

# Fuji Electric's Semiconductors: Current Status and Future Outlook

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## 1. Introduction

Influenced by economic growth and an increasing population, by 2025 the global consumption of primary energy will be 1.5 times that consumed in 2001, and will be the equivalent of 15.7 billion tons of oil. As a result, carbon dioxide (CO<sub>2</sub>) emissions are predicted to rise to 1.5 times that of 2001, or to 37.1 billion tons. Unless the trend toward increasing atmospheric concentrations of CO<sub>2</sub> and other greenhouse gases is slowed, it has been reported that by the end of the 21st century there will be a worldwide average increase in land temperature of 1.4 to 5.8°C and sea levels will rise by 9 to 88 cm due to the greenhouse effect. The effects of global warming are not limited to a rise in sea levels, and wide-ranging large-scale effects including damage to the ecosystem, severe droughts, adverse impact on food production, frequent flooding and storm surges, increased incidence of tropical diseases, and the like, have been predicted and reported.

Improving industrial productivity is essential for raising living standards and for economic development, and among the types of energy consumed, an especially large increase in the consumption of electrical power is forecasted. As shown in Fig. 1, by 2025, the global consumption of electrical power is forecasted to increase to 23 trillion kWh, approximately 1.7 times that consumed in 2001<sup>(1)</sup>. From the perspective of people involved in the power semiconductor business, one

sector of the power electronics field that targets the effective use of electric power energy, the above figures underscore the importance of their mission to strike a balance between global improvements to the standard of living and economic development on one hand, and protection of the global environment on the other.

For power semiconductors to contribute to this mission, the efficiency of electric power utilization in power electronic equipment must be improved, and the savings of natural resources (miniaturization) and expanded range of use (lower cost and wider range of applications) must exhibit positive effects. Specifically, performance improvements to power semiconductors and improved control and sensing functions must contribute to advances in performance, smaller size, higher reliability and lower cost, and must also expand the power semiconductor product lineup and its range of applications.

This paper discusses the current status and future outlook for Fuji Electric's representative semiconductor products of power modules, power discretes and power ICs.

## 2. Power Modules

High-power semiconductor devices used for electric power conversion and other applications in industrial machinery and robots, air conditioner compressors, semiconductor manufacturing equipment, motor drives of automobiles and hybrid electric vehicles, welders and UPS (uninterruptible power supplies), medical equipment, and the like, are supplied mainly as power modules. From the commercialization of IGBT (insulated gate bipolar transistor) products in 1988 through the present, due to their excellent performance and controllability, IGBTs have evolved to become the type of transistors used most commonly in power modules.

Figure 2 shows the historical changes in performance and technology of Fuji Electric's IGBT modules, using the 1,200 V series as an example. At present, the latest generation is the 5th generation U-series released in 2002. By using an FS (field stop) structure for the device, and using a trench-gate structure for the gate, dramatically lower loss and higher rugged-

Fig.1 Forecast of global electric power consumption<sup>(1)</sup>

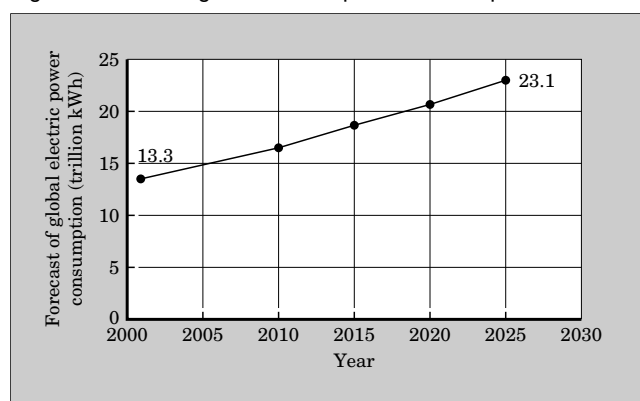


Fig.2 Changes in performance and technology of Fuji Electric's IGBT modules

	1985	1990	1995	2000	2005		
Product changes		1st generation	2nd generation L, F series	3rd generation J, N series	4th generation S series	5th generation T, U series	6th generation V series
Figure of merit Inverter loss (example of 1,200 V, 300 A model)		350 W	280 W	218 W	194 W	160 W	< 140 W
Figure of merit representing size Chip area (example of 1,200 V model)		100	100	71	71	43	< 35
Device technology		PT			NPT	FS	Advanced FS
Device structure		Planar DMOS					Trench gate
Gate structure							
Design rule		6 μm	4 μm	3 μm	1.5 μm	0.8 μm	0.5 μm
Product series		Standard module			Standard module, econo module		
		Standard IPM			Standard IPM, compact IPM		
		PIM					
							For matrix converter
							For hybrid electric vehicle
Rated voltage		600 V, 1,200 V, 1,400 V				to 1,700 V	to 3,300 V
Rated current		8 to 400 A		10 to 600 A		10 to 3,600 A	8 to 4,800 A

ness have both been realized, and by using an anode structure known as a SAS (shallow anode structure) that suppresses carrier injection, the performance of the FWD (free wheeling diode) has also been improved. In the example of the 1,200 V series, approximately 20 % lower loss and approximately 40 % smaller chip area as compared to the 4th generation IGBT modules have been realized in the case of 6 kHz inverter operation. In the upcoming 6th generation V-series, additional improvements to the device structure (advanced FS structure) and an improved gate structure are planned to further reduce power loss and shrink the chip size, and FWD improvements are also planned at this time. 1,200 V models of the V-series are slated for release in fiscal year 2006, and 600 V models for fiscal year 2007.

As its IGBT module lineup, Fuji Electric first began supplying a standard module series, but then with the 2nd generation of modules, added an IPM (intelligent power module) and PIM (power integrated module) series and with the 3rd generation dramatically increased the number of types of models, and then with the 4th generation, added a small-size low-cost EconoPACK<sup>\*1</sup> series. With the 5th generation, Fuji Electric added a 1,700 V series of modules, expanded

the large-current series to 3,600 A, started to provide custom designed IGBT modules for hybrid vehicles, and advanced the commercialization of reverse-blocking IGBT modules for matrix converter use. Fuji Electric is committed to continuing to expand the voltage and current range of high-power IGBT modules, to achieve even smaller size and lower cost in low-power IGBT modules, and to actively support new applications.

When considering the future of power modules, the most important issue is when to make the transition from silicon (Si) devices such as IGBTs to compound semiconductor devices such as silicon carbide (SiC) devices. Fuji Electric estimates that the transition of power modules to SiC technology will occur at the time of the 7th or 8th generation. SiC wafer technology has made steady progress in reducing defect density and developing larger diameter wafers. By the time when the 7th generation is released in 2009 or 2010, a killer defect density of less than 10 cm<sup>-2</sup> may be achieved for the 4-inch wafers needed to mass-produce 5 mm chips. However, the cost of SiC wafers presents an extremely large challenge. Even with the assumption of other improvements such as the realization of smaller package sizes as a result of the effective utilization of the smaller chip size, and the realization a large increase in the maximum rated junction temperature, the price

\*1: EconoPACK is a trade mark of Eupec GmbH. Warstein.

per unit area of SiC wafers must be reduced to about 1/30th of their present cost in order for them to be a viable substitute for IGBT chips, and the present cost reduction trend is not on track to meet this requirement. We look forward to further technical innovation and effort by the SiC wafer manufacturers. Power device manufacturers must concentrate on researching SiC processes and devices, while at the same time hedging their risk by continuing to improve the performance of Si devices. However, with the 6th generation of devices, IGBT performance improvements will approach their limit, and a radically innovative device structure will be needed to realize the 7th generation devices. Efforts must also focus on research into new types of Si devices such as MOS (metal oxide semiconductor) gate thyristors, and research into package technologies<sup>(9), (10)</sup> capable of utilizing the Si devices at higher current densities.

### 3. Power Discretes

Medium-power semiconductor devices used in switching-mode power supplies, UPS for IT (information technology) equipment, automotive-use drivers for motors, relays or solenoids, and the like, are supplied mainly as power discrete products. Because of their excellent high-frequency performance and drivability, power MOSFETs (MOS field effect transistors) are the most commonly used type of discrete transistors, and also from the perspective of high-frequency performance, LLDs (low loss diodes) are the mainstream diode for high-voltage applications, and similarly, SBDs (Schottky barrier diodes) are used for low-voltage applications.

This chapter discusses the present status and

future outlook for power MOSFETs, LLDs and SBDs.

#### 3.1 Power MOSFETs

Figure 3 shows the historical changes in performance and technology of Fuji Electric's power MOS FETs. Fuji Electric's 600 V series is shown as a representative example of a high-voltage series for use in switching-mode power supplies, and the 60 V series is shown as a representative example of a low-voltage series for automobile-use.

The flagship of the high-voltage series is presently the 3rd generation SuperFAP-G series released in 2001. With the two independent technologies of a quasi-plane junction and an optimized guard ring, this SuperFAP-G series realizes high performance that approaches 10 % to the theoretical limit for Si. In the example of the 600 V series, an approximate 60 % reduction in the figure of merit  $R_{on}Q_{gd}$  indicating low-loss performance was achieved compared to the 2nd generation products, and a smaller size corresponding to an approximate 40 % reduction in the figure of merit  $R_{on}A$  representing chip size and assurance of repetitive avalanche ruggedness at elevated temperature were achieved at simultaneously. For the upcoming 4th generation, the use of super-junction technology to realize even lower loss and smaller size is being studied.

In the low-voltage series, the shipment of samples of the 5th generation FAP-T2 series (2nd generation of trench MOSFETs) started in 2004. With a trench gate structure and improved quasi-plane junction technology, the 60 V series achieves an approximate 30 % reduction in  $R_{on}Q_{gd}$  and an approximate 20 % reduction in  $R_{on}A$  compared to the 4th generation products, while maintaining the high reliability (high avalanche

Fig.3 Changes in performance and technology of Fuji Electric's power MOSFET modules

	1985	1990	1995	2000	2005	
600 V product changes	1st generation (FAP-1, FAP-2 series)		2nd generation (FAP-2A, FAP-2S series)	3rd generation (SuperFAP-G series)	4th generation	
$R_{on}Q_{gd}$	20 Ω·nC		15 Ω·nC	5.5 Ω·nC	3 Ω·nC	
$R_{on}A$	130 mΩ·cm <sup>2</sup>		125 mΩ·cm <sup>2</sup>	76 mΩ·cm <sup>2</sup>	24 mΩ·cm <sup>2</sup>	
Device technology	Planar DMOS			Quasi-plane junction DMOS	Super-junction	
60 V product changes	1st generation (FAP-1 series)	2nd generation (FAP-3A series)	3rd generation (FAP-3B series)	4th generation (FAP-T1 series)	5th generation (FAP-T2 series)	6th generation (FAP-T3 series)
$R_{on}Q_{gd}$	800 mΩ·nC	540 mΩ·nC	260 mΩ·nC	175 mΩ·nC	125 mΩ·nC	90 mΩ·nC
$R_{on}A$	3.5 mΩ·cm <sup>2</sup>	2.3 mΩ·cm <sup>2</sup>	1.4 mΩ·cm <sup>2</sup>	0.8 mΩ·cm <sup>2</sup>	0.65 mΩ·cm <sup>2</sup>	0.5 mΩ·cm <sup>2</sup>
Device technology	Planar DMOS		Quasi-plane junction DMOS	Quasi-plane junction trench		

Fig.4 Fuji Electric's diode (LLD and SBD) performance improvements and expansion of product lineup

	1985	1990	1995	2000	2005
Product changes	1st generation (standard series)			2nd generation (application-specific series)	
Low-loss diode (LLD)	Low-loss diode (LLD) (200 to 600 V)			Super-low-loss SuperLLD (600 V)	SuperLLD (400 to 800 V)
Schottky barrier diode (SBD)	Low $V_F$ SBD (40 to 90 V)	Ultra-low $V_F$ SBD (30 V)	High-voltage SBD (120 to 250 V) Low $I_R$ SBD (40 to 100 V)		High-current
Expanded package series	TO-220 Full-mold	TO-3P Complete full-mold	TO-220 Complete full-mold	TO-247 (100 A)	TO-3PL (200 A)
Standing-type package					
SMD package	D <sup>2</sup> -Pack (30 A)	D-Pack (7 A)	2-terminal SC (1 A)	TFP (30 A) 2-terminal SD (3 A)	Expanded series

ruggedness, high short-circuit withstand capability, high breakdown voltage of the gate, high power-cycling capability) of the 4th generation. In the upcoming 6th generation, we plan to further optimize the trench gate structure and the quasi-plane junction technology to realize smaller design rules, while maintaining the trends towards improved performance and smaller size.

### 3.2 LLDs and SBDs

Figure 4 shows historical performance improvements and expansion of the series of Fuji Electric's LLDs and SBDs. LLDs are used primarily in the secondary-side rectification of switching-mode power supplies and in power-factor control circuits, and the 200 to 600 V standard series and the 600 V SuperLLD series are presently the flagship models. The SuperLLD series contains a low switching loss series for use with continuous conduction mode PFC (power-factor control) and a low conduction loss series for use with discontinuous conduction mode PFC. In the future, we plan to expand the rated current and voltage ranges of our LLDs.

SBDs are used primarily in DC-DC converters and in the secondary-side rectification of switching-mode power supplies, and the 120 to 250 V rated high-voltage SBDs and the 40 to 100 V rated low-reverse-leakage-current (low  $I_R$ ) SBDs are presently the flagship models. The high-voltage SBDs use newly developed barrier metals to realize higher voltage and, at the same time, reduced leakage current and lower switching noise. By using these high-voltage SBDs in applications in which 200 to 400 V LLDs had been used previously, lower loss and lower noise can be achieved. As expected, by using newly developed barrier metals, low- $I_R$  SBDs can reduce leakage current to approximately one-tenth that of conventional SBDs, and can be used at junction temperatures of up to 150°C, and are therefore especially effective in applications where the heat radiation is poor such as in AC adapters. In the future, we plan to increase the

current capacity of these products and to expand the lineup of available packages.

## 4. Power ICs

### 4.1 Power ICs for automotive-use

Fuji Electric supplies many series of power ICs. Automotive-use power ICs include single-chip and hybrid igniters for ignition, IPS (intelligent power switches) for driving the solenoid valves of an electronic transmission controller, smart power MOSFETs for driving solenoid valves in ABS (antilock brake systems) and ESC (electronic stability control) systems and for driving lamps, and integrated power ICs for integrating multiple I/O channels in ECU (electronic control units).

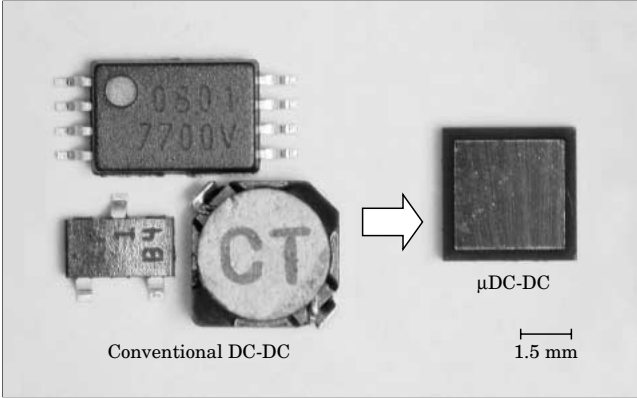
### 4.2 Power ICs for power management systems and IT equipment

As power ICs for power management systems of IT equipment, Fuji Electric is focusing on power IC for power systems (hereafter referred to as power supply ICs). Figure 5 shows the historical changes in performance and technology of Fuji Electric's power supply ICs. Fuji Electric's latest generation of power supply ICs is its 4th generation 0.6  $\mu\text{m}$  CDMOS (complementary double diffused MOS). With an optimized structure and advanced design rule, the lateral DMOS achieves an approximate 17 % improvement in  $R_{\text{on}}Q_{\text{gd}}$  and an approximate 25 % improvement in  $R_{\text{on}}A$  compared to the 3rd generation products. In the upcoming 5th generation, we plan to transition to a CTMOS (complementary trench lateral power MOS) device that contains a TLPM (trench lateral power MOS) integrated into its output stage, and expect an additional approximate 40 % improvement in  $R_{\text{on}}Q_{\text{gd}}$  and approximate 67 % improvement in  $R_{\text{on}}A$ . Power supply ICs are either for AC-DC use or for DC-DC use. AC-DC power supply ICs include AC-DC driver ICs, single-chip power ICs with an integrated high-voltage output power MOSFET, and M-power series for high-current

Fig.5 Changes in performance and technology of Fuji Electric's power ICs for power management systems and IT equipment and PDP driver ICs

		1985	1990	1995	2000	2005	
Power ICs for power management systems of IT equipment	Product changes	1st generation >> 2nd generation >> 3rd generation >> 4th generation >> 5th generation					
	Power supply IC						
	$R_{on}Q_{gd}$ 30 V	200 mΩ·nC >> 120 mΩ·nC >> 90 mΩ·nC >> 60 mΩ·nC					
	$R_{on}A$ 30 V	300 mΩ·mm <sup>2</sup> >> 78 mΩ·mm <sup>2</sup> >> 60 mΩ·mm <sup>2</sup> >> 20 mΩ·mm <sup>2</sup>					
	Device technology	Bipolar >> BiCMOS >> CDMOS >> CTMOS					
	Product series	AC-DC, DC-DC					
		High-voltage >> High-current					
Integrated MOS, system power supply IC							
						μDC-DC	
PDP driver ICs	Product changes	Buried epitaxial	1st generation	2nd generation	3rd generation	4th generation	5th generation
	Address driver		220 (Index)	150	100	68	48
	Chip area per bit	SOI	1st generation	2nd generation	3rd generation	4th generation	5th generation
	Product changes		150 (Index)	110	100	78	62
	Scan driver		5 μs >> 15 μs				
Chip area per bit							
Short-circuit withstand capability							

Fig.6 Fuji Electric's μDC-DC (micro DC-DC converter) that will contribute to the smaller size and lighter weight of portable electronic equipment



and high-efficiency power supplies. DC-DC power supply ICs include DC-DC power supply ICs with and without integrated power MOSFETs, system power supply ICs, and micro DC-DC converters. Among these devices, the micro DC-DC converter is a new product that uses Fuji Electric's proprietary technology and was just released at the end of 2004. As shown in Fig. 6, the micro DC-DC converter integrates the three components of a conventional power supply IC, a power MOSFET and an inductor into a single chip, thereby realizing a large reduction in the mounting area required on a printed circuit board. The micro

DC-DC converter is especially effective in achieving smaller size and lighter weight in portable electronic equipment. This is one of the products that Fuji Electric intends to promote the most.

4.3 Drivers for plasma TV

The increase in demand for plasma TVs has resulted in a recent sudden increase in shipments of PDP (plasma display panel) drivers. There are two types of PDP drivers, scan drivers that drive the horizontal direction and address drivers that drive the vertical direction, and Fuji Electric has been supplying both types since the inception of the PDP era. Figure 5 shows the historical changes in performance and technology of Fuji Electric's PDP drivers. Address drivers began to be mass-produced with the 4th generation in 2005. By transitioning to 0.6 μm CD MOS technology and optimizing the lateral DMOS, these 4th generation address drivers achieve an approximate 32 % improvement in chip-area-per-output-bit as compared to 3rd generation products, and make it possible to support 192-bit driver ICs. In the upcoming 5th generation address drivers, further shrinkage of the design rules and device optimization to realize an additional improvement of approximately 30 % in the chip-area-per-output-bit, and the application of LVDS (low voltage differential signal) technology to increase the high-speed data transmission capability, are expected to provide the capability for

supporting 256-bit driver ICs. 3rd generation scan drivers are presently being supplied. These 3rd generation scan drivers feature an improved output IGBT that realizes a 10 % reduction in the chip-area-per-output-bit and smart-gate control technology that has been developed to increase the short-circuit withstand capability to approximately three times its former value, and contribute to the realization of high quality plasma TVs. In the 4th generation scan drivers slated to begin mass production in fiscal year 2005, and the application of smart-gate control technology to the upper IGBT results in increased current density in the upper IGBT and reduces the chip-area-per-output-bit by an additional 22 %.

## 5. Transition to Lead-free Technology

In order to protect the global environment, efforts are underway to eliminate certain hazardous substances from the environment. For semiconductor products, the lead contained in solder on external terminals has presented special problems. Fuji Electric has already begun eliminating lead from its power ICs and power discretes, and has been delivering lead-free products upon request to its customers. Fuji Electric also plans to phase-in the supply of lead-free power module products.

## 6. Conclusion

Fuji Electric looks forward to continuing its contribution to the advancement of both social development and global environmental protection through innovating and promoting power electronics technology. Power semiconductors are important products that form a pillar of support for such efforts, and this paper has discussed the present status and future outlook for the major products of power semiconductors.

In response to questions of whether social development and global environmental protection can be advanced simultaneously, and whether science and technological development contribute to the well-being of society, although some people may have negative opinions, the answer can only be known by those people who will live in the world 1,000 or 10,000 years from now. Living in the 21st century as individuals whose occupation involves technology and as individuals engaged in the manufacturing industry, we intend to promote technology to advance both social development and global environmental protection, and to develop and commercialize products to contribute to the well-being of society, so that the answer to those questions will be known.

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