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Patent Analysis of Power Electronic Technologies for Electric Mobility

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Abstract

This paper examines the research landscape for automotive power electronics as key technology for electric mobility in a time frame from 2000 until 2012 by conducting in-depth patent and publication analyses. Using complex and dedicated search strategies, more than 3,800 peer-reviewed scientific publications and 47,000 patent applications in 6 different world regions could be identified. With the help of automated text and data mining functionalities, the evaluation of patent and publication content was possible to achieve, resulting in sophisticated statements for technology development trends and research activities. Results visualize the situation of Japan, USA, China, Europe, Germany and France in comparison based on the assessment of the respective patent markets on the one hand as well as technology driving and leading institutions on the other hand. The scope of the study comprises automotive power electronics on system level, semiconductor technologies on component level as well as Silicon Carbide and Gallium Nitride on material level. The analysis shows that Japanese institutions are by far leading the technology development, while China's patent market has gained significant importance for international patentees since 2010.

Keywords: Battery Electric Vehicle, Powertrain, Power Electronics, Semiconductors, Technology Assessment, Research Landscape, Patent Analysis

1 Introduction

One of the main trends for current vehicle development is the further electrification of the automotive powertrain and by that the development of new or improved technologies in the field of electric mobility [1]. Key technologies for electrified vehicles include e.g. energy storage and energy converter devices like batteries, supercapacitors, electric machines, range extenders and power electronics [2].

Electrified vehicles like PHEVs (Plug-In Hybrid Electric Vehicles) or BEVs (Battery Electric Vehicles) make it possible to significantly reduce local emissions of greenhouse gases compared to conventionally powered vehicles and to increase the efficiency of energy usage. This allows OEMs to meet ambitious CO_2 reduction targets defined by politics, to avoid penalty fees and to account for changes in the awareness of customers concerning environmental issues. In order to gain competitive advantages and to realize supreme and innovative products in a global environment, all of the electric mobility key technologies are subject to strong investments in research and development (R&D) activities carried out by automotive OEMs, suppliers as well as research institutions and universities worldwide [3].

Beside the battery as most important and cost-intensive key technology of the electrified vehicle, the power electronics system will gain significant relevance in the future by strongly influencing the economic feasibility and the overall energy efficiency of the electrified car while controlling and regulating the energy flows and adapting them to different requirements during vehicle operation. Therefore, the optimization and further improvement of the power electronic system is one of the main goals of funding programs and R&D activities in the field of electric mobility [4][5].

Strong efforts are carried out e.g. for the development of ‘active’ components of power electronic systems like new semiconductor technologies that will enable next generations of power electronics to become smaller and highly integrated, to work with higher efficiency as well as to realize advantages considering size and complexity of the thermal management. The function of these active elements is to switch the necessary current flows inside the vehicle with very high frequencies with the aim to provide the right components with the right amount of electricity at the right time. As semiconductor switching devices in the automotive area mainly transistors are being used. Here, basically three different types can be distinguished: Bipolar transistors (BPT), field effect transistors (FET) and bipolar transistors with isolated gate electrode (IGBT). In the automotive area primarily IGBTs and, for lower electric power requirements, MOSFETs (metal oxide semiconductor field-effect transistor) are of importance.

Of particular importance for the technical performance of power electronics are semiconductor materials. State of the art today is mono-crystalline Silicon, the most common material used. However, the use of silicon restrains the possible temperature limit of semiconductor devices to about 175 °C and by that the maximum possible switching frequency. A considerable need for efficient thermal management and cooling solutions arises by this, which at the same time reduces the achievable power density of the whole power electronics package.

Hence, one aim in power electronics development is to use semiconductor materials which can withstand very high temperatures. Possible solutions are, for example, Silicon Carbide and Gallium Nitride which enable theoretical temperatures up to 600°C and, in addition, better switching characteristics as well as higher switching frequencies [6]. However, the higher production costs which are caused mainly by a more complex production of wafers and crystal growing are problematic and need to be reduced in future. A clear trend towards sinking prices can be identified already: While in case of Silicon Carbide the costs in 2007 were about 100 times the one of Silicon, the factor decreased to only 3 to 6 in 2013 [7]. Taking into account the positive effect of SiC semiconductors on the overall power electronic system (reduced cooling requirements, reduced size of coils because of higher switching frequencies), even lower system costs than with Silicon could be achieved in future.

Wide Bandgap (WBG) materials are seen as most important enabler of future automotive high-level integration [8]. Different technologies and solutions compete in a highly dynamic world market and it is uncertain which solution will prevail in the future [9].

However, detailed knowledge about R&D activities of leading institutions for automotive power electronics and its single components considering a wide timeframe is missing [10]. The aim of this paper is to identify the most relevant world regions for power electronics in terms of patent market importance on the one hand and technology leaders on the other hand in a global comparison and to derive trends in power electronics technology development by carrying out in-depth analysis of the international patent and publication landscape.

2 Methodology and Scope

For the analysis in this paper, an indicator-based approach of technology assessment is carried out using patent and publication analyses in the field of automotive power electronics with the aim to identify all relevant research activities related to electric mobility over the years 2000-2012.

The patent analysis originally serves as an instrument for the strategic management of technologically driven companies and is used to investigate and evaluate activities in technology fields gauged as relevant for competition. As a tool to support planning and decision making, it helps in developing recommendations for a strategic management of technology and innovation [11]. To achieve this, the close correlation between monetary investments in R&D as an input factor

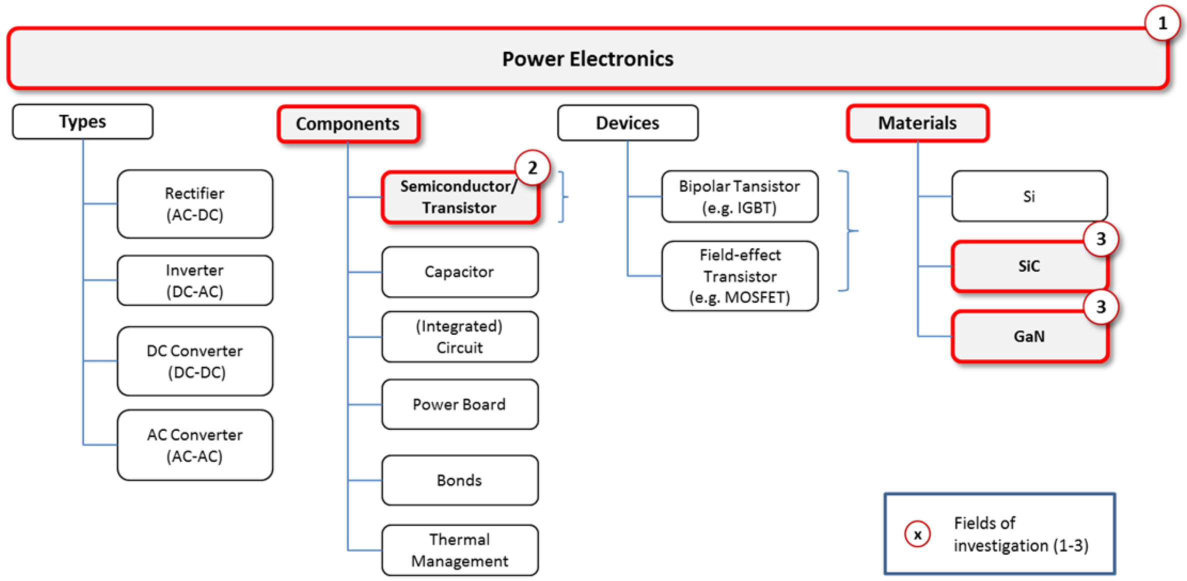

Figure 1: Fields of investigation in the scope of this study

and patent applications as an output factor is used. Patents by definition contain inventions which advance the state-of-the-art of single technologies and with economic interest could be applied in future products that allow for e.g. supreme performance characteristics [12]. Beside the use as a strategic planning tool, the patent analysis is also suitable to conduct technology- and trend-oriented competition analyses. Thus, patent information is used as an indicator to identify technology development trends as well as to evaluate the relative strength, the technological position and the competitiveness in comparison of institutions, countries and/or world regions.

In addition to patent applications, also peer-reviewed scientific publications can be interpreted as result of research activities and therefore serve as another indicator for investments in ongoing R&D [13]. In this paper, both methods will be used in combination to draw a holistic picture on research and development activities in the area of automotive power electronics. While publications mainly serve as a means for the documentation of basic or fundamental scientific achievements and therefore rather originate from research institutions and universities, patents focus more on the concrete use and economic utilization of an invention in e.g. innovative or improved products. Hence, patents are applied mainly by industrial companies.

To achieve objective and scientifically relevant results in the context of this paper, the methodology follows a structured seven-step approach:

1. Identification and definition of relevant fields of investigation on power electronics system and component level.
2. Definition of the patent and publication search strategies by using IPC classes (International Patent Classification) and combining keywords where necessary.
3. Data acquisition in citation, abstract and patent databases (e.g. SCOPUS, Espacenet).
4. Structuring and harmonization of raw data, including relevant bibliometric indicators related to R&D (e.g. author/institution, title, abstract, year and geographical scope of application, citation) and the technology (e.g. technology field, component, parameter).
5. Design and buildup of technology databases containing patent and publication information.
6. Analysis of patent and publication (meta-) information (quantitative analysis).
7. Analysis of patent content by using text and data mining functionalities (qualitative analysis).

As to be seen in Figure 1, the scope of the study comprises three different levels of investigation:

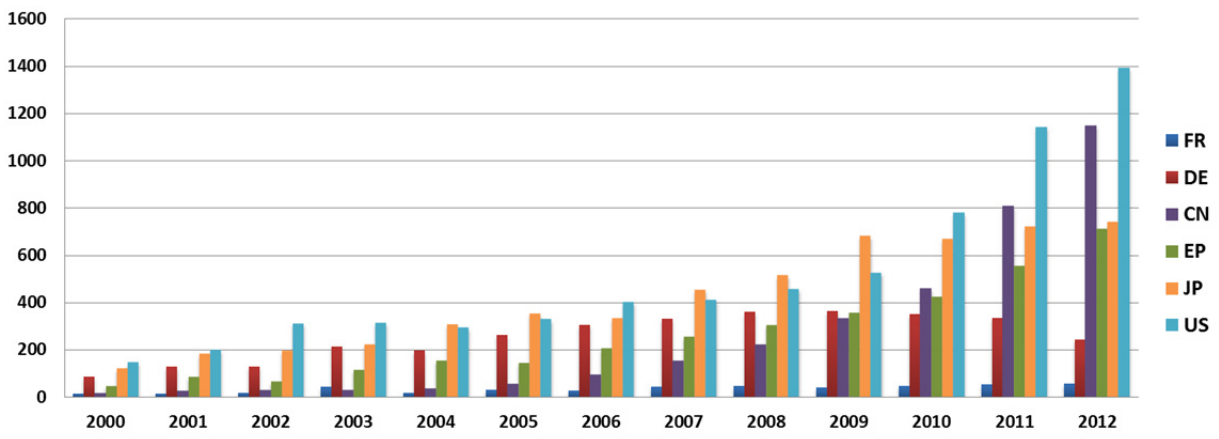

Figure 2: Number of patent applications in the field of "power electronic systems" by world region, 2000-2012

1. The system level, where patents and publications are identified for power electronics as a complete system in the powertrain of electrified vehicles.

2. The component level, where patents for single elements within the power electronics are part of the investigation. This analysis will focus on semiconductors/ transistors, and

3. The material level, where patents related to innovative material technologies like Silicon Carbide (SiC) and Gallium Nitride (GaN) are part of the assessment.

For each field of investigation, the above-named steps were carried out, resulting in worldwide new and unique statements for the patent and publication landscape in comparison of different world regions. The analysis covers six different geographical regions (China, Japan, USA and Europe with special focus on Germany and France). As a result, over 3,800 publications and 47,000 patents are analyzed in the context of this paper.

3 Results

Results of the patent and publication analysis will show international trends in R&D, leading institutions and their respective research networks as well as innovation dynamics over a wide timeframe for automotive power electronics on system level, semiconductor technologies on component level as well as SiC and GaN on material level.

3.1 Patent and Publication Landscape for Automotive Power Electronic Systems

For the analysis of the patent landscape in the area of „power electronics in the powertrain of electrified vehicles", a decided search strategy has been developed and applied at the patent database 'Espacenet' of the European Patent Office (EPO). For this, a total of 52 IPC classes (International Patent Classification) have been used (e.g., B60L, B60W, B60K) and combined with a keyword-based search strategy where necessary.

Altogether, more than 47,000 patents could be identified from which about 23,000 (48%) were published in the world regions relevant for this evaluation: Japan (JP), USA (US), China (CN), Europe (EP), Germany (DE) and France (FR). The predominant majority of patents which refer to inventions in this technology field in the time frame from 2000 to 2012 were registered in the USA (6,700; 29%), followed by Japan (5,500; 24%) and evenly distributed China, Europe and Germany with each about 3,400 patent applications and 15% market share. Only about 450 patents were published on the French market for intellectual property (IP). Over time, an increase of applied patents can be identified starting with 430 in the year 2000 and reaching a maximum of 4,293 in 2012 (see Figure 2).

The Japanese (orange) and US-American (light blue) IP-markets show a relatively constant and similar increase in patent numbers from 2000 on until the year 2010. While the number of applied patents in Japan then remains relatively static at about 700 per year, the USA further advances and is able to increase its patent output to a maximum of 1,400 in 2012. The relevance of the Chinese market (purple) grows continuously and overtakes Europe (green) and Germany (red) in 2010, taking the 3rd place. This development culminates in the fact that Japan for the first time is pushed from 2nd to 3rd place in 2011.

In direct comparison of the patent situation in 2000 and 2010, an increase in total numbers of about 1,000% (430 to 4,293) can be registered. In particular, the USA with a leading position already in 2000 was able to even increase the gap in total numbers, although loses market share of applied patents of about 5% within the following ten years, reaching a total of 29% in 2010. Similar to the US market, the German IP market lost importance for international patentees and the market share of 20% in 2000 decreased to only 13% in 2010. The pure number of patent applications in Germany grew about only approx. 400% within this period of time, far behind the market average. However, the German market growth still lied ahead of the one of France (approx. 300%), but behind the USA (530%), Japan (560%), Europe (920%) and in particular China with very substantial growth rates (2,870%).

By far the most dynamic development is thus to be observed in China. Here, the market share could be increased from 3.7% to 16.8% within the last 10 years. The absolute number of applied patents at the same time reached 459 in 2010, the third best figure behind the USA and Japan. Even more remarkable dynamics can be identified from this point in time on: Within the following 2 years, China was able to increase the share of patents published on the own IP market from 16.8% to nearly 27%, while at the same time the share of Japan decreased from 24% in 2010 to only 17% in 2012. The USA was able to raise its share again slightly after losses until 2010 again and reached the leading position in 2012 with 32% share.

In Germany, a steady reduction can be identified until 2012, so that after a peak in 2009 only 242 patents were applied in 2012 and the market share was reduced about another 14% to only 6% in total. In France (blue), an only slight increase of the total numbers is recognizable and the market share stagnated accordingly at a relatively low level between 1.3 and 1.7%.

The analysis of patent application numbers over time aims at identifying activities and dynamics in comparison of different world regions to finally evaluate the relevance of the respective IP markets for international patentees. For the derivation of statements in terms of the technology position of different world regions, however, it is necessary to identify the main drivers of technology development and leading institutions within the technology field. This will be indicated in the following ranking for technology leaders in the area of automotive power electronic systems.

Because the explanatory power of statements derived from pure patent numbers is limited, for the following ranking patents that protect the same content in different world regions or are assigned to the same patent family will be ignored. Thus, multiple countings of similar inventions will be avoided and the ranking of the TOP institutions will be based only on patents with relevant content that advance the state of the art of the technology.

In the ranking of technologically leading institutions in a global comparison, Asian enterprises hold 9 positions within the TOP10, as Table 1 shows. In particular, it is Japanese institutions that by far are most important drivers of technology development for automotive power electronics. They are leading with a total number of 14.055 inventions, with only Toyota (Motors & Jidosha) altogether being responsible for 7,591 inventions.

Table 1: Leading institutions in the field of automotive power electronic systems

Rank	Institution	No. of inventions	Country
1	TOYOTA MOTOR	6.049	🇯🇵
2	NISSAN MOTOR	1.977	🇯🇵
3	TOYOTA JIDOSHA	1.470	🇯🇵
4	HONDA MOTOR	1.208	🇯🇵
5	HYUNDAI MOTOR	696	🇰🇷
6	GM GLOBAL TECH OPERATIONS	575	🇺🇸
7	DENSO	573	🇯🇵
8	HITACHI	571	🇯🇵
9	HONDA MOTOR	558	🇯🇵
10	AISIN AW	530	🇯🇵
11	**ROBERT BOSCH**	**496**	🇩🇪
12	FORD GLOBAL TECH	375	🇺🇸
13	**DAIMLER**	**345**	🇩🇪
14	TOSHIBA	319	🇯🇵
15	MITSUBISHI JIDOSHA KOGYO	299	🇯🇵
16	MAZDA MOTOR	263	🇯🇵
17	**ZF FRIEDRICHSHAFEN**	**248**	🇩🇪
18	KIA MOTORS	247	🇰🇷
19	FUJI HEAVY IND	238	🇯🇵
20	**BAYERISCHE MOTOREN WERKE**	**233**	🇩🇪

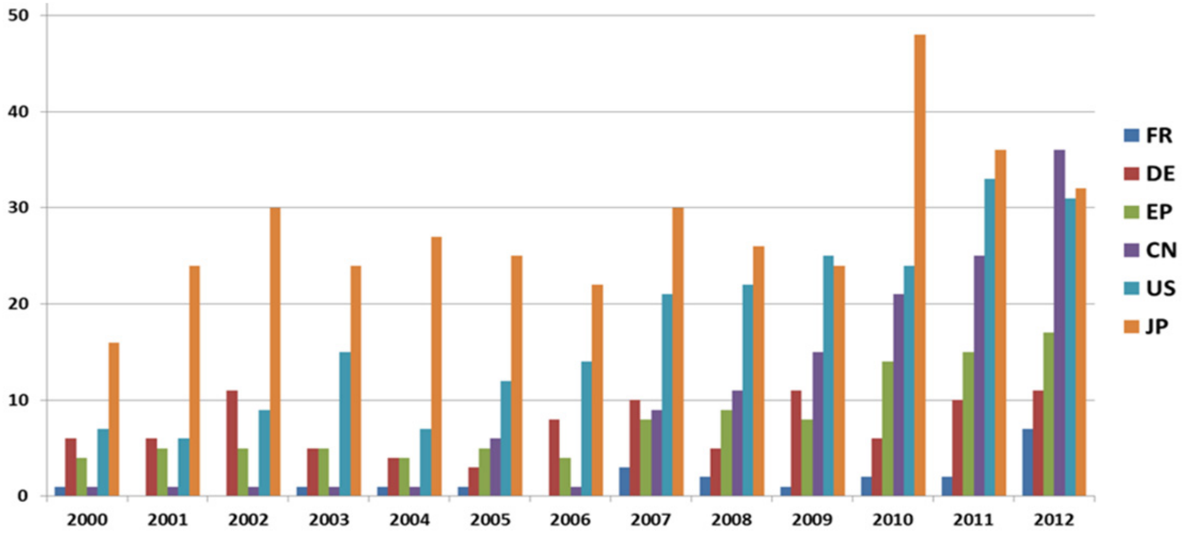

Figure 3: Number of patent applications in the field of "semiconductors" by world region, 2000-2012

In comparison to that, German OEMs hold only 469 inventions and are ranked with Daimler (incl. DaimlerChrysler) on position 13 and BMW on 20. Best-placed German enterprise is a tier 1 supplier on position 11 with 496 inventions: the Robert Bosch GmbH.

The USA is represented by GM (575) and Ford (375) on rank 6 and 12, Tesla Motors all in all holds 9 patents in the area of power electronics for electrified vehicles. Best-placed Chinese enterprises are Chery Automobile and BYD with 90 and 50 inventions, followed by the Tsinghua University in Peking with 40 inventions.

3.2 Patent and Publication Landscape for Semiconductor Technologies

Altogether, 939 patents have been applied in the area of semiconductor technologies within the time frame from 2000 to 2012. The Japanese IP market owns approx. 40% of all patents, followed by the USA with about 25%, China (14%), Europe (11%) and Germany (10%), as Figure 3 shows. However, massive shifts in market shares can be identified over time: While Japan in 2000 held over 45% of all patent applications and lost only small amounts until 2010 (42%), the market share during the next two years dropped to only 24%.

The patents applied on the Chinese IP market on the other hand increased constantly from 2007 on to a total of 36 in 2012, so that China with 27% share takes the leading position ahead of Japan (24%) and the USA (23%). The German market remains relatively static in this time period with between only 3 and 11 patents applied per year. In comparison of 2000 and 2010, Germany lost 12% market share.

Table 2: Leading institutions in the field of semiconductor technologies

Rank	Institution	No. of inventions	Country
1	TOYOTA MOTOR	82	
2	HITACHI	48	
3	HONDA MOTOR	32	
4	TOSHIBA	30	
5	TOYOTA JIDOSHA	25	
6	NISSAN MOTOR	18	
7	HYUNDAI MOTOR	17	
8	GM GLOBAL TECH OPERATIONS	15	
9	DENSO	15	
10	**DAIMLER**	**15**	
11	MITSUBISHI DENKI	14	
12	**SIEMENS**	**14**	
13	FUJI ELECTRIC	13	
14	TOYODA AUTOMATIC LOOM WORKS	11	
15	SUMITOMO ELECTRIC IND	10	
16	HITACHI AUTOMOTIVE SYSTEMS	8	
17	**ROBERT BOSCH**	**9**	
18	AISIN AW	6	
19	NIPPONDENSO	6	
20	TOSHIBA TRANSPORT ENG	6	

In the ranking of leading patentees for semiconductor technologies (component level) in a worldwide comparison, Asian institutions again are main drivers of the technological development and take 8 positions in the TOP10 (Table 2). Japanese companies are by far leading with a total number of 440 inventions that were applied for patent protection. While only Toyota owns 107 relevant inventions, German OEMs altogether account for only 18, with Daimler having 15 inventions in its technology portfolio. Audi, Volkswagen and BMW each have only one. Siemens AG and Robert Bosch GmbH as German

Tier-1 suppliers hold 14 and 9 inventions, respectively.

Chinese institutions altogether account for 16 relevant patents, with Tianjin Santroll Electric Automobile Technology leading (3). BYD and Chery Automobile have each developed one relevant invention. In the USA, Ford (4) and Chrysler (3) take position 2 and 3, following GM on first position with 15 inventions.

When expanding the patent search strategy for semiconductors to include not only inventions relevant for power electronics in the automotive sector and in the context of electrified vehicles, but for all possible application fields of semiconductor technologies like aerospace, energy or robotics, the picture of leading institutions in this technology field changes into the direction of South Korea: Hynix Semiconductor (South Korea) with 9,324 inventions is leading here, followed by Toshiba (8,742, Japan) and Samsung Electronics (8,226, South Korea). IBM as best-placed US-American enterprise follows on rank 9 with 3,732 inventions in its portfolio. Infineon leads the ranking for German patentees with 2,738 (position 14 in the overall ranking), followed by Siemens (971) and Qimonda (433, meanwhile insolvent).

3.3 Patent and Publication Landscape for Semiconductor Materials: Silicon Carbide (SiC)

In the special field of the patent applications which are connected to inventions in the area of SiC as semiconductor material for automotive power electronic systems, the Japanese market for intellectual property (1,284 patents) is leading in terms of absolute numbers within the timeframe 2000-2012, closely followed by the USA (1,096). For each year, both countries lay very closely together in terms of relevance for international patentees. However, the Japanese market managed to takes over the leading position in particular from 2007 on and by then increased the number of patent applications every year constantly, as to be seen in Figure 4.

Again, it is remarkable to point out Chinas leap to the TOP 3 in 2012. During the time period examined, China was able to consolidate its third position which was first adopted in 2009 and again in 2011 against the EU while then strongly expanding its advance, doubling the patent output until the next year 2012. Also Germany was able to raise the number of patents until the year 2006, but then stagnates at about 20-25 applied patents per year. Only 11 patent claims were published in the whole period in France.

In direct comparison of 2000 and 2010, Japan was able to increase its market share heavily from 28% to approx. 40%, while at the same time the US-American IP market lost 15 percentage points. China could not realize significant changes in the importance of its IP market for SiC technologies until 2010 (7% in 2000, 9% in 2010), the dynamics then increased rapidly, so that it owned more than 20% in 2012.

Similar to the analysis in the field of semiconductors on component level, Japanese institutions are also leading in the special field of semiconductors on material level (SiC) and take 9 out of 10 positions in the TOP10, (see Table 3).

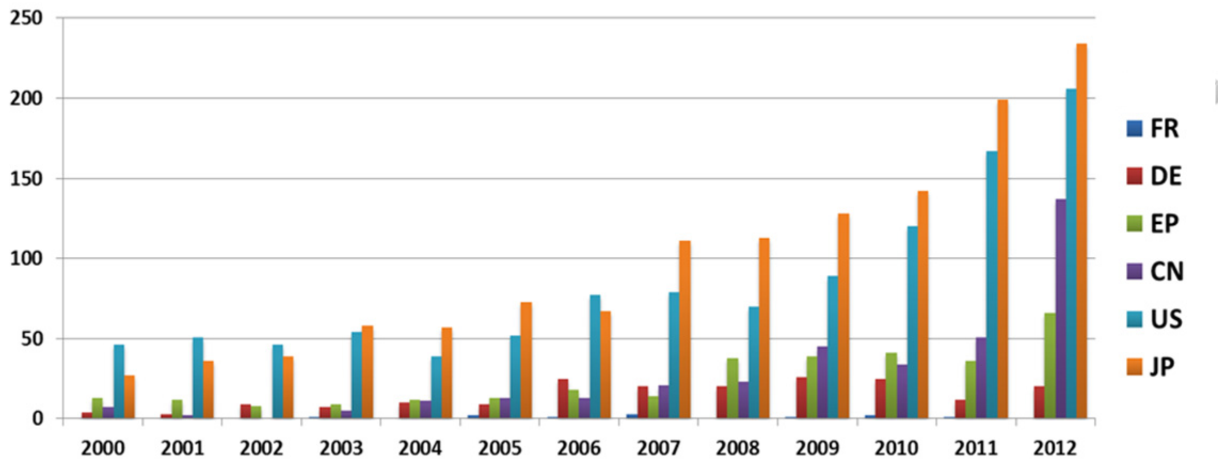

Figure 4: Number of patent applications in the field of "semiconductor materials (SiC)" by world region, 2000-2012

Table 3: Leading institutions in the field of semiconductor materials (SiC) technologies

Rank	Institution	No. of inventions	Country
1	DENSO	178	
2	SUMITOMO ELECTRIC IND	167	
3	MITSUBISHI DENKI	123	
4	NISSAN MOTOR	95	
5	MATSUSHITA ELECTRIC IND	89	
6	TOSHIBA	70	
7	CREE	66	
8	FUJI ELECTRIC	74	
9	NATIONAL INST ADVANCED	57	
10	PANASONIC	44	
11	HITACHI	41	
12	TOYOTA MOTOR	37	
13	**SIEMENS**	30	
14	FUJITSU	25	
15	KANSAI ELECTRIC POWER	25	
16	SANYO ELECTRIC	23	
17	**INFINEON TECH**	21	
18	INTL BUSINESS MACHINES	20	
19	ROHM	18	
20	GEN ELECTRIC	17	

Denso (178 inventions) stands before Sumitomo Electric (167), Mitsubishi (123), Nissan (95), Matsushita Electric (89) and Toshiba (70), before the first non-Japanese enterprise with Cree (66) follows on rank 7. It is noteworthy that in spite of this very special technology field and research at material level, Nissan as well as Toyota as automotive OEMs are to be found in the ranking list. A total of 126 institutions could be identified that pursue research on the subject of SiC in Japan.

Germans OEMs in the whole ranking are represented only by Daimler with 2 inventions in its portfolio. In France, the USA as well as in China no OEM at all could be identified that claims industrial property rights. On supplier-level, Siemens and Infineon with 101 and 57 patents (30 and 21 inventions) could be ranked on position 13 and 17, respectively. Beside Siemens and Infineon, the TOP4 in Germany is completed by SiCED Electronics with 73 patents (15 inventions) and Bosch with 6 patents (5 inventions). Altogether, 19 different institutions carry out research in this subject in Germany, as shown in Figure 5.

In the US besides Cree and IBM, another 72 enterprises are pursuing research activities for Silicon Carbide, e.g. General Electric (18 inventions), Micron Technology (15), the Semisouth Laboratories (15) and Texas Instruments (13). China provides a total of 26 institutions, with the Xidian University (14), Semiconductor Manufacturing Internationally (14) and China Electronics Technology Group (7) leading the TOP3 in the national ranking. It is noteworthy that a university is leading the ranking in China in this technology field.

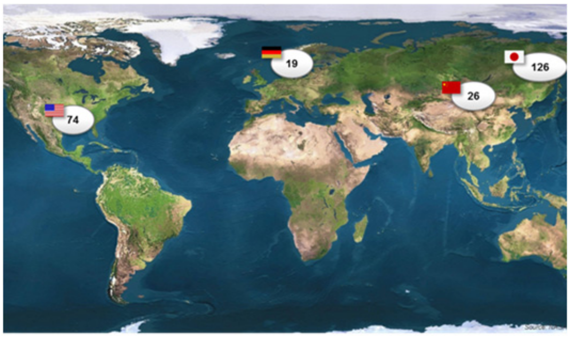

Figure 5: Number of institutions active in R&D for SiC by world region

In addition to the analysis of the geographic distribution, it is also possible to identify joint and cooperative R&D activities in terms of innovation networks and dynamics by conducting patent analyses. For this, connections of different institutions and/or inventors by means of jointly applied patents will be visualized in the following for SiC technologies. The Japanese technology leaders Denso and Nissan will be contrasted to the US-American and German ones, Cree and Siemens.

As shown in Figure 6, Japanese institutions carry out R&D activities in a relatively wide and open innovation network when directly compared to European or American networks. Interesting dynamics can e.g. be identified for Nissan as Japanese OEM – on position 4 in the ranking for patent applications in the field of SiC. The analysis illustrates strong connections to suppliers like Rohm, Toshiba and Sanyo Electric as well as to research institutions. By cooperating with Sanyo Electric, Nissan is able to achieve a strategic link to Hitachi and by that, opens up the innovation network to technology leader Denso (on position 1 in the ranking) and several institutions within the Toyota Corporation: Motor, Jidosha and Central R&D Labs.

On the other hand, the leading institutions from Germany and the USA are far less connected by means of joint patent applications. While connections for Siemens in particular exist to Infineon and SiCED Electronics, on the second level also IBM and Qimonda are (or were) part of the network. For the US-American enterprise Cree,

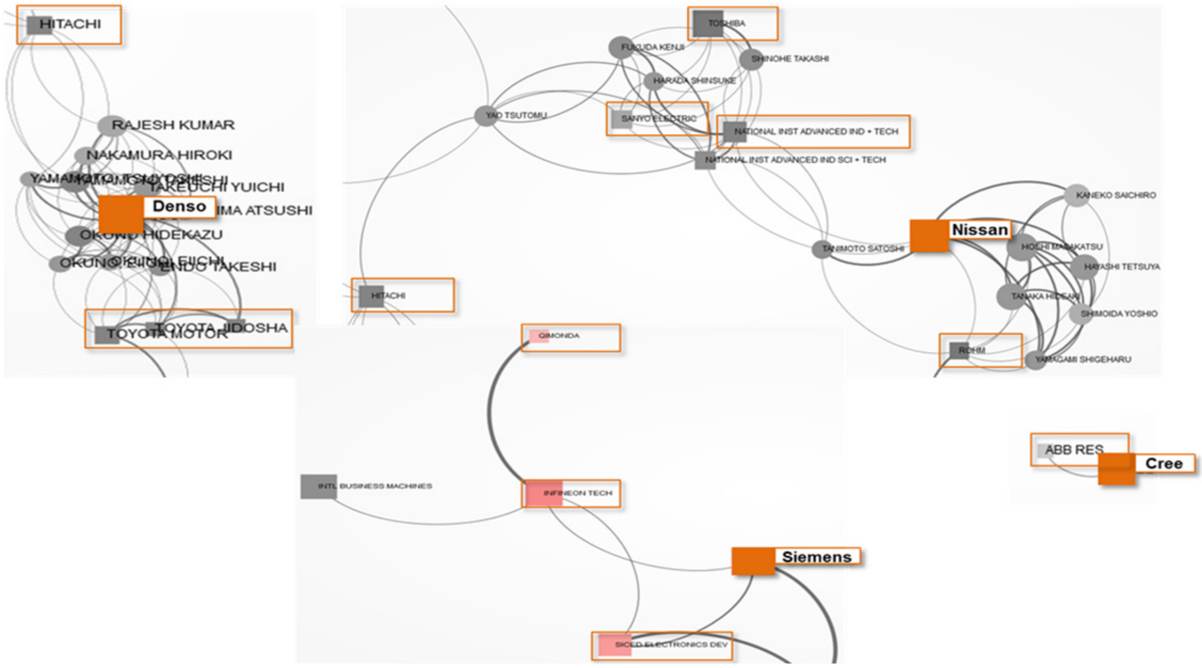

Figure 6: Japanese, German and US-American innovation networks for SiC technologies

cooperative R&D activities within the scope of this study can only be identified to ABB. With the relatively high number of patents in Cree's portfolio (nearly 500), this could imply that Cree conducts a relatively defensive technology strategy with the aim to mainly secure know-how in this technology field.

3.4 Patent and Publication Landscape for Semiconductor Materials: Gallium Nitride (GaN)

In the analysis of patent applications in the context of inventions for Gallium Nitride as semiconductor material for automotive power electronics, Japan is leading with a total number of 900 applied patents in the time frame 2000-2012. The USA with approx. 740 patents is based second. The IP markets of both countries showed relatively similar numbers over the years, however, Japan was able to claim the top position from 2007 on consistently and gained a significant advantage particularly in the years 2008 and 2010, as Figure 7 illustrates.

Similar to the previously shown analysis in the field of SiC, China was able to increase the patent output on the own IP market from 2007 to 2008 significantly and conquer the third place from the EU in 2008. Germany within the scope of this analysis was not able to keep up in terms of patent numbers and stayed at a very low level in terms of market share of only 1%.

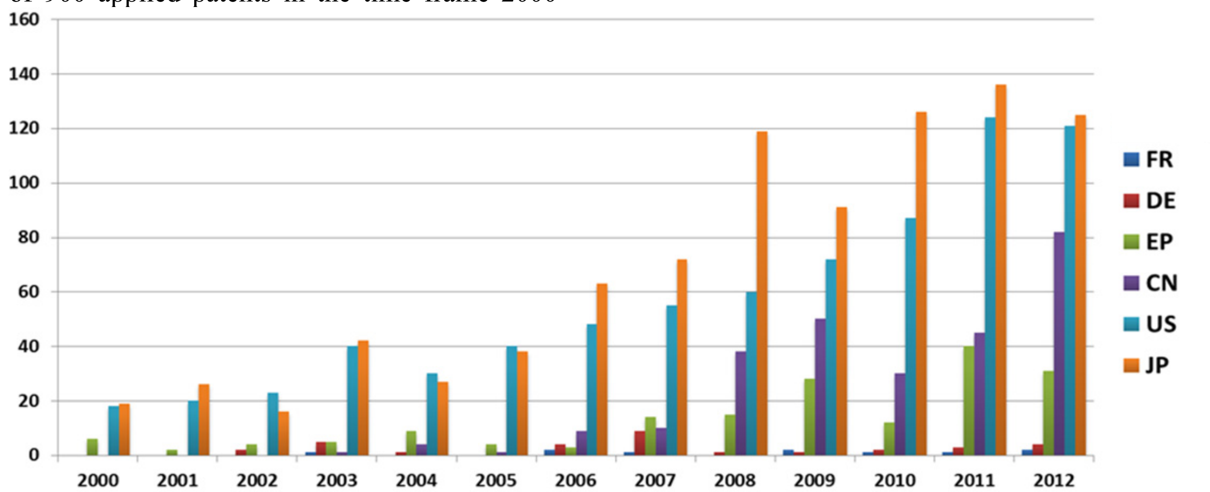

Figure 7: Number of patent applications in the field of "semiconductor materials (SiC)" by world region, 2000-2012

In comparison of the years 2000 and 2010, the output of applied patents could be increased by a factor 6 overall, besides, in comparison to 2012 even by a factor 8. Japan lost market shares of more than 10% until 2012 to arrive at a total of 34%. Also the USA lost approx. 9% of share in the same period of time and claimed 33% of all patent applications in 2012. China, in 2000 still without any activity in the area of GaN, was able to register already 30 patents in 2010, arriving at more than 80 in 2012. By this, the Chinese IP market was able to double its market share in comparison to 2010 and held more than 22%.

In the area of GaN semiconductor materials, Japanese institutions dominate the technology development nearly completely. The only non-Japanese enterprises within the TOP 20 are the Xidian University from China on rank 16 with 20 inventions and Cree (USA) on rank 17 with 19 inventions.

Again it is noteworthy that a Japanese OEM is important driver of technology development at power electronics material level and part of the leading institutions for research activities (see Table 4): Toyota Motors with 38 inventions takes position 9 in the TOP ranking behind Toyota Central R&D on position 8 with 39 inventions.

Table 4: Leading institutions in the field of semiconductor materials (GaN) technologies

Rank	Institution	No. of inventions	Country
1	FURUKAWA ELECTRIC	77	
2	SUMITOMO ELECTRIC IND	68	
3	MATSUSHITA ELECTRIC IND	66	
4	TOSHIBA	64	
5	FUJITSU	49	
6	NIPPON TELEGRAPH	44	
7	SHARP	40	
8	TOYOTA CENTRAL R & D LABS	39	
9	TOYOTA MOTOR	38	
10	PANASONIC	35	
11	ROHM	35	
12	OKI ELECTRIC IND	32	
13	EUDYNA DEVICES	25	
14	HITACHI	25	
15	SONY	21	
16	XIDIAN UNIV	20	
17	CREE	19	
18	SANKEN ELECTRIC	19	
19	TOYODA GOSEI	19	
20	NEC	18	

A total of 84 enterprises develop GaN technologies in Japan and hold industrial property rights. The global distribution of institutions active in R&D for GaN shows a similar picture as SiC, illustrated in Figure 8. In Germany, a total of 11 institutions carry out R&D in this technology field, including Daimler with one invention in its portfolio. The national ranking in Germany lists the 'Research Association Berlin' on position 1 with 3 inventions, followed by Siemens (2).

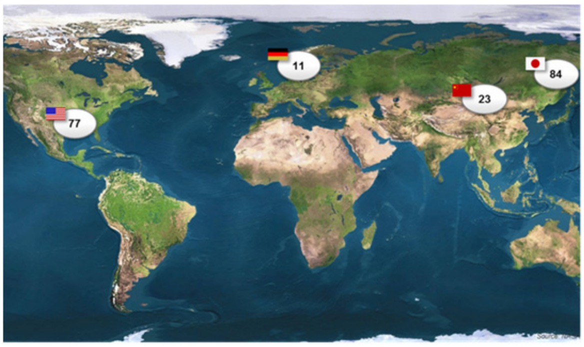

Figure 8: Number of institutions active in R&D for GaN by world region

The USA are active with a total of 77 institutions that claim property rights on inventions in the area of GaN. Cree with 19 inventions is leading R&D activities in the US, followed by Internationally Rectifier (16) and the University of California (12). In China, a total of 23 institutions could be identified, again with the Xidian University on position 1 (20), followed by the University of Electronic Science and Technology (17) and the Institute of Microelectronics of the Chinese Academy of Sciences (17).

Within the scope of this investigation only 2 OEMs (Toyota and Daimler) carry out research activities for GaN technologies. The prevailing majority of inventions in this field are driven by suppliers, research institutes and universities.

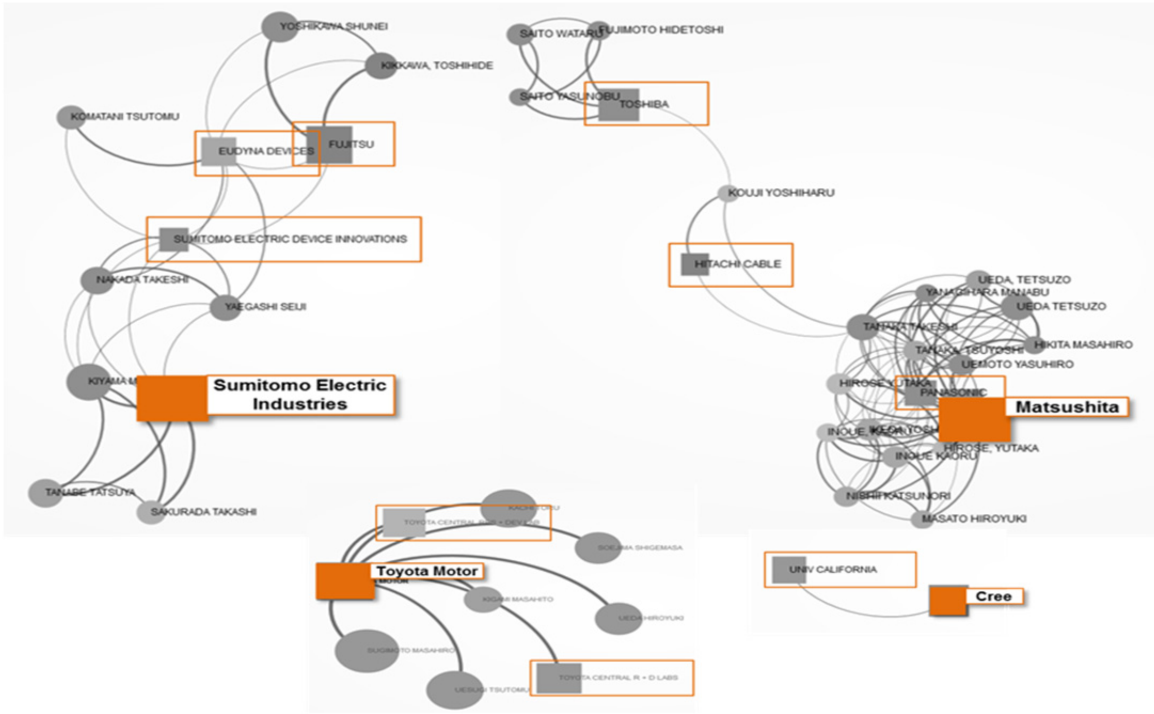

Figure 9: Japanese and US-American innovation networks for GaN technologies

Besides, it is interesting that cross-border, trans-national innovation networks in the field of GaN R&D do not exist at all. Furthermore, the identified networks are rather closed concentrate upon the cooperation of few national institutions, as Figure 9 points out.

4 Summary and Conclusion

In the following section, the ‘technological basis’ of the analyzed world regions in the field of automotive power electronics will be illustrated. This will summarize all of the conducted analyses above and by contrasting will highlight the patent landscape in terms of market and technology development over time in a portfolio chart.

The „growth of the patent market“ on the y-axis shows the increase in the respective countries Japan, USA, China, Germany and France in comparison to applied patents for a period of 10 years. The focus of the illustration lies on 2007 (with base year 2002) and in 2012 (with base year 2007). The „share of the patent market“ on the x-axis indicates how much percent of the patents were announced in the respective country to protect the intellectual property there. By that, it accordingly serves as an indicator for the importance of the respective country for internationally active patentees and their inventions. The size of the land flags indicates, furthermore, how strong the respective country itself is involved in the technology development, measured in the percentaged share of globally applied patents of institutions headquartered in the respective country in the years 2007 and 2012 („technology share“). All together, the chart illustrates the situation and the dynamics of the market as well as the technology in combination.

As Figure 10 illustrates, Japanese companies are leading the technological position in the field of automotive power electronics by far and are responsible for the development of more than 53% of all patents in 2012. The Japanese market however, lost large shares during the years 2007 to 2012, so that only 17% of all patents were applied in Japan in 2012. Furthermore, the dynamics of the market growth decreases in the same time period, with only approx. 160% growth rate to be identified for 2012 (on the basis of 2007), a loss of more than 60%.

The USA over the last 10 years was responsible for a very constant amount of inventions to drive automotive power electronics technology development with shares of about 18%. By that, US-American institutions lay behind Japan and Germany on the third rank in 2012. The share of patents applied at the US market, however, increased significantly and reached nearly 40% in

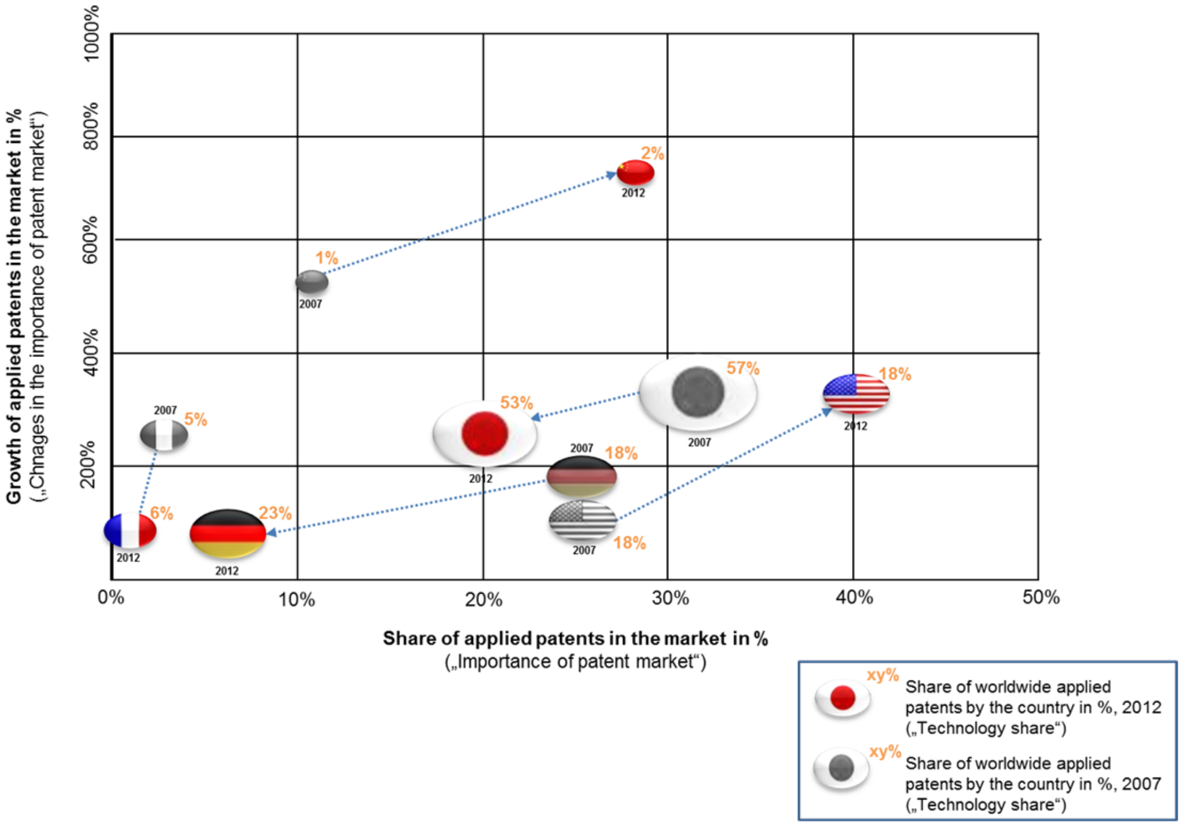

Figure 10: Technological basis for automotive power electronics by world region

2012, starting from 30% in 2007. The dynamics of the market growth also rose strongly and accounted for about 380% in 2012, an increase of a total of 210 percentage points. Although having a virtually stagnating situation in terms of technology development in the USA, the importance and growth of the US-American patent market could be increased substantially – in particular in comparison to the Japanese market.

German companies could raise the technology share from 18% in 2007 to more than 23% in 2012 and by that overtook the USA as second most important driver of automotive power electronics development. However, the relevance of the German IP market strongly decreased for international patentees within this period of time, so that only about 7% of all patents were applied on the German market, a decline by approx. 17%. In addition to that, also the market growth lost dynamics and reached only 73% growth rate in 2012, while in comparison of the years 2002 and 2007 approx. 260% of growth could be achieved.

France within the scope of this investigation plays a minor role in terms of market importance as well as technology share. While French enterprises could slightly increase their share in technological development (5% in 2007; 6% in 2012), the meaning of the French market in terms of market share within this period decreased from 3% to on only 1.5% in 2012. At the same time, the growth rate of at the French IP market applied patents also decreased to only 130% in 2012 (with base year 2007), starting at 250% in 2007 (with base year 2002).

Very remarkable is the situation in China in comparison of the years 2007 and 2012: The Chinese patent market reached more than 32% of share in 2012 and by that, takes the second position in terms of importance for international patentees behind the USA. Within the years 2007 to 2012, about 21% market share could be won accordingly. Besides, the dynamics of the market growth increased constantly and claimed more than 750% in 2012 in comparison to the base year 2007. The share in terms of technological development in the area of automotive power electronics on the other hand is negligible, so that in 2007 only 1% of all patents were announced by Chinese enterprises, 2% in 2012.

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