NANOTECHNOLOGY-ENHANCED THIN-FILM SOLAR CELLS: ANALYSIS OF GLOBAL RESEARCH ACTIVITIES WITH FUTURE PROSPECTS

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Abstract: Nanotechnology-enhanced, thin-film solar cells are a promising and potentially important emerging technology. This paper examines global research patterns to assess development prospects. We apply the "tech mining" approach to R&D publications in this field. Records are compiled from Web of Science for the time period 2001-08. These indicate that the United States (US) is the leading author on nanotechnology-enhanced, thin-film solar cells. In addition, quality-related measures place the US in an even stronger position. Germany and Japan show slowed research growth rates in terms of both quantity and quality. China and India show dramatic rise on both counts, but they can not yet match the US. We also find that collaboration patterns within the US and Germany are quite different. In the US, we see little cooperation between institutes and no absolute leading institute; however, Germany shows the opposite attributes. Finally, this paper illuminates that nano-structured ZnO is particularly promising in thin-film solar cells, showing a sharp rise in publications since 2005, led by China.

Keywords: nanotechnology publications, thin-film, solar cells, bibliometric analysis, tech mining, technology forecasting

1. Introduction

Renewable energy is increasingly viewed as critically important globally. Solar cells, or photovoltaics, convert the energy of the sun into electricity. In theory all parts of the visible

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spectrum from near-infrared to ultraviolet can be harnessed. The mainstay at present is the silicon solar cell which accounted for 90% of the market in 2004. However these are costly to manufacture and have limited efficiency (around 14% in most production modules, and up to 25% in the lab). The cost per unit of power is at least several fold higher using silicon solar cells than that derived from fossil fuel combustion (The Institute of Nanotechnology, 2006).

Thin film is a more cost-effective solution and uses a cheap support onto which the active component is applied as a thin coating. As a result much less material is required (as low as 1% compared with wafers) and costs are decreased. Most such cells utilize amorphous silicon, which, as its name suggests, does not have a crystalline structure and consequently has a much lower efficiency (8%), however it is much cheaper to manufacture (Chopra1 K et al. 2004; Konenkamp R et al. 2002).

Nanotechnology (“**nano**”) incorporation into the films shows special promise to both enhance efficiency and lower total cost (Escolano C et al. 2005). Many nano-structured materials are now being investigated for their potential applications in photovoltaics. Nano-structured layers in thin film solar cells offer three important advantages. First, due to multiple reflections, the effective optical path for absorption is much larger than the actual film thickness. Second, light generated electrons and holes need to travel over a much shorter path and thus recombination losses are greatly reduced. As a result, the absorber layer thickness in nano-structured solar cells can be as thin as 150 nm instead of several micrometers in the traditional thin film solar cells. Third, the energy band gap of various layers can be tailored to the desired design value by varying the size of nano-particles. This allows for more design flexibility in the absorber and window layers in the solar cells (Singha R et al. 2004).

Forecasting the extent of nanotechnology incorporation into photovoltaics would be valuable intelligence to facilitate technology management (Porter, et al., 1991). One solution to forecast technology is to find the recent position of leading countries/institutes. Such information can help optimize photovoltaic R&D investments and speed operational applications. There has been much interest in the positioning of countries relative to one another in scientific performance, particularly in emergent fields such as nanotechnology. Much of this analysis emphasizes publication counts and impacts as measures of research strength (Glanzel, et al., 2003; Kostoff, et al., 2007; Miyazaki, et al., 2007; Youtie, et al., 2008). Given the dynamic development and expansion of nanotechnology-enhanced thin-film solar cells research, it is useful to assess international scientific performance. Drawing on a newly constructed and comprehensive dataset of global nanotechnology thin-film solar cells publications, this article examines both quality and quantity patterns by leading large countries in this research area.

2. Data

Data are firstly derived using a multi-stage Boolean search strategy for identifying research publications in the nanotechnology domain and the data-cleaning methods described in Porter et al. (2007)[iv]. This provides a global dataset of nanotechnology publication records (for the period 2001 through mid-2008) downloaded from the Science Citation Index ("**SCI**") of the Web of Science. Then we defined "thin film and (solar or photovoltaic)" as our search expression to create a sub-dataset. Finally, we acquired the dataset containing 1659 records for time period from 2001 to mid-2008 in the field of nanotechnology-enhanced thin-film solar cells for this paper.

3. Results and Approach

Participating research fields

To gain a sense of which research fields are engaged in this work, Figure 1 overlays the concentrations of the 1659 articles on a base map of science. This mapping process categorizes articles indexed in Web of Science according to the journals in which they appear (Rafols and Meyer, forthcoming; Leydesdorff and Rafols, forthcoming). Those journals are associated with Web of Science "Subject Categories." In Figure 1, these constitute 175 nodes reflected by the background intersecting arcs among them. The Subject Categories are then grouped into "macro-disciplines" using a form of factor analysis (Principal Components Analysis) based on degree of association. Those macro-disciplines become the labels in the figure. The nano thin-film solar cell research concentrations appear as nodes on this map.

What we see is that nano thin-film solar cell research is concentrated in the Materials Science and Chemistry macro-disciplines. It engages many specific Subject Categories (research fields). So, this is highly multidisciplinary research. This paper is particularly interested in cross-national differences in research and development on this technology. With that in mind, we have compared the relative emphases of the leading countries (discussed shortly). We generate such science overlay maps for each country (not reproduced here). What stands out among those is that all of them show very similar involvement of the key component research fields:

(ⅰ) Materials Science, Multidisciplinary
(ⅱ) Physics, Condensed Matter
(ⅲ) Physics, Applied

[iv] To operationalize the definition of nanotechnology, it is a two-stage modularized Boolean approach. The first stage of the search process involved application of eight search strings. These are detailed in Porter et al. (2007, Table 2a). The second stage involved exclusion of articles that fell outside the nanotechnology domain and those only referencing measurement (e.g., nanometer) without another substantive combination of nano-related terms.

(ⅳ) Chemistry, Physical

(ⅴ) Materials Science, Coatings & Films

But one of the countries, India, shows by far the most research in “energy & fuels.” Such concentration differences could be important in distinguishing national (or institutional) emphases. They can also help technology managers identify appealing collaboration opportunities to take advantage of complementary strengths.

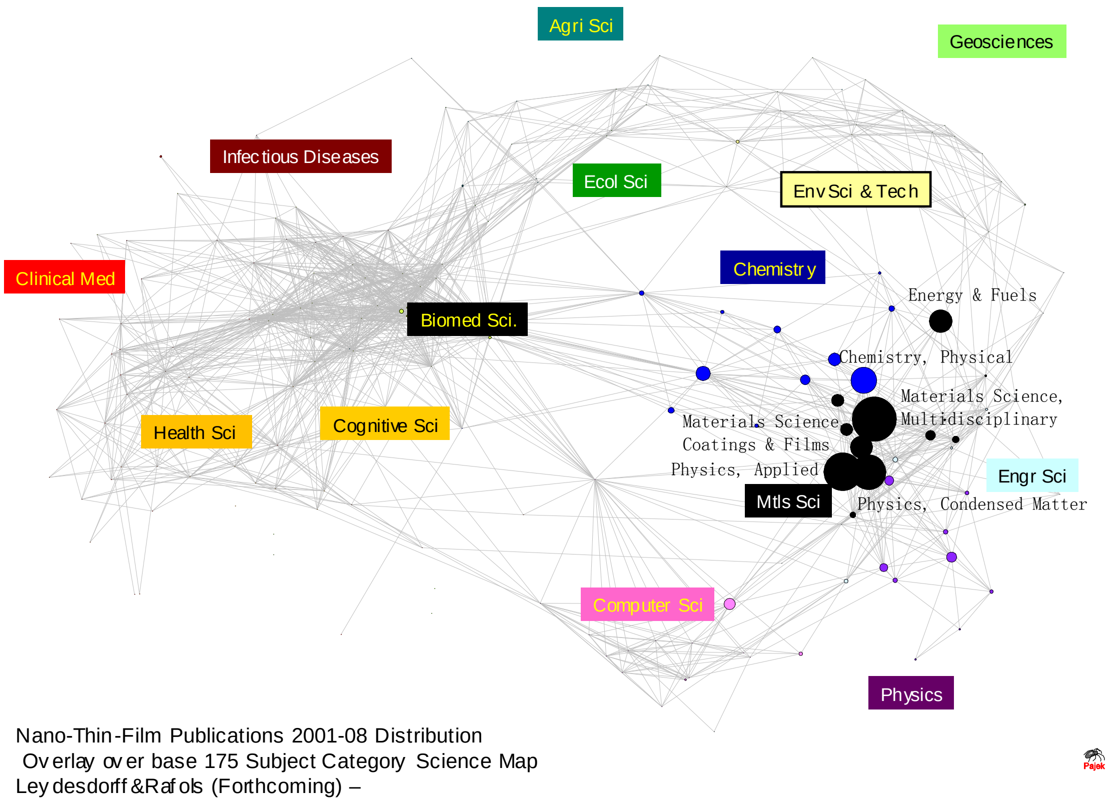

Fig.1: Nanotechnology Thin-film Solar Cells Publications by Research Field

National differences in research character

Figure 2 shows the number of publications by country based on the location of any author/co-author’s affiliation. We sought to use this comprehensive perspective to capture the widest range of publication activity by author country. Figure 2 shows that, in terms of individual countries, the US is at the top followed by India, Germany, China and Japan. We can see that the top 10 countries are quite widely distributed globally, but Asian countries take three places in the top 5, especially, India is in a really notable position.

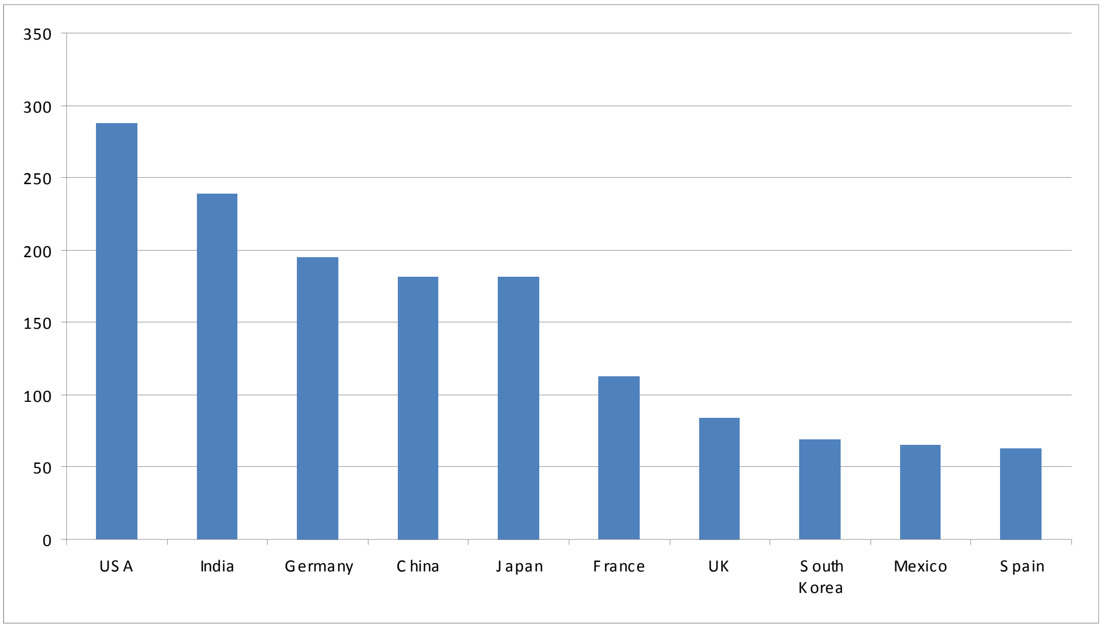

Fig.2: Nanotechnology Thin-film Solar Cells Publications by Countries [Science Citation Index, 2001-08 (part-year)]

In order to provide a further sense of leading country positioning, we show the percentage publication shares of the top 5 countries for 4 years—2001, 2003, 2005, and 2007—in Fig. 3. In 2001, Japan accounted for the highest share of countries in nanotechnology thin film solar cells publications at 17.7%. By 2003, the US comprised 22% of publications compared to 15.6% for the Germany. At this year, Japan is in fourth position following India. By 2005, there is not such difference between the top 5 countries and China accounts for nearly 14%, which is much higher than before and in third position, just behind the US and India. By 2007, China is the only country in these top 5 that is still rising in the percentage of publications; at the same time, Germany and Japan demonstrate an obvious downswing in representation, accounting for less than 10% respectively. As a whole, China's rise in nanotechnology thin-film solar cells research stands out boldly, in contrast to Germany and Japan.

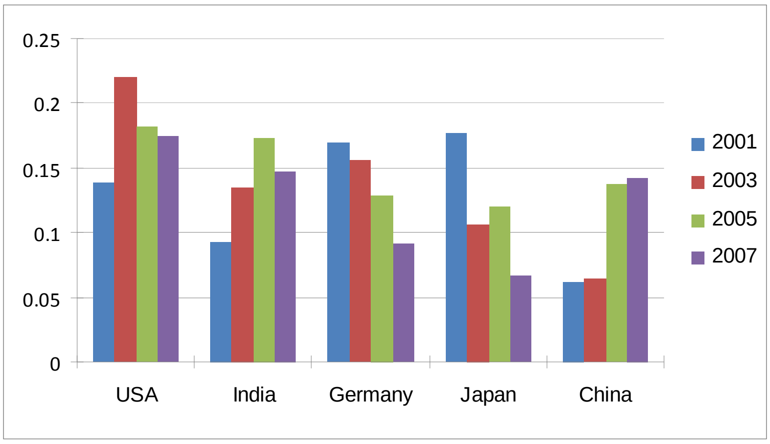

Fig.3: Percentage of Nanotechnology Thin-film Solar cells Publications by Country for Selected Years.

Figure 4 shows the activity and diversity of the top 10 countries in the nanotechnology thin-film solar cells research for the time period from 2001 to 2008 (half-year). Number of publications is used to measure the research activity of each country and number of Subject Categories (SCs) shows the diversity of this country's research. It should be noted that we only take the SCs with two or more publications of that country. Figure 4 shows that, no matter the particular degree of activity or diversity, the top 5 countries stand out from the countries in sixth to tenth position. As expected, the US is the most active country, however, it has the least diversity of the top 5. China is leading in the diversity of research fields represented, followed by Germany. Japan and India show almost the same level of diversity but India is ahead in activity. The UK, South Korea, Spain and Mexico are different in diversity, but maintain about the same level of activity. We think that such analyses of R&D patterns can help technology managers understand differences in approach.

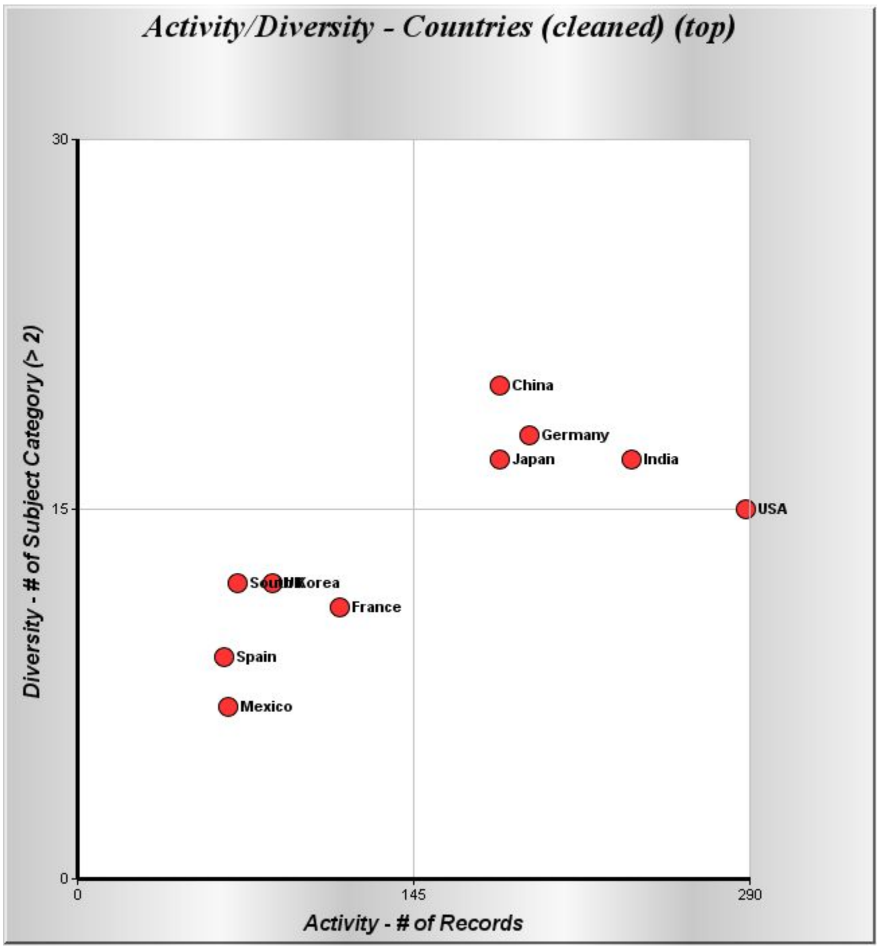

Fig.4: Activity and Diversity of Top 10 Countries in Nanotechnology Thin-film Solar Cells Publications

Research activity and impact characteristics

However, quantity (activity) and diversity are not sufficient to describe country position in the nanotechnology thin-film solar cells research arena. Quality and influence in the field is important to consider in depicting inter-country standing in nanotechnology (Glanzel W et al. 2003). Citations, as measured by the number of times a paper has been cited, are used here to gauge the level of quality of the publications of a country. We, of course, recognize that this is an imperfect measure as citations reflect many purposes. However, citations reflect attention to the work, and the Scientometrics community has found them to be a valid indicator of the impact of the research outputs (publications) (c.f., van Raan, 1988).

Citation counts are related to publication counts, in that the greater the number of publications, the higher the probability of larger citation counts. Thus, we make a scattergram plot to see both publication and citation counts (Fig. 5). The X-axis represents the number of publications, while the Y-axis shows the number of citations. This kind of figure helps assess research quality relative to activity. The particular method used in this part of the analysis focuses on the country location of the affiliation of the first author of the publication. This focus is designed to preclude duplicating citation counts.[v] The first author's country is used to assign citation numbers to that country.

Turning to the results of the citation counts, Figure 5 compares the activity and quality of the top 10 countries. Nodes above the diagonal suggest relatively higher quality, represented by the US and UK. Comparing these two countries, we see that both the number of citations and publications is quite high for the US; the UK, in contrast, has a relatively small number of publications, but notable quality. The quality analysis places the US in an even stronger position, combing with the counts of nanotechnology thin-film solar cells (see Fig.2). The other top 5 countries—India, Germany, China and Japan—are all below the diagonal. In that case, the closer to the diagonal, the higher the quality of that country's research. We see that Japan and Germany are closer to the diagonal than India and China, that is to say, taking the time period from 2001 to 2008 as a whole, both Japan and Germany have much higher number of nanotechnology thin-film solar cells citations relative to their number of publications than do India and China. China and India's citation levels do not approach those of Japan and Germany the way that their publication counts do.

[v] Youtie et al. (2008) have shown how different the publication counts by country based on first author versus all authors are. The country counts of publications based on first author's locations are slightly lower, but within range, of the country counts based on all authors' locations.

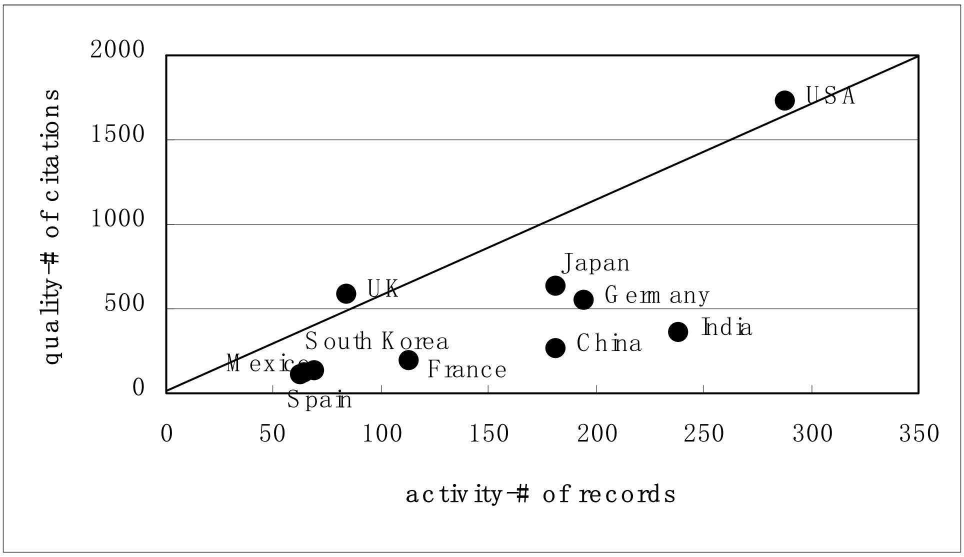

Fig.5: Activity and Quality of Top 10 Countries in Nanotechnology Thin-film Solar Cells Publications (Counted by 1st Author Country)

One problem is, for some countries with dramatically increasing publications in recent years, such a citation analysis may dampen them, because earlier articles have more occasions to receive citations than do recent articles. To probe the quality of each country's R&D further, we show the trend of citations for the top 5 countries in recent years. In this article we employ an aging practice based on dividing the citations in a given year by the number of years of opportunity to be cited. Figure 6 averages 2001 and 2002 to get the initial points. Their average publication date would correspond to the end of 2001 (or the very start of 2002), which provides about 6.5 years to attract citation relative to the endpoint of our dataset (mid-2008). So the number of citations to articles from this initial period is divided by 6.5. Similarly, the year 2006 and 2007 papers have about 1.5 years of opportunity to attract citations; hence the citations counts are divided by 1.5.

Figure 6 shows the change over time in publication and citation intensity, with a line connecting the results for the initial period – "2001" (combining 2001 and 2002 publications) and the recent period -- "2006" (combining 2006 and 2007 publications). The steeper the slope of the line connecting these two points, the greater the increase in quality of the country's research on this topic. Taking the aging effect into consideration, the US has the steepest slope, suggesting that its nanotechnology thin-film solar cell research receives the greatest attention by researchers. Likewise for China and India, although they lag on both quality and quantity in 2001, their trend relative to Germany and Japan also shows a promising rise. Compared to Fig.5, the slope of the lines for China and India shows that their research is increasingly recognized in recent years.

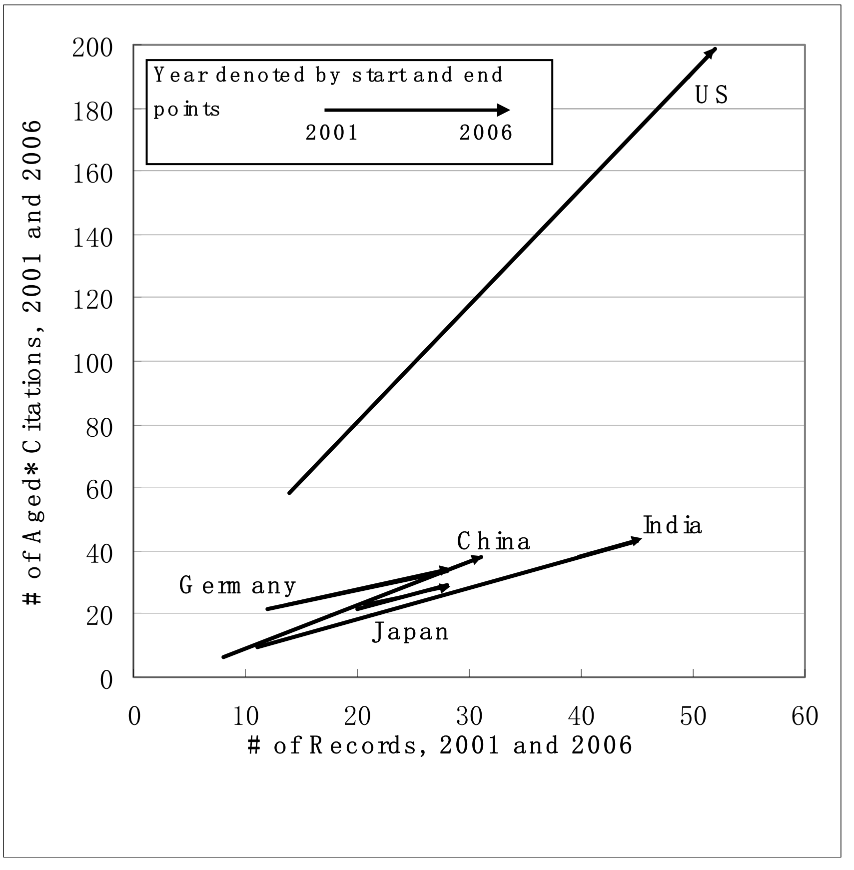

Fig.6: Number of aged nanotechnology thin-film solar cells citations in the end of 2001 and the end of 2006 relative to number of articles by first author.

*Aged citations (AC) for a country is calculated as ACi = Cti / (Yn - Yt) where Cti = total number of citations for articles in target year for country i; Yn = most recent year in dataset (2008, mid-year); and Yt = the end of target year. For 2001, Yn - Yt = 6.5; for 2006, Yn - Yt = 1.5. Country is based on an article;s first author's affiliation address.

Research networking

We next examine the collaboration pattern within a country by mapping the leading affiliations. We choose the US and Germany as our cases to illustrate in the paper. We use VantagePoint software to create the map.[vi] These maps apply cross-correlation techniques to compare analyzed objects (countries or organizations) by measuring and visualizing the connection between them. The computer-generated map (Fig. 7) uses physical distance to symbolize the proximity or divergence of academic focus.

First, we import the 1659 SCI publication records into VantagePoint for analyses. Then we map "Affiliation by Affiliation" for those with 7 or more publications by US authors in the

[vi] See www.vantagepoint.com .

area of nanotechnology thin-film solar cells. Similarly, we create such a map for Germany for affiliations with 6 or more publications. Figure 7 shows both. Strong links between affiliations are indicated by heavier lines. Node size represents the relative number of records published by that affiliation. We find that the core researchers and nature of collaboration in the US and Germany are quite different! In the US, the number of publications for each institute differs only slightly, that is to say, no institute is in an absolutely leading position in nanotechnology thin-film solar cells in US. At the same time, the cooperation among them is relatively limited and weak. For Germany, “Hahn Meitner Inst Berlin GmbH” shows its great advantage by its node size. All the affiliations are considerably interconnected, most of which are linked with “Hahn Meitner Inst Berlin GmbH.” Therefore, “Hahn Meitner Inst Berlin GmbH” stands out as especially important to the area of nano thin-film solar cells research in Germany.

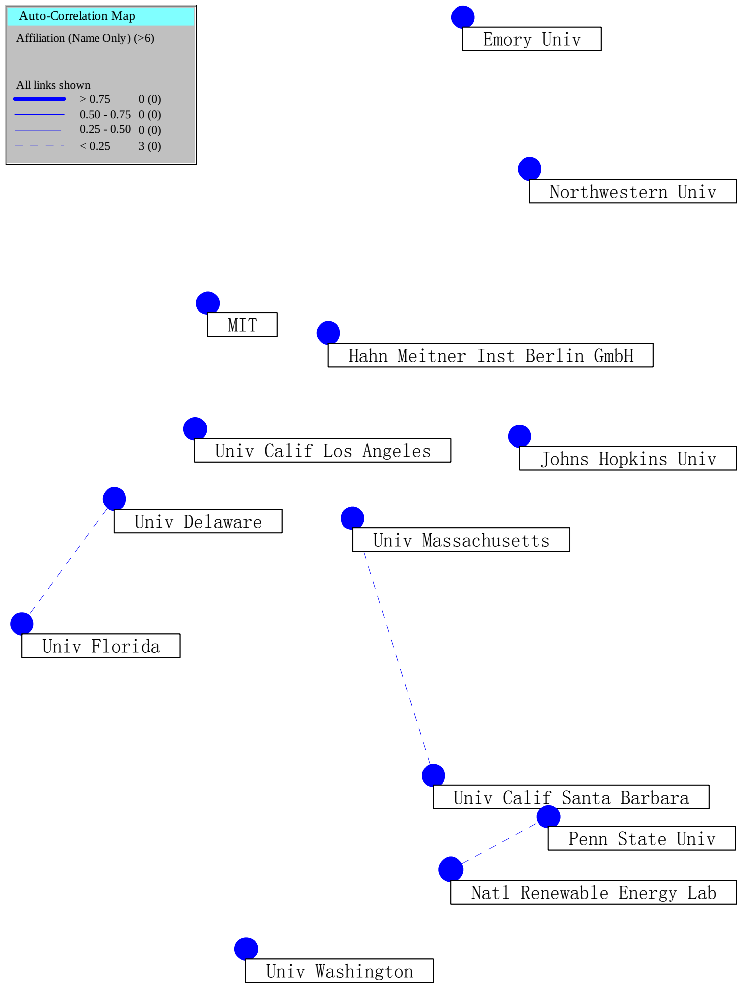

Fig.7a: Cooperation within US by mapping affiliations with 7 or more publications[vii]

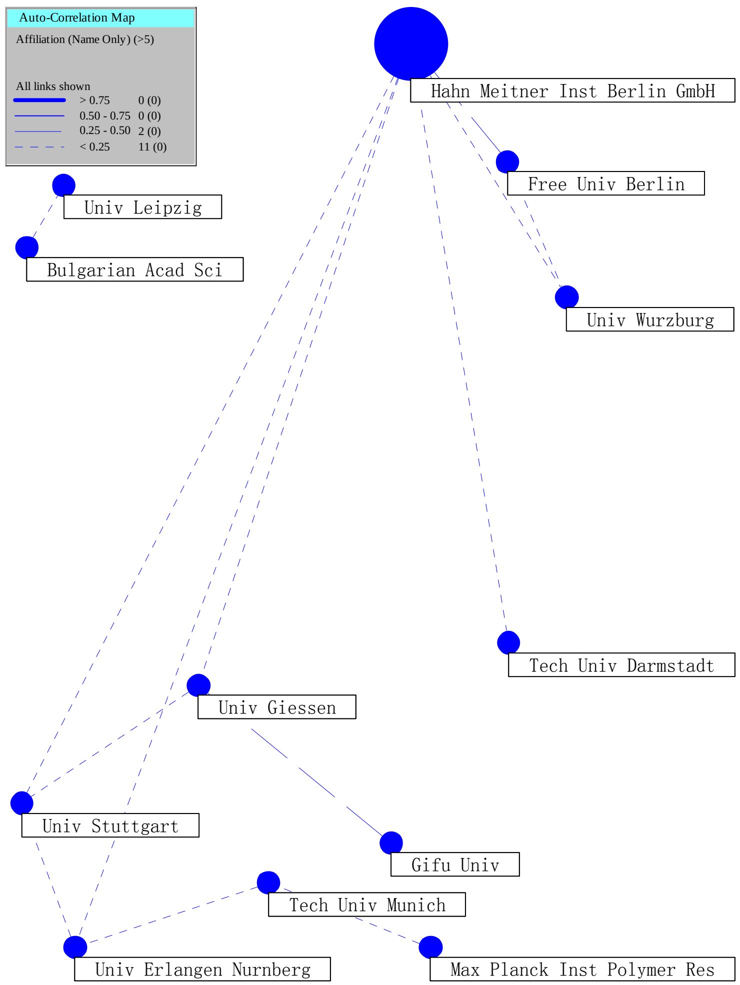

Fig. 7b: Cooperation within Germany by mapping affiliation with 6 or more publications

[vii] This is a Multi-Dimensional Scaling ("MDS") representation. Location along the axes has no inherent meaning. Proximity reflects degree of association. However, to accurately depict the association among N nodes would, in principle, require an N-1 dimensional representation. So this 2-D visualization is a rough approximation. Accordingly, a Path-Erasing Algorithm is applied to show relative strength of association between pairs of nodes. As per the legend, stronger ties are shown by heavier connecting lines.

Exploring a "Hot" research sub-field

Besides macro-analysis of nanotechnology thin-film solar cells, we also find that even though many nano-structured materials are now being investigated for their potential applications in photovoltaic cells, zinc oxide (ZnO) is particularly promising for such applications as a way to enlarge the active part of a solar cell. Therefore, it has been the object of quickly growing attention in the last few years owing to its potential applications (Cembreroa J et al. 2004). This compares with nano-structured TiO2, which is widely used as window and absorber layers in thin film solar cells. ZnO attracts increasing attention in recent years and is on trend to catch up with TiO2 (which shows a steady, but slower growth rate), as shown in Fig.8. The trend for ZnO suggests exponential increase since 2005, before which it is around 10 publications per year.

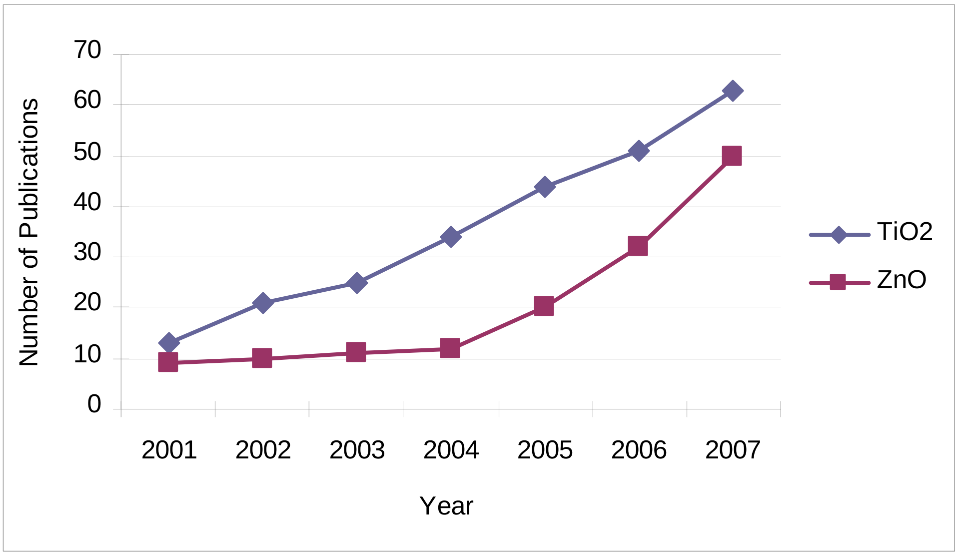

Fig.8: TiO2 and ZnO Publications in nanotechnology thin-film solar cells by Year
[Source: TiO2 and ZnO used as search terms within the dataset above]

To get a further sense about the situation of nano-structured ZnO applied in thin-film solar cells, we compare the top 10 countries in this area by publication years, as shown in Fig.9. To sum up, China is the leading country in this research area. In 2001, China only contributed 1 publication to the international literature, but in 2007, there are 14 publications from Chinese scientists indexed by SCI. Especially in 2005, along with a global increase in nano-structured ZnO thin-film solar cell articles, China shows a sharp jump in activity.

The percentage for Chinese publication of the top 10 countries increased from 10% in 2001 to more than 30% in 2007 (Fig.10). We also find that India is contributing notably to the increase of this research area. It takes a steadily growing share of the top 10 countries' publications in recent years. In other words, both India and China show acceleration in publications in nano-structured ZnO thin-film solar cells compared to the other leading countries.

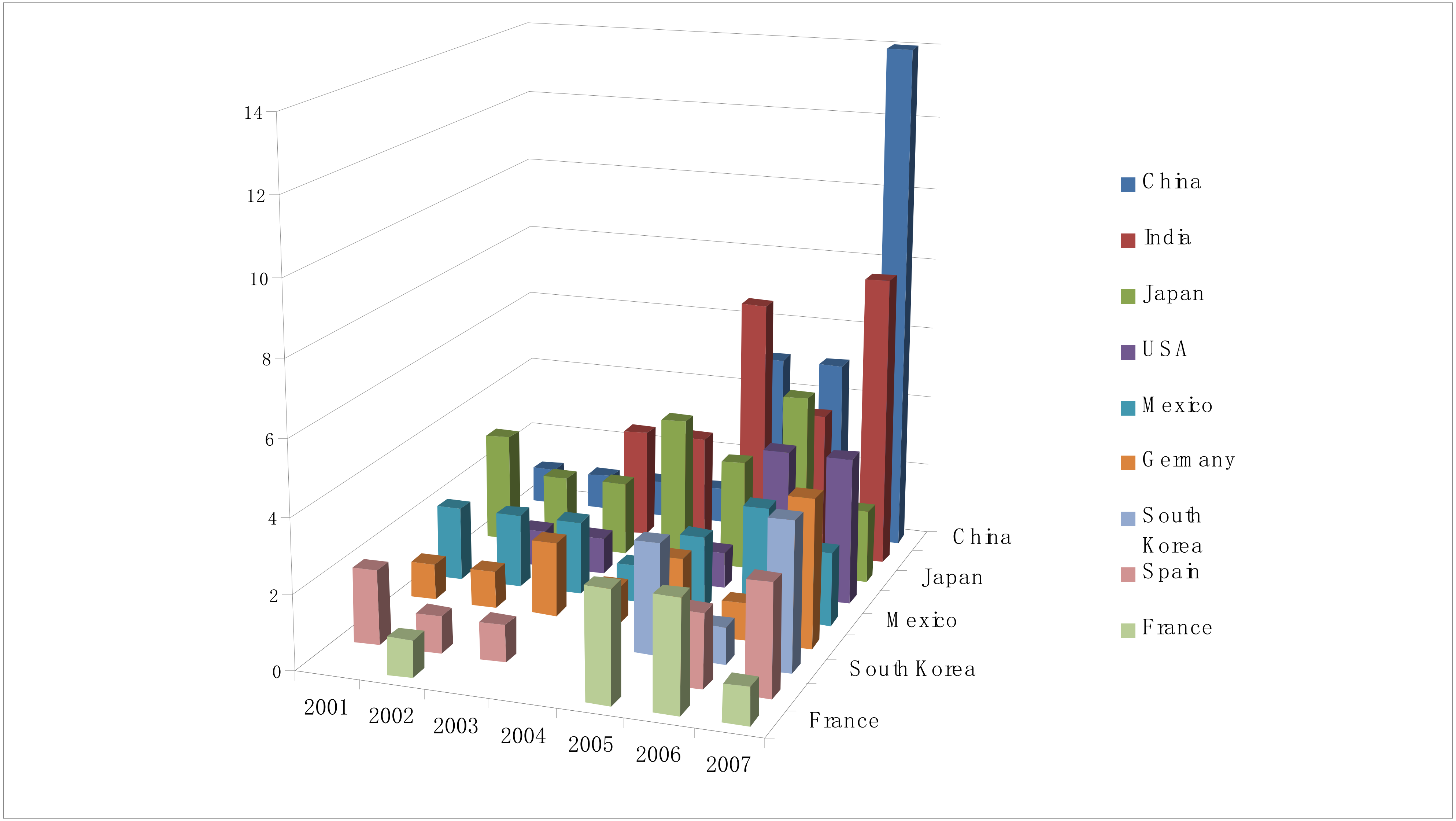

Fig.9: Nano-Structured ZnO Thin-film Solar Cells Publication by Countries and Years

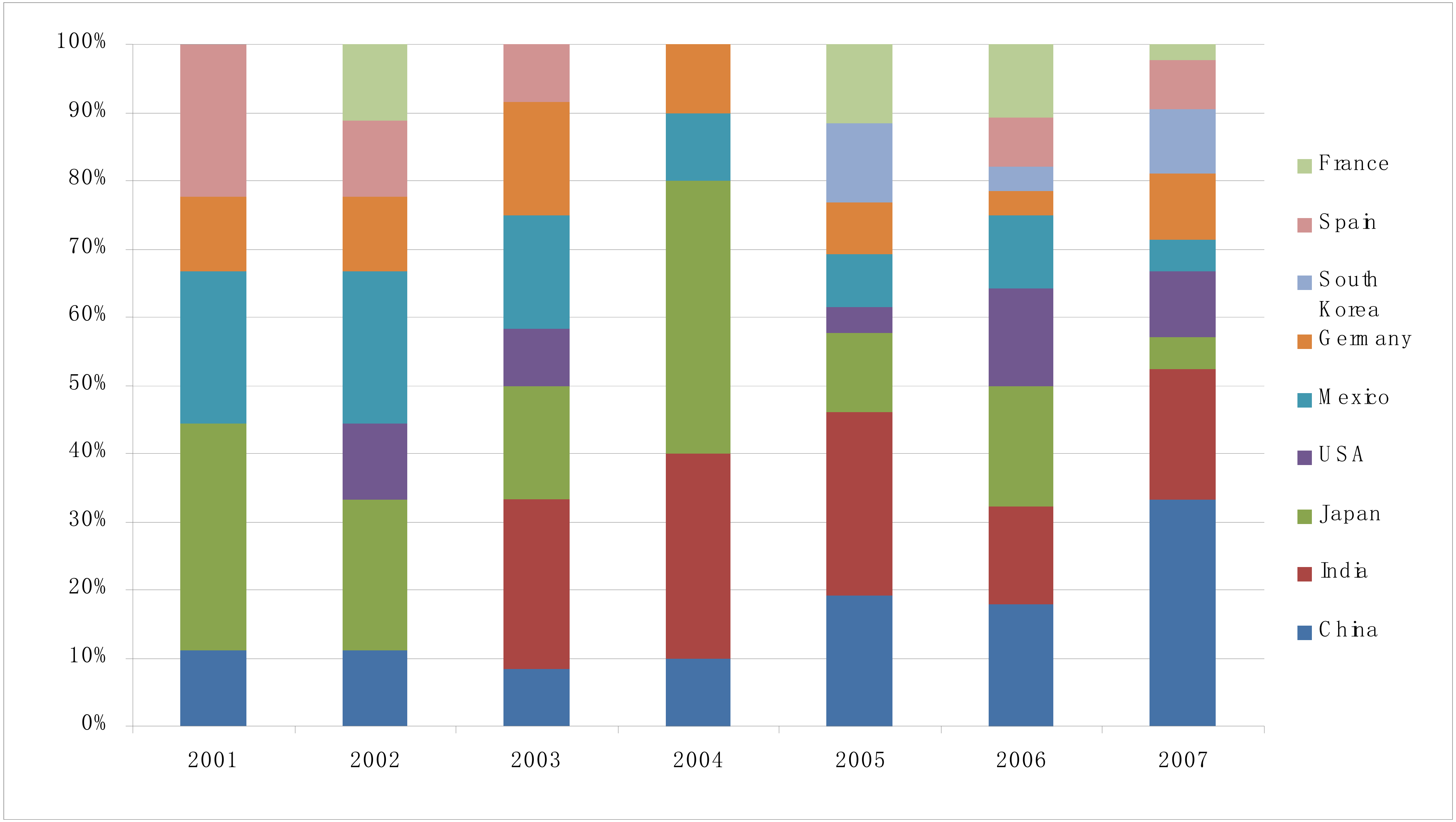

Fig.10: Percentage of each country of Nano-Structured ZnO Thin-film Solar Cells Publication in top 10 countries by Years

4. Conclusions

Detailed analyzes internationally help identify national R&D strengths and weaknesses. They can illustrate the existing status and aid in forecasting likely future developments of an emerging technology, such as nanotechnology thin-film solar cells. Such analyses can be useful for science and technology policy makers and managers in establishing development strategy. The technology managers can gauge relative opportunities for collaborative development, as well as monitoring emerging competitors.

We explore multiple characteristics of the research in this emerging technology – quantity (publication numbers), quality (citations), and diversity (variety of research fields involved). These provide multiple perspectives on nations R&D efforts. They can also offer insights into the strategic purposes of nations (or organizations) – vital information for informed technology management and policy formulation.

The paper shows that the United States (US) remains the leader in international research publication concerning nanotechnology thin-film solar cells as of mid-2008, based on the Science Citation Index. The US also leads in terms of citation intensity of its publications, a measure of research impact or quality. Comparing the leading countries in research on this emerging technology finds today's "usual suspects" — Japan, Germany, and China. Somewhat surprisingly, India is a leader in this Materials Science/Chemistry field as well. Furthermore, India and China show strong trends of relative increase in both the research activity (publication rates) and quality (citations received). We would forecast continuing gains from Asia in R&D on this emerging technology. As "technology watchers," we want to track whether the increasing citation of Indian and Chinese research continues; if so, this could really indicate that their research is bearing fruition. And if so, that could well transfer to cutting edge applications.

We also explore patterns of research networking. This can be done within organizations as well; here, we do so within countries. We only present resulting collaborative network maps for the US and Germany in this paper. Those are quite different. For the US, no institution dominates the research publication and inter-institutional networking appears weak. For Germany, we identify strong networking with an apparently key, central organization (Hahn Meitner Inst Berlin GmbH). Those interested in competitive technical intelligence would want to obtain expert review to check that this pattern is a good representation of the research networking. If so, this is vital information to use in monitoring competition and possibly developing research and development alliances.

Studies of research publication patterns – "tech mining" (Porter and Cunningham, 2005) – can be conducted at multiple tiers. We illustrate here by investigating which nano materials are prominently addressed by the nano thin-film solar cell research. Results point toward nano-structured ZnO as potentially important. Research on ZnO shows a marked rise since 2005. China and India especially are actively engaging this topic. Again, those concerned with technological intelligence and forecasting of likely development pathways, might well want to explore this further. Presentation of research profiles to topical experts could help elucidate potential functional advantages of this material. Further discussions could then explore possible key applications in the solar cell arena.

This paper is offered to illustrate the potential of tech mining as a key component of competitive technical intelligence ("CTI") efforts. CTI, in turn, forms the base for tech forecasting. These analyses of nano thin-film solar cells, keying at a national level, point to key players to watch and their differential emphases. Depending on the paramount technology management issues one is addressing, we see utility in going beyond basic bibliometrics (e.g., activity trends, tabulations of the leading players). Here we demonstrate ways to combine analyses of R&D quantity, quality, and diversity to gain insights pertinent to technology management and policy. We also illustrate alternative visualizations to help convey "who is doing what" to technology managers.

Acknowledgements

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