Present Status and Trends of Power Semiconductor Devices

Hisao Shigekane
Yasukazu Seki
Tatsuhiko Fujihira

1. Introduction

In the midst of prolonged economic stagnation and sluggish economic conditions, demand for technological development is still strong, and it is our belief that technological development will steadily advance in the future. With a concerted drive toward technological development, we have been building up the infrastructure of our society in order to realize a better future.

At present, one of the major technologies supporting such technological development is power electronics, which is widely used in almost every field of our daily life. Fuji Electric has vigorously been developing power devices, the basis of power electronics technology. With the advances in power electronics technology, higher reliability as well as enhanced functionality and higher performance has come to be required of power devices.

To meet these demands, Fuji Electric is leveraging its sophisticated technological development expertise to provide highly reliable, leading-edge power devices.

2. Recent Trends of Power Device Development

The latest trends of power devices can be found in the trends of the ISPSD (International Symposium on Power Semiconductor Devices & ICs), the leading authoritative international academic society for power devices. The ISPSD was established in Japan in 1988 under the sponsorship of the Institute of Electrical Engineers of Japan (IEE) and has been promoted by engineers concerned with power devices. The annual ISPSD conference rotates between Japan, the United States and Europe. In Japan, the conference is sponsored jointly by the IEE and IEEE, and in the U.S. and Europe it is sponsored by the IEEE. ISPSD'01 was held in Osaka, Japan in 2001. In the banquet keynote address, Mr. Kunihiko Sawa, president of Fuji Electric Co., Ltd., delivered a lecture titled "My Experiences in Developments of Power Electronics — What I expect to young researchers and engineers —," based on his experiences in the development of power electronics.[1] The lecture made a great impression on many participants, researchers and engineers, and is still fresh in our collective memories.

ISPSD'02 was held in Santa Fe, New Mexico in early June 2002. There were 40 oral and 31 poster presentations. Fuji Electric made three oral presentations.[2]~[4]

Table 1 shows the number of research papers presented per presentation field. From the table, it can be seen that papers on MOS-gated devices, which include IGBTs (insulated gate bipolar transistors) and MOSFETs (metal-oxide-semiconductor field effect transistors), greatly outnumber papers of other fields, and are followed by papers on Power IC/HVIC.

One reason for the keen interest in the field of power devices is the tremendous improvement in power device characteristics due to the introduction of LSI wafer process technology and because several innovative and interesting reports on power-device-specific design and process technology have been published.

In the field of recent power devices, for example, great attention is given to power-device-specific technologies such as super-junction construction with epitaxial layers of multiple thicknesses in power MOS FETs and field-stop type IGBTs with extremely thin wafers.

Another reason is the strong desire by application engineers to construct compact, highly reliable power circuit blocks that include integrated drive and protective functions in addition to the power device unit. This has resulted in the presentation of many papers related to Power IC/HVIC technology.

There is also a steady stream of presentations on SiC (silicon carbide), a new promising material. SiC is expected to be a very useful material for high-voltage power devices because SiC's maximum allowable electric field strength is approximately ten times higher than that of Si. On the other hand, there are many technical challenges to be overcome through technological innovation before SiC power devices can commercially replace Si power devices.

Table 1 Change in the number of ISPSD research papers by field during the past six years

Venue / Presentation fiel	ISPSD '97 Weimar (Germany)	ISPSD '98 Kyoto (Japan)	ISPSD '99 Toronto (Canada)	ISPSD '00 Toulouse (France)	ISPSD '01 Osaka (Japan)	ISPSD '02 Santa Fe (U.S.)
Application	4	4	7	8	13	5
Simulation	6	1	1	4	1	2
Bipolar device	0	1	0	1	1	1
MOS-gated device	23	29	28	25	37	28
Power IC/HVIC	26	26	11	8	2	11
Power module	1	3	3	5	0	1
Thyristor/diode	6	12	10	8	15	4
GTO	5	6	1	0	2	0
Si device	2	3	0	0	1	0
Material/process	5	7	8	16	13	7
Packaging	2	0	1	1	6	1
SiC	8	7	6	8	11	11
Total	88	99	76	84	102	71

3. Fuji Electric's Development Policy on Power Devices

Fuji Electric is engaging in semiconductor business worldwide through marketing IGBT, power MOSFET and power diode products, concentrating on the four fields of general industry, automobile, information and consumer electronics. Fuji Electric's policy for developing new products is not to develop commodity devices for general-purpose applications but to develop products that can become the leading or the only product in limited application segments of the above four fields. Such products are referred to as killer products. Fuji Electric plans to increase its ratio of sales of killer products to total sales of semiconductors from 35 % in 2000 to 48 % in 2002.

The development of these killer products requires power device engineers to not only refine their technology but also to closely cooperate with application engineers. Fuji Electric is basically developing new products through forging strong and sustainable strategic partnerships with leading customers in various market segments. Customers do not pay money for power devices themselves, but for the results of applying such devices to electronic products. Thus, the development of new products should strive to provide device solutions that solve customers' technical problems.

Based on this viewpoint, Fuji Electric is planning to increase its sales percentage of MOS-gated devices, active devices which form the core of its device solutions, from 52 % in 2000 to 55 % in 2002, and to increase its sales percentage of smart devices and intelligent power devices, which integrate driving and protective functions into MOS-gated devices, from 28 % in 2000 to 33 % in 2002. The development of MOS-gated devices aims to combine power diodes, passive devices, with state-of-the-art MOS-gated devices to bring about new effects in applications.

In other words, Fuji Electric's power device development policy is to develop the latest high-tech, high-performance power devices, and to provide smart and intelligent power device solutions, by combining IC technology and power devices through a concerted effort with customers.

4. Fuji Electric's IGBTs

The first half of this special issue is a collection of research papers on the fifth-generation IGBT "U-series," which is subject to rapid technological innovation. These papers summarize the recently developed 600 V, 1,200 V and 1,700 V modules. For details of the U-series technological innovations, refer to the next paper, "Technological Innovation for Super-low-loss U-series IGBT modules," and for details of modules by withstand voltage, refer to the three papers thereafter.

Figure 1 shows the transition from first- to fifth-generation IGBTs and the technologies employed.

In first- to third-generation IGBTs, so-called epitaxial wafers were used to optimize lifetime control technology and to improve the IGBT performance due to micromachining technology. In fourth- and fifth-generation IGBTs, FZ (floating zone) wafers are used in place of epitaxial wafers to significantly improve performance, which resulted in drastic changes to the traditional IGBT design policy.

In designing IGBTs using epitaxial wafers, large amounts of carriers are injected at the collector side, and by means of conductivity modulation, the IGBT body is filled with carriers to achieve low on-voltage. When the current is interrupted, carriers that filled the IGBT body due to conductivity modulation are re-bound together and annihilated through application of lifetime control technology. When lifetime control

Fig.1 Change in application technology for Fuji Electric's IGBTs

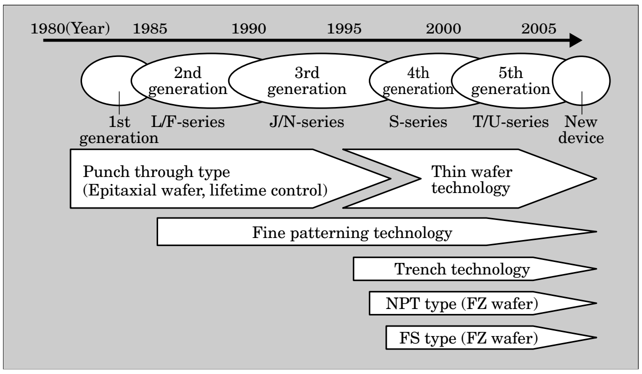


Fig.2 Change in cross-section structure of 600 V IGBT chips

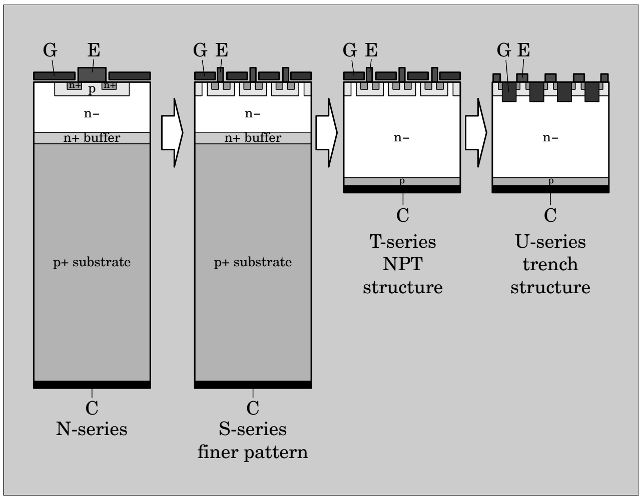
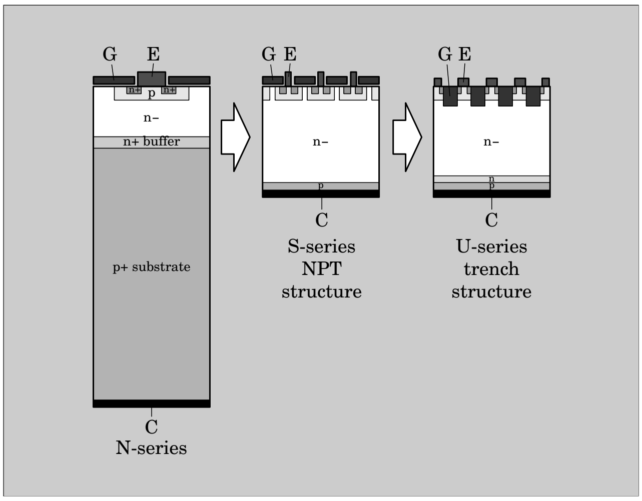


Fig.3 Change in cross-section structure of 1,200 V IGBT chips



technology is applied, carrier transport efficiency decreases in the normal on-state due to the effect of lifetime control technology. Thus, to compensate for the reduced transport efficiency, larger amounts of carriers are injected to lower the on-voltage. The design of IGBTs using epitaxial wafers was basically involved with the principles of high carrier injection and low transport efficiency.

In designing IGBTs using FZ wafers, the basic IGBT design should be changed to suppress carrier injection at the collector side, and to increase carrier transport efficiency through reducing carrier injection efficiency. If only carrier injection efficiency is reduced, on-voltage increases. To overcome this problem, carrier transport efficiency was increased in the IGBT body. As a result, lifetime control became unnecessary. Fuji Electric started to apply this design to fourth-generation 1,200 V "S-series" IGBTs having NPT (non-punch through) structure.

The use of FZ wafers requires technology for reducing wafer thickness to achieve NPT construction, in addition to conventional semiconductor device development technology. Fuji Electric was the first to develop this technology and has actively promoted application of FZ wafers to IGBTs. Enabled by further reduction of wafer thickness, the 600 V "T-series" of IGBTs were developed.

Trench process technology at the emitter side of a chip surface is also essential for improving IGBT performance. When applying trench process technology to IGBTs, there had been a problem for some time in that on-voltage decreased but short-circuit withstand capability also decreased. Optimization of the surface design and NPT design, however, solved that problem and contributed to significant performance improvement in the 600 V fifth-generation IGBT U-series.

For further performance improvement, IGBT structure evolved from NPT to FS (field stop) structure. In FS structure, n+ buffer layers in conventional IGBTs are used as FS layers. While maintaining low carrier injection and high transport efficiency, FS layers are made thinner than those in NPT construction to improve transistor performance. Improved technology for reducing wafer thickness and the development of process technology for forming FS and P layers at the collector side enabled realization of the 1,200 V- and 1,700 V-fifth-generation IGBT U-series.

Figures 2 and 3 schematically show the cross-section structures of these 600 V and 1,200 V IGBT chips and their transition from generation-to-generation. As can be seen in these figures, recent IGBT chips are significantly thinner than conventional IGBT chips, and advanced technologies such as trench process and FS structure have been incorporated into IGBT chips.

5. Intelligent Power Devices

Fuji Electric has been promoting the development of intelligent power devices in line with the abovementioned development policy. These power devices incorporate driving, self-diagnostic, and computing functions. Fuji Electric's major objective in developing power devices has been to satisfy customers by providing power devices that solve customer problems. This special issue introduces the newly developed "R-IPM3" series with T-series IGBTs, aiming to reduce power loss, temperature dependence and current concentration, and the "Econo IPM" series, aiming to reduce package size and thickness. Fuji Electric is determined to deliver easy-to-use and low-noise power devices that provide the customer with a comprehensive solution.

In the field of power supplies, the "M-Power1" series has already been commercialized and applied to color televisions, CRT monitors, and other equipment. Recently, Fuji Electric has developed a new system capable of high-speed control even at light loads and proposed the "M-Power2" series which facilitates design of power supplies for LCD (liquid crystal display) monitors, leading to smaller-size, lighter-weight and more efficient power supplies.

In the past, Fuji Electric delivered enhanced-function MOSFETs and intelligent power devices for igniters to the automobile industry. Now, Fuji Electric has developed new vehicle-mounted enhanced-function MOSFETs capable of instantaneously passing a large current at the time of turn-on, such as when switching on a lamp or starting a motor. In addition, protective functions such as overcurrent detection, overcurrent limit and overheat detection are incorporated into the multi-layered fail-safe design.

Through concerted effort with customers, Fuji Electric has been conducting solution-oriented new-product development, concentrating on the fields of general industry, automobile, information and consumer electronics.

6. High-performance Discrete Elements

In 2001, Fuji Electric delivered the power MOSFET "SuperFAP-G" series, which achieved a significant reduction in loss through simultaneously achieving both low R_{on} (on-state resistance) and low Q_{gd} (gate-to-drain charging capacity). In the 450- to 600 V-class, approximately 40 types of power MOSFETs are already being mass-produced. Fuji Electric has recently introduced a series of medium-voltage (100 to 250 V) power MOSFETs for DC-DC converters, and high-voltage (700 to 900 V) power MOSFETs for 200 V AC switching power supplies. In the Super FAP-G series, Fuji Electric's proprietary surface construction mitigated electric field strength on the surface and realized 97 % of the theoretical withstand-voltage limits of silicon, thus allowing the use of low resistance wafers. It was indeed a great technological breakthrough.

In the field of switching power supplies, there is demand for improved diodes having lower loss characteristics. In reality, power loss in the secondary output diodes of a switching power supply comprises approximately half of the total loss. In the past, p-n junction diodes were used for 200 to 300 V power MOSFETs. In order to reduce this loss, Fuji Electric promoted the development of Schottky barrier diodes (SBDs), taking note of their excellent characteristics. A major challenge was optimization of the barrier metal. If the barrier height is too large, forward voltage (V_F) increases, and if barrier height is too small, leakage current (I_r) increases. By overcoming this trade-off relationship, high-voltage SBDs were developed.

7. Conclusion

For the past several years, technological development related to power devices has advanced at a tremendous pace. In a fiercely competitive environment, Fuji Electric has always led in developing power devices with state-of-the-art technology. Fuji Electric has maintained its consistent policy of developing only new products that have the potential to become the leading or only product worldwide in limited market segments.

This special issue introduces Fuji Electric's power devices developed in line with its development policy. The first half of this issue focuses on Fuji Electric's fifth-generation IGBTs (U-series), on which great expectations are placed. Technological innovation related to the U-series, and 600 V, 1,200 V and 1,700 V IGBT modules is also presented in detail.

In addition to IGBTs, this special issue introduces the present status of Fuji Electric's customer-oriented development related to power devices, including intelligent devices in specific fields, dedicated devices for specialized applications and technological innovations for discrete devices.

Fuji Electric is confident that the new products introduced in this special issue will contribute to improved customer satisfaction.

In conclusion, in proclaiming that "***Quality is our message***" and judging itself against that standard, Fuji Electric is determined to provide customers with reliable, high-quality products.

References

(1) Sawa, K. My Experiences in Developments of Power Electronics. Proceedings of ISPSD'01, 2001, p.461.

(2) Otsuki, M. et al. Investigation on the Short-circuit Capability of 1,200 V Trench Gate Field-Stop IGBTs. Proceedings of ISPSD'02, 2001, p.281.

(3) Ohnishi, Y. et al. 24 mohm cm^2 680 V Silicon Super Junction MOSFET. Proceedings of ISPSD'02, 2001, p.241.

(4) Sugi, A. et al. A 30 V Class Extremely Low On-resistance Meshed Trench Lateral Power MOSFET. Proceedings of ISPSD'02, 2002, p.297.