Present Status and Trends of Power Semiconductor Devices

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1. Introduction

The curtain has been raised on new century. Prior to discussing the present status and trends of power semiconductor devices, allow us to briefly review Fuji Electric's history with power devices. The semiconductor device was invented and developed in the latter half of the 20th century. When Shockley, Brattain, and Bardeen invented a transistor in 1948, they did not think that this transistor could control a current large enough to turn a motor, we suppose. Transistor devices began as small signal devices and later developed into ICs, and then broadened their range of application to power devices. These new power devices gave birth to new control technology and developed into new power electronics technology.

Fuji Electric has been developing power devices and their control technology ever since the early stages, including the power transistor in 1972, and has continued as a leader and developer of this industry.

In the 1980s, the highly anticipated MOS (metal-oxide-semiconductor) gate power device was introduced. Next, the power MOSFET (MOS field-effect transistor) was invented and was soon followed by the IGBT (insulated-gate bipolar transistor). Production of the power MOSFET utilized the cutting-edge semiconductor technology of those days. Though it was a power device, it required production in a clean room where the cleanliness level was on par with that of necessary for LSI (large-scale integrated circuit) production. Figure 1 shows the progress of device design rules over time. The design rule for LSI memories is also shown for comparison. When the design rule for LSI memories was on the level of several microns in the latter half of the 1970s, the design rule for the power devices of thyristors and bipolar transistors was on the level of several tens of microns. However, when MOS gate devices such as MOSFETs and IGBTs appeared in the latter half of the 1980s, the difference in design rules between these and LSI chips rapidly decreased. In 2000, both achieved device design with sub-micron rules. At present, power devices and LSI chips are produced using equivalent level clean rooms and production equipment.

In the "Special issue on MOS gate power device technology" (Vol. 63, No. 9) of the "Fuji Electric Journal" issued in 1990, Dr. Uchida described the MOSFET and IGBT in an article entitled, "Progress of MOS-gate power device technology." At that time, Fuji Electric was marketing 2nd generation IGBTs and was promoting the development of 3rd generation IGBTs. We predicted future development of the IGBT through improving the characteristics, adding intelligence and increasing capacity.

The capacity of power devices has also undergone great changes. Figure 2 shows the progress in capacity of Fuji Electric's power devices over time. Power devices started as discrete transistors in the 1970s, then changed to transistor modules, and then to IGBT modules in the latter half of the 1980s. In 2000, a flat-packaged IGBT device rated at 4.5kV-2kA appeared.[(1)] Please refer to the separate article in this special issue for details of this flat-packaged IGBT.

In the "special issue on power semiconductor devices" (Vol. 72 No. 3) of the "Fuji Electric Journal" issued in 1999, Dr. Shigekane described the year of 1998 as a historical year for the research and development of power devices in "Present status and trends of power semiconductor devices." He cited the ISPSD (International symposium on power semiconductor devices & ICs) tenth anniversary symposium held in Kyoto as the reason for its historical importance. The

Fig.1 Progress of the design rule

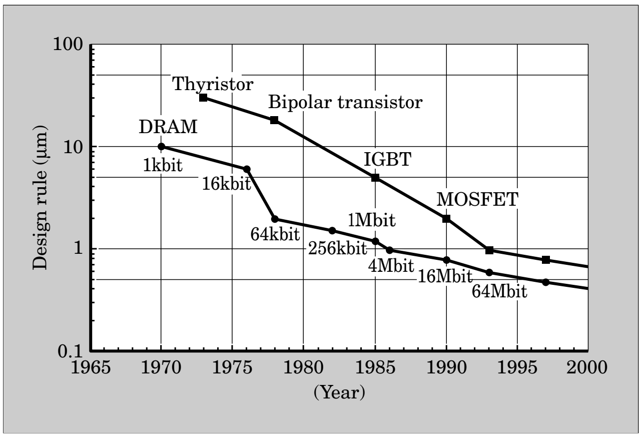
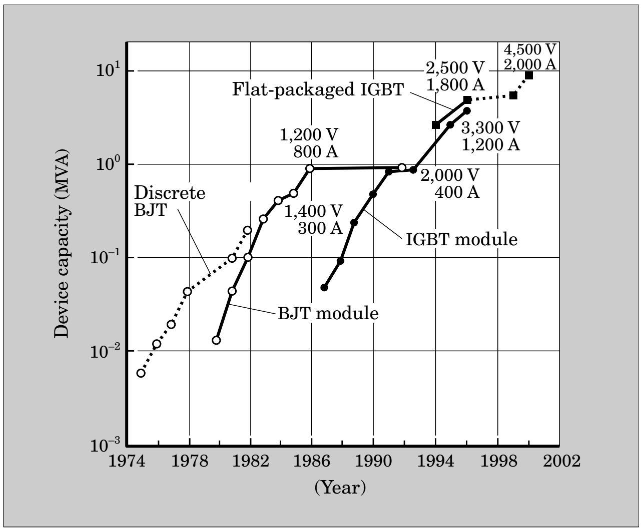


Fig.2 Progress in the power device capacity



IEE of Japan and the IEEE of the USA cosponsor the ISPSD and the location of the annual symposium rotates among the three regions of Japan, USA and Europe. It is the most authoritative international symposium in the power semiconductor device field. In the first symposium held in 1988, only 31 papers were presented; in the tenth anniversary symposium, more than 70 papers were presented, and in the 13th symposium to be held in Osaka in June 2001, more than 90 papers will be presented. Thus the symposium has become an association that issues guideline for the research and development of power devices. Fuji Electric has presented many highly rated papers at each ISPSD, ever since the first symposium.

Over the past several years of presentations, ISPSD papers on the following three themes have been increasing.

(1) MOS gate devices (MOSFETs, IGBTs, MOS gate thyristors, etc.)
(2) Power ICs and HVICs
(3) SiC (silicon carbide).

In accordance with the trends of power device research and development, the MOS gate device is still the mainstream; however, at the ISPSD to be held in Osaka in 2001, it is notable that many papers that discuss SiC as a next generation power device material have been accepted.

2. Trends of Fuji Electric's Device Development

The development of semiconductor devices is the history of fine pattern processing and device design optimization. Recent development of simulation technology has made it possible to precisely estimate device characteristics. Integrated simulation systems that incorporate not only device and process simulation but also heat conduction and stress simulation make a great help to device development. From early on, Fuji Electric has utilized various simulation tools to accelerate device development.

This chapter outlines the power MOSFET, IGBT, and assembly technologies that represent the leading edge of Fuji Electric's power device development.

2.1 SuperFAP-G series

Fuji Electric has newly developed the "SuperFAP-G series" of power MOSFETs. Please refer to the separate article in this special issue for details. The biggest problem facing development of the power MOSFET, a unipolar device, is how to reduce on-state resistance while maintaining the withstand voltage. Development of the SuperFAP-G series began with lofty goals. The design aimed to achieve the lowest on-state resistance theoretically possible with silicon. To attain the targeted specifications, micro-processing was used, of course, and the device was designed using a stripe-construction cell to optimally weaken the electric field of the cell structure part and to achieve the desired withstand voltage even at the low-resistance epitaxial layer. As the result, the power MOSFET attained a withstand voltage near the theoretical withstand limit of silicon in a low-resistance epitaxial layer. With this design, the new 600V device attained approximately one-half of the $R_{on} \cdot A$ value compared with conventional devices. Also in the case of application to a switching power supply, power MOSFET loss was measured to be 35% less in the standby mode compared with the conventional product, and consequently, conversion efficiency was improved by 3.2%. Also, having the advantage of approximately 20°C less temperature rise with a normal load, the power MOSFET is a highly promising device. A product lineup ranging from 150V to 900V is planned for this series and will be put on the market successively from 2000 to 2001.

2.2 Trends of the IGBT

Fuji Electric started producing and marketing IGBTs in 1988. Through introduction of a new IGBT generation every several years, improvement in characteristics rapidly progressed from the 1st generation to the 2nd and then to the new 3rd generation. The last decade of the 20th century was a golden era for the IGBT, and this movement is expected to continue for some time into the 21st century. Conventional IGBT chips of the 1st through new 3rd generation offered improved characteristics while using epitaxial wafers and controlling switching speed by lifetime control. Next generation IGBT chips are being developed using FZ (floating zone) wafers instead of epitaxial ones and employing NPT (non-punch-through) types without lifetime control and PT (punch-through) types. In the production of 1,200V IGBT modules in 1999, Fuji Electric commercially produced IGBT modules using NPT type chips as the 4th generation IGBT-S series.

To use FZ wafers for fabricating IGBT chips of the 600V and 1,200V class, the wafer thickness must be reduced to approximately one-third or less of the former thickness, and a major technical innovation in wafer processing is required. Fuji Electric will strive for the technical development of IGBT chips using FZ wafers and will promote FZ wafer applications starting with the 1,200V IGBT module S series of the 4th generation.

The separate article of this special issue introduces the new "EconoPACK-Plus" package, which uses new generation IGBT chips that are the successor to the 4th generation. This series is developed to meet the need for large capacities, and Fuji Electric plans to produce a series of 1,200V-225A to 450A modules. This EconoPACK utilizes PT type chips that employ the newly developed FZ wafers, and provides greatly improved characteristics. The diodes that are used concurrently were also improved and overall loss has been significantly reduced.

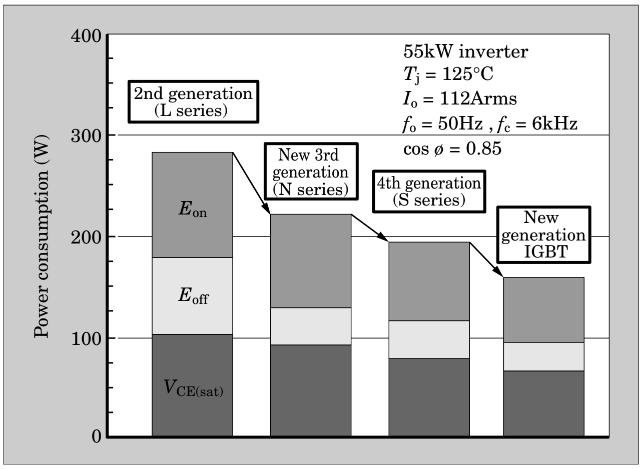
Figure 3 shows the change in loss reduction of an inverter using a 1,200V-300A IGBT module. This is an example of a 55kW inverter. Losses are indicated for the cases of the 2nd generation (L series) of 1990, the new 3rd generation (N series) of 1994, the 4th generation (S series) of 1999, and the above-mentioned new generation IGBT modules.

2.3 Assembly technology

In power devices, the power chip and the assembly technology are necessarily similar to the device technology. Recently, particularly from the viewpoint of power management, treatment of the heat generated in the chip has become a serious issue. The most important problem is how to ensure high reliability.

Fuji Electric has so far actively promoted research and development into the reliability of power devices. This special issue analyzes in detail and from a new perspective, the life of the power cycle within a module and investigates factors that detract from module reliability such as the problems of wire bonding and solder cracks as well as their countermeasures. Mindful of these analysis results and of environmental measures, we newly developed highly reliable lead-free Sn/Ag solder. Although conventional lead solder ensures sufficient power cycle endurance, modules

Fig.3 Comparison of inverter loss using various generation IGBT modules (1,200 V-300 A)



using the new Sn/Ag solder proved that it has even higher power cycle endurance. Fuji Electric will apply this new solder to its power transistor modules in turn and provide highly reliable modules to the market.

3. Conclusion

Power semiconductor device technology is rapidly progress and there is no time to be wasted. As mentioned in the beginning, enormous changes occurred in the last ten years of the 20th century. Now is the Renaissance of the power device, and the author feels privileged to be involved in the activities.

This paper introduces the power MOSFET, IGBT and assembly technology, which are at the forefront of development. Moreover, intelligent power devices are an indispensable technology. Without such technologies, "user-friendly" power devices cannot be realized.

Through declaring "***Quality is our message***" and realizing "user-friendly" devices by ourselves, we will fully satisfy users with our products.

Reference

(1) Fujii, T et al. 4.5kV-2000A Power Pack IGBT. Proceedings of ISPSD'00. 2000, p. 33-36.