Fuji Electric's Semiconductors: Present Status and Future Outlook

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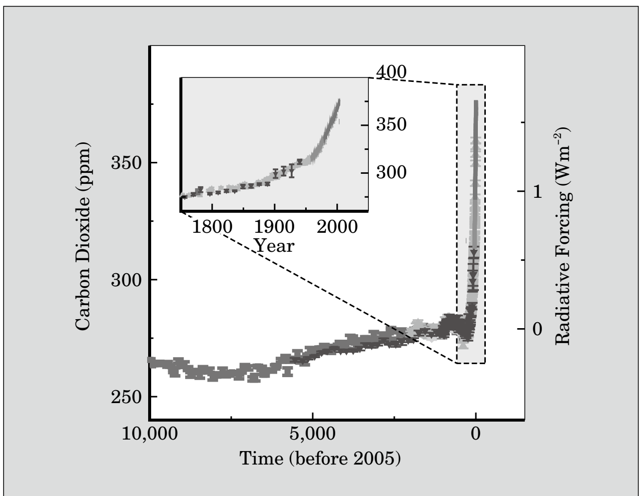
1. Introduction

In the chairman's summary statement of the G8 Summit held in Heiligendamm, Germany in early June 2007, it was announced that the G8 nations would "devote serious effort to decrease global greenhouse gas emissions at least by half by 2050." Behind this statement is the IPCC's (Intergovernmental Panel on Climate Change) 4th Assessment Report(1). This report concluded that the cause of global weather changes over the past 50 years in the latter half of the 20th century, as typified by the average temperature rise and average sea level rise, is attributable with greater than 90% certainty to an increased concentration of greenhouse gas due to human activities. In comparison to the 3rd Assessment Report which reached the same conclusion but with a certainty of slightly greater than 66%, it can be concluded that mankind is obligated to make drastic reductions in greenhouse gas emissions, chiefly CO_2. For reference, Fig. 1 is an excerpt from the 4th Assessment Report and shows the changes in CO_2 concentration in the atmosphere over the past 10,000 years. The sudden increase in CO_2 concentration over the past 50 years is likely to be judged abnormal by anyone who views this chart. It can be understood intuitively that a significant reduction in greenhouse gas emissions must be pursued urgently.

Fig.1 Changes in the global atmospheric concentration of carbon dioxide over the past 10,000 years(2)



Promoting "harmony with nature" as a basic philosophy, the entire Fuji Electric Group is committed to protecting the global environment by providing products and technologies that contribute to the protection of the global environment, reducing the burden on the environment during product lifecycles and reducing the burden of business activities on the environment as pillars of basic policy for environment protection. Fuji Electric Group is concentrating on power electronics, which aims to utilize electric power energy effectively, and power semiconductors, which are the key components of power electronics, as an important business that will contribute to global environmental protection and especially to a reduction in CO_2 emissions. Electrical power generation accounts for approximately 40% of primary energy consumption, and because that percentage is predicted(2) to increase steadily, the importance of power electronics and power semiconductors is expected to increase in the future.

The role of power semiconductor in reducing CO_2 emissions is to increase the utilization efficiency of power electronics equipment, and to be effective in conserving resources (through miniaturization) and expanding utilization (through lower cost and an expanded range of applications). More specifically, the trends toward lower loss and lower noise, smaller size, higher reliability, lower cost, and expansion of the product series and applications must be advanced. In order to achieve lower loss, switching loss must be reduced, but recklessly increasing the switching speed causes the generated electromagnetic noise to increase, resulting in incorrect operation of the control system and peripheral equipment. Accordingly, a tradeoff relation exists between lower loss and lower noise, and both low loss and low noise are being requested of recent power semiconductors. Lower loss contributes to improved power utilization efficiency, and lower noise contributes to a reduction in the number of anti-noise components and resource conservation. Miniaturization, higher reliability and lower cost contribute to resource conservation in power semiconductors themselves and in power electronics equipment, and longer service life of the equipment, reduced maintenance, and a fewer number of protection components also contribute to resource conservation. Lower cost and an expanded product series and range of applications contribute to energy conservation through the expanded utilization of power-savings power electronics equipment.

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

2. Power Modules

The most significant achievements for Fuji Electric's power modules in the past one year have been the technical development[3] of the "V-series" of 6th generation IGBTs (insulated gate bipolar transistors) and the use of the "U-series" of 5th generation IGBTs in the Toyota LEXUS*[1] models LS600h and LS600hL.

The V-series IGBT modules have further advanced the FS (field stop) and trench-gate structures that had been developed with the U-series. As a result, the chips are thinner and the carrier density distribution is improved, thus advancing the trends toward smaller chip size and lower loss. The design of the trench-gate structure utilizes a further evolved version of the noise reduction technology developed with the U4-series so that the chips realize lower loss, lower noise and a smaller size. The design of the package utilizes a thick copper layered DCB (direct copper bonding) substrate[4] to achieve higher reliability and to assure operation at 150 °C. Moreover, the internal wiring was designed in consideration of radiation noise generating mechanism that has been clarified through joint research with a university, and as a result a package is realized that is unlikely to emit noise. Figure 2 shows the trade-off relationship between radiation noise and loss measured by changing the gate resistance on a Fuji Electric test bench, and compares the V-series to other series. Despite its smaller size, the V-series achieves a 5 to 10% reduction in loss compared to the U-series at commonly used radiation noise levels. A product line is presently being developed and sample deployment for industrial applications has started in early 2008.

The PCU (power control unit) of the LEXUS LS600h and LS600hL maintains high reliability while achieving significantly lighter weight and higher output. Contributing to this lighter weight and higher output is Fuji Electric's IGBT chip technology that enables Denso Corporation's double-sided cooling technology for efficiently cooling the heat generated by power semiconductor devices and double-sided soldered mounting technology which achieves a high current density of 300 A per device. Figure 3 shows the power semiconductor peripheral configuration for the PCU of the LEXUS LS600hL. Fuji Electric's IGBT chip which improves upon the high current density specifications of the U-series and a FWD (free wheeling diode) chip are mounted onto the double-sided cooling power module made by Denso Corporation, and the double-sided cooling power module is sandwiched on both sides by a cooling tube and is assembled into a water-cooled power stack.

For both industrial applications and automotive applications, lower loss, smaller size and lower cost are strongly requested of power modules. With an eye toward further improvement in the future, Fuji Electric is developing high reliability and high heat radiating package technology, and at the same time is also researching and developing low loss MOS (metal-oxide-semiconductor) gated conduction modulation devices and FWD and SiC devices.

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

Fig.2 Relationship between radiation noise and loss

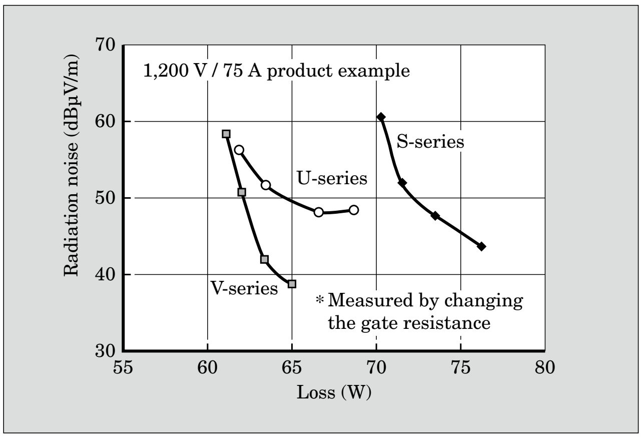
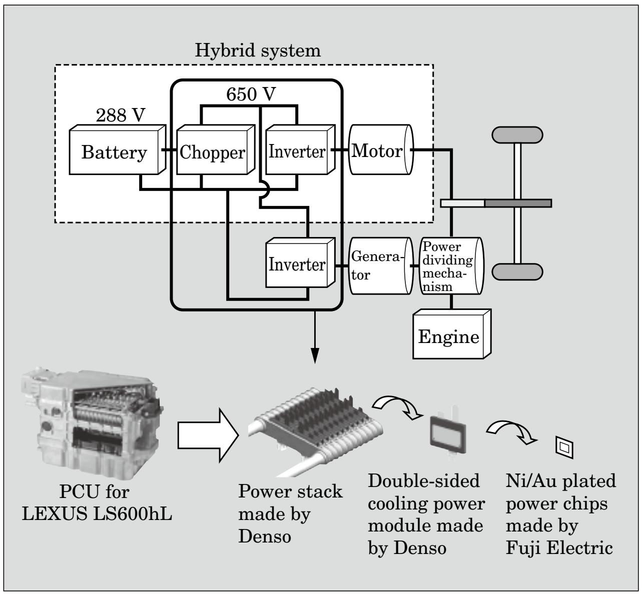


Fig.3 PCU for LEXUS LS600hL, double-sided cooling structure made by Denso, Ni/Au plated power chips made by Fuji Electric



3. Power Discretes

Recent significant achievements for Fuji Electric's power discretes include the product launches of the SuperFAP-E^3 series of 6th generation high-voltage MOSFETs (MOS field-effect transistors) and the SuperLLD3 series of 4th generation low-loss diodes.

The SuperFAP-E^3 series further optimizes the quasi-plane-junction technology[(5)] developed with the 5th generation SuperFAP-G series to achieve an approximate 15% improvement in the figure of merit $R_{on} \cdot A$ that indicates low on-resistance and also optimizes the gate capacitance to realize both low loss and low noise. Figure 4 compares the SuperFAP-E^3 series and SuperFAP-G series trade-off relationships between radiation noise and switching loss measured by changing the gate resistance on a Fuji Electric test bench. The SuperFAP-G series has low loss, but is sensitive to stray inductance, and is difficult to use because the layout on a printed circuit board requires care and attention in order to avoid voltage and current ringing. The SuperFAP-E^3 series, in which the gate capacitance has been optimized, is built to be resistant to voltage and current ringing during switching even when the stray inductance is somewhat large. Without having to struggle with the layout on a printed circuit board, the user is able to design high efficiency switching-mode power supplies that comply with noise regulations and to reduce the number of noise-suppressing components.

The SuperLLD3 series, provided with a junction structure and drift layer design that have been improved compared to those of the conventional SuperLLD1 and SuperLLD2 series, realizes significantly lower loss. Figure 5 shows the importance of a low-loss diode by comparing the trade-off relationships between reverse recovery time and forward voltage drop for the SuperLLD3 and conventional series. Compared to the SuperLLD1 series in the same application to a continuous current mode power factor control circuit, the SuperLLD3 series has a forward voltage that is approximately 0.5 V lower, and a reverse recovery time that is approximately 25% shorter. The reduction in forward voltage leads to a reduction in conduction loss. The shorter reverse recovery time leads to a reduction of the diode's own switching loss and also contributes to a reduction in turn-on loss of the power MOSFET that is paired with the diode. Accordingly, use of the SuperLLD3 series is expected to be effective in reducing loss of the power factor control circuit as a whole. Furthermore, the low-loss diode for the power factor control circuit has already achieved lower noise in the conventional series, and the SuperLLD3 series is fabricated with the same low noise characteristics as those of the conventional series.

Power discretes are also strongly requested to provide lower loss, smaller size and lower cost while maintaining low noise performance, and research and development activities are focused on satisfying these requests. Recently, the development of a 3rd generation trench MOSFET and of a SuperFAP-E^3 900 V series, and the expansion of the product lines of the SuperLLD3 series, a high-voltage SBD (Schottky barrier diode) series and a low I_r SBD series have been advanced with urgency. With an eye toward the future, research and development activities are advancing the technology for combining low on-resistance and low cost in a superjunction MOSFET[(6)].

Fig.4 Trade-off relationship between radiation noise and switching loss

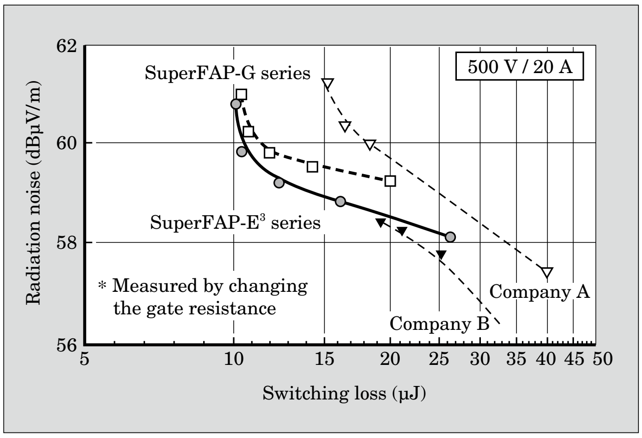
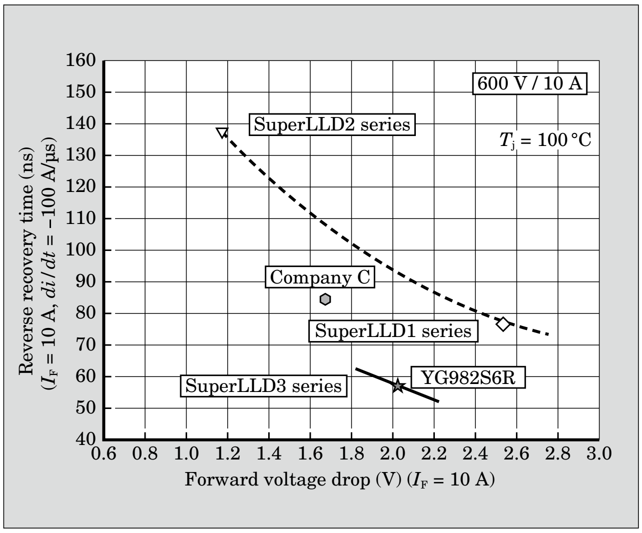


Fig.5 Trade-off relationship between reverse recovery time and forward voltage drop



4. Power ICs

Power ICs have realized many achievements as listed below.

(1) Mass-production of a Li-ion battery protection IC that integrates the world's first low on-resistance bidirectional power MOSFET[(7)], and use of this IC by a major Li-ion battery manufacturer

(2) Mass-production of the new M-Power 2 A series of high-efficiency low-noise power ICs for switch-

ing-mode power supplies, and their use by a major manufacturer of power supplies for LCDs (liquid crystal displays) televisions

(3) Mass-production of the FA5553/5547 series of multifunction low-standby-power PWM switching-mode power supply controller ICs

(4) Mass-production of the FA5550 series of switching-mode power supply controller ICs for continuous-current-mode PFC circuits

(5) Development of the FB8632J, 3rd generation micro DC-DC converter

(6) Mass-production of the FA7748/7749 series of DC-DC converter ICs for step-down rectification circuits

(7) Mass-production of a 5th generation 256-bit PDP (plasma display panel) address driver IC

(8) Mass-production of a 5th generation 96-bit PDP scan driver IC

(9) Mass-production of an IGBT driver IC for hybrid electric vehicles

(10) Mass-production of a single-chip low-noise ignitor for automobiles

(11) Mass-production of the F5052H miniature high-current IPS (intelligent power switch) for automobiles using COC (chip-on-chip) technology

Among these achievements, the Li-ion battery protection IC applies Fuji Electric's proprietary low on-resistance three-dimensional power device TLPM (trench lateral power MOSFET[7]) and is the world's first single-chip Li-ion battery protection IC provided with an integrated low on-resistance bidirectional MOSFET. Figure 6 shows the external appearance of this chip, an example of the chip mounted on a battery pack printed circuit board, a chip photograph, and a TLPM cross-sectional photograph. The integration into a single chip results in a smaller mounting area of 2.4 mm^2, which is less than 30% of the previously required mounting area, and contributes significantly to making thinner Li-ion battery packs, as well as thinner and smaller cell phones and other mobile electronic equipment.

As a high-efficiency, low-noise power IC for switching-mode power supplies, the M-Power 2 A series is a 3rd generation product that uses Fuji Electric's proprietary control technology to continue to enable the easy configuration of a current-resonance switching-mode power supply without concern for resonance shifting. Since high-efficiency and low-noise high-power switching-mode power supplies of up to 400 W can be configured easily, this IC is compatible with larger screen sizes of LCDs and flat panel televisions.

The 5th generation PDP address-driver IC supports the transition to 256-bit multi-bit implementations, and contributes to a reduction in panel cost by supporting LVDS (low voltage differential signal) and RSDS (reduced swing differential signal) input to decrease the number of signal lines. The 5th generation PDP scan-driver IC supports the transition to 96-bit multi-bit implementations, and achieves lower cost by improving SOI (silicon on insulator) technology and increasing the current density to reduce the area per bit while supporting full-HD (high definition) as a result of a higher breakdown voltage.

The micro DC-DC converter, as shown on the left side of Fig. 7, integrates an inductor, power MOSFET and controller IC in order to configure a DC-DC switching-mode power supply. Fuji Electric's proprietary inductor technology and chip-on-chip assembling technology[8] contribute to reducing the mounting area. Through circuit design innovations and optimized specifications, the 3rd generation micro DC-DC converter reduces the standby current and realizes an approximate 20% smaller size than the 2nd generation device. The right side of Fig. 7 compares the external appearance of the 3rd generation micro DC-DC converter with that of prior generations, and it can be seen that the size decreases steadily with successive generations of devices.

In order to reduce the loss and decrease the size of a power IC, lower loss and smaller size of the integrated output power device are the most important factors. Fuji Electric is vigorously advancing research and development into reducing the loss and decreasing the size of the integrated power devices in future power ICs[9][10]. For an even more distant future, Fuji Electric is researching the potential of digital control and is examining the possibility of converting existing analog control to digital control in order to realize higher precision control, smaller size and lower standby power.

Fig.6 Li-ion battery protection IC

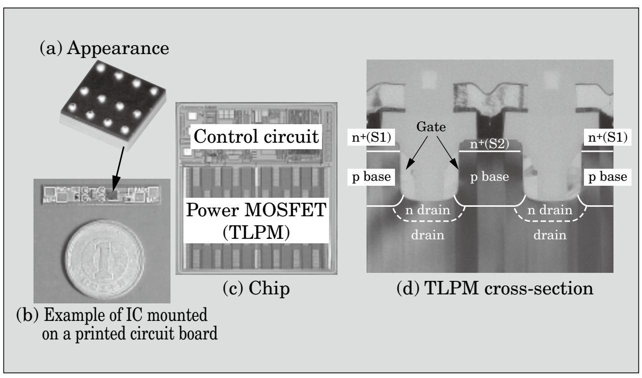
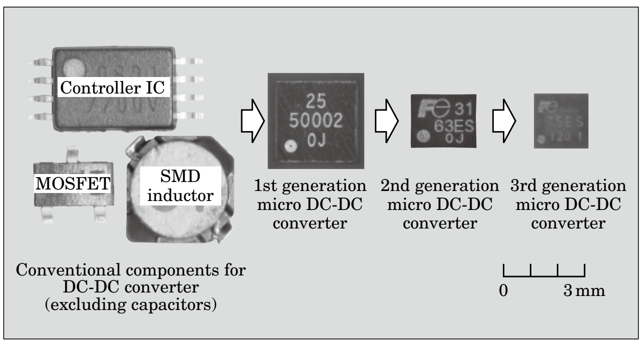


Fig.7 Appearance of 3rd generation micro DC-DC converter (comparison with conventional device)



5. Pressure Sensors

Fuji Electric has completed the development of a 5th generation pressure sensor, and is moving ahead with preparations for mass-production. The 5th generation pressure sensor corresponds to a 2nd generation single-chip digital-trimming type pressure sensor. Compared to the 4th generation device, the designs of the diaphragm, digital-trimming circuit, operational amplifier, electromagnetic noise filter and surge protection circuit were optimized to achieve an approximate 30% reduction in chip area. Pressure sensors are being used in increasing numbers in order to improve the fuel economy of automobiles and motorcycles, realize cleaner emission gas, improve safety, and also to increase the efficiency of industrial and residential air conditioners. Depending on the application, the precision of these pressure sensors is linked directly to improved fuel economy and efficiency. Therefore, pressure sensors are strongly requested to provide higher precision and lower costs, and with their expanding range of applications, compatibility with special environmental conditions is also being requested. In the future, Fuji Electric will continue to satisfy customer requests by improving our proprietary diaphragm technology and single-chip digital-trimming technology in order to achieve higher precision and lower costs and by developing products compatible with high-pressure and special environmental conditions.

6. Postscript

By innovating and promoting power electronics technology, Fuji Electric wants to help reducing CO_2 emissions, protect the global environment and contribute to sustainable development for human society. Power semiconductors are a key supporting element of this intention, and this paper has described chiefly the present status and future outlook for the main power semiconductor products.

For power semiconductors to contribute to reducing CO_2 emissions, protecting the global environment and achieving sustainable development for human society, the trends towards lower loss, lower noise, smaller size, higher reliability, lower cost, and expanding the product lineup and range of applications must progress at faster rates. On the other hand, quite a few technologies are thought to be approaching their theoretical limits, and future innovation is needed in the materials, process, device, circuit, package and test fields. Fuji Electric intends to put additional effort into technical development and intends to bolster efforts to cultivate personnel capable of creating technology and personnel capable of realizing technical innovation.

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