce“ (www.spacedaily.com)

new visionary spacecrafts such as solar sails, Gossamer-Spacecrafts or solar power plants in space (Seboldt 2001).

Organic solar cells with high development potential

In the future, organic solar cells could also play a role in space travel, which in principle can be manufactured substantially more economically than inorganic cells, at present however exhibit still relatively small conversion efficiencies. Organic solar cells use dyes, conjugated polymers or also fullerene derivatives for the conversion of sunlight (Leo 2001). A special type of organic solar cell, the Graetzel cell, uses a nanoporous titanium dioxide layer coated with organic dyes, in order to achieve a higher conversion efficiency by surface enlargement and a better electron transfer from the light absorber to the electrode. Graetzel cells at present reach conversion efficiencies of approx. 10 % under diffuse illumination. Organic solar cells are investigated intensively and possess a high development potential for the future.

5.2.3.2 Thermoelectrics

Thermoelectric space solar cells based on diamond thin film technology

Another approach for the conversion of solar light into electric energy is based on thermoelectrics. Thermoelectric converters produce electricity from solar energy through a two-step thermoelectric process in which electromagnetic radiation is first converted to heat and then into electricity. Thermoelectric converters harness the whole spectrum of solar light and have therefore high theoretical conversion efficiencies of up to 70% (Oman 2002). Particularly interesting for space applications are thermoelectric converters based on thin polycristalline diamond films, consisting of myrads of nanoscale diamond tips. When heated, these diamond nanotips act as a field emitter cathode, that emits electrons, flowing across an intervening vacuum to the anode and creating an electric current. For this temperatures of 1000 °C to 1500 °C have to be achieved by means of a solar absorber plate. Advantages of thermoelectric converters in comparison to photovoltaic cells are an increased conversion efficiency as well as a high radiation resistance. Such diamond thin film solar cells can be manufactured by CVD processes. R&D activities aiming at utilization of this technology for space applications are accomplished at present e.g. by the Vanderbilt University School of Engineering.[32]

5.2.3.3 Fuel Cells

Nanomaterials for optimized catalysts, membranes and hydrogen storage for fuel cell technology

Fuel cells represent an efficient method for chemical energy conversion and possess substantial application potential in space due to their clean operation and their compactness. At present NASA develops in cooperation with US-American companies PEM fuel cell modules, which should be available for space qualification procedures in 2005. Application of fuel cells is an objective in particular pursued within the range of

[32] SpaceDaily news from 10.04.2001: „Turning Diamond Film Into Solar Cells“ (www.space-daily.com)

re-usable space transporters.[33] But fuel cells in principle represent alternatives for batteries in many other space applications. For example SOFC fuel cells could be used for the electrochemical oxygen production in manned space stations or for the in-situ resource production on other planets. Nanotechnology offers different possibilities to increase the conversion efficiencies of fuel cells, in particular within the ranges of catalysts, membranes and hydrogen storage, which in many cases is critical for the employment of fuel cell technology in space.

Precious metal nanoparticles improve the high-efficient production of hydrogen in direct methanol fuel cells. This type of fuel cell needs liquid methanol as fuel, from which the hydrogen is generated by a catalyst. The main obstacle here is the poisoning of the catalysts through byproducts like carbon monoxide. Improved nanotechnological catalysts, which are more insensitive against carbon-containing gases, could contribute to a solution of this problem. Also the electrolyte of PEM fuel cells can be improved by nanoparticles. For example the Max-Planck-Institute for solid state research in Stuttgart, acting in co-operation with MPI for polymer research in Mainz, developed custom-made polymer membranes, with densely packed nanoparticles, which are immobilized on the surface of imidazole molecules and provide an optimized proton transportation. For SOFC, ceramic nanopowders (e.g. yttrium stabilized zirconium, YSZ) are used for the production of solid electrolyte membranes with improved ionic conductivity and better thermal stability.

One of the main obstacles to the implementation of fuel cells for mobile application is at present still the technologically and economically reasonable storage of the fuel (especially hydrogen). Nanomaterials, due to their increased active surface area, basically possess potential to be a lightweight high-efficient storage media for hydrogen. With regard to operating conditions (temperature, pressure) different material types should be taken into consideration. Nanocrystalline light metal hydride particles from magnesium-nickel alloys are suitable for operating temperatures up to 300 °C, and $LaNi_5$ alloys for low temperature hydrogen storage up to 80 °C. Also for CNT materials or alkalimetal doped graphite nanofibers high hydrogen absorption capacities are reported, but were partly not reproducible (Liu et al. 1999, Chambers et al. 1998).

5.2.3.4 Batteries/Accumulators

Nanoparticles increase charge capacity of Li-ion batteries

High performance batteries (especially Li ion or nickel metal hydride accumulators) are a substantial element of the power supply in space systems. The capacity and reversibility of rechargeable lithium batteries depend strongly on the microstructure of the electrodes. Nanostructured materials offer improvements regarding power density and durability by

[33] NASA Aerospace Technology News from 14.12.2001: „Fuel Cells for Launch Vehicles?“ (www.aero-space.nasa.gov)

control of charge diffusion and the oxidation state on a nanoscale level. As nanostructured materials for electrodes e.g. carbon aerogels, CNT, vanadium oxide or $LiCoO_2$-particles are examined as cathode materials and nanostructured Sn/Sb oxides as anode materials. It has been reported that in lithium ion batteries a sixfold increase in reversible charge capacity could be obtained by evenly distributed nanoparticles from cobalt, nickel and ferric oxides in the electrode material (Poizot et al. 2000).

The increasing miniaturization of electronic components requires flexible batteries integrable into circuits. Here thin film batteries (in particular Li ion batteries), whose dimensions and power density can be adapted to the respective chip components, offer advantages. For energy generation thin film solar cells can be integrated directly into the same device (Hepp et al. 2000). For the production of thin layers with good electronic characteristics usually complex high vacuum deposition procedures are required. Cheaper and simpler thermal spray procedures could be applied by using nanoscale precursors, which yield high-quality layers due to the increased reactivity of nanoparticles.

„Nanocaps" for space applications

5.2.3.5 Capacitors

Capacitors represent a further important component for energy storage in space systems, particularly for short term high power applications (pulsed power applications). In relation to power density however, capacitors are clearly inferior to batteries. The development of supercapacitors or "nanocaps" aims at a significant increase of power density. This could be realized for example by metallic nano-electrodes with ultra thin pseudo capacity, increased internal resistance and capacity. Such nanostructured thin film electrodes are developed at present in a BMBF research project with the participation of Dornier GmbH. As electrolytes, self assembled electrically charged polymer layers are used. [34]

Also nanoporous carbon aerogels, because of their extremely large internal surface, controllable pore distribution and pore diameter, are suitable as graphitic electrode materials for supercapacitors (Proebstle et al. 2002, Firsich et al. 2002). The electrical conductivity can be increased by intercalation with alkali metals nanoparticles. Likewise nanoscale spinel structures ($MgAl_2O_4$) and carbon nanotubes are considered as electrode material in supercaps, which however are still too expensive for competitive applications. Companies such as Panasonic, Maxwell or Ness already offer supercapacitors commercially, whereby performance characteristics do not correspond yet to those of a postulated "nanocap", which is to be realized approx. by 2005 (Leiderer et al. 2002).

[34] Joint project: „Nanostructured thin film electrodes for advanced supercaps“, BMBF-Funding Cat-No. 03N3076A/2

5.2.4 Life support

Within the range of life support numerous potential applications of nanotechnology arise. As substantial tasks of life support systems in space travel, the following should be mentioned:

- O_2-/ N_2 supply
- pressure monitoring
- ventilation
- heat absorption and rejection
- waste water treatment
- monitoring of water quality
- CO_2- removal
- hygienics
- air cleaning and filtration
- control of air quality and humidity

Life support systems could benefit from nanotechnology in many areas

According to statements of NASA, no applications of nanotechnology are registered within these ranges so far. As potential applications however, the following topics were mentioned (Graf 2001):

- gas storage (high-efficient nanomaterials with high capacity-weight-ratio primarily for nitrogen and oxygen storage, possibly as spin offs of hydrogen storage developments)
- waste water treatment (here at present activated charcoal filters and ion exchangers are used, potentials are seen for regenerative nanomembranes)
- Sensors (e.g. for monitoring filter processes within the range of water purification, for monitoring the air quality in space stations by means of electronic noses or for the detection of pathogenes)
- Heat exchangers (heat exchanger so far are one of the largest and heaviest life support systems on the ISS; therefore a high demand for weight reduction and miniaturization by means of nanostructured materials with more efficient heat exchange and transfer properties is existent)

Some developments should be noticed within the range of so-called electronic noses for the monitoring of air quality in manned space stations or also for early fire warning. Different types of gas sensors can be used for such applications e.g. metal oxide sensors, Schottky diodes or thin polymer films, which were deposited as nm to µm thick coatings on aluminum substrates and form electrical resistance varying with the absorption of gaseous molecules. Unfortunately the selectivity of gas sensors is quite low. Therefore arrays of a multiplicity of sensors are usually used, which produce specific signal outputs in dependence of the air composition. A chemometric pattern recognition allows a reliable identification of gaseous analytes, whereby several analytes can be determined at the same time. The Jet Propulsion Laboratory of NASA developed an electronic nose, which has already been tested successfully in a space shuttle mission and which should be implemented on the ISS in the future. In this range, nanotechnology might provide approaches for miniaturization and improvement by more selective and sensitive sensors (see chapter 5.2.5.1).

In the area of water purification nano-membranes offer the possibility of an efficient removal of pollutants and germs. At present nano-porous ceramic filter membranes for the sterilization of treated water are developed by the company Argonide in the frame of a SBIR project of NASA. Such nanomembranes based on nanostructured aluminum fibers can remove viruses very efficiently and are less susceptible against pore blockage than conventional membranes.[35] For the future, there is still a huge potential for applications of nanotechnology for life support systems in human spaceflight.

5.2.5 Sensors

Sensor technology will gain in particular from nanotechnological developments. Out of the multiplicity of different sensor systems in space technology only a few examples are described below, where nanomaterials offer significant application potentials. Furthermore optical and electronical sensors based on nanoscale sensors are mentioned in the chapters 5.3, 5.4 and 5.5.

5.2.5.1 Gas sensors

Gas sensors have broad application fields in space technology

Gas sensors are used in a wide area of technical and scientific space applications, among other things for the detection of hydrogen leakages in rocket engines (Pijolat 2000), for the measurement of the oxygen content in upper atmosphere layers (Fasoulas et al. 2001) or for the monitoring of the air quality in manned space systems (see above). In principle three different gas sensors are used for space applications (Hunter 2002):

- Schottky diodes (e g. based on SiC)
- resistive sensors (e.g. polymer films)
- electrochemical sensors (e.g. based on tin oxide)

Regarding the employment of nanomaterials, in particular electrochemical sensors are concerned. Miniaturized electrochemical gas sensors with sensitive metal oxide coatings (e.g. SnO_2) are energy saving and can be easily integrated into CMOS circuits. The use of nanopowders for sensor and electrolyte coatings offers in principle advantages both regarding the production process (reduced sintering temperatures, which allow „co-firing" of metals and ceramics) and the sensitivity and robustness of the sensors by improved ionic conductivity. By variation of the working

[35] Nanotechweb news from 24.7.02: „Argonide gets into water filter space“ (www.nanotechweb.org)

temperature of the electrode or the electrolyte material, different gases can be detected (e.g. H_2, CO_2, NO_x, CO, CO_2 or hydrocarbons). As e-lectrolyte membranes ZrO_2 or YSZ are for example used. Electrochemical gas sensors for applications in space are developed for example by the company Escube in Germany. For the production of the electrolyte membranes, sub µm powders (average particle size 200 nm) are used. Schottky diodes, which change their electrical conductivity by absorption of gas molecules, can be used in particular for the detection of hydrogen or hydrocarbons under the harsh space conditions. The automobile industry is likewise interested in gas sensors, so that spin off effects from space technology could arise in this area.

5.2.5.2 Sun sensors

Another application for nanomaterials in sensor technology are sun sensors on the basis of nanoporous silicon. Advantages of nanoporosity are for example decreased reflection losses and improved quantum yields. A prototype of a miniaturized sun sensor with use of nanoporous silicon has been developed in the frame of a Spanish nanosatellite project under the leadership of the Instituto Nacional de Técnica Aerospacial (Martin-Palma et al. 1997).

Improvement of the biomedical supply of astronauts is essential for future manned space missions

5.2.6 Biomedical applications

Biomedical applications in the area of spaceflight aim at the reduction of medical risks for astronauts. As critical risks, the following should be mentioned among other things (Stilwell 2001):

- bone loss
- heart and blood circulation problems
- performance loss
- distortion of the sense of balance
- distortion of the immune system
- muscle loss
- radiation damages
- insufficient methods for on-board medical therapy and diagnostics

Within the biomedical range, NASA aims at the development of the following applications with possible contributions from nanotechnology (Hines 2001):

- minimal invasive, efficient and mobile detection systems for malfunctionings in the entire organism (e.g. biomolecular sensors for measurements of the bone density/condition, blood chemistry or the radiation load)
- methods of early diagnosis of cancer (in particular important for longer manned missions)
- biomolecular imaging (sensor technology and visualization)

- miniaturized diagnostics (e.g. lab-on-a-chip systems) whereby both the measuring and the analysis unit should be miniaturized
- autonomous therapy forms for a multiplicity of possible diseases and health damage

At present numerous research programs of NASA are accomplished in the area of Life Sciences also in co-operation with other federal institutions (e.g. NIH) or industrial partners. To be mentioned here among other things are the following research sectors of priority:

Lab-on-a-chip systems for an autonomous health monitoring of astronauts

- fundamental technologies for the development of biomolecular sensors (NASA/ NIH)
- advanced human support technology programme (NASA)
- human operations in space (NASA, Johnson Space Center, Small Business Technology Transfer Program)

Application potentials for nanotechnology can be identified for example in the range of miniaturized analytical devices for medical diagnostics, e.g. lab-on-a-chip-systems. Although biochips or lab-on-a-chip-systems are microfluidic devices, they are often discussed in context with nanotechnology. One of the underlying reasons is the fact that frequently nanoparticles are used for the detection of the analyte molecules. For example gold nanoparticles, semiconductor nano-crystals (so-called quantum dots)[36] or also magnetic nanoparticles[37] are used as markers for the substances to be determined (proteins, DNA etc.). The detection methods are based on different methods such as fluorescence spectroscopy, magnetic field measurings, electron microscopy or optical color change. The latter procedure offers the advantage that the test result is indicated without further reading instruments and therefore is in principle suitable for self diagnosis of patients.

The manufacturing of high-density oligonucleotide biochips (e.g. for gene analysis) is performed frequently by means of optical lithography, serving to produce binding positions for the individual nucleotide molecules. The advantages of biochips are the simultaneous detection of different analytes, the high speed of analyses, as well as small and compact test kits. In development are lab-on-a-chip systems, which allow complex analysis sequences by individual controllable micro valves and channels. Particularly in human space flight biochips and lab-on-a-chip systems will improve an autonomous self diagnostics of astronauts.

Nanoscale drug-delivery systems

Rather visionary at present are nanotechnological approaches which aim at the development of biomolecular and biomimetic sensors for the online monitoring of cellular processes, for example by utilization of carbon nanotubes as molecular probes (Hoenk et al. 2001). Major obstacles for such kind of applications are the connection of such molecular probes to

[36] Rosenthal 2001
[37] Colton 2001

macroscopic measuring devices as well as the amplification of the measuring signals, for which at present no technological solutions exist.

In medical therapy a substantial application field for nanotechnology is the controlled and targeted transport of drugs ("drug delivery"). The use of nanoscale transportation vehicles should make it possible to achieve, that the active drugs affect selectively the targeted regions of the human body only, minimizing unwanted side effects. Such transportation systems could be realized in principle from nanoscale cage molecules (e.g. liposomes, fullerenes or other cage molecules such as dendrimers) or by coupling with nanoparticles. The goal here is to carry the active drugs selectively to the targeted cells by means of nanoparticles with specific surface functionalization. Nanoparticles are small enough to penetrate cell membranes and overcome physiological barriers (e.g. blood-brain barrier) in the organism. Furthermore nanoparticles and nanoscale suspensions improve the solubility and bio-availability of drugs and allow the application of drugs, which are so far not applicable.

By the coupling of drugs with nanoparticles less burdening application procedures can be realized like inhalation instead of infusions for example. By functionalised nanostructured coating of the drug particles the deposition speed can be controlled and smaller doses can be applied reducing unwanted side effects.

With the help of nanotechnological therapy procedures a distinct progress in the autonomous self medication of astronauts is expected in the future including counter measures for acute intoxication (Partch 2001). An autonomous medical supply of astronauts is an important prerequisite for the realization of long manned space missions outside of the earth orbit. During a manned Mars mission, which is considered as a long term objective both of NASA and ESA, there would be no possibility of external medical supply of the astronauts for a period of up to three years, apart from capabilities of tele medicine which will be developed until then.

5.2.7 Other applications

Aluminum nanopowders as additive for more thrust in solid rocket propulsion

Beside the above mentioned technology fields there are further possible applications of nanomaterials in space. For example, aluminum or boron oxid nanopowders, which are coated with thin polymer films (thickness between 20 and 300 nm) to prevent agglomeration, can be used as solid propellants in rocket engines (Mordosky et al. 2001). Due to their increased surface area the nanopowders create more thrust in solid-propellant rockets. The agglomeration of the particles can be avoided by polymer coatings and addition of a stabilizer, which also improves the handling of the materials. Also for liquid propellant rockets, an increased power density can be obtained through addition of nanopowders to hydrocarbon fuels. Suspended in organic solvents, nanopowders can also be used for bi-propellant-systems (e.g. ethanol/LOX, which represents a more environmentally friendly solution than hydrazine/N_2O_4). Such nanopowders are developed in the frame of a SBIR programme of NASA in co-operation with different nanotechnology companies (DWA Aluminum Composites, Argonide, Sigma Technologies etc.) and aerospace companies.

Aerogels as lightweight isolation material

Aerogels, which consist of a highly porous 3d-network of nanoparticles, offer the advantages of a high internal surface as well as a small density and thus good options for application, e.g. as electrode material for improved capacitors and batteries or as thermal isolation material. Aerogels can be made of different materials e.g. silicates or carbon. In space, aerogels have already been used as thermal isolation material in the Mars Rover of the Pathfinder mission[38] as well as particle collector in the NASA Stardust mission.[39] A disadvantage of conventional aerogels is their brittleness and small mechanical stability. Recent developments demonstrate however, that the mechanical characteristics of aerogels can be improved significantly by using inorganic and organic material combinations (e.g. silicate/Polyurethane) substantially. Therefore in the future aeroels may find applications as high strength ultralight structure material in space (Leventis et al. 2002).

Magnetic nanocomposites consist of nanoscale magnetic crystallites in an amorphous or crystalline matrix (e.g. polymers or silicates). Both soft and hard magnetic (low resp. high coercivity) nanomaterials can be obtained. Soft magnetic materials are suitable for transformers and inductors in electronic components, whereas hard magnetic materials possess application potentials in energy storage, data memories and sensor technology. With nanostructured materials physical parameters such as coercivity can be adjusted selectively, which opens up new applications. Examples for magnetic nanocomposites are polymers or SiO_2 coated cobalt nano-particles, which can be produced economically via a wet-chemical procedure. These nanocomposites possess a higher permeability, curie temperature and electrical resistance than conventional ferrite materials due to quantum coupling effects between neighbouring nanoparticles. Another example are polyimide-coated Fe nanoparticles, which can be manufactured by compression moulding of nanoscale iron powders and polyimide and possess TMR (tunneling magneto resistance) properties (Wincheski and Namkung 2000). The advantages of theses composites are an increased sensitivity to detect changes of magnetic field and a higher working temperature range, which could be utilized for the development of miniaturized and energy saving microwave antennas, inductors, sensors or data memories for space applications (Jonson 2001). At present different research projects in the frame of the SBIR programme of NASA and also a joint project of the BMBF exist in this context [40].

[38] Press release NASA-MSFC from 08.07.97: „Aerogel- and the Mars rover“
[39] http://stardust.jpl.nasa.gov/mission/details.html
[40] BMBF joint project: „Application of nanopowders for the production of Mn-Zn-ferrites with improved magnetic characteristics“, Source: BMBF funding catalogue

At present a still rather visionary application of molecular nanotechnology is the production of „intelligent" materials with intrinsic sensing properties, programmable optical, thermal and mechanical characteristics or even self-healing properties. First approaches in this direction were realized e.g. in form of nanocomposites, consisting of conjugated polymers in a nanostructured silicate matrix, which changes the color with respect to mechanical, chemical or thermal stress. Applied as coatings for construction materials, mechanical or corrosion damages as well as critical changes of temperature could be detected promptly and economically.[41]

Long-term and visionary nanotechnological conceptions however go far beyond these first approaches. This applies in particular to the development of biomimetic materials with the ability of self organization, self healing and self replication by means of molecular nanotechnology. One objective here is the combination of synthetic and biological materials, architectures and systems, respectively, the imitation of biological processes for technological applications. This field of nanobiotechnology is at present still in the state of basic research, but is regarded as one of the most promising research fields for the future (European Commission 2001).[42] Due to the postulated high innovation potential for space technology, NASA invests a substantial part of its nanotechnology budget into this field of basic research. For example NASA at present establishes the Institute for Biologically Inspired Materials, with different universitary research institutes e.g. the Princeton University as participants. This institute is funded for a period of 10 years with annually 3 million $ and its main task is to transfer basic inventions to the development of materials with extrordinary mechanical and self-healing properties like those of some biological materials such as shells or bones.[43]

NASA funds basic research for the development of biomimetic materials

5.3 Ultrathin functional layers

For the production of ultra thin layers, which play an important role as functional coatings in many technical components, in particular chemical and physical deposition techniques in the gaseous phase are employed. The differences between the multiciplity of procedures lie mainly in the methods for the supply of the deposition material, reachind from CVD to high-energy particle beam procedures. Also by ion implantation nanostructured surfaces can be obtained. All methods are already used in the range of microtechnologies. For application in nanotechnology, a highly precise control of all process parameters is important. Also from liquids, extremely thin layers with controlled molecular architecture (e.g.

[41] SpaceDaily news from 25.04.01:„ Intelligent Nanostructures React To Environmental Changes“ (www.spacedaily.com)
[42] For a description of the actual state in nanobiotechnology see e.g. VDI-TZ 2002
[43] SpaceDaily news from 26.09.02: „NASA Turns To Universities for Research in Space-Age Materials“ (www.spacedaily.com)

Langmuir Blodgett films or self assembling monolayers) can be produced. With nanostructured layers varied surfaces can be obtained with super hard, corrosion resistant or friction-reducing properties with dependence on the used coating materials and processes. In the following possible space applications of such functional layers are discussed.

5.3.1 Friction and wear reducing layers

Nanoscale solid films are important for space technology as friction and wear-reducing layers, e.g. for the development of MEMS components. As determining factors for the tribological characteristics of materials their relative hardness, fatigue resistance as well as the kind and strength of the chemical bondings should be mentioned. Important in this context are intermediate layers (lubricants, coverage layers, oxide and reaction layers) between the friction partners, which behave in space (high vacuum) significantly different than under terrestrial conditions.

Tribology in space differs strongly from terrestrial conditions

As solid lubricants and mechanical protection coatings for space components in principle chalcogenides (MoS_2, WS_2, etc.), chalcogenide composites, carbides (WC, TiC, etc.), nitrides (e. g. TiN, BN) as well as carbon materials should be taken into consideration. The illustration 12 gives an overview of the relation of hardness and friction coefficients in different material classes. Carbon materials such as diamond and Diamor (ta-C) exhibit both a large hardness and small friction coefficient. By means of nanostructuring an improved adhesion of the carbon layers on the substrate can be obtained. For space applications it has to be taken into account however, that the tribological behaviour under space conditions (high vacuum) differs strongly in comparison to terrestrial conditions.

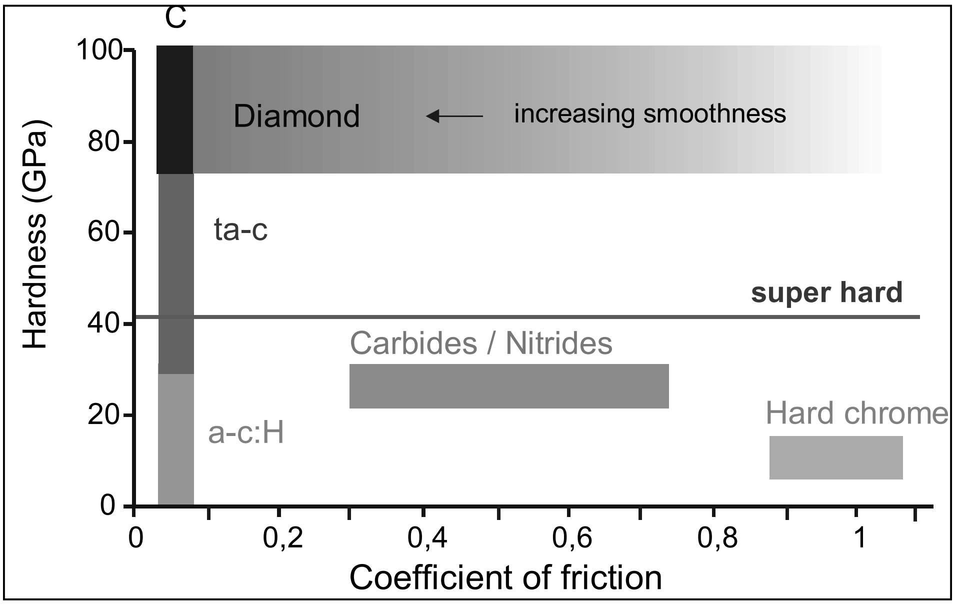

Illustration 12: Hardness and tribological properties of different coating materials against steel (without lubricant, medium humidity, source: Schultrich 2002)

In high vacuum a strongly decreased effect from intermediate layers is noticed, because no fluids lubricants can be applied, so that the coverage layers (e.g. water or hydrocarbons) can not be regenerated. Beyond that, a very broad range of application conditions exist in space regarding mechanical impact, temperature variations or floating speeds. Therefore a direct transfer of approved terrestrial tribological systems to space is not feasible. Thus it is noticed that the coefficient of friction of ta-C increases strongly with the transition from humid air to ultra high vacuum, whereas strongly decreases for a-C:H (> 40 % H). An explanation for this is that in the vacuum, in case of a-C:H, the high hydrogen content can supply the needed hydrogen for the saturation of free surface bindings originating from the tribological contact (Schultrich 2002).

For space applications nanocomposites appear promising which combine the tribological properties of different material systems. For example the material system ta-C/WC/W_2S, which can be manufatured by means of pulse laser ablation of graphite targets and magnetron sputtern of WS_2-targets, has been evaluated for space applications (Voevodin et al. 1999). In this case the high hardness and the mechanical stability of ta-C and tungsten carbide are combined with the low friction coefficient of WS_2 in vacuum. Application potentials in space are conceivable for example for low-friction and lubricant free bearings, cryogenic coolers for liquid hydrogen or thermal control layers in nanosatellites.

Tribological layers based on nanocomposites are promising for space applications

5.3.2 Thermal protection layers

Thermal protection layers in space technology can be used among other things for re-entry technologies (see chapter 5.2.2) or for the thermal insulation of rocket engines. In a research project of the Fraunhofer Institute IWS, the technical university Dresden and the company Astrium, nanostructured heat-insulating layers for combustion chambers of cryogenic cooled H_2/O_2 engines, as typically used for Ariane rockets, were developed and tested under relevant conditions. Concerning heat-insulating layers in rocket engines, high demands are made with regard to temperature stability, strain tolerance and adhesion strength. The manufacturing process must allow to produce an interior coating of the relevant components, exhibit high precision and reproducibility, as well as ensure a small temperature loading of the substrate material (Gawlitza 2002).

Thermal protection layers for rocket engines

As a solution for this, the PLD (pulse laser deposition) procedure allows to combine laser ablation and laser evaporation and thus to obtain a broad layer thickness range (from 1 nm to 100 µm). The PLD procedure ensures low temperatures during deposition and a multiplicity of target materials can be used. Thus gradient layers with different functionality can be produced (adhesion layers, effect layers, sealing layers etc.), which can be adjusted to the respective load profile.

The principle of the interior wall coating by means of PLD procedures, a schematic layer structure and a REM image of a cross section of a heat-insulating layer manufactured with PLD are represented in the illustration 13. Present development activities concentrate among other things on the interior coating of ceramic combustion chamber structures (CMCs) with high temperature-stable corrosion protection layers.

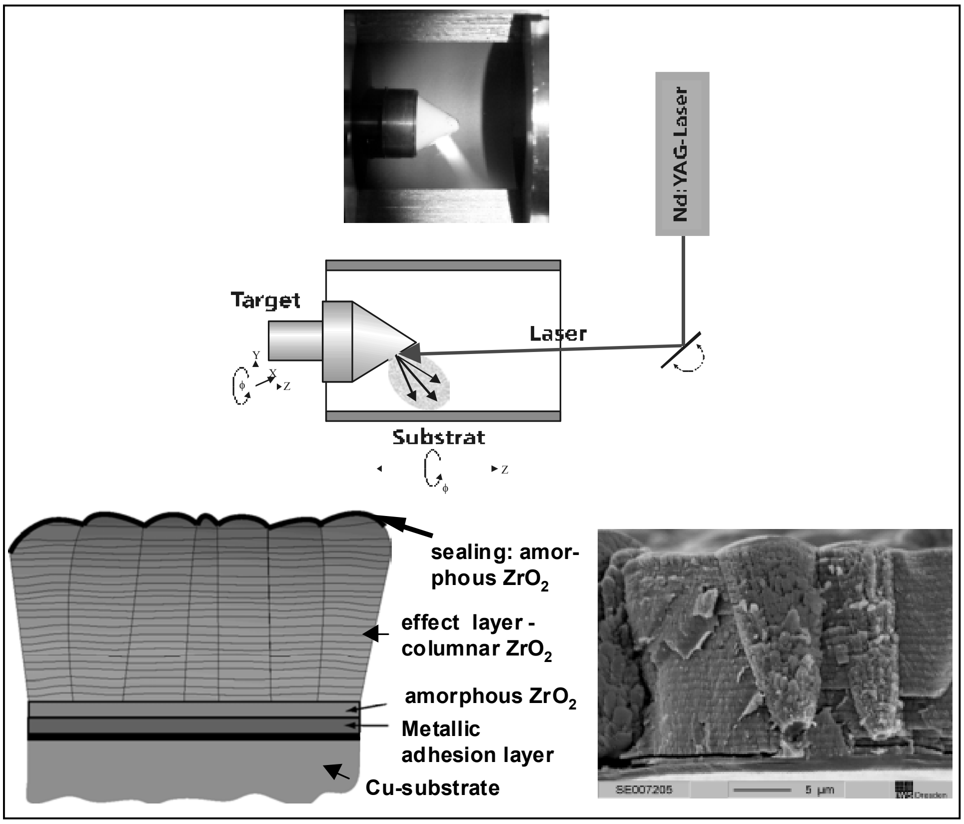

Illustration 13: PLD-process for the production of nanostructured heat-insulating layer for combustion chambers in rocket engines, above: principle of interior wall coating with PLD process; below: schematic layer structure and REM image of a heat-insulating layer manufactured with PLD (source: FhG-IWS)

5.3.3 Optics and electronics

The deposition and functionalization of ultra thin layers play a key role in a multiplicity of applications in optics and electronics. Examples in the field of optics are:

- X-ray mirrors, which consist of multiple nanometer thick layers
- antireflection coatings and scratch resistant layers for plastic optics, e.g. eyeglass lenses or displays
- transparent insulating layers for window panes (low emission layers), which almost completely prevent thermal emission losses from window surfaces

In optoelectronics a multiplicity of new components like organic light emitting diodes (OLED) or semiconductor diode lasers are based on nanostructured layer systems (see chapter 5.4). Sensors and actuators in microelectronic applications often require the integration of the sensor and actuator materials into the components by means of coating processes such as PVD, CVD, or sol gel techniques. Here also ISAM (Ionic Self Assembled Monolayers) are important, showing functional characteristics, e.g. electrical conductivity, optical, piezoelectric or photovoltaic properties, which are selectively adjustable by chemical modification. Such applications are important for components such as silicon circuits, micromechanical and microfluidic systems as well as SAW elements.

As nanotechnological components with importance for space applications in particular SAW elements should be mentioned, which are used in satellite telecommunications. Here the transition to ever higher frequencies requires a structuring of the associated SAW elements in the nanometer range. For example communication systems with working frequencies from 10 to 15 GHz require lateral structures from 50 to 100 nm and a layer thickness from 10 to 30 nm for the respective SAW elements.[44] Further nanotechnologically influenced electronical high speed components are HEMT (High Electron Mobility Transistor) and HBT (Heterojunction Bipolar Transistor), which already found entrance into industrial mass production as fast variants of bipolar and field-effect transistors. These transistors possess an outstanding signal-to-noise ratio in microwave receivers and transmitters for the application in modern radar and communication systems. Here in particular components on the basis of WBG (Wide Band Gap) semiconductors such as SiC or GaN will gain significance in the future. These materials allow increased operating voltages, higher power densities, better signal-to-noise ratios and thus smaller and more efficient components with lower requirements concerning cooling systems, which is important especially in the context of the miniaturization of satellite systems.

A further interesting application of nanolayers are transparent coatings on the basis of nanotubes developed in a SBIR project of NASA, which can be manufactured by means of sol gel procedures. Through the dispersion of the nanotubes in the polymer matrix a high electrical conductivity of the composites is obtained, which might be interesting for application as anti-static coatings in space structures and components as well as electrode materials for solar cells.

5.3.4 Magnetoelectronics

Ultra thin layers are the base for the development of magnetoelectronic sensors and memory chips with high potential for space applications. Such elements are based on magnetic resistance effects (e.g. Giant

[44] see competence center „ultra thin functional layers“ (www.nanotechnology.de)

Magneto Resistance, GMR), which occur in magnetic multilayer systems. For the production of such multilayers a controlled deposition of extremely thin metal and insulator layers (monolayer thickness approx. 1 nm) is necessary. The GMR effect, which has already been utilized for different commercial applications such as read heads in hard disc drives, occurs in the case of antiferromagnetic coupling of two (or several) magnetic layers seperated by a very thin (< nm) layer of non ferromagnetic material (e.g. Cu). If the antiparallel orientation of the magnetization in the ferromagnetic layers is disturbed by an exterior magnetic field, the electrical resistance is reduced along the layer system. Reasons for that are the spin dependent scattering of the electrons and changes in the electronic band structure. As a further magnetic resistance effect with a similarly broad application range, the magnetic tunnel resistance effect (TMR) should be mentioned. Here the spin dependent tunneling current between two magnetic layers, which are separated by a very thin insulator layer (< nm), is controllable by an exterior magnetic field.

Magnetoelectronic sensors and data memories with a high potential in space applications

Possible applications of magnetoelectronics in space are for example magnetic field sensors as position, acceleration or rotation sensors instead of conventional semiconducting magnetic field sensors (Hall effect sensors).[45] For magnetoelectronic sensors, different resistance effects like GMR, TMR, CMR or EMR can in principle be utilized. Problematic for space applications is however the limited working temperature range of the sensors. Here magnetoresistive sensors on the basis of silver chalcogenides could offer a solution. Thus researchers of the NEC Research Institute in Princeton developed a magnetoresistive sensor on the basis of $AgSe_2$, which is applicable over a far temperature (1.5 to 290 K) and magnetic field range (up to 50 T) (Soh and Aeppli 2002).

A further important application range of magnetoelectronics are magnetic memories (MRAM) as replacements for conventional CMOS memory chips. The advantages of MRAM are the non volatileness (data remain preserved also in case of a power failure), a small energy consumption and the resistance against electromagnetic radiation. Some years ago the company Honeywell already developed MRAM chips, which were based on the anisotropic magneto resistence, with a size of 16 KB for special space applications. Meanwhile all main semiconductor manufacturers pursue the development of MRAM on a world-wide basis. In the USA for example IBM, Motorola and Honeywell, in Japan Fujitsu, Hitachi and Toshiba and in Europe Infineon and Philips. The general market readiness of MRAM memory, apart from special space applications, is expected for the year 2004. Also other types of memory chips, which are based on nanoscale structures, offer in principle application potentials in space (e.g. FRAM or phase change RAM, see section 5.5.2).

[45] Kyle, Buckley 2000

5.3.5 Thin film technologies for space structures

Newer research efforts for example of NASA aim at the miniaturization of space systems only in one dimension, i.e. very large self-deployable systems consisting of very thin foils. For the development of these so called GOSSAMER spacecrafts the integration of e.g. the following subsystems into the thin film structure is pursued (Seboldt 2001):

NASA uses thin film technology for the development of so-called Gossamer spacecrafts

- thin film solar cells (e.g. on kapton substrates)
- antennas (phased arrays) in thin-film technology
- semiconductor circuits deposited on foils
- attitude and orbit control through evaporation of foil material
- fuelless propulsion (sunsails, or laser/microwave propelled sails)

In this context various nanomaterials and layers are examined for the production e. g. of electrically controllable layers for optical mirrors or self assembling layers for ultrathin solar cells (Moore 1999, NASA 2000b). As potential application for such space structures the following should be mentioned, among other things:

- large telescopes, mirrors, antennas (optical, x-ray and radiowave)
- interplanetary spacecrafts (solar sails)
- large star coverage structures for planet detection
- large extremely light solar generators (Solar Power Satellites)
- intelligent multi-functional structures (e.g. active form control)

Vision: solar power plants in space

The illustration 14 shows a conception of a so called Sun Tower, that is based on NASA studies regarding the feasibility of solar power stations in space (Mankins 1995, Feingold 1997). Such structures are supposed to to be several kilometers large and deployed in sun-synchronous or geostationary orbit. The energy might be transferred by means of microwave or laser radiation to earth. Also in Europe and in Japan conceptions for solar power stations in space are discussed. The realization of such conceptions still fails at present due to the extremely high costs of space transportation and technical problems still to be solved (transformation efficiency of the solar cells, possibly with optical concentration of the sun light, temperature and radiation resistance of the thin film materials as well as multi-functional integration of subsystems). Some experts however, regard an economic application as possible in 15 to 25 years.[46]

Illustration 14: NASA Sun Tower Concept (source: NASA)

[46] NASA Science news from 23.03.2001: „Beam it Down, Scotty!“ (http://science.nasa.gov)

5.4 Nano-optoelectronics

Diffractive optical elements, optoelectronic transducers and photonic components, which play an important role in optical data communication, can be substantially improved by lateral nanostructures. With the development of lateral optoelectronic nanostructures the way to controllable diffractive optics is paved. For this, elements with specific interference structures are necessary, which act as specific and possibly controllable transmission or reflection filters. Nanostructured optoelectronic components (e.g. quantum well or quantum dot lasers, photonic crystals) offer large market potentials in the future, e.g. for optical data communication or in the range of consumer electronics (for example laser television).

Laser systems for optical intersatellite links

Nanostructured optoelectronic components offer promising application in space in the fields of optical satellite telecommunications or sensor technology (infrared sensors, high resolution CCD etc.). With optical wireless data links (OWL) for intrasatellite communication[47] as well as optical intersatellite links, significantly smaller and lighter devices and a higher bandwidth could be realized in comparison to conventional microwave communications. Optical intersatellite links were demonstrated in the frame of the ARTEMIS mission of the ESA. For the data transmision extremely frequency-stable solid state lasers (Nd:YAG lasers) are used, which are pumped with diode lasers (Smutny et al. 2002). The German company Tesat is a leading manufacturer of laser terminals for optical intersatellite communication. Such laser terminals are also interesting for scientific applications for example as injection seeder for a satellite-based Doppler-Lidar (ALADDIN), as satellite-based measuring device for gravitation wave detectors (LISA, with SMART as demonstration mission) or as frequency normal for a satellite-based FT-spectrometer (POISON). In the following, some nano-optoelectronic components and their possible applications in space are described.

5.4.1 Quantum dot laser

QD lasers with interesting properties for space applications

Semiconductor quantum dots, which can be manufactured since approx. 5 years in high quality by means of self organization, offer a new degree of freedom in selecting the working wavelength of photonic elements. They allow to cover almost completely the entire spectral region from the ultraviolet to the far infrared with a small number of substrate materials. Further advantages of QD lasers are a small energy consumption through low threshold current densities, a high modulation range for high-speed applications as well as an improved temperature stability. The illustration 15 represents the threshold current densities of different types of semiconductor diode lasers.

[47] Guerrero et al. 2000

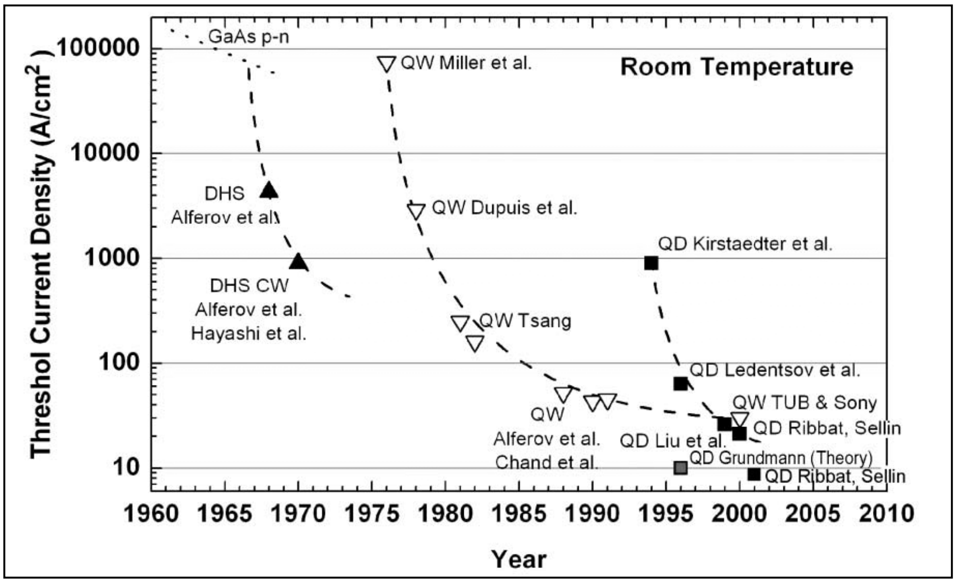

Illustration 15: Comparison of threshold current densities of different semiconductor lasers (source: Bimberg 2002)

Beyond that, an improved radiation hardness has already been proven by QD lasers compared with quantum well lasers (Bimberg 2002, Leon et al. 2000). First commercial uses of quantum dot lasers are expected in 2003. Illustration 16 shows the schematic structure of a QD VCSEL.

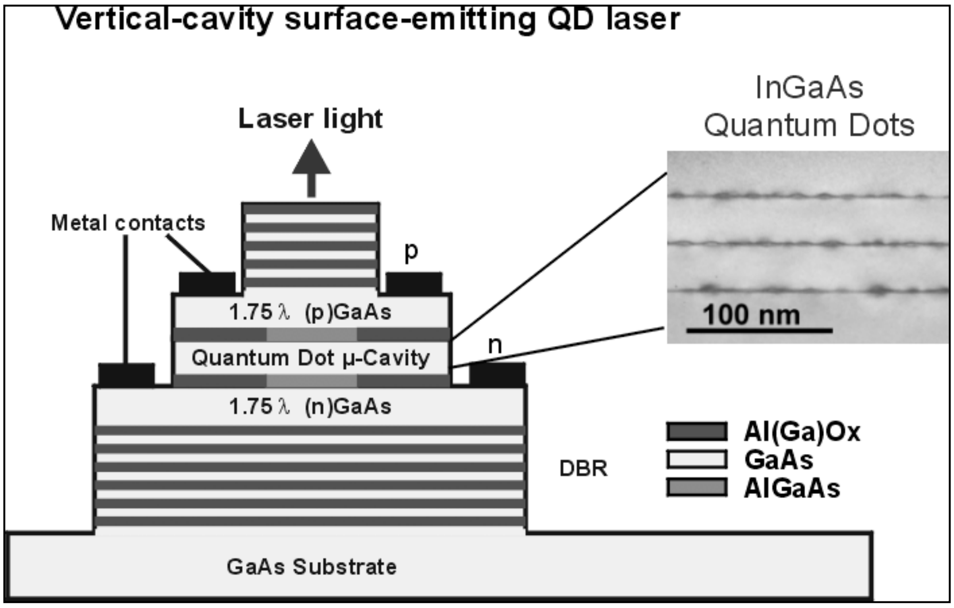

Illustration 16: Schematic structure of a QD VCSEL (source: TU Berlin)[48]

Due to their radiation hardness and the low energy consumption, QD lasers in principle are relevant for space applications, e.g. as pump lasers for solid state lasers, which are needed for different applications (see

[48] BMBF joint project: „Surface emitting laser for 1300 nm based on quantum dots; FKZ 1BC 913

above). In order to realize the potential of QD lasers in space applications, appropriate measures have to be accomplished by the space industry for the specification, system integration and space qualification.

5.4.2 Photonic crystals

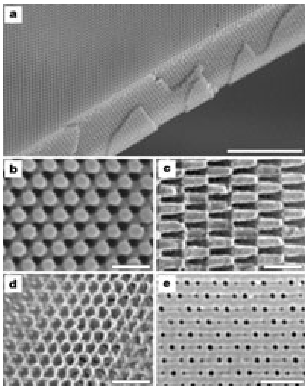

Illustration 17: SEM Images of two-dimensional photonic crystals. Scale of length (a) 10 µm, (b-e) 1 µm, (Source: Campbell et al. 2000)

Photonic crystals are a further example of nano-optoelectronic components with application potential in optical data communication. Photonic crystals exhibit a periodic refractive index and possess an analogy to semiconductors in electronics, a "photonic band gap" for certain frequency in the visible and IR wavelength ranges. The lattice constant of photonic crystals lies in the range of half the wavelength of the light in the medium. For visible light this means that for the production of photonic crystals a precision within the range of 10 nm is necessary. Two-dimensional structures today can be routinely manufactured with high precision. At present, intensified efforts are made for the development of three-dimensional photonic crystals, e.g. with utilization of lithography and self-organization procedures, in which nanoscale colloids (e.g. from polymers or silicates) arrange spontaneously to a cubic lattice. These lattices are used as templates for lattices from more interesting materials such as metals and metal oxides. Three-dimensional photonic crystals would open up new possibilities in optical data communication (light could be guided and branched to arbitrary directions) and offer in principle the potential for the realization of purely optical circuits (optical computing). Such photonic transistors are however at present still very far from realization (Yablonovic 2002). In the long run, photonic crystals will find applications in optical satellite communications.

5.4.3 Infra-red sensors

IR sensors offer a multiplicity of application potential in space, e.g. for the satellite-based earth observation and atmosphere research, for astronomy, as navigation aid for space systems or for optical data communication. Approaches for the miniaturization and futher improvement of infrared sensors are based among other things on the application of two- (quantum well), one- (quantum wire) or zero-dimensional (quantum dot) nanostructures. With the help of quantum well or quantum dot structures the detection characteristics of IR sensors can be adjusted selectively to the relevant spectral region (band gap engineering). Quantum well IR sensors, based on GaAs are developed for example by the Center for Space Microelectronics Technology of NASA for special space applications. This QWIP consists of a GaAs-layer, which is embedded sandwich-like in two $Al_xGa_{1-x}As$ layers. The characteristics of the quantum wells can be adjusted by varying the thickness of the GaAs layer and the composition of the barrier layer. By means of molecular beam epitaxy, nm-thick layers can be produced on large areas with atomic precision. Ga-As QWIP can be realized also for long-wave IR radiation > 6 µm.

The technical university of Munich pursues a different approach in the frame of a BMBF joint project on the self organization of Si/Ge islands on silicon.[49] The research activities are focused on controlling the characteristics of epitactical, defect-free Si/Ge islands on silicon substrates, which can be produced with the self-organizing, parallel Stranski-Krastanow procedure in the material system Si/SiGe (Brunner 2002). The objective here is to develop coupled systems with several layers of quantum dots in a homogeneous layer system, which exhibit new functions by charge transfer and electrostatic coupling and can be used as optical detectors particularly in the mid IR range. With combined QD/QW structures a 50-fold increased photoresponse can be obtained compared with sole quantum dot structures (Brunner, 2002b). Expected advantages of QD MIR detectors to be mentioned are the extended spectral range, a high durability and reproducibility, radiation hardness and a low dark current. For 2003 the realization of a prototype 2-colour IR detector in co-operation with DaimlerChrysler is planned.

Si/Ge quantum dots for the optimization of infra red sensors

5.5 Lateral nanostructures

Functional lateral nanostructures open up new dimensions on the level of subcomponents for products within the ranges of information technology, electrical engineering and optics. These are partly based on completely different physical principles, but can be realized with a relatively uniform process technology, which is derived from the development of the CMOS technology. As mentioned in chapter 4, an immense demand for efficient information technologies exists in space technology, in order to improve the on-board autonomy of spacecrafts and to process the increasing data flood of the payload in space. Components, in which lateral nanostructures make a substantial contribution to functionality, offer potentials for the development of efficient energy-saving data memories and processors. In the following, some nanotechnological components and conceptions within the ranges of data processing and storage as well as their possible application in space are discussed.

Nanoelectronics for an improved on-board-autonomy and intelligent space systems

[49] BMBF joint project: „Self-organized growth on silicon- Subproject: Self-organization and self-ordering lattice adjusted semiconductor structures on Si; FKZ: 13N7870

5.5.1 Alternatives for CMOS electronics

In information technology the performance of microprocessors has increased for two decades now with a steady pace. According to this so-called Moores law, the device complexity and thus performance of microprocessors doubles every three years. This performance gain is possible only with a drastic size reduction of the CMOS transistors, the core of microprocessors. CMOS electronics, today already, are based on structures of about 100 nm. So function-critical components of a transistor have at present only dimensions of few atomic layers. In the near future the structures of CMOS components will reach the sub-100-nm range. For the production of sub-100-nm structures several procedures, for example EUV-, x-ray or electron beam lithography are discussed at present, as well as scanning probe procedures, nanoimprinting or self-organization processes. Conventional CMOS technology will reach its physical limits on structure widths of 20-30 nm due to the wave characters of electrons. The problem of electromigration requires furthermore a reduction of current densities in miniaturized wires. Also from a financial point of view, limits are imposed on a further miniaturization of the circuits, since the manufacturing costs are expected to increase more strongly than the profits, realizable on the market with such microchips. As future alternatives for the present CMOS technology, several conceptions are discussed, e.g. molecular electronics, spintronics, quantum information processing, which all contain genuine nanotechnological functional elements.

Future limits of CMOS electronics

5.5.1.1 Molecular electronics

In molecular electronics, organic and/or biological molecules form the basis of realization of electronic functions and/or elements. Fundamental questions within this research field are in particular the reversibility of switching processes, the switching speed, the scaling up to large molecular circuits, the design of appropriate processors and their interfaces to the macroscopic world. For the production of molecular circuits in particular, methods of self-organization are considered, which should allow a cost-advantageous production. The area of molecular electronics is at present still in the stage of basic research and far from market readiness. Due to their special electrical properties, CNT is a material class with high potential for molecular nanoelectronics, for example as nanoscale connecting wires or components of transistors and logics. After having been able to demonstrate the suitability of CNT as active channels in transistors, researchers of IBM have recently developed the first field-effect transistor circuit on the basis of CNT (Derycke et al. 1999). Further research approaches aim at the realization of molecular computer architectures based on DNA molecules. Here the conductivity of the DNA molecules and the ability for self organization might be utilized for the production of molecular electronic components.

Electronic components on basis of CNT

5.5.1.2 Spintronics

Spintronics with potential for ultra fast data processing

Spintronics is regarded as the logical advancement of magnetoelectronics. It utilizes not only the charge but also the magnetic moment of the electron for data processing. There are already forecasts according to which elements that only switch the spin of electrons could be clearly faster than those which function on the basis of electrical charge. Additionally the switching process would need less energy than a comparable charge transfer. Spintronics could be established in addition to the charge based data processing, since the magnetic moment represents a further degree of freedom of the electron. On a long-term scale the utilization of the electron and/or nuclear spin could contribute to the development of quantum computers. Within the range of data storage the first element, which uses the electron spin, has already successfully been developed into a mass product. Based on the GMR effect, the "spin valve" read head is applied in the new generation of thin film read heads in hard disk drives. A further much promising candidate for future spintronic elements in the range of data storage is the MRAM (Magnetic Random Access Memory) as an alternative to DRAM or Flash memory.

5.5.1.3 Quantum Computing

In conventional components, quantum effects emerge as disturbing influences on the nanoscale, which impair the function of the element. Quantum information processing on the opposite side is based on the specific utilization of quantum effects for a completely new form of highly parallel data processing. In a quantum computer, the fundamental unit of information (called a quantum bit or qubit), is not binary but rather more quaternary in nature. By clever utilization of the properties of superposition and entanglement, a new form of "quantum parallelism" appears achievable, wherein an exponential number of computational paths can be explored "at once" in a single device. The field of quantum information processing has made numerous promising advancements since its conception, including the building of two- and three-qubit quantum computers capable of some simple arithmetic and data sorting. However, a few potentially large obstacles still remain that prevent us from building a quantum computer that can rival today's modern digital computer. Among these difficulties, error correction, decoherence, and hardware architecture are probably the most formidable.

5.5.1.4 Logics with tunneling components

Tunneling components (e.g. resonant tunneling diodes, RTD) harness the extraordinarily fast quantum-mechanical tunneling effect. This promises a clear speed increase in comparison to conventional elements. RTD from III/V semiconductors are already used as high frequency oscillators in the THz range, optoelectronic switches, photodetectors etc. Application potentials in space exist in particular as ultra fast, energy saving processors for digital electronics in the range of the satellite communication systems. Disadvantageous is that at present there are hardly any transistor concepts based on RTD. First logical circuits were however already developed. Difficult is in particular the demanding production process, since the properties of the elements depend very strongly on the geometry of the components. Without substantial progress in this area, RTD will remain a niche application. Better chances are predicted for Si/SiGe RTD, since these would be integrable into conventional silicon circuits, whereby however numerous technical problems must still be solved (Compano 2000). With regard to possible space applications of RTD their radiation sensitivity should be classified as a critical factor, which is examined among other things in a co-operation project of the Naval Research Laboratory and the company Raytheon. First tests regarding the radiation sensitivity of RTD revealed, that the tunneling current is reduced significantly by radiation defects (Weaver et al 2000).

5.5.2 Nanotechnological data storage

Also in the area of data storage, nanotechnology offers potentials for the production of miniaturized mass memories with extremely high storage density as well as for the development of new non volatile working memories for computer systems, which will compete in the future with conventional memory chips like DRAM.

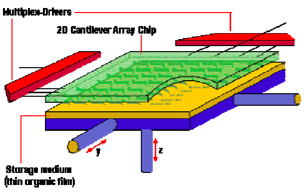

Illustration 18: Millipede: ultra dense data storage on basis of scanning probe technology (Source: IBM)

Nanotechnology could lead to improved mass data storage systems in the future based on thermomechanical, optical or holografic principles, which at present are still under basic research. The IBM research department in Rueschlikon works on the development of the so-called Millipede memory, which is a micromechanical device with an array of nanoscale read/write/erase tips based on scanning probe technology. The active storage medium is a thin polymer film on the surface of the chip that represents bits in the form of 10-nanometer-diameter holes. For writing the tips are heated to 400 °C causing intendations in the polymer film. To read out, the same tips are heated to just 300°C to prevent damaging the polymer. When the tip drops into a hole marking a bit, it is abruptly cooled by the better heat transport, and a measurable change in its resistance can be detected that is enough to distinguish "1" from "0." Advantages of the millipede data storage are nonvolatility, low power and large capacity storage up to 1 Tbit per square inch, thus making the millipede interesting for mobile applications and perhaps also for space applications. If existing technological problems could be solved, the millipede will become competitive especially for mobile applications as a replacement for flash memories in some years.[50]

[50] EE Times news from June, 24 2002: „IBM stores terabits of memory on a single chip“ (www.eetimes.com)

Optical data memories with a 3-d array of optically adressable quantum dots offer likewise the potential for a substantially increased data storage density. Data memories can in principle also be realized by making use of biological molecules. In particular bacteriorhodopsin (bR) has been examined intensively for applications in data memories. This protein complex can be switched into different configurations by laser light, which can be used for data reading and writing in a three-dimensional medium. Such three-dimensional optical memories have been investigated for several years now, but are still in their infancy (Birge et al. 1999). Problematic among other things, are the high demands regarding the laser arrangement and control as well as the production of the storage medium. At present efforts are made on genetic mutations of bR in order to stabilize individual configurations of the protein for increasing the data stability. The development target is a mass storage, which however is hardly regarded as a serious competitor for established storage media in the near future.[51]

Another approach for a biological memory is developed by the company NanoGen. This memory consists of micro arrays, on which modified DNA molecules with different fluorescence markers for different colors are attached. These can be utilized to read out the data, which are stored as specific configurations of the DNA strands. Since the data writing procedure is extremely slow, first applications of such storage systems might be the large archiving of large data sets.

MRAM as nonvolatile radiation hard data memory for space applications

In the range of main memories, different nanotechnologically influenced storage types are in development, which will step into competition to DRAM chips in the near future. The research activities of the main chip manufacturers here essentially focus on both competitive ferroelectrical (FRAM) and magnetoelectronic (MRAM) storage technologies. The main advantages of both storage types lie in the non-volatile information storage, i.e. the data remains without external current supply. That means data cannot be lost upon a sudden power failure and the booting procedure of PC‘s would become unnecessary. Beyond that, the necessity for the data refresh is cancelled clearly, which reduces time lags and the energy dissipation as compared with DRAM. MRAM exhibit here, in comparison to other non volatile storage types such as EEPROM, Flash or FRAM some advantages, which are particularly interesting for aerospace and military applications: [52]

- Low energy consumption
- Inherent radiation resistance
- Suitability for high temperatures

The temperature stability of MRAM is clearly better than that of FRAM, whereby data durability already decreases significantly at temperatures of

[51] VDI-TZ 2002, p. 81
[52] Honeywell Solid State Electronics Center (http://www.ssec.honeywell.com)

70 to 85 °C. Magnetoresistive MRAM memory at present still possess no market readiness, although the company Honeywell already manufactured MRAM chips for special space applications some years ago. These MRAM chips were based on the AMR resistance effect, while modern concepts utilize the GMR or TMR effect. Meanwhile Honeywell has developed GMR based prototype MRAM chips for military applications, while the readiness for the civilian terrestrial market is expected for 2004 (see chapter 5.3.4).

FRAM are based on the ferroelectricity of certain crystals, in which lattice mobile atoms with stable configurations can be found, which can be switched by electrical fields in nanoseconds. The ferroelectrical memory cells retain the written data for more than 10 years. A disadvantage of FRAM is that the life span is limited due to material fatigue on approx. 10 billion writing cycles. FRAM were manufactured as 8Mbit-chips and were already used for example in SmartCards.[53] In particular Japanese and Korean companies (Toshiba, Fujitsu, Samsung) but also German companies (Infineon) accomplish intensified efforts in order to develop ferroelectrical memories.

SOI memory chips for space applications with moderate storage demand

As further nanotechnological storage concepts with potential for space application SOI memory (silicon on insulator) and phase change memories (PC RAM) should be mentioned. SOI memory chips can be used for space applications with moderate storage requirements. Honeywell introduced radiation-hard 4 Mbit SOI SRAM for space applications, which exhibit access times of 25 ns and are suitable for temperature ranges from -55 to 125 °C.[54] SOI chips utilize a thin SiO_2 isolation layer (about 25 nm thin) deposited on Si wafers, on which the transistor is built. SOI memory exhibits a higher speed and a smaller energy consumption in comparison to CMOS technology (Isaac 2000). The Naval Research Laboratory holds a patent on microelectronic components based on SOI technology for space applications.

In phase change memories (PC RAM), which for example are subject to development work done by the companies Intel and Ovonyx, data are stored by electronically excited phase transitions of semiconductor alloys in an amorphous (high electrical resistance) respective crystalline state (low electrical resistance). Possible advantages of this technology are the simplified production process and a high integrateability into circuits.

5.5.3 Nanostructures in microelectronics/micro system engineering

Also within the range of micro system engineering, nanostructures and nano-technologically optimized components will gain importance in the

53 C't magazine 5/2001, p. 24: „Energy crisis- Highlights from the ISSCC in San Francisco"

54 http://www.ssec.honeywell.com/aerospace/new/080699.html

future. In space travel MEMS offer the possibility of miniaturization in a variety of subsystems (e.g. AOCS, propulsion, thermal control). The progressive miniaturization makes an increasing integration of different functions and components in a circuit necessary. Modern micro manufacturing processes for example make the integration of different sensor and actuator units for attitude and orbit control as well as a propulsion unit possible. A still higher integration and compactness offer approaches like vertical MMIC structures (Monolithic Microwave Integrated Circuit), MAFET (Microwave and Analog Front-End Technology) or Ultra-Thin-Chip-Stacking (piles of µm thick Si or III/V semiconductor circuits),[55] which will play an important role regarding the miniaturization of space subsystems and systems. Also microelectromechanical thermal control systems are in development, which use among other things nanoscale electrochrome coatings. Likewise MEMS based switches and antennas are examples of space relevant applications of MST, which will be influenced increasingly by nanotechnology in the future.

Micro manufacturing processes for highly integrated space subsystems

Apart from photoelectric IR sensors described above, also bolometers find application in space, for example as earth sensors for attitude and orbit control of spacecrafts or for scientific purposes (e.g. in astronomy particularly in the far infrared range as well as in atmosphere research). For the production of miniaturized bolometers, nanotechnological coating and lithography procedures are applied. The thermoelectric substances are separated from each other by nanoscale isolation layers. For bolometers, different material systems are used as absorber layers, among other things also high temperature superconductors like nanocrystalline Y-Ba-Cu-O. This material offers the advantages of a high thermoelectric resistivity, a low noise factor and a good CMOS compatibility (Sedky 1997).

Another example are micromechanical actuators, which could be used as miniaturized positioning modules in robotic space applications. Piezomotors help to achieve positioning systems with a resolution of 10 nm over distances of several centimeters. A prominent manufacturer of these "nanomotors" is the Aachener company Klocke Nanotechnik.[56] Possible applications in space technology comprise miniaturized positioning systems with many degrees of freedom for spectrometers, high frequency tuner or nanomanipulators, which could be used for an accurate dosage of tiny drops for microgravity experiments on ISS. According to data of the manufacturer such nanomotors possess good applicability in space (Rosenberger 2000).

„Nanomotors" for space technology

[55] see Coello-Vera et al. 2000
[56] www.nanomotor.de

5.6 Ultraprecise surface processing

Ultraprecise surface processing comprises all manufacturing processes allowing to produce macroscopic bodies and surfaces are produced with extremely high precision and smoothness. Ultra precise surfaces exhibit improved functionalities for a multiciplity of applications.

5.6.1 Manufacturing of ultraprecise surfaces

Mechanical/chemical and optical manufacturing processes as well as ion beam and plasma procedures belong to the most important procedures for ultraprecise surface figuring and form correction. Ion beam and plasma processes allow form correction and/or shaping of large surfaces (cm^2 to m^2) with accuracies within the nanometer range and a roughness reduction in a sub nanometer range. Due to the low working speed and the high costs for the maufacturing equipment, the application range is limited so far to the production of high performance optics. Also optical procedures using UV lasers are applied for ultraprecise surface treatment in particular for polymer surfaces.

The main application field of ultraprecise surface figuring is optics. Apart from ever smoother and more precise lenses in the visible range, there is an increasing demand for optics of other spectral ranges, i.e. infrared, UV and x-ray. Also in the range of joining techniques, especially in microelectronics, ultraprecise surface processing plays an important role. For the cost-advantageous manufacturing of microsensors and actuators the directbonding of silicon wafers and other components gains importance. This concerns both the joining of silicon and other semiconductor elements (optical elements on III/V semiconductor basis) on a chip and the assembly of different optical and mechanical microcomponents (e.g. quartz micro lenses, piezoelectric actuators etc.). During direct bonding two ultraprecise surfaces are brought in contact, so that they can be irreversibly connected through a pressure and a temperature treatment without additional adhesives.

Ultra precise surfaces for the direct-bonding of semiconductor and micro-components

A high innovation and market potential lies further in the production of defined microstructures in the surface of components and in figuring more complex component geometries. By manufacturing microscopic bars, pyramids or cube segments, special optical, chemical, mechanical, tribological or thermal surface properties can be achieved. Applications are particularly in the lighting, communication and measuring technologies. As examples micro radiators, sealing surfaces or microstructured air bearings should be mentioned.[57]

In space technology ultraprecise surface processing is important for the production of components for optical satellite communication or of optics (IR to x-ray range) for the earth observation and astronomy. Telescope

[57] see CC Ultraprecise Surface Figuring (www.upob.de)

optics must be manufactured more precisely, the smaller the wavelength of the observed light is, in order to avoid light scatterings. Particularly high demands are made on X-ray optics. X-ray mirrors, which are important components of observation instruments for the detection of X-ray sources in space, require ultra smooth surfaces with a roughness less than 1 nm to avoid light scattering. By means of pulse laser deposition these mirrors can be manufactured in high vacuum with precision of a few hundredths nanometers. The optics of the 1990 commissioned German X-ray satellite ROSAT counted with a surface roughness of 0,35 nm at that time as the smoothest mirror in the world.

Extremely smooth X-ray mirrors for X-ray astronomy

Conventional x-ray mirrors according to the Wolter principle are manufactured from glass ceramics with a thin metal coating. The disadvantages of these conventional glass-ceramic, monolithic optics are a relatively high weight and a limited collecting surface. Modern x-ray mirrors are based on very thin single mirrors and mirror foils with a nested design. Thus the collecting surface of the optics can be substantially increased. Examples for this design are the European XMM (X-ray Multi Mirror) x-ray telescope, which consists of three telescopes each of which have 27 single nickel mirrors, and the Astro-E with 5 telescopes and 180 mirror foils each.[58] Such mirror foils, with a diameter of typically about 200 µm, permit a very close nesting and thus an increased collecting area in particular for high-energetic radiation as well as a drastic weight reduction compared with monolithic optics. At present three efficient x-ray telescopes are deployed in space with the American Chandra, the European XMM and the Japanese-American Astro-E. For future missions in x-ray astronomy such as Constellation X of NASA or XEUS of the ESA still higher demands are made with regard to the performance of the telescopes. For their manufacturing the ultraprecise surface figuring of foil substrates will play a key role.

5.6.2 Characterisation of nano-surfaces

A further important field in the range of ultraprecise surfaces is the characterisation of the mechanical-physicochemical properties of surfaces including local defects. For space applications the behavior of nano-surfaces under space conditions is of particular interest. During exposition in space, different effects on nanosurfaces occur, which can lead to a functional deterioration, for example through crystal growth, increasing roughness or droplet formation. In the frame of the DLR project SESAM, a measuring device was developed, making it possible to analyze changes of surfaces under space conditions on a nanometer scale and to correlate them with the ambient conditions, e.g. influence of atomic oxygen (Toebben 1999). Here different nanoanalytic procedures are applied such

SESAM: measuring device for the charaterization of nano-surfaces in space

[58] see NASA Laboratory for High Energy Astrophysics: „X-Ray Optics", (http://lheawww.gsfc.nasa.gov/docs/xray/astroe/MirrorLab/xoptics.html)

as scanning probe and scanning force microscopy, quantitative Nomarski microscopy and field emission scanning electron microscopy.

5.7 Nanoanalytics

The characterisation of materials, structures and surfaces with nanoscale respectively atomic resolution is a basic prerequisite for nanotechnological developments and is therefore of central importance for the technology field. A considerable arsenal of high performance measuring techniques exists in the field of nanoanalytics, some of which have already been established a long time ago. These methods work for example with electron-, ion or photon beams, field emission or tunneling effects or are based on electrical, optical, thermal, acoustic or magnetic principles. Analytical procedures on the nanoscale concern the determination of structures, surfaces and thin films as well as physical and chemical material properties.

Nanoanalytics play a key role in all technology developments described in the previous chapters. In the following a restriction is therefore made on nanoanalytic methods, which can be applied in space for the characterisation of materials and particles with a nanoscale resolution, particularly in the range of scientific space missions.

5.7.1 Secondary Ion Mass Spectrometer

Secondary ion mass spectrometers offer the possibility of investigating comet matter and interstellar dust particles with a nanoscale resolution (Nano-SIMS). The Max-Planck-Institute for Chemistry in Mainz developed in cooperation with the French company Cameca and the Laboratory for Space Sciences of the Washington University of St. Louis, a secondary ion mass spectrometer for applications in space, which was taken into operation in the year 2001. The SIMS method finds a broad application in cosmo chemistry and is used e.g. for the investigation of interstellar dust particles, which have diameters varying between a few nm and some µm. The nano-SIMS is expected to provide important findings in connection with the galactic chemical evolution as well as the chemistry of atmospheric aerosol particles.

5.7.2 Scanning probe and tunnel microscopy

Scanning probe microscopy belongs to the most important methods in the field of nanoanalytics. Scanning probe methods are based on a local reciprocation between a surface and a scanning probe tip, which is brought very near (in atomic dimensions) to the surface of the sample. The measuring procedure can be compared in principle with a miniaturized record player, where a tip moves over a surface, scans it on an atomic scale and converts the signals into an image. The received information can concern for example the chemical composition of the surface, the distribution of surface potentials, magnetic or electrical fields. The development of miniaturized, automated scanning probe devices for space missions, offers the possibility of characterizing solids and dust particles in space with nanoscale resolution without a sample transport to earth. A concrete example is the use for the investigation of soil and dust particles on the Mars surface. An appropriate AFM device was developed by a Swiss consortium for the Mars Surveyor mission of NASA (Gautsch 2000). To increase the dependability of the system, eight microprobes were installed on the AFM chip, although however just one cantilever is used for the measurements (see illustration 19).

Miniaturized scanning probe microscope for space missions

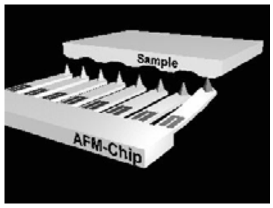

Illustration 19: AFM-Chip with 8 cantilever probes for the investigation of soil and dust particles on the MARS surface (Quelle: Uni Basel)

http://monet.physik.unibas.ch/famars/index.htm

The microelectronic components of the AFM equipment have been adapted to the extreme space conditions (vibrations, temperature gradients, radiation etc.). Due to the cancelling of the Mars Lander mission in the frame of the Mars Surveyor 2001 mission of NASA, the equipment was not in operation yet.

The LMU Munich (working group of Professor Heckl) developed a high resolution scanning tunnel microscope (STM) for applications in space, which was already tested in parabolic flights and at present is prepared for employment on the ISS. The microscope is intended to investigate the growth of defective-free DNA crystals under microgravity with nanoscale resolution.[59]

[59] IDW press release from 5.12.2001: „Premiere: test of a scanning tunnelling microscope under microgravity“, (http://idw-online.de)

5.8 Summary and evaluation

Table 8 gives a rough overview on nanotechnologically influenced components and systems with space application potential as described in the preceding chapters.

Field of technology	**Nanotechnological application**
Structure materials	• Nanoparticle reinforced polymers • CNT/CNT-composites • Metal matrix composites • Nanocrystalline metal/alloys • Nanostructured ceramic(s)...
Energy generation and storage	• III/V semiconductor solar cells • Thin film solar cells • QD solar cells • Fuel cells • Supercapacitors • Batteries/thin film batteries...
Data processing and storage	• SOI memory • Phase-Change-RAM • MRAM • Biological data memories • Molecular electronics • Spintronics ...
Data communication (optical/EHF)	• QD Laser • Photonic crystals • HF-components (HEMT, HBT, RTD) • SAW- components ...
Sensor technology/instruments	• Gas sensors • QD IR sensors • Magnetoelectronic sensors • Scanning probe devices • X-ray optics/- mirrors...
Life support systems/biomedical applications	• Heat exchanger • Nanomembranes • Lab-on-a-chip Systems • Drug-Delivery-Systems ...
Thermal protection/control	• Ceramic fiber composites • Thermal protection layers and isolations • Ferrofluids ...

Table 8: Selection of nanotechnologically influenced components and systems with application potential in space

The spectrum of nanotechnology applications in space reaches from short to medium-term applications up to long-term and visionary developments. Significant differences can be determined regarding the economic potential in the terrestrial market, the contribution to space technology goals and the economic benefits for the space sector. Beyond that, numerous obstacles concerning nanotechnological applications in space can be identified. In order to assess the relevance of the nanotechnology applications outlined in chapters 5.2 to 5.7, an evaluation has been accomplished regarding the following criteria:

Criteria for evaluating the space relevance of nanotechnological components

- State of development of the technology
- Economic potential in terrestrial markets
- Contribution to space technology objectives
- Economical benefit for the space sector
- Potential application obstacles in space

Semi-quantitative evaluation summarized in table I in the appendix

The evaluation was performed in a semiquantitative manner on a three step rating scale from 0 = low to 2 = high. For the assessment of the state of development a more differentiated scaling was used from 0 = theory to 5 = space qualification. The individual evaluations for the nanotechnology topics are summarized in table I in the appendix. The evaluations are based on the results of the study and reflect the subjective evaluation of the contractor. For a final evaluation of the single topics the unweighted average value of the five evaluation criteria was used. In order to facilitate the comparability and interpretation of the numerical values, the data in table I was indicated in per cent of the maximally possible score, i.e. the maximally possible value of 2,6 corresponds to 100 %. The higher the indicated percentage, the more relevant the respective nanotechnological component is assessed. It should be taken into account that the evaluation is more or less semiquantitative and therefore should be interpreted rather qualitative. In the following the respective evaluation criteria are described explicitly.

5.8.1 State of development of the technology

The state of development of a technology indicates, in which time scale the market entrance of technology-based products is to be expected, and/or to which extent a market penetration has already taken place. As rough classification of the maturity of a technology the following phases from the theory to the diffusion of commercial products can be distinguished:

- Visionary application (approx. > 15 years, theory)
- Long-term application (approx. 10 to 15 years, concept)
- Short to medium-term application (0 to10 years, prototype)
- Innovation, market entrance
- Diffusion

In space technology a somewhat modified evaluation scale is usually applied, which additionally includes the criterion of space qualification. All materials and components used in spaceflight must be tested and qualified regarding their applicability under space conditions. This covers among other things tests under relevant conditions (e.g. radiation and temperature influences) as well as an employment in space under operating conditions. As evaluation scale for space qualification, for example, the nine-level scale of the Technology Readiness Level (TRL) can be used according to NASA (see illustration 20).

Technology Readiness Level for the evaluation of space technologies

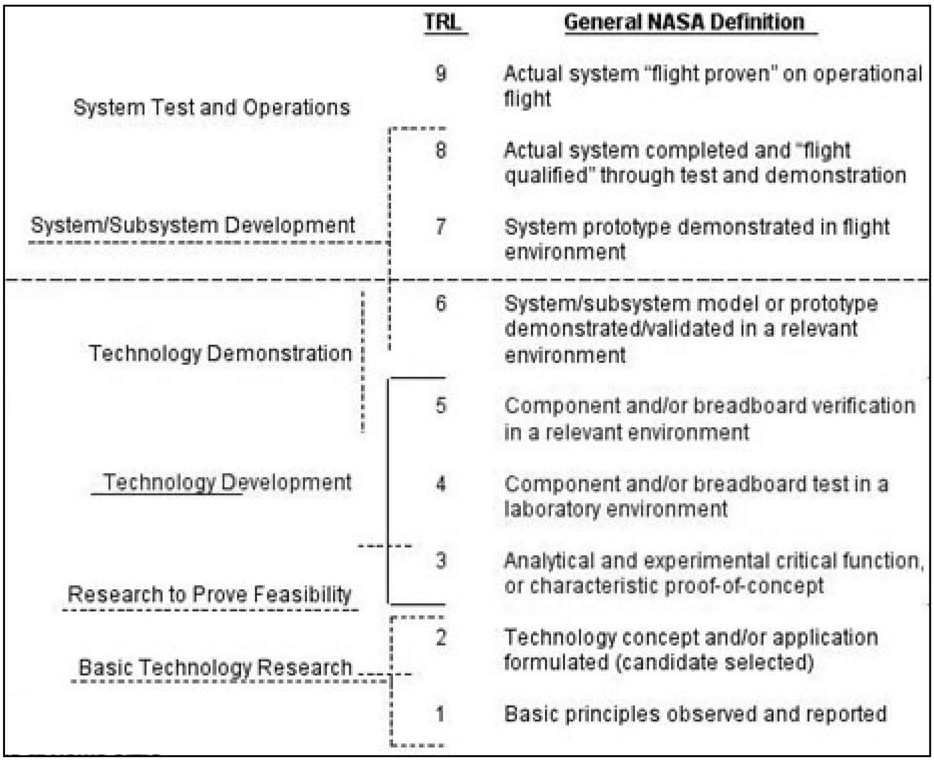

Illustration 20: Technology Readiness Level for the evaluation of the maturity of space travel technologies (source: NASA)

In the illustration 21 nanotechnological topic areas are classified in correlation to their respective state of development, differentiating between space components, subsystems and systems. The state of development of the technology is indicated both as TRL level as well as time interval up to market readiness in the terrestrial market. The illustration gives a qualitative estimation for some selected examples and lays no claim to completeness.

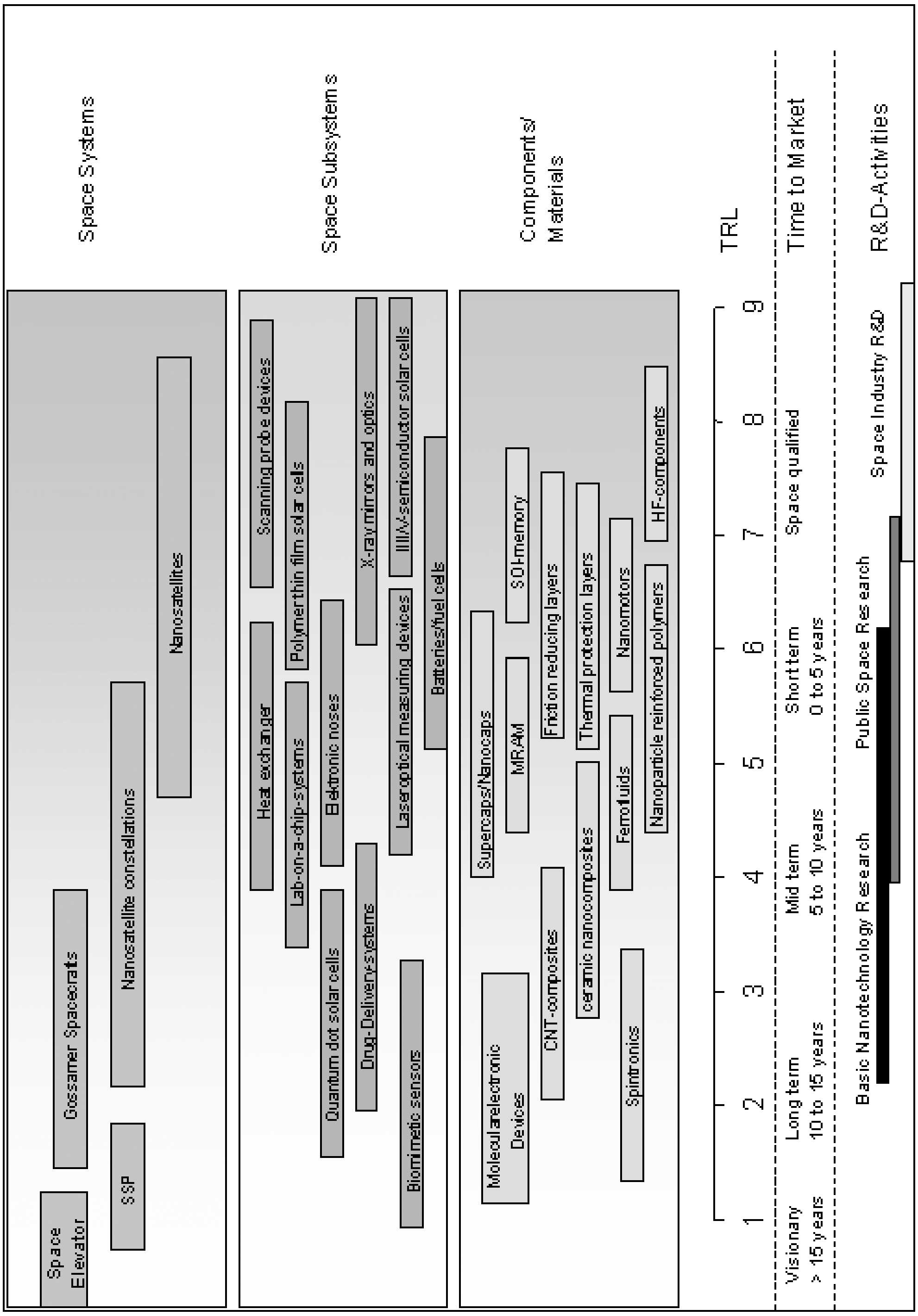

Illustration 21: State of development of nanotechnologically influenced space components, subsystems and systems (explanations see text)

R&D activities regarding nanotechnology developments for space applications can be assigned to different sectors in relation to the state of technology development. R&D activities of the space industry will usually only start from a TRL level of 6 (prototype is tested in relevant environment) to mitigate the development risk. Public funded space research, due to limited budgets, has to focus on first qualification steps of nanotechnology components, which will reach market readiness in the terrestrial range in a short term. The mid to long-term research expenditures for nanotechnology developments will be mainly the task of public funded terrestrial nanotechnology programmes. The main drivers here will be applications in terrestrial mass markets like information and communication technology or the Life Sciences range. An exception here concerns NASA activities, where substantial funds are invested into long term basic nanotechnology research.

5.8.2 Economic potential in terrestrial markets

Terrestrial market as main driver for nanotechnology product development

The economic potential of nanotechnological developments in terrestrial markets is consulted as a further evaluation criterion. This is in so far relevant as the space sector is usually not able to spend own resources on cost-intensive nanotechnology developments, but is rather dependent on terrestrial technologies and products (see chapter 5.8.5). The probability of actual nanotechnological product developments correlates here with the expected market potential in the respective terrestrial markets. On the other hand it can also be argued that in individual cases nanotechnology developments within the space sector, as they are accomplished for example by NASA, can lead to spin off effects in other industries and thus make a contribution to the refinancing of the R&D expenditures. For the evaluation the following branches were taken into account, which exhibit a more or less strong overlap with space technologies:

- Information and communication technologies
- Automotive engineering
- Medicine/Life Sciences
- Energy engineering
- Environmental technologies

5.8.3 Contribution to space technology objectives

An important criterion for the employment of potential nanotechnology applications in space is to ascertain their contribution to space technology objectives. For the evaluation the following objectives were applied, which are described in detail in chapter 4.1:

- Cost reduction
- Improved capabilities
- Lowering of mission risks
- Higher mission flexibility
- New system conceptions

5.8.4 Economic benefit for the space industry

For an evaluation, it is further relevant to examine in what respect nanotechnology applications can contribute to an economic benefit for the space industry, i.e. to analyze how these applications can contribute to improved space products and services. This is a particularly important criterion, as the commercial utilization of space in the long term is expected to change from a hightech niche market to a volume market. The driving force here is above all the telecommunication sector with satellite-based services such as FSS (Fixed Satellite Service), MSS (Mobile Satellite Services), DARS (Digital Audio Radio System) VSAT (Very Small Aperture Terminal), Internet etc., which will find an increasing spreading as supplement to terrestrial services. Further important market segments are satellite-based navigation and GIS (Geographic Information Services) as well as earth observation including meteorological satellites.

Nanotechnology could support the realization of market potentials in commercial space

Over a long-term time horizon also the range of space tourism could develop beyond present beginnings to a lucrative market. According to a prognosis of Collins, the world market of space tourism could rise up to 100 billion $ in the year 2030, provided that the public sector invests a significant part of its budgets into the development of appropriate transportation systems and space infrastructure (Collins 1999). If it should succeed to clearly lower the space transportation costs from at present approx. 10.000 €/kg by new technological conceptions and on the basis of economy-of-scale effects, further commercial utilizations of space could be be possible. What should be mentioned here for example is the energy generation in space by means of satellite-based solar power stations (Solar Power Satellites SPS), where the energy produced by large area sun collectors in space will be transferred to earth by means of microwave or laser radiation.

The market segments in space can be differentiated into space products (hardware) and space services:

Space Products	Space Services
• Spacecrafts (e.g. satellites, ISS) • Ground equipment (e.g. terminal) • Space transportation equipment (e.g. ARIANE, shuttle)	• Telecommunications (FSS, MSS, DARS, InterNet, VSAT) • Utilization of data generated in space (e.g. GIS, GPS, remote sensing) • Utilization of space infrastructure (e.g. microgravity experiments)

Table 9: Market segments within the space sector

A market study of the International Space Business Council prognosticated for the year 2005 a rise of the market volume within the range of space products of approx. 70 billion $ and within the range of space services of approx. 80 billion $. The illustration 22 shows the segmentation of the two respective sectors. From a present view however, these figures from 2000 seem to be a bit over estimated in consideration of the current world economy development.

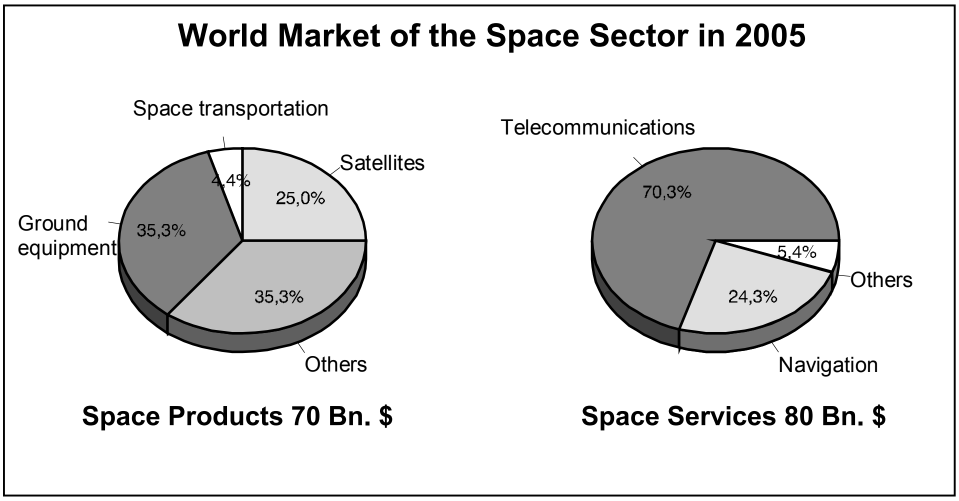

Illustration 22: Prognosticated market volume in 2005 for space products and services (source: ISBC 2000)

As evaluation criterion here, it is assessed in what respect nanotechnological components could make a contribution for development of these market potentials.

5.8.5 Potential application obstacles in space

Some economic and technological barriers as well as application obstacles oppose the utilization of nanotechnological components in space, which are discussed in the following.

5.8.5.1 Economic barriers

Space financed nanotechnology developments unprobable due to budget restrictions

Adaption and qualification of nanotechnological products for space

The development of nanotechnology products is as a rule connected with high financial R&D expenditures, for example in the range of nanoelectronics or nanobiotechnology. Therefore the development of commercial space specific nanotechnology products is hardly expected, since the space sector now only represents a niche market due to the small quantities of items. On the other side, cost intensive nanotechnology developments by the space sector are likewise unlikely in a short to medium term due to budget restrictions and the long process chain up to the space qualified product. Nanotechnology applications in space are thus primarily realizable in cases where the space sector, similar to the range of microsystem engineering, rather acts as a „technology follower“ than a „technology pusher“. This means that the space sector adapts and qualifies nanotechnology products developed for terrestrial market to space specific applications. Own nanotechnology developments by the space sector are to be expected only with public funding. In Germany and in Europe however, only very limited resources are available for these purposes, while in the USA, NASA spends substantial funds for space specific nanotechnology research.

5.8.5.2 Technological barriers

The extreme ambient conditions in space (high-energy radiation, high vacuum, extreme temperature gradients and temperatures, extreme mechanical and thermal loads during launch and re-entry) in principle limit the application possibilities of nanotechnological components. Thus for example, the radiation sensitivity of electronic components increases generally with miniaturization. On the other side, some nano-components and systems offer even inherent advantages concerning robustness and radiation hardness despite the small structure sizes due to the utilization of new physical effects, e.g. magnetoelectronic memories and quantum dot lasers. Also within the range of nanomaterials, nanostructuring leads frequently to advantages regarding the applicability in space, so that the extreme requirements in spaceflight do not represent a general barrier for nanotechnology products, but should be regarded differentiated for each respective component.

Nanotechnology offers partly inherent advantages with regard to radiation hardness and robustness

A further technological obstacle refers to the miniaturization of complete space systems, which is limited by the necessary functionalities of the payload (e.g. large telescopes and antennas, high communication performance, high propulsion power, high on board autonomy). This however cannot be regarded as a general obstacle for nanotechnology, since also in case of large space structures and components the application of miniaturized, energy saving and high performance components and subsystems usually offers substantial advantages, among other things regarding cost reduction.

5.8.5.3 Communication barriers

As a further barrier for nanotechnology applications in space few contacts and little cooperation between the space and nanotechnology scene can be determined, resulting in information deficits. The undrlying reasons are among others different attitudes and philosophies as well as insufficient communication processes between both specialized scenes. This is at least valid for Europe and Germany, while in the USA the collaboration of nanotechnology and space scenes is much more intensive.

5.8.6 Result

The evaluation of possible nanotechnology developments for space application, the results of which are summarized in table I in the appendix, allows a differentiated assessment regarding space relevant topics. Although the evaluation of individual components is surely problematic, for example regarding the contribution of a single component to space objectives or to economic benefits, and a very rough evaluation grid was used, at least qualitative statements can be derived regarding the potential benefits of nanotechnological components for space applications.

In illustration 24 the total evaluations of the individual nanotechnological components are depicted. It should be noted that a higher importance was attached to the state of technology developments (maximum score 5) in the evaluation than to the remaining evaluation criteria (maximum score 2), which appeared meaningful in the sense of a short term utilization for space technology.

The following nanotechnological topics/components were rated as most relevant:

Most relevant nanotechnology applications in space technology

- MRAM/Magnetoelectronics (78 %)
- Nanooptoelectronics, particularly QD lasers (75 %)
- III/V- semiconductor solar cells (75 %)

In illustration 23 the evaluation of these topics is shown in a net diagram classified with regard to the single evaluation criteria.

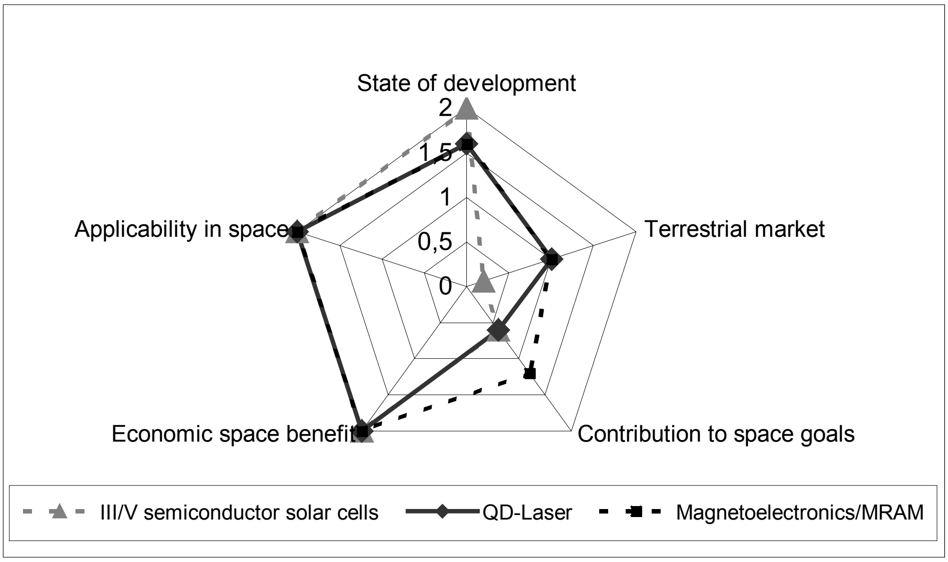

Illustration 23: Evaluation diagram for space travel-relevant nano-technology components (data source see table I in the appendix, level of development standardized on diagram scale)

A common feature of these components is a high applicability under space conditions, a high potential economic benefit for space as well as a relatively high state of technology development, i.e. a high market readiness for the terrestrial market and/or first qualifying measures for space already accomplished, so that a short to medium-term space utilization is possible. Regarding the applicability under space conditions all three components were rated with „high“, since magnetoelectronic components, QD lasers and III/V semiconductor solar cells exhibit properties, which favour the employment under the extreme ambient conditions in space, e.g. an increased radiation hardness.

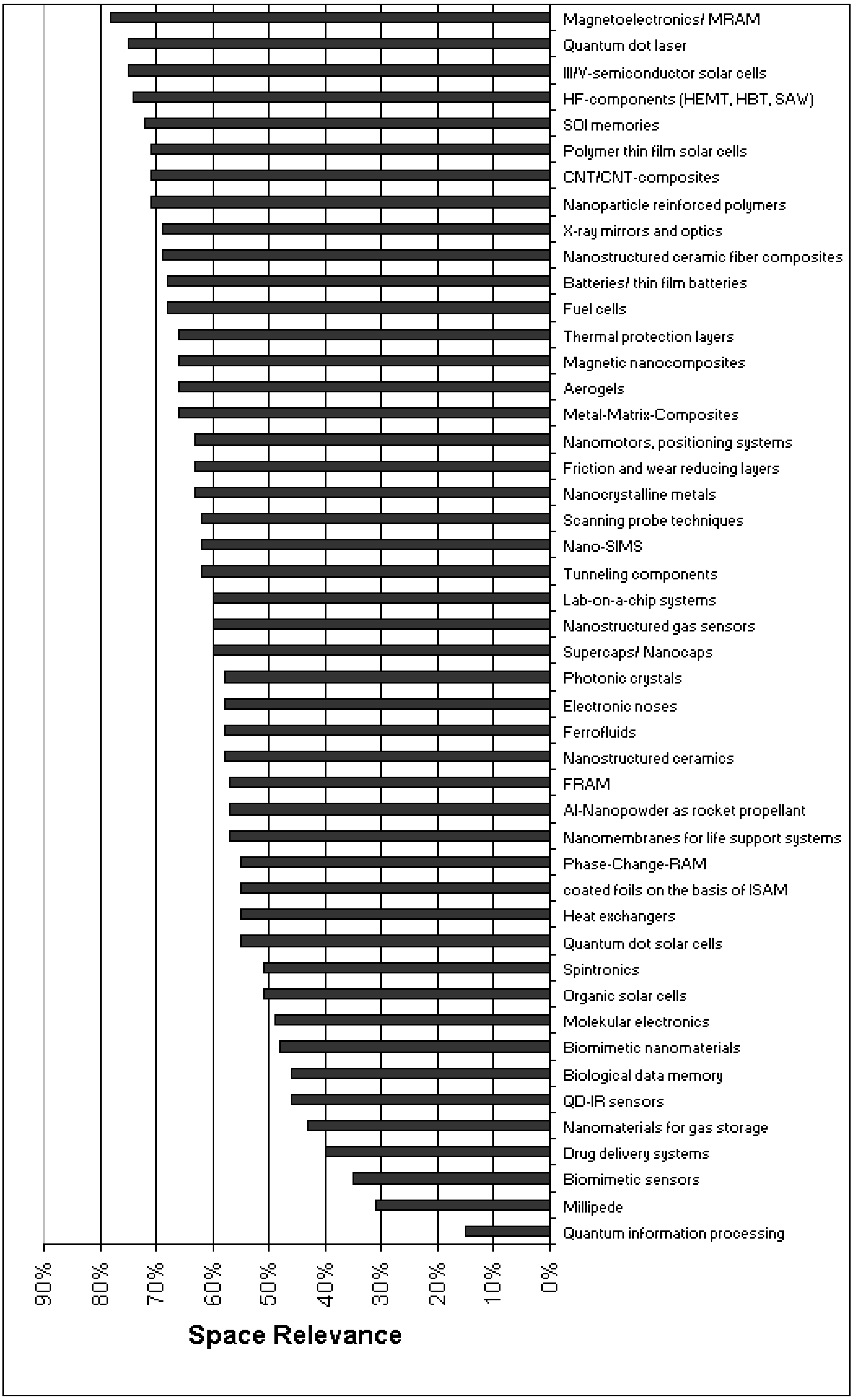

Illustration 24: Total evaluation of selected space relevant nanotechnological components (data source table I in the appendix, explanations see chapter 5.8)

High potential economic benefit for space

Regarding a potential economic space benefit all three components were also evaluated high. Magnetoelectronic sensors and memory chips offer the potential for the miniaturization of space subsystems such as AOCS or the on board data processing, whereby mass and energy savings can be realized, which are directly connected with cost savings as described in chapter 4.1. III/V semiconductor solar cells due to their clearly higher conversion efficiency compared with other types of solar cells likewise allow weight reductions, respectively an improved power supply, which in particular represent a crucial competition advantage for commercial telecommunications satellites. QD Lasers offer application possibilities in the optical satellite telecommunications, which are regarded as a future market in space.

The state of development was rated highest for III/V semiconductor solar cells, since these have already been used in space for some years in particular by NASA, but however still exhibit optimization potential. Also magnetoelectronic components show a high level of development. So, magnetoelectronic sensors are already widespread in the terrestrial market and MRAM chips are expected to penetrate the market in 2004. Low performance MRAM have already been manufactured by the company Honeywell for special military and space applications for some years now. The market readiness for QD lasers in the terrestrial market is expected soon and first space qualifying measures have already been accomplished.

High potential for magnetoelectronic and optoelectronic nano-components in terrestrial markets

Larger differences exist regarding the economic potential in the terrestrial market. Here III/V semiconductor solar cells are rated low, since they are clearly more expensive compared with competitive systems, and the higher conversion efficiency represents a smaller competition advantage in the terrestrial market than in space. Magnetoelectronic components however exhibit a high marktet potential in different industrial sectors. In the field of information technology GMR sensors are used for example in read heads for hard disk drives and for MRAM a high market potential is prognosticated as replacement for DRAM memory. Applications of magnetoelectronic sensors are also found in the automobile and Life Sciences sectors. Nano-optoelectronical components, in particular QD lasers, offer high marktet potentials, particularly in the ICT sector e.g. for future laser TV or in the optical data communication.

Regarding the contribution to space objectives, all three components are rated medium. Although the contribution to space objectives of an individual component surely is difficult to evaluate, it can be anticipated that the described nanotechnological components could bring significant advantages. Magnetoelectronical components could improve the capabilites and the on-board autonomy of spacecrafts, reduce the mission risks, increase mission flexibility as well as supply contributions to cost reductions through improved, miniaturized sensors and memories. III/V semiconductor solar cells contribute primarily to an improved functionality through a more efficient power supply. Nano-optoelectronic components could supply a contribution to an increased functionality, cost reduction and new conceptions for optical data processing and transmission in the range of optical satellite telecommunications.

As a result regarding the application potential of nanotechnology in space, the following statements can be derived:

- A potential for short to medium-term applications in space is in particular shown by components for data processing and transmission systems, which exhibit higher performance, lower energy consumption and improved radiation hardness compared with conventional components (e.g. MRAM, SOI, QD laser etc.)
- The main nanotechnological innovation impulse for space is only to be expected in a period of 10 to 15 years from now. Still unclear is in how far nanotechnology can fulfill the high expectations, as they were formulated for example in different technological roadmaps of NASA. Intensive research activities within these ranges appear at least in Germany to be unrealistical in view of restricted space budgets. Different however is the situation in the USA, where NASA spends approx. a quarter of their nanotechnological budget for basic research.

Main innovation impulse of nanotechnology for space technology is to be expected in 10 to 15 years

- Some approaches of molecular nanotechnology and nanobiotechnology reach still further into the future and have partly visionary character. Biomimetic sensors, materials with self-healing properties or ultra strong materials on the basis of carbon nanotubes should be mentioned here for example.

6 SPACE AS RESEARCH INSTRUMENT FOR NANOTECHNOLOGY

The application of microgravity as research instrument for nanotechnology, e.g. in the context of a possible industrial utilization of the ISS by nanotechnology companies, is a further aspect, which was examined in the frame of the ANTARES study. In the following some approaches, chances and barriers for the application of microgravity research for nanotechnolgy are pointed out.

6.1 Microgravity research for nanotechnology

The research in space offers the possibility for investigations under conditions, which can not or only partly be simulated on earth like the nearly complete absence of the gravity force (microgravity) and the cosmic radiation. From experiments in space thus realizations can be derived, which would not be accessible under terrestrial conditions. The historical development of the microgravity research in space reaches from the American Skylab at the beginning of the 70's to the International Space Station, which is installed since 1998 in the earth orbit. Current topics of microgravity research are among other things (see Seibert et al. 2001):

- Changes of the human physiology in space and space medicine
- Biological processes and biotechnology (cell and molecular biology, plant development, protein crystallization etc.)
- Basic and applied research in physics (crystal growth, fluid physics, plasma and combustion processes etc.)

The following phenomena, processes and procedures investigated in the context of microgravity research are also relevant here for nanotechnological developments (see Meier 2000):

Nanotechnology relevant microgravity experiments

- Obtaining exact data for the optimization of process technologies in gas phase synthesis of nanopowders and particles (among other things CVD and flame synthesis)
- Investigation of particle-particle/gas interactions concerning the aggregation in high vacuum, in sprays, in flames and in plasmas
- Investigation of the formation and stability of nanoemulsions
- Investigation of thermal transportation phenomena in magnetic liquids
- Self organization phenomena
- Advancement of analytical devices (nano-/micro system engineering, e.g. STM or AFM devices, lab-on-a-chip systems or laser-optical procedures)

Concrete research projects in this areas have been accomplished for some years e.g. by NASA in the frame of the PSRD (Physical Sciences Research division) and the MRD (Microgravity Research Division) programmes as well as ESA in the frame of the MAP (Microgravity Application Project) programme. In the following some of the most relevant topics of microgravity research relating to nanotechnology developments are summarized.

6.1.1 Formation of nanoparticles in gaseous phase

Investigation of formation and aggregation of nanoparticles without convection and sedimentation

A topic area, which moves increasingly into the focus of nanotechnology relevant microgravity research, is the formation and the production of nanoparticles in gaseous phase reactions. Research objectives in this context are a better understanding of particle-particle and particle-gas interactions within particle aggregation as well as obtaining accurate data for the characterisation of the flow conditions in gaseous phase reactors. Microgravity allows here among other things the investigation of the influence of thermal convection on the agglomeration process, the size and the morphology of the nascent particles. Likewise sedimentation effects are excluded, which play a role however only for larger particle aggregates.

6.1.1.1 Inert gas condensation

The inert gas condensation process is one of the established procedures for the production of nanopowders, e.g. for nanoporous metal powders. These metal powders are technically utilized for electrical conductive adhesives and polymers, which find application among other things for the surface mounting technique in electronics. Experiments under microgravity permit a detailed investigation of the agglomeration process (Meier 2000) e.g.:

- the determination of convection influence and inhomogeneities of the particle density on the morphology of the particle aggregates (form, porosity)
- the assignment of parameter changes to powder morphology and thus possibly an improved control of the aggregates formation of sintering active nanoparticles in gases

The illustration 25 gives a schematic overview of the inert gas condensation procedure from evaporation over particle formation and aggregation up to separation.

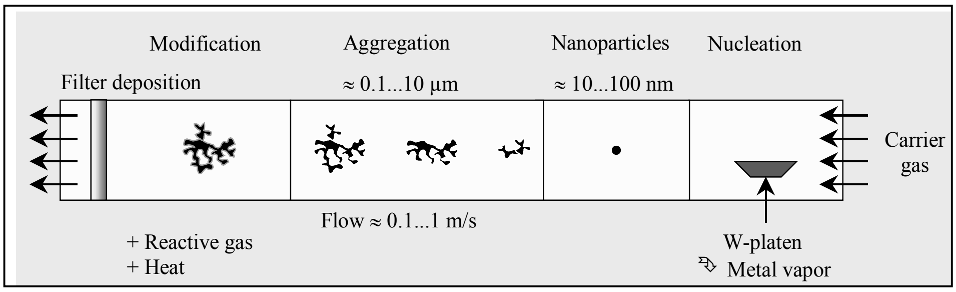

Illustration 25: Powder formation in the IGV procedure (source: Guenther et al. 2002)

Investigations of the formation of metal nanoparticles under microgravity

The Fraunhofer-Institute for Applied Material Research (IFAM) and the BTU Cottbus developed in a DLR supported project[60] a measuring device for investigation of particle aggregation processes, which is applicable in parabolic flight experiments. As measuring methods here a PIV/LDA procedure, optical microscopy and an in-situ sampling device were used. The method has an analytical resolution within the micrometer range. The illustration 26 shows the microscopy system PATRICIA developed by the University of Jena and an image of a measurement of silver aggregates. First microgravity experiments were accomplished in parabolic flights. Here it became obvious, that the evaporation technique had to be modified for µg-experiments, in order to obtain a steady particle density. Further research need exists regarding the supplementing employment of a laser measuring technique for sub-µm particles and agglomerates. To what extent the results can be used for the optimization of IGV processes under terrestrial conditions, can not to be assessed at present.

[60] DLR joint project MENAPA, FKZ 50 WM 0053/-54

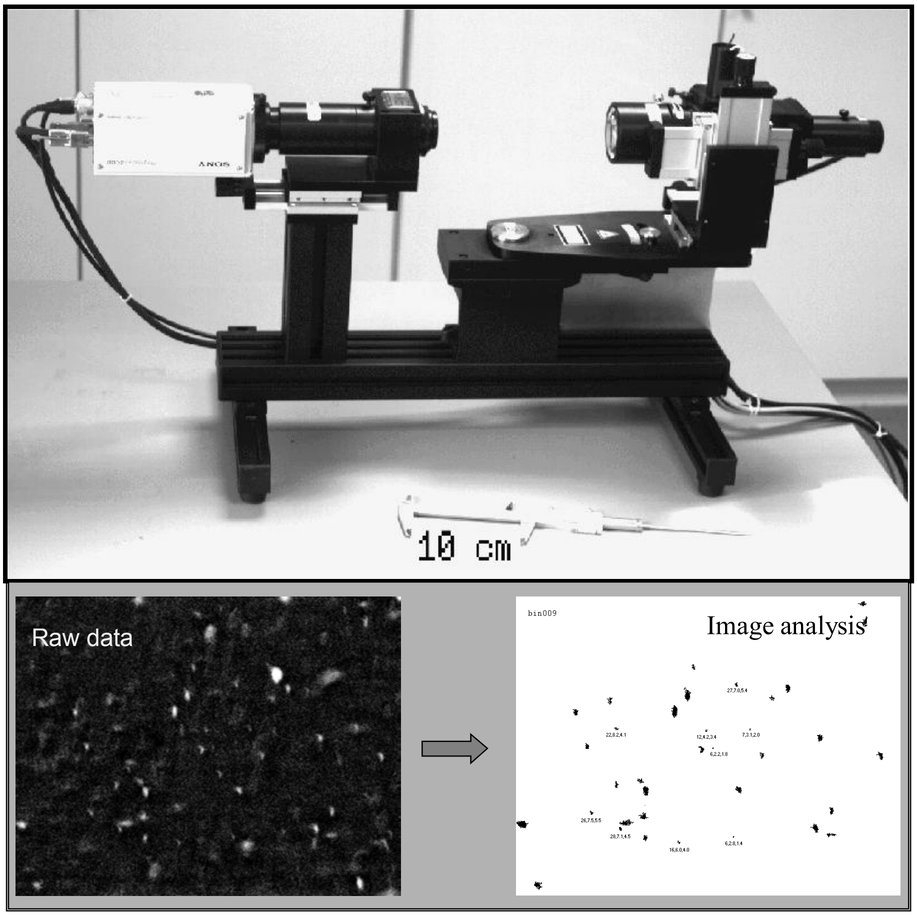

Illustration 26: Above: Image of the measuring device PATRICIA, below: image analysis of a measurement of silver particles (source: Guenther et al. 2002)

6.1.1.2 Flame synthesis

Investigation of nanoscale carbon particles by means of LII-procedures

The formation of nanoparticles in flames is a further current topic in microgravity research. In the frame of an ESA MAP project for example the LII (Laser Induced Incandescence) procedure was applied, by which the formation of nanoscale carbon particles in a flame can be examined online with high resolution. Here the soot particles are heated with a laser beam and the thermal radiation is recorded time-resolved with a CCD camera system. From the signal both the volume concentration and the aggregate size of the soot particles can be determined (Will 2002). The illustration 27 shows a schematic experimental setup. The procedure was already applied in microgravity in the frame of parabolic flights and drop tower experiments.

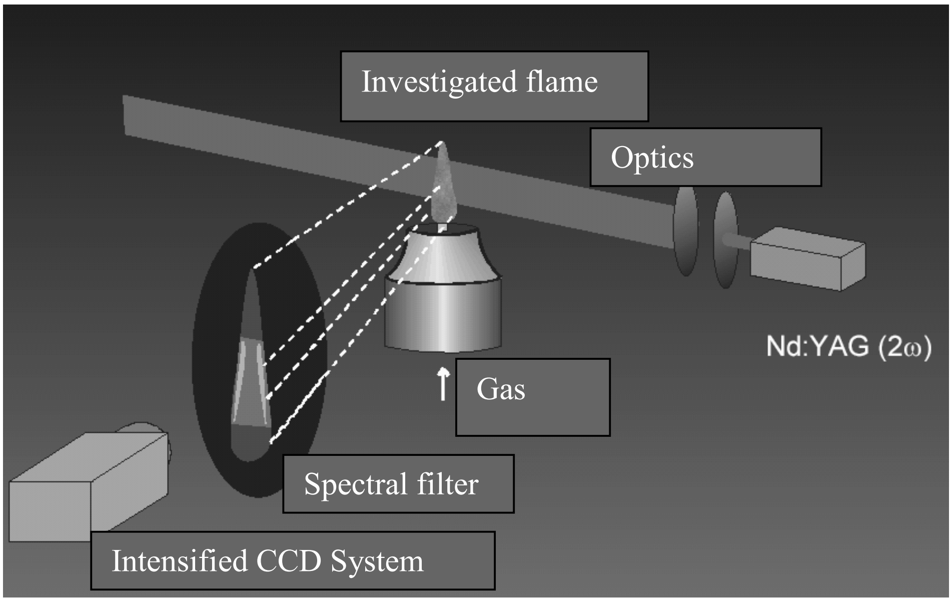

Illustration 27: Schematic experimental set-up for investigations of soot particles by means of LII procedure (source: Will 2002)

The illustration 28 shows the measuring data of a laminar ethene diffusion flame:

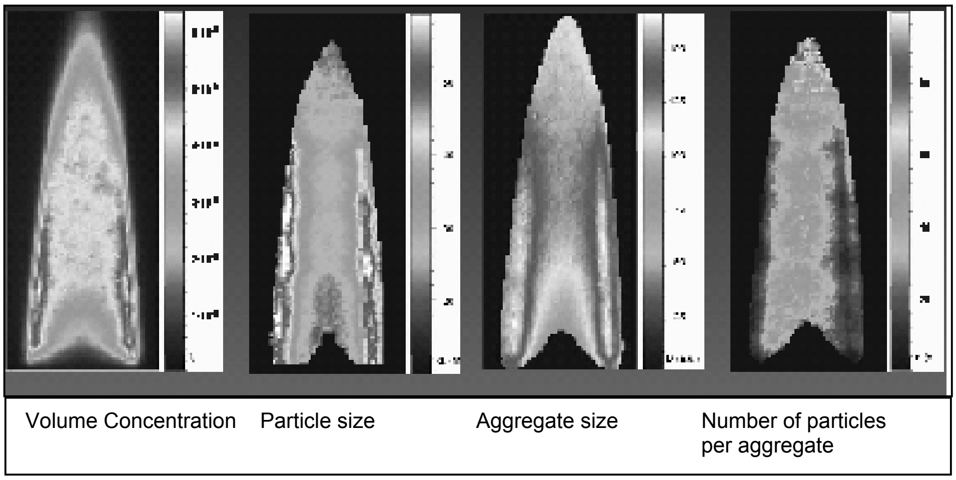

Illustration 28: Measurements of a laminar ethene diffusion flame by means of LII procedure (source: Will 2002)

An exclusion of the gravity and buoyant force makes it possible to control the retention time of particles in the flame. Microgravity has a significant influence on the particle concentration and sizes, as can be seen in the illustration 29. First microgravity investigations were accomplished in parabolic flight and drop tower experiments. As a goal of the investigations a broad database for the modelling of flame synthesis processes and approaches for the production of new material configurations is envisaged.

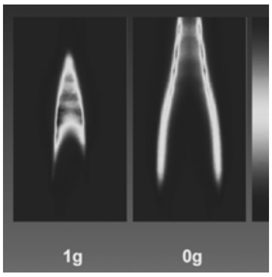

Illustration 29: Measurements of the particle concentration in a flame under terrestrial and microgravity conditions (source: Will 2002)

Besides, soot-particle formation in flames the LII method in principle can be used for the in-situ characterization of other types of nanoparticles with a high temporal and spatial resolution. For this however, first intensive investigations of the laser/particle interactions have to be accomplished with respect to the material classes involved.

6.1.2 Formation of nanoparticles in liquids

The most important procedures for the production of nanopowders and/or deposition of thin layers from the liquid phase include the sol gel procedure and the electro-chemical deposition. Both procedures are further suitable for the building of nanoporous materials. Nanophased systems in liquids (nano-suspensions and emulsions) were already investigated in different microgravity research projects. Topics of interest are for example the adsorption dynamics and the mass transfer on individual liquid/liquid boundary surfaces, droplet/droplet interactions as well as stability and phase inversion of model emulsions. Apart from realizations within the basic research range also approaches for the optimization of wet-chemical procedures for terrestrial applications are expected to be realized by means of microgravity experiments.

Microgravity experiments for the optimization of aerogels

Although the gravimetric sedimentation of very small particles is to be neglected in relation to the random Brownian movement (see Roessler et al. 2001), gravitaty effects can play a role in wet-chemical processes in view of the long duration of particle aggregation as well as the impact of gas bubbles on EPD processes, which arise under the influence of the gravity force. The investigation of the influence of gravitation effects on the formation and characteristics of nanomaterials by Sol gel processes (e.g. of aerogels) could serve a better understanding of the gel aggregation with the gelling process, which could be used in principle for the optimization of the appropriate process technologies and materials. In a NASA research project an appropriate measuring device is currently developed, helping to examine the gelling process of aerogel formation by means of optical measuring procedures under microgravity conditions. Furthermore there are indications that the production of aerogels under microgravity can lead to improved material properties. Thus microgravity experiments are conducted by the University of Wisconsin with the aim of reducing the pore sizes of aerogels to obtain transparent, colorless aerogels which would be better suited for technical applications.[61] Conventional aerogels with pore sizes of up to 200 nm appear frequently bluish and/or transluzent due to light scattering effects, which limit the technical applicability.

Also the electrophoretic deposition for the production of nanomaterials

[61] „Reduced Gravity Aerogel Formation“ (http://www.cae.wisc.edu/~aerogel/)

offers starting points for microgravity research. Although structures with an unusually high degree of order can be produced under terrestrial conditions by means of EPD, however a more or less strong deviation from the ideal course of the nanoparticles along the electrical field occurs by gravitational effects. This could lead to disturbances in the microstructure of the deposited nanomaterials. For fundamental investigation with the purpose of understanding the mechanisms of the EPD process this means that an accurate empirical analysis is not possible due to gravitational influence, so that a verification of the postulated models and simulations is likewise not accurate.

In principle both electrophoretic deposition and impregnation can be accomplished in aqueous as well as organic solvents. Although these two basically different procedures exhibit specific advantages, the use of organic solvents usually is not economical due to the clearly higher process times and the environmental incompatibility, so that aqueous dispersions have to be used for technically relevant processes. However the electrolytic decomposition of water, applying voltages above approx. 2 V within EPD/EPI processes, leads to the formation of gas bubbles on the electrodes, which disturbs the particle movement and causes defects in the microstructure of the deposited materials. While defects in the microstructure can mostly be avoided by applying ion permeable membranes, an investigation of the movement of the dispersed nano-particles in the electrical field is however influenced through gas bubbles. Thus the investigation of the electrophoretic caused movement and deposition of nanoparticles under microgravity could lead to a crucial contribution to understand the relevant mechanisms and thus accelerate the conversion into industrial development significantly.[62]

Results from micro gravity research could be relevant for the commercial application of electrophoretic nanoparticle deposition

A further relevant topic field is the self-organization of molecules in liquids, which will significantly gain importance in the future for bottom-up strategies for the production of nanomaterials. Experiments under microgravity showed that gravitational effects had a crucial influence on self-organization processes of biological molecules. Although the influence of gravity on a single particle is only small, effects could arise in systems of a multiplicity of particles, which lead to a macroscopic self-organization into so-called dissipative structures. Thus in microgravity experiments it was observed, that molecules of the protein tubulin arrange themselves in a completely irregular form, while under the same conditions ordered structures arise in a terrestrial laboratory (Papaseit et al. 2000). The investigation of such self-organization phenomena under microgravity could be relevant for the development of nanostructured materials by self-organization processes. Within the nanotechnology scene however, no concrete approaches are at present recognizable to take up this topic in the context of own research activities.

[62] Jan Tabellion, Institute for powder technology of glass and ceramics, Saarland University, personal communication from 04.09.2002

Investigation of thermal transportation phenomena in ferrofluids

For the investigation of the physical properties of ferrofluids micrograviy experiments are utilized to examine thermal transportation phenomena and magnetic effects without distortion through gravity influences. Ferrofluids, which consist of a suspension of magnetic nanoparticles (approx. 10 nm diameters) in a carrier liquid (e.g. oil or water), offer potential e.g. for the employment in thermal control elements, since their physical properties (e.g. the viscosity, thermal conductivity) can be controlled by exterior magnetic fields. Experiments under microgravity are expected to lead to a better understanding and controllabibity of mass and heat transport processes, which is necessary for potential technical applications of ferrofluids. Appropriate investigations are accomplished e.g. by the Center for Applied Space Technology and Microgravity (ZARM) in Bremen with parabolic flights and drop tower experiments in the frame of an ESA Map project. At a later time also experiments in the space shuttle and on ISS are planned (see chapter 6.2).

6.1.3 Formation of nanoparticles in plasmas

Plasmas are denoted frequently as fourth aggregate state and consist of ionized gases, in which gas atoms are splitted into positively charged ions and electrons. Plasmas containing colloids are called complex or dusty plasmas. In 1994 scientists of the Max-Planck Institute for Extraterrestrial Physics proved that such complex plasmas can self-organize under certain conditions spontaneously to a crystalline-like state, the so called plasma crystal. Plasma crystals are an up to then unknown state in a complex/dusty plasma and can be used to study material characteristics in phase transitions from gas to liquid and solid states. Such three-dimensional plasma crystals can only be produced under microgravity, since on earth gravity squeezes the crystals together. In the year 2001 the plasma crystal experiment on ISS was realized under the leadership of the German Kayser Threde GmbH. The illustration 30 shows a schematic experimental setup, which is similar to the experiment on ISS. The control and the manipulation of the microparticles in the investigated low-temperature plasmas are achieved here by means of a so-called adaptive electrode. This adaptive electrode is composed of several separate, electronically controllable electrode segments. This allows local modifications of the plasma boundary zone.

Plasma crystal experiment

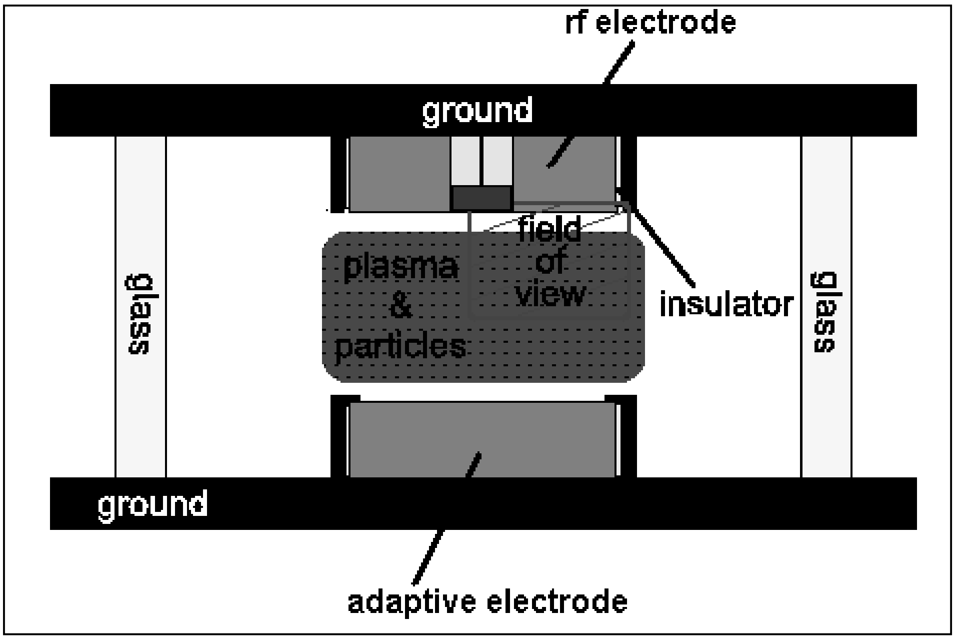

Illustration 30: Schematic diagram of a possible plasma crystal experiment chamber (source: Kayser Threde GmbH and Max-Planck-Institute for Extraterrestrial Physics, see Stuffler 2001)

Investigation of application relevant aspects

Apart from basic research in fundamental and plasma physics, also application orientated questions like particle coating, the production of nanoporous materials or the optimization of plasma processes in semconductor industries can be examined with the experimental setup in principle. It is expected that knowledge about complex plasmas obtained in microgravity research will contribute to the optimization of industrial terrestrial plasma processes. To be mentioned as relevant application fields among others is the coating of pharmaceutical drugs and surface refinement in semiconductor technology (Stuffler 2001). Also the formation of nanoscale carbon structures (nanotubes or diamond films) by electrical arc discharge plasma synthesis has already been investigated in microgravity experiments of NASA. Complex plasmas are furthermore relevant for processes, in which a particle formation is to be prevented if possible, as for example within plasma etching processes for microchip production. Here a contamination of the sensitive circuits with particles must be absolutely avoided.

Development potential concerning the experimental setup can be determined in the advancement of the adaptive electrode. The objectives pursued here are the integration of a larger number of manipulation channels with reduced surfaces and a miniaturized electrode structure as well as the availability of dynamic and automated methods for an appropriate manipulation of the plasma. A further stimulation for the plasma research in microgravity is expected with the implemenation of the International

Microgravity Plasma Facility (IMPF), whose employment on ISS is scheduled for the year 2005/2006.[63,64]

6.2 ISS as research instrument

The ISS opens up new dimensions in microgravity research

The ISS is mainly designed as a research station. The station will possess six laboratory modules in its final form. The area for experiments will be four times larger and the energy supply will be sixty times larger than on the former Russian space station "MIR". With a constant human crew on board and a planned operation time over 10 years the ISS opens up new dimensions for the research in space. Table 10 shows a comparison of the test conditions (quality of the microgravity conditions and maximum experiment duration and payload capacity) of different facilities for microgravity research.

µg-Testing Facility	µg-Level	µg-Phase Duration	Payload (kg)
Drop tower	$< 10^{-5}$ g	5 sec	125
Parabolic flights	10^{-2} g	20 to 30 sec	50*
Maxus-rockets	10^{-4} g	2 to 15 min	450
Shuttle Pallet Satellite (SPAS)	10^{-6} g	2 days	< 900
Spacelab	10^{-4} g	2 weeks	4500
Eureca	10^{-4} g	11 months	1000
ISS/ Columbus-Module	10^{-3} - 10^{-6} g	Years	4000

Table 10: Comparison of different µg-testing facilities (source: Seibert et al. 2001), * free floating experiments

A prerequisite for the utilization of the ISS for nanotechnology relevant experiments is the development of suitable hardware and measuring devices. In this context, among others, the following programmes and projects with European respective German participation are to be mentioned, which aim at the utilization of the special conditions on the ISS for nanotechnology relevant investigations.

6.2.1 ICAPS (Interactions in Cosmic and Atmospheric Particle Systems)

The ESA project ICAPS aims at the investigation of the physical interactions of small particles among themselves, with gas and with light.

[63] ESA press release from 27.03.2001: „Hightech from Euroland“
[64] Personal communication Dr. Stuffler (Kayser-Threde GmbH) from 22.11.02

Scientific objective are investigations regarding the following topic fields (see fig. 31):

- Aerosol physics
- Phoretic effects
- Aggregation of particles
- Characteristics of Regolith
- Optical and morphologic characteristics of aggregates
- Radiation transport and light scattering theories

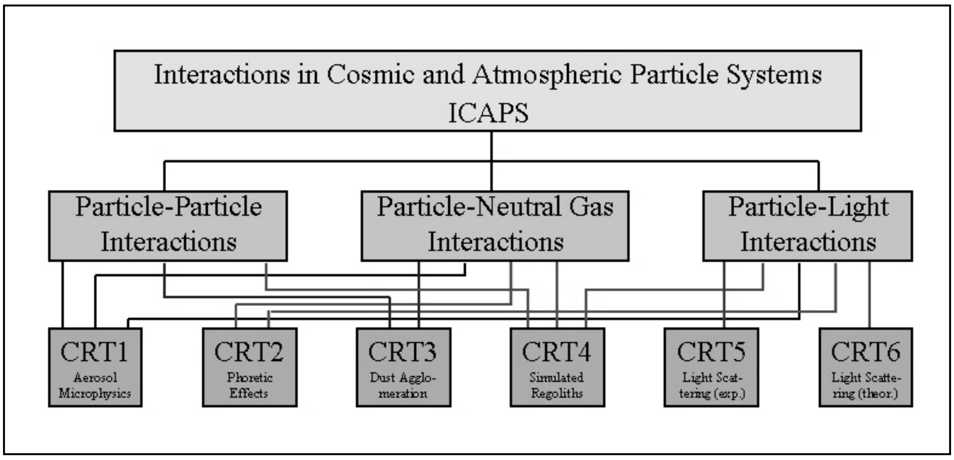

Illustration 31: Research objectives of the ICAPS project (source www.icaps.org)

For the investigation of an ensemble of levitating particles without disturbing external influences, experiments under microgravity are essential, in order to maintain particle clouds with a multiplicity of particles sufficiently long or to produce loose structures, which would collapse under their own weight on earth (Poppe 2000). Apart from scientific research also a benefit for application orientated purposes is aimed at, e.g. for the production of nanoporous materials or the advancement of characterisation methods for particles. The ICAPS project is at present in the evaluation phase serving to examine a realization in a suitable rack on the ISS, possibly in combination with the Plasma Facility IMPF.[65] The project will be conducted by an international consortium with participation of the astrophysical institute of the University of Jena in a coordinating role.

6.2.2 IMPF (International Microgravity Plasma Facility)

The IMPF as new modular concept is targeted for the investigation of complex plasmas on ISS for scientific and application orientated purposes. The IMPF is developed by an international scientific consortium

[65] http://www.estec.esa.nl/spaceflight/facilities/icaps/

under industrial leadership of the Kayser Threde GmbH. The employment of the first experiment module on ISS, which serves to investigate RF plasmas, was planned for 2005/2006. The experiments are to be exchanged regularly within the next 10 years, so that appropriate scientific continuousness is guaranteed. The research approaches aim at aspects of fundamental physics, plasma physics and application relevant aspects (e.g. optimization of plasma lamps). Although gravity influences are relevant only for particles with a size of more than 1 µm, the findings of microgravity experiments can be useful for nanotechnolgy, e.g. for the investigation of particle aggregation or for the production of nanoporous materials (see Kayser Threde 2000).

6.2.3 Microgravity Experiments on Ferrofluids

Magneto viscous effects as well as thermal transportation phenomena in magnetic fluids have been a topic in microgravity research for some time already. In order to prove tension differences in ferrofluids, use is for example made of the rising of a free surface on a rotating shaft, the so-called Weissenberg-effect. The rising of the liquid is dependent on 1/g, so that under microgravity also weak tension forces in ferrofluids can be detected easily (Völker 2002). In the frame of an ESA Map project[66] an experimental set-up is developed at present for the investigation of thermal transportation phenomena in ferrofluids (e.g. the Soret effect). The hardware for the employment in the European Drawer Rack on ISS is developed in co-operation of Astrium and the Center for Applied Space Technology and Microgravity in Bremen (ZARM). NASA is already conducting microgravity experiments on ferrofluids on the ISS in the frame of the project in-SPACE ("Investigating the Structure of Paramagnetic Aggregates from Colloidal Emulsion"). Here the phenomenon is examined, that magnetic particles in ferrofluids clump together by the influence of high frequency exterior alternating magnetic fields, whereby the magnetorheological characteristics of the ferrofluids get lost. This effect does not occur in mixed ferrofluids, but can be problematic however for certain applications. The clumping process, which extends over a period of up to several hours, is affected strongly by gravity, so that exact patterns of the particle complexes can be studied only under microgravity.[67] Due to the long-lasting processes and the availability of human astronauts the ISS is the suitable platform for this experiment.

ISS as testbed for space qualification of nanomaterials

6.2.4 Space Qualification of Nanomaterials

A further possible utilization of the ISS is the space qualification of nanomaterials. NASA already accomplishes investigations regarding the

[66] ESA-MAP-Project: „Thermally driven effects in magnetic fluids under reduced gravity conditions“
[67] NASA Science news from 23.08.02: „Amazing magnetic fluids“ (http://science.nasa.gov)

stability of nanoparticle reinforced polymers at the exterior surfaces of the ISS in the frame of the Materials International Space Station Experiment (Thibeault et al. 2001). The ISS represents an ideal test bed also for long-term stability tests of nanomaterials under the influence of space radiation, atomic oxygen and extreme temperature gradients, which can only incompletely be simulated in the laboratory.

6.2.5 Commercial use of ISS for nanotechnology

Microgravity experiments are rarely considered for own research activities of nanotechnology companies

Apart from the basic research the ISS shall increasingly be used for applied research in particular with participation of industrial partners. A possible commitment of nanotechnology companies concerning own experiments on the ISS was likewise an investigation subject of the ANTARES study. As result of a written questioning and different experts meetings with representatives of German nanotechnology companies it is to be stated that microgravity research at present is hardly considered for own R&D activities. This applies not only to the utilization of the ISS, but generally to microgravity research. The reasons for that are discussed in detail in chapter 6.3. Also a use of the ISS for the production of nanoparticles and nanomaterials in space for commercial purposes appears at present rather doubtful due to the extremely high transportation costs, limited possibilities of production scaling as well as a hardly quantifiable added value of materials manufactured under microgravity conditions.

6.3 Summary and evaluation

The microgravity research supplies knowledge about gravity-dependent phenomena and procedures, which would not be accessible under terrestrial conditions. These realizations in the context of nanotechnology research can contribute to a better understanding and a more accurate modelling of nanotechnological procedures. Contact points result particularly within the following ranges:

- Obtaining exact data for the optimization of process technologies for the production of nanopowders and particles in the gaseous phase, in liquids and in plasmas
- Investigations regarding the formation and stability of nanoemulsions
- Investigation of thermal transportation phenomena and aggregation processes in magnetic liquids
- Self-organization phenomena

Additionally microgravity research stimulates the advancement and miniaturization of measuring devices in the range of nanoanalytics and micro system engineering (e.g. miniaturized STM or AFM devices, lab-on-a-chip system, laser-optical devices or nano-manipulators for microgravity experiments). Here spin-off effects are likewise to be expected for other industries as for example the environmental or medical technology. Concerning the above mentioned topics several microgravity experiments are conducted or are in preparation in the frame of public space research (NASA, ESA, DLR etc.).

On the other hand, particularly within the range of applied industrial research, the following application obstacles for microgravity research in the field of nanotechnology can be identified:

- An added value of microgravity research is little transparent for nanotechnology companies. Furthermore the expected technologically usable results do not justify the estimated expenditures for such experiments in view of the questioned experts (cost-benefit aspect).
- The simulation of nanotechnological procedures for terrestrial application is already highly developed, moreover still sufficient optimization potential exists also without microgravity experiments.
- In particular smaller start-up nanotechnology companies must obtain a return on invest in a given time period, in order to sustain their businesses; therefore microgravity experiments, which usually require a time consuming preparation and are connected with much imponderableness regarding the realization of the experiments, are hardly considered.
- Adequate measuring devices for the investigation of nanoscale phenomena are so far available only to an incomplete extent.

As further obstacle surely information deficits on the side of nanotechnology companies regarding the applicability of microgravity experiments for own research activities can be mentioned. Not least the lack of cooperation between space and nanotechnology companies can also be traced to different attitudes and philosophies as well as missing communication processes between both specialized scenes.

7 RESULT AND RECOMMENDATIONS

7.1 Applications of nanotechnology in space

The ANTARES study has identified a multiplicity of application potentials for nanotechnology in space both in the scientific as well as commercial range particularly within the fields of structure materials, energy generation and storage, data processing and storage, data communication (optical/EHF), sensor technology/instruments, life support systems, biomedical applications and thermal protection and control. Short term implementations however will be rather an exception due to the high efforts required for space specification and qualification and the partially low technological maturity of nanotechnology developments. The actual innovation impulse of nanotechnology for space is to be expected only in a period of 10 to 15 years.

Continous monitoring of the topic field recommendable

In order to sustain a competitive European and German space industry in the future, a continuous monitoring of the technology field appears advisable to early identify space-relevant nanotechnology developments and to derive measures for a space utilization. Further attention should be paid to an intensification of the communication processes between the space and nanotechnology scene, since in Germany, different to the USA, only a small linkage of the respective participants is to be determined. In order to advance potential applications of nanotechnology in space, a longer proclamation and knowledge diffusion phase seems to be necessary, similar to the activities in micro system engineering. The information flows should be improved here e.g. through focused expert discussions, workshops and newsletters on current developments in the technology field. An objective should be to reach an intensified consciousness and increased attention for technological requirements of the respective specialized scene.

Intensifying the communication between both communities

Integration of nanotechnology in long term space programmes

Further a stronger integration of nanotechnology as a strategic cross section topic into long-term DLR and ESA research programs would be recommendable. With regard to ESA, nanotechnology is already integrated at least partly into long term research programmes e.g. the AURORA programme. Appropriate roadmaps and technological requirements are formulated at present. In this context it should be examined to what extent the DLR should be integrated into this process.

Participation of German nanotechnology institutions in ESA-programmes

Likewise stronger activities of DLR research institutes in the frame of the nanotechnology competence centers should be aimed at. So far only four DLR research institutes are involved with the nanotechnology centers. Further a stronger linkage of nanotechnology and micro system engineering (MST) in the range of space technology should be achieved, i.e. a stronger consideration of nanotechnology aspects within MST specific workshops and call for proposals. In particular within the ranges of elect-

Stronger linkage between micro- and nanotechnology

ronics and sensor technology nanotechnology can contribute only components, which are not usable without integration into appropriate space (micro)systems. An intensified consideration of nano/micro interfaces appears therefore to be essential in particular in the above mentioned technology fields.

Measures for the space utilization of selected nanotechnology components

Both nanotechnology and space technology are very broad, heterogeneous fields of technology. Nanotechnological developments are frequently still in the range of basic research and usually require high R&D expenditures for product development. In some fields however, nanotechnology has already reached a level of development, which could lead to short to medium-term applications in space. Here concrete measures should be accomplished for space utilization, which include detailed feasibility studies as well as technological requirement catalogues for the respective nanotechnological component/material in consideration of concrete space projects and missions and derived technological requirements of the space industry. With participation of technology developers from the space and nanotechnology scene the space specification and qualification demand should be determined as basis for deriving R&D projects for space utilization to be accomplished. In view of the limited resources for technology developments in space, it appears necessary to focus on nanotechnological components, which are to be evaluated most favorably regarding the cost-benefit ratios. For the selection of possible R&D projects the following criteria should be considered:

- High technological competence in Germany in the respective nanotechnology and space technology field
- Readiness of the nanotechnolgy component in the terrestrial market will be reached in a short time
- The nanotechnological component leads to cost-benefit advantages compared with conventional components
- Demand/benefit for the German space industry

To avoid doubled efforts a coordination with other funding programs should be pursued, as in some ranges (e.g. QD solar cells, supercapacitors or ceramic nanocomposites) a number of nanotechnology projects for space applications are already promoted by some institutions (BMBF, research fundations etc.).

With regard to the further advancement of nanotechnology applications in space thus four action fields can be derived for a time horizon of three years:

I. Monitoring of the technology field
II. Intensified communication between nanotechnology and space travel scene
III. Strategic integration of nanotechnology into long-term space programs
IV. Measures for the space utilization of nanotechnological components

Four recommended action fields for further examination of the topic

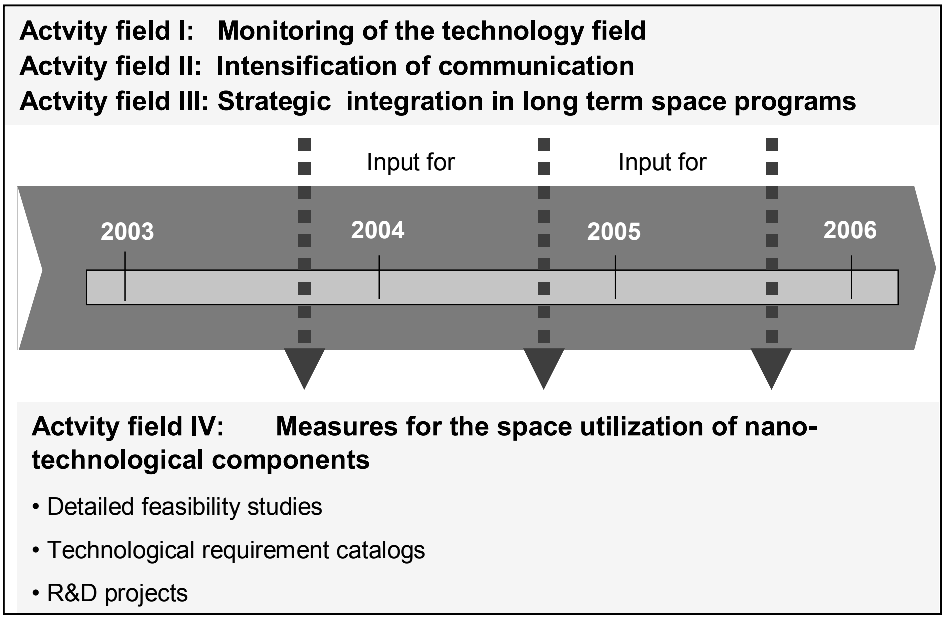

Illustration 31: Recommendations for measures and action fields regarding the further advancement of nano-technology applications in space (planning horizon 2003 to 2006)

As substantial objective the short to medium-term space utilization of nanotechnological components is to be mentioned in consideration of cost-benfit aspects. From the action fields I to III technical input is to be generated continuously to derive concrete measures for space utilization (action field IV). The following topics with potential for short to medium-term space applications are suggested for further promotion within the action field IV:

Selection of nanotechnology topics for a short to medium term space utilization

7.1.1 Nano-optoelectronic components particularly QD lasers

Optoelectronic components offer application potential in space particularly within the ranges of sensor technology and telecommunications. QD lasers possess a high level of development and exhibit potential advantages for space applications due to their characteristics like a small energy consumption, an improved radiation hardness and an adjustable emission wavelength. Concrete application possibilities for QD lasers exist for example as pumping lasers for solid state lasers in space, which are used e. g. in optical satellite communication and in different scientific missions. Concerning the development of optical satellite communication systems and nano-optoelectronic components, a high technological competence exists in Germany. Optical satellite telecommunications is regarded as a future market for space.

7.1.2 Magnetoelectronic components particularly MRAM

Promising applications of magnetoelectronics in space are for example non volatile magnetic memories (MRAM) or magnetoresistive sensors as positioning-, acceleration- and rotation sensors instead of conventional semiconducting magnetic field sensors (Hall sensors). MRAM possess a high economic potential in the terrestrial market as replacement for DRAM memories and will presumably attain market readiness in 2004. Because of the special characteristics of MRAM such as non volatileness of the data (data remain preserved also in case of a power failure), a low energy consumption and an inherent radiation hardness, substantial system advantages for numerous applications in space are expected. Since however space represents only a niche market for the chip manufacturers, measures for the space specification and qualification has to be done by the space sector. In Germany there are several research activities in the range of magnetoelectronics in particular in the frame of the funding activities of the BMBF as well as the DFG. Due to the necessary high capital investments the technological development of MRAM is accomplished predominantly by international industrial consortia in the USA also with participation of German companies such as Infineon.

7.1.3 Nano-composite materials for space structures

Nano-composite materials offer potential for high-strength, lightweight space structures, which could lead to substantial cost savings with regard to space transportation. To be considered here are nanostructured ceramics and fiber composites, nanostructured MMC as well as nanoparticle reinforced polymers. Concerning the development of such materials significant progresses were obtained in the last years also in Germany. To be mentioned here are among others high-strength transparent corundum ceramics or SWCNT reinforced polymers with clearly improved mechanical characteristics. In the range of nanostructured ceramic fiber composites for high temperature rocket engines in space a joint project is conducted in Germany under the leadership of the company Astrium and funding of the Bavarian research foundation.

7.1.4 Nanotechnologically improved components for energy generation and storage

Within the range of energy production and storage for space systems there are several approches for nanotechnological improvements. In the field of solar cells for space applications III/V compound semiconductor solar cells at present are the most efficient systems. The technology is highly developed, whereby the USA is leading with regard to space applications. Also in Germany activities are to be registered concerning the space utilization of III/V semiconductor solar cells with funding of the DLR.

In a long-term period also thin film solar cells based on polymer foils are relevant for space applications, which are light and cheap but however exhibit low efficiencies of approx. 10 %, so that further progress has to be achieved. The development of supercondensers is likewise a topic with space relevance. In this field a BMBF funded joint project with participation of the company Dornier is accomplished at present.

7.1.5 Thermal and mechanical protection layers

Nanoscale protection layers offer broad application potentials in space, e.g. as friction and wear reducing layers for microelectromechanical components (MEMS), oxidizing protection layers and thermal protection layers for rocket propulsions. The surface coating technology is highly developed and Germany possesses a high technological competence. First development projects in this context have been accomplished in cooperation with the space industry, which could serve as a basis for further activities.

7.2 Space spin-off for nanotechnology

The microgravity research can in future supply impulses for nanotechnology research in the basic range. Results from microgravity research could contribute to a better understanding and a more accurate modelling of nanotechnological procedures. This applies particularly to the formation of nanoparticles in gaseous phase, in liquids and in plasmas as well as gravity dependent phenomena in nanophase systems (e.g. magnetofluids). A substantial prerequisite for the use of microgravity for nanotechnology is the development of space suitable experimentation and measuring devices, as designed for the employment on the the ISS at present (among other things ICAPS, IMPF). The requirements regarding the analysis of relevant parameters with a nanoscale resolution however are only partly fulfilled in these conceptions.

At present the possibility of microgravity experiments for own research purposes is used rarely within the nanotechnology scene. As reasons for that, beside the time and money consuming preparation of the experiments, also information deficits regarding the funding modalities and the usable experimental devices in space can be mentioned. As a condition for an intensified utilization of microgravity research by nanotechnology institutions it is therefore advisable to pay greater attention to funding programmes of the ESA in microgravity research, e.g. in the frame of the

MAP programme, within the nanotechnology scene. The information base could be improved for example through specific workshops or newsletters, in which among other things nanotechnology relevant best practise examples of microgravity research are presented.

Apart from microgravity research, particularly the ISS offers fields of application, which are already used by NASA, for the space qualification of nanomaterials and components. An industrial utilization of the ISS by nanotechnological companies appears however rather unrealistic from today's perspective both for commercial microgravity research as well as for the production of nanomaterials in space, since the expected technologically usable results respectively improved characteristics of materials manufactured in microgravity do not justify the required investments, according to assessmets of the questioned enterprises.

8 APPENDIX

8.1 Abbreviation list

µg	Microgravity
AFM	Atomic Force Microscopy
AOCS	Attitude and Orbit Control System
ASIC	Application-specific Integrated Circuit
BMBF	Federal Ministry of Education and Research
bR	Bacteriorhodopsin
CC	Competence Center
CCD	Charge Coupled Device
CMC	Ceramic Matrix Composite
CMOS	Complementary Metal Oxide Silicon
CMR	Collossal Magnetoresistance
CNT	Carbon Nanotube
COTS	Commercial off-the-Shelf
CVD	Chemical Vapor Deposition
DLC	Diamond Like Carbon
DLR	German Aerospace Center
DNA	Desoxyribo Nuclein Acid
DoD	Department of Defense
DoE	Department of Energy
EEPROM	Electrically Erasable Programmable Read-Only Memory
EHF	Extremely High Frequency
EMR	Extraordinary Magnetoresistance
EPD	Electrophoretic Deposition
EPI	Electrophoretic Infiltration
EUV	Extreme Ultraviolet
FRAM	Ferroelectric Random Access Memory
GEO	Geostationary Earth Orbit
GMR	Giant Magneto Resistance
HBT	Hetero Bipolar Transistor
HEMT	High Electron Mobility Transistor
ICAPS	Interactions in Cosmic and Atmospheric Particle Systems
IMPF	International Microgravity Plasma Facility
ISAM	Ionic Self Assembled Layers
ISS	International Space Station
LDA	Laser Doppler Anemometry
LII	Laser-Induced Incandescence
LOX	Liquid Oxygen
MBE	Molecular Beam Epitaxy
MEMS	Micro-Electromechanical Systems
MEO	Mid Earth Orbit
MMIC	Monolithic Microwave Integrated Circuit
MOCVD	Metal Organic Chemical Vapor Deposition

MRAM	Magnetic Random Access Memory
MST	Micro System Technology
MWCNT	Multi Wall Carbon Nanotube
NIH	National Institutes of Health
NIR	Near Infra Red
PEM	Polymer Electrolyt Membrane
PIV	Particle Image Velocimetry
PKE	Plasma Kristall Experiment
PLD	Pulsed Laser Deposition
PVD	Physical Vapour Deposition
QD	Quantum Dot
QW	Quantum Well
QWIP	Quantum Well Infrared Photodetector
SEM	Scanning Electron Mckroscopy
RF	Radio Frequency
RTD	Resonant Tunneling Diode
SAW	Surface Accoustic Wave
SBIR	Small Business Innovation Research
SOFC	Solid Oxid Fuel Cell
SPS	Solar Power Satellite
STTR	Small Business Technology Transfer
SWCNT	Single Wall Carbon Nanotube
TMR	Tunneling Magneto Resistance
VCSEL	Vertically Cavity Surface Emitting Laser
VDI	Association of Engineers
WBG	Wide Band Gap

8.2 Literature list

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8.3 Evaluation of nanotechnology applications in space

The following table I is to be interpreted meaningfully only in connection with the explanations in chapter 5.8. The total evaluation of the respective nanotechnological component reflects its space relevance and is indicated as average of the values of the bold-printed columns in per cent of the maximum possible score (100 % corresponds to maximum space relevance).

Table I: Evaluation of nanotechnological applications in space

			Evaluation scale: 0 = small 1 = medium 2 = high															
			Economic potential in terrestrial markets						**Contribution to space objectives**									
Reference Chapter	**Nanotechnological components ↓**	**State of development** (0 = theory... 5 = Space Qualified)	a) Information and communication	b) Automotive engineering	c) Medicine/ Life Sciences	d) Energy engineering	e) Environmental technology	**Average of columns a to e**	f) Cost reduction	g) Improved functionality	h) Lowering of mission risks	i) Higher mission flexibility	j) Potential for new system conceptions	**Average of columns f to j**	**Economic benefit for the space sector**	**Applicability under space conditions**	**Total evaluation** (average of the bold-printed columns in per cent of the maximum possible score of 2,6)
5.2	**Nanomaterials/ Nanochemistry/ Nanobiotechnology**																
5.2.1	*Structure materials*																
	Nanoparticle reinforced polymer	**4**	1	2	2	0	1	**1,2**	2	1	1	1	0	**1**	**1**	**2**	**71 %**
	CNT/CNT-nanocomposites	**2**	2	2	1	1	1	**1,4**	2	2	1	2	2	**1,8**	**2**	**2**	**71 %**
	Metal matrix composites	**4**	0	2	0	1	1	**0,8**	2	0	1	1	0	**0,8**	**1**	**2**	**66 %**
	Nanocrystalline metals	**4**	0	1	0	1	1	**0,6**	1	0	1	1	0	**0,6**	**1**	**2**	**63 %**
	Nanostructured ceramics	**3**	1	1	1	1	1	**1**	1	1	0	1	0	**0,6**	**1**	**2**	**58 %**
5.2.2	*Thermal protection/ control*																
	Ceramic fiber nanocomposites	**4**	0	1	0	2	1	**0,8**	1	1	1	2	1	**1,2**	**1**	**2**	**69 %**
	Ferrofluids	**4**	0	2	2	0	1	**1**	0	2	0	0	1	**0,6**	**0**	**2**	**58 %**
5.2.3	*Energy production/storage*																
	III/V- Semiconductor solar cells	**5**	0	0	0	1	0	**0,2**	0	2	0	1	0	**0,6**	**2**	**2**	**75 %**
	Polymer thin film solar cells	**4**	1	2	0	2	1	**1,2**	2	0	0	1	2	**1**	**1**	**2**	**71 %**
	Organic solar cells	**3**	1	1	0	2	1	**1**	2	0	0	1	0	**0,6**	**1**	**1**	**51 %**
	QD Solar cells	**2**	0	0	1	2	0	**0,6**	1	2	0	0	0	**0,6**	**2**	**2**	**55 %**
	Fuel cells	**4**	1	2	0	2	1	**1,2**	1	1	0	1	0	**0,6**	**1**	**2**	**68 %**
	Supercaps/Nanocaps	**3**	1	2	0	2	1	**1,2**	0	2	0	1	0	**0,6**	**1**	**2**	**60 %**
	Batteries/thin film batteries	**4**	2	1	0	2	0	**1**	1	2	0	0	1	**0,8**	**1**	**2**	**68 %**

Reference Chapter	Nanotechnological components ↓	**State of development** (0 = theory... 5 = Space Qualified)	*Evaluation scale: 0 = small 1 = medium 2 = high*														
			Economic potential in terrestrial markets						**Contribution to space objectives**								
			a) Information and communication	b) Automotive engineering	c) Medicine/ Life Sciences	d) Energy engineering	e) Environmental technology	**Average of columns a to e**	f) Cost reduction	g) Improved functionality	h) Lowering of mission risks	i) Higher mission flexibility	j) Potential for new system conceptions	**Average of columns f to j**	**Economic benefit for the space sector**	**Applicability under space conditions**	**Total evaluation** (average of the bold-printed columns in per cent of the maximum possible score of 2,6)
5.2.4	*Life support systems*																
	Gas storage	**2**	0	2	0	2	1	**1**	1	1	0	1	0	**0,6**	**1**	**1**	**43 %**
	Heat exchanger	**3**	0	0	0	2	1	**0,6**	2	1	0	0	0	**0,6**	**1**	**2**	**55 %**
	Nanomembranes for water treatment	**4**	0	0	2	0	2	**0,8**	1	1	0	1	0	**0,6**	**0**	**2**	**57 %**
5.2.5	*Sensor technology*																
	Nanostr. gas sensors	**4**	0	2	1	1	2	**1,2**	0	1	2	0	0	**0,6**	**0**	**2**	**60 %**
	Electronic noses	**4**	0	0	2	0	2	**0,8**	0	1	2	1	0	**0,8**	**0**	**2**	**58 %**
5.2.6	*Biomedical applications*																
	Lab-on-a-chip-systems	**4**	0	0	2	0	2	**0,8**	1	1	1	2	0	**1**	**0**	**2**	**60 %**
	Drug-Delivery-systems	**2**	0	0	2	0	0	**0,4**	0	0	2	2	0	**0,8**	**0**	**2**	**40 %**
	Biomimetic sensors	**1**	1	1	2	0	2	**1,2**	0	2	2	2	1	**1,4**	**0**	**1**	**35 %**
5.2.7	*Other applications*																
	Aluminum nanopowder as rocket fuel addiditve	**4**	0	0	0	0	0	**0**	1	1	0	0	0	**0,4**	**1**	**2**	**57 %**
	Aerogels	**4**	1	0	0	2	2	**1**	0	2	0	1	0	**0,6**	**1**	**2**	**66 %**
	Magnetic nanocomposites	**4**	2	1	1	1	1	**1,2**	0	2	0	0	0	**0,4**	**1**	**2**	**66 %**
	Biomimetic nanomaterials	**1**	1	1	2	1	2	**1,4**	1	2	2	2	2	**1,8**	**1**	**1**	**48 %**
5.3	**Ultra thin layers**																
5.3.1	Friction and wear-reducing layers	**4**	1	2	0	2	1	**1,2**	1	2	1	0	1	**1**	**1**	**1**	**63 %**
5.3.2	Thermal protection layers	**4**	0	1	0	2	0	**0,6**	1	2	1	1	0	**1**	**1**	**2**	**66 %**
5.3.3	HF-Components (HEMT, HBT, SAW)	**4**	2	1	1	0	0	**0,8**	1	2	1	0	0	**0,8**	**2**	**2**	**74 %**
5.3.3	Coated foils on basis of ISAM	**3**	1	1	1	0	1	**0,8**	2	1	0	2	2	**1,4**	**1**	**1**	**55 %**
5.4	**Nano-optoelectronics**																
5.4.1	QD Laser	**4**	2	1	1	0	1	**1**	1	1	0	1	1	**0,8**	**2**	**2**	**75 %**
5.4.2	Photonic crystals	**2**	2	0	1	0	1	**1**	1	2	0	0	1	**0,8**	**2**	**2**	**58 %**
5.4.3	QD IR sensors	**2**	2	0	0	0	1	**0,6**	0	2	0	0	0	**0,4**	**1**	**2**	**46 %**

Reference Chapter	Nanotechnological components ↓	**State of development** (0 = theory... 5 = Space Qualified)	***Evaluation scale: 0 = small 1 = medium 2 = high***														
			Economic potential in terrestrial markets						**Contribution to space objectives**								
			a) Information and communication	b) Automotive engineering	c) Medicine/ Life Sciences	d) Energy engineering	e) Environmental technology	**Average of columns a to e**	f) Cost reduction	g) Improved functionality	h) Lowering of mission risks	i) Higher mission flexibility	j) Potential for new system conceptions	**Average of columns f to j**	**Economic benefit for the space sector**	**Applicability under space conditions**	**Total evaluation** (average of the bold-printed columns in per cent of the maximum possible score of 2,6)
5.5	**Lateral nanostructures**																
5.51	Molecular electronics	**1**	2	1	1	0	1	**1**	2	2	1	1	1	**1,4**	**2**	**1**	**49 %**
5.5.1	Spintronics	**2**	2	1	1	0	0	**0,8**	2	2	0	0	0	**0,8**	**2**	**1**	**51 %**
5.5.1	Quantum logics	**0**	2	0	0	0	0	**0,4**	1	2	0	0	0	**0,6**	**1**	**0**	**15 %**
5.5.1	Tunneling elements	**4**	2	0	0	0	0	**0,4**	1	2	0	0	0	**0,6**	**2**	**1**	**62 %**
5.5.2	SOI-Memory	**4**	2	1	0	0	0	**0,6**	2	1	1	0	0	**0,8**	**2**	**2**	**72 %**
5.5.2	Phase-Change-RAM	**3**	2	0	0	0	0	**0,4**	2	2	0	0	0	**0,8**	**2**	**1**	**55 %**
5.5.2	FRAM	**4**	2	1	0	0	0	**0,6**	2	2	0	0	0	**0,8**	**2**	**0**	**57 %**
5.5.2	Magnetoelectronics / MRAM	**4**	2	1	1	0	1	**1,0**	2	2	1	1	0	**1,2**	**2**	**2**	**78 %**
5.5.2	Millipede	**2**	2	0	0	0	0	**0,4**	1	2	0	0	0	**0,6**	**1**	**0**	**31 %**
5.5.2	Biological data memories	**3**	2	0	0	0	0	**0,4**	1	2	0	0	0	**0,6**	**1**	**1**	**46 %**
5.5.3	Nanomotors, Nanopositioning	**4**	1	0	1	0	0	**0,4**	0	2	0	1	1	**0,8**	**1**	**2**	**63 %**
5.6	**Ultraprecise surfaces**																
5.6.1	X-ray optics	**5**	2	0	0	0	0	**0,4**	0	2	0	0	1	**0,6**	**1**	**2**	**69 %**
5.7	**Nanoanalytics**																
5.7.1	Nano-SIMS	**5**	0	0	0	0	2	**0,4**	0	2	0	1	0	**0,6**	**0**	**2**	**62 %**
5.7.2	Scanning probe techniques	**5**	0	0	1	0	1	**0,4**	0	2	0	1	0	**0,6**	**0**	**2**	**62 %**

8.4 Question catalog for written expert questioning

- Does your institution already perform own research activities concerning nanotechnological applications in space? If yes, which? (indication in notes)
- With regard to which topic in the field of nanotechnology applications in space is further research needed in your opinion? (indication in notes)
- Would your institution/company be interested in R&D projects concerning nanotechnology applications in space? If yes, in which topic areas? (indication in notes)
- Which obstacles exist concerning nanotechnological applications in space (indication in notes)
- Does in principle a demand for microgravity experiments e.g. on the ISS exist in the frame of your research activities? If no, why? If yes, in which topic areas? (indication in notes)
- Are you in principle interested in participation in a workshop about nanotechnology applications in space?

8.5 Lists of participants of the ANTARES meetings

8.5.1 Participants of the expert meeting on 14.12.01 in Düsseldorf

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