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Using of Power Electronics for the Development of Energy Infrastructures

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1 Introduction

The environment that surrounds electrical energy is reaching a turning point due to the growth of power demand mainly in the civilian sector, promotion of electrification, and the increase in electrical demand in developing countries involving in China.

Power electronics is a basic technology for energy infrastructures that contributes to the efficient utilization of electrical energy. A familiar example is the inverter control that provides smooth control of the output of electrical equipment such as air conditioner and motor enabling the reduction of power consumption, which is consequential technology for solving energy and environmental problems not only in Japan but also on the global scale.

It has been reported[1] that if ultra-low-loss power electronics devices currently being developed become widely used, which is estimated that electrical power totaling 29.78 TWh ($T=10^{12}$) will be saved in the fields including fuel cell vehicles and inverters for dispersion type power sources in Japan at 2020. This saving energy efficiency is equal equivalent of the annual power generation by four million kW class nuclear power plants.

The “Strategy for the Development of the Energy Sector (September 2001)” at Council for Science and Technology Policy announced that aims at practical applications of new materials such as ultra-low-loss power device (power semiconductor devices) etc is key research field for the promotion of energy infrastructures.

The industry has taken a major role in the construction of energy infrastructures using power electronics in Japan. However, it is currently difficult for a single business enterprise to actively work on such technical development because of the costs required under the flagging economy. Universities also have problems in this field especially for the personnel training education. On the other hand, the United States and European countries have realized the importance of this area and are actively conducting research activities by establishing research centers in collaboration between the industry and academia.

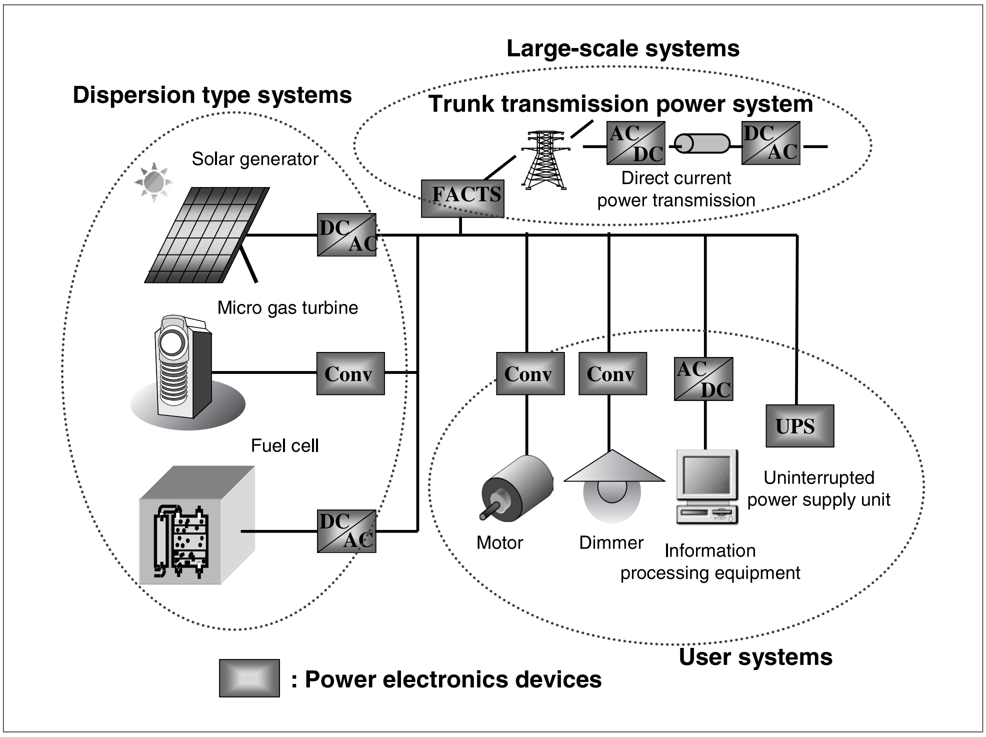
Based on such circumstances, this report will review that should be taken in order to maintain and develop the power electronics technology in Japan.

2 What is power electronics?

“Electrification ratio,” which is the ratio that the primary energy such as petroleum and coal is used for electricity as secondary energy after conversion, is increasing year by year, and recently it has become higher than 40% in Japan[2]. As the informatization and aging of society progress, it is expected that the electrification ratio will become still higher due to the convenience and safeness of electricity.

Power electronics is a technology that converts the form of electricity from alternating current to direct current or from direct current to alternating current, or changes the frequency making use of power semiconductor devices. The IEC (International Electrotechnical Commission) defined power electronics as the “technical field related to electric power conversion and switching in which technologies of electrical power engineering, electronics, and control

Figure 1 : Interfaces between electrical power systems and power electronics devices



FACTS: Flexible AC Transmission Systems
C o n v: Converter; usually AC-DC-AC power conversion equipment.
Source: Authors' compilation based on data provided by the Power Electronics Research Center of the National Institute of Advanced Industrial Science and Technology.

engineering are comprehensively integrated". The targets of power electronics are the conversion and handling of electrical energy, whereas those of electronics are the conversion of electrical signals and information processing.

As the use of dispersion type power sources such as fuel cells with direct current output and information devices using direct current expands in the future, more and more electrical power systems and power electronics devices will be used to form interfaces in various fields as shown in Figure 1. It is expected that power electronics, which utilizes power semiconductor devices for the conversion and control of electricity, will be key technology and an important role in the promotion of efficient utilization of electric energy, which is expected to increase by the electrification ratio increases.

In Japan, elemental technologies for new power semiconductor devices used for electrical power systems and fuel cell electric vehicles have been developed aiming at ultra-low-loss, downsizing, and weight saving. Investigation on the Commercialization of the Next-generation of power semiconductor Devices Committee for the Development of Ultra-low-loss Power Device Technology Project (1998 to 2002) expected that ultra-low-loss power devices including silicon carbide (SiC) and gallium nitride (GaN) would be applied to automobiles, motor control inverters, CPU power sources[*1], UPS (uninterrupted power supply), inverters for dispersion type power sources and transmission elements of communication base stations, and estimated the effects on energy saving and reduction of CO_2 emissions in Japan at 2020 (see Table 1). The annual reduction of CO_2 emissions of 10.93 million tons corresponds to 0.98% of the total CO_2 emissions of 1,119 million tons in Japan at 1990. This fact indicates that the introduction of ultra-low-loss power devices will be able to an important role as a measure against global warming as well as contributing much to energy saving.

3 Applied technologies of power electronics

As shown in Table 2, power electronics is applied to large-scale and dispersion type electrical power systems, and further to traffic and transportation systems, household electric

Table 1 : Examples of the estimation of effects brought about by the introduction of new devices (SiC, GaN) in 2020

Application	Quantity (2020)	Energy saving (TWh/y)	Reduction of CO_2 emissions: (10 thousand tons CO_2/y)
EV/FCEV	5 million vehicles	6.25	229
Motor control	41 million units	9.96	366
CPU power source	65 million units	2.73	100
UPS	23 million units	4.71	173
Dispersion type power source	20.02 million kW	3.83	141
Communication base station (GaN)	500 thousand units	2.3	84
Total		29.78	1,093

(Unit CO_2 emission: 0.367 kg-CO_2/kWh)

* An example of the calculation for EV/FCEV (electric vehicle/fuel cell electric vehicle):
Assuming that the average output is 50 kW, the annual running time is 500 hours, and the devices are introduced into 5 million vehicles (2020: by the Fuel Cell Commercialization Study Group). If the inverter loss is improved by 5% (Si: 7% → SiC: 2%), the amount of energy saving/reduction of CO_2 emissions=50 (kW)×500 (h/year)×0.05×5 (million vehicles) =6.25 (TWh/year)= 2.29 (million tons CO_2/year)

Table 2 : Major application fields of power electronics

Field		Current major application fields (Major technical needs in the future)	Expected new application fields
Electrical power system	Large-scale	- Direct current power transmission (low-loss, downsizing)	-Flexible AC Transmission Systems (FACTS)
	Dispersion type	- Inverters for dispersion type power sources (low-loss)	-Loop controller -Direct current power supply system
Traffic and transportation system (Transport sector)		- HEV (downsizing, weight saving) - Electric railroad system (downsizing, weight saving)	-EV / FCEV
Household and office appliances (Civilian sector)		- Electromagnetic range - Air conditioner - Refrigerator - Personal computer - Illumination	
Industrial equipment (Industrial sector)		- Elevator - FA equipment - Uninterrupted power supply unit	

appliances, office equipment, and industrial equipment. In this chapter, the current major application fields, future needs for technical development, and the application fields that will appear in the future relating to electrical power systems and traffic and transportation systems are described.

3.1 Application technologies of power electronics in electrical power systems

(1) Large-scale systems

In the Japanese trunk transmission power systems, in addition to the alternating current transmission systems, direct current transmission systems of "Hokkaido-Honshu" and "Honshu-Shikoku" as well as frequency conversion facilities between "50 Hz and 60 Hz" are provided. In these systems, many thyristor elements, which are power semiconductor devices, are utilized by being connected in a series according to the operating voltage. This results in the large size of equipment, thus requiring the realization of small-size low loss power electronics devices that use high-efficiency power semiconductor devices. In the United States, power transmission systems are so complicated so that a particular transmission system has limited operation therefore consequently, the Electric Power Research Institute (EPRI) has proposed the concept of FACTS (Flexible AC Transmission Systems) which is increasing of the transmission line utilization factor (power flow control) and stabilize the system. This concept involves electrical power control systems to improve the weak of alternating current transmission systems using power electronics, and, self-exciting SVC (static var compensator), UPFC (unified power flow controller), etc., have been developed mainly in the United States.

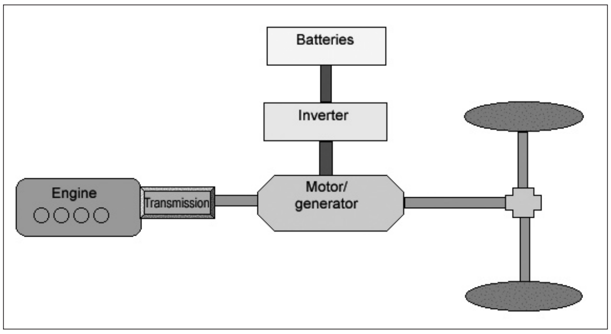
(2) Dispersion type systems

Recently, the number of new energy systems and cogeneration systems installed in the neighborhood of consumption areas (power distribution systems) is increasing. Since the dispersion type power sources such as solar generators and fuel cells generate direct current electricity, the generated electric power is supplied to electrical power systems after being converted to alternating current using inverters that are power electronics devices. It is estimated that the loss caused by inverters for dispersion type power sources is 6% for Si and 2% for new power semiconductor devices of SiC. As for new energy, it is expected by 2010 that 2.2 million kW will be generated by fuel cells, 4.82 million kW by solar generators, and 3 million kW by wind power generators[3]. Electrical power of 6.5 million kW is already being generated by cogeneration systems[4], and still more systems are expected to be built as the ESCO projects are promoted. Therefore, it is necessary to reduce the loss from power electronics devices which form the interfaces between these dispersion type electrical power sources and electrical power systems.

When a large number of dispersion type power sources are introduced, we must concern that the quality of electrical power is affected by the variation of output, making it necessary to develop measures to reduce the effects on the total system. Those researches enhanced the optimization of the system voltage and accidental current controlling using a device which called a loop controller, that consists of power semiconductor devices is being conducted with the Central Research Institute of the Electric Power Industry as the hub of research activities in Japan[5].

Although the electrical power systems in Japan are based on alternating current, with the increase of equipment and devices using direct current power sources such as routers and servers, and dispersion type power sources such as solar generators and fuel cells that provide direct current in principle, a practical idea is to construct power supply systems mainly of direct current within buildings (homes and offices) or consumption areas. DC/DC converters are indispensable for the conversion of direct current also a type of power electronics device.

Figure 2:An example of a hybrid electric vehicle (HEV)[6]



3.2 Application technologies for power electronics in traffic and transportation systems

Recently, the electric motors are attracted for the purpose of fuel saving, low noise, and low exhaust gas emissions as well as for the application of hybrid electric and fuel cell vehicles. Hybrid electric vehicles (HEV) which combined with gasoline and electric motor have already been developed and introduced into the market. Also the development of fuel cell electric vehicles is keen and leasing and has started competition. Furthermore, the development of electric vehicles (EV) had been suspended by most of the automobile manufacturers by 1990, then it has been restarted because of the increasing concerns over global environmental problems and the enforcement of ZEV (zero emission vehicle) regulations of the state of California in the United States[6]. Thus, while most of the present automobiles use gasoline as the energy source, future automobiles will use electric energy that is stored in batteries using inverters, which are power electronics devices, to drive the motor (see Figure 2).

In addition, recent automobiles are equipped with many complicated in-vehicle electric systems in order to provide safety, amenity, and convenience. As a result, the current 14V power supply system is reaching the limit of voltage source capacity, and it is now being investigated to raise the system voltage to 42 V. Power electronics is the key of the next-generation automobile power source systems which using 42 V*2.

In the electric railcar systems, power regenerative braking is widely used in order to return the braking energy to the overhead wire system. Power regenerative braking is a system in which the motor is used as a generator when the brake is operated to convert the kinetic energy of the railcar to electric energy and to return the generated electric energy to the overhead wire system so that the recovered energy is used to run other railcars. In the regeneration process, generated electric power is returned to the overhead wire system through the inverters for electric railcars, which are also power electronics devices.

For the sake of fully-fledged dissemination of hybrid electric vehicles and fuel cell electric vehicles, and further energy saving of electric railcars, downsizing, weight saving, and cost reduction of power semiconductor devices used for the inverters are required.

As has been described above, power electronics is not only the basic technology that supports the energy infrastructures in various fields including the industrial, civil, and transport sectors, but also it is indispensable for future prospective electrical power systems such as dispersion type electrical power supply systems that use loop controllers and direct current power supply systems.

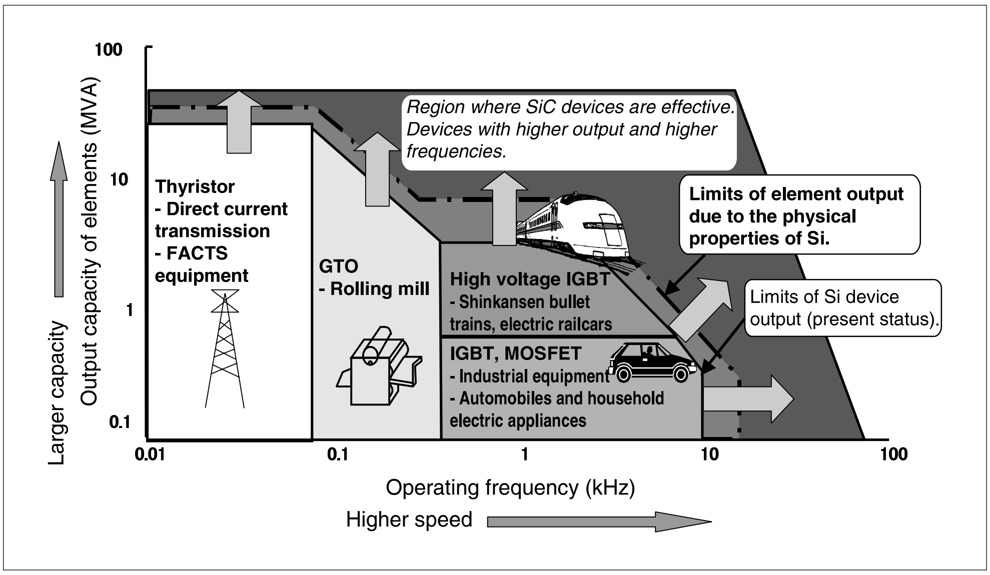
4 Trends in the development of power semiconductor devices

4.1 History of the device's development

Power semiconductor devices which are used for switching between "On" and "Off," are the most important component of power electronics equipment that consists of filters, cooling devices, etc. The less the conducting loss and the loss in on-off switching (the switching speed is faster), the electrical power conversion is much effective.

Most of the present power semiconductor devices are made of silicon (Si). General Electric in the United States was the trigger of the development and commercialized the thyristor which enhancement of power electronics in 1956[7]. Although Japan was behind the United States and Europe in the development of power semiconductor devices, that having a high capacity was successfully developed around 1970 in a project relating to automobiles, and, as a result, catapulted Japan to the top level of the world in the power electronics technology[8]. Afterwards to the latter half of the 1980s, GTO(Gate Turn-Off Thyristor), the optical trigger thyristor, MOSFET (metal oxide semiconductor field effect transistor), IGBT (insulated gate bipolar transistor), etc., were rapidly developed making it possible to meet the diversified needs in electrical power conversion ranging from small capacity to large capacity[9] (see Figure 3).

Figure 3 : Application fields of power semiconductor devices



Source: Data of Power Electronics Research Center of the National Institute of Advanced Industrial Science.

From the 1990s to now, research and development aiming at high performance has been conducted by utilizing the fine processing technology for LSIs.

However, it seems that the technology is reaching the limits of Si material, so long as the conventional technologies are applied for achieving high performance. It is required for the development of prospective fuel cell electric vehicles to improve fuel consumption by downsizing and weight saving as well as by simplifying the cooling system. It is also hoped for the motor control to develop inverters integrated with the motor by improving heat resistance. Under such circumstances, the "Development of Ultra-low-loss Power Device Technology" Project aimed at developing new materials such as SiC and GaN, considering the needs of the technical development described above. According to the post-project evaluation report[1], among the achievements relating to basic technology development are large-diameter crystals and high performance of the products. As for the production technology of elements, it has been demonstrated that the "on-resistance" of SiC basic elements is less than one tenth that of Si elements and that the power density is ten times or higher than that of Si elements. However, it remains that many problems need to be solved for commercialization such as cost reduction of substrates, mounting technology, and development of peripheral technologies.

4.2 Application effects of SiC power semiconductor devices

SiC semiconductors have excellent indices performance for power semiconductor devices with a band gap at about three times that of Si semiconductors, dielectric breakdown electric field at about ten times, and thermal conductivity at about three times. SiC semiconductor elements would enable the realization of high withstanding voltage, high-speed operation, low loss in power conversion, and high temperature operation. For example, high temperature operation at 400°C or more higher will become possible because the characteristics of a semiconductor can be retained up to 1,500°C or higher due to the broad band gap[10]. Probable merits of the use of SiC semiconductors for power semiconductors including downsizing are as follows:

(1) High withstanding voltage

The withstanding voltage of conventional power electronics devices is between 6 and 8 kV at the highest, and when higher withstanding voltage is required, as in the case of Kii Suido HVDC (High Voltage DC) whose rated direct current voltage is 250 kV, devices are connected in series to obtain the equivalent of devices with a high withstanding voltage. Since the dielectric breakdown electric field of SiC semiconductors is approximately ten times of Si semiconductors, it is expected that the dielectric withstanding voltage of SiC semiconductors will also become ten times of Si semiconductors. If the dielectric withstanding voltage of a device becomes higher, the number of devices connected in series can be decreased so that devices are downsized and conducting loss and switching loss are reduced resulting in a low total loss.

(2) High speed operation

To increase the operation speed of switching device means to operate with higher frequencies. A high dielectric breakdown electric field enables a reduction in the layer thickness so that the length of the device (running distance of carriers) can be decreased, thereby making it possible to operate at high speed. In addition, when magnetic parts such as a transformer are involved, power electronics devices can be downsized in inverse proportion to the switching frequency. Furthermore, high-speed operation improves controllability, waveforms of input/output voltage and current, suppression of higher harmonic waves, and then it is enabling the elimination or downsizing of filter devices.

(3) Low loss of power conversion

Reduction in the loss of power of devices significantly contributes to reducing the loss of power of electronics devices. The loss of power conversion of SiC semiconductors is theoretically one 100th to 300th that of Si semiconductors. Since a higher dielectric breakdown electric field enables a reduction in the layer thickness, electrical resistance will be significantly reduced and result in low loss.

(4) High temperature operation

If devices can be operated at high temperature, a high degree of freedom will be provided for the cooling design of power electronics devices. Conventional devices require a certain amount of surface area due to the thermal restriction. The use of air cooling instead of water cooling will also contribute to the downsizing of devices. For example, hybrid automobiles are equipped with a cooling system consisting of many parts including a radiator, so downsizing will bring about an improvement in fuel consumption.

5 Current status in Japan

5.1 Structural transformation of industries

The development of power electronics technology in Japan has been supported by industries, particularly by the heavy electric machinery industry. However, the heavy electric machinery industry is in a severe business environment while the Japanese economy is suffering from a recession.

The power electronics is much sought after in the amenity-oriented fields such as automobiles and household electric appliances in order to attract consumers' attention, but at the same time it is utilized for energy infrastructures such as electrical power systems having an important meaning as a social infrastructure type technology. Currently in Japan, dichotomization of the heavy electric machinery manufacturers is proceeding as a result of reduced orders due to the domestic suppression of investment particularly by electrical power companies (Toshiba Corp. + Mitsubishi Electric Corp. → TMT & D, Hitachi, Ltd. + Fuji Electric Co., Ltd. + Meidensha Corp. → Japan AE Power Systems).

Although the Japanese heavy electric machinery industry has grown keeping pace with the rapidly increased domestic electrical power demand, it now stands at a turning point because new domestic businesses have decreased due to the saturation of electrical power demand in Japan, whereas the demand for electrical power in developing countries particularly in China is increasing.

While it is an objective of companies as to how to maintain the business within the country, being unable to actively invest in the development of power semiconductor devices that require additional costs, another problem is how to expand international business in order to carry on global price competition.

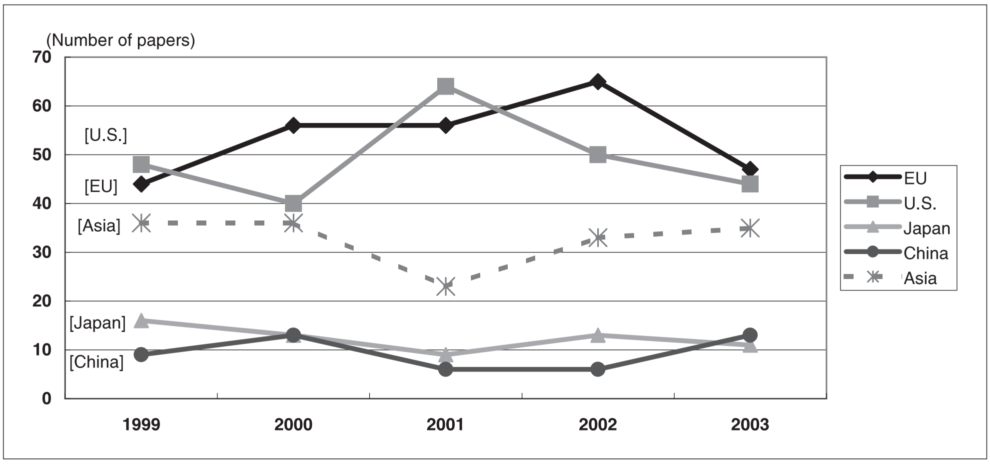
5.2 Development of human resources in universities and the efforts of The Institute of Electrical Engineers of Japan

Fewer students are interested in the hardware-oriented semiconductor industry (power electronics) than in the semiconductor industry (electronics). Newell of the United States defined power electronics in 1973 as a technology in which three technical fields-power (electrical power and electrical equipment), electronics (devices and circuits), and control-are completely combined. As this definition indicates, power electronics is progressing, being supported by the development of these technical fields, and the areas that it covers are getting more and more diversified and complicated[11].

In the field of education, the following questions are being discussed: "what are the fundamentals of power electronics?", "how should lectures be improved to induce students' interest?", and "how can the expansiveness and importance of power electronics be communicated?".

The Institute of Electrical Engineers of Japan has established the "Collaborative Study Committee on the Education of Power Electronics" (April 2000 to March 2002) and the "Collaborative Study Committee on the Education of Power Electronics in the IT period" (October 2002 to September 2004)[12]. The objectives of these committees are to carry out investigation on the methods of education in power electronics including field research and to obtain guidelines for improvement. In these committees, the following issues have been and are being discussed in pursuit of the measures that should be taken to make the education of power electronics more attractive: i) choice and arrangement of curriculum and syllabus, ii) effective utilization of multimedia that induce the interest of students, iii) optimum balance between hardware and software, iv) effective application of simulation, and v) comprehensive training of students with a view to international

Figure 4 : Comparison of the numbers of papers on power electronics



Source: Database of Thomson ISI on papers.

activities.

6 Trends in research

In order to analyze the domestic and international trends in the research on power electronics, the numbers of papers reported on power electronics were compared by countries (regions) (see Figure 4). The database of Thomson ISI was searched for papers that include any of the keywords-"power electronics," "power electronic," and "power semiconductor"—in the title, abstract, or keywords. The term searched was five years from 1999 to 2003. When authors of a paper belong to two or more countries, the paper was counted for each country.

EU was top in the number of papers reported during the five years, which was 268; the United States comes next with 246; Japan reported 62; and China 47. Although not shown in the chart, Canada 30, Taiwan 22, and Australia 20 respectively. Judging from the numbers of papers, the United States and Europe are leading the research on power electronics, and Japan and China are following on almost the same level (Hong Kong was included in China for 1999). The dotted line in the chart shows the total of Asian countries including Japan and China, indicating that the Asian group can become the third power that follows the United States and Europe.

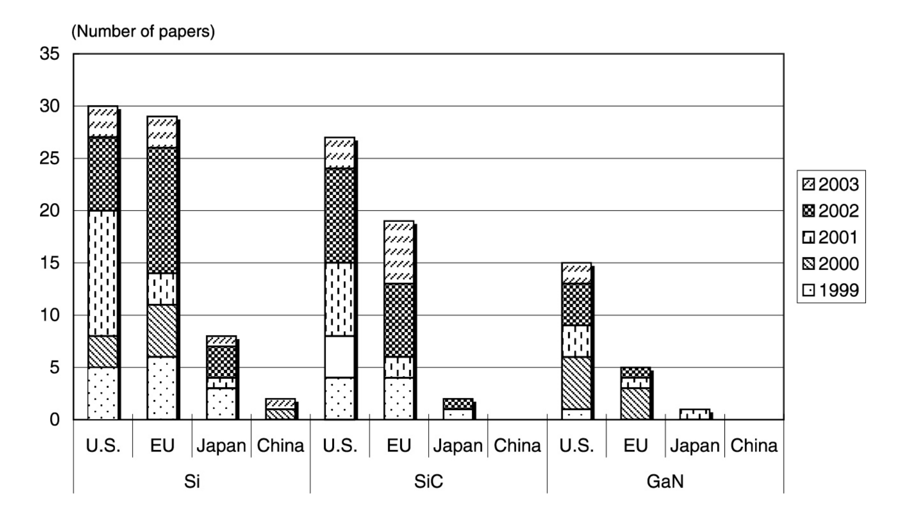
Among the papers reported by Japanese researchers, the number of papers involving industrial companies was 37 and that of universities was 35, which indicates that the numbers are comparable. The fact that the number of papers reported by the industry is comparable to that reported by universities, where much importance is published papers, shows that industrial circles have contributed much to the development of power electronics.

And then, analyzing the domestic and international trends in research on power semiconductor devices, which are important components of power electronics devices, the numbers of papers that include any of the keywords relating to the materials of devices-Si ("Si" or "Silicon"), SiC ("SiC" or "Silicon Carbide"), and GaN ("GaN" or "Gallium Nitride")- in the title, abstract, or keywords of the papers are shown in Figure 5. The numbers are in the order of the United States, EU, Japan, and China for all of Si, SiC, and GaN, which indicates that research on power semiconductor devices using new materials such as SiC and GaN is being actively conducted in the United States as compared to other countries (regions).

In the United States and Europe, collaboration between universities and industry is being promoted in the field of power electronics.

In the United States, CPES (Center for Power Electronics Systems) was established in August 1998 as one of the research centers of the National Science Foundation (NSF)[13]. A consortium consisting of five universities was organized, allocating special technical fields to each university. Its integrated system program provides a strong interdisciplinary approach with collaboration of more than 80 companies through an industrial cooperation program. In Europe as well, ECPE (Engineering Center for

Figure 5 : Comparison of the numbers of papers on semiconductor power semiconductor devices



Source: Database of Thomson ISI on papers.

Power Electronics) has been established with the objective to promote research, education, and technology transfer to the industries[14].

7 Conclusion

Power electronics is a basic technology for energy infrastructures and, at the same time, an important technology that helps to solve environmental problems because it can provide measures to realize low loss, downsizing, and weight saving of various equipment and devices used for electrical power systems and automobiles.

In the past, we, in Japan succeeded in the development of power semiconductor devices having high capacity by Si and climbed to the top level in the world. Recently the "Development of Ultra-low-loss Power Device Technology" Project has been finished and the next step of development is being investigated. In the future, it is necessary to plan a project that aims at the practical applications of the results of material development on which the past project placed emphasis. Based on the standpoint that the research results for new materials that have been obtained should be put to practical use, a series of research and development activities covering a wide range from device development to system applications must be continued.

Power electronics covers a lot kind of diversified areas including electrical power systems, traffic and transportation systems, and household electric appliances; therefore, it is necessary to establish a roadmap based on the needs for technical development required by each field and to promote research and development. Since the recent expansion of the use of dispersion type power sources has brought about concerns the electric power quality of Japanese electric power systems, it is particularly important to quickly realize the practical application of power electronics devices that contribute to the stabilization of electric power systems when dispersion type power sources are used in large quantities.

Although power electronics has been developed primarily by industry, particularly by heavy electrical machinery manufactures, it is now difficult for a single company to actively invest in the development of new power semiconductor devices. In the universities as well, which have the responsibility to supply human resources to the industry, there are problems in the education of human resources. Furthermore, judging from the numbers of papers, research on power electronics is being conducted more actively in the United States and Europe than in Japan, and collaboration between industry and academia is being promoted steadily there. Also in China, where demand for electrical power is expected to grow rapidly and the technology is considered to bring about significant ripple effects, the number of papers on power electronics is already comparable to that of Japan. Projects that aim at practical applications of power electronics must be promoted with a view that the industry, academia, and government should cooperate in fostering researchers and engineers who will play a major role in the development of next-generation technology.

Acknowledgements

This report has been prepared based on the November 6, 2003 lecture, "Power Electronics and Energy Management," given at the National Institute of Science and Technology Policy by Professor Tadashi Fukao, who is president of The Institute of Electrical Engineers of Japan, together with the results of our investigation. In addition, we would like to express our sincere thanks to Professor Ryuichi Shimada of the Research Laboratory of Nuclear Reactors, Tokyo Institute of Technology; Professor Hiromichi Ohashi of the Graduate School of Science and Technology, Tokyo Institute of Technology; Director Kazuo Arai of the Power Electronics Research Center, National Institute of Advanced Industrial Science and Technology; and Principal Research Scientist Tadashi Ishii of the Energy Electronics Institute, National Institute of Advanced Industrial Science and Technology, for the material and advice they have provided for this report.

Notes

*1 When power is supplied to the CPU, alternating current is converted to direct current using power semiconductor devices and, then, the required voltage is obtained by direct current to direct current conversion (DC/DC converter).

*2 The value of 14 V (42 V) is a nominal value of the circuit voltage during the operation of the electric system of a vehicle, and the voltage of batteries used is 12 V (36 V).

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