Fuji Electric's Semiconductors: Current Status and Future Outlook

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1. Introduction

The June 1, 2006 issue of "nature" reported[1] the results of an investigation of deposits on the North Pole ocean floor indicating that the ocean surface temperature at the North Pole approximately 55 million years ago was about 23°C, which is 10°C or more higher than had been previously estimated by mete-orological simulations. The expanding global economy and growing population are driving an increase in energy consumption and CO_2 emissions[2], and unless this trend is slowed, serious impact from the greenhouse effect is a concern[3]. The abovementioned article in "nature" indicates that the predicted greenhouse effect and its impact might be reconsidered for the worse, and that the limiting of CO_2 emissions is a more important issue for mankind.

All member companies of the Fuji Electric Group, whose corporate mission includes "seeking harmony with nature", have been working to protect the global environment through providing products and technologies that contribute to the conservation of the global environment, reducing the environmental burden over the course of a product's lifecycle, and promoting business activities that also reduce environmental burden as part of Fuji Electric's basic corporate policy. Fuji Electric especially focused on the business areas of power electronics, which aims to utilize electric power energy effectively, and power semiconductor devices, the main components in this field, as businesses whose contribution is crucial to protecting the global environment. Electric power accounts for more than 40 % of primary energy, and since this percentage is expected[2] to increase unilaterally, power electronics and power semiconductor devices will be expected to become even more important in the future.

Power semiconductor devices help to protect the global environment and in particular, to reduce CO_2 emissions by increasing the efficiency with which electric power is used, thus contributing to resource conservation (miniaturization) and to expanding the usage (by lowering the cost and expanding the range of applications) of power electronic equipment. In particular, the specific performance of power semiconductor devices themselves must be improved, control and sensing functions must be enhanced to realize better performance, smaller size, higher reliability and lower cost, and the lineup and applications of power semiconductor products must be expanded.

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

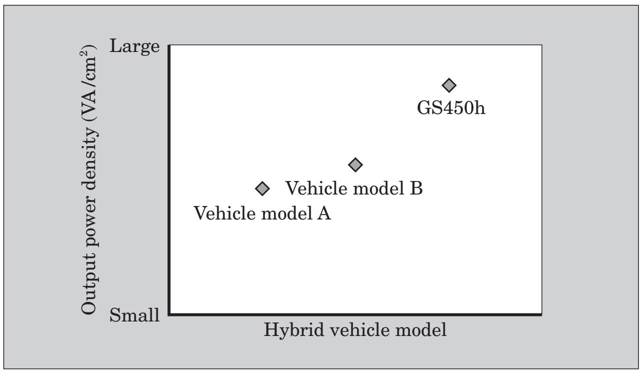
2. Power Modules

Fuji Electric's recent major accomplishments involving power module products are the mass-production of IGBT (insulated gate bipolar transistor)-IPMs (intelligent power module) for use in hybrid vehicles and the market launch of the U4 series of IGBT modules.

As is explained in detail in this issue, last year for the first time, Fuji Electric's IGBT-IPM is being utilized in the PCU (power control unit) of a hybrid vehicle, and is being mass-produced. The vehicle model is the LEXUS*1 GS450h, and we take pride in the acceptance of Fuji Electric's proprietary technology to realize high power, low loss, small size and high reliability in

*1: LEXUS is a registered trademark of the Toyota Motor Corporation.

Fig.1 Comparison by car model of output power density (IPM output power / IPM base area) of hybrid vehicle-use DC-DC converter IPM



the global LEXUS brand of hybrid cars that feature rapid acceleration, good fuel economy, excellent design and high quality. Figure 1 shows a comparison with the output power density (IPM output power per IPM base area) of conventional IPMs used in a DC-DC converter for the same application. It can be seen that the output power density has been improved dramatically compared to that of the IPMs used in vehicle models A and B. The use of the U series IGBT chip set that incorporates Fuji Electric's proprietary technology(4)(5) to realize low loss, high durability and small size, and the design of a package optimized for the particular application contribute to the dramatic improvement in output power density. This IPM uses an alumina DCB (direct copper bonding) + Cu base structure to realize high heat dissipation and high reliability(6), and is the world's first application of this structure to an automotive IPM, successfully realizing a dramatic decrease in cost. Also, the use of Fuji Electric's independently developed lead-free solder has resulted in the world's first all lead-free automotive IPM.

The U4 series of IGBT modules were developed based on Fuji Electric's U series technology, and realize a higher carrier frequency and lower noise emission. The U4 series is effective in industrial-use motor driver applications for increasing the carrier frequency while suppressing emission noise and conduction noise(7). Figure 2 compares the tradeoff between emission noise and power loss, as measured on a Fuji Electric test bench while varying the gate resistor, for the U4 and other series. The U series, characterized by ultra-low loss, was very effective in reducing inverter loss, but was difficult to use because adjustment of the gate resistor and optimization of the main circuit wiring were sometimes required in order to reduce noise. The U4 series enables a significant reduction in noise to be achieved through adjustment of the gate resistor only, and is extremely easy to use.

6th generation V series IGBT modules have been developed for release at the end of fiscal 2006. With an improved FS (field stop) structure and trench gate structure to realize significantly lower loss and smaller size than the U series, and the incorporation of low noise technology acquired during development of the U4 series, the V series is expected to be easy to use, even for noise reduction.

2006 was the year in which RoHS*2 compliance and lead-free implementation of power modules was achieved. All new products are already RoHS-compliant, and existing products have been made fully RoHS-compliant and lead-free during 2006.

Fuji Electric is advancing the development(8) of higher reliability and higher heat dissipating packages, MOS (metal oxide semiconductor) gate type conduction modulation devices and SiC devices, and plans to introduce them in this journal within several years.

3. Power Discretes

Low voltage MOSFETs (MOS field effect transistors) are one of the main types of power discretes, and in 2005, Fuji Electric began mass-producing a 2nd generation trench MOSFET. Figure 3 shows a cross section of this MOSFET structure. By integrating Fuji Electric's proprietary quasi-plane junction technology and drain ballast resistance technology with trench technology, the specific on-resistance per unit area was reduced by approximately 20 % and the $R_{on}\cdot Q_{gd}$ figure of merit was improved by approximately 30 % while ensuring the same level of short-circuit withstand capability and avalanche tolerance as a 1st generation device.

Fuji Electric's main power discrete products are the Super FAP-G series(9) of high voltage MOSFETs, the high voltage SBD (Schottky barrier diode) series

*2: RoHS is restriction of the use of certain hazardous substances in electrical and electronic equipment.

Fig.2 Comparison of the tradeoff between emission noise and power loss measured by varying the gate resistor

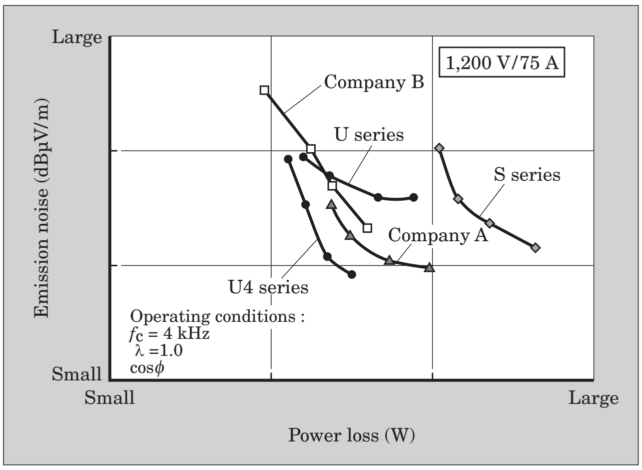


Fig.3 Cross section of 2nd generation trench MOSFET structure

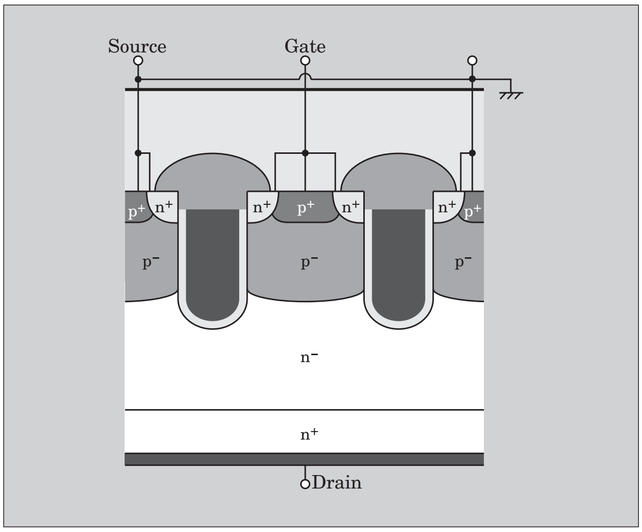
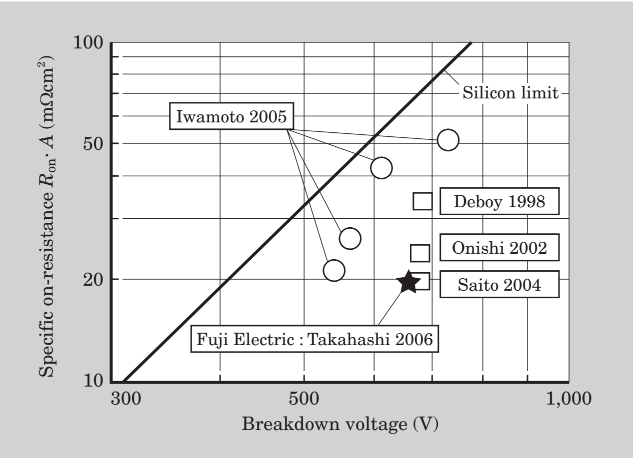


Fig.4 Data presented at scientific conferences concerning the relation between on-resistance and breakdown voltage of high voltage superjunction MOSFETs



and low reverse leakage current (low I_r) SBD series of SBDs and the Super LLD (low loss diode) series of LLDs. Demand for these product groups is extremely strong, and Fuji Electric is working to expand its supply capability.

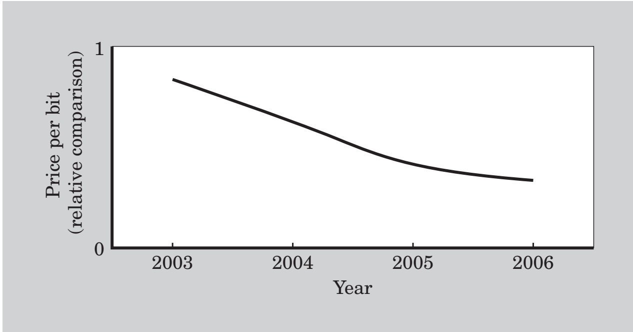
Looking toward the future, Fuji Electric is focusing on research and development aiming for even higher performance and smaller size. An example of Fuji Electric's latest success, shown in Fig. 4, is the attainment of a superjunction MOSFET(10) having the world's highest level of low specific on-resistance of 19.8 mΩcm^2 (at the breakdown voltage of 660 V) in a prototype of a trench refilled type superjunction MOS FET that is expected to achieve lower cost. This result has been announced at an international conference(11).

4. Power ICs

Fuji Electric has achieved many successes with power ICs, including the mass-production of M-Power 2, a power IC for use in high-efficiency low-noise switching-mode power supplies, and the adoption of the M-Power 2 by the major manufacturers of power supplies for LCD (liquid crystal display) TVs, the mass-production of a 4th generation 256-bit PDP (plasma display panel) address driver IC(12), the development of a 4th generation 96-bit PDP scan driver IC, the mass production of a control IC for quasi-resonant low standby AC-DC switching-mode power supply, the mass production of a multi-channel input integrated power IC for use in an automotive ECU (electronic control unit), the mass-production of a CSP (chip size package)-IPS (intelligent power switch) for use also in the automotive ECU, the development of a control IC for a single-channel DC-DC buck converter, the development of a 2nd generation micro DC-DC converter, and so on.

The M-Power 2 power IC is a 2nd generation product for use in high efficiency and low noise switching-mode power supplies, and the incorporation of Fuji

Fig.5 Trend of decreasing price-per-bit for PDP driver ICs (example of address driver IC)

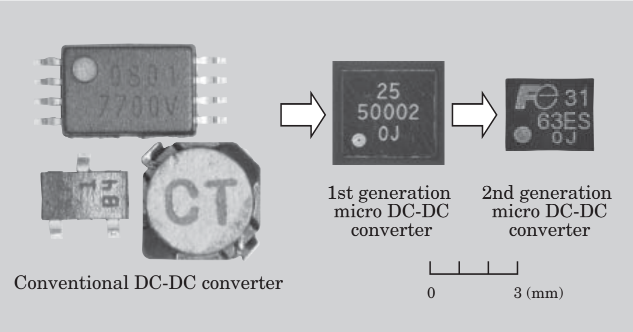


Electric's proprietary control technology enables a current resonant switching-mode power supply without resonant shift to be realized for the first time with a power IC. Because the M-Power 2 enables the easy configuration of high-efficiency low-noise high-power switching-mode power supplies of up to 250 W, its usage is increasing in power supplies for flat panel televisions such as LCDs where noise is undesirable and high efficiency is required. Fuji Electric is also developing the M-Power 2A series which realizes even higher power output with the same package to support larger size flat panel televisions.

PDP driver ICs are power ICs that make full use of Fuji Electric's expert high-voltage technology, and many of Fuji Electric's proprietary technologies have been used in a 100 V BCD (bipolar, complimentary and double-diffused MOS) process for address driver ICs and 200 V SOI (silicon on insulator) process for scan driver ICs. In particular, the 200 V SOI process is the world's first process that integrates IGBTs in a SOI chip(13), thus enabling a significant reduction in chip area per output bit. Figure 5 shows an example of the decreasing price-per-bit trend for PDP driver ICs. Until now, the price-per-bit for power ICs has been falling steadily due to improved device processes and an increased number of integrated bits per chip. In the future, however, a straight-line decline in prices-per-bit will be difficult to attain due to the unique problem of power ICs of not permitting scaling of the supply voltage, and due to the theoretical limits of silicon material. Fuji Electric intends to provide continuous improvements that benefit the user by introducing LVDS (low voltage differential signal) and RSDS (reduced swing differential signal) technology to reduce the number of signal lines and support electric power recirculation in order to lower the cost and increase the performance of the entire display panel.

In the field of power ICs for switching-mode power supplies and for automobiles, Fuji Electric's strengths are in the high voltage processes that utilize power device technology and in the processes for integrating high voltage devices and high current devices in the ICs. All the processes can integrate 30 V or higher devices, and provide distinctive product groups that

Fig.6 Appearance of 2nd generation micro DC-DC converter

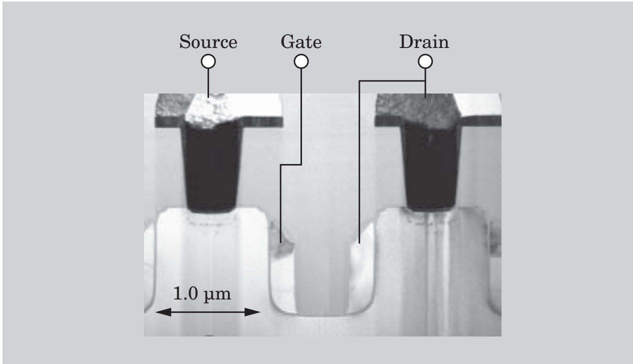


include an integrated 500 V start-up device for use in AC-DC switching-mode power supplies, an integrated 600 V IGBT for use in automotive igniters[14], an integrated 60 V power MOSFET for use in automotive power ICs[15], or integrated 30 V to 60 V low on-resistance DMOS (double diffused MOS) circuits for use in DC-DC power supply ICs and in integrated power ICs for automobiles. Also being used recently is COC (chip on chip) technology which, in addition to these process technologies, involves laminating and integrating into a single package of multiple silicon chips and micro-inductors. COC technology is beginning to demonstrate its effectiveness in achieving smaller sizes and higher outputs. Figure 6 shows the appearance of a 2nd generation micro DC-DC converter, samples of which are presently being deployed. Using COC technology to integrate a micro inductor with a silicon chip already integrated with an output power MOSFET, the world's smallest DC-DC converter was realized with a 1st generation micro DC-DC converter[16]. A subsequent 2nd generation micro DC-DC converter achieved an even 40 % smaller size while maintaining the same power output.

To increase the performance and reduce the size of power ICs, it is important that the integrated output power devices provide higher performance and smaller size. For future applications, Fuji Electric is working vigorously to advance its research and development into realizing higher performance and smaller size integrated power devices for power ICs. In particular, such research and development efforts are focusing on Fuji Electric's proprietary three-dimensional TLPM (trench lateral power MOSFET[18]) power device for use in Li-ion battery protection ICs[17] and DC-DC converters, and for possible future applications to automobiles. Figure 7 shows a photograph of a cross-section of Fuji Electric's latest device. This device, usable as a high-side switching element, has a $R_{on} \cdot Q_{gd}$ figure of merit of 16.4 mΩnC (at the breakdown voltage of 20 V) and, as a device for integration into a power IC, realizes the world's highest level of performance. This device also attains a high electrostatic discharge withstand capability, which is usually the weak point of this class of devices, of 2 kV with a HBM (human body model)[19].

Fuji Electric is also advancing its research into

Fig.7 Cross section photograph of Fuji Electric's latest TLPM that realizes both the world's highest figure of merit and a high electrostatic discharge withstand capability



digital control[20] and is considering the possibility of converting the present analog control to digital control to achieve higher accuracy, lower power consumption and smaller size.

5. Conclusion

Fuji Electric desires to contribute to the development of society and to the protection of the global environment through innovating and popularizing power electronics technology. Power semiconductor devices are one of the key products that support power electronics, and this paper has described the current status and future outlook for the main power semiconductor devices.

For power semiconductor devices to contribute to the development of society and to the protection of the global environment, their transition to higher performance, smaller size, higher reliability and lower cost must be accelerated more than ever. On the other hand, a considerable portion of the relevant technology is thought to be approaching its theoretical limit, and technical innovations are needed in various fields, including materials, processing, device, circuits, packaging, testing and the like. Fuji Electric intends to place extra emphasis on technical development, and to foster a workforce capable of creating new technology and capable of technical innovation

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