Commemorative lecture at the 38th Honda Prize
Award Ceremony on the 16th November 2017

Research and Development of SiC and Practical Use

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HONDA FOUNDATION

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■Date of Birth

June 5th, 1939

■Biography

1962: Department of Electronic Engineering, Faculty of Engineering, Kyoto University

1964: Master's Degree, Graduate School of Engineering, Kyoto University

1964: Research Associate, Kyoto University

1970: Doctor of Engineering, Kyoto University

1971: Assistant Professor, Kyoto University

1976–1977: Visiting Associate Professor, North Carolina State University, U.S.A.

1983: Professor, Kyoto University

2003: Mandatory retirement from Kyoto University and appointed as Professor Emeritus

2004–2012: Director, Innovation Plaza Kyoto, Japan Science and Technology Agency

■Academic Society/Association Activities

President, SiC Alliance, General Incorporated Association (2015–)
The Japan Society of Applied Physics; The Institute of Electronics, Information Science and Communication Engineers; The Institute of Electrical Engineers of Japan; The Japanese Association for Crystal Growth; IEEE (The Institute of Electrical and Electronics Engineers, Inc.)

■Selected Publications

Silicon Carbide Vol. I, II (Akademie Verlag, 1997)
Silicon Carbide—Recent Major Advances— (Springer, 2003)
Semiconductor SiC Technology and Applications (Nikkan Kogyo Shimbunsha, 2003)
Semiconductor SiC Technology and Applications Second Edition (Nikkan Kogyo Shimbunsha, 2011)
Wide Gap Semiconductors—From Dawn to the Frontlines—(Baifukan, 2013)

■Awards and Honors

2001: The 1st Yamazaki-Teiichi Prize (in the field of semiconductors and semiconductor devices), Foundation for Promotion of Material Science and Technology of Japan

2002: The Commendation for Science and Technology by the Minister of Education, Culture, Sports, Science and Technology in 2002 (Research Contribution Award)

2004: The 4th (2003) Research Achievement Award, The Japan Society of Applied Physics

2004: The 41st (2003) Research Achievement Award, The Institute of Electronics, Information Science and Communication Engineers

2005: The SSDM Award-2005

2013: The 2012 Asahi Prize (pioneering research of power semiconductor silicon carbides)

2016: The IEEE David Sarnoff Award

2017: The Academia Prize

Also, appointed to Fellow of the Japan Society of Applied Physics, Fellow of the Institute of Electronics, Information and Communication Engineers, and Life Fellow of the IEEE

This report is the gist of the commemorative lecture at the 38th Honda Prize Award Ceremony at the Imperial Hotel, Tokyo on 16th November 2017.

It's a great pleasure and honor for me to receive the Honda Prize. I would like to take this opportunity to express my deepest appreciation to the nominator for recommending me and to the members of the Selection Committee for choosing me.

Last year, I was awarded the IEEE David Sarnoff Award, and, recently, major advances have been made around silicon carbide (SiC) on a global scale, and now I am here to receive the Honda Prize. To be blessed with a series of unexpected good fortunes and happy events, I myself have become overwhelmed and at a loss about how to express my feelings.

Today, I would like to deliver a talk entitled "The Path a Crazy Boy Walked" as a commemorative lecture. It was when I was still a fledgling young man that I started to work on an outrageous research subject, and at first, I could not even see where I was heading. Still, I never forgot my former mentor's word. He often said: "An engineering technology becomes meaningful only when it is used in society," which has always been my motto to live up to. Also, I have never changed my attitude of "not imitating others" and "having courage to challenge something that others haven't done" even until now.

The contents of the talk are shown here. First, I would like to talk about ICT innovation through the development of semiconductors. Let me explain the current situation. I heard that most of the people present here are not experts in science & technology. If you are familiar with that field, you may find this talk tedious. Therefore, I would like to humbly ask you to remain patient to the end.

Next comes the effective use of electric energy. In this part, I will explain about the important role that power semiconductors play. And, also, from the viewpoint of energy conservation, I want to emphasize why now is the time that we should give our full attention to silicon carbide (SiC). I conducted basic research at Kyoto University, which became my turning point and led me to make an epoch-making presentation. I would speak about the basic research I conducted at university, in which I studied crystal growth by "step-controlled epitaxy," and the devices. I proposed such as an SBD (Schottky-barrier diode) and a MOSFET (metal-oxide-semiconductor field-effect transistor) using this method.

For a research outcome to be actually used in society, it has to be put into practical use by business enterprises; however, they only make such efforts when that is promoted by a national project with a guideline showing "which direction to go." I would like to explain how we have addressed this challenge, and at the end of this, I would like to talk about future prospects.

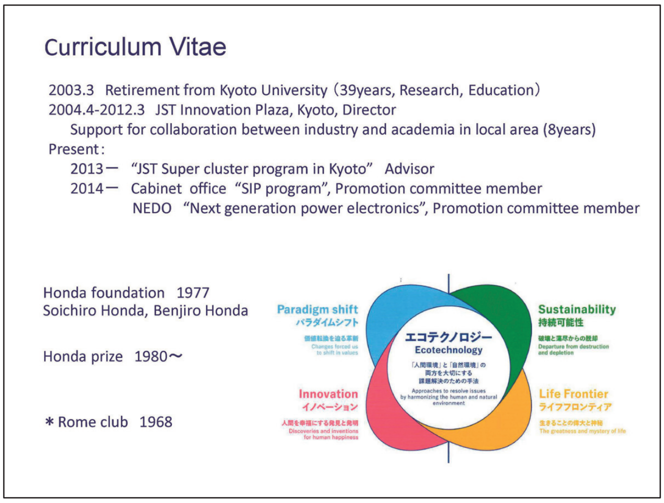


Fig. 1

〈Fig. 1〉 Since my profile has already been introduced, let me omit it here.

When I was young, I heard from my former mentor that the Club of Rome gave a warning in 1968, saying: "If the current trend continues, human beings will continue on toward destruction. Something must be done to deal with global warming, food shortages and population growth." In order to solve these complex problems, the Honda Foundation was established in 1977 by Soichiro Honda and his younger brother Benjiro. And in the field of ecotechnology, under the banner of four items, namely, sustainability, paradigm shift, innovation, and life frontier, they instituted Japan's first international prize. I would like to express my heartfelt admiration to their keen insight.

■ ICT Innovation through the development of Semiconductors (20th century)

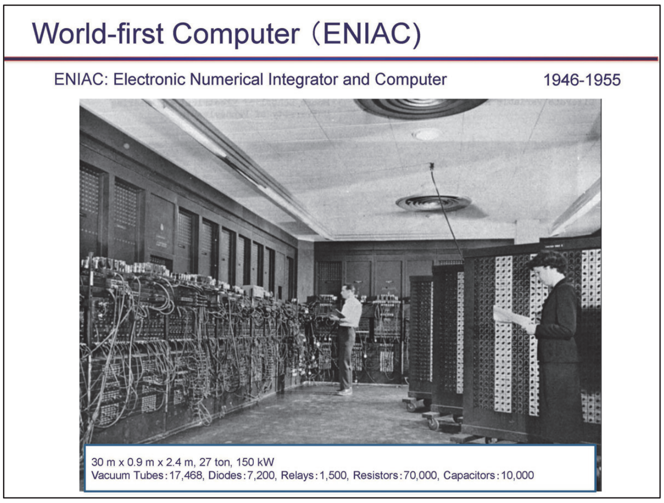


Fig. 2

〈Fig. 2〉 Now, I would like to briefly explain how much we presently benefit from semiconductors.

I think many of you have seen this picture before; this is the world-first computer, which included vacuum tubes. It seems to have worked a little from 1946 to 1955. It was a super-jumbo computer using vacuum tubes measuring 30 m in depth, 2.4 m in height and 90 cm in width, and it could be used only at night. Due to its enormous power consumption, it had to be used only in the nighttime; otherwise, a blackout would take place in the area where it was situated.

If one of the 17,000 vacuum tubes got broken, it took 30 minutes to repair it, and even if reliable tubes were used, one tube got broken every two days. That was the way it was then. It was the invention of a transistor using semiconductors that brought about the computers evolution to modern models.

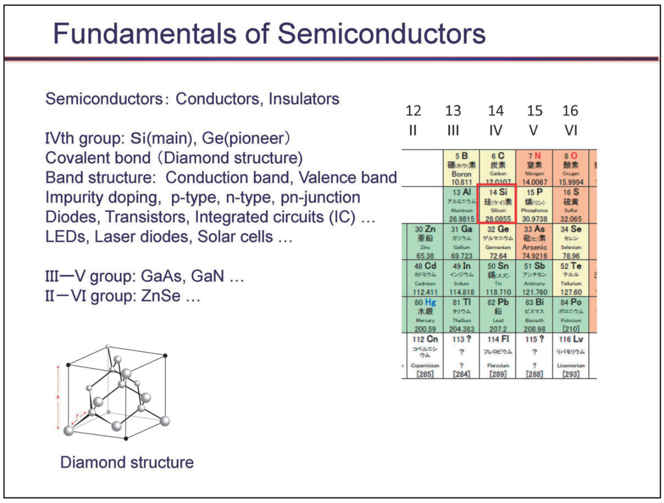


Fig. 3

〈Fig. 3〉 Actually, my younger brother asked me "What is a semiconductor?" the other day, so I think it would be better to briefly explain about it. In order to pass an electric current, you need a conductor. But, a bare wire is dangerous and you cannot touch it, so you need to use insulators like rubber, to cover it. A semiconductor falls between a conductor and an insulator, whose properties are literally something between them.

However, semiconductors have hidden interesting properties. In terms of materials, silicon in the periodic table plays a major role. And, also, the III-V group and the II-VI group on both sides of silicon in the table are also used as semiconductors. Semiconductors form a crystalline structure called a diamond structure, which has the same structure as that of natural diamonds.

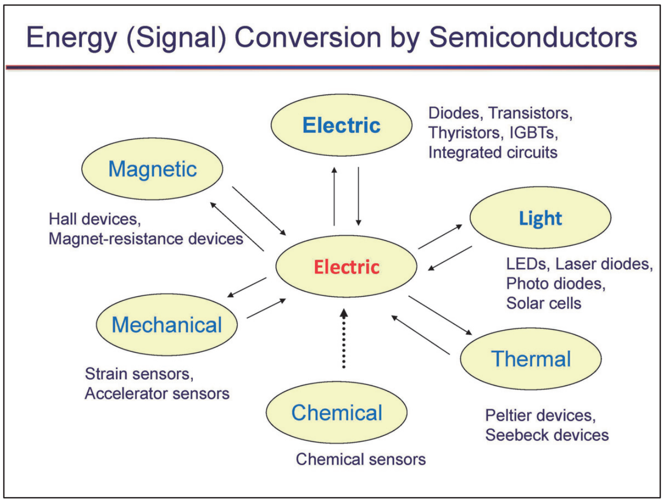


Fig. 4

〈Fig. 4〉 Use of semiconductors enables conversion between various types of signals and energy. Presently, semiconductor devices that enable conversion between electricity and electricity and between electricity and light are widely used throughout the world.

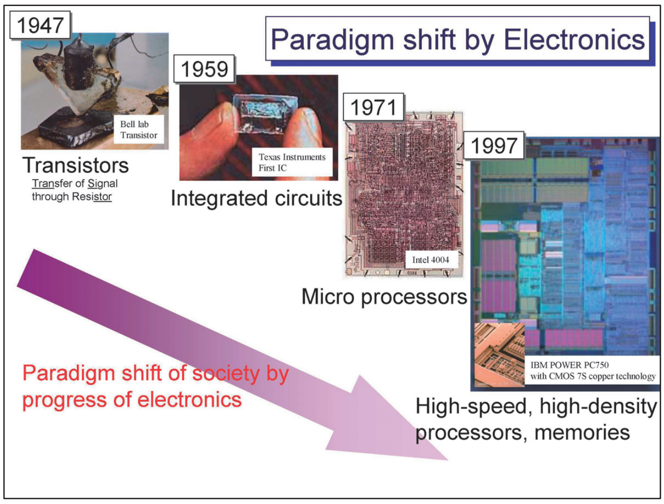


Fig. 5

〈Fig. 5〉 The invention of transistors led to the development of an integrated circuit, and then, a program was added to it; thus, a microcomputer was realized around 1970. After that, the use of cutting-edge CMOS (complementary metal-oxide-semiconductor) further advanced the development of computers, and their development has continued until today. This is the great contribution that semiconductors have made, and at the same time, the invention of transistors has promoted the progress of electronics, which has led to major changes in society.

Fig. 6

〈Fig. 6〉 Along with the shift in computers from desktop PCs to tablet PCs, semiconductors have been increasingly used for digital cameras, the most recent iPods, iPads and smartphones, etc. In such an area, however, a motor to turn a hard disk that has been used in a computer is not needed anymore. Instead, they all come loaded with semiconductors. A large amount of memory is stored in the cloud, and you take only things you need out of it. That is the way things work now.

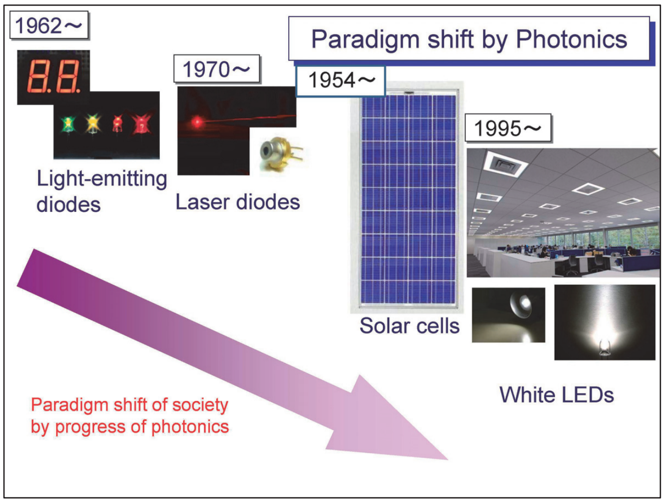


Fig. 7

〈Fig. 7〉 Another remarkable contribution of semiconductors to society is associated with the interconversion of light and electricity. The invention of light-emitting diodes (LEDs) led to the development of laser diodes, which is used in a laser pointer. Solar cells are playing a principal role in renewable energy. After the introduction of blue LEDs, white LED lamps, the combination of blue LEDs and yellow fluorescence agents, were produced. Probably, in a few years, almost all the fluorescent lamps will be replaced by LED lights. Thus, we can say that during the 70 years after the invention of transistors, semiconductors emerged and have come to play a leading role in society and totally changed our view of the world.

■ Effective Use of Electric Energy (Role of Power Semiconductor)

Well, so far, I have talked about the role of electricity in information processing or communication, where a relatively small amount of electric energy is used. In an area where larger amounts of electric power are used, such as when you need to drive a motor to move an electric car, power semiconductors come to play an important role.

Effective Use of Electric Energy using SiC

Development of society → needs much energy
Information society → needs much electric energy
For environmental protection: Increase of power plants?

Economic use of energy: Efficient use of electric energy !

Development of power semiconductors → Effective use of energy
→Prevent increase of CO_2 → Reduction of environmental load

Semiconductor Si(silicon): leading parts
High-efficiency use of electric energy: SiC (silicon carbide) emergently progress!!

Fig. 8

〈Fig. 8〉 Since electric energy is very easy to use, its consumption has continued to rise. In order to make up for power shortages, power plants have to be built; however, since the great earthquake in 2011, most nuclear power plants have ceased to operate, and fossil fuels such as coal, petroleum, and LNG (liquefied natural gas) are being burned at thermal power plants. That means we are producing a lot of CO_2 and accelerating global warming, which is not good for the environment. If we can reduce the energy loss resulting from power consumption, it will become possible to launch a new industry, which will also satisfy your requirements.

It is power semiconductors that are utilized in the use of electric energy. Semiconductors bear the responsibility of reducing the energy loss taking place there. Or I would rather say that we are expected to focus our efforts on this important point. Silicon has so far played a major role in power semiconductors, however, silicon carbide has rapidly come to the forefront.

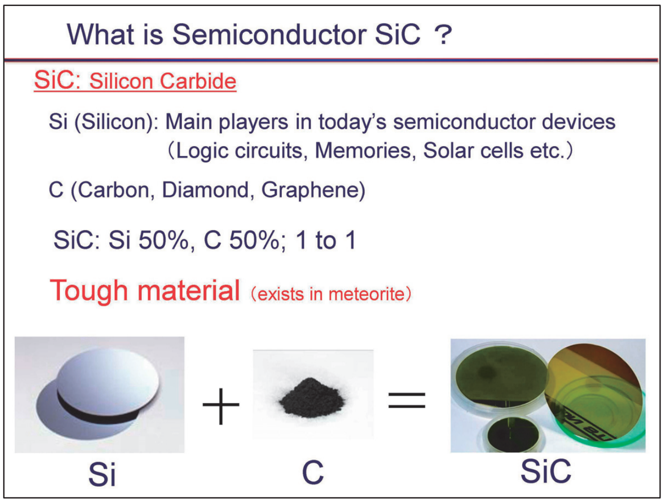


Fig. 9

〈Fig. 9〉 A SiC semiconductor is made from silicon carbide, which is a compound created by combining silicon and carbon in a proportion of one to one. Raw materials for silicon are all around us here on earth. For example, you can take silicon from sand. If you burn something, charcoal is produced. Since silicon carbide consists of such things, we certainly have sufficient raw materials.

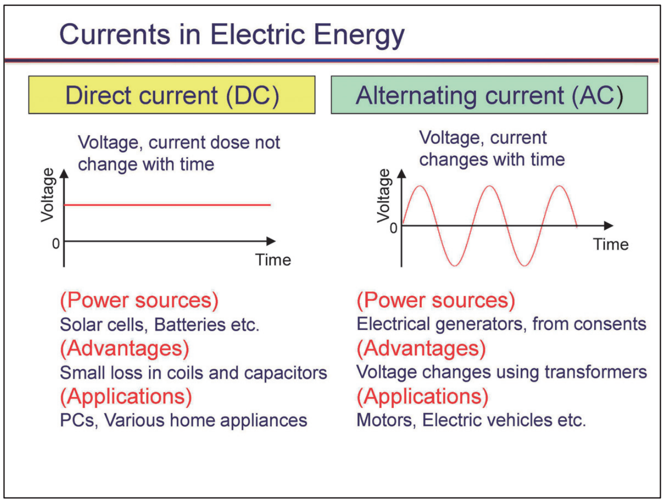


Fig. 10

〈Fig. 10〉 As you all know, direct current is sent from batteries. Direct current flows in one direction and returns to the ground through a grounding wire. On the other hand, alternating current flows while changing its waveform over time as shown in the figure. Both current and voltage demonstrate a similar change. Personal computers and smart phones are powered by direct-current batteries. But power plants provide alternating-current power. Therefore, as you can see, conversion between direct current and alternating current is very important.

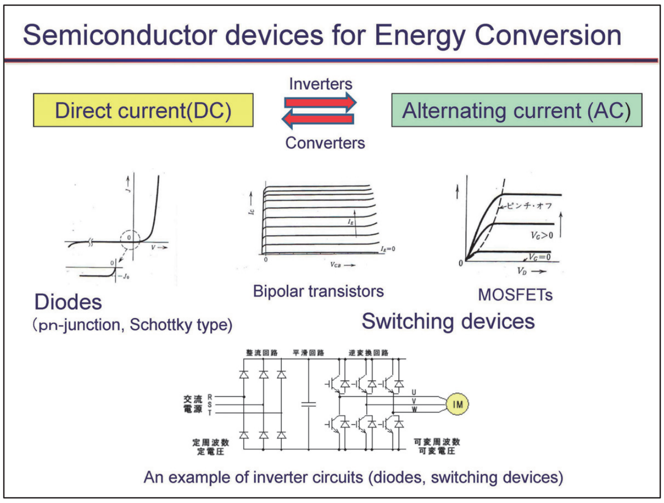


Fig. 11

〈Fig. 11〉 For converting power from alternating current to direct current, you need diodes that have a property of allowing electricity to flow only in one direction, while blocking it in the opposite direction. From electric power companies, alternating-power with 50 Hz is provided in East Japan, and alternating-power with 60 Hz is provided in West Japan. Household appliances you are using at home such as inverter air conditioners, inverter refrigerators, inverter washing machines, or inverter fluorescent lamps are designed to convert power from alternating current to direct current, and then, to cut it off with fast switching to create a high-frequency alternating current. For these appliances to achieve that, they have to have transistors. There are two types of transistors, but today, we want to pay attention to MOSFETs. We need diodes and transistors to achieve conversion between direct current and alternating current.

By the way, when you try to rotate an AC induction motor in the alternating-current state, first, the alternating current is converted to direct current, which is then cut off with fast switching of an inverter to rotate the motor. This is the operating principle of high-speed rotation.

■ Economic Use of Energy and Expectation for SiC Power Semiconductors

Then, what impact does the use of silicon carbide (SiC) have on the effective use of electricity?

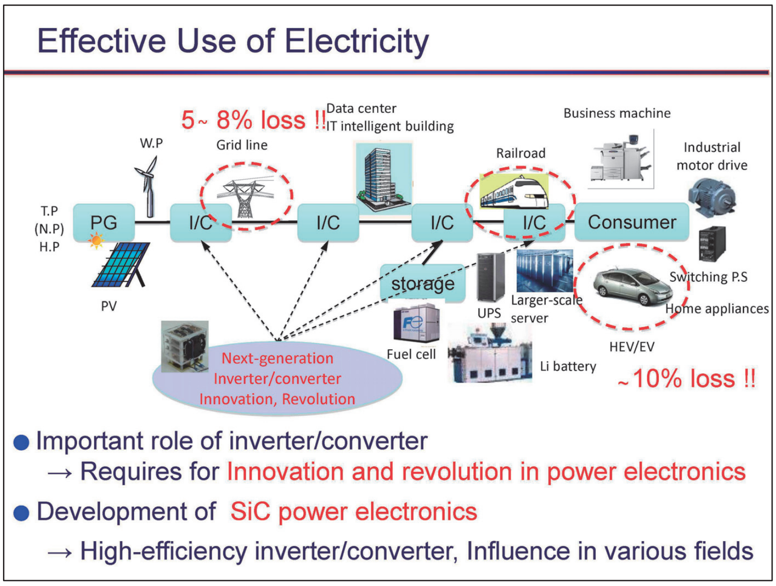


Fig. 12

〈Fig. 12〉 The figure shows the flow of electricity from power plants to users. During the electricity transmission process, frequency conversion, conversion from direct current to alternating current, and conversion from alternating current to direct current take place, and this process is believed to result in the loss of about 5% of all the electricity generated.

Let's say one user has a 2 kW air conditioner. About 10% of that power is wasted as heat. Since currently used bipolar-type inverters called Si-IGBTs (silicon-insulated gate bipolar transistors) have a problem of allowing electricity to flow in a reverse direction due to slow switching speed, this causes a significant energy loss. That means the electric power that reaches users is 85% of the entire power generated at power plants. This is a serious problem.

Replacing silicon IGBTs with silicon carbide MOSFETs at places where conversion is performed can greatly reduce energy loss.

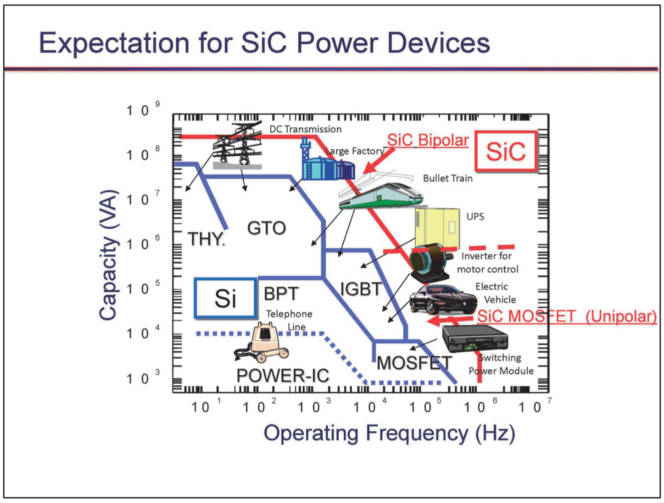
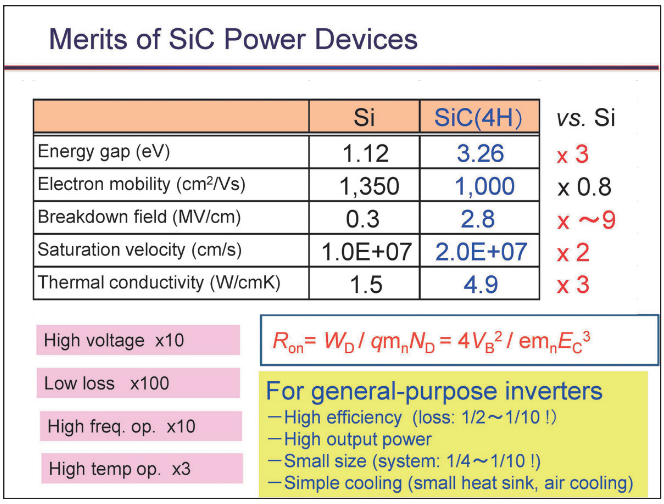


Fig. 13

〈Fig. 13〉 This figure shows what silicon power devices are like and what they are used for. As you can see, if silicon carbide MOSFETs are created, considering their performance, silicon IGBTs, which are currently the mainstream of power devices, can be almost completely replaced by them.

Silicon MOSFETs are used at low power levels, which is the limitation determined by the property of the material. Silicon carbide could be used at power levels tens of times higher than that at which silicon MOSFETs are used. This is a significant difference.



	Si	SiC(4H)	vs. Si
Energy gap (eV)	1.12	3.26	x 3
Electron mobility (cm²/Vs)	1,350	1,000	x 0.8
Breakdown field (MV/cm)	0.3	2.8	x ～9
Saturation velocity (cm/s)	1.0E+07	2.0E+07	x 2
Thermal conductivity (W/cmK)	1.5	4.9	x 3

Fig. 14

〈Fig. 14〉 This is a figure that compares the physical properties of silicon and silicon carbide. When a comparison is made by using general-purpose inverters, you can see that the limit of this physical property makes a profound difference in performance.

Since the energy gap of silicon carbide is about three times as much as that of silicon, it can be used at a temperature more than three times as high as the temperature where silicon can be used. Also, in addition to being more highly efficient, silicon carbide is more resistant to voltage and makes it possible to draw out large quantities of electric power. As it is small in size, it does not need a large cooling device. According to circumstances, it does not need water; just wind will do. Silicon Carbide is expected to demonstrate remarkable high performance.

■ **Fundamental Research (Contribution of Kyoto University)—Turning Point, Epoch-Making—**
At first, I did not realize that silicon carbide would be a useful material for making power devices. My policy to do something that other people have not done led me to silicon carbide, and since then, I have conducted a study on it. After finally finding that it can be used for power semiconductors, I have come to realize the great difference between silicon IGBTs and silicon carbide MOSFETs.

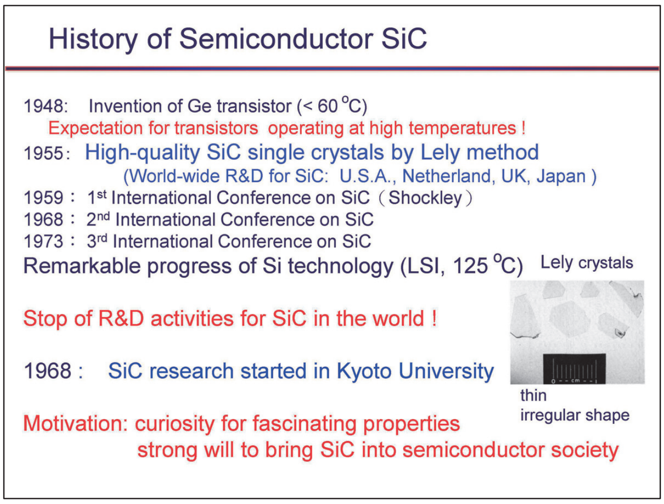


Fig. 15

〈Fig. 15〉 This figure shows the history of research on silicon carbide. Shockley and his fellow researchers were the first to succeed in producing germanium transistors. Those days, however, when placed under the temperatures of 60°C or over, the difference between p-type and n-type became indistinguishable, as a result of which transistors did not operate. That gave rise to a growing expectation for electronics that can operate at higher temperatures.

In order to promote research for development of devices that can be used at high temperatures, country-level projects were launched in America and other countries such as the Netherlands, the United Kingdom, and Japan. Since silicon had not appeared yet at that time, when Lely, a German researcher, made an announcement that it became possible to produce high quality crystals of silicon carbide, everyone jumped at that. Thus, the first round toward the development of silicon carbide started with great anticipation in the mid 1950's. However, silicon came on stage, and it was found to be usable under temperatures of up to 125°C. That led to a decline in the interest in silicon carbide, because it was difficult to grow its crystals.

Since crystals of silicon carbide in those days were very thin and had irregular shapes, device makers were not motivated to produce devices with such a thing. Around 1968, while I was writing my master's thesis and doctoral thesis, I was conducting research on how electrons move in semiconductors, which means I tried to delve into details of the physical properties of semiconductors from the angle of what is referred to as transport phenomenon. In a frustrating situation, I was wondering what fruit my engineering research would produce, and when it could make a contribution to society.

At that time, research on silicon was becoming mainstream, so business enterprises were making efforts not be left behind in that research race. In addition, Gunn diodes, gallium arsenide-based semiconductors, were introduced to the world. When direct current voltage is simply applied, gallium arsenide gives off microwaves. A lot of university researchers got involved in research on gallium arsenide. However, I knew that just going in the same direction in the same phase would end up just holding a subordinate position, and also I thought that without the right equipment, I would not be able to do anything. In my master's thesis and doctoral thesis, I discussed that II-V semiconductor compounds have a composition that is difficult to crystallize, and that even if that was successfully done, it was unlikely to be used in the world.

On the other hand, however, silicon carbide came to be known to have excellent physical properties in the first round. In particular, since silicon carbide was found to be able to be used at high temperatures and have high resistance to radiation, I thought this material might make it possible to do something that could not be realized with silicon. Also, it was already known those days that it was possible to create blue light emitting diodes, which many people were waiting for, if p-type and n-type were able to be controlled by silicon carbide. We could not make an electronic device because there was no substrate. Then, I will make silicon carbide on silicon and make a transistor in that manner. That was a dream I had.

The interatomic spacing of silicon differs from that of silicon carbide by as much as 20%. I applied for research funding, but I was not selected. When I look back, it was really crazy of me to challenge such a thing. I simply wanted to try something that seemed impossible and that no one else had ever tried. And my target was to produce electronics that could be used at high temperatures or transistors that have high resistance to radiation and could still be used. I launched my research with a focus on blue light emitting diodes and silicon carbide transistors on silicon. Now I look back and think that it was because I was working on these two things that I came to find an excellent crystal growth method called a "step-controlled epitaxy" method. If I had been pursuing only one thing, instead, I imagine it would have taken a much longer time before silicon carbide could come under the spotlight as a material for power devices around the world.

Fig. 16

〈Fig. 16〉 We worked on the creation of blue LEDs. If you melt silicon in a crucible of graphite and put a seed crystals in it, p-type and n-type layers are formed on the crystal. SANYO Electric Co., Ltd. put this technology to practical use and produced marketable products. When this was achieved, I enjoyed a sense of fulfillment, and I said to myself: “Ah, I finally see the fruits of my research.”

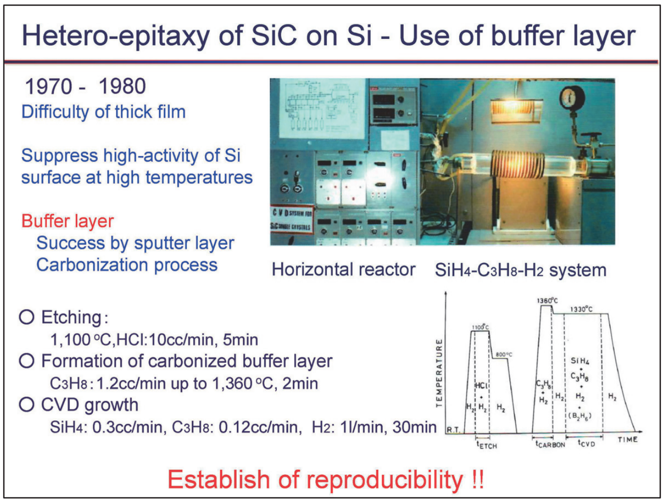


Fig. 17

〈Fig. 17〉 Now, let me move on to the subject of the epitaxial growth of silicon carbide on silicon. The photo shows a hand-built equipment. Since it was very easy for my research group to create such a thing in the university, I immediately worked on my experiment. In an attempt to apply silicon carbide on a silicon plate, I added source gases while keeping the silicon at a high temperature, which led to an increase in the activation level of the silicon surface. As a result, since silicon carbide grew rapidly after it adhered to silicon, which took place in quick succession, I did not succeed in producing single crystals. It took about 10 years to produce single crystals of silicon carbide with high reproducibility.

After I found adding source gases onto the active surface of silicon substrate did not work well, I came up with the idea of covering the surface with something like a cushion and adding gases onto it. I applied this idea and added carbon-based gas onto a silicon substrate at a low temperature, which solved this problem. I had different students try this experiment, which produced the same result. Thus, I succeeded in realizing its reproducibility.

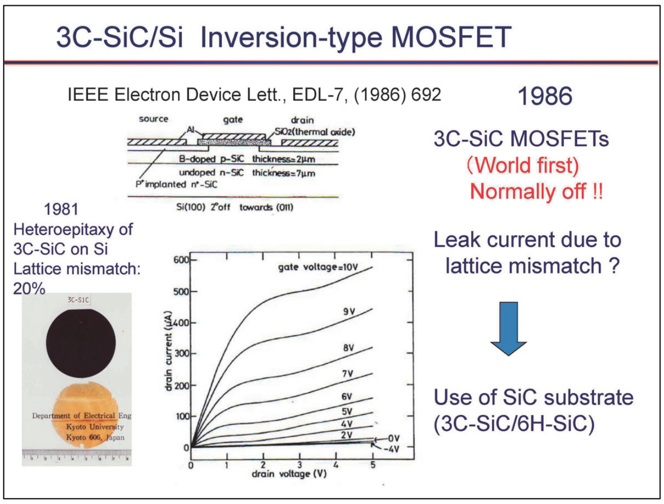


Fig. 18

〈Fig. 18〉 After this, which I call my "10 years of endurance," I announced the realization of silicon carbide MOSFETs on silicon with delight and excitement. I think it was the first such announcement relating to such a discovery in the world. I expected that the transistor characteristic would demonstrate a saturated curve, however, a leak was detected somewhere. Actually, due to irregularity caused by the 20% difference in interatomic spacing between silicon and silicon carbide, the interface of the p-n junction of the silicon carbide did not become flat, but developed a jagged structure, which resulted in the concentration of large electric field and the flow of leakage current. I realized that after all, I had to produce crystals on silicon carbide substrates. However, such substrates were not commercially available.

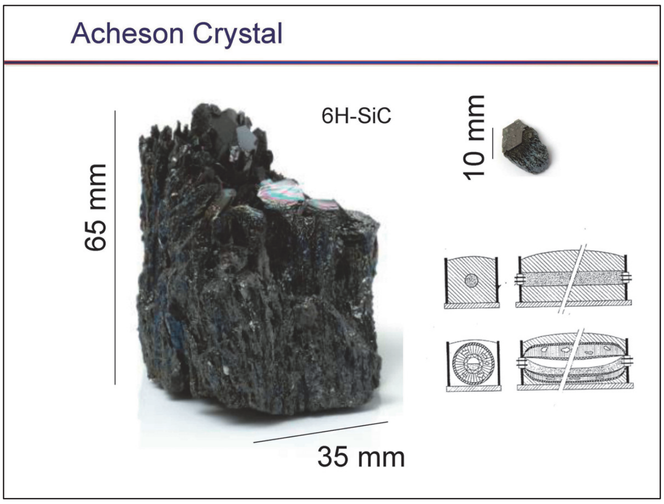


Fig. 19

〈Fig. 19〉 As a last resort, I decided to use a crystal like the one in the figure. It is used as an abrasive or as a material for fire-proof bricks. After putting sand called quartz sand and coke in a tremendously large-scale furnace, you add salt and sawdust so that gas can escape, and then raise the temperature. This is a chunk of what was made in such a furnace.

Those days, when I went to a company producing these, a person working there told me: "Surface parts are useful because they are easy to pulverize, but chunks of crystals are hard to pulverize, so if you collect and put them in a cardboard box, I will send them to you later." Accepting his kind offer, I took out small crystals on the surface of which single crystals are exposed with my students using a chisel and a hammer. Since a chunk has a shape like the one shown in the figure, you have to polish its back parallel to a single crystal face. Since it is the hardest material next to diamonds and boron carbide, sometimes it is very difficult to polish its back perfectly parallel to the front face. You can produce crystals by raising the temperature of the obtained wafer and adding the gases necessary for the growth of silicon carbide.

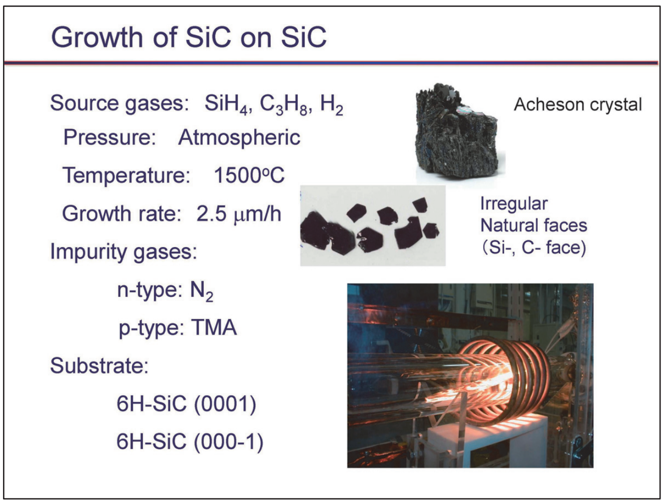


Fig. 20

〈Fig. 20〉 One day, I received a report, saying: "I have always seen a strange mosaic pattern, but I cannot see that today.” One student seemed to have made a conscious effort to grow silicon carbide on a polished surface out of a spirit of adventure. I saw it and found that student succeeded in making a uniform and beautiful surface.

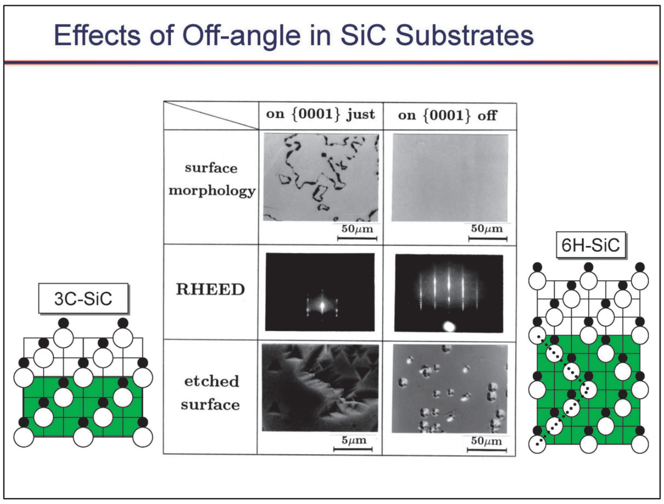


Fig. 21

〈Fig. 21〉 I checked this by simple evaluation methods. When it was applied with etching by using slightly high-temperature alkali, a totally different result was obtained. Etch pits on one crystal were close to hexagons. The others were like triangles, placed on both sides of a boundary ditch on a surface. The triangles on one side had the 180-degree inverted shape of those on the other side. Later, when I observed them by using the reflection energy electron diffraction method, it was found that the former was a zigzag stack of hexagonal crystals which was the same as a substrate, and on the other hand, the latter was the growth of cubic crystals of silicon carbide. That was really a good job. This happened in 1986.

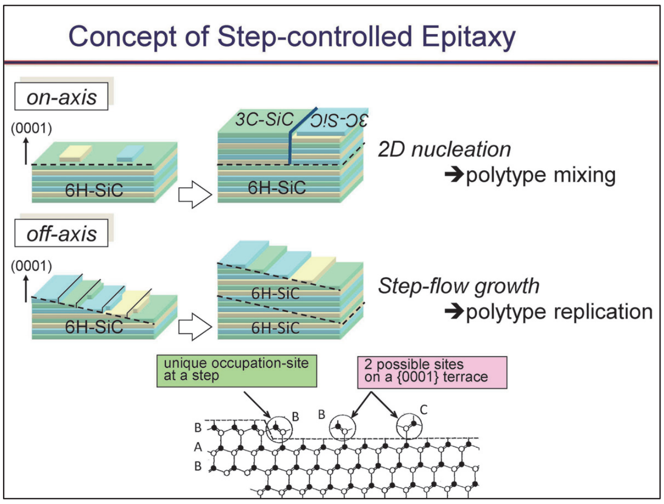


Fig. 22

〈Fig. 22〉 Experts in crystal growth probably know that when a substrate has a step structure, making crystal growth start from the step edge will lead to the proper growth of the entire crystal, but since we are mainly working on device research, we did not have this idea at first. If we had advanced our research based on the logic that effectively using steps will promote high-quality crystal growth, other people might have said; “He is amazing,” but actually, in our case, it was by accident that we successfully used that structure. I believe that was a blessing for me.

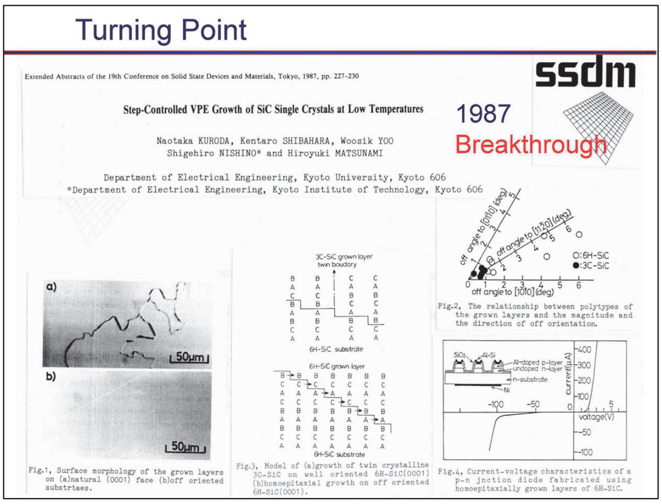


Fig. 23

〈Fig. 23〉 Immediately, I started to make a p-n junction. With silicon carbide on silicon, there was a leak at 2 V and over in the reverse direction; however, when I made a p-n junction with a growth of 2 μm, withstand voltage rapidly went up to 100 V. I knew what I should do after that. I examined all the optimum conditions regarding in what direction and to what angle the inclination should be provided.

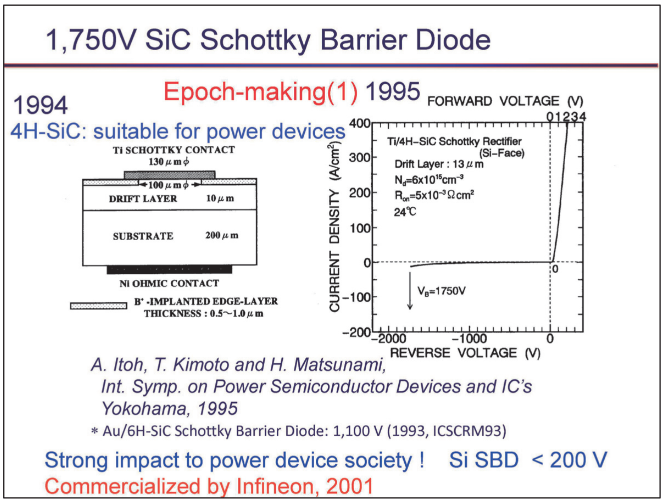


Fig. 24

〈Fig. 24〉 Based on the findings, I introduced Schottky barrier diodes in 1993, and in 1995, I succeeded in raising withstand voltage to 1.75 kV at a stroke with a full-fledged Schottky barrier diode structure.

A thickness of 13 μm and a specific on-state resistance of 5mΩcm² were realized. This had a tremendous impact on the power device industry. Because if the same thing is done by using silicon, you can achieve up to only 200 V. To hear that, many people handling power devices started to come to us. After our announcement, we were vigorously pursued by various organizations.

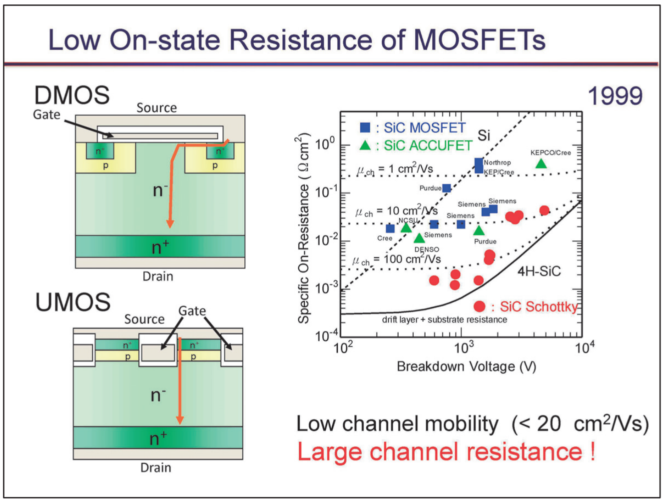


Fig. 25

〈Fig. 25〉 In the late 1990s, MOSFETs were produced, and by using them vertically as shown in the figure, we finally were able to throw off the limitations of silicon. However, the crystal face they were using was the least desirable one. I thought that they would be replaced by trench MOSs.

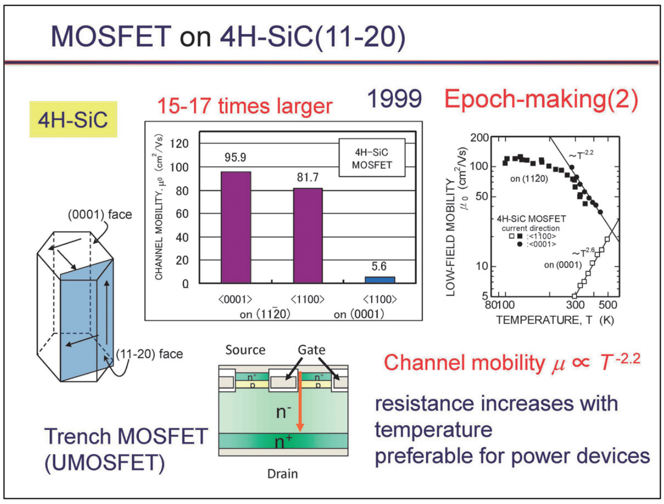


Fig. 26

〈Fig. 26〉 After examining a planer structure and characteristics of a MOSFET on the conventional face (0001) and on a vertical face (11-20), it was found that it would be possible to improve performance up to 20 times as high as previously seen at one time.

I said: “the age of trench MOSFETs will arrive soon,” a very advanced company in Kyoto called

“ROHM” introduced what I did at Kyoto University in industry-academia collaboration in an appealing manner, and, as I will describe later, developed the world’s first trench MOSFETs.

■ Present Technologies of SiC Power Devices

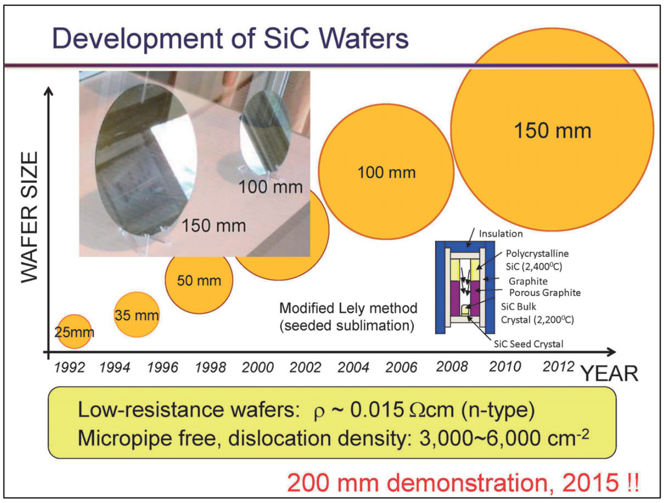


Fig. 27

〈Fig. 27〉 Wafers, for the development of which experts have spent a lot of time and energy, have generally had a size of 100 mm in diameter, but recently, ones with a size of 150 mm (6 inches) have been becoming more mainstream. They have already demonstrated ones with a size of 200 mm in diameter. When you compare them with the stone-like chunks I used before, you can see how much improvement has been made. In response to our success in operating devices, material makers have invested great efforts to improve materials thus far.

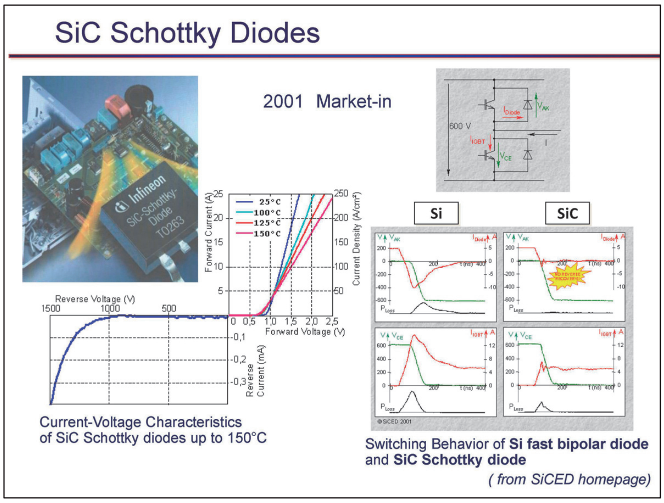


Fig. 28

〈Fig. 28〉 In 2001, a German company called Infineon showed how much loss can be reduced by the use of silicon carbide Schottky diodes. After considering business-related factors, the company started to produce them right away. Silicon cannot achieve a withstand voltage of around 1000 V.

In the figure, a silicon carbide Schottky diode and a silicon p-n diode are compared, which shows that the use of the latter caused a significant loss. By this comparison, the superiority of silicon carbide Schottky diodes was demonstrated.

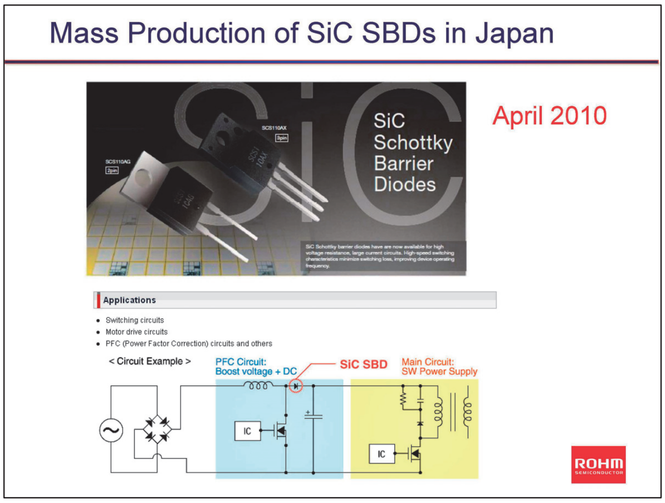
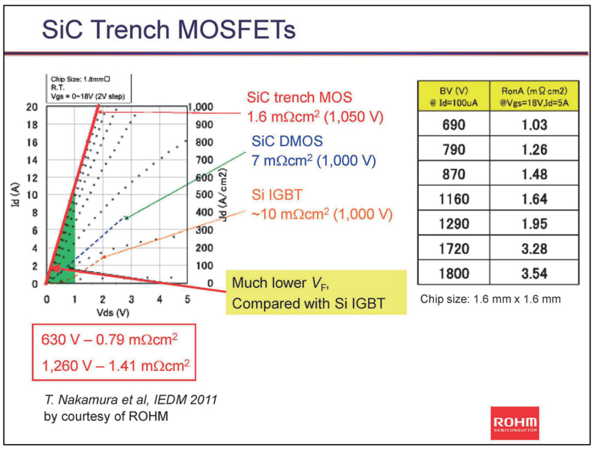


Fig. 29

〈Fig. 29〉 After that announcement, a lot of attention was attracted instantly; however, since it was after the burst of the economic bubble in Japan that this announcement was made, this technology was not commercialized immediately. Nine years after that, in April 2010, ROHM announced the mass production of SiC Schottky barrier diodes.



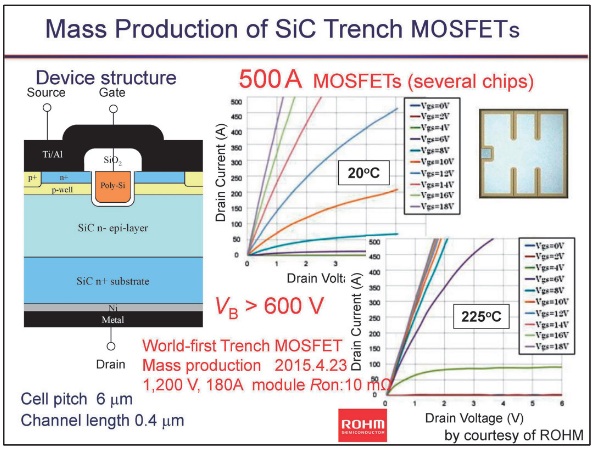


Fig. 30 Fig. 31

〈Fig. 30 and 31〉 In December of 2010, ROHM announced the mass production of planar MOSFETs which are capable of operating at temperatures of up to 200℃. Then, they announced high-performance of trench MOSFETs at an academic conference. Furthermore, in 2015, ROHM created modules equipped with trench MOSFETs basting current of 180 A, which was really an amazing result. This was a truly remarkable event in Japan as well as the first time in the world that this was achieved.

■ **Development of National Project toward Practical Applications**

So far, I have explained to what extent technologies have been developed. Now, I want to talk about the reality that we cannot advance our research without companies' support and efforts.

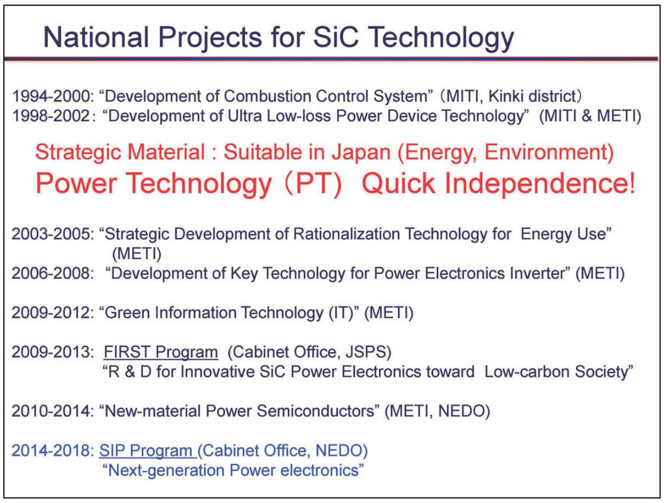


Fig. 32

〈Fig. 32〉 I listed many things in the figure, but the point I want you to give attention to is the Lehman Shock that took place in 2008. The industrial world found itself in a critical situation. In such a situation, the government found it was necessary to take some actions to revitalize businesses, and as part of such efforts, the "Funding Program for World-leading Innovative R&D on Science and Technology" called FIRST, and the "New Material Power Semiconductor" project were launched. In such an environment, I made various proposals and participated in various projects.

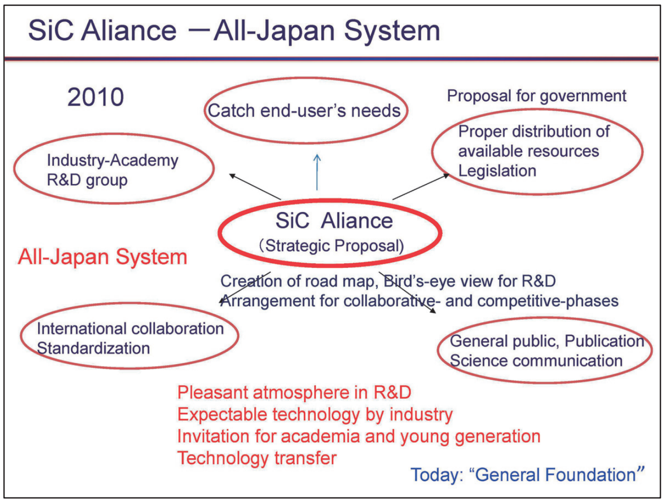


Fig. 33

〈Fig. 33〉 At the same time, the SiC Alliance came into being. As I mentioned earlier, when three different programs are proceeded with at the same time separately, all the people participating in the programs look at only their sponsors. They are doing the similar things without ever associating with each other, which is not reasonable. So, to provide a table where they can share what they have, the alliance was organized. The organization has been incorporated, and presently, it is operating as a general incorporated association.

In the SiC Alliance, we consider in which direction to go in the future from a neutral standpoint and make various proposals. Also, we discuss what needs to be done in the next program, how we can effectively report the fruits of research through science communication as well as how we can support the industry-academia-government collaboration.

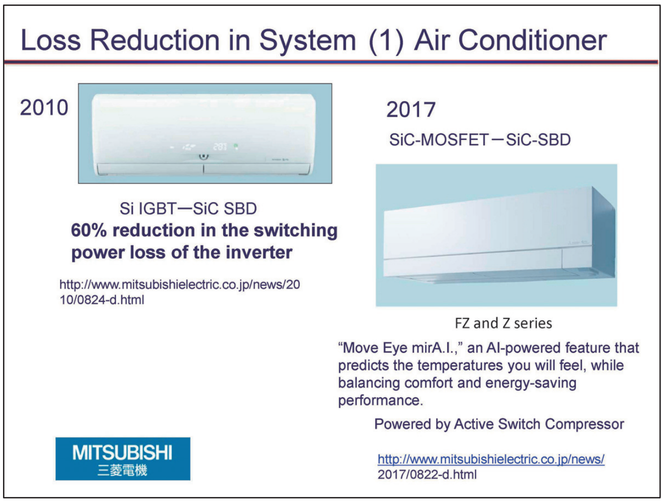


Fig. 34

〈Fig. 34〉 Mitsubishi Electric Corporation was the first to work on the commercialization of our research achievement. At first, Mitsubishi produced an air conditioner, which is capable of reducing switching loss by 60%, like the one in the figure by using silicon carbide Schottky diodes and silicon IGBTs. According to this year's announcement, their new air conditioner is equipped with an artificial intelligence, having a function of automatically turning off the switch when there is no person around it. It also has a function of sensing the movements of a person and adjusting the direction of cool or warm wind accordingly. It adopts "Active Switch Compressor," which facilitates switching.

It is also reported that its energy saving effect is greater in winter than in summer. In summer, you need to lower the room temperature from 35 or 36°C to 28°C, at most; however, in winter, you need to raise the room temperature from single-digit cold to as high as 18°C, which requires a considerable amount of power.

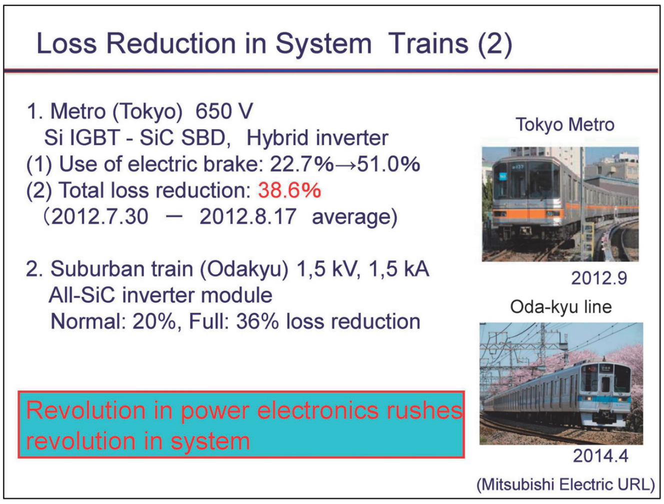


Fig. 35

〈Fig. 35〉 First, they were used in hybrid-type subway vehicles. In an experiment with the use of silicon IGBTs and silicon carbide Schottky diodes, about 40% of loss reduction was achieved. When a train is running at high speed, a regenerative brake can be used, and then, the regenerated energy is sent to another train running nearby, which is how the system works. An Odakyu train fully equipped with silicon carbides also achieved about 40% of loss reduction.

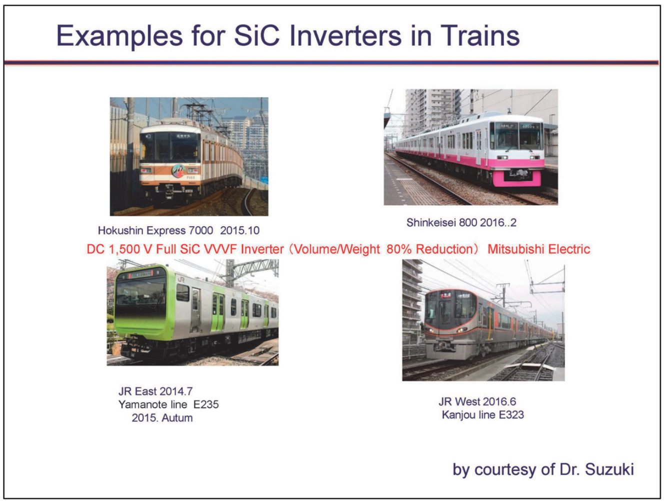


Fig. 36

〈Fig. 36〉 Currently, silicon carbides are used in various trains in different regions. This is a train running on the Yamanote Line. Old-type brown-colored trains used to run on the Kanjo Line in Osaka. Silicon carbides were introduced to trains which are currently running.

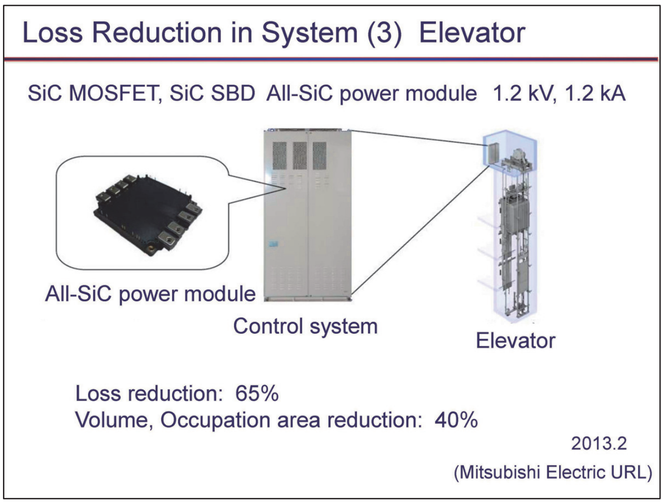


Fig. 37

〈Fig. 37〉 Elevators. Since they stand side-by-side, by sending regenerated energy to each other, 65% of loss reduction can be achieved.

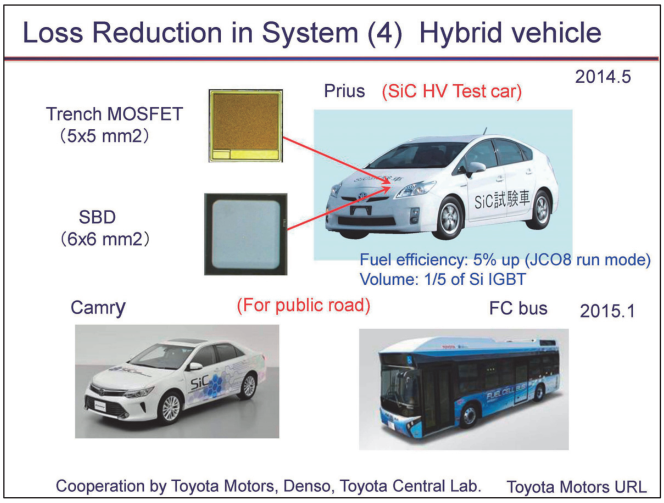


Fig. 38

〈Fig. 38〉 They are also used in automobiles, hybrid vehicles. At first, in a test run, they succeeded in improving fuel economy by 5%. I heard it is amazing to make a 5% improvement at once simply by changing devices. It has been announced that they will be released around 2020.

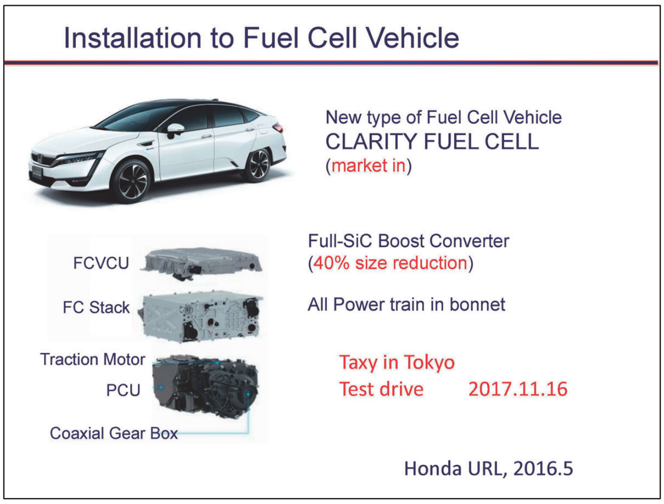


Fig. 39

〈Fig. 39〉 Honda Motor Company began to use silicon carbide power devices for fuel cell vehicles in 2016. Now, they are already being commercially supplied to various companies including taxi companies.

Yesterday, I went to the Smart Hydrogen Station in Odaiba to learn various things such as how to fill a cylinder. It is truly an energy-saving product. It uses a solar cell to produce hydrogen by electrolysis of water. Indeed, it is totally an economical and energy-saving vehicle.

Besides, the fuel cell-powered car I tried was a five-seat sedan, whereas today four-seat fuel cell cars dominate the world. This increase in capacity stems from its driving section which is packed under the hood; this was enabled by the overall compactness of parts designed to manage that structure. I really enjoyed its comfortable ride.

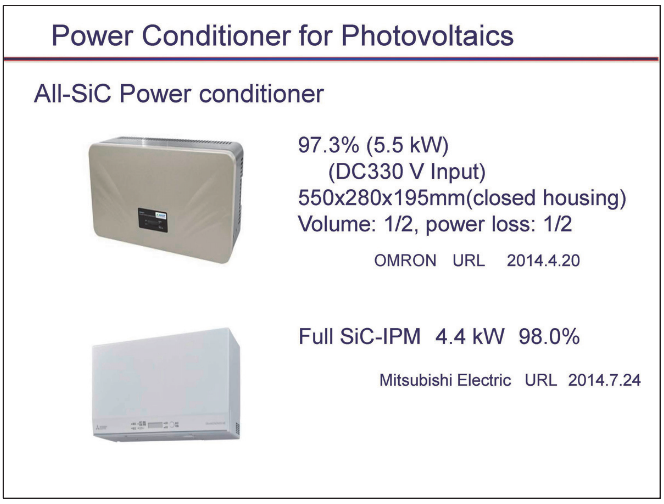
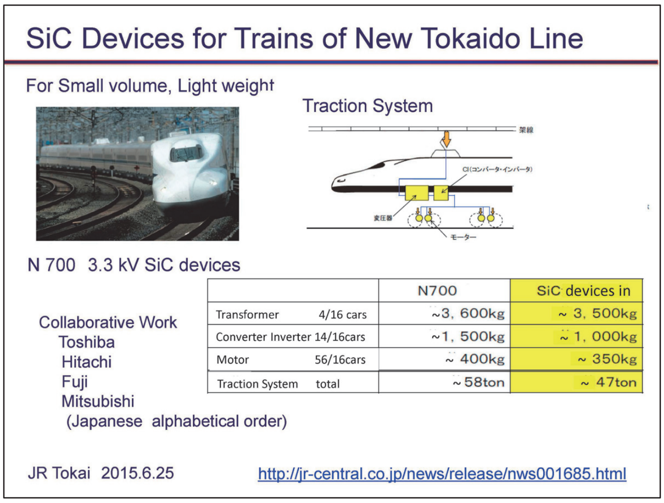


Fig. 40

〈Fig. 40〉 They are controllers for solar cells of which I have already explained.



	N700	SiC devices in
Transformer 4/16 cars	~3, 600kg	~ 3, 500kg
Converter Inverter 14/16cars	~1, 500kg	~ 1, 000kg
Motor 56/16cars	~ 400kg	~ 350kg
Traction System total	~58ton	~ 47ton

Fig. 41

〈Fig. 41〉 The most exciting use of silicon carbide will be found in JR Tokai. It was announced that it would be put into practical use in 2020. That means both new silicon carbide-powered automobiles and trains will appear during the year of the Olympic games here in Japan. In addition, I find the strategy to be taken is very amazing. JR Tokai is using N700 series Shinkansen train-cars, but since a long time has passed since they were introduced, they will have to be replaced. At the timing of their replacement, JR Tokai is going to start to use silicon carbides, and specifically, perform an overall review of transformers, converters, inverters, and motors, which will enable an 11 ton weight reduction per 16 train cars. Next year, JR Tokai is planning to install those silicon carbide devices in the trains on a four cars-by-four cars basis. Presently, 16-car trains are running between Tokyo and Osaka, but 12-car trains and 8 car-trains are also running in western Japan. If standard products are prepared on a four cars-by-four cars basis, it will become possible to promptly meet orders in the future, instead of offering designing systems from scratch responding to individual orders. This Shinkansen system initiated mainly by JR Tokai is much appreciated by other countries in the world, but even when this system is employed by one of those countries, they don't need to change its design from region to region. If standard products become available, it will become possible to provide quick delivery at a low price. That is what is going to happen.

A Forecast of SiC Power Device Market Size and Energy-Saving Effect

Application field	The market size of SiC power devices (million units)		Energy-saving effect in 2020*5			
	2010	**2020**	Introduction no./amount	Energy consumption reduction (TWh/year)	CO2 emission reduction (ten thousand ton/year)	Energy consumption reduction in crude-oil equivalent (ten thousand kl/year)
Electric car/hybrid car/fuel cell car	**2.4*1)**	**6～20*2)**	5 million cars	**6.25**	**229**	**145**
General-purpose inverter (motor)	**0.1*1)**	**43*3)**	41 million inverters	**9.96**	**366**	**231**
CPU power supply	**1*1)**	**100*4)**	65 million supplies	**2.73**	**100**	**63**
Uninterruptible power supply (UPS)	**0.5*1)**	**50*1)**	23 million supplies	**4.71**	**173**	**109**
Distributed power system	**0.01*1)**	**2*1)**	20.02 GW	**3.83**	**141**	**89**

*1) A forecast by the j-STAR
*2) Forecast by the "Research report on fuel cell cars," the Japan Automobile Research Institute
*3) Forecast by the "Annual report on machinery statistics," Research and Statistics Department, the Economic and Industrial Policy Bureau,
*4) Forecast by the "Medium- and long-term prospects on the world electronic equipment and semiconductor market," the Japan Electronics and Information Technology Industries Association the Ministry of Economy, Trade and Industry
*5 Forecast by the "Survey on practical use of next-generation power semiconductor devices," the Engineering Advancement Association of Japan

Source: EE Times Japan 2007.5

Fig. 42

〈Fig. 42〉 After all, how to control a motor determines how much energy can be saved. Controlling general-purpose motors used in the industrial world and daily life would produce the highest energy-saving effect. This means its CO_2 equivalent would be reduced as well. However, there are various types of motors, so it is difficult to clearly say with what specific inverter and how motors should be controlled.

Unique Results in Kyoto Super-Cluster Program

Small and Medium Enterprise's Activities

- Unified System for Micro Smart Grid
- High-voltage SiC Pulse Generator
- SiC-Inverter implementation for Motors
- DC High-voltage Power Supply
- Power Supply for Pulse Plasma
- Power Supply for High-frequency Induction Heating
- Size Reduction of X-ray Generator

Successes in more than 10 companies !!

Fig. 43

〈Fig. 43〉 It is the Super Cluster Program in the Kyoto area that now I'm looking at with great anticipation.

The Ministry of Education, Culture, Sports, Science and Technology (MEXT) supported local regions for 11 years through the cluster project, which however, did not lead to substantial results. Accordingly, the MEXT decided to stop the project. With that, it was decided that JST would take responsibility for proceeding with the project.

I proposed that incentives should also be provided for businesses. Since silicon carbide power devices run at extremely high speed, ringing oscillations occur. Thinking that we need experts in electric circuits to prevent that phenomenon, we asked professionals at the Department of Electrical Engineering at Kyoto University to join us. It seems like we are going to produce very interesting results. More than 10 companies have produced successful results.

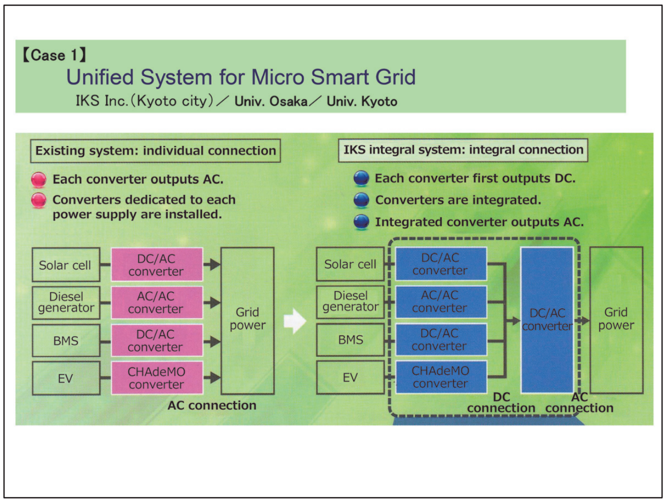


Fig. 44

〈Fig. 44〉 Here is one successful example by one of the small and mid-sized enterprises. This company developed a very interesting idea called HEMS (Home Energy Management System). First, install a 10 kW photovoltaic battery, or solar cell, at home, and then, bring a Nissan Leaf to connect to the battery. This way, electric energy can be transferred.

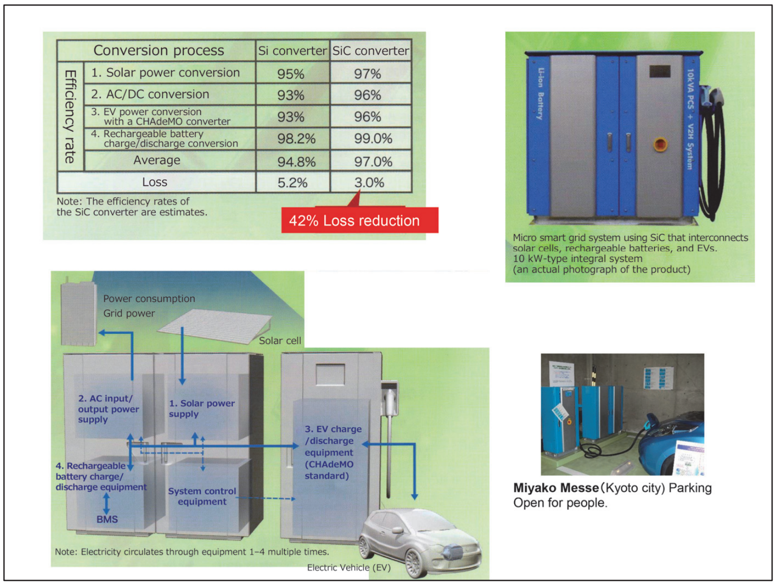


Fig. 45

〈Fig. 45〉 According to the data presented here, replacing silicon IGBTs, which have been widely used, with silicon carbide MOSFET will be able to achieve a 42% loss reduction.

Presently, a quick charging device has been placed in the underground parking lot of "Miyako Messe" owned by Kyoto City. If you pay a parking fee, you can freely use it to charge your car. After that, with a general constructor, I have made collaborative efforts in the development of BEMS (Building Energy Management System), in which one big enterprise that showed interest in this system participated, which also led to the development of CEMS (Community Energy Management System) in Maui, Hawaii. At the current moment, the president of that company went to Canada and is likely to receive support from the Canadian government.

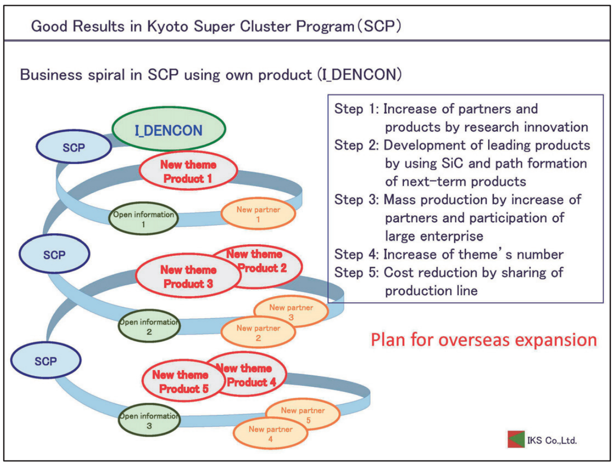
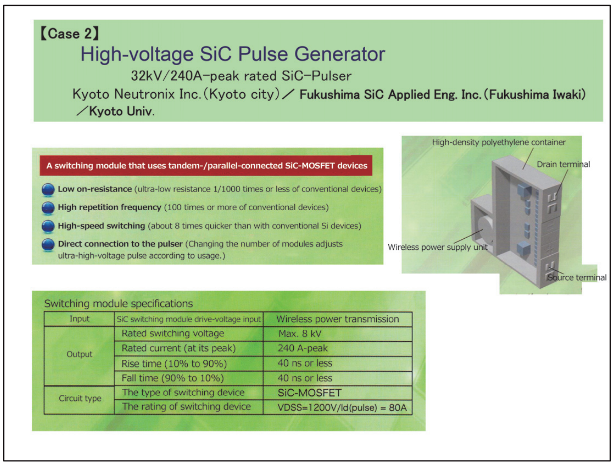


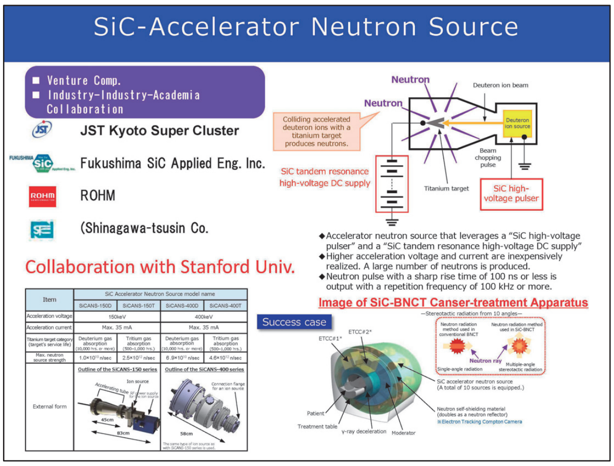
Fig. 46

〈Fig. 46〉 Small and mid-sized enterprises are making use of this system and growing steadily. I think this is an amazing thing about Kyoto. A variety of new problems arise spirally, and they are solved, which leads to the acquisition of new users. This is how things are working.



Input	SiC switching module drive-voltage input	Wireless power transmission
Output	Rated switching voltage	Max. 8 kV
	Rated current (at its peak)	240 A-peak
	Rise time (10% to 90%)	40 ns or less
	Fall time (90% to 10%)	40 ns or less
Circuit type	The type of switching device	SiC-MOSFET
	The rating of switching device	VDSS=1200V/Id(pulse) = 80A

Fig. 47



Item	SiC Accelerator Neutron Source model name			
	SiCANS-150D	SiCANS-150T	SiCANS-400D	SiCANS-400T
Acceleration voltage	150keV		400keV	
Acceleration current	Max. 35 mA		Max. 35 mA	
Titanium target category (target's service life)	Deuterium gas absorption (10,000 hrs. or more)	Tritium gas absorption (500–1,000 hrs.)	Deuterium gas absorption (10,000 hrs. or more)	Tritium gas absorption (500–1,000 hrs.)
Max. neutron source strength	1.0×10^{10} n/sec	2.5×10^{12} n/sec	6.9×10^{10} n/sec	4.6×10^{12} n/sec
External form	Outline of the SiCANS-150 series		Outline of the SiCANS-400 series	

Fig. 48

〈Fig. 47 and 48〉 Another company I would like to introduce is Fukushima SiC Applied Engineering Inc., which is exclusively working on the practical application of silicon carbide. Their products can be made only with silicon carbide, not with silicon. As part of the attempt to prepare for the replacement of klystrons, they provide composition examples of acceleration neutron generators.

Presently, a very large piece of equipment called a cyclotron is generally used as an accelerator, but if you use silicon carbide, it will not be necessary to use that. One of the advanced variations resulting from the use of silicon carbide is a BNCT (Boron Neutron Capture Therapy) cancer treatment apparatus, which can be used for the treatment of large internal organs such as the liver, the gallbladder and the pancreas. If you disperse the therapeutic drug with boron by using DDS (Drug Delivery System), you can cure cancer, even if the cancer cells are scattered. Although this sounds like a dream, it could be a treatment in the future.

■ Summary and Future Prospects

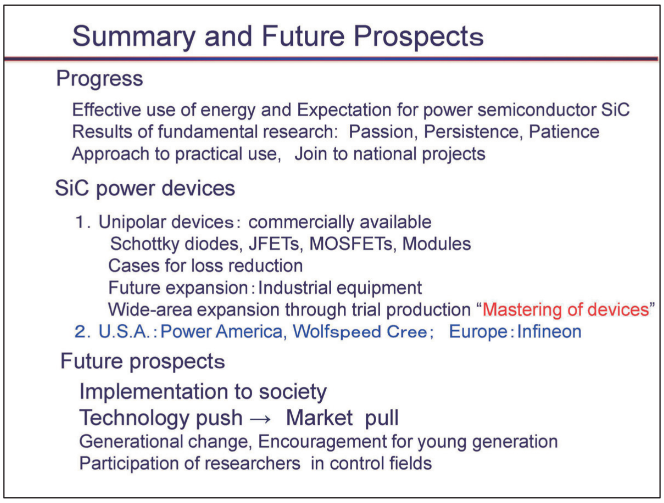


Fig. 49

〈Fig. 49〉 Now, let us consider our future direction. It is needless to say that now silicon carbide power devices are widely used around the world, but I still emphasize the importance of mastering devices.

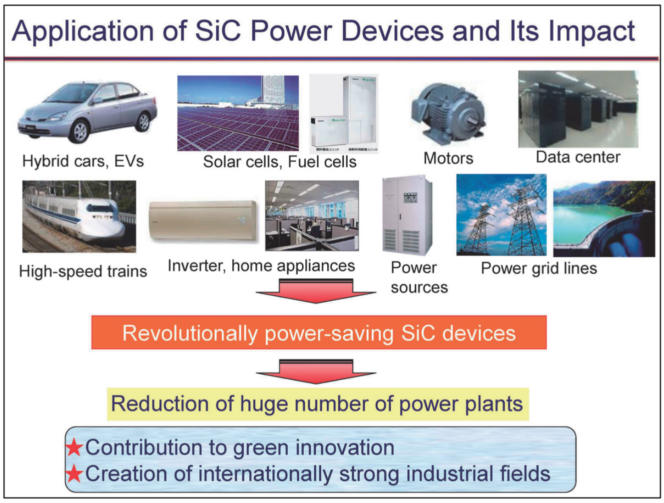


Fig. 50

〈Fig. 50〉 In Japan, the technology-push approach is well supported; however, unless Japan becomes like America and Europe, where the attitude of "If you make something good, I will be happy to use it" is prevalent, those who deserve the reward will miss it. Unless we address this issue now, it will become a serious problem for the industrial world. Now is the time to make a shift from "technology push" to "market pull." Also, it is necessary to cultivate young researchers and help them to get familiar with a specific way of handling such a product. I want to emphasize that it is very important.

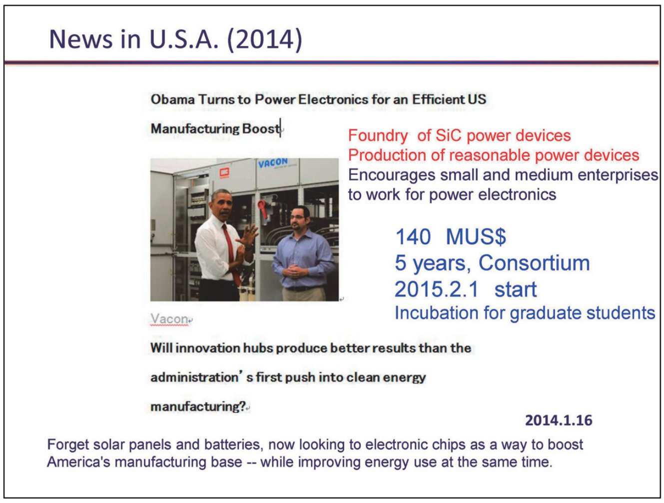


Fig. 51

〈Fig. 51〉 Thanks to its national projects, Japan is presently two to three years ahead of America.

In the U.S., President Obama announced "Power America" in the State of the Union address in 2014, and a new project launched in February 2015 has been working. The goal was to establish a foundry to produce reasonable power devices and encourage small and mid-sized enterprises to work on the development of power electronics with 7 billion yen provided from the government and another 7 billion yen from a newly established regional consortium.

Expecting to see their efforts bearing fruit in about two years, people in CPES (Center for Power Electronics Systems) who are experts in applying new technologies are eagerly waiting. CPES, established at the Virginia Polytechnic Institute and State University, commonly known as Virginia Tech, has a large group of researchers with more than 15 years of experience. I have received a lot of reports on electric circuits showing what great results they attained by using silicon carbide. Japan belatedly started to follow them.

Fig. 52

〈Fig. 52〉 At the International Conference of Silicon Carbide and Related Material held in September 2017, the participants from all over the world emphasized "Moving from Niche to Mainstream." To see such a global trend around silicon carbide, the committee decided to launch the conference with this catch phrase.

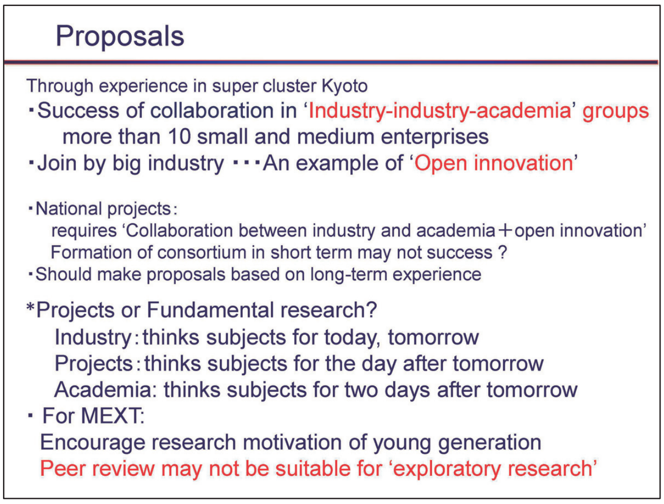


Fig. 53

〈Fig. 53〉 Since I heard many officials from related ministries and agencies supporting us are here today, I would like to make a proposal. Judging from what the super cluster in Kyoto experienced, when industry-academia collaboration is working quite well, big enterprises are likely to join, which can unexpectedly lead to open innovation. I would like you to make sure that this flow will continue to work smoothly. Recently, every ministry or agency has come to emphasize the importance of industry-academia collaboration and open innovation. For a research group that was hastily arranged in response to such an announcement, it is usually impossible to produce an outcome in three years to five years, unless the group members have previous achievements. I often hear people say even a probability of success of one hundredth or even three thousandth will do; however, since budgets for research projects are limited, I hope they are to be used as effectively as possible.

The primary problem facing young researchers is that since they cannot receive financial support for their research unless they join a project, they move from one project to another. Today's environment surrounding academic research is totally different from that of the day when I was a crazy boy doing whatever I wanted. Researchers who want to conduct research out of curiosity or out of the spirit of seeking truth cannot receive financial support.

It has been 13 years since the transformation of national universities into independent administrative institutions was carried out. As a result, management expenses grants have been reduced by 1% a year. Due to the impact of budget cuts on universities, three large universities have already been closed. Additionally, there is no system that encourages young researchers to do what they really want. I want you to give careful consideration to this. I believe transformative research that has a potential of producing great outcomes is very important.

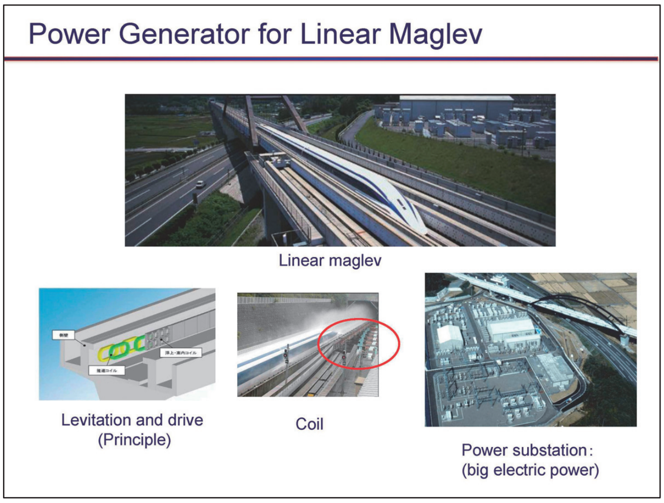


Fig. 54

〈Fig. 54〉 This is my future dream. I want silicon carbide power devices to be used for maglev linear motor cars.

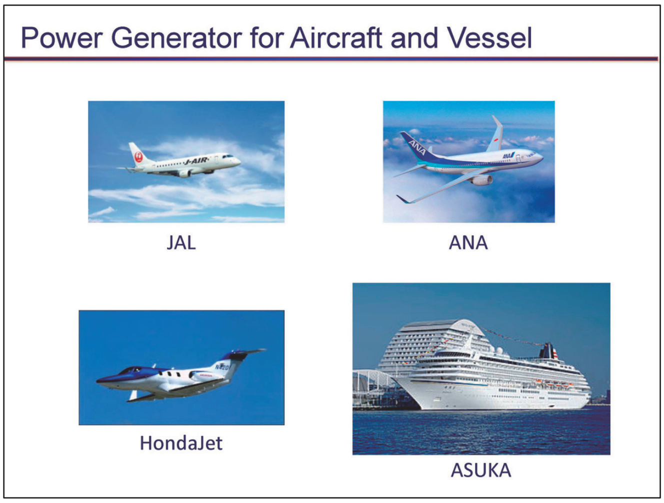


Fig. 55

〈Fig. 55〉 At the same time, it is possible to extend their application to large vessels or aircraft.

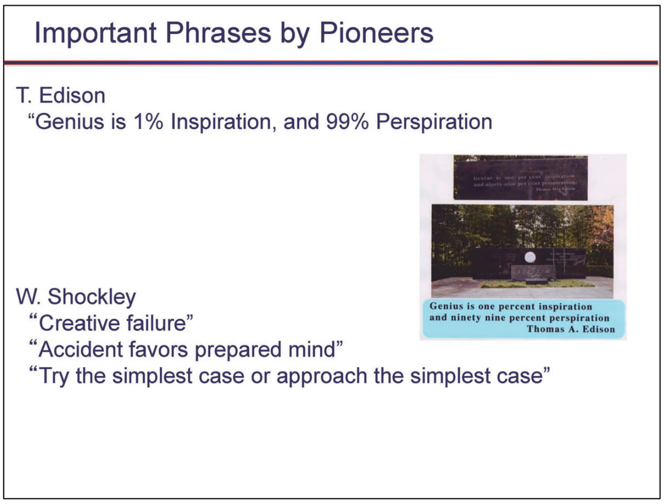


Fig. 56

〈Fig. 56〉 They are my favorite quotes of the pioneers. Edison said: "Genius is one percent inspiration and ninety-nine percent perspiration," which means that a great result a genius produces is not only the product of inspiration but the product of ninety-nine percent perspiration.

Shockley, the creator of transistors, used the expression "Creative failure," which sounds very clear when translated into Japanese. "Accident favors prepared mind," which means that if you always use your mind, when there is an accident, you will come up with a creative solution. It is very important to have such a mind-set.

He also said: "Try the simplest case or approach the simplest case," which means that when you achieve something after making a lot of efforts, you should stop and think how you can do the same thing in a simpler way. That is my favorite quote.

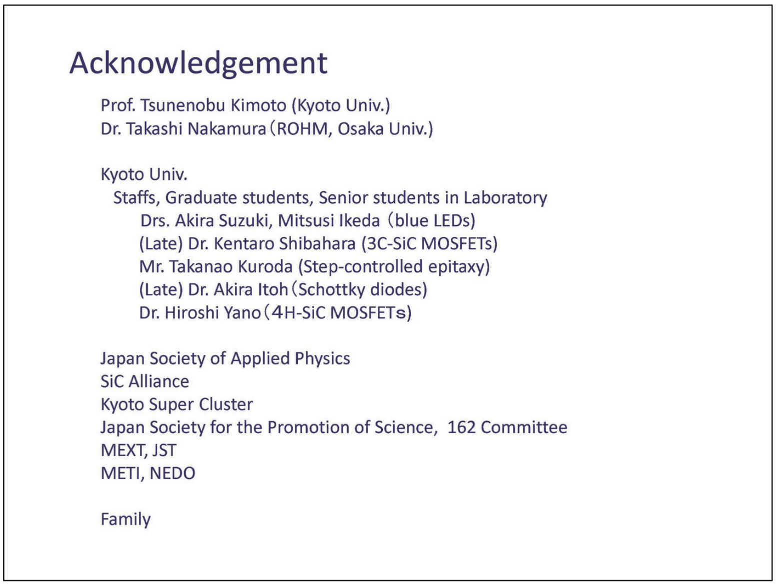


Fig. 57

〈Fig. 57〉 At the end, I would like to express my sincere appreciation for all your support. Especially, I have had great help from Professor Kimoto at Kyoto University, who is now playing a major role in the world arena. Dr. Nakamura, who was with ROHM and now works at Osaka University, was the first to introduce the results produced at Kyoto University to the industrial world, and also, made a great contribution to the realization of mass production of SBDs and DMOSs, and realized the practical application of trench MOSFET ahead of others. I would like to extend my heartfelt gratitude to my students who worked very hard in various areas, the company that produced blue light emitting diodes, Mr. Kuroda who also made a great contribution when we first developed MOSFETs by using the step-controlled epitaxy method, and the late Akira Itoh who greatly contributed to the development of Schottky diodes. And I cannot forget Dr. Yano who made a contribution to the development of MOSFETs. Additionally, I would like to express my deepest appreciation to many people at the academic society and various support organizations. At the very end, I want to say thank you to my family, especially my wife, Fumiko, from the heart for letting me pursue what I wanted to do. Please excuse me for talking too long. Thank you very much.

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