Present Status and Future Prospects for Power Semiconductors

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1. Introduction

From the viewpoint of a highly information-oriented society in the coming 21st century, the social infrastructure will undergo rapid repairs and reformations. What will bring us to a society where computers and communications are closely intertwined? Technical innovations have always brought us advantages as well as disadvantages. Any future technical innovations must definitely exclude disadvantages.

A highly information-oriented society will result in a great increase in electric energy consumption. Problems of the global environment, social environment, and energy resources must be improved through more serious consideration, with electrical manufactures leading these technical innovations. Development of high power generation and conversion efficiency and energy-saving technology for electron devices are core technologies. More specifically, power electronics that control electric energy increases in importance, and especially power semiconductor devices as the key devices are required for further advances in performance and functions. The major directions of the research and development are:

(1) low power dissipation devices
(reduction in conduction and switching losses)
(2) system-integrated devices
(system-on-a-chip devices and system-integrated modules)

Under these circumstances, Fuji Electric plans to work with a leading company of power devices for intelligent motion control and intelligent power management.

In particular, power MOSFETs (metal oxide semiconductor field effect transistors), IGBTs (insulated gate bipolar transistors), IPMs (intelligent power modules), and power ICs (integrated circuits) with advanced performance and functions will rapidly enlarge the market.

This special issue describes the present status and future prospects for Fuji Electric's power semiconductor devices in the highly information-oriented society of the future. Listed below are the device items classified by application fields.

(1) Devices related to multimedia
① High-voltage silicon diodes and damper diodes with high-speed switching performance to improve the picture quality of the CRT (cathode ray tube) display monitors and televisions
② Low on-resistance SOP-8 power MOSFETs that extend the battery life of portable electronic appliances such as notebook computers

(2) Vehicles and rolling stock
① Intelligent power MOSFETs that decrease the size and improve reliability of car electronics systems
② High-voltage, high-power NPT (non punch-through)-IGBT modules and flat IGBTs that reduce rolling stock size, weight, and energy consumption

(3) Power conversion (inverter control)
① Molded IGBTs, IGBT modules, and IGBT-IPMs for applications including NC (numerical control) equipment, general-purpose inverters, servo mechanisms, welding machines, and UPSs (uninterruptible power system)

2. Technical Trends of Power Semiconductor Devices

These applications extend over a wide range of equipment including power systems, transportation, industries, information, communications, and household appliances. Major technical developments follow the trend toward decreased power loss, high speed, high reliability, and advanced functions.

2.1 Technical trends

Figure 1 shows the progress of improvement in power MOSFET on-resistance. In low-voltage devices (100V or less), their on-resistance has been greatly reduced by fine patterning technology for LSIs (large-scale integrated circuits). It is further reduced by adopting trench gate technology. On the other hand, no great improvement has been made in high-voltage devices. The reason is that the main on-resistance component of high-voltage MOSFETs is in the drift region and therefore, great reductions cannot be ex-

Fig. 1 Improvements in on-resistance

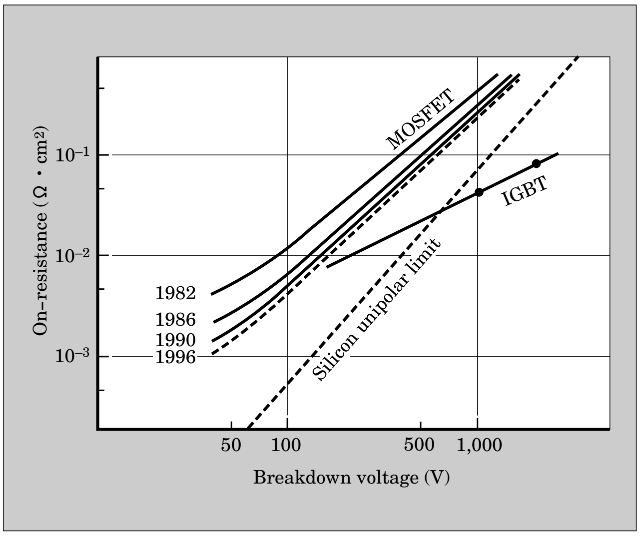


Fig. 2 Development of process design rules

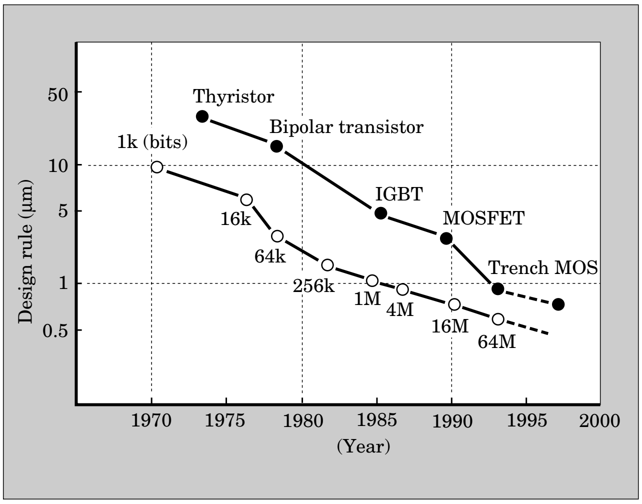
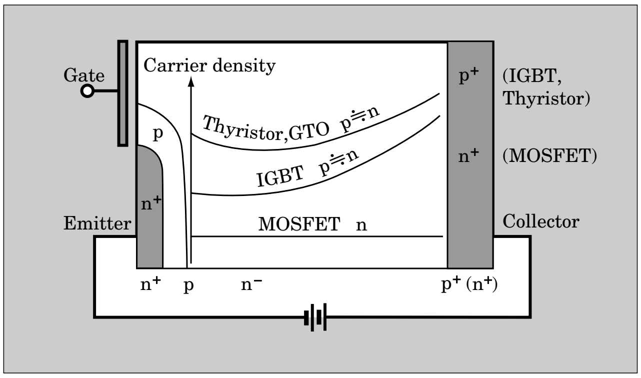


Fig. 3 Carrier distribution of typical devices



pected by adopting finely patterned cells. To reduce the on-resistance of high-voltage devices, an IGBT was developed. As shown in the figure, the IGBT on-resistance is much lower than the silicon unipolar limit due to the conductivity modulation effect. From the viewpoint of on-resistance, the application range is thought to be less than 150V for power MOSFETs and more than 150V for IGBTs.

The performance of power semiconductors will improve with the following technical innovations:

(1) A merger of semiconductor action physics and the application of new concept devices
(2) A breakthrough in a trade-off with intelligent functions (drive, protection, sensor functions, etc.)
(3) Application of LSI process technology
(4) Notable advances in the performance of devices using new semiconductor material

Figure 2 shows the transition of design rules for power devices in comparison with that for DRAMs (dynamic random access memories). When compared with DRAMs, the application of fine patterning technology to power devices was delayed by about two generations. The fine patterning level of the power devices has greatly advanced by application of the trench process. In particular, the on-resistance of low-voltage MOSFETs has been greatly reduced by the trench gate application. As for the new concept devices, the application of trench gates will also result in further improvement. The application of various LSI process technology as well as the submicron-level patterning technology to power semiconductors will be rapidly promoted in the future, and a positive influence on their performance is expected.

Next we will describe the merger of action physics. Figure 3 shows the on-state carrier distribution of various power devices. The carrier distribution of a device determines its on-voltage drop and switching speed performance. The next goal is the merger of MOSFET and thyristor actions. More than ten years have passed since an MCT (MOS-controlled thyristor) was announced. However, because of low controllable current density, its weakest point, it has not been widely accepted. Various new-concept devices for improvement have been announced, such as the EST (emitter switched thyristor), IGCT (insulated gate controlled thyristor), and BRT (base resistance controlled thyristor). In addition, an attempt at easier application of the thyristor and attainment of high performance by introducing dual gate control has begun. However, it is not yet marketable. It is difficult to efficiently remove excess carriers at turn-off, and the excess carriers necessarily prolong the switching time. To improve these problems, various means have been contrived in the LSI process technology and the parasitic thyristor for prevention of latch-up.

Another movement is toward intelligent devices. The rapidly developed ICs were motive power to the current social reformation. In the future, they are expected to continue to play a role. However, in the mid-1980s, Dr. Adler et al. of General Electric Co. predicted that a second reformation would be caused by intelligent power devices. We feel that the technical innovation toward them has been quite remarkable. These power ICs have developed remarkably, especially toward large capacities and advanced functions. On the market are high-side and low-side switching, high cost performance, advanced function power MOSFETs for automobiles and power ICs for igniters up to 400V and tens of amperes. The one-chip inverter IC that incorporates a power supply, various protective circuits, and PWM control circuits has also been commercialized. The biggest problem of these devices is high-cost isolation technology. Recently, direct bonded SOI (silicon on insulator) technology has gained attention. The age of on-a-chip systems with an integrated power device is not very far in the future. System-integrated modules will be mainstream in comparatively large capacities. Fuji Electric plans to complete them all with silicon devices and silicon sensors concurrently realizing compactness, advanced functions, and high cost performance. We intend to promote the commercialization of the next generation IPM series and power supply devices. Figure 4 shows a power system block diagram. The target of Fuji Electric's power semiconductors are the smart discrete, IPM, and SIM (system-integrated module). Their definitions are shown in the figure.

2.2 Technical trends for the power MOSFET

The driver for power MOSFET technology is cost/ampere. The performance index is given by $1/[R_{ds(on)} \times C$ (capacitance)], and more advanced technology gives lower $R_{ds(on)} \times$ Area.

Loss reduction for the power MOSFET is promoted by the following:

(1) Application of VLSI (very large scale integrated circuit) technology (trench-gate, etc.)
(2) A structure that reduces parasitic capacitance
(3) A structure that improves avalanche withstand capacity
(4) New-concept devices (carrier injection control, etc.)

As mentioned previously, the on-resistance of low-voltage MOSFETs is greatly reduced by adopting trench gates. However, trench gate MOSFETs have the following problems:

① a complicated process (high process cost)
② the reliability of MOS gates and the yield rate of chips

Many efforts have been made to solve these problems. Table 1 shows a comparison of power MOSFET performances. Overall, judging from these, manufacturers are promoting commercialization under their own technical strategies.

Intelligent low-voltage MOSFETs using power MOSFETs as output devices are expected to be widely used for automobiles and power supply systems. In response to this, we are promoting development and manufacture of the smart discrete (such as advanced function MOSFETs and IGBTs). These have driver, overcurrent and overheating protection functions and are expected to be used in many applications due to their high reliability and cost performance. To advance the functions even further, we will promote commercialization of the IPS (intelligent power switch) and development of system-on-a-chip devices using BCD (bipolar, CMOS and DMOS transistor) and SOI technologies.

2.3 Technical trends of the IGBT

The IGBT aims at reduction in power loss, system-integrated modules, downsizing, and high cost performance. To realize these goals, we strive for the following innovative technologies:

(1) Approaching the limits of IGBTs

Fig. 4 Block diagram of a power system

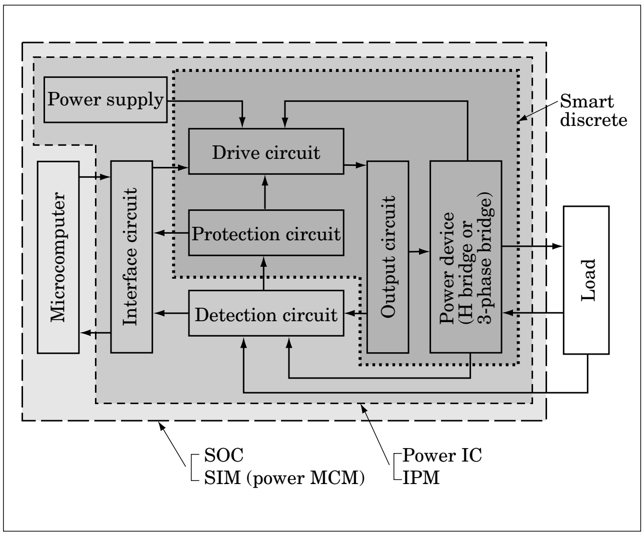


Table 1 Comparison of power MOSFET performances

Item / Type	$R_{ds(on)}$ ×area	Gate SiO_2 reliability	Process	Yield rate	Cost/ ampere
VDMOSFET *1	△	◎	◎ (easy)	◎	○
Trench-gate MOSFET	◎	△	△ (complicated) trench process	○	◎
LDMOSFET *2	○	○	△ (complicated) multilayer	○	?

*1 VDMOSFET : Vertical double diffused MOSFET
*2 LDMOSFET : Lateral double diffused MOSFET

Table 2 Comparison of IGBT performances

Device structure	On-resistance	Switching loss	RBSOA	SC performance	High V_{ces}	Parallel
PT-IGBT	○	○	○	○	○	○
Trench-gate IGBT	◎	○	○	×	△	×
NPT-IGBT	△	◎	◎	◎	◎	◎
AS-PT-IGBT *	×	△	◎	◎	◎	◎

* AS-PT-IGBT : Anode short-punch through-IGBT

(2) Application of VLSI technology
(3) Low-loss NPT-IGBT technology
(4) Smart IGBT technology (high-precision sensing)
(5) Exclusive, comprehensive, high-voltage driver IC technology
(6) New module-package assembly technology (based on all silicon-chip technology)
(7) Realization of new-concept devices

Using these core technologies, we plan to produce a series for low-loss 4th generation modules (600V, 1,200V 1,800V, etc.), high-cost-performance, all-silicon 3rd generation IPMs (R-IPMs), and advanced function 4th generation IPMs. Furthermore, we plan to develop 2,500V and 3,300V-class, high-voltage, high-power IGBT modules. In addition, we plan to apply these core technologies to small capacities to produce high cost performance IGBTs.

Table 2 shows the comparison of various IGBT performances. With regard to the trench-gate IGBT and in addition to the MOSFET problems mentioned previously, there is a serious problem of withstand capability against excessive current in a short-circuit condition. It will be indispensable to add a self-protective function in practical applications. The NPT-IGBT leaves room for improvement, and we believe that it has the most suitable structure among the high-voltage IGBTs.

As mentioned above, we regard the trend toward intelligent devices as major. Based on the medium and long-term strategy for following this trend, we will promote commercialization of high-value-added IPMs.

2.4 New-concept device technology

The limit of reduction in on-voltage for a 600V IGBT (with turn-off loss equivalent to the 3rd generation) is thought to be about 1.5V (assuming the various withstand capabilities are at the necessary levels for hard switching applications).

Therefore, the development of low-loss next-generation devices exceeding IGBTs has attracted notice and many new-concept devices have been announced. These can be roughly classified into MOS-controlled thyristors and action-mode-shift types using a dual gate or the like. Among the MOS-controlled thyristors are nonsaturated (MCT) and saturated thyristors (EST). The turn-off types for these are emitter-shorted, emitter-open, and action-mode-selection types. In any case, the basic action uses thyristor action by MOS control. Device performance is dependent on the way in which to increase turn-off controllable current by operating efficiently and conquering parasitic actions with excess carriers in a latch-up state. Both emitter short-circuiting and opening are the responsibility of the MOSFET, and it is indispensable in minimizing the MOSFET on-resistance. The mode-shift type changes the thyristor action (during forward conduction) into the IGBT action just before turn-off and aims to increase controllable current and switching speed with a turn-off in the IGBT action. The point is the prevention of the parasitic thyristor from activating at an IGBT turn-off action. For that purpose we are investigating device structures that can attain the application of LSI process technology and the uniformity of current.

As IGBT performance improves, a target on-voltage of the next-generation device is required to be about 1.0V. In actual applications, there is a demand for devices that have not only low loss but also well-balanced characteristics with various withstand capabilities. We are making efforts to realize them and believe we can do so in the near future.

3. Power Semiconductor Devices for Equipment Related to Multimedia

3.1 Power semiconductor devices for the CRT

CRTs are used as displays for personal computers and workstations as well as televisions. They are becoming popular on a more personal level. There is an intense need for high-resolution pictures that make the viewer feel as if he were actually there. In response to this, the horizontal deflection circuit operating frequency is increasing year by year. At the same time, a need for energy reduction is also strong. To satisfy both, high-performance diodes with low switching loss in the high-frequency operation range are required.

To meet this requirement, in addition to the former damper diode series, we have developed and marketed new damper diodes which have greatly improved transient forward characteristics and can drive as high horizontal deflection frequency as 120kHz.

We have also developed and marketed high-voltage silicon diodes in which the high-speed switching characteristics and reverse-spike voltage withstand capability during CRT discharge have been improved.

In the future, Fuji Electric will strive to complete a line of devices such as CRT main power supply devices, S-shaped capacitor selector devices for compensating display distortion, and switching devices for horizontal deflection so that we can offer comprehensive proposals for CRT power semiconductor devices.

3.2 Power semiconductor devices for portable electronic appliances

The common problem of portable electronic appliances typically represented by personal notebook computers, mobile phones, and PDAs (personal digital assistants) is to extend service time by prolonging battery life. For this purpose, although the high performance of batteries is important, the key is to reduce power consumption for longer battery use.

From this point of view, the power MOSFET used for charging and discharging the safety circuit of long-life lithium ion batteries and the DC-DC converter must have low on-resistance to improve efficiency and must also be utilized in the synchronous rectifier circuit. In addition, in order to be mounted in the limited space of portable electronic appliances, it must be assembled in a small surface-mount package.

To meet these requirements, we have realized a low on-resistance chip utilizing fine patterning technology and have developed and marketed n-channel SOP-8 power MOSFETs with the chip mounted on a SOP-8 package.

To prolong battery life, a management power MOSFET that cuts off power for unused peripheral equipment is also important. In the future, we plan to complete a series of p-channel SOP-8 power MOSFETs for this purpose.

4. Power Semiconductor Devices for Vehicles and Rolling Stock

4.1 Power semiconductor devices for car electronics

To meet the requirements for automobiles regarding "safety", "environmentally friendly", and "energy-saving", the mounting of electronic equipment such as anti-skid brake systems (ABS) and air bags is rapidly increasing. External circuit components added to these power MOSFETs in the electronic equipment are protective circuits that protect the devices from various surge voltages and short circuits generated in automobiles and gate drive circuits.

The number of electronic parts has increased yearly and has resulted in a fear of lowered reliability and difficulties in mounting parts in the limited space of an automobile. To solve these problems, Fuji Electric marketed an IPS using a power MOSFET with built-in protective, driver, and self-diagnostic circuits on a single chip.

In addition, we have developed and marketed an advanced function MOSFET by simplifying the IPS and facilitating its use. This new MOSFET is expected to be used not only in car electronics but also in uses that demand system downsizing and high reliability.

4.2 Power devices for rolling stock and electric vehicles

The improvement of drive performance is directly connected with power conversion technology. IGBT-applied control has rapidly spread in response to recent demands for rolling stock such as improvement in energy efficiency, size reduction, and comfort. Especially high-voltage, large-power, flat IGBTs such as the 2.5kV/1,000A originally developed by Fuji Electric are expected to greatly improve equipment efficiency and size not only in rolling stock but also in high power industries.

Further focusing on devices for urban transportation use, we have developed 1,800V/800A and 3,300V/1,200A IGBT modules using new NPT-IGBTs. A through investigation into loss reduction and reliability improvement of the chips, packages, etc. was carried out to obtain optimum conditions for the rolling stock. To protect the global environment from air pollution due to automobile exhaust gas, the development of practical and nonpolluting electric vehicles (EV) has been taken up in earnest. At present, the IGBT is top-rated as an EV inverter power device, and the IGBT-IPM is especially thought to be important because of its real-time protection and reliability. However, IGBT loss is still high and further improvement is desired. In the future, high-efficiency inverters using new-concept devices will be applied.

5. Power Semiconductor Devices for Industrial Power Converters

5.1 Power semiconductor devices for small capacity (several kilowatts or less) power converters

Small capacity power converters, typically represented by inverters for variable-speed motors and UPSs, require a reduction in size, weight, and price for further use. In this field, aiming to minimize the mounting cost in applications, Fuji Electric has offered IGBT modules with six IGBTs built into a package and PIMs (power integrated modules) with a built-in power supply converter.

Recently, small capacity power converters have been used in various fields, and requirements for IGBT mounting methods have diversified. In response, in addition to the previous approach by modules and with the concept of minimizing device cost and free mounting in applications, we have developed and marketed discrete molded-package IGBTs.

The molded IGBTs based on 3rd generation IGBT technology has low-loss and a resistance to high breakdowns and is expected to contribute to a reduction in equipment size and weight.

5.2 Power semiconductor devices for power converters

Following are uses of these devices, generally classified by the field of application. In the generation and conversion of electric power and energy, utilization of new energy resources such as photovoltaic power generation and fuel cells is expected to develop rapidly. In the industrial field, inverters used for motor control in motor applications such as pumps, blowers, and machine tools are expected to greatly increases to include a wide range of equipment. In the field of information and communications, they are expected to be utilized as devices for computer systems' power supply; the UPS is one example. Power MOSFETs and IGBTs used for the PWM (pulse width modulation) converters and PWM inverters are expected to expand. In household appliances, the use of energy-saving inverters is expected to give impetus to the development of power semiconductor devices. Inverters will be applied to the motor control of air conditioners, refrigerators, etc., resulting in high efficiency, downsizing, and advanced functions.

Up to now, Fuji Electric has been highly rated in the field of medium capacity (up to several tens of kilowatts) inverter control. In the future, by applying the new technologies mentioned above, we plan to develop timely devices to match broadening fields. In the range less than several kilowatts, we will aim at the development of special modules and IPMs and at expansion of integrated devices (PIMs and IPMs) for a transition period. The 4th generation modules up to several hundred amperes and from several hundred to nearly two thousand volts, new NPT-IGBT modules, 3rd generation IPMs, and advanced-function 4th generation IPM series are all under development.

6. Conclusion

As stated in the Introduction, there are many problems to be solved by technology on the road to a highly information-oriented society. Unlike in the past, there should be increased recognition of problems of the environment and resources. Specially, the goals will include “user-friendly inverters”, “energy-saving electronic appliances”, and “new energy resources development”. The role played by power semiconductor devices in pursuit of these goals will increase in importance. Fuji Electric will make a continuous effort to play a vital role in their attainment.

The present status and future prospects of Fuji Electric’s power semiconductor devices have been described above. In particular, we intended to focus on our attitude towards their development. Although the descriptions may be somewhat rough, we appreciate your understanding of our intentions. We will continue our technical innovations in developing characteristic products in response to the needs of the market and contribute to the further development of electronics.