Carbon Nanotubes – A scientometric study

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1. Introduction

In contrast to our previous study (Barth & Marx, 2008) dealing with a currently decreasing research field (high-temperature superconductors) we analyzed here a topic which has raised a strongly increasing interest among researchers: research activities around carbon nanotubes (CNTs or NTs). Carbon nanotubes (often named only nanotubes) are graphite sheets rolled up into cylinders with diameters of the order of a few nanometers and up to some millimeters in length with at least one end capped with a hemisphere of the fullerene structure. There are two main types of nanotubes: the single-walled nanotubes (SWCNTs or SWNTs) and the multi-walled nanotubes (MWCNTs or MWNTs), in particular the double-walled nanotubes (DWCNTs or DWNTs). MWCNTs consist of a single sheet of graphite rolled in around itself (like a rolled up newspaper) or consist of multiple layers of graphite arranged in concentric cylinders (like a Russian Doll).

Nanotubes exhibit some remarkable properties: They feature extraordinary strength, show efficient conductivity of heat, and unique electrical properties (metallic conductivity and semiconductivity). These properties make them potentially useful in a wide range of applications like in materials science, electronics, and nanotechnology. The one-atom thick single graphite layers building up the nanotube cylinders are named graphene, the newest member of this structural family. This species was presumed not to exist in the free state before it was discovered in the year 2004.

The large number of articles with respect to nanotubes has brought about that scientists being active in this research field have increasingly problems to overview their discipline. On the other hand, modern information systems offer databases and analysis tools providing remedy. However, due to lack of access and experience, many scientists do not take advantage of them. In this analysis we demonstrate the potential of such tools with respect to different kinds of meta-information. The data presented here are not expected to reveal surprising insights for experts working in this research field. However, they provide a quantification of (1) the productivity of the active players and (2) of the impact of their works. Moreover, the data could also be interesting for scientists working in neighboring research fields.

2. Methodology and Information Sources

The data presented in this study are based on the Science Citation Index (SCI) including the Conference Proceedings Citation Index, Science (CPCI-S) under the Web of Science (WoS). The SCI under the WoS stretches back to 1900 and the CPCI-S covers conference proceedings published since 1992. The WoS is accessible under the Web of Knowledge (WoK), the search platform provided by Thomson Reuters (Thomson Reuters, 2009), the former Institute for Scientific Information (ISI). The research field analyzed here stretches throughout most natural sciences disciplines being covered by the multi-disciplinary SCI and CPCI-S. However, the WoS source journals selected by the Thomson Reuters staff as contributing to the progress of science do not cover all publications being relevant here, in particular with respect to application and technology.

Therefore, the literature file of the Chemical Abstracts Service (CAS), a division of the American Chemical Society (ACS), has been consulted as an alternative information source. The CAS literature file is available via the online service STN International (STN International, 2009). The literature file CAplus is seen as the most extensive source of substance related publications (either articles or patents) in the fields of chemistry, materials science, and physics. Specific functions of the STN search system for carrying out statistical investigations have made it possible to perform extensive scientometric studies. Additional information is accessible via STN AnaVist, an analysis tool developed by STN International. However, the competent use of such databases and search systems requires some experience and awareness of the possibilities and pitfalls: e.g. about the coverage of the research disciplines by the various databases, the appropriate search and analyze functions available under the different search systems or the significance and the limitations of citation analysis (bibliometry).

3. Overall Productivity: Nanotubes vs Fullerenes and Graphene

The WoS offers two search modes: The General Search and the Cited Reference Search (the latter is not relevant for this study). The General Search mode reveals publications which appeared in WoS source journals (in particular articles, reviews, and meeting abstracts - no books, no popular scientific publications, no conference proceedings unless they appear in source journals or in the CPCI-S). The number of articles published in the WoS source journals has become a standard measure for scientific productivity (output in terms of the number of publications). The number of publications per year can easily be plotted as a function of the publication years using the WoS analyze function.

At the date of search (01-07-2009) the SCI including the CPCI-S revealed altogether 57128 publications related to nanotubes. The terms “nanotub*” or “nano tub*” (* = wildcard allowing to include the plural or synonyms like tubulus) were searched in the title and the abstract search fields. The search has not been restricted to WoS specific document types. Additionally searching the relevant abbreviations in common use to distinguish single walled, double walled, and multi walled nanotubes (SWCNT, SWNT, DWCNT, DWNT, MWCNT, MWNT) increased the total number of papers only marginally (57208). Due to the fact that the abbreviations hardly appear without additionally mentioning the full term and the potential ambiguity, the abbreviations were not taken into consideration here. Figure 1 shows the time curve of the articles of the entire nanotubes research field. The time evolution of the related fullerene and graphene literature are shown for comparison. The total number of articles covered by the SCI is included as a measure for the growth of the overall scientific literature.

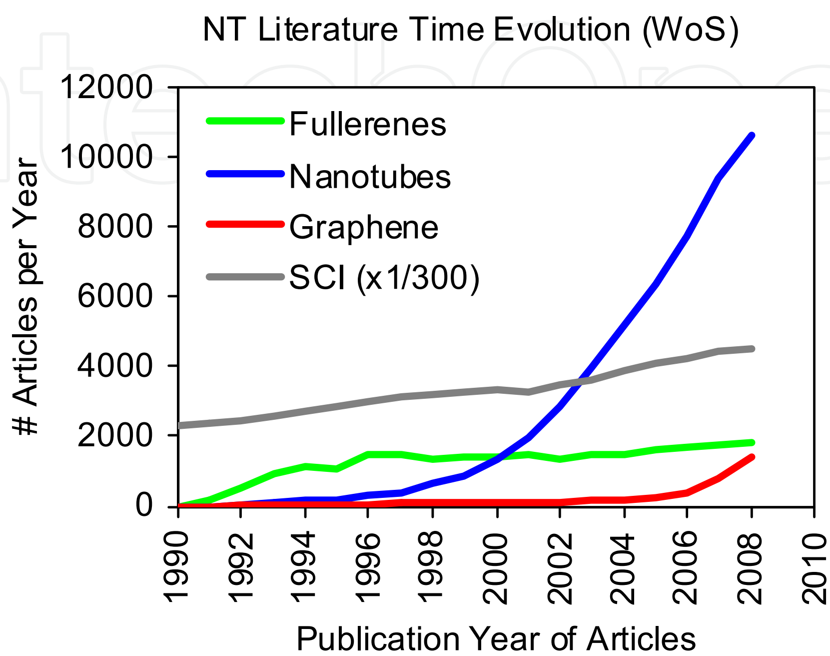

Fig. 1. Time dependent number of articles dealing with fullerenes, nanotubes, and graphene. The total number of articles covered by the SCI is shown as a rough measure for the growth of scientific literature. Source: SCI and CPCI-S under WoS.

According to Figure 1, the productivity (total number of articles per year) of the research activities dealing with nanotubes steadily increased, reaching about 11000 papers published in the year 2008 (compared to "only" 2000 fullerene papers published in the same year). The output increased by a factor of ten since 2000, which is far above the growth of the overall scientific literature in the same time period (about a factor of 1.25 with respect to the literature appearing in the source journals covered by the SCI).

In contrast to the nanotubes productivity, the time evolution of the fullerene literature shows a distinct saturation since about five years after discovery (Braun, 1992). Obviously, the nanotubes are one of the hottest research topics within the last decades with an undamped evolution. Since 2000 they have supplanted the (firstly) more promising fullerenes. The graphene related articles (meanwhile about 4500) show a rather similar increase, obviously starting a follow-up boom beside the ongoing fullerenes and nanotubes research activities.

Google and Google Scholar have become powerful search engines for web resources. Searching the world wide web for "nanotube(s)" with Google results in the large number of 3.1 million entries, while Google Scholar results in 0.27 million hits. The Google searches were carried out without any limitations concerning format, language, or time.

4. Productivity: Authors and Research Organizations

The almost 60,000 articles dealing with nanotubes and selected under the WoS were analyzed using the WoS analyze function. The most productive authors and research organizations, the countries of authors, and the leading journals were determined and are given in the Tables 1-4 below (date of search: 01-07-2009).

Rank	Author	Country	# Articles
1	Iijima, S	Japan	333
2	Bando, Y	Japan	307
3	Ajayan, PM	USA	294
4	Dresselhaus, MS	USA	291
5	Chen, Y	PR China	288
6	Roth, S	Germany	269
7	Lee, YH	South Korea	262
8	Chen, J	PR China	259
9	Wang, J	USA	258
10	Wang, Y	PR China	258
11	Zhang, Y	PR China	258
12	Zhang, J	PR China	248
13	Kataura, H	Japan	246
14	Goldberg, D	Japan	239
15	Li, Y	PR China	238
16	Terrones M	England	232
17	Wang, X	PR China	230
18	Liu, J	USA	225
19	LI, J	PR China	212
20	Smalley, RE	USA	209
21	Liu, Y	PR China	208
22	Zhang, L	PR China	208

Table 1. Top authors with at least 200 nanotubes articles based on the SCI and the CPCI-S under WoS.

Among the authors is a clear dominance of researchers from the East Asian countries and the US. Only a single author from a European country (S. Roth, Germany) is found in the group of the top ten authors in Table 1. Please note: Except for reprint authors, the SCI author addresses (and countries) are not allocated to the corresponding author names. In addition, some authors changed their affiliation. Asian names with only one forename initial comprise namesakes. Hence, the countries of authors given in Table 1 are not fully definite.

The top research organizations with respect to the number of articles dealing with nanotubes are shown in Table 2. Among the top positions are many Chinese research organizations and universities. The "weight" of the Chinese nanotubes research is confirmed further with Peoples Republic of China on rank two of the top countries of authors given in Table 3 further below.

Rank	Research Organization	# Articles	% Articles
1	Chinese Acad Sci	2840	5.0
2	Tsing Hua Univ	903	1.6
3	Russian Acad Sci	881	1.5
4	Peking Univ	684	1.2
5	Tohoku Univ	630	1.1
6	Rice Univ	628	1.1
7	Univ Sci & Technol China	616	1.1
8	Univ Cambridge	609	1.1
9	MIT	607	1.1
10	Univ Tokyo	607	1.1
11	Osaka Univ	573	1.0
12	Nanjing Univ	556	1.0
13	Zhejiang Univ	551	1.0
14	Natl Univ Singapore	514	0.9
15	NASA	513	0.9
16	Univ Illinois	497	0.9
17	CNRS	496	0.9
18	Seoul Natl Univ	479	0.8
19	Univ Calif Berkeley	476	0.8
20	Penn State Univ	460	0.8
21	Natl Inst Mat Sci	453	0.8
22	Natl Inst Adv Ind Sci & Technol	449	0.8
23	Natl Tsing Hua Univ	445	0.8
24	Sungkyunkwan Univ	427	0.7
25	Rensselaer Polytech Inst	414	0.7
26	Nanyang Technol Univ	406	0.7
27	Georgia Inst Technol	401	0.7

Table 2. Top research organizations with at least 400 nanotubes articles based on the SCI and the CPCI-S under WoS.

Please note: (1) In contrast to author names and journal titles, author addresses are not fully standardized in literature databases. Hence, the data offer only a rough picture of the leading research organizations and do not provide an exact ranking. (2) Many publications have been assigned to more than one country of author resulting in a substantial overlap.

5. Productivity: Countries and Continents

The ranking of the countries of authors having published articles dealing with nanotubes is given in Table 3.

Rank	Country of Author	# Articles	% Articles
1	USA	15845	27.7
2	Peoples R China	13386	23.4
3	Japan	6683	11.7
4	South Korea	3660	6.4
5	Germany	3423	6.0
6	France	2469	4.3
7	England	2391	4.2
8	Taiwan	1743	3.1
9	Russia	1691	3.0
10	Italy	1394	2.4
11	India	1335	2.3
12	Spain	1177	2.1
13	Canada	1094	1.0
14	Australia	994	1.7
15	Singapore	965	1.7
16	Switzerland	756	1.3
17	Belgium	694	1.2
18	Brazil	662	1.2
19	Poland	599	1.0
20	Israel	589	1.0
21	Sweden	523	0.9
22	Mexico	508	0.9

Table 3. Top countries of authors with at least 500 nanotubes articles based on the SCI and the CPCI-S under WoS.

The countries of authors ranking given in Table 3 is based on articles dealing with any type of nanotubes. A ranking based on articles dealing only with multi-walled nanotubes reveals that the top position is taken up by the Peoples Republic of China. A broader view is given in Figure 2, showing the share of the continents of the authors publishing nanotubes related articles being covered by the WoS source journals.

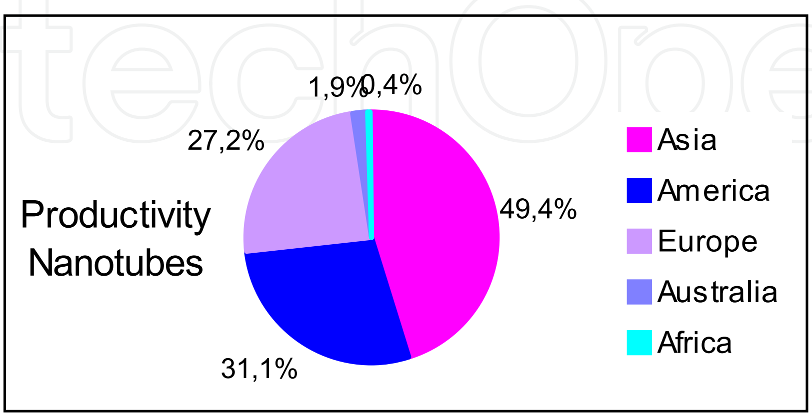

Fig. 2. Share of the continents of the authors of nanotubes related articles (with Europe incl. Russia and Australia incl. New Zealand).

6. Research Output: Journal Articles and Patents

The scientific literature dealing with nanotubes has been published in about 500 different WoS source journals. Almost half of this literature appeared in only 25 key-journals (according to Bradford's law of scattering). The leading journals each with their number of nanotubes articles are given in Table 4. Among these journals about one fourth are journals around nanotechnology or material science. For scientists, such information could be valuable with respect to the selection of the appropriate journals for publishing their own results.

Rank	SCI Source Journal	# Articles	% Articles
1	Physical Review B	2428	4.3
2	Applied Physics Letters	2242	3.9
3	Nanotechnology	1671	2.9
4	Carbon	1652	2.9
5	Chemical Physics Letters	1295	2.3
6	Nano Letters	1286	2.3
7	Journal of Physical Chemistry B	1164	2.0
8	Journal of Physical Chemistry C	1106	1.9
9	Journal of the American Chemical Society	919	1.6
10	AIP Conference Proceedings	915	1.6
11	Physical Review Letters	880	1.5
12	Journal of Nanoscience and Nanotechnology	865	1.5
13	Advanced Materials	825	1.4
14	Abstracts of Papers of the American Chemical Society	801	1.4
15	Journal of Applied Physics	779	1.4
15	Proceedings of the Society of Photo-Optical Instrumentation Engineers (SPIE)	717	1.3
17	Chemistry of Materials	618	1.1
18	Diamond and Related Materials	610	1.1
19	Langmuir	536	0.9

Table 4. Top WoS source journals with more than 500 nanotubes articles based on the SCI and the CPCI-S under WoS.

A search in the CAS literature file CAplus (based on the corresponding WoS search query) revealed 53772 publications and 13184 patents. The lower number of publications in CAplus compared to the multidisciplinary WoS (57128) results from the narrower field coverage of CAS mainly focusing on chemistry. The publications searched in CAplus have been taken for establishing a nanotubes research landscape (see Figure 4 further below) - this is not possible with the WoS records. At first we had a closer look at the patents and show in Figure 3 the time evolution of the articles and patents as covered by CAS. The patents have been further analyzed with respect to technical applications in broad areas of activity. The country specific number of patents are presented in Table 5 as a heat map.

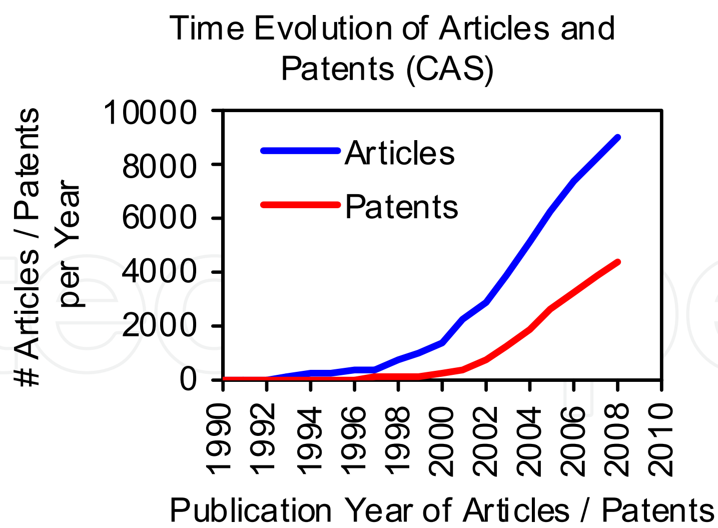

Fig. 3. Time dependent number of articles and patents dealing with nanotubes and covered by the CAS literature file. Source: CAplus under STN International.

	Health Care	Sensors	Electronics & Logic	Mass Data Storage	Displays & Field Emiss.	Energy Storage	Materials & Reactions	Total Sum
Japan	66	368	722	52	919	704	1206	4037
USA	251	552	825	90	627	388	865	3598
S. Korea	19	196	342	44	588	276	385	1850
P. R. China	26	216	235	24	410	202	564	1677
Taiwan	3	66	82	7	182	72	125	537
Germany	17	72	112	20	62	37	107	427
France	12	23	46	4	44	46	67	242
United Kingdom	6	15	28	2	21	11	30	113
Canada	2	12	9	0	13	12	22	70
Switzerland	2	6	14	0	11	13	14	60
Netherlands	1	8	15	3	12	3	10	52
Singapore	2	8	6	0	11	8	16	51
Russia	3	6	8	0	9	5	16	47
Austria	1	7	5	0	10	3	17	43
Italy	0	5	12	4	4	2	11	38
Australia	7	8	5	1	5	4	8	38
Israel	1	5	8	0	10	5	6	35
Sweden	1	3	12	0	6	3	9	34
Belgium	0	7	6	0	7	1	10	31
Brazil	2	2	4	1	4	8	4	25

Table 5. Number of patents with respect to nanotubes published by the top 20 countries (country of author) in the order of ranking with respect to the research areas.

The ranking of nations can be depicted from the last column in Table 5 which shows the total number of patents for each country. The data show a clear dominance of East Asian countries with Japan (1), S. Korea (3), P. R. China (4), and Taiwan (5). USA is second in the ranking while most European countries show a lower rank: Germany (6), France (7), and United Kingdom (8). The same tendency can be seen with respect to the research areas analyzed. In Health Care, Sensors, and Electronics & Logic, however, the ranking between Japan and the United States is flipped. The highest number of patents has been published in the area of Materials & Reactions.

7. Content Analysis: Research Landscape

STN International has recently launched a new interactive analysis tool called STN AnaVist (STN AnaVist, 2009) which focuses mainly on patent analysis (Fischer & Lalyre, 2006). This tool can also be applied to journal articles exploring basic research topics. STN AnaVist has been used to refine the nanotubes literature analysis. The selection of the articles to be analyzed has to be done in the CAS literature file. Currently, the STN AnaVist system limits do not allow to process more than 20,000 articles. Therefore, the literature analysis had to be restricted to the time period 2008-2009.

One of the functions offered by STN AnaVist implies the creation of so-called research landscapes: "Significant keywords and concepts are derived from document titles and abstracts. These keywords are used to determine the similarity between documents. An algorithm uses document similarity scores to position each document relative to one another in a two-dimensional space, with each document positioned at one point. This process is repeated until all documents have been clustered and each assigned to a single x, y coordinate pair. A graphical map is generated. The z coordinates, determining the height of each 'peak', are calculated based on the density of the documents in an area." (STN International, 2009). The research landscape of the past-2007 articles dealing with nanotubes is shown in Figure 4.

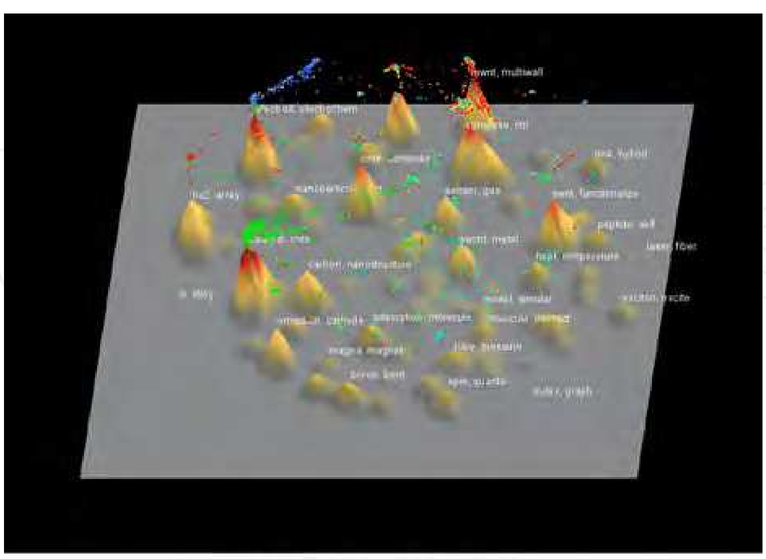

Fig. 4. Research landscape of the nanotubes literature published in the time period 2008-2009 established using STN AnaVist (cnts = carbon nanotubes, swnt = single-walled nanotubes, mwnt = multi-walled nanotubes).

The nanotubes landscape in Figure 4 shows two different layers one upon the other: (1) the mountains with the related keyword pairs based on the text analysis as mentioned and (2) the colored patches above based on the CAS classification categories (technical indicators). The keyword analysis reveals major studies on composites, catalysis, and electrochemistry. The mountains are characterized by the two top clustering words, e. g. “catalyst, cnts” at the left of the landscape or “compose, cnt” top right. The colored dots correspond to documents with different technical indicators (green: vapor deposition process, red: nanocomposites, blue: biosensors, cyan: electric conductivity, and yellow: overlaps). Please note: STN AnaVist is an interactive tool that allows to focus and to zoom according to the specific needs. The research landscape, for example, can be twisted for better analysis.

8. Most Highly-Cited Papers

The number of citations is often taken as a measure of the attention an article, a researcher, an institute or even a country has attracted. Although citation numbers are no ultimate scale of the final importance and quality of articles, they reflect strengths and shortcomings of

Author(s)	Title	Journal	# Citations
Iijima S	Helical microtubules of graphitic carbon	Nature 354, 56-58 (1991)*	8545
Thess A, Lee R, Nikolaev P, et al.	Crystalline ropes of metallic carbon nanotubes	Science 273, 483-487 (1996)	2872
Pan ZW, Dai ZR, Wang ZL	Nanobelts of semiconducting oxides	Science 291, 1947-1949 (2001)	2680
Xia YN, Yang PD, Sun YG, et al.	One-dimensional nanostructures: synthesis, characterization, and applications	Advanced Materials 15, 353-389 (2003)	2621
Tans SJ, Verschueren ARM, Dekker C	Room-temperature transistor based on a single carbon nanotube	Nature 393, 49-52 (1998)	2539
Baughman RH, Zakhidov AA, de Heer WA	Carbon nanotubes - the route toward applications	Science 297, 787-792 (2002)	2299
Morales AM, Lieber CM	A laser ablation method for the synthesis of crystalline semiconductor nanowires	Science 279, 208-211 (1998)	2137
Kong J, Franklin NR, Zhou CW, et al.	Nanotube molecular wires as chemical sensors	Science 287, 622-625 (2000)	2103
Iijima S, Ichihashi T	Single-shell carbon nanotubes of 1-nm diameter	Nature 363, 603-605 (1993)	1975
Kitagawa S, Kitaura R, Noro S	Functional porous coordination polymers	Angewandte Chemie (Int. Edit.) 43, 2334-2375 (2004)	1907

Table 6. The top ten most highly-cited nanotubes papers based on the SCI and the CPCI-S under WoS (date of search: 01.07.09).

research activities and are therefore frequently used for research evaluation. Being cited means that a given article appears as a reference in the article of another author for additional reading. The number of citations of a specific paper is thus a rough measure of the importance or usefulness of the paper within the scientific community. The top ten most highly-cited nanotubes articles until present are given in Table 6. Note that such lists actually imply no real ranking because the various papers accumulated their citations over different time periods.

Please note: The Iijima paper on rank 1 illustrates the problems when selecting literature by using search terms: Primarily, this paper has not been included in the answer set, because the term "nanotube" does not appear within the title or the abstract of this early paper.

The graph displaying the time evolution of the citations of a single article is called its citation history. Each article develops its own life span as it is being cited. With time, the citations per year (citation rate) normally evolve following a similar pattern: The citations generally do not increase substantially until one year after the publication. They reach a summit after about three years, the peak position depending somewhat on the research discipline. Subsequently, as the articles are displaced by newer ones, their impact decreases, accumulating citations at a lower level. Finally, most of the articles are barely cited or forgotten.

Normally, articles receive only a few citations in the first years after the publication. Those which are decisive for research usually garner hundreds or even thousands of citations and keep being cited for a longer time, often for decades. The five most highly-cited nanotubes articles given in Table 6 are no exceptions. Figure 5 shows the citation history of these high-impact nanotubes papers.

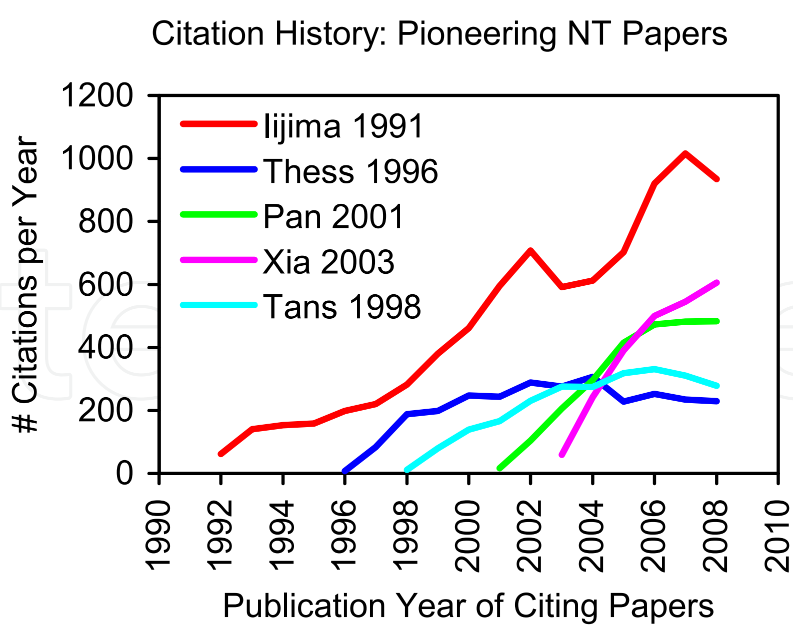

Fig. 5. Time dependent number of citations (citation history) of the five most highly-cited nanotubes papers (see Table 6).

Recently, an article published in Carbon, one of the leading nanotubes journals (see Table 4) discussed the nanotubes history and raised the question, to whom the credit for the discovery should be given (Monthioux & Kuznetsov, 2006). The first evidence for nano-sized carbon tubes is believed to have been published 1952 in the Russian Journal of Physical Chemistry by Radushkevich and Lukyanovich (Radushkevich & Lukyanovich, 1952). The article contains clear images of carbon tubes with about 50 nanometers in diameter based on Transition Electron Microscopy (TEM). However, due to the Russian language and the limited access of Western scientists to Russian publications during the time of the Cold War the discovery was largely unnoticed. Another important article prior to 1991 was published 1976 by Oberlin et al. (Oberlin et al., 1976).

The citation history of these two articles is shown in Figure 6. The Radushkevich paper received altogether 73 citations (many from Russian scientists) and was barely cited until present (19 citations in 2008). The Oberlin article received altogether 600 citations (72 citations prior to 1991) showing a remarkable impact increase (75 citations in 2008). These two articles seem to belong to the few papers in science being nearly ignored for decades and then are "rediscovered" (so-called sleeping beauties).

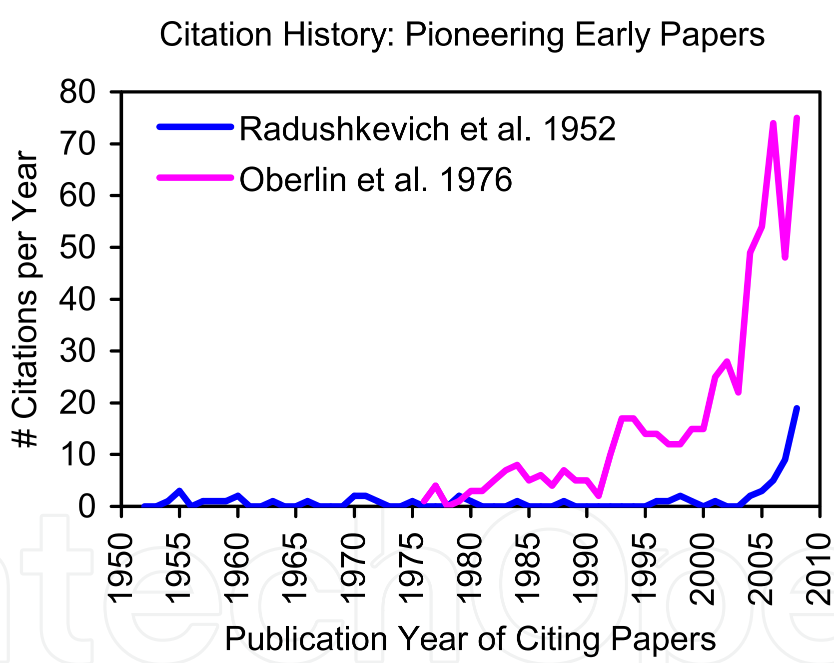

Fig. 6. Time dependent number of citations (citation history) of the Radushkevich & Lukyanovich and the Oberlin paper.

The "weight" of research fields can be indicated by their Hirsch index (h-index, h-number). The h-index is defined as the number of articles in WoS source journals that have had h citations or more. For example, a researcher with an h-index of 40 will have published 40 articles that have received at least 40 citations each. The h-index can be seen as a rough indicator for measuring the output and impact of a researcher in a single number (Hirsch, 2005). This index reflects a researcher´s contribution based on a broad body of publications rather than on a few high-impact papers. The h-index may well be extended to journals (Bornmann et al., 2009) as well as to research fields (Banks, 2006). The h-index for the overall literature related to nanotubes, fullerenes, graphene, and further research fields is given in Table 7. The data can be taken as a rough measure of the relative "weight" of these fields in terms of both publications and citations.

Rank	Research Field	# Articles	h-index
1	Nanotubes	57128	305
2	Fullerenes	24552	204
3	Graphene	4639	112
4	Quantum Dots	38457	245
5	Nanowires	27939	201
6	Amorphous Silicon	18060	145
7	Porous Silicon	8824	134

Table 7. Number of articles related to nanotubes, fullerenes, graphene, and further research fields and their corresponding h-index (date of search: 01-07-2009).

9. Citation Graphs

Using the HistCite® software of Eugene Garfield, we established the citation graph shown in Figure 7, which is based on the most highly-cited nanotubes articles accessible in WoS at the date of search (22.09.09). This graph visualizes the citation network within the high impact nanotubes literature published so far: The nodes represent the papers with at least 1000 citations (31 papers). Lower citation limits increase the number of nodes considerably without changing the node pattern substantially (see Figure 8 further below). The specific papers represented by the circles of the citation graph of Figure 7 are given in Table 8 in short form only. Like STN AnaVist®, also HistCite® is used in an interactive mode and can deliver much more information than given in the limited citation graphs shown here.

The citation graph of Figure 7 shows the Iijima 1991-paper (see Table 6) as the starting point of the nanotubes research field activities at the top. The graph reveals a pronounced cluster of high-impact publications based on nanotubes within the time period 1995-2003. The more recently published articles are increasingly rare because of the time delay of citations. These publications had so far not sufficient time for accumulating enough citations to reach the high limit of 1000 citations specified in Figure 7.

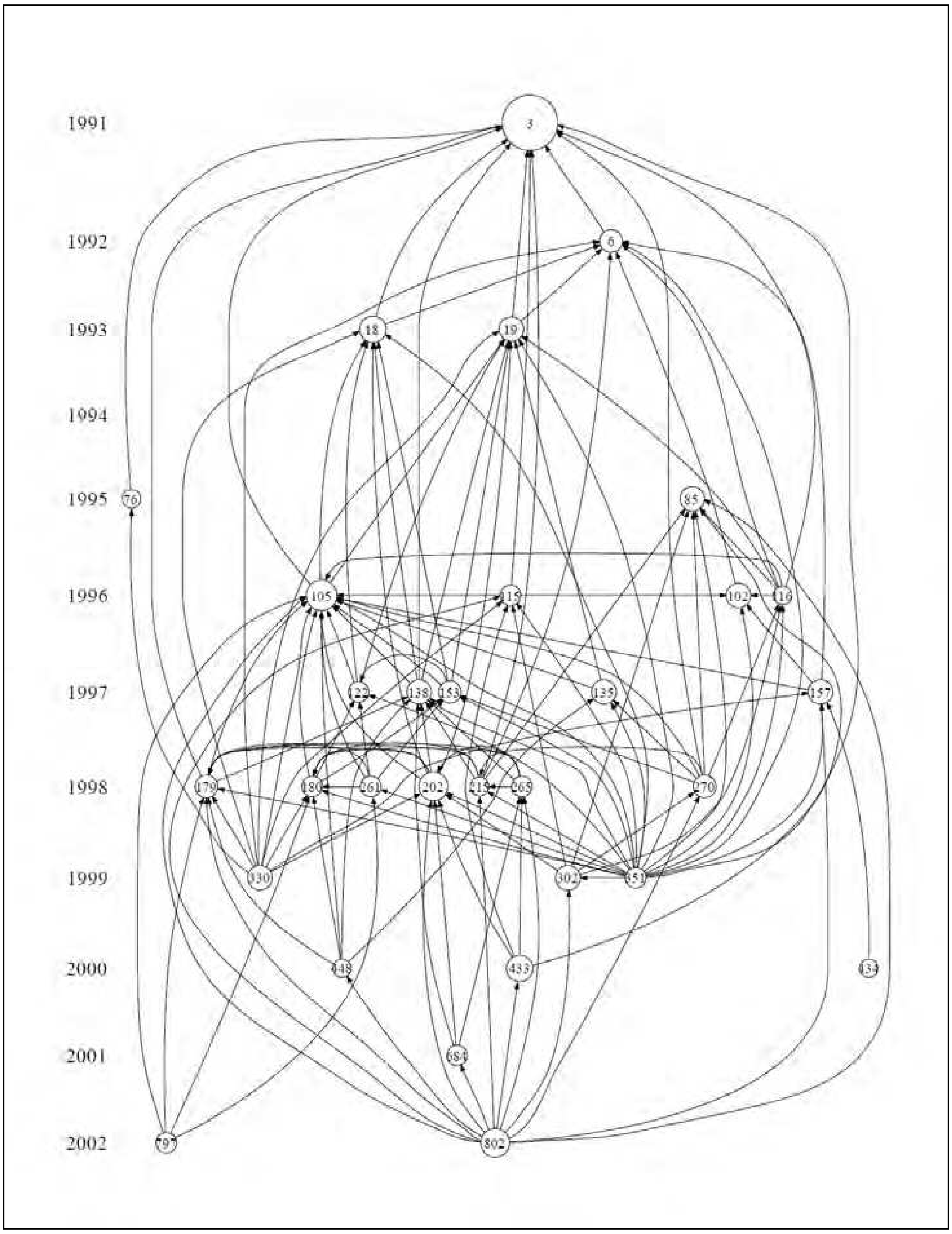

Fig. 7. Citation graph based on the most highly-cited nanotubes articles searched in the WoS. The nodes represent the currently 31 nanotubes papers with at least 1000 citations until the date of search. The circle diameter is proportional to the overall number of citations and the arrows indicate the citation direction. The numbers within the circles originate from the consecutive numbering of the nanotubes papers by the software (see Table 8) and do not represent their citation counts. Source: HistCite® and SCI under WoS.

#	No.	Papers	LCS	GCS
1	3	IIJIMA S, 1991, NATURE, V354, P56	377	8787
2	6	EBBESEN TW, 1992, NATURE, V358, P220	150	1628
3	18	IIJIMA S, 1993, NATURE, V363, P603	161	2005
4	19	BETHUNE DS, 1993, NATURE, V363, P605	125	1686
5	76	CHOPRA NG, 1995, SCIENCE, V269, P966	48	1133
6	85	DEHEER WA, 1995, SCIENCE, V270, P1179	105	1831
7	102	Treacy MMJ, 1996, NATURE, V381, P678	125	1779
8	105	Thess A, 1996, SCIENCE, V273, P483	264	2917
9	115	Dai HJ, 1996, NATURE, V384, P147	68	1245
10	116	Li WZ, 1996, SCIENCE, V274, P1701	75	1066
11	122	Rao AM, 1997, SCIENCE, V275, P187	96	1259
12	135	Dillon AC, 1997, NATURE, V386, P377	75	1854
13	138	Tans SJ, 1997, NATURE, V386, P474	131	1708
14	153	Journet C, 1997, NATURE, V388, P756	111	1519
15	157	Wong EW, 1997, SCIENCE, V277, P1971	102	1756
16	179	Wildoer JWG, 1998, NATURE, V391, P59	141	1497
17	180	Odom TW, 1998, NATURE, V391, P62	121	1194
18	202	Tans SJ, 1998, NATURE, V393, P49	143	2606
19	215	Frank S, 1998, SCIENCE, V280, P1744	57	1143
20	261	Chen J, 1998, SCIENCE, V282, P95	120	1280
21	265	Martel R, 1998, APPL PHYS LETT, V73, P2447	68	1322
22	270	Ren ZF, 1998, SCIENCE, V282, P1105	78	1496
23	302	Fan SS, 1999, SCIENCE, V283, P512	75	1708
24	330	Hu JT, 1999, ACCOUNT CHEM RES, V32, P435	11	1682
25	351	Ajayan PM, 1999, CHEM REV, V99, P1787	45	1153
26	433	Kong J, 2000, SCIENCE, V287, P622	89	2181
27	434	Yu MF, 2000, SCIENCE, V287, P637	35	1036
28	448	Collins PG, 2000, SCIENCE, V287, P1801	63	1060
29	684	Bachtold A, 2001, SCIENCE, V294, P1317	36	1232
30	797	O'Connell MJ, 2002, SCIENCE, V297, P593	60	1243
31	802	Baughman RH, 2002, SCIENCE, V297, P787	48	2432

Table 8. List of the specific papers of the HistCite® based citation graph of Figure 7 represented by the numbered circles. LCS = local citation score: citations collected within the ensemble of the selected nanotubes articles, GCS = global citation score: overall number of citations as given by the WoS under "times cited".

The citation graph of Figure 8 shows more clearly the pattern of the citation network based on the highly-cited papers, in particular within the starting period after 1991. Again, the past-2002 papers are increasingly rare because of the time delay of the citations.

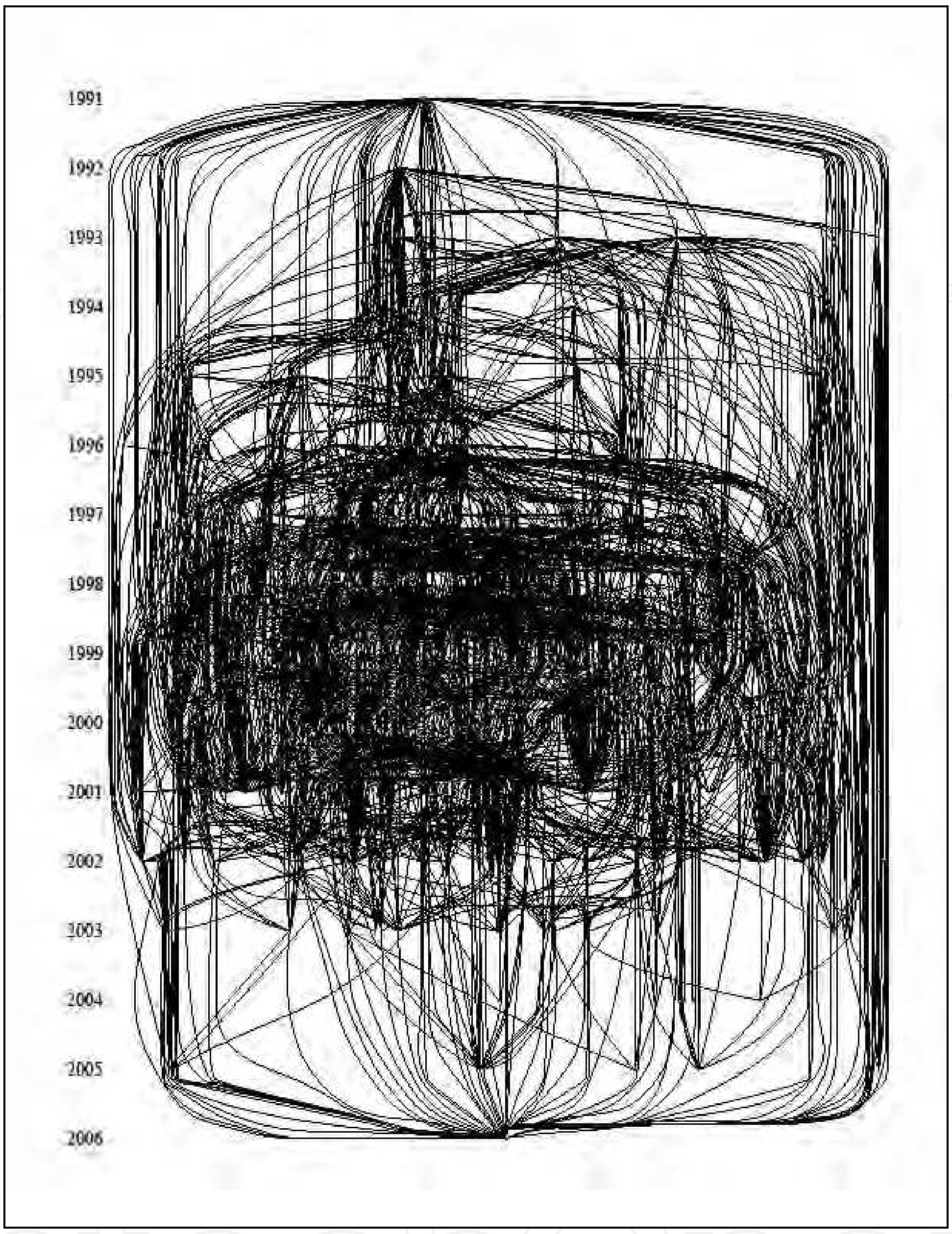

Fig. 8. Citation graph based on the highly-cited nanotubes articles searched in the WoS. The nodes represent the currently 226 nanotubes papers with at least 300 citations until the date of search (rather than only the 31 papers with at least 1000 citations as in Figure 7). Source: HistCite® and SCI under WoS.

Summary

A currently most popular research discipline has been reviewed by scientometric methods. The time dependent overall number of nanotubes articles is given, revealing a still strongly increasing research activity in this field. The nanotubes articles were analyzed with respect to the most productive authors, research organizations, countries of authors, and leading journals. Among the authors is a clear dominance of researchers from the East Asian countries and the US. Among the top positions are many Chinese research organizations and universities. The time evolution of the nanotubes patents shows a similar increase as the evolution of the articles. The number of patents of the various organizations related to broad areas of research and technology were determined and visualized as a heat map. The research landscape of the nanotubes research field was established using the new analysis tool STN AnaVist. The STN AnaVist based landscape shows a pronounced clustering with respect to specific keywords and technical indicators. The time evolution of the most highly-cited nanotubes papers shows an unusually long-lasting impact. Two early papers may be characterized as "sleeping beauties". Finally, a citation graph has been established revealing the historiography of the nanotubes research with regard to the high impact papers.

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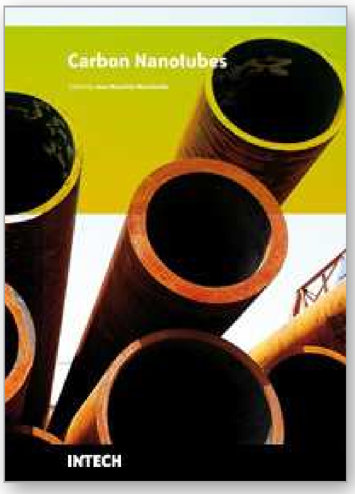

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This book has been outlined as follows: A review on the literature and increasing research interests in the field of carbon nanotubes. Fabrication techniques followed by an analysis on the physical properties of carbon nanotubes. The device physics of implemented carbon nanotubes applications along with proposed models in an effort to describe their behavior in circuits and interconnects. And ultimately, the book pursues a significant amount of work in applications of carbon nanotubes in sensors, nanoparticles and nanostructures, and biotechnology. Readers of this book should have a strong background on physical electronics and semiconductor device physics. Philanthropists and readers with strong background in quantum transport physics and semiconductors materials could definitely benefit from the results presented in the chapters of this book. Especially, those with research interests in the areas of nanoparticles and nanotechnology.

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