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Cyclical long-term Development of Complex Technologies – Premature Expectations in Nanotechnology?

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Abstract

After many years of tremendous growth, the patent activities in nanotechnology have slightly decreased and the growth of publication numbers in this field is slowing down. With these patterns nanotechnology exhibits typical characteristics of the cyclical development of complex science-based technologies which may be labelled double-boom development. However, the decrease of patents should not be interpreted as the end of the growth of nanotechnology, but rather as an intermediate stagnation before a second steep growth. This intermediate period will probably be short compared to other science-based technologies, as cognitive bottlenecks are largely compensated by a strong market pull and substantial public support from the science side.

1 Introduction

Many authors described nanotechnology as a promising field with a tremendous growth and enormous economic prospects (see, for instance, Huang et al. 2004; Hullmann 2006; 2007; Kostoff et al. 2007; Meyer et al. 2008; Roco et al. 2010; Salerno et al. 2008). However, in the past years some scholars have seen indications of an end of growth or even a decline of nanotechnology (Reiss/Thielmann 2010), so that the former expectations seem to be premature. In a more general perspective, a stagnation or even decline of nanotechnology could be expected. Nanotechnology can be characterized as a science-based complex technology, and with this type of technology cyclical long-term developments with intermediate stages of decline occur quite frequently (Schmoch 2007). In this paper, the nanotechnology development is examined in more detail, to assess whether such a cyclical development applies to this special case. The analyses will be based on patent and publication indicators as well as market forecast reports in order to achieve a coherent picture. Finally, an evidence-based outlook for the future development of nanotechnology is given.

2 The concept of double-boom development

The observation of a long-term cyclical development of science-based complex technologies refers to the meso-level of technology fields, in contrast to a micro-level of specific technologies within a field. Another line of debate is long-term cycles of technology with regard to whole industries or even clusters of several industries, thus at a macro-level. One of the most famous theories on the course of such big technology cycles is proposed by Kondratiev (1925); he assumed a link between long waves of economic development and the rise and fall of technologies. These thoughts are taken up by Freeman (1982) and put in the context of innovation theory; he published an up date in collaboration with Louça (Freeman/Louça 2001). The discourse on cyclical development at the meso-level is presented in Schmoch (2007)in more detail.

First indications of the cyclical development of complex science-based technologies were already found by Grupp and Schmoch (1992) for the fields of polyamides and laser beam sources. Based on these findings, Grupp (1993) designed a general illustrative model of the long-term development of science-based technologies. According to this concept, these technologies develop in a long-term perspective of several decades. After a first stage of strong patent growth, a maximum of patent applications is reached and then a substantial turn, even a decrease, follows. After that a second stage of patent growth follows in parallel with significant market growth. The activities in science, and thus publications, are performed over the whole period, even in the later stages of technology development. In the same book, Grupp (1993) already predicted a strong growth of nanotechnology, that is, at a time where almost nobody was aware of the existence of such an approach.

These basic reflections were taken up by Schmoch (2007). The basic approach in this analysis was to systematically consider the long-term development of patent applications, publications and market figures (e.g., turnover) concomitantly. The major findings may be resumed as follows: 22 of 44 complex technologies exhibited a distinct double-boom development, i.e. a development in two cycles with a first maximum, a following decline and a second growth stage (second boom). Thus, this type of development is not a strict law, but happens quite often. The decrease of patent applications after the first maximum peak is due to insufficient market results compared to high R&D investments. The publications exhibit an intermediate stagnation, already beginning before the first patent peak. The second boom is owed to decisive scientific-technological breakthroughs (e.g. the availability of complex IT control in robotics). The first boom primarily reflects scientific exploration. The second boom is linked to solutions in the form of specific applications of the technology. In consequence, the first and second booms may be generally associated with science push and market pull in a new perspective, without falling back on simple linear models. A major finding is that, as predicted by Grupp in 1993, the cycles are quite long: e.g., in the fields of industrial robots and immobilized enzymes the time lag between the first visible activities and the maximum of the first boom is about 15 years, the second boom starts about 10 years later.

The concept of the double boom was taken up by some scholars, in particular Wong and Goh (2010) who discussed self-propagating growth processes, Lecocq and van Looy (2009): who looked at the dynamics of collaboration between scientific and technical institutions and Phaal et al. (2011) who examined the emergence of industries. An interesting case is the analysis of fuel cells for automobiles by Bertram (2011). Here a cyclical development of patent applications can be observed, but the decisive bottleneck hampering a real breakthrough are not unsolved scientific-technological problems, but rather a still moderate oil price and in consequence moderate fuel costs, so that fuel cells are still sub-marginal.[1] In this example, the interplay between technology emergence and market pull becomes obvious also in fields of science-based technology and it underlines that market influence of markets has always to be taken into account.

However, the concept was not yet applied to nanotechnology, although Finardi (2011), Huang et al. (2004), or Heinze (2004) already studied patents and publications in nanotechnology concomitantly.

3 Study conduct and database

In this study, the technology development is described by patent indicators. For a summary of the advantages and shortcomings of patent indicators, we refer to the seminal papers of Pavitt (1984) and Griliches (1990) without discussing further details, as many authors have already dealt with this issue in detail.

To analyse the development in science, publication statistics in the Web of Science in particular in its sub-database Science Citation Index are used. The general methodology is described in further detail in Schmoch et al. (2012).

As to market development, the basic problem is that nanotechnology is not an industrial sector or a clearly defined product. Therefore the customary statistical sources collected by national or international agencies, based on sector or product classifications, cannot be applied. In consequence, the only available sources are specific market studies on nanotechnology provided by different private consultancy firms.

The database Worlds Patents Index (WPI) in the version of the host STN was used for the patent statistics. The decision in favour of this database was made, as very good results for searches by keywords are achieved. This is possible as the database producer provides own abstracts with a higher quality than the original ones. The searches were conducted with a complex strategy primarily based on keywords with about 40 interlinked commands (cf. Annex A1). This keyword strategy proved to be necessary, as the official class B82 in the International Patent Classification (IPC) covers the field

1 Further factors also hamper a breakthrough, such as problems of hydrogen storage or a missing infrastructure for hydrogen gasolines.

of nanotechnology insufficiently. The search strategy was elaborated in 2001 (Noyons et al. 2003). For the searches of this paper, some parts of that strategy were improved and updated. Compared to a simple strategy with “nano" and open right-hand truncation, the detailed keyword strategy achieves a similar recall, but much more precise, as confirmed by many manual checks of selected sub-samples.

In order to provide better coverage of nanotechnology and its application fields, the European Patent Office (EPO) introduced the new code Y01N. For this paper searches with this code were conducted in the database PATSTAT of the EPO. Recently, the EPO transferred the Y01N code to B82Y, thus the former IPC class B82 was enlarged. However, in the present transition period, long-term searches with the new code are not appropriately established in the available databases yet. The final searches were therefore exclusively conducted in WPI with the keyword-based strategy.

For an improved understanding of the development in nanotechnology, it proved to be useful to break it up into sub-fields. For the definition of sub-fields, various suggestions are made in the literature, for instance, by the BMBF (2006; 2009), Islam and Miyazaki (2009), Palmberg et al. (2009), or Meyer et al. (2008). We decided to use the following sub-fields for the patent analysis:

- Chemistry,
- Energy,
- Optics,
- Electronics,
- Advanced materials and surfaces,
- Biotechnology,
- Environment,
- Other fields.

These sub-fields were defined by an intersection of the documents identified by the keyword search and a set of classes and sub-classes of the International Patent Classification (IPC) (cf. Annex A2). Materials, surfaces (e.g. understanding and influencing chemical, optical, mechanical, etc. properties of surfaces, in the case of mechanical properties this is nanotribology) and materials design (e.g. mechanical engineering with nanomaterials components) are combined in one field called advanced, tailored or engineered materials and surfaces. Chemistry in contrast includes research e.g. on small to large molecules, complexes, compounds or substances and their chemical reactions (e.g. for catalysis, chemical functionalisation or design for controlled chemical reactions). The other categories point to application fields (e.g. energy applications like photovoltaics, batteries or environmental applications like membranes for water filtration, sensors for gas detection) or the use of certain properties (e.g. optical, electronic, biological) of the nanotechnological components, devices or systems.

In the patent analysis, so-called 'transnational patents' were considered where patent applications at the World International Property Organisation (WIPO), so-called PCT applications, and applications at the European Patent Office (EPO) are combined without double counting (Frietsch/Schmoch 2010) to achieve a useful dataset of relevant patent applications without mixing domestic and foreign applications.

The publication analyses were performed by the Science Citation Index as available through the database SCISEARCH of the host STN. A nearly identical keyword strategy as for the patent searches was used as elaborated (cf. Annex A3). In the case of publications, the following sub-fields were analysed in addition:

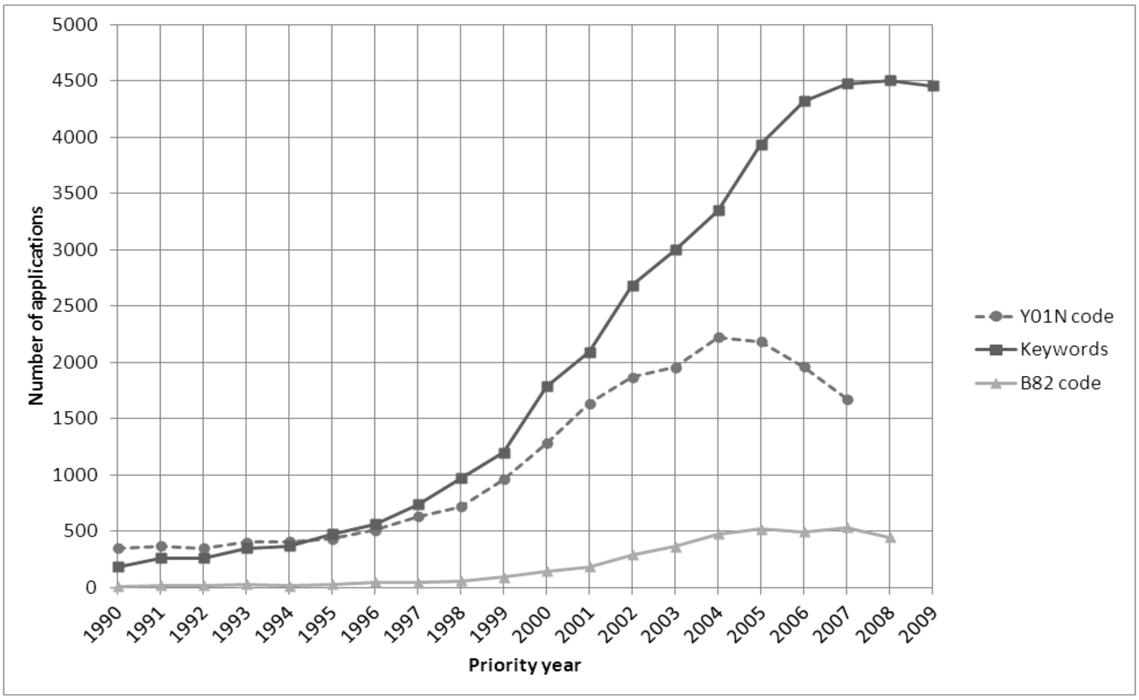
- Chemistry,
- Advanced materials and surfaces,
- Biotechnology (and medicine),
- Physics, nanotechnology basics,
- Other fields.

The sub-fields were defined by the intersection of the documents identified by the keyword strategy and category codes (subject codes) of the SCI (Web of Science, WoS) referring to journals in total, not to the topic of the specific article considered (cf. Annex A4). First analyses showed that the number of nanotechnology papers in journals in the fields of energy, optics, electronics, and environment were rather low or it was difficult to identify suitable subject codes to fully cover the fields (the categories are motivated more by scientific rather than by application fields), so that these fields used in the context of patents were not taken up for publications. Furthermore, the number of papers in typical biotechnology journals proved to be modest and a relevant number of publications could only be generated by including journals in medicine. In contrast to patent applications (representing technology), the number of publications (representing science) in physics journals is substantial. Now physics includes sub-fields such as optics, electronics, or energy, but at a more basic level. This finding confirms the results of a survey at German universities in 2004 according to which about 75% of the research in nanotechnology could be described as basic research (Jansen et al. 2007). Thus the high number of nanotechnology publications in journals of physics can be taken as an indicator of the still strong basic orientation of scientific research in this field.

4 Findings of patent and publication analyses

The searches for patent applications in nanotechnology by the three strategies B82, Y01N, and keywords, as described above, lead to quite different results documented in Figure 1. The lowest figures are yielded by the search with the B82 code referring to applications dealing with core techniques at the nano-level. The Y01N code includes inventions dealing with specific applications of nanotechnology in different fields of use in addition to B82. The number of the referring applications proves to be substantially higher than that of the B82 or core applications, but since the priority year 2005, that is the very first year of application for an invention, the number of applications has been declining.

Figure 1: Transnational patent applications in nanotechnology according to different search strategies



Sources: WPINDEX (STN), PATSTAT (EPO), searches and calculations by the authors

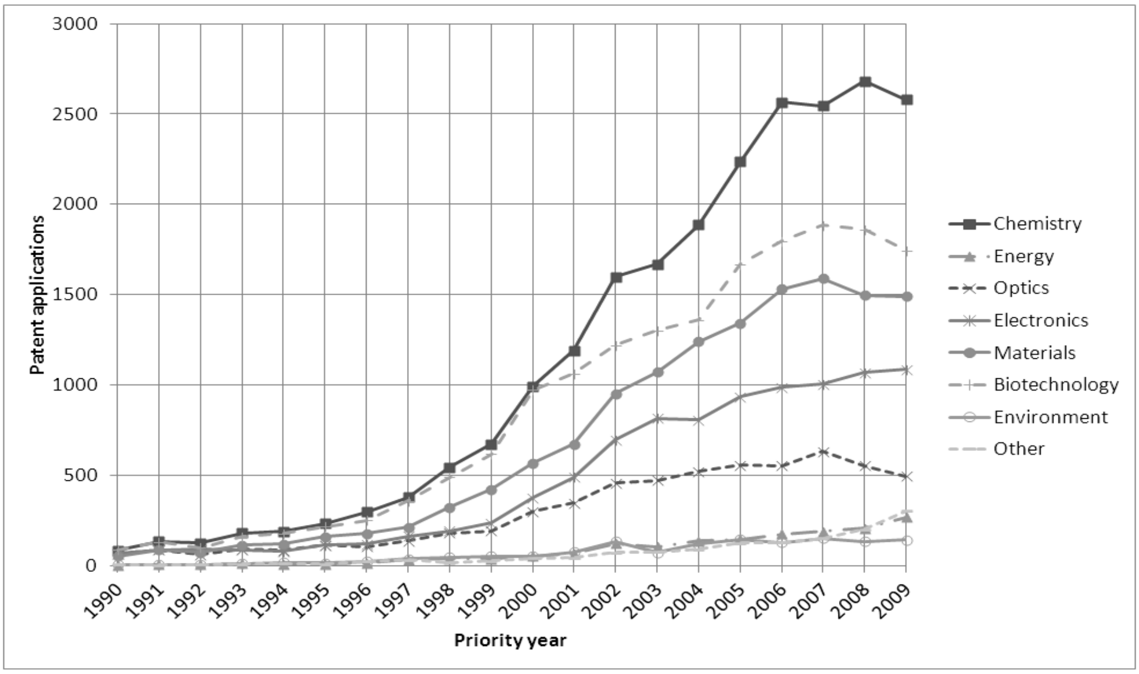
The number of applications according to the Y01N and the keyword strategies are rather similar until about 2001, but then the number of applications according to the keyword strategy appears to be much higher than in the Y01N case and continues to increase strongly until 2007. Then the increase becomes slower and in 2009 even a slight decrease is observed. In comparison to the Y01N strategy, the keyword strategy includes applications where nanotechnology is only one element of the invention, but not the only one. In these cases, nanotechnology is not the core, but it enables the concept of a new artefact.

In all three strategies, a decrease in recent years becomes obvious, even in the keyword strategy. A similar slowing down of patent applications was already observed by Palmberg et al. (2009) or Aschhoff et al. (2010) relying on the Y01N EPO classification approach, but this was not identified as the end of a first growth cycle.

In any case, the parallel of the present development of nanotechnology to the first growth cycle of the double-boom concept suggests itself. It is obvious that a technology cannot grow permanently, but the question arises whether the observed deceleration marks the general end of nanotechnology and a replacement by competing technologies, or just an intermediate reprieve.

For an improved understanding of the mechanisms behind the present slow-down, we examined the development of the sub-fields of nanotechnology in more detail, as depicted in Figure 2 (Annex A5). Within the sub-fields, chemistry, biotechnology, and optics depict a decrease in the last two years, in materials a drop in 2008 seems to stabilize in 2009. Environment stagnates at a low level. In electronics and other fields, the number of patent applications are still growing. Thus the dynamics in the sub-fields does not always follow the general dynamics of nanotechnology as a whole. In electronics the growth is not as extraordinary as between 1999 and 2003, but it is still relevant.

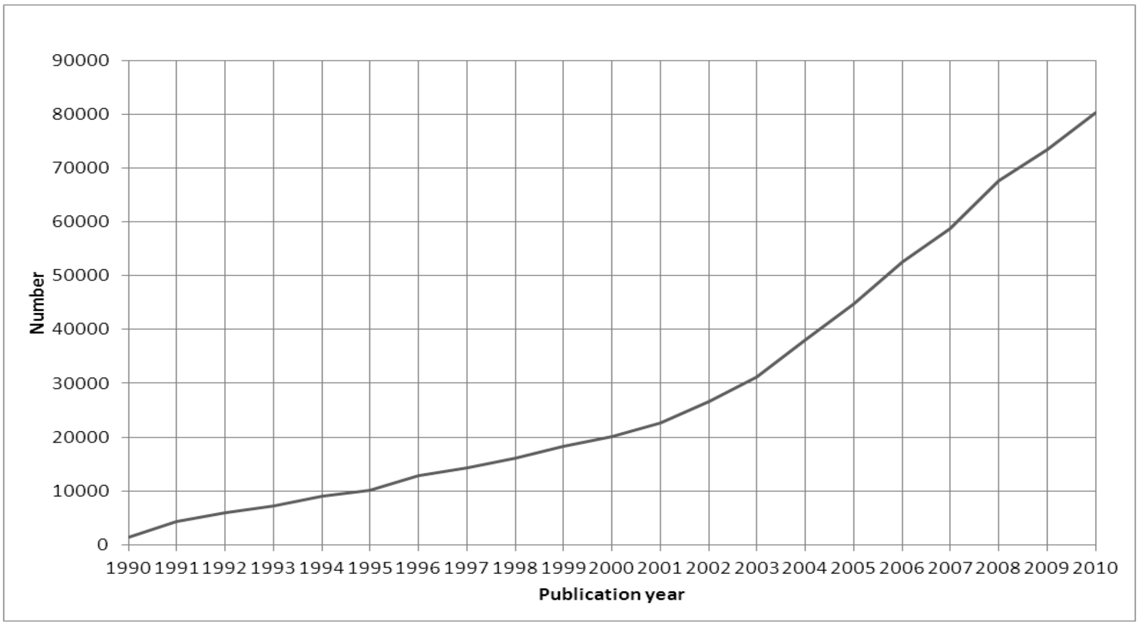
Figure 2: Transnational patents in sub-fields of nanotechnology



Sources: WPINDEX (STN), searches and calculations by the authors

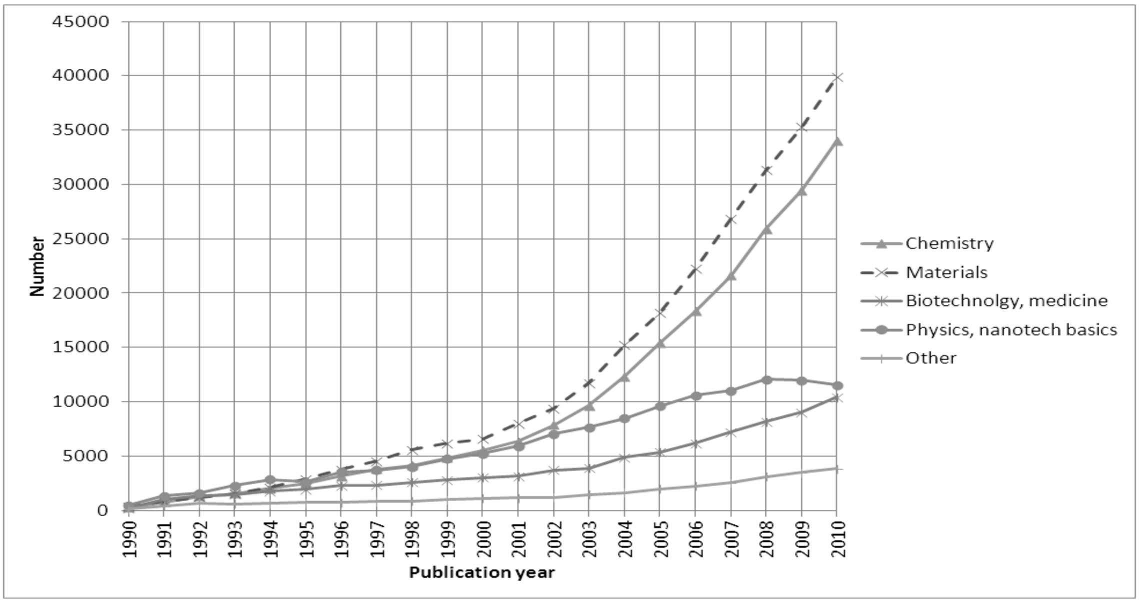
Looking at the publications in scientific journals, the growth of nanotechnology (nanoscience) is slightly slowing down compared to the annual maximum between 2001 and 2002 of 22%, But it still achieves a high rate with annually 9% since 2008 (Figure 3). In any case, the publications do not exhibit the standard picture of the double-boom development where they should stagnate in parallel to the decrease of patent applications. This special feature of nanotechnology is certainly due to the substantial public support for nanotechnology in the last years (see e.g., Hullmann 2006; Palmberg et al. 2009; WTEC 2010) which is primarily reflected in growing activities of public research institutes and universities in nanotechnology. A further break-down by sub-fields reveals a similar tremendous growth (Figure 4, Annex A6). In particular, the strong scientific increase in chemistry reflected in publications is striking in contrast to the technological decrease in chemistry reflected in patents. The only obvious stagnation of publications can be noted for physics. However, this observation should not be interpreted as decrease of scientific activity, but may rather point to a shift from basic to more applied research. For the public sponsors of nanotechnology are urging a stronger orientation to practical purposes.

Figure 3: Scientific publications in nanotechnology/nanoscience



Sources: SCISEARCH (STN), searches and calculations by the authors

Figure 4: Scientific publications in sub-fields of nanotechnology/nanoscience



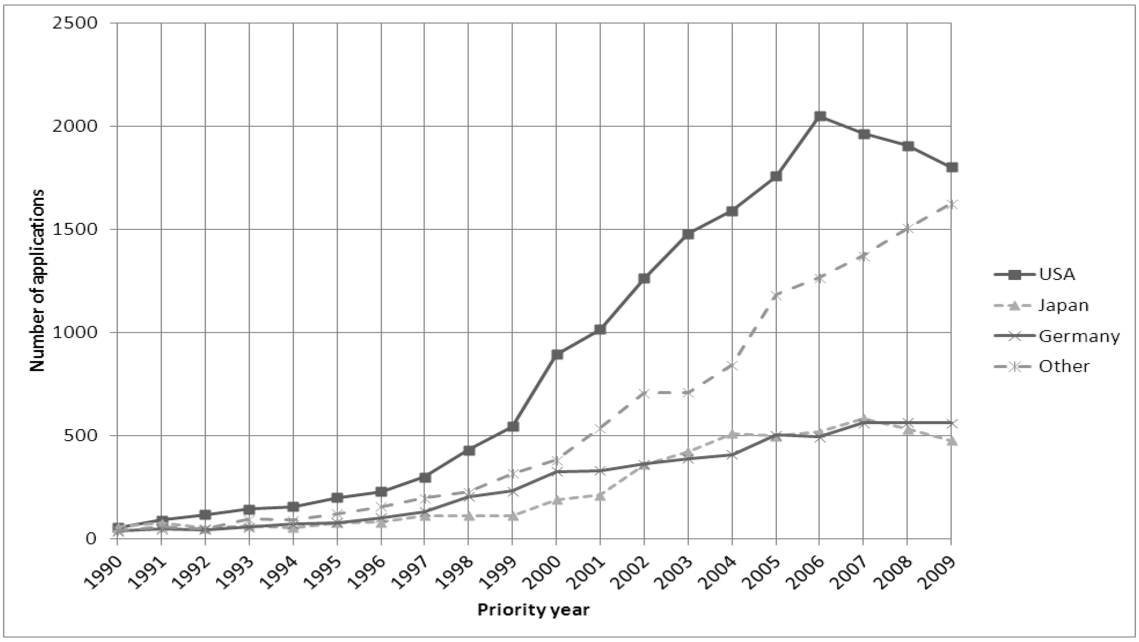
Sources: SCISEARCH (STN), searches and calculations by the authors

A breakdown by the “big three" in nanotechnology, USA, Japan and Germany, was performed in order to observe in further detail whether the observation of a decrease of patents and a slower, but still strong growth of publications at the world-wide level also applies to specific countries. In the case of patents, the decrease of applications primarily applies to the USA since 2006, but a decrease is also visible for Japan since 2007. Germany exhibits stagnation since 2007 (Figure 5). The other countries still follow a strong growth path. Thus the worldwide slow-down refers to the development in the three largest countries, which is qualitatively consistent with the findings of Reiss and Thielmann (2010) for patent analyses based on the EPO classification scheme.

As for publications, a stagnation, similar to the typical double-boom model, can be observed only for Japan. All other countries still exhibit a clear growth, in particular the “other" countries. It is remarkable that the group of “other" countries is much stronger in terms of publications than patents (this is mainly due to emerging Asian countries such as China, Korea, Singapore, etc.). Obviously, many countries invest in scientific research with the expectation of participating in the strong economic expectations in nanotechnology, but the transformation of the results into marketable applications appears to be difficult.

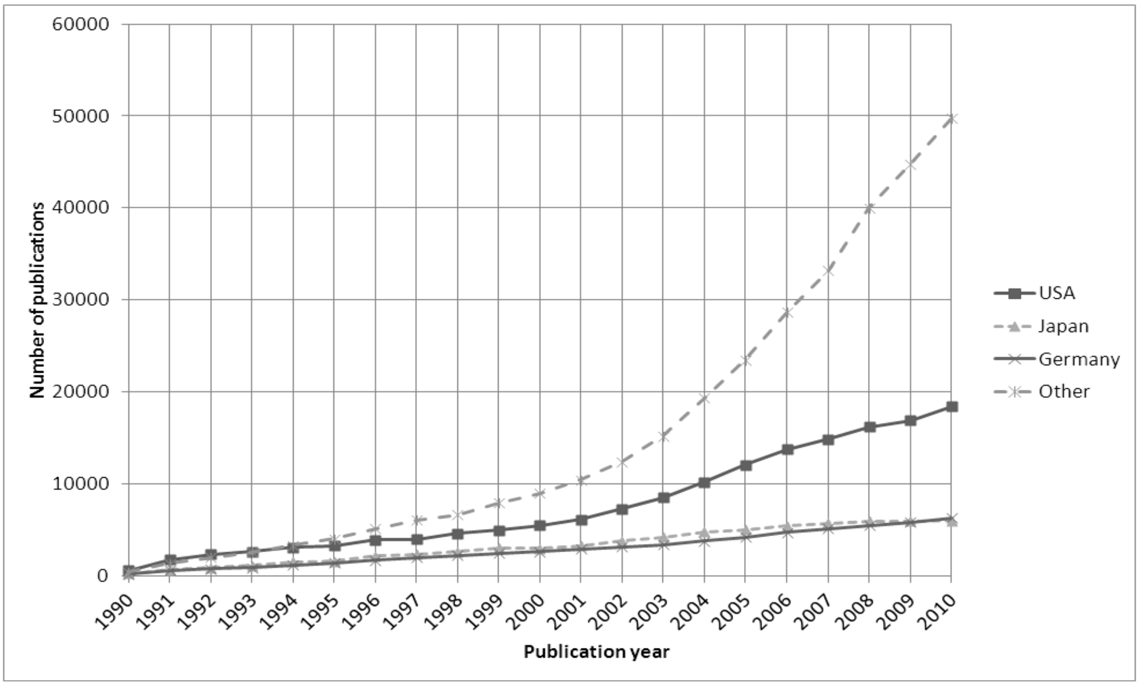
As an interim result, the question can be asked whether the research in nanotechnology will stop, if public financial support were to be cut.

Figure 5: Transnational patent applications in nanotechnology for selected countries



Sources: WPINDEX (STN), searches and calculations by the authors

Figure 6: Scientific publications in nanotechnology/nanoscience for selected countries



Sources: SCISEARCH (STN), searches and calculations by the authors

5 Forecasts of economic development

As far as the economic development in terms of turnover, export volume etc. is concerned, no official statistical data are available, as nanotechnology is not a clearly defined product or sector. The only useful documents are assessments and forecasts by private consultancy firms (BCC 2011; Cientifica 2011; Frost & Sullivan 2010; Lux Research 2005; 2006; 2009)[2]. In a number of recent studies, the different market forecasts were summarized (Aschhoff et al. 2010; BMBF 2009; Palmberg et al. 2009) and relativized. The prospects of the development of the nanotechnology markets vary considerably:

The market for "novel nanomaterials" is to reach US$ 4.2 billion by 2011 from US$ 1.5 billion in 2006 (EURONANO 2009). Other, even more up-to-date studies report market volumes between US$ 0.4 billion in 2005 and US$ 1.4 billion in 2010 (Frost & Sullivan 2010)

On the value added step of nanomaterials and devices for manufacturing or analysis of nanostructures, world market volumes of approx. US$ 50 billion are forecast by 2010 (BMBF 2009). For comparison, the current "classical nanomaterials" market is estimated to have a volume of around US$ 30 billion per year (EURONANO 2009).

On the other hand, the world market influenced by nanotechnology (or more specifically: by nano-enabled products) has been estimated to be in the range between 100 and 1.000 billion euro between 2005 and 2015 (in a lower or pessimistic scenario). Market estimates for 2015 even approach US$ 3,000 billion in an upper or optimistic scenario (Figure 5), being a significant percentage of the world gross national product (GDP) of about 5% or about 15% of the global production of goods.

The forecasts, however, have in common that they predict a substantial increase of the market for nanotechnology products, taking off around the early 2010s.

The differences in estimates was already well illustrated by Hullmann (2006), her results are depicted in Figure 5. The estimates on turnover cannot be simply characterized as pessimistic or optimistic, but the underlying definition of nanotechnology is however crucial. In this regard, the distinction made in the Lux report (Lux Research 2005) between

- nanomaterials,
- intermediates (components substantially based on nanotechnology) and
- nano-enabled products and processes

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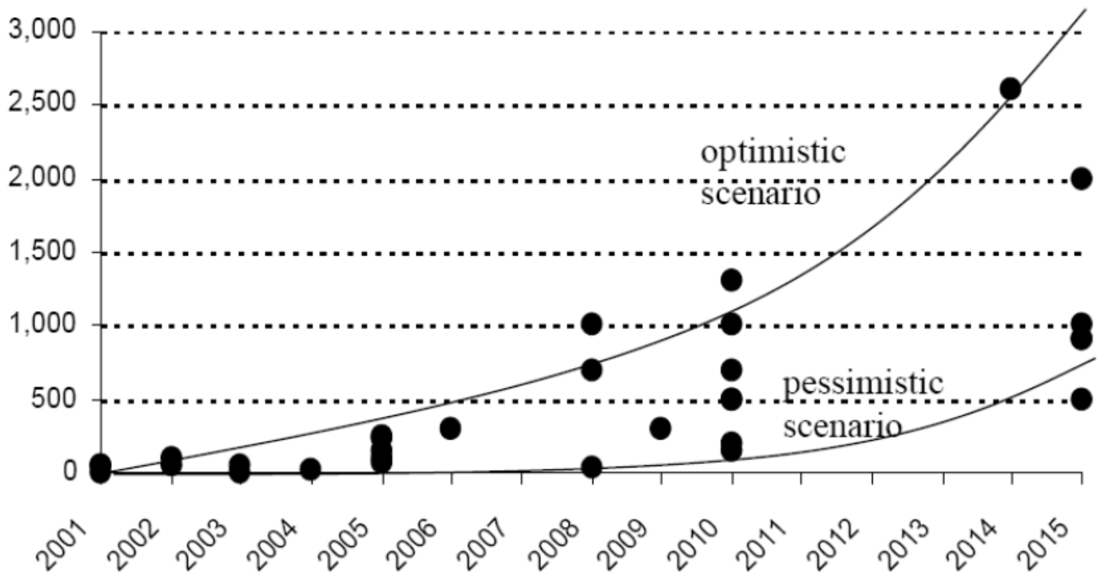
2 For more information, see the Web pages of the consultancies.

proves to be very helpful and points to the obviously different depiction of the field nanotechnology by the various consultancies.[3] According to their assessment, for the (basic) nanomaterials, the level of turnover is and will be quite modest (0.5% of the turnover with nano-enabled products), that of nano-intermediates is steadily growing and is of substantial size already today. It achieves about 20% of the turnover with nano-enabled products.

In this perspective, the patent search with the B82 codes (for nanostructures) may roughly be associated with nanomaterials, the Y01N search with intermediates and the keyword strategy with nano-enabled products. In any case, considerable market growth of products substantially based on nanotechnology appears to be realistic.

Figure 7: Estimates of nanotechnology market size. Scenarios on the basis of 17 sources (in US$ billion)



Source: Hullmann (2006)

6 Conclusions

At first sight, the present stagnation of patent applications and the strong market prospects in nanotechnology seem to be contradictory. However, there are some bottlenecks which should not be neglected: First of all, many effects in nanosciences arising due to the enhanced surface to volume ratio of the nanostructured materials (e.g. en-

3 Lux Research Report "Sizing Nanotechnology's Value Chain (http://www.luxresearchinc.com/)

hanced reactivity and quantum effects on the nanoscale, leading to new electronic, optical, chemical, mechanical etc. properties) are not really understood yet, thus further basic research is necessary to exploit the real potential of nanotechnology. Consequently, the future practical applications are also often unclear. The stagnating number of publications in physics may be an indication that a shift towards application is probable in the next years and the technology is maturing in some research fields.

For the commercialization of nanotechnologies, however, at present, often processes for producing high quantities of nanomaterials at moderate costs are still missing, or up-scaling laboratory results and prototype applications to the industrial production scale of intermediates proves to be difficult, thus limiting various potential applications. Also, as research on the toxicity of nanomaterials is still ongoing, there is no valid/ available database or more detailed information on the potential hazards of nanomaterials. Hence, there is a major concern that nanotechnology could gain a negative image, which would hinder its broad commercialization. Thus, an essential element of the integrated, safe and responsible approach is to integrate environmental, health and safety (EHS) aspects in the development of nanotechnology and to establish an effective dialogue with all stakeholders (public awareness, trust, code of conduct).

To summarize, the most important challenges for a broad commercialization of nano-based products are:

1. to find energy-efficient and cost-effective processes/ production processes,
2. to avoid, minimize or substitute critical (rare, expensive, toxic) materials,
3. to upscale from laboratory and prototype to industrial scale.

This is linked with the technological challenges of:

1. identifying new materials with improved functions (ration of functionality to costs has to be optimized) and
2. understanding and controlling surfaces and interfaces, crucial to connecting the used effects to the environment (i.e. the system or device).

Finally, in its present stage of development, nanotechnology is an enabling technology and not an end product. It operates sometimes with still unformed value chains in which technology push strategies have to meet market needs. Thus, there is a need for clear market drivers, for example, industrial problems that can be solved by the application of nanotechnologies (EAG 2009). The number of worldwide nanotechnology firms is still limited today.

Despite these problems, the probability of a distinct double-boom development with a clear intermediate decrease of patent applications is low. An intermediate stage of stagnation is possible, linked to the low turnover for the producers of basic nanomaterials or the problems of producers of components and nano-enabled products to transfer the patented inventions into commercially competitive products on an industrial scale.

But the typical double-boom model depends on cognitive bottlenecks in the development of complex science-based technologies. In the case of nanotechnology, these cognitive problems exist, but are largely compensated by a dynamic market development. Nevertheless, the total cycle of nanotechnology will be very long, including steady scientific research over several decades. In this context, the observation of Zucker and Darby (2005), that there is a substantial time lag between the very first basic scientific inventions (in nanotechnology breakthroughs in microscopy in the mid-1980s) and broader related technological activities (comparable to biotechnology) and they interpret this phenomenon as characteristic for science-based technologies. In this perspective, the real lengths of the double-boom are even much longer than visible in the patent and publication activities.

The decline after the first maximum peak may be shorter in nanotechnology than in other research-intensive fields due to the substantial market demand and to the ongoing public support (which is still increasing worldwide and, in recent years, has acquired a stronger focus on applications addressing grand challenges, such as climate change, energy and resource needs), so it is likely that the cognitive bottlenecks will be removed earlier than in other fields.

From the perspective of the double-boom concept, nanotechnology exhibits major characteristics, in particular cognitive bottlenecks which hamper the technological development, but the drop after the first cycle will probably be less deep and less long, due to compensation by massive public support and substantive market demand. In any case, a sharp cutback of public support as the reaction to the decline of patent activities would be counterproductive.

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8 Annex

Annex A1: Keyword-based search strategy for patent applications in the database WPINDEX (STN) formulated as Messenger commands

S (((Nanometer# or nanometre# or nm or submicro?) and (chip# or electron? or engineering or diameter or size# or layer# or scale or order or range or dimensional))/TI not (Wavelength# or roughness)/TI)
S (((Nanometer# or nanometre# or nm or submicro?)(A)(chip# or electron? or engineering or diameter or size# or layer# or small? or scale or order or range or dimensional)) not (Wavelength# or roughness))
S (((Nanometer# or nanometre# or nm or submicro?)(2W)(chip# or electron? or engineering or diameter or size# or layer# or small? or scale or order or range or dimensional)) not (Wavelength# or roughness))
S (nanoparticl? or nano(w)particl?) not (ink or polish?)
s (nanoanaly? or nanobar? or nanobot# or nanocage# or nanochannel? or nanoceramic or nanochannel# or nanochip# or nanocircuitry or nanocluster# or nanocoating# or nanocoll? or nanocomput? or nanocompos? or nanoconduct? or nanocry or nanocrystal? or nanodevice# or nanodes)
S (nanodimensional or nanodispers? or nanodomain# or nanodrop? or nanoengin? or nanoelectr? or nanofabric? or nanofeature# or nanoarray? or nanobio? or nanoreact? or nanocatal? or nanophoto? or nanohol? or nanopit# or nanopillar#)
S (nanogap# or nanogel or nanoglass? or nanograin? or nanogranular or nanogrid? or nanoimprint? or nanoindentation or nanoinstructions or nanoillumination)
S (nanolayer? or nanolitho? or nanomachin? or nanomanipulator# or nanomagnet? or nanomaterial?)
S (nanomechanical or nanomembrane or nanometric? or nanomicr? or nanomotor# or nanopeptid? or nanophase# or nanophotolithography or nanopipel? or nanoplotter# or nanopowder# or nanosensor# or nanoscale? or nanoarchitecture or nanopattern or nanocavitiy)
S (nanopor? or nanoprinting or nanoprobes or nanoprocess? or nanoprogram? or nanoribbons or nanorod# or nanorope# or nanoscien? or nanoscop? or nanoscratching or nanosemiconductor# or nanosens? or nanosequencer or nanosilic? or nanosilver or nanosiz?)
S (nanospher? or nanospreading or nanostats or nanostep? or nanostruct? or nanosubstrate or nanosuspension or nanoswitch? or nanosyst? or nanotechnolog? or nanotextur? or nanotips or nanotribology or nanotropes or nanotub? or nanowire? or nanowhisk?)
S (nanotopography or nanochemistry or nanoregognition or nanodot or nanopump# or nanocaps?)
s scanning probe microscop? or scanning tunnel? microscop? or scanning force microscop? or atomic force microscop? or near field microscop?
s functionally coated surface# and nano?
S (biochip or biosensor) and (a61# or G01N or C12Q)/IPC
S DNA(W)CMOS
S (bacteriorhodopsin or biopolymer# or biomolecule#)and (G11# or G02# or G03# or G06#)/IPC
s biomolecular templat? or virus(2a)encapsulation or modified virus
S nano? and implant?
S (Pattern? or organized) and (biocompatability or bloodcompatability or blood compatability or cell seeding or cellseeding or cell therapy or tissue repair or extracellular matrix or tissue engineering or biosensor# or immunosensor# or biochip or cell adhesion)
S micro?(2a)nano?
S nano(w)(architect? or ceramic or cluster# or coating# or composit## or crystal?)
S nano(w)(device# or disperse# or dimensional or dispersion# or drop# or droplet or engineering or engineered or electrodes or electronic#)
S nano(w)(fabricated or fabrication or filler# or gel or grain? or imprint or imprinted or layer#)
S nano(w)(machine# or manipulator# or material# or mechanical or membrane or metric?)
S nano(w)(phase# or powder# or pore# or poro? or printing or rod# or scalar)
S nano(w)(size? or spher# or structure# or structuring or suspension or system# or technolog?)
S nano(w)(textur? or tips or tropes or tub? or wire? or whisk?)
S atomic(w)layer# or molecular templates or supramolecular chemistry or molecular manipulation
S quantum device# or quantum dot# or langmuir blodgett or quantum wire?
S single electron? tunneling or molecul? engineer? or molecul? manufactur?
S molecul? self assembl? or ultraviolet lithography or PDMS stamp or soft lithography
S fulleren? or molecular motor or molecular beacon or nano electrospray or ion channels or molecule channels
S Lab(3W)chip
S (nanofilt? or nanofib? or nanofluid?) and (C0## or A61# or B0##)/IPC
S (electron beam writing) and (H01L or H01J)/IPC

```
S monolayer and (G03G or H01J)/IPC
S thiol and H01L/IPC
S (B82B or A61K009-51 or G01N013-10 or G12B021)/IPC
S L1-L39
S L40 and (EP or WO)/PC
```

S	search command
#	zero or one character
?	any number of characters including none
/TI	search in the title field
(A)	adjacent terms, either order
(nW)	adjacent terms, in the order specified, n or fewer words apart
/IPC	search in the field International Patent Classification
/PC	search in the field Patent Country
Ln	search step number n

Annex A2: Definition of patent subfields as intersection with the total of A1 formulated as messenger commands

Chemistry
S L41 AND (((C07B or C07C or C07D or C07F or C07H or C07J or C40B) not A61K) or A61Q or A01N or A01P or C05! or C06! or C09B or C09C or C09F or C09G or C09H or C09K or C09D or C09J)/IPC
S L41 and (C10B or C10C or C10F or C10G or C10H or C10J or C10K or C10L or C10M or C10N or C11B or C11C or C11D or C99Z or B05C or B05D or H05H or B32! or C23! or C25! or C30! or B81! or B82!)/IPC
S L41 and (B01B or B01D001! or B01D003! or B01D005! or B01D007! or B01D008! or B01D009! or B01D01!! or B01D02!! or B01D03!! or B01D041 or B01D043 or B01D057 or B01D059 or B01D06!! or B01D07!!)/IPC
S L41 and (B01F or B01J or B01L or B02C or B03! or B04! or B05B or B06B or B07! or B08! or D06B or D06C or D06L or F25J or F26! or C14C or H05H or A61L or D01F)/IPC
S L42-L45

Energy
S L41 AND H01M/IPC

Optics
S L41 AND (G02! or G03B or G03C or G03D or G03F or G03G or G03H or H01S or H01J or H05B)/IPC

Electronics
S L41 AND (H01L or G11B or G06F)/IPC

Materials
S L41 AND (C08B or C08C or C08F or C08G or C08H or C08K or C08L or C01! or C03C or C04! or C21! or C22! or B22! Or B21! or B23! or B24! or B26D or B26F or B27! or B30! or B25B or B25C)/IPC
S L41 and (B25D or B25F or B25G or B25H or B26B or F01B or F01C or F01D or F01K or F01L or F01M or F01P or F02! or F03! or F04! or F23R or G21! or F99Z or C08J or B29C)/IPC
S L50 or L51

Biotechnology
S L41 AND (C07G or C07K or C12M or C12N or C12P or C12Q or C12R or C12S or A61K or C40B or G01N or A61F)/IPC

Environment
S L41 AND (A62D or B01D045 or B01D046 or B01D047 or B01D049 or B01D050 or B01D051 or B01D052 or B01D053 or B09! or B65F or C02! or F01N or F23G or F23J or G01T or E01F008 or A62C)/IPC

S search command

/IPC search in the field International Patent Classification

Ln search step number n

! exactly one character

Annex A3: Keyword-based search strategy for publications in the database SCISEARCH (STN) formulated as messenger commands

S (((Nanometer# or nanometre# or nm or submicro?) and (chip# or electron? or engineering or diameter or size# or layer# or scale or order or range or dimensional))/TI not (Wavelength# or roughness)/TI)
S (((Nanometer# or nanometre# or nm or submicro?)(A)(chip# or electron? or engineering or diameter or size# or layer# or small? or scale or order or range or dimensional)) not (Wavelength# or roughness))
S (((Nanometer# or nanometre# or nm or submicro?)(2W)(chip# or electron? or engineering or diameter or size# or layer# or small? or scale or order or range or dimensional)) not (Wavelength# or roughness))
S (nanoparticl? or nano(w)particl?) not (ink or polish?)
s (nanoanaly? or nanobar? or nanobot# or nanocage# or nanocontainer# or nanochannel? or nanoceramic# or nanochannel# or nanochip# or nanocircuitry or nanocluster# or nanocoating# or nanocoll? or nanocomput? or nanocompos? or nanoconduct? or nanocry or nanocrystal? or nanodevice# or nanodes)
S (nanodimensional or nanodispers? or nanodomain# or nanodrop? or nanoengin? or nanoelectr? or nanofabric? or nanofeature# or nanoarray? or nanobio? or nanoreact? or nanocatal? or nanophoto? or nanohol? or nanopit# or nanopillar#)
S (nanogap# or nanogel or nanoglass? or nanograin? or nanogranular or nanogrid? or nanoimprint? or nanoindentation or nanoinstructions or nanoillumination)
S (nanolayer? or nanolitho? or nanomachin? or nanomanipulator# or nanomagnet? or nanomaterial?)
S (nanomechanic? or nanomembran? or nanometric? or nanomicr? or nanomotor# or nanopeptid? or nanophase# or nanophotolithography or nanopipel? or nanoplotter# or nanopowder# or nanosensor# or nanoscale? or nanoarchitecture or nanopattern or nanocavitiy)
S (nanopor? or nanoprinting or nanoprobe? or nanoprocess? or nanoprogram? or nanoribbon? or nanorod# or nanorope# or nanoscien? or nanoscop? or nanoscratching or nanosemiconductor# or nanosens? or nanosequencer or nanosilic? or nanosilver or nanosiz?)
S (nanospher? or nanospreading or nanostats or nanostep? or nanostruct? or nanosubstrate or nanosuspension or nanoswitch? or nanosyst? or nanotechnolog? or nanotextur? or nanotips or nanotribology or nanotropes or nanotub? or nanowire? or nanowhisk?)
S (nanotopography or nanochemistry or nanoregognition or nanodot or nanopump# or nanocaps?)
s ((scanning probe microscop?) or (tunnel? microscop?) or (scanning force microscop?) or (atomic force microscop?) or (near field microscop?))
s ((functionally coated surface#) and nano?)
S (biochip or biosensor)
S (DNA(W)CMOS)
S (bacteriorhodopsin or biopolymer# or biomolecule#) and nano?
s (biomolecular templat?)
S (nano? and implant?)
S ((Pattern? or organized) and (biocompatability or bloodcompatability or (blood compatability) or (cell seeding) or cellseeding or (cell therapy) or (tissue repair) or (extracellular matrix) or (tissue engineering) or biosensor# or immunosensor# or biochip or (cell adhesion)))
S (micro?(2a)nano?)
S (nano(w)(architect? or ceramic or cluster# or coating# or composit## or crystal?))
S (nano(w)(device# or disperse# or dimensional or dispersion# or drop# or droplet or engineering or engineered or electrodes or electronic#))
S (nano(w)(fabricated or fabrication or filler# or gel or grain? or imprint or imprinted or layer#))
S (nano(w)(machine# or manipulator# or material# or mechanical or membrane or metric?))
S (nano(w)(phase# or powder# or pore# or poro? or printing or rod# or scalar))
S (nano(w)(size? or spher# or structure# or structuring or suspension or system# or technolog?))
S (nano(w)(textur? or tips or tropes or tub? or wire? or whisk?))
S ((atomic(w)layer#) or (molecular templates) or (supramolecular chemistry) or (molecular manipulation))
S ((quantum device#) or (quantum dot#) or (langmuir blodgett) or (quantum wire?))
S ((single electron? tunneling) or (molecul? engineer?) or (molecul? manufactur?))
S ((molecul? self assembl?) or (ultraviolet lithography) or (PDMS stamp) or (soft lithography))
S (fulleren? or (molecular motor) or (molecular beacon) or (nano electrospray) or (ion channels) or (molecule channels))
S (Lab(3W)chip)
s (coulomb blockade)
s ((drug carrier?) and nano?)
s ((positional assembl?) and nano?)
s ((drug delivery) OR (drug targeting) OR (gene therapy) OR (gene delivery)) and nano?
s (Immobilized AND (DNA OR template OR primer OR oligonucleotide OR polynucleotide)) and nano?

s Polymer AND (protein OR antibody OR enzyme OR DNA OR RNA OR polynucleotide OR virus) and nano?
s (Surface modification) AND ((self assembl?) OR (molecular layers) OR multilayer OR (layer-by-layer))
s (Self assembl?) AND (biocompatibility OR bloodcompatibility OR (blood compatibility) OR cellseeding OR (cell seeding) OR (cell therapy) OR (tissue repair) OR (extracellular matrix) OR (tissue engineering) OR biosensors OR immunosensor OR biochip OR nano-particles OR (cell adhesion))
s (Single molecule)
S (nanofilt? or nanofib? or nanofluid?)
S (electron beam writing)
s L1-L45 not C/DT

S search command

zero or one character

? any number of characters including none

/TI search in the title field

(A) adjacent terms, either order

(nW) adjacent terms, in the order specified, n or fewer words apart

/DT search in the field Document Type

Ln search step number n

Annex A4: Definition of publication sub-fields as intersection with the total of A3 formulated as messenger commands

<u>Chemistry</u>
S L46 and (chemistry or electrochemistry)/CC

<u>Materials</u>
S L46 and (engineering or mechanics or materials or polymer or Metallurgy or crystallography)/CC

<u>Biotechnology</u>
S L46 and (Biochemical or Biochemistry or Biotechnology or Biology or biology or biomethods or microbiology or biophysics or pharmacy)/CC
S L46 and (cytology or surgery or ophthalmology or orthopedics or otorhinolaryngology or dentistry or medicine or ergonomics or rehabilitation or critical medicine or anatomy or histology)/CC
S L46 and (pathology or allergy or andrology or anesthesiology or oncology or vascular or dermatology or endocrinology and metabolism or gastroenterology and hepatology or geriatrics)/CC
S L46 and (hematology or immunology or infectious or pediatrics or psychiatry or rheumatology or toxicology or virology or urology and nephrology or tropical medicine or transplantation)/CC
S L46 and (neurology or obstetrics and gynecology or abuse or physiology or neurosciences or health or medical or nursing or Cardiac or public or health or respiratory or medicinal or parasitology)/CC
S L49-L53

<u>Physics</u>
S (L46 not L47-L54) and (physics or nanotechnology)/CC

S search command

Annex A5: Number of transnational patents in nanotechnology according to searches in WPINDEX (update September 2011)[4]

Year	Chemistry	Energy	Optics	Electronics	Materials	Biotechnology	Environment	Other	Total
1990	84	1	65	65	51	87	4	4	182
1991	133	5	86	86	88	129	6	3	265
1992	124	6	61	89	72	97	5	6	260
1993	180	12	89	87	113	160	10	8	352
1994	190	8	85	79	120	176	18	10	369
1995	233	9	114	114	159	215	13	9	476
1996	296	15	105	120	177	250	23	23	564
1997	378	30	137	163	212	357	38	30	736
1998	543	37	180	192	324	488	46	16	969
1999	672	37	192	236	422	618	52	27	1198
2000	991	52	299	374	566	972	51	41	1786
2001	1190	66	347	490	673	1062	74	43	2092
2002	1599	122	458	695	952	1219	133	71	2685
2003	1668	104	470	814	1072	1302	73	76	2997
2004	1887	137	522	806	1241	1359	120	90	3347
2005	2235	144	557	935	1342	1667	145	126	3935
2006	2564	175	554	986	1532	1797	128	127	4320
2007	2544	189	632	1004	1588	1884	151	151	4475
2008	2680	208	553	1067	1496	1859	135	200	4504
2009	2580	267	496	1085	1491	1742	141	304	4454

Source: WPINDEX, searches and calculations by the authors

Annex A6: Number of publications in nanotechnology according to searches in SCISEARCH (update September 2011)[5]

Year	Total	Chemistry	Materials	Biotechnolgy (medicine)	Physics	Other
1990	1380	246	368	225	457	128
1991	4274	756	825	1047	1337	407
1992	5920	1270	1209	1355	1604	691
1993	7172	1568	1534	1461	2267	581
1994	8992	2032	2129	1760	2829	630
1995	10198	2465	2885	1954	2618	714
1996	12798	3131	3759	2280	3537	732
1997	14309	3799	4533	2335	3728	831
1998	16020	4143	5564	2606	3994	873
1999	18297	4818	6178	2798	4755	998
2000	20044	5534	6548	3016	5249	1132
2001	22661	6368	7998	3147	5913	1178
2002	26625	7852	9368	3714	7045	1195
2003	31218	9632	11719	3905	7645	1464
2004	38013	12317	15201	4869	8478	1641
2005	44720	15393	18146	5337	9599	1974
2006	52501	18331	22220	6158	10577	2252
2007	58775	21623	26875	7227	11018	2559
2008	67604	25891	31293	8153	12062	3094
2009	73423	29444	35280	9020	11987	3505
2010	80352	33974	39891	10408	11543	3826

Source: SCISEARCH, searches and calculations by the authors

4 Double counting of fields due to multiple classification of applications.

5 Double counting of fields due to multiple classification of publications