Review

# Power Devices for Automotive Applications - Reviews of Technologies for Low Power Dissipation and High Ruggedness -

Tsutomu Uesugi


## Abstract

Electronics technology is indispensable for improving automotive performance. Especially, in electric vehicles (EV) and hybrid electric vehicles (HEV), electric systems are the heart of the automobile. Power devices are one of the most important components of car electronics systems and they are applied to many systems, for example, oil-pressure valve control of the ABS system, and motor control of the power windows or inverter system of an electric vehicle that converts the DC voltage of the battery into AC voltage. Therefore, the power devices that have low power dissipation and high ruggedness are definitely required in order to realize a reduced cost of the automotive systems. In this paper, I review the characteristics of the power devices that are used in automotive applications, and the technologies that realize the low power dissipation and high ruggedness.


Keywords: Power device, Automobile, EV, HEV, Low power dissipation, High ruggedness, Power transistor, Power MOSFET, IGBT, BSIT, Trench, Buried structure, Module technology, Intelligent technology, New material, SiC, GaN

## 1. Introduction

As the term "car electronics" indicates, electronics has become an essential technology for improving the performance and functionality of automobiles. Particularly in electric vehicles, the use of a motor drive employing a power device means that electronic devices are no longer auxiliary equipment, but have assumed the status of primary equipment. One reason that electronics have come to occupy a critical position where they are used widely in on-board equipment is the evolution and development of power devices for automotive applications.[1)]

Power devices, which are semiconductor switching devices, are used in numerous car electronics systems. They control hydraulic valves in the anti-lock braking system (ABS), gasoline injection valves in the electronic fuel injection (EFI) systems, and motors for power windows and other accessories, and also convert the battery's DC voltage into AC voltage in inverter systems.

This paper discusses the state of the art and future outlook for power devices which serve as the back-bone of car electronics, with a particular emphasis on low power dissipation and high ruggedness.

## 2. Types of power devices and their characteristics

The voltages that power devices handle widely vary, from around twenty volts for mobile terminals that are powered by the battery to the several kilovolts required by electrical generation and transmission systems, and the optimum devices are selected and used according to the voltage capacity. **Figure 1** summarizes the breakdown voltage required of power devices by automotive systems, as well as the maximum values of the electrical current they can handle (the maximum rated current). With the 12-volt battery systems most commonly used in automobiles today, a power MOSFET with a 60-volt breakdown voltage is used for the ABS and power window system. In contrast, the 288-volt system used in electric vehicles is the domain of the insulated gate bipolar transistor (IGBT), which has a breakdown voltage of 600 volts. A bipolar power transistor or a bipolar mode static induction transistor (BSIT) is used for systems which lay in the mid-range between these two applications.

This section provides an overview of the structures and characteristics of these power devices.

### 2. 1 Power transistor

**Figure 2**(a) shows an example of the cross-sectional structure of a power transistor. In a power transistor, holes are injected from the base to the collector, and electrons flow from the emitter to the collector in proportion to the hole injection. Due to the conductivity modulation effect, which increases the effective carrier concentration, the resistance of the device decreases in proportion to the hole injection. This in turn decreases the power dissipation of the device. Power transistors were among the first semiconductor power devices to be used for automotive applications.

However, because the device is driven by the injection of current, the drive circuit is complex, and the driving power dissipation is high. Also, the current has a positive temperature coefficient, which makes it easier to undergo thermal runaway compared to other devices. For these reasons, power transistors have been replaced by the power

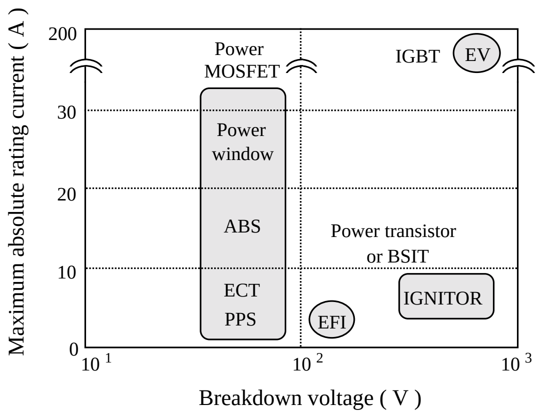



**Fig. 1** Relation between maximum absolute rating current and breakdown voltage for automotive applications.

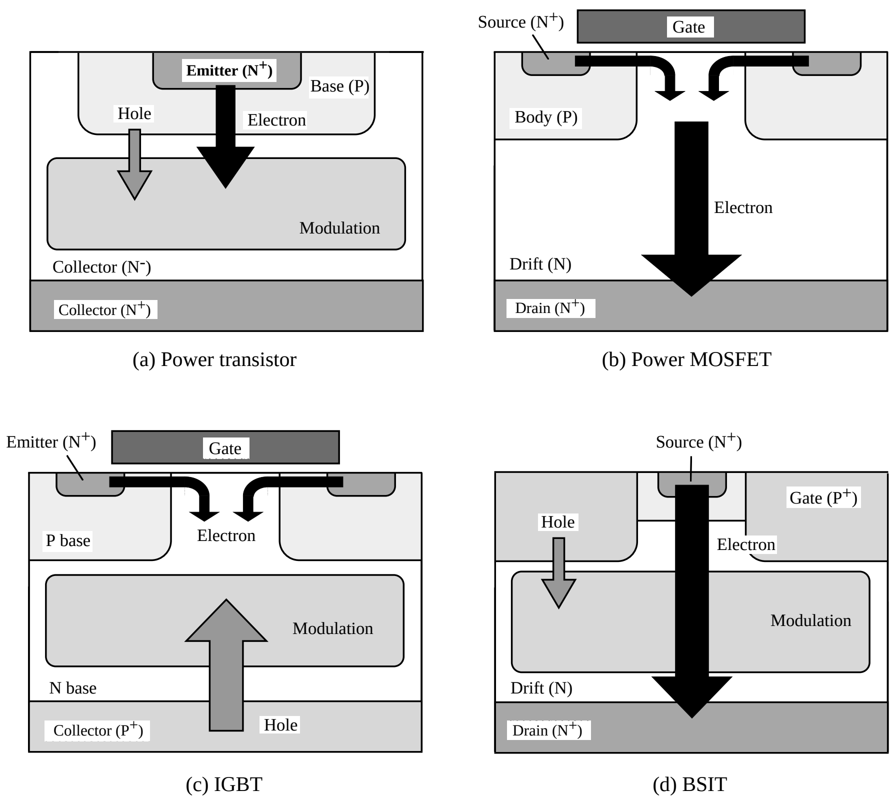



**Fig. 2** Cross-sectional view of power device, (a) power transistor, (b) power MOSFET, (c) IGBT, and (d) BSIT. Black arrows indicate electron flow and gray arrows indicate hole flow.

MOSFET for low-voltage applications of 100 volts or less, and by the IGBT for high-voltage applications of 400 volts or more.

**2. 2 Power MOSFET**

Figure 2(b) shows the cross-sectional structure of a power MOSFET. This device is voltage-controlled and easy to drive, and the ON-state current has a negative temperature coefficient, so a power MOSFET has the advantage of being resistant to thermal runaway. Also, unlike the bipolar transistor, the power MOSFET is a unipolar device with a single carrier that contributes to the electrical conduction, so there is no minority carrier storage and the speed is high. However, it also has no conductivity modulation effect to reduce the power dissipation, and as the breakdown voltage increases, the ON-state resistance abruptly increases in a ratio equal to the voltage capacity raised to the power of 2.5, so the power MOSFET is mainly used as a low-voltage device.

**2. 3 IGBT**

Figure 2(c) shows the cross-sectional structure of an IGBT. The point that differs from Fig. 2(b) is that the substrate is not an $N^+$ substrate, but a $P^+$ substrate. This creates major differences in the characteristics of the device. With an IGBT, the application of voltage to the gate causes electrons to inject from the emitter to the N base via channels that are formed in the P base, while holes are injected in the same manner from the collector, which is the $P^+$ substrate, to the N base. This creates a conductivity modulation effect in the N base, in the same manner as with the power transistor, thereby significantly reducing the resistance of the device. That is to say, the IGBT can be called a device that combines the advantages of simplicity of drive due to the voltage-controlled device and low power dissipation due to the conductivity modulation effect. For that reason, the IGBT is used for the electric vehicle inverter systems, which requires a high breakdown voltage of 600 volts or more, and is increasingly being used for some ignitor systems.

**2. 4 BSIT**

The cross-sectional structure of a BSIT is shown in Fig. 2(d). The BSIT is a device that controls the potential between the gate and the drain by means of a minority carrier that injects from the gate. It also controls the current. The BSIT achieves higher current gain than that of the power transistor and has the advantage of being resistant to thermal runaway. It can also reduce the ON-state voltage using the conductivity modulation effect. However, its driving dissipation is high, because it uses a current driving method, so its scope of application is limited. However with the shift to higher-voltage vehicle batteries in the near future, it is anticipated that the BSIT will be more widely used.

## 3. Improving the performance of power devices for automotive applications

Low power dissipation and high ruggedness are the two characteristics that are currently considered most important for automotive power devices. This section discusses the state of the art and future outlook for the technologies that provide these characteristics.

**3. 1 Reducing power dissipation**

Reducing the power dissipation per unit area has become the most important issue in power device research and development, because shrinking the chip area to satisfy the system requirements reduces the chip cost, which in turn reduces the total system cost.

The micro-processing technology that was developed for LSIs plays a major role in reducing the power dissipation of power devices. For example, looking at the reduction of power dissipation in the power MOSFET, making the cell pitch smaller also reduces the ON-state resistance step by step (**Fig. 3**). This is due to the reduction in

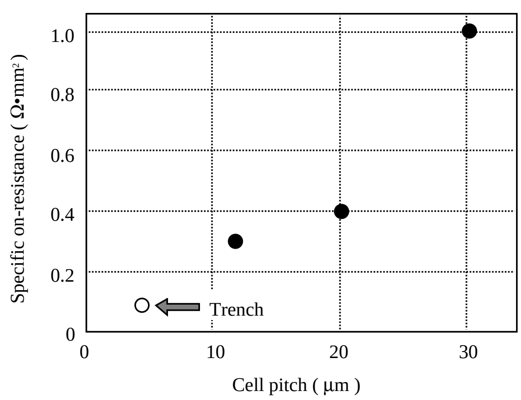



**Fig. 3** Specific on-resistance of power MOSFETs versus unit cell pitch. The symbol of "○" indicates the resistance of the trench gate structure.

the channel resistance that is the main component of the resistance in the power MOSFET. However, as shown in **Fig. 4**(a), as the cell pitch is made smaller, and particularly as the gate is made smaller, the area through which current flows is narrowed by the depletion layer of the body junction, and the so-called parasitic JFET resistance becomes noticeable. For this reason, a cell pitch of approximately 12 $\mu$m was thought to be one limit. The technology that broke through this barrier is the trench gate structure. With the trench gate structure (Fig. 4(b)), the widening of the depletion layer of the body junction means that there is no constriction of the current path, which is to say, no parasitic JFET resistance, so the gate dimensions can be reduced as much as the process allows and resistance can be dramatically reduced.[2, 3] Reducing the resistance further requires that the source region be made smaller, and a technique has been proposed for achieving this by self-aligning formation.[4-6] Modifications to the gate layout are also being made. For example, it has been reported that replacing the conventional stripe layout with a mesh layout results in an ON-state resistance of only 0.08 $\Omega$ mm$^2$ for a breakdown voltage of 72 volts.[7]

This trench structure is also used in the IGBT, which achieves an ON-state voltage of 1.4 volts with a turn-off time of 0.2 $\mu$sec at 200 A/cm$^2$, compared to an ON-state voltage of 1.8 volts with a turn-off time of 0.2 $\mu$sec at 140 A/cm$^2$ for the conventional planar gate structure.[8] The injection enhanced gate transistor (IEGT)[9] and the carrier stored trench-gate bipolar transistor (CSTBT),[10] which increase the conductivity modulation effect in the N base and can reduce the resistance to the same level as that of a thyristor, have been proposed in order to reduce resistance even further than the conventional trench IGBT.

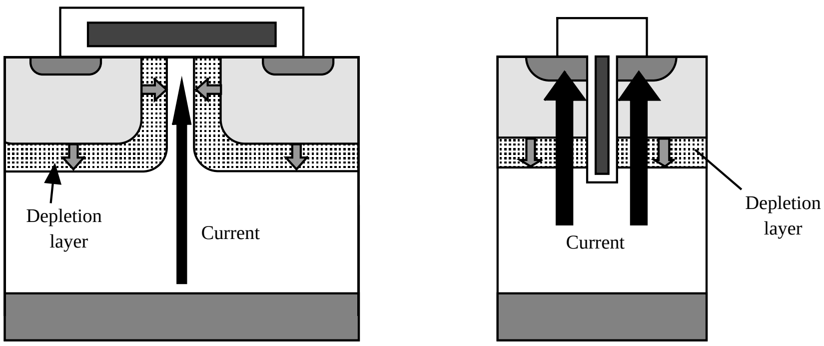
### 3. 2 Improving ruggedness

If one compares semiconductor devices that are used in automobiles with those used in consumer products, the most striking difference is the environment in which the devices are used. In the automotive environment, the usage temperatures are high and the effect of noise is strong. For that reason, greater ruggedness is required than for consumer product applications. When one considers the loads that are driven by automotive power devices, there are many inductance loads such as motors, solenoid valves, etc., so the improvement of how to suppress the avalanche breakdowns that occur when inductance loads are driven is critical.

Avalanche breakdown is a phenomenon whereby the counter-electromotive force generated by the inductance load when the device is turned off triggers the breakdown of the device. It is strongly correlated with the action of the parasitic transistor that exists within the device. It is believed that avalanche breakdown can be suppressed by suppressing the action of the parasitic transistor, and the following two techniques have been proposed to accomplish this:

(1) Improve the ruggedness of the unit cells that make up the device.

(2) Avoid breakdown in an active region of the device.




(a) Planar gate (b) Trench gate

**Fig. 4** Cross-sectional view of the planar gate structure (a) and the trench gate structure (b) under on-state.

The method to improve the ruggedness of the unit cells include reducing the base resistance of the parasitic transistor by forming a deep P-type layer with a high concentration,[11] reducing the concentration of the source region,[12, 13] reducing the $h_{FE}$ of the parasitic transistor using a lifetime killer,[14] increasing the speed of the internal diode,[15] and adding a Zener diode between the source and the drain.[16, 17] The adding of a Zener diode between the source and the drain has also been proposed as a means of avoiding breakdown in the active region of the device.[18-20] However, these technologies involve trade-offs, particularly with the need to reduce resistance, because they increase the chip area, thereby increasing resistance. Therefore, the balance between greater ruggedness and lower resistance must be optimized.

As an other approach to these technologies, a technique has also been proposed to improve ruggedness by activating the parasitic transistors throughout the chip, and avoiding current crowding. The cell pitch can be made still smaller with this structure, so it is expected that this approach could achieve both a higher ruggedness and lower resistance, which is difficult under the other proposals made to date.[21]

## 4. Associated technologies that improve power device performance

### 4. 1 Module technology

Power devices are never used in systems as chips only, but are always incorporated in the form of packages or power modules. Therefore, the development of module technology, including packages and power modules, is important for improving the performance of power devices. Technical issues in this area include high thermal conductivity characteristics and low inductance. Development work is proceeding on structures that achieve these characteristics, such as by using a composite silicon carbide/aluminum material for the heat sink to improve thermal conductivity performance, decreasing parasitic inductance by forming the main current wire into a loop shape,[22] or sandwiching the chip between metallic electrode materials on both faces, then pressing them together to form a pressure-welded package.[23, 24] This press-pack package allows both faces of the chip to be cooled, and because wires are not needed to act as electrodes, parasitic inductance is reduced and reliability is improved, so it is anticipated that this package will be used for automobile applications in the future.

### 4. 2 Intelligent technology

Another direction for improving the performance of power devices is to build in intelligence in the form of logic, etc. For example, power ICs are being developed with built-in self-protective functions against overheating and overcurrent.[25] These power ICs require technology to build in CMOSFETs to act as digital circuits, bipolar transistors to act as analog circuits, and power devices that constitute the output stages, as well as technology to electrically isolate these devices. For the initial substrate structure, a simple, self-isolating type of full CMOS power IC was developed, but because a more accurate analog function was required, a P-N isolation-type BiCDMOS technology was developed that can also incorporate a bipolar transistor, and this is now the mainstream technology.[26] A dielectric isolation technology without a parasitic structure is becoming the mainstream isolation technology in conjunction with the development of SOI substrate technology.[27]

Proposals for intelligent functions are not only the conventional self-protective functions, but also communicate functions to be used in a LAN in the passenger compartment.[28]

## 5. Future trends

### 5. 1 Post-trench devices

The development of post-trench devices is currently an important theme of research and development for power devices. It is the creation of devices that allows for greater decreases in resistance than do trench devices. The most recently proposed structure is the "super junction" structure (**Fig. 5**).[29, 30] In the super junction structure, the depletion layer extends horizontally from a vertical P/N junction that is formed in the depth direction of the substrate, making complete depletion of the drift region possible over a wider range than the conventional structure can achieve. This allows high breakdown voltage to be achieved even at high impurity concentrations, so that an ON-state resistance of 3 $\Omega$ $mm^2$ can be obtained at a breakdown voltage of 600 volts. This value is equal to one-third of the silicon limit, which is the material limit on the ON-state resistance that is determined by the breakdown voltage.[30] However, the resistance is three times higher than that of an IGBT of the same breakdown voltage, so it is believed that the super junction structure will be used for applications where high speed, rather than low resistance, is required.

Another structure that has been proposed reduces resistance by burying an electrode or a dielectric film in the silicon substrate.[31-33] **Figure 6** shows an example of this applied to a power MOSFET. The channel resistance is reduced by the effect of the surface gate and the buried gate, while the buried electrode suppresses the potential in the interior of the substrate, thereby increasing the voltage capacity.[31] A horizontal power MOSFET has also been proposed that can reduce the drift resistance by combining the buried structure with trench technology.[32] The buried structure is also used for the BSIT, and it has been confirmed that burying a dielectric film in the source region improves $h_{FE}$.[33]

As this brief introduction indicates, any number of post-trench technologies have been proposed, but they have not yet reached the point where they can replace trench devices. The creation of post-trench technologies in the form of new technologies or combinations of the technologies described above is anticipated.

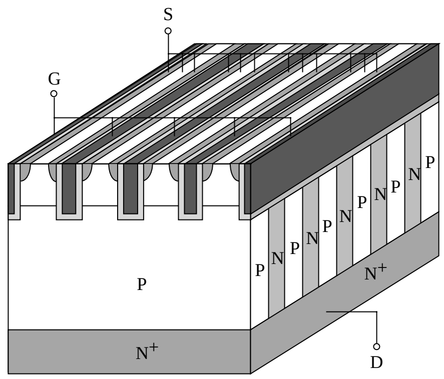



**Fig. 5** Cross-sectional view of the super junction power MOSFET.[29]

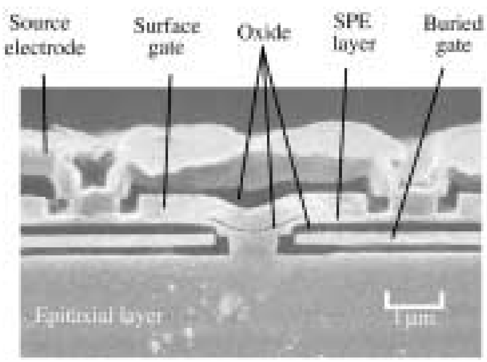



**Fig. 6** Cross-sectional SEM photograph of the double gate power MOSFET.[31]

**5. 2 Post-silicon devices**

It has already been mentioned that with silicon power devices, the characteristics achieved are close to the silicon limit. For this reason, studies of new semiconductor materials to replace silicon are underway. Silicon carbide is the most promising material for power devices, because its dielectric breakdown field is ten times greater than that of silicon, it can be used at high temperatures, it has a high thermal conductivity, and it can be manufactured using the same process technology that is used for silicon.[34] Trial calculations indicate that the resistance of the drift layer, which is closely related to the breakdown voltage, can be reduced to 1/300 of the value for silicon.[35] However, the characteristic currently obtainable by a silicon carbide power MOSFET, i.e., an ON-state resistance of 6.6 ohms times one square millimeter at a breakdown voltage of 750 volts, is only about half the silicon limit, so it is not considered superior to the super junction device described earlier. Thus, the superior characteristics of silicon carbide predicted from the theoretical considerations have not been realized, and issues such as improving the quality of the crystal and channel mobility remain. Future research and development is needed.

Gallium nitride is said to be superior to silicon carbide as a power device material.[36] The channel mobility that can be obtained is higher than that for silicon carbide,[37] so it is a material that will be promising in the future. However, many problems remain to be resolved, including technology to achieve the same high-quality crystals as silicon carbide and compatibility with the silicon manufacturing process.

A problem that is common to these new materials is that their manufacturing cost is higher than that of silicon. Therefore, it is important not only to develop technology that will produce devices at lower cost, but also to pioneer new applications that can use the advantages of these materials and can produce cost benefits for the system as a whole.

## 6. Conclusion

This paper has examined the current status of power devices for automotive applications and the prospects in the future. The development of car electronics is indispensable to the pursuit of high-performance, environmentally friendly vehicles, and energetic research and development of power devices is required to attain that goal.

## Reference


1) Mihara, T. : J. Soc. Automot. Eng. Jpn., **46**-2(1992), 73-79
2) Ueda, D., et al. : "A New Vertical Power MOSFET Structure with Extremely Reduced On-Resistance", IEEE Trans. Electron Devices, **ED32**-1(1985), 2-6
3) Matsumoto, S., et al. : "A 70-V, 90-m$\Omega\cdot$mm$^2$, High-Speed Double-Layer Gate UMOSFET Realized by Selective CVD Tungsten", Proc. ISPSD, (1994), 365-369
4) Matsumoto, S., et al. : "A High-Performance Self-Aligned UMOSFET with a Vertical Trench Contact Structure", IEEE Trans. Electron Devices, **ED41**-5(1994), 814-818
5) Suzuki, T., et al. : Unexamined Pat. Pub., H09-266309
6) Uesugi, T., et al. : Unexamined Pat. Pub., H10-150191
7) Matsuki, H., et al. : 1997 Nat. Convention Record IEE Jpn., 805(1997), 4-44-4-45
8) Harada, M., et al. : "600V Trench IGBT in Comparison with Planar IGBT", Proc. ISPSD, (1994), 411-416
9) Kitagawa, M., et al. : "A 4500V Injection Enhanced Insulated Gate Bipolar Transistor (IEGT) Operating in a Mode Similar to a Thyristor", IEDM Tech. Dig., (1993), 679-682
10) Takahashi, H., et al. : "Carrier Stored Trench-Gate Bipolar Transistor (CSTBT) - A Novel Power Device for High Voltage Application", Proc. ISPSD, (1996), 349-352
11) Baliga, B. J., et al. : "Suppressing Latch-up in Insulated Gate Transistors", IEEE Electron Device Lett., **EDL5**-8(1984), 323-325
12) Uesugi, T. : Unexamined Pat. Pub., H08-186254
13) Baliga, B. J. : Power Semiconductor Devices, (1995), PWS, Boston
14) Yamaguchi, H., et al. : Unexamined Pat. Pub., S62-39069
15) Tsunoda, H., et al. : Unexamined Pat. Pub., H03-259537
16) Matsushita, T., et al. : "A Surge-Free Intelligent Power Device Specific to Automotive High Side Switches", IEEE Trans. Electron Devices, **ED38**-7 (1991), 1576-1581
17) Hoshi, M., et al. : "A DMOSFET Having a Cell Array Field Ring for Improving Avalanche Capability ", Proc. ISPSD, (1993), 141-145
18) Phipps, J. P., et al. : U. S. Pat. 5, 365, 099, (1994)
19) Yamazaki, T., et al. : *Denki Gakkai Kenkyukai Shiryou* (In Japanese), EDD-93-27/SPC-93-49 (1993), 67-74
20) Kawai, F., et al. : Unexamined Pat. Pub., H08-172190
21) Uesugi, T., et al. : "A New Power MOSFET Having Excellent Avalanche Capability", Proc. ISPSD, (2000), 379-382
22) Arai, Y., et al. : Proc. JSAE Annu. Congr., 982(1998), 61
23) Takahashi, Y., et al. : "2.5kV 100A *m*-stack IGBT", Proc. ISPSD, (1994), 25-30
24) Hiyoshi, M., et al. : 1997 Nat. Convention Record IEE Jpn., 795 (1997), 4-32-4-33
25) Izumida, T., et al. : Toshiba Rev., **47**-11(1987), 853
26) Kurishna, S., et al. : "An Analog Technology Integrates Bipolar, CMOS, and High-Voltage DMOS Transistors", IEEE Trans. Electron Devices, **ED31**-1 (1984), 89-95
27) Nakagawa, A., et al. : "New 500V Output Devices Structures for Thin Silicon Layer on Silicon Oxides Film", Proc. ISPSD, (1990), 97-101
28) Nikkei Microdevices, No.9(1992), 33, 37
29) Fujihira, T. : "Theory of Semiconductor Superjunction Devices", Jpn. J. Appl. Phys. Part 1, **36**-10(1997), 6254-6262
30) Deboy, G., et al. : "A New Generation of High Voltage MOSFETs Breaks the Limit of Silicon", IEDM Tech. Dig., (1998), 683-686
31) Kodama, M., et al. : Trans. Inst. Electron. and Commun. Eng. Jpn., **J80-C-II**-5(1997), 157-163
32) Uesugi, T., et al. : "New 3-D Lateral Power MOSFETs with Ultra Low On-Resistance", Proc. ISPSD, (1998), 57-60
33) Kawachi, S., et al. : 9th Symp. Static Induction Devices, SSID-96-7(1996), 28-33
34) Baliga, B. J. : "Semiconductors for High-Voltage, Vertical Channel Field Effect Transistors", J. Appl. Phys., **53**-3(1982), 1759-1764
35) Yao, T. : Proc. Electron., Inf. and Systems Conf., (1997), 243-246
36) Chow, T. P. and Tyagi, R. : "Wide Bandgap Compound Semiconductors for Superior High-Voltage Power Devices", Proc. ISPSD, (1993), 84-88
37) Detchprohm, T., et al. : "Hybrid Vapor Phase Epitaxial Growth of a High Quality GaN Film Using a ZnO Buffer Layer", Appl. Phys. Lett., **61**-22(1992), 2688-2690


( Report received on Feb. 11, 2000 )

**Tsutomu Uesugi**
Year of birth : 1958
Division : Power Device Lab.
Research fields : Power Devices for Automotive Applications
Academic society : Inst. of Electr. Eng. of Jpn., Inst. of Electron. Inf. and Commun. Eng., Jpn. Soc. of Appl. Phys.