

Fuji Electric's Power Semiconductor Devices Aim for Higher Performance and Higher Functionality

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1. Introduction

Ever since Fuji Electric first began to manufacture selenium rectifiers in 1953, our company has continued to introduce new types of power devices, one-after-another, to the market with the silicon diode in 1959, the thyristor in 1961, the discrete BJT (bipolar junction transistor) in 1975, the BJT module in 1980, the power MOSFET (metal oxide semiconductor field effect transistor) in 1986, the discrete IGBT (insulated gate bipolar transistor) in 1987, the IGBT module in 1988, the BJT-IPM (BJT-intelligent power module) in 1989, and the IGBT-IPM in 1993.

Since 1991, Fuji Electric has been working to increase the performance and functionality of these devices. At present, Fuji's distinctive and abundant product lineup includes typical power devices for industrial power electronics machinery such as IGBT modules and IGBT-IPM, typical power devices for information and consumer devices such as power MOSFETs and rectifier elements, and typical power devices for vehicle-mounted electronic equipment such as smart MOSs and IPDs (intelligent power devices). This product lineup has received high praise from the market.

Also, as will be discussed later, power devices and power electronics technology have a close and cooperative relationship, and both fields have developed while mutually promoting each other. Fuji Electric places special emphasis on this close relationship, and has advanced its research and development of power devices based on close cooperation with its customers.

This paper describes the relationship between the power devices and variable speed driving of electric motors in the industry as the typical example, and presents the history and recent trends of their development.

2. Development of Power Devices and Power Electronics

2.1 Relationship between power devices and related technologies

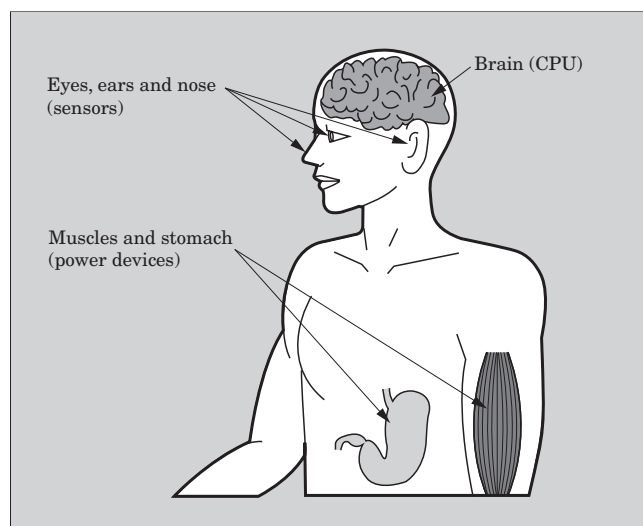
It is no exaggeration to say that requests for the

development of electronic equipment in recent years has been based on a desire to remove the limitations of machines and make them more human in form. Such human desires as the ability to be able "to see further," "to converse from any location," and "to be stronger," have given rise to televisions, cellular phones and robots and the like.

Electronic devices have played a large role in enabling machines to more closely approximate the human body. As shown in Fig. 1, machines are approximating the human body through the use of microprocessors and memory that function as the brain, semiconductor sensors that function as the eyes, ears and nose, and so on. Not to be forgotten are the power devices which correspond to the muscles and stomach of the human body. Power devices have a behind-the-scenes-like existence, but this rapidly developing technology is no less important than that of cutting-edge LSI (large scale integrated) circuit technology.

Power devices have established three major elemental technologies of power device design technology, power device application technology and micro-fabrication technology for semiconductors for power device-use. In other words, as shown in Fig. 2, device design

Fig.1 Role of power devices



technology and micro-fabrication technology can be considered to have been developed in order to satisfy various requirements of power electronics technology, or conversely, it can be considered that advances in device design technology and micro-fabrication technology have enabled the development of new power devices which were then used to develop power electronics technology. In this manner, power devices and power electronics technology are closely related and have developed while mutually promoting each other.

In various power electronics equipment fields, a common theme relating to the progress of recent power devices is the transition from thyristors (SCRs (silicon controlled rectifiers) and GTOs (gate turn-off thyristors)) to power transistors (BJTs, IGBTs and MOSFETs).

Figure 3 shows the applicable range of various power devices. IGBTs and MOSFETs are rapidly expanding their applicable range and are becoming the mainstream power devices.

Fig.2 Power devices and related technologies

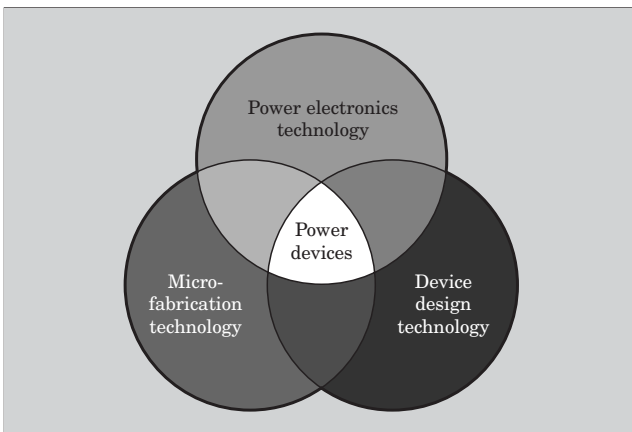
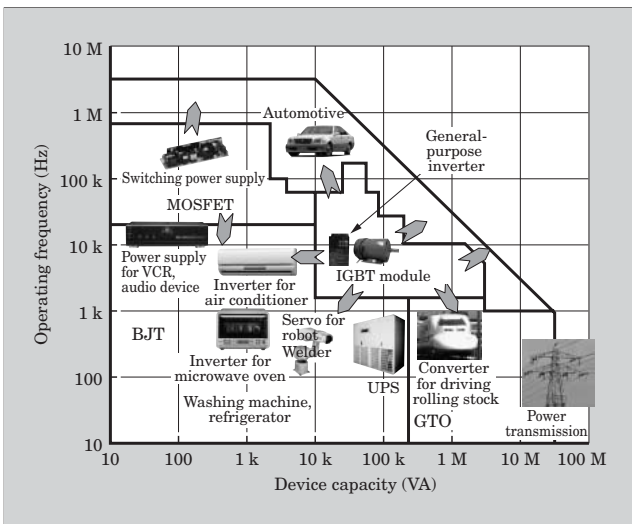


Fig.3 Power device applications



2.2 Development and history of the variable speed driving of electric motors

As can be seen in Fig. 4, in the history of the variable speed driving of electric motors, there was a drastic change in 1970 with the transition from DC motors to AC motors, and the power electronics equipment for driving those motors changed from thyristor Leonard systems to transistor inverters.

1979 was the year in which Japan experienced a second oil crisis, and under the circumstances of that time, there was growing demand for the use of inverter-based variable speed driving of AC motors in order to satisfy requirements for energy savings, maintenance-free operation and the like. The practical application of an inverter system requires a high-voltage, large-capacity, self-commuting device capable of relatively high speed switching. The BJT module was introduced as a device capable of satisfying those requirements, and a drastic changeover to BJT modules occurred. Similarly to the case above.

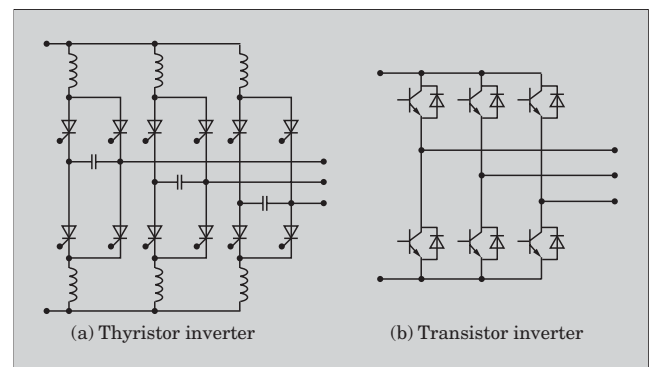
Figure 5 shows a comparison of the thyristor inverter and transistor inverter. The power devices used in an inverter system subsequently changed from BJTs to IGBTs. At present, high voltage and high frequency PWM (pulse wave modulation) control inverters are most prevalent.

Ever since Fuji Electric led the industry to intro-

Fig.4 History of variable speed driving systems and power devices

| | 1960 (year) | 1965 | 1970 | 1975 | 1980 | 1985 | 1990 | 1995 |
|------------------|-------------------------|----------------|------------------|----------|--|---------|----------------|------|
| Market request | Static power conversion | | Maintenance-free | | Highly responsive, highly accurate control | | Energy savings | |
| Electric motor | DC motor | | | AC motor | | | | |
| Converter system | Ward Leonard | Static Leonard | | | Voltage-type inverter | | | |
| Device | Mercury rectifier | Thyristor | | | BJT | | IGBT | |
| | | | | | GTO | | | |
| Control | Analog | | Hybrid | | | Digital | | |

Fig.5 Comparison of inverter main circuits

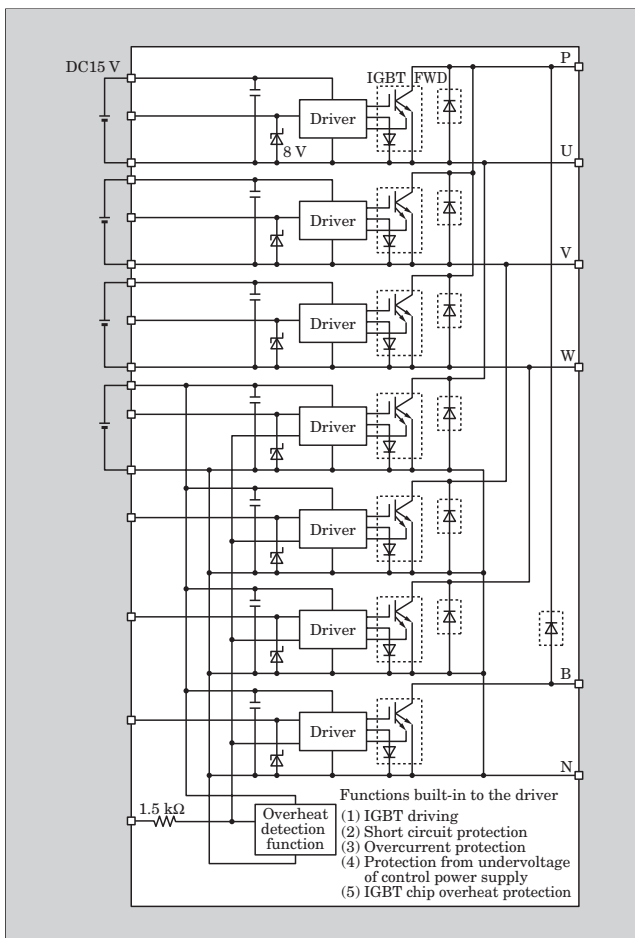


duce the BJT module, we have made great strides in increasing the capacity and intelligence of power devices, and the introduction of our new IGBT modules in 1988 initiated a changeover to these new generation devices.

The changeover from BJTs to IGBTs was supported by the capability for high speed switching and for the manufacture of low loss IGBTs that would enable inverter systems to be made lighter, more compact and quieter, as would be increasingly requested.

Meanwhile, to increase the functionality of power devices, Fuji Electric was early to develop and bring to market IPMs that contained built-in drive circuits, overheat detection circuits, self-diagnosis circuits and the like. When the main device transitioned from BJTs to IGBTs thereafter, in conjunction with improvements in IGBT characteristics, Fuji Electric made progress in reducing the size and increasing the performance of power devices. With the power transistor modules thus far, an application engineer had to design a peripheral circuit in order to use the module in a system, and the function of power devices approximated that of a single muscle tendon of the human body. Desiring to change this functionality to the level of reflexive muscles (that will stop in case an accident occurs), Fuji Electric continued its develop-

Fig.6 Block diagram of the R-IPM3



ment work. At present, IPMs are used not only in such industrial fields as machine tools and robotics, but also a wide range of fields including home air conditioners and electric automobiles.

Figure 6 shows an internal block diagram of Fuji Electric's latest IGBT-IPM (R-IPM3).

3. Recent IGBT Development Trends

Figure 7 shows the history of changes in Fuji Electric's IGBT application technology. Figure 8 shows, as a typical example, the changes in the cross-sectional structure of a 1,200 V IGBT chip. Figure 9 shows a comparison of 1,200 V IGBT chip tradeoff characteristics. In Fig. 9, the vertical axis indicates turn-off loss which is representative of switching loss, and the horizontal axis indicates saturation voltage which is representative of saturation loss. A tradeoff point that approaches zero on both axes indicates a high performance device capable of realizing a low loss system.

At present, 5th generation IGBTs are being produced as commercial products and the family of these products is being expanded. The 1st through 3rd

Fig.7 History of Fuji Electric's IGBT chip application technology

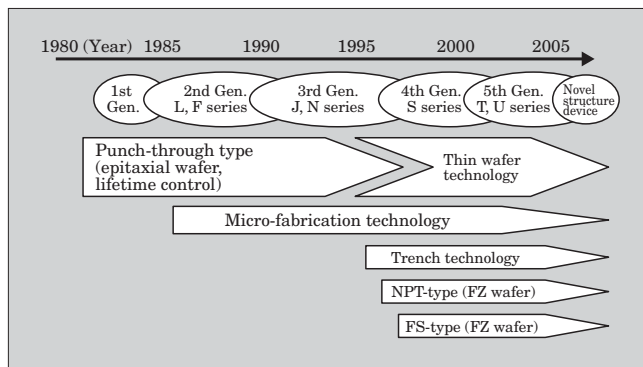


Fig.8 Changes in the cross-sectional structure of a 1,200 V IGBT chip

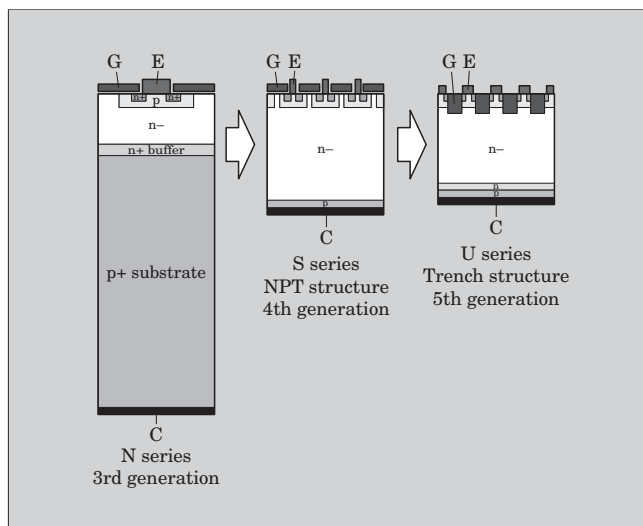
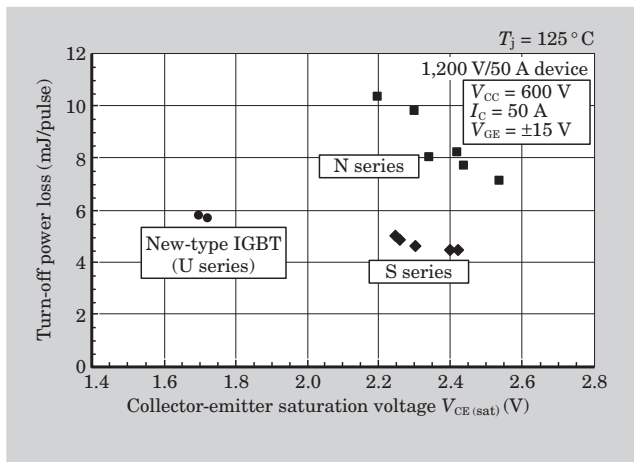


Fig.9 Comparison of 1,200 V IGBT chip tradeoff characteristics



generation IGBTs sought to achieve a high performance construction by using epitaxial wafers, implementing lifetime control and micro-fabricating the surface gate structure. The 4th and subsequent generations sought to improve performance by adopting drastic design changes such as the use of FZ (floating zone) wafers and a NPT (non-punch through) structure. In order to realize an NPT structure, it was necessary to establish technology for making the wafer thinner. Consequently, not only was performance improved, but also the need for lifetime control was eliminated and the fluctuation in device characteristics during manufacture was reduced. The 5th generation additionally uses a trench structure at the surface gate and an FS (field stop) to achieve further improvement in performance. Fuji Electric is presently advancing products that use a trench-and-FS structure in its 1,200 V-and-above class of IGBT chips, and products that use an NPT structure in its 600 V-class of IGBT chips.

The key technologies for these devices are the technology for thinning the wafers to approximately 100 μm and the technology for forming a layer having a diffused junction on the backside of the wafers. These technologies can be said to be unique to power devices.

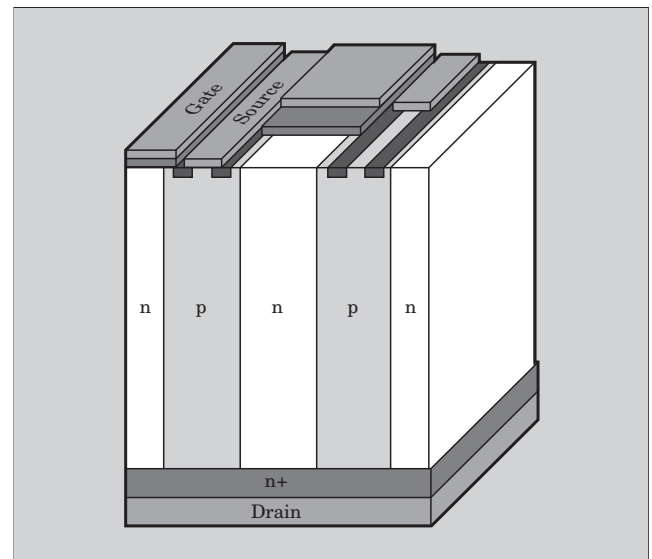
The 5th generation U series IGBT module is presently making great contributions to reducing the size and weight and increasing the efficiency of various types of systems.

4. Research and Development Trends for Next Generation Power Devices

4.1 SJ-MOSFETs

The theoretical performance limit for a high-voltage power MOSFET that uses silicon (Si) material was thought to have been reached with the Super FAP-G series introduced by Fuji Electric in 2000, but an SJ (super junction)-MOSFET, which also uses Si material, achieves a performance level that sufficiently exceeds that of the so-called theoretical performance.

Fig.10 Cross-sectional structure of SJ-MOSFET chip



As can be seen in the cross-section of the chip construction shown in Fig. 10, the SJ-MOSFET has structure in which consecutive pnpn ... impurity regions are sandwiched by drift regions in the body of the device. Consequently, the depletion layer is extended horizontally, making it possible for all drift regions to become depleted at the same time, which was not possible with a conventional structure. As a result, the SJ-MOSFET can achieve a higher impurity concentration and lower ON-resistance than a conventional structure.

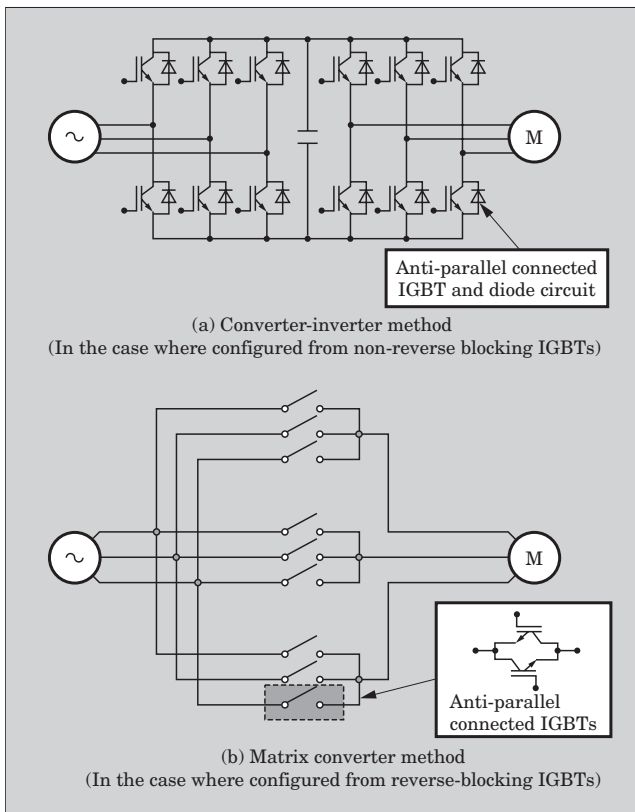
Commercial SJ-MOSFET devices have already appeared on the market and Fuji Electric is continuing its development efforts in the aim of commercializing a SJ-MOSFET device in the near future.

4.2 Reverse blocking IGBTs

Fuji Electric led the industry in introducing a reverse blocking IGBT, for which Fuji developed proprietary technology for a thin wafer IGBT process, and through the close-knit exchange of information and cooperation between power device engineers and power electronics engineers, a new method for power conversion is about to be proposed.

As described above, the most common method at present for the variable speed driving of electric motors is AC motor control based on a voltage-type high-frequency PWM inverter. In this method, as shown in Fig. 11(a), commercial AC current is first converted into a DC current, and then is reconverted by the inverter into a variable-frequency variable-voltage AC current and then output. Application of this method to voltage-type high-frequency PWM inverters was one goal of the abovementioned power device research and development. Alternatively, as shown in Fig. 11(b), a method in which commercial AC current is converted directly into a variable-frequency variable-voltage AC current has also been suggested, but practical applica-

Fig.11 Comparison of main circuits of converter



tion has been difficult as this method requires a bi-directional high-speed switching device.

In a conventional IGBT, the breakdown voltage (reverse blocking voltage) between the emitter and collector is not high. However, if an IGBT having high reverse blocking voltage could be realized and such devices were connected in a anti-parallel connection, the realization of a bi-directional switching device is thought to be possible. This is the context for the development of reverse blocking IGBTs.

Compared to a converter system configured from non-reverse blocking IGBTs, a converter system that

uses reverse blocking IGBTs has the following characteristics.

- (1) Because current flows through two IGBTs, instead of flowing through four non-reverse blocking IGBTs in the other method, the amount of generated power loss can be reduced.
- (2) Because a DC smoothing capacitor is unnecessary, the system can be made smaller and lighter in weight.

The matrix converter, a direct AC-AC converter system that uses high-frequency PWM control with reverse blocking IGBTs, is soon to be commercially practical.

5. Conclusion

Based on our policies of “realizing high-performance power devices with the world’s most advanced technology to develop products that are number-one worldwide” and “working in concert with the customer to integrate power device and IC technology and to realize and provide solution-proposing-type smart devices and intelligent devices,” Fuji Electric has developed and provided new products based on the desires of our customers.

This paper has discussed the development history and trends of representative products developed based on the above policies.

There is no end in sight for the progress of power devices, and research and development continues to be fiercely competitive. Devices such as the reverse blocking IGBT are being proposed that urge reconsideration of long-established mainstream power conversion methods.

Fuji Electric is committed to working to develop even more advanced power electronics products and will press on with efforts to decrease the power loss and to increase the performance of power devices further.



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