The Current Status and Future Outlook for Power Semiconductors

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ABSTRACT

With the increased focus on efforts to protect the global environment, power semiconductors, which are the main power electronics products, are becoming increasingly important. Using 6th-generation IGBT V-Series technology, Fuji Electric has developed and commercialized high voltage, large capacity power modules that are capable of operating at high temperatures. As post-silicon technology for the next generation, we are pursuing the development of devices that utilize wide band gap semiconductor material and the development of superjunction MOSFETs. Additionally, MOSFETs designed for applications in outer space and used in the Japanese experimental module known as "Kibo" attain high reliability and low loss, while ICs designed for use in power supply control achieve low noise and energy savings. Exhaust system pressure sensors for use in automobiles and control ICs for use in hybrid vehicles have been newly commercialized.

1. Introduction

In 2009, the Obama administration established and inaugurated the Green New Deal. In September of the same year, at the United Nations Summit on Climate Change, Japanese Prime Minister Hatoyama announced a new mid-term goal of cutting Japan's greenhouse gas emissions by 25% from 1990 levels by 2020. Among the new policies set forth by leaders from the various countries, projects related to energy and environment attracted the most attention.

Fuji Electric is presently reforming its business structure to focus on "energy and the environment." Also, Fuji Electric has long been involved in efforts to develop innovative power electronics technology which is crucial for protecting the global environment and reducing CO_2 emissions. Power electronics technology is a key technology for converting energy into power, and as the main components, power semiconductors are becoming more and more important.

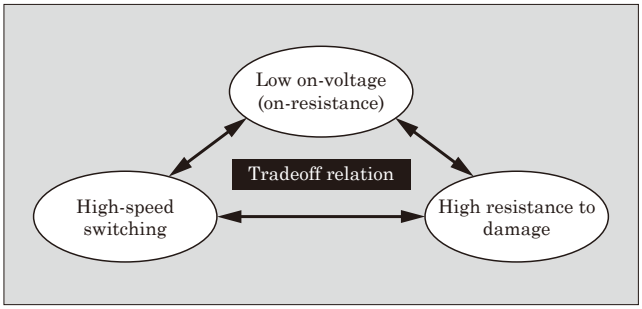
The performance characteristics requested of power semiconductors are low loss, high speed switching, low noise and ease of use.

This paper discusses the current status and future outlook for the energy-saving and environmentally-friendly power semiconductors which are being developed by Fuji Electric and their representative products of power modules, power discretes, power supply ICs and automotive devices.

2. Power Modules

With a commitment to energy savings and eco-friendliness, IGBT (insulated gate bipolar transistor) power modules are being deployed in various fields. The IGBT chip at the core of these modules is a 6th generation IGBT chip, which has begun to be deployed in Fuji Electric's "V-Series." As can be seen in Fig. 1, many items are requested of the IGBT modules but a tradeoff relation exists between the requested items and performance characteristics, and numerous technological breakthroughs would be needed to satisfy all the requests.

Fig.1 Requested characteristics of IGBT modules



With the "V-Series" 6th generation IGBT module, the attained characteristics are close to their theoretical limits and dissipation loss was reduced. Also, the design was implemented with good awareness of the environment. For example, the "V-Series" complies with the RoHS directive*1 through the use of lead-free materials, the package structure significantly reduces generated noise, and a small size and light weight are realized simultaneously. Additionally, high temperature operation up to 175 °C is possible.

A series of 600 V, 1,200 V and 1,700 V IGBT modules and IPMs have been commercialized using these

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*1: RoHS: EU Directive on the restriction of the use of certain hazardous substances in electrical and electronic equipment

superior V-Series IGBTs.

Fuji Electric has previously developed IGBT modules and IPMs (intelligent power modules) for use in hybrid vehicles. As key components for hybrid vehicles, Fuji Electric has also previously developed plated IGBT and FWD (free wheeling diode) chips housed in a package having a double-sided cooling structure. This IGBT achieves approximately twice the current density of a general-purpose IGBT. Now, with the additional application of 6th generation IGBT V-Series technology and microfabrication technology, and by improving the FS (field stop) structure, a dramatic improvement in characteristics has been achieved. Moreover, temperature sensing and current sensing functions have been built-in to realize a chip that is even easier to use.

As an example application to the energy and environment field, high-voltage high-power IGBT modules have begun to be used in wind power generators. As a result of recent trends of applications involving wind power generation, there is strong demand for high-voltage and high-power IGBT modules, and in response, Fuji Electric has prepared 1,200 V, 1,700 V and 3,300 V high-power modules. A wide variety of standard package groups including the HPM (high power module), EconoPACK+ and the like, have been assembled and are being deployed by our customers.

As new types of IGBTs, the RB-IGBT (reverse blocking IGBT) and RC-IGBT (reverse conduction IGBT) are being developed by Fuji Electric. In particular, as next-generation applications for the RB-IGBT, application to the highly-anticipated matrix converters and application to a new 3-level inverter are promising.

3. Next Generation Power Modules

The characteristics of the 6th generation IGBT V-Series are approaching the theoretical limits of silicon. Silicon carbide (SiC) and gallium nitride (GaN) are the leading candidates for materials to be used instead of silicon in next-generation power devices. Due to material properties well suited for use in power devices, research and development of SiC material has been ongoing for a long time, and recently, practical applications have begun to be considered. SiC material is very expensive due to the difficulty of growing its crystals and the process technology involved, but a way toward a technical solution is gradually becoming visible, and sooner or later the cost issue is also expected to be resolved.

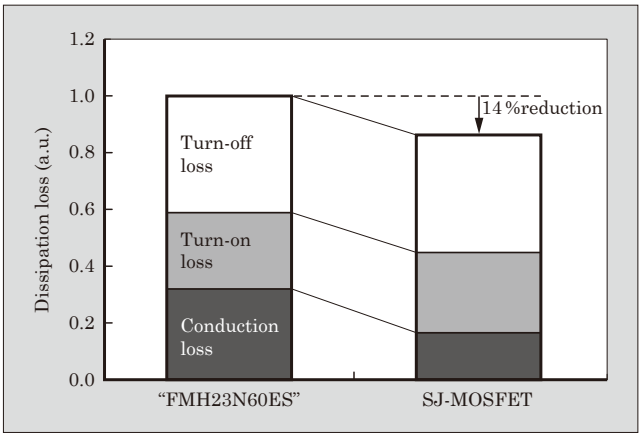
Moreover, GaN, which became prominent with blue diodes, has also been found to be a promising material for power devices, and is a candidate for the material used in next-generation power devices. Despite having only a short history of use as a power device material, the decisive factor for GaN, which can be fabricated on a silicon wafer, will be whether or not the advantage of its inexpensive cost can be leveraged.

Both SiC and GaN are promising candidates as the material of future power devices. Fuji Electric and the National Institute of Advanced Industrial Science and Technology (AIST) are conducting joint research of SiC material. Also, Fuji Electric and Furukawa Electric Co., Ltd. have jointly established a next-generation power device technical research association to research GaN, and plan to incorporate the results into the next-generation power modules.

4. Power Discretes

As a high-voltage MOSFET (Metal-Oxide-Semiconductor Field-Effect-Transistor), Fuji Electric has newly developed the "Superjunction MOSFET" (SJ-MOSFET). In 2008, Fuji Electric developed the "SuperFAP-E^{3S} 600 V Series" having the industry's lowest level of $R_{on} \cdot A$ (on-resistance normalized to a unit area) as a planer MOSFET, which realized low noise and an improved tradeoff relation between low loss and switching performance, and contributed to higher efficiency in devices. Recently, in the field of switching power supplies, which is the main application of MOSFETs, efforts to realize higher efficiency have been accelerated in order to comply with international energy-saving regulations such as the International Energy Star Program. In particular, a power supply efficiency of 92% or above (at 50% load) is requested of the large-capacity servers and the like used at internet data centers, which are essential for IT companies. To realize this high efficiency, MOSFETs must also have lower loss characteristics, and therefore Fuji Electric developed the new low on-resistance SJ-MOSFET. The SJ-MOSFET has the industry's lowest level of $R_{on} \cdot A$, and realizes approximately 1/4th the on-resistance of the previous "SuperFAP-E^{3S} Series." When installed in the power factor improvement circuit of a power supply, as shown in Fig. 2, loss is reduced by approximately 14% and development is accelerating toward the goal of early product commercialization.

Fig.2 Comparison of power MOSFET dissipation loss (input AC100 V/output 400 W)



Fuji Electric has also commercialized highly reliable MOSFETs for space applications such as in artificial satellites. In 1994, Fuji Electric's initial space-use devices were installed in and contributed to the successful launch of the first rocket built exclusively in Japan. Leveraging that experience and incorporating subsequent research and development results, the present lineup of space-use MOSFETs overcame prior obstacles to achieve low on-resistance and the required tolerance to ionization radiation and high-energy charged particles in outer space. Additionally, these MOSFETs are installed in "Kibo," the Japanese Experimental Module of the International Space Station, and have continued to operate properly since being launched into orbit in 2008. In the future, Fuji Electric intends to expand the range of applications to overseas space industries as well.

Meanwhile, Fuji Electric has developed a Schottky barrier diode (SBD) having an ultra low I_R and suitable for use in a high temperature environment such as for photovoltaic power generation. The reverse leakage current I_R has been reduced to 1/10th that of a conventional SBD, enabling guaranteed operation at junction temperatures of up to 175 °C.

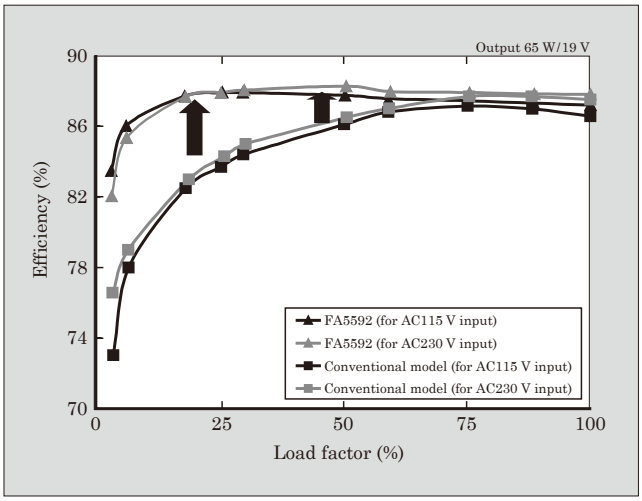
Through joint development with third parties, as described above, Fuji Electric is accelerating the development of next-generation devices that use SiC and GaN to realize dramatically lower loss compared to the present generation of silicon-based devices.

5. Power Supply Control ICs

To help achieve energy savings and lower noise in switching power supplies and to lower the cost of devices, Fuji Electric has independently developed and applied a control method for power supply control ICs. Devices such as televisions, PCs and printers that are plugged-in continuously an electrical outlet remain in a standby state for extended periods of time. Their consumption of power during standby must be reduced in order to save energy. The EPA 5.0 standard issued by the U.S. Environmental Protection Agency prescribes the average efficiency even during light-load operation, and in response, Fuji Electric developed the "FA5592 Series" of current mode PWM control ICs that comply with the EPA 5.0 standard. The FA5592 significantly improves efficiency during light load operation, as shown in Fig. 3, by reducing the switching frequency when the load rate is below 60%. Moreover, with a built-in switching frequency distribution function that realizes lower noise and an internal startup circuit that ensures operation at up to 750 V, the FA5592 can be used in countries or regions in which there are large fluctuations in power supply voltage.

For relatively large-capacity power supplies, "FA5604/FA5605" multifunction voltage mode PMW control ICs and "FA5610/FA5611" low-noise continuous current mode PFC control ICs have been developed, and realize both high performance and small size in a SOP8 pin package. In particular, the FA5610N realizes a high power factor and low noise with an oscillation frequency distribution function, enabling the input filter to be simplified.

Fig.3 Dependence of power supply efficiency on load current for FA5592



In the power supply control IC field, to satisfy increasingly severe requirements for higher efficiency, energy savings, smaller size, lower device cost and the like, Fuji Electric continues to research and develop a distinctive, proprietary control method.

6. Automotive Devices

As automotive devices, IPSs (intelligent power switches), exhaust system pressure sensors, and the "Fi009" hybrid vehicle IGBT drive IC have been developed by Fuji Electric.

(1) Exhaust system sensor

Automotive exhaust gas regulations are becoming more stringent year after year, and in 2009, the Post New Long-term Regulations in Japan and the Euro 5 emissions standards in Europe came into force. As a result, exhaust gas recirculation systems, in which a portion of exhaust gas is recirculated to the intake side so as to control combustion in an engine, have begun to be used. Newly developed exhaust system pressure sensors, based on the CMOS (Complementary Metal-Oxide-Semiconductor) single-chip technology that has been applied to conventional intake system pressure sensors, utilize a new structure to realize dramatically improved corrosion resistance. On the basis of this technology, product development continues with the aim of application to heavy machinery and the like.

(2) Fi009 driving IC for hybrid vehicle IGBTs

The demand for highly fuel-efficient hybrid vehicles, which are provided with both a gasoline engine and an electric motor so as to optimize load-sharing according to the running conditions of the automobile, is increasing rapidly. IGBTs are the main devices used

in the inverter systems that drive the motor in hybrid vehicles. The control IC that drives this IGBT has the important function of protecting the IGBT in order to ensure high reliability of the inverter system. The newly developed control IC has a function that protects against overheating and overcurrent, and receives signals from temperature and current sensors inside the IGBT chip made by Fuji Electric.

In addition to the products introduced herein, Fuji Electric's automotive devices also include single-chip igniters and other products that use Fuji Electric's proprietary and distinctive technology. Leveraging this technology, Fuji Electric intends to continue to develop highly reliable and high performance products that satisfy customer needs.

7. Postscript

With protection of the global environment being an important topic of today, the implementation of environmental measures such as reducing CO_2 emissions and the development of new energy sources that do not depend on fossil fuels are urgently needed. With a commitment to energy savings and eco-friendliness, Fuji Electric is actively addressing these problems and aims to contribute their solutions. For this purpose, technical innovation in power semiconductors, the key components of power electronics technology, is absolutely necessary.

As has been discussed in this paper, Fuji Electric is working to develop distinctive power semiconductor products, and will apply innovative technology to realize lower loss, more advanced functionality, smaller size, higher reliability and lower noise. Fuji Electric intends to continue to advance technical development with the aim of developing products from the customer's perspective.