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PROGRESS IN MOS-GATED POWER DEVICES

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1. Foreword

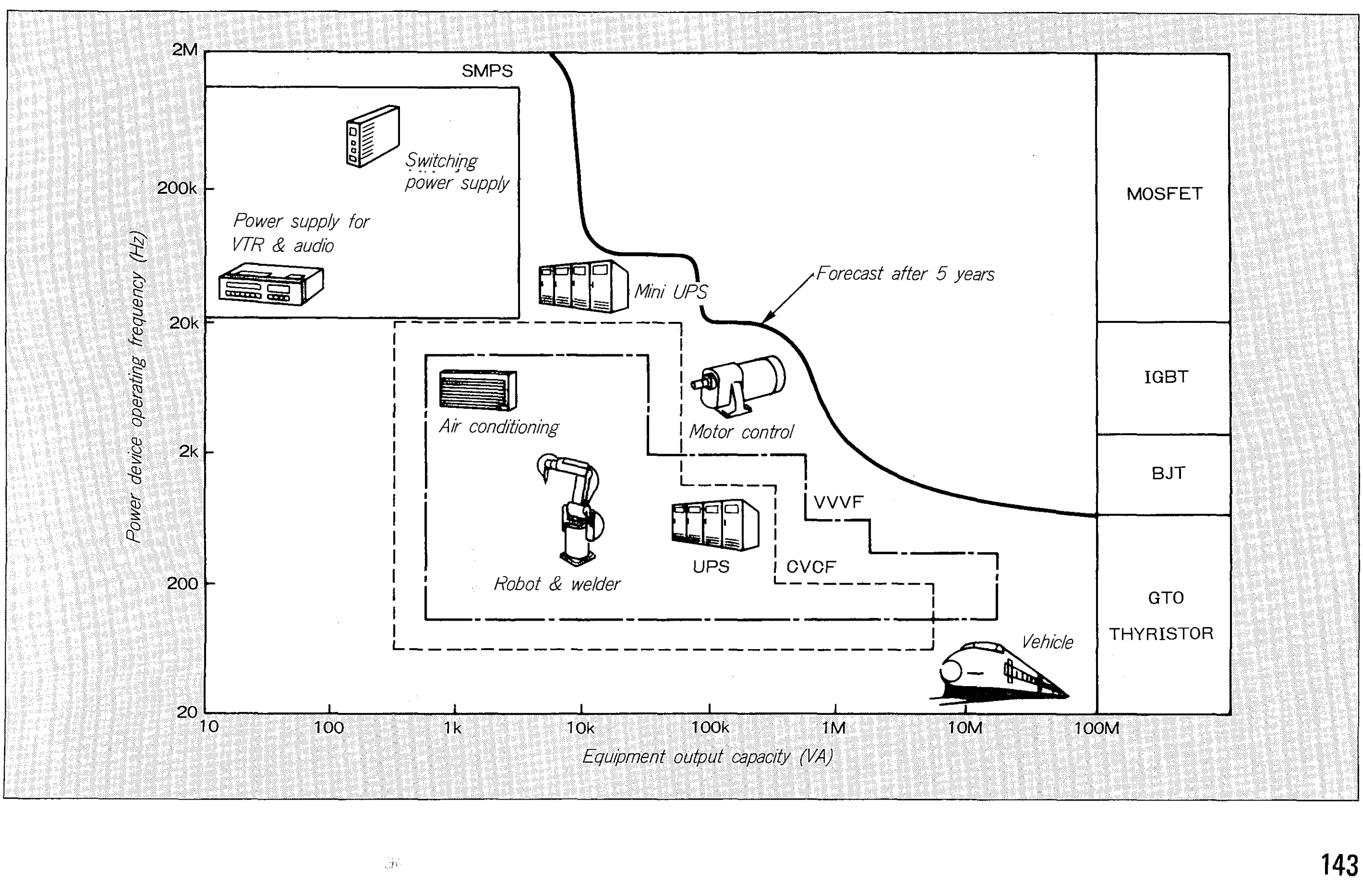
Power semiconductor devices. the key component in the aim toward advanced, efficient, small, light, and low acoustic noise power electronics equipments and system, are being developed and improved. Application to MOS (Metal-Oxide Semiconductor) gated power devices allows high speed switching and simplification of the gate driving circuit (voltage driving) of power switching devices and has led to major breakthroughs in the power electronics field. The current state of MOS-gated power device technology that has played a leading role of power devices, is described and future trends are considered.

In *Fig. 1,* the output (VA) of such typical power eletronic equipments as the VVVF (Variable Voltage Variable Frequency) inverter, CVCF (Constant Voltage Constant Frequency) inverter, and SMPS (Switching Mode Power Supply) is shown on the horizontal axis and the operation frequency of the power device used is shown on the vertical axis. The power device operating frequency is set in steps. Each set value is considered to have the following meaning:

(1) Several hundred Hz : Use in high capacity equipment
(2) Several kHz : High quality output waveform
(3) 10-20 kHz : Low acoustic noise
(4) Higher : High efficiency (switching power supply)

IGBT (Insulated-Gate Bipolar Transistor) or power MOSFET and other MOS-gated devices are used in category (3) and (4) devices. The forecast after five years is shown in the figure. The operating frequency of opwer devices will be increased in the future to increase equipment efficiency

Fig. 1 Power electronics equipment output capacity and current and forecast operating frequency of power device used



and quality. This is expected to be accompanied by a sudden rise in demand for MOS-gated power devices and advanced, high performance, and smaller devices.

2. POWER MOSFET

Taking advantage of their excellent high speed switching performance, the power MOSFET has already becomes the main power device for switching power supplies and its field of application is spreading. Compared to the bipolar transistor, the power MOSFET features (1) short switching time, (2) low gate driving power, (3) wide safe operating range (ASO), etc. The line-up of Fuji power MOSFET products is shown in *Table 1*. Recent technological topics are discussed below.

2.1 Improvement of basic performance

Power MOSFET are used in switching power supply, fluorescent lamp ballast, and a wide range of other fields. The performances demanded in common are (1) low on-state resistance, (2) high-speed switching, and (3) high ruggedness at abnormal circuit operation.

The annual transition of the product of the on-resistance and effective chip area ($R_{on} \cdot A$) is shown in *Fig. 2*. Lowering of the on-state resistance by technological revolution, centered about microfabrication technology, is especially noticeable with low blocking voltage devices. Trench structure devices, etc. are also being studied as a means of reducing the on-state resistance tremendously. Lowering of the on-state resistance is expected to advance further in the future. Lowering the input capacitance (C_{iss}), especially, the gate-drain (C_{GD}) capacitance, is effective in raising the switching speed. The C_{iss} of leading devices has becomes less than one-half that of the initial devices by optimiza-

Table 1 Fuji power MOSFET product line-up

Series	Features	Application
F-I	Standard series	Switching power supply, fluorescent lamp ballast, etc
F-II	30% t_{off} reduction	
FAP*-II	High ruggedness	
F-III	Logic level device	Battery-powered equipment, automobile, etc.
FAP-III	High ruggedness	
IPS	Intelligent power switch	
F-V	FRED (Fast Recovery Diode) FET	Inverter

*FAP: Fuji Avalanche Proof

Fig. 2 Annual transition of on-state resistance and effective chip area ($R_{on} \cdot A$) product versus power MOSFET blocking voltage (BV_{DSS})

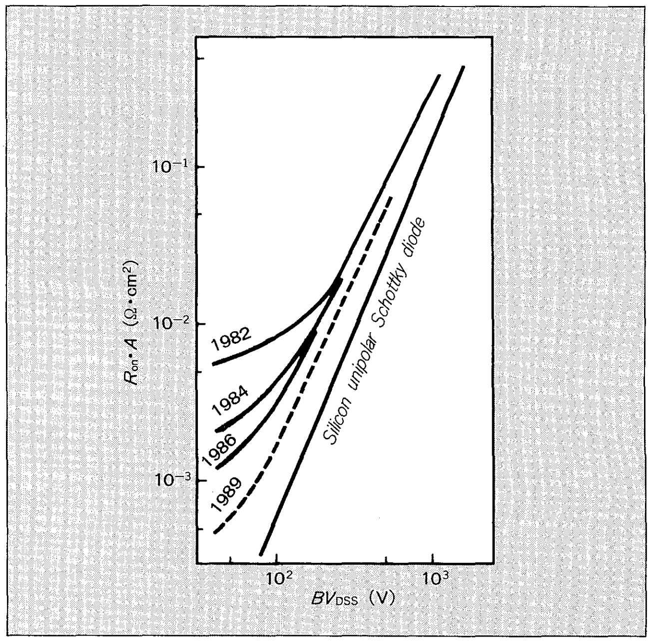
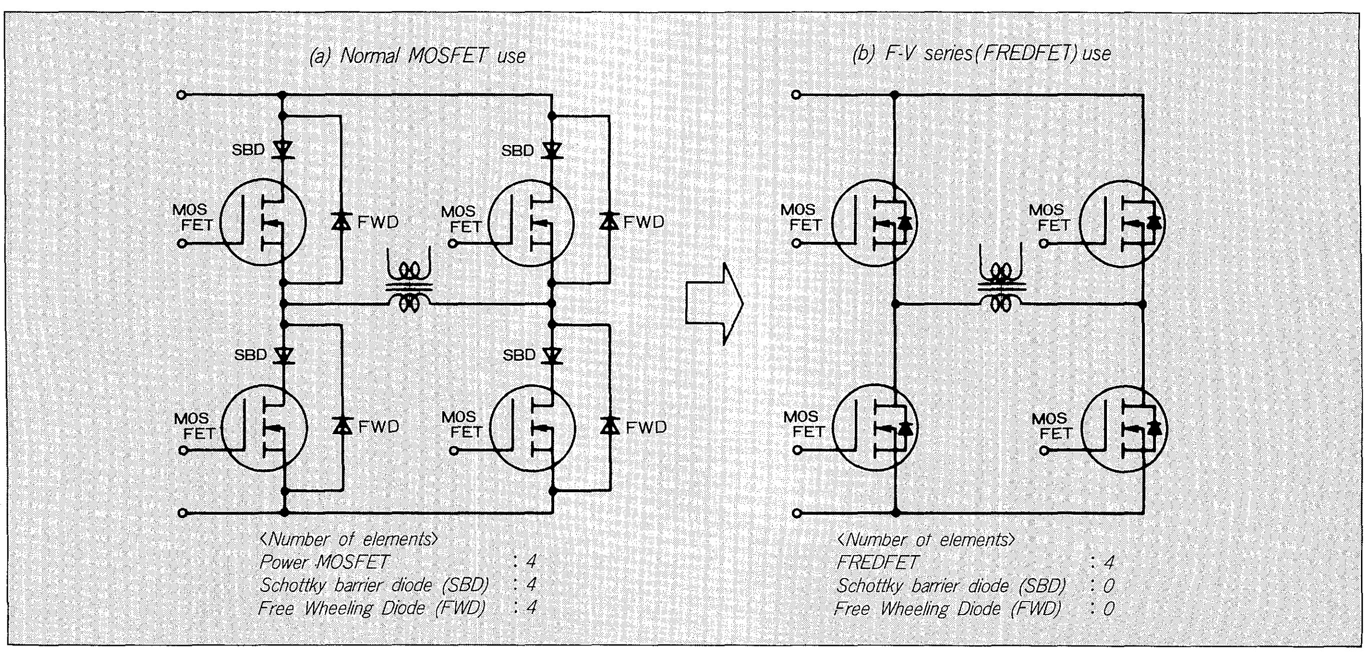


Fig. 3 Motor control circuits



tion of the gate oxide film thickness and optimization of the chip pattern by device simulation technology.

The main failure modes of power MOSFET are caused by (1) gate breakdown by static electricity, (2) counter electromotive force at inductance load, etc. The quality of the gate oxide film was improved as a countermeasure against the former, but a zener diode is also provided between the gate and source. In mode (2), a device that can resist breakdown even when a counterelectromotive force exceeding the maximum rating is applied and the device enters the avalanche region. Fuji Electric has developed and serialized the FAP (Fuji Avalanche Proof) series for these applications.

2.2 Logic level device (F-III)

Logic level devices that can be driven directly by microcomputer or other IC have been commercialized. These are the F-III series of *Table 1.* The normal gate driving voltage of about 10V has been lowered to 4-5V with these devices by reducing the gate film thickness and channel region resistance value control. Their application to battery-powered apparatus, including automobiles, is expanding steadily.

2.3 Devices with built-in free wheeling diode (F-V)

Motor control and similar applications require switching power devices and free wheeling diodes. Theoretically, a diode built-in between the drain and source of a power MOSFET can also be used as a free wheeling diode. However, for conventional devices, diode performance is insufficient and the diode is easily destroyed under actual usage condition. Therefore, it was used with a circuit configuration that killed the built-in diode by using a Schottky-barrier diode (SBD) in addition to a discrete free wheeling diode as shown in *Fig. 3*(a). Recently, a device with built-in free wheeling diode was developed through advances in carrier lifetime control process and device design technology which eliminates current localization during turning-off of the diode. The F-V series is shown in *Table 1.* The circuit configuration can be simplified as shown in *Fig. 3* (b) by using F-V series power MOSFET. Dual packs and six packs power modules using F-V series chips are also available for inverter applications.

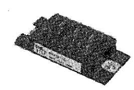
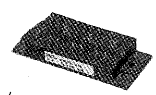
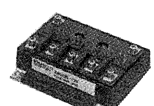
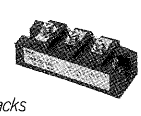
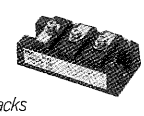
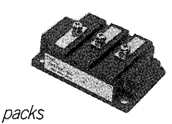
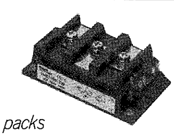
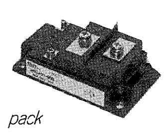
3. IGBT

Power MOSFET have excellent high-speed switching performance. Device with a comparatively low blocking voltage (up to about 300V) have a low on-state voltage. However, because they are unipolar devices, conductivity modulation does not occur and a big disadvantage of high blocking voltage devices is that their on-state voltage is high. Therefore, overall replacement of bipolar transistor (BJT) by power MOSFET is impossible. IGBT, which is a bipolar device with MOS gate, appeared as a device which covers the field of applications not covered by power MOSFET and technological advances are being made rapidly and will soon take over the main role of conventional

Table 2 Fuji IGBT product line-up

Class	Application		Series
Module	Motor control, UPS	~20kHz	Standard series 600V/10~400A 1200V/ 8~300A High-speed switching series (L series) 600V/10~400A 1200V/ 8~300A
		~5kHz	Low on-state voltage series (F series) 600V/10~400A 1200V/ 8~300A
Discrete	Microwave oven, IH cooker		900V/50~60A
	Television, display horizontal deflection circuit		1500V/12A
	Motor control		600V/10~50A 1200V/ 8~25A

Fig. 4 Fuji IGBT module series

Package	*600V series*	*1200V series*
 *Six packs*	10A 15A 20A	8A
 *Six packs*	30A	15A
 *Six packs*	50A 75A 100A	25A 50A
 *Dual packs*	50A 75A 100A	25A 50A
 *Dual packs*	150A	75A
 *Dual packs*	200A	100A
 *Dual packs*	300A	150A
 *Single pack*	400A	200A 300A

switching power devices from BJT. At the present time, the features of the IGBT are:

(1) Gate drive circuit can be simplified (voltage drive)
(2) Higher switching speed than BJT
(3) High blocking voltage an low on-state voltage are available simultaneously

The Fuji Electric IGBT product line-up is shown in *Table 2*. The Spectrum of the discrete and module products are being expanded.

3.1 Module

The Fuji Electric IGBT module series is shown in *Fig. 4*. A full line-up of 600V and 1200V voltage product has been serialized.

The standard series modules called 1st generation IGBT are currently being widely used. Its main application is a low acoustical noise inverter that takes advantage of the high-speed switching performance of the IGBT. PWM (Pulse Width Modulation) control inverters usually use a carrier frequency of 1 to 3 kHz. Since the audible noise can be reduced tremendously by making the carrier frequency 10kHz or higher, some low output low acoustical noise inverters using conventional power MOSFET have been practicalized. The low acoustical noise inverter using an IGBT has become popular through the development and commercialization of the IGBT in recent years.

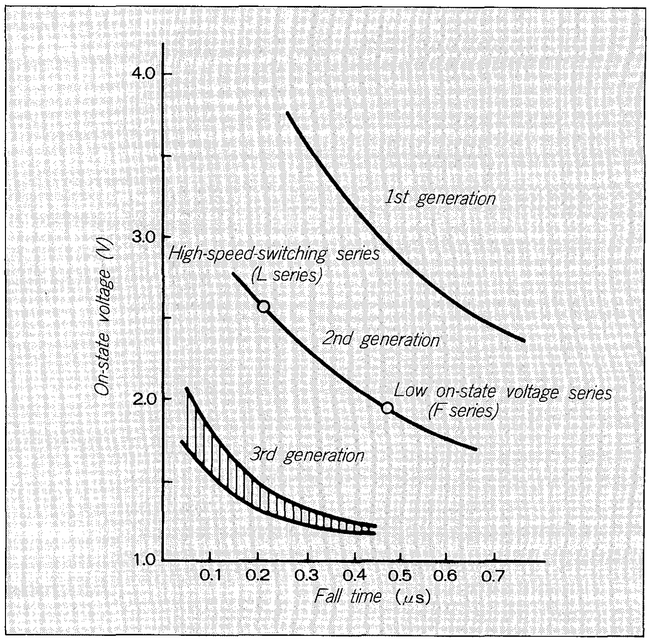
The advance of IGBT technology is amazing and a 3rd generation IGBT module is being developed. *Figure 5* shows the so-called trade off characteristic of the IGBT turn-off fall time (t_f) and on-state voltage ($V_{CE(sat)}$). Fuji Electric has developed (1) microcell use and (2) lifetime control process optimization, and other new technology, in addition to 1st generation IGBT technology, and established 2nd generation IGBT technology that improved the trade-off characteristic tremendously. The following two series have been commercialized as 2nd generation IGBT:

(1) High-speed switching series (L series)
(2) Low on-stage voltage series (F series)

The L series is for low acoustical noise inverter and other high frequency applications and features high-speed switching performance. On the other hand, the F series has a much better on-state voltage than the 1st generation standard series. It features voltage drive and low power loss and was developed with the fields in which the BJT is currently used as the target. Both the L and F series are based on the same 2nd generation technology with the design point changed. Therefore, when there were new market needs, we want to point out that design can be performed freely even with the series centered about any point on the curve of *Fig. 5* that represents 2nd generation technology.

The appearance of a 3rd generation IGBT is expected in the future. The performance target of the 3rd generation IGBT should be a leap from the 2nd generation. Performances that cannot be realized in the near future are meaningless. *Figure 5* shows the tradeoff characteristic of the 3rd generation IGBT with a width. To realize a 3rd generation IGBT, development of farther breakthrough technology is indispensable.

Fig. 5 Improvement of on-stage voltage and fall time trade off of IGBT



3.2 Discrete device

Development of TO-3P, TO-3PL, and other molded package type IGBT is progressing and the development of devices for the various applications shown in *Table 2* is being completed. a typical type is the IGBT for inverter microwave oven and about three years have passed since mass production was started. Increasing the frequency of the horizontal deflection circuit is being planned to increase television and display screen quality. In the past, a BJT was used as the horizontal deflection device, but Fuji Electric performed this development based on the idea that the IGBT is the optimum device for a high frequency horizontal deflection circuit. Especially, the applicability of the IGBT which can ignore the delay time to an autoscan circuit was confirmed. In addition, serialization for medium capacity motor control applications is advancing.

4. INTELLIGENT DEVICE

Today, intelligent power devices is a clear technological trend. The intelligent power switch (IPS), which integrates self-protection function, diagnosis function, etc. IC circuit on a power MOSFET with a blocking voltage under 100V is reaching the practicalization region in the automotive electric parts and other fields.

Announcement of high blocking voltage single-chip intelligent power devices integrating a control function in an IGBT is becoming steadily active. Realization of inexpensive isolation technology is becoming the most important technological topic and its development is progressing. Economical high blocking voltage products are expected to appear in the near future.

BJT type intelligent power modules (IPM) for inverter application were practicalized first. The IPM integrates the drive circuit, self-protection function, diagnosis function, etc. in the same module for the conventional three-phase power module and is being received widely by the market because the system engineer design time can be effectively shortened. Recently, development and commercialization of IMP using IGBT capable of higher speed switching has progressed.

5. FUTURE TREND

As mentioned by Professor Baliga at the Foreward, the realization of MOS-gated power devices is contributing substantially to improvement of the efficiency and reduction of the size and weight of power electronics systems. The impact of IGBT is especially strong. It is predicted that the IGBT will replace the BJT completely with the shift from the 2nd generation to the 3rd generation and tremendous improvement of device performance. In the next several years, technological development for realization of a 3rd generation IGBT will be one highlight. Intelligent power devices based on the IGBT will become an important development topic. It is forecast that practicalization of 600V and 1200V class blocking voltage single-chip intelligent power devices will take several years. They will have a large effect on simplification and miniaturization of the construction of the applied equipments.

High capacity MOS-gated power devices for high output capacity equipments are desired by the market. GTO with a rating of several thousand kA and several thousand kV are used in high capacity, inverter for traction and industrial use. However, a large capacity gate driving circuit (power) is necessary in GTO control. If a large capacity voltage drive type MOS-gated thyristor is developed, a noticeable affect in reducing the size, weight, energy, and price of equipment will be possible. However, technology for manufacturing large area MOS type devices cannot be developed in very short time. Development of technology for repair of faulty parts is also necessary. We will continue our efforts in many branches aimed at practicalization of large capacity MOS-gated devices.