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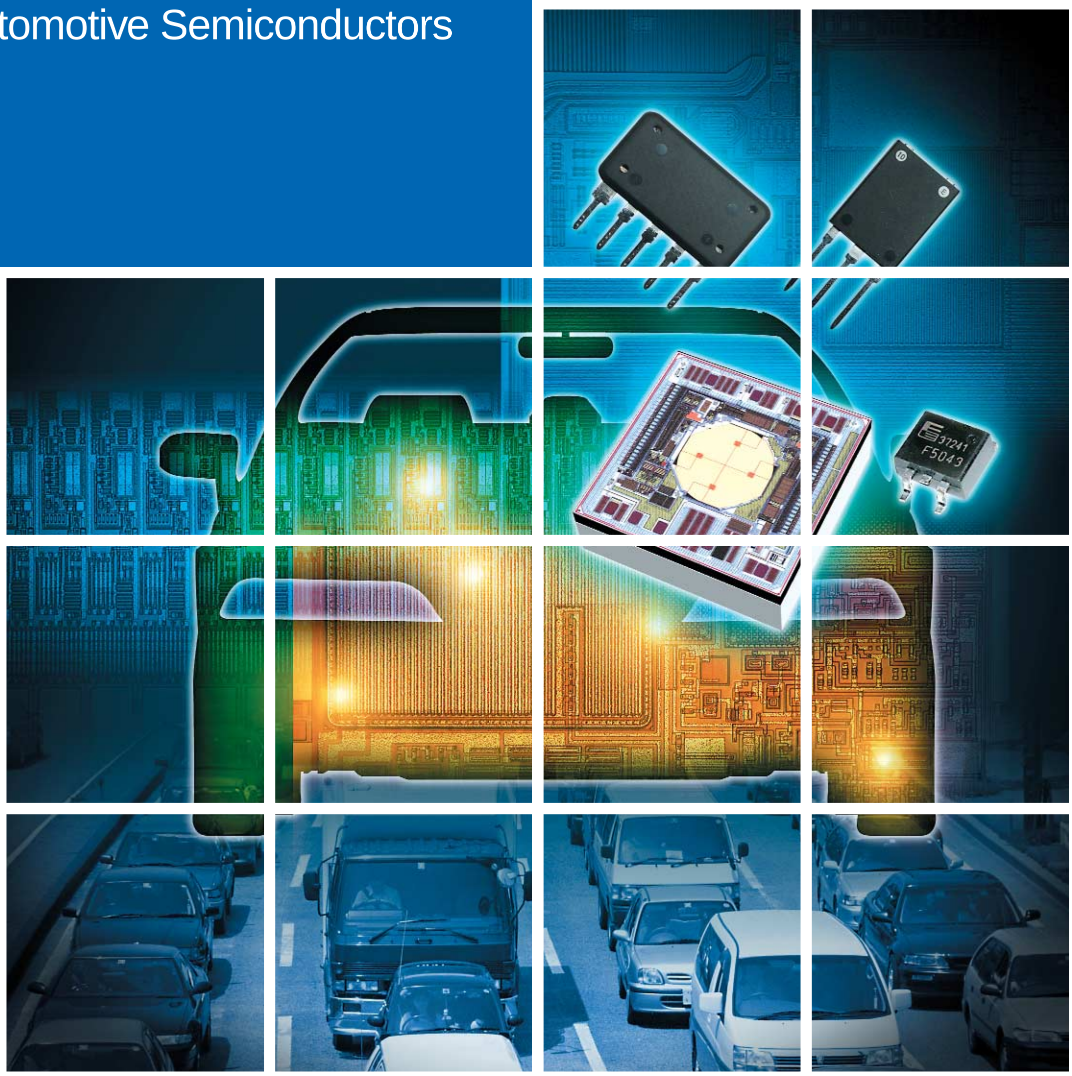
e-Front runners

FUJI ELECTRIC REVIEW

2

2004 VOL.50

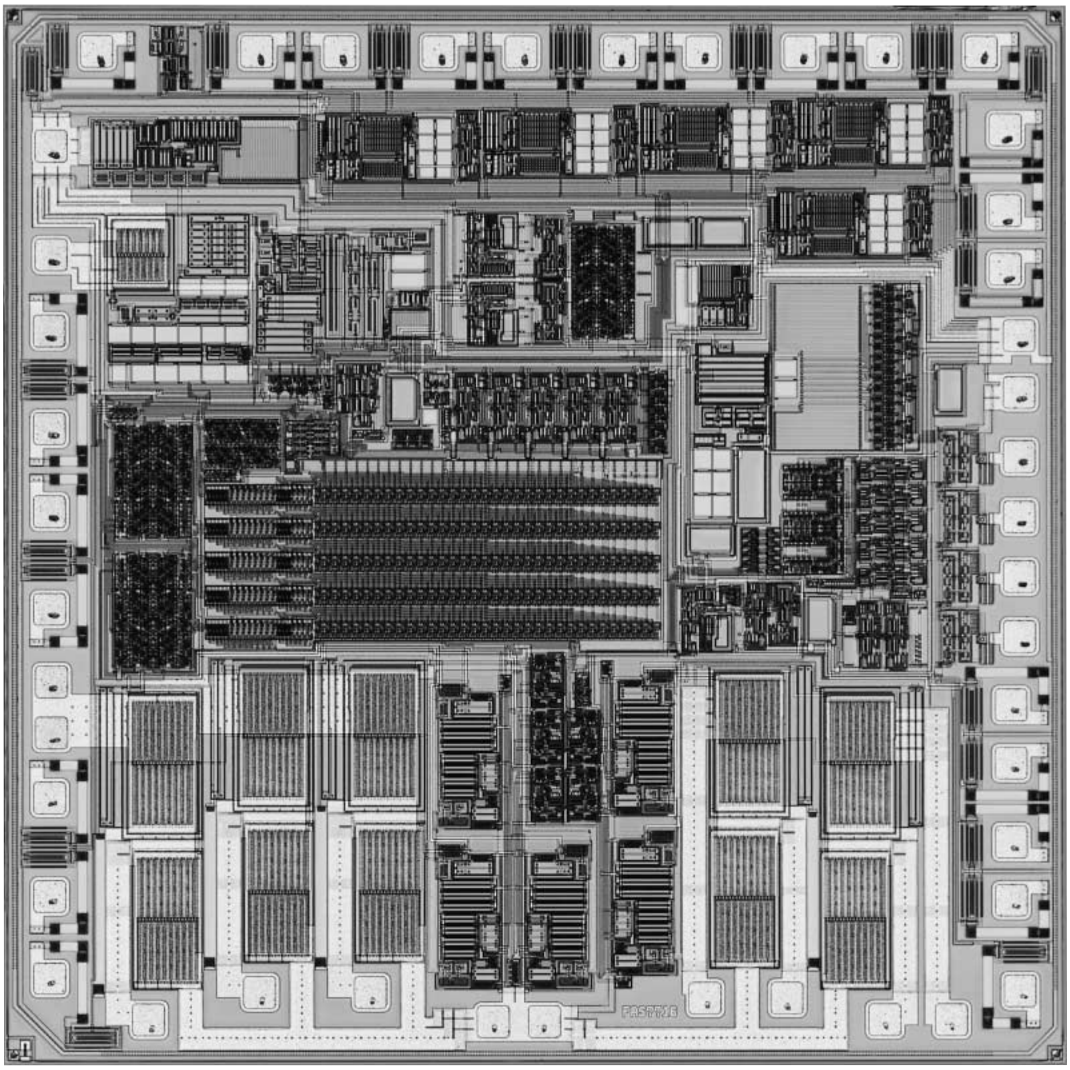
Automotive Semiconductors



Fuji Electric Group

Fuji Electric Power Supply ICs
Providing Multiple Solutions for Multiple Requirements

e-Front runners

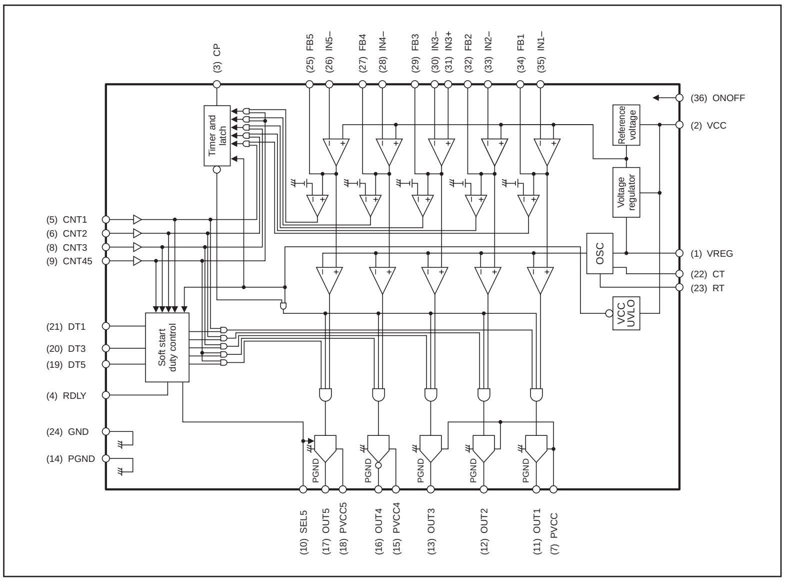


Energy-saving Power Management Realized with a Single Chip

Examples: 1-channel FA7700V, FA7701V, FA7702P
2-channel FA3686V, FA3687V, FA7703V, FA7704V, FA7715J
3-channel FA7711V
5-channel FA7708R, FA7716R
6-channel FA3675F, FA3676F, FA7709R

Uses: Power supplies for TFT panels, car audio systems, car navigation systems, etc.

Features:
- The single chip solution integrating power transistors and control circuits by C/DMOS process capable of built-in low on-resistance DMOS output transistors.
- Low power consumption by CMOS analog circuits.
- Wide range of applications for various power supply configurations such as synchronous rectification, switching polarity of drive transistors, etc.
- Various protection functions against overcurrent, overheat, short circuits, etc.
- Wide variety of packages meeting demands for smaller and thinner size. TSSOP-8, TSSOP-16, TSSOP-24, SON-16, QFN-36, VQFN-48, LQFP-48, etc.



Example block diagram of FA7716R

Fuji Electric Power ICs for Power Supply Applications

Quality is our message

FUJI ELECTRIC
REVIEW

2

2004 VOL.50

Automotive Semiconductors

CONTENTS

Cover photo:

Advances in electronics technology have led to remarkable improvements in the higher energy efficiency, reduced emissions of environmental pollutants, and increased safety, comfort and convenience of automobiles. The use of electronics technology in automobiles is expected to increase in the future.

Semiconductors such as sensors, microcomputers, memory, system LSI chips, analog ICs, power ICs and power devices are a core technology of car electronics. In response to requirements based on the severe environments in which they are used and safety, these devices must be high reliable.

Drawing on its distinctive power electronics-based technology, Fuji Electric has supplied outstanding high-reliability semiconductor products to many sectors of the automotive industry.

The cover photo shows several of Fuji Electric's representative automotive semiconductor products juxtaposed against the silhouette of an automobile as a representation of the progress in car electronics technology.

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Present Status and Future Prospects of Fuji Electric's Automotive Semiconductors

Tatsuhiko Fujihira
Masaru Okumura

1. Introduction

Advanced by such powerful driving forces as initiatives to increase energy efficiency and reduce emissions in order to protect the global environment and user requirements for greater safety, comfort and convenience, electronics applications in automobiles have increased rapidly since the 1970s. Accordingly, there has been a dramatic increase in the types of semiconductors used in automobiles and their applications, and the usage of semiconductors per automobile has also continued to increase.

While increasing the usage of semiconductors, it is important that a low failure rate, spacious headroom and legroom, light weight, and low cost be maintained for the automobile as a whole. For this reason, higher reliability (lower failure rate), smaller size (smaller volume, smaller footprint and lighter weight) and lower cost are strongly required of automotive semiconductor products.

In response to requests from automobile manufacturers and automotive electrical equipment manufacturers, and to contribute to the higher energy efficiency, lower emissions, and enhanced safety, comfort and convenience of automobiles, Fuji Electric has developed and supplied many distinctive automotive semiconductor products and endeavored to realize greater reliability, smaller size and lower cost of those products.

Table 1 lists the automotive semiconductor products that Fuji Electric presently supplies or plans to supply in the future and their applications

For engine systems, Fuji Electric is presently supplying pressure sensors for manifold air pressure measurement and atmospheric pressure compensation, smart IGBTs and hybrid ICs as igniters for the ignition sub-system, high-voltage diodes to prevent premature ignition, MOSFETs for fuel injection-use and so on. In the future, Fuji Electric plans to supply smart MOSFETs and hybrid ICs for fuel injection-use, MOS-IPMs (intelligent power modules) for motors and generators, IGBT-IPMs for driving the motors of hybrid vehicles, integrated power ICs for use in electronic throttle valve control, in integrated control sub-systems and in electronic control unit (ECU) power supplies, etc.

For chassis systems, Fuji Electric is presently supplying diodes, MOSFETs and smart MOSFETs for such applications as transmission control, traction control, brake control, suspension control, and power steering sub-systems in which the use of electronic control technology has advanced. Fuji Electric's future plans are to supply integrated power ICs for relatively low current applications, hybrid ICs and IPMs for relatively high current applications, and pressure sensors for oil pressure measurement.

As for body systems, Fuji Electric's MOSFETs and diodes are being used in power window, power lock, automated mirror, windshield wiper and other sub-systems.

For other systems, Fuji Electric is providing diodes, MOS FETs, smart MOSFETs and the like for air conditioner, dome lamp, air bag, other lamps and ECU power supply sub-systems. In the future, Fuji Electric plans to supply power modules and pressure sensors for car air conditioner applications, an 80 V class of smart MOS FETs for dome lamp applications, and integrated power ICs for various other applications.

This paper will describe the current status and technological trends of Fuji Electric's representative automotive semiconductor products and then will discuss the future outlook for those products.

2. Automotive Diodes

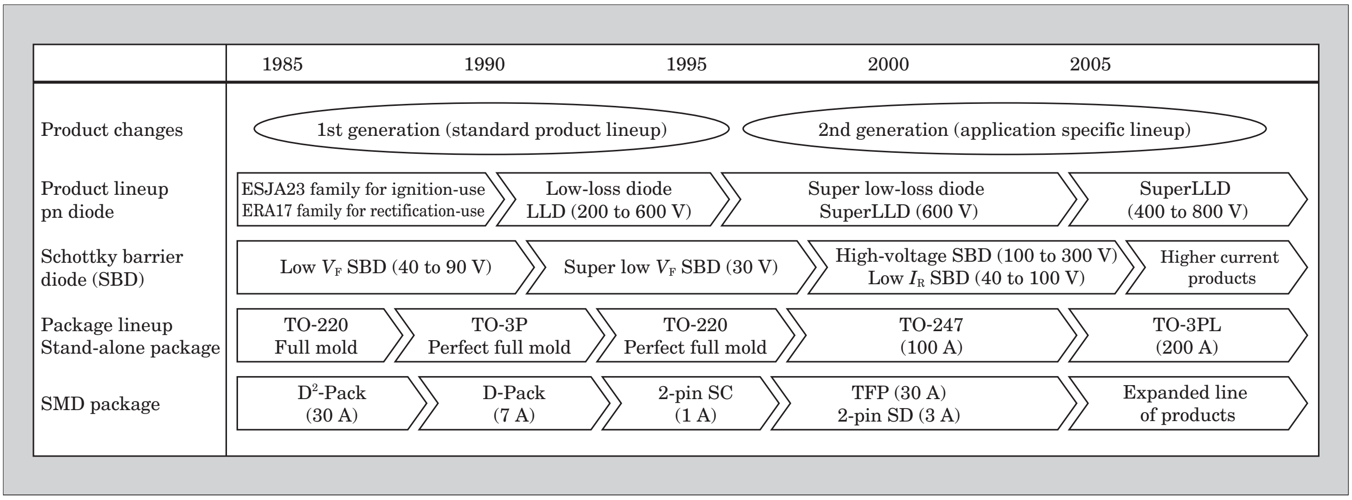
Fuji Electric's diodes are characterized by high reliability and low loss, and our product line has been expanded to include smaller size diodes for a wide range of automotive applications.

Figure 1 shows the roadmap of Fuji Electric's automotive diodes. Product development through 1997 was focused on supporting a wide range of applications and Fuji Electric's standard line of products included the ESJA23 family for ignition-use, the ERA17 family for rectification-use, low-loss diodes (LLDs), Schottky barrier diodes (SBDs) and so on. As of 1998, however, development pursued the goal of supplying application specific products having characteristics tailored for

Table 1 Fuji Electric's automotive semiconductor products and their applications

System	Sub-system	Diode	Power MOSFET	Smart MOSFET	Smart IGBT, IGBT, BJT	Power IC	Hybrid IC	IPM, Power module	Pressure sensor
Engine	Engine control	○		○		○			○
	Ignition	○			○		○		
	Electronic fuel injection		○	○			○		
	Electronic throttle valve control					○			
	Motor and generator		○				○	○	
	Motor drive for hybrid electric vehicle							○	
Chassis	Electronic transmission control	○	○	○		○			○
	Traction control	○	○	○		○			○
	Anti-lock braking	○	○	○		○			○
	Electronic suspension	○	○	○		○			
	Electronic power steering		○	○			○	○	
Body	Power window		○						
	Power lock		○						
	Automated mirror	○	○						
	Windshield wiper		○						
Others	Air conditioning	○	○		○			○	○
	Dome lamp	○	○	○					
	Air bag		○	○					
	Headlight	○	○						
	Flasher lamp		○	○					
	Instrument panel lights			○		○			
	Power supply for ECUs	○	○			○			

Fig.1 Roadmap of Fuji Electric's automotive diodes



specified applications. Such application specific products included super low-loss diodes (super LLDs) and high voltage SBDs for DC-DC converters used in vehicles having multiple power supply lines such as hybrid vehicles, low reverse leakage current (low I_R) SBDs for applications requiring lower standby current and higher temperature environments and the like. The package lineup was also newly expanded to include the TO-247 package for higher current applications and the smaller and thinner 2-pin SC and 2-pin SD SMD packages, in addition to the standard axial-lead packages, the standard stand-alone TO packages (including full mold products) and SMDs (surface mounted devices).

3. Automotive Power MOSFETs

Benefiting from device technology innovation, typi-

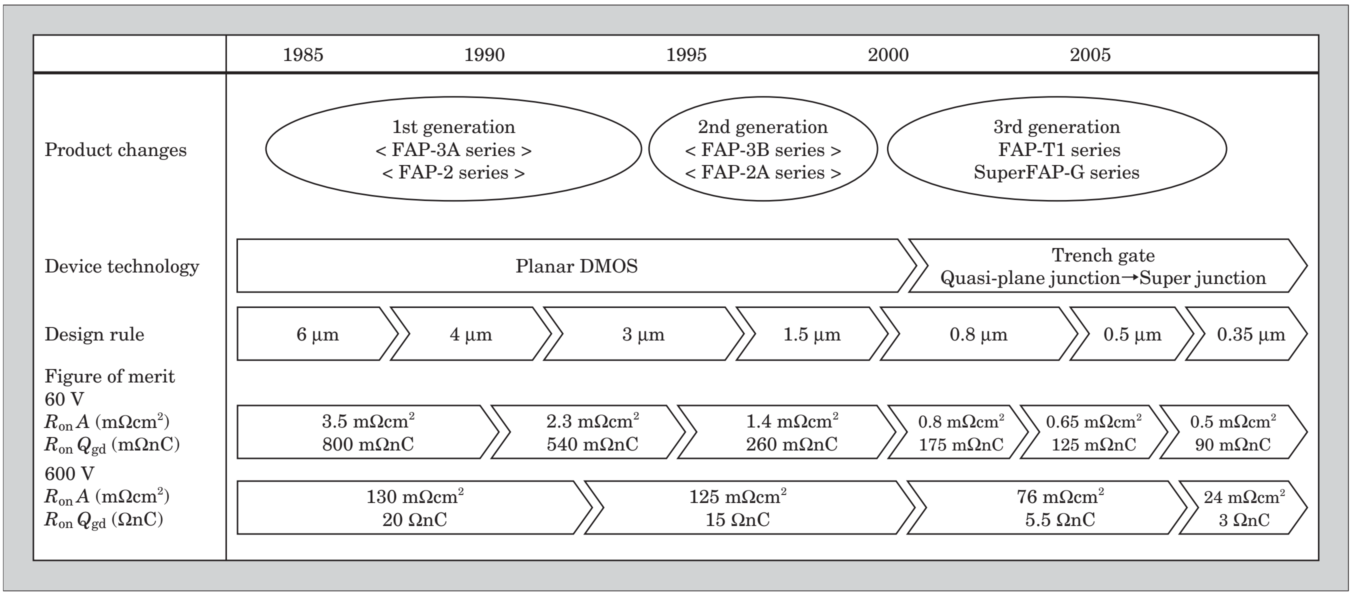


Fig.2 Roadmap of Fuji Electric's automotive power MOSFETs

fied by trench-gate MOSFETs[(1)], quasi-plane junction MOSFETs[(2)] and super junction MOSFETs[(3)], and the unrelenting progress in semiconductor process technology as symbolized by shrinking design rules, there is no end in sight to the performance improvements for power MOSFETs.

Figure 2 shows the roadmap of Fuji Electric's automotive power MOSFETs. In contrast to the product development of diodes, which focused mainly on augmenting and expanding the line of application specific products, product development for power MOS FETs is a cyclic process in which previous generation products are repeatedly replaced by higher performance products of the next generation. From this trend, the dramatic rate of technological progress can be understood.

For low-voltage power MOSFETs, which are used in many applications such as power steering and air conditioning and whose range of applications is expected to expand in the future to include motors, generators and the like, the introduction of trench gate technology and the shrinking of design rules has achieved a reduction in specific ON-resistance to 0.8 mΩcm^2 in the case of 60 V mass-produced products, and to 0.5 mΩcm^2 in engineering samples. An approximate 40 to 50 % decrease in ON-resistance every 4 to 5 years has been an ongoing trend.

Meanwhile, the high-voltage power MOSFET used in such applications as DC-DC converters for hybrid electric vehicles and electronic ballast circuits for high-intensity discharge lamps has been improved in terms of reliability and ruggedness, but efforts to improve its performance have remained at an impasse for the past 10 years or so. The recently released SuperFAP-G series, however, uses the quasi-plane junction technology to realize an approximate 40 % decrease in specific ON-resistance and an approximate 50 % reduction in switching time.

In the low-voltage range, finer line widths of trench-gate MOSFETs and in the high-voltage range, super-junction MOSFET technology, are expected to bring about future improvements to the performance of power MOSFETs.

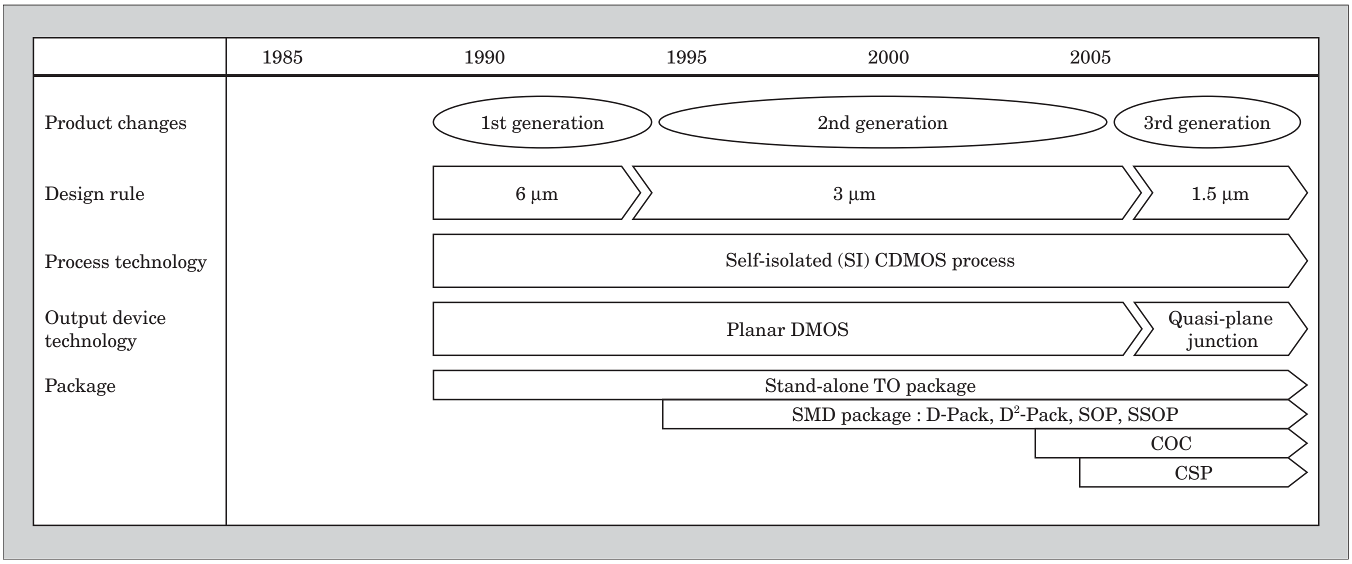
4. Automotive Smart MOSFETs

In the 1980s, power MOSFETs began to be used in automotive ECUs and the breakdown of power MOS FETs was scrutinized as one cause of ECU failure. The cause of breakdown was thought to be due to an excessive rise in temperature or the like brought about by such abnormal conditions as over-current caused by a short-circuit to the supply-line or ground in the lines leading from the outputs to the loads of the ECU, over-voltage caused by a load dump surge or the like, or a problem with the control software, and consequently it was requested that the power MOSFET be protected so as not to breakdown when these type of abnormal conditions occur. The smart MOSFET, a power MOSFET provided with built-in over-current, over-voltage and over-temperature protection functions, was developed in the latter half of the 1980s in response to this request.

Fuji Electric has responded by providing two lines of products, a low-cost smart MOSFET that is integrated with protection functions only, and an IPS (intelligent power switch) that is integrated with not only protection functions but also a power MOSFET drive circuit and diagnostic functions that are capable of detecting load abnormalities and notifying a microcomputer.

Figure 3 shows the roadmap of Fuji Electric's automotive smart MOSFETs. The process technology has consistently used a self-isolated CDMOS (comple-

Fig.3 Roadmap of Fuji Electric's automotive smart MOSFETs



mentary and double-diffused MOS) process, and the use of vertical power MOSFET in the output stage provides the characteristics of low ON-resistance and high ruggedness. The self-isolated CDMOS process is also advantageous in that enables lower cost manufacturing than the junction-isolation process used by many other companies.

Smart MOSFETs have been used widely in automotive applications ever since the 1990s, and with their increased usage per automobile, demands have grown stronger for smart MOSFETs that are smaller in size. In the future, low-current smart MOSFETs will trend toward using an integrated power IC process to integrate multiple channels into a single chip and to achieve smaller size, and smart MOSFETs themselves will become capable of handling higher voltage and higher current applications, but will require miniaturization for those applications. Fuji Electric plans to respond to these needs by advancing the development of 80 V products for applications that do not have a power Zener diode, chip-on-chip (COC) technology for high current applications, chip-size packages (CSPs) for achieving smaller size, and a 3rd generation process that provides the output MOSFET with a quasi-plane junction for achieving a smaller size chip.

5. Automotive Igniters

Electronic engine control and the increasing sophistication of that technology are said to have been the largest factors contributing to the higher fuel efficiency and lower emissions of automobiles since 1970. The precise control of air intake quantity, fuel injection timing and quantity, ignition timing and energy has enabled the realization of combustion closer to the ideal and has achieved improved fuel efficiency and lower emissions. The igniter is a key component that supplies electrical energy for ignition via an ignition coil to the ignition plug.

Fuji Electric has been supplying transistors for igniters ever since the first half of the 1970s when igniters initially began to be provided with transistors. In 1978, Fuji succeeded in mass-producing an ignition hybrid IC that used thick-film circuit technology to integrate an igniter-use transistor and control power IC. Then in 1998, using self-isolated CDMOS process technology to integrate an ignition IGBT and control circuit into single chip, Fuji Electric began to mass-produce the world's only single-chip igniter with IGBT output.

Figure 4 shows the roadmap of Fuji Electric's single-chip igniter. The single-chip igniter is characterized by small size, high reliability and low cost and Fuji Electric has provided single-chip igniter products containing built-in current-limiting, voltage-clamping and waveform smoothing functions. In 2003, Fuji Electric began mass production of a new product containing a built-in function for over-temperature protection.

Most igniters of today are built-in to the ignition coil and attached directly to the engine. High surge-absorption capability, high reliability as typified by thermal cycling ruggedness, and high noise immunity such as immunity to EMI (electro-magnetic interruption) are required. Fuji Electric intends to use its accumulated technology and know-how to satisfy these requests while promoting the next generation process for more sophisticated single-chip igniters and working to make igniters smaller in size and at lower cost.

6. Automotive Pressure Sensors

The importance of engine control for improving fuel efficiency and reducing emissions has been discussed above, but pressure sensors are also critical for realizing those objectives and are an indispensable

Fig.4 Roadmap of Fuji Electric's single-chip igniter

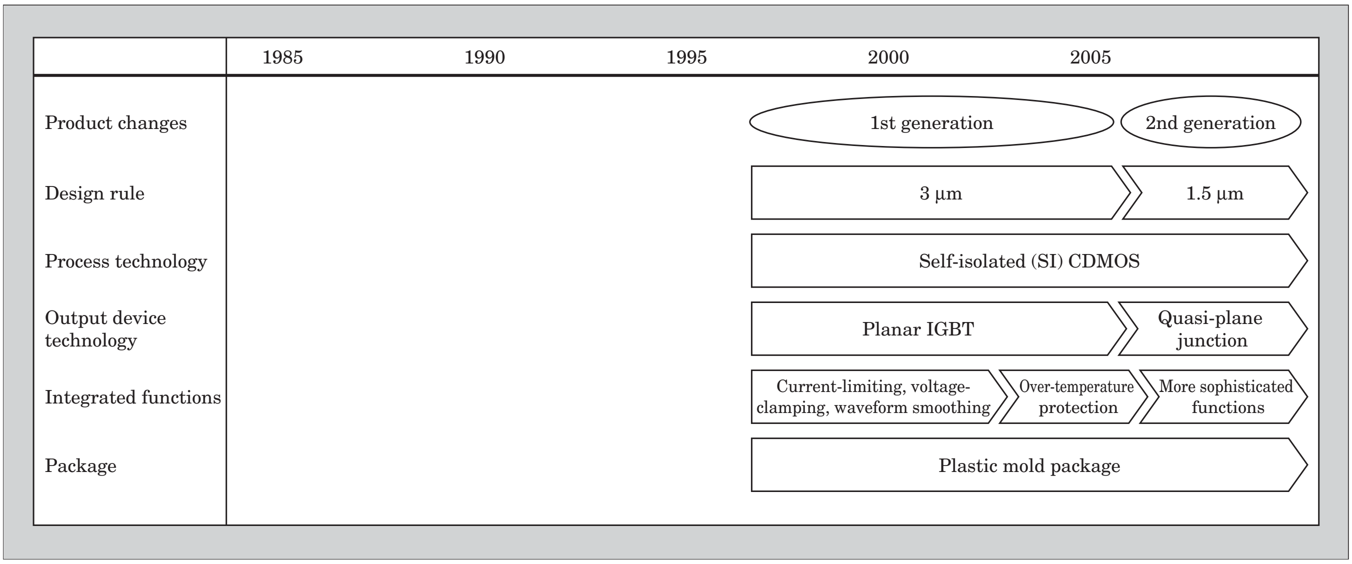
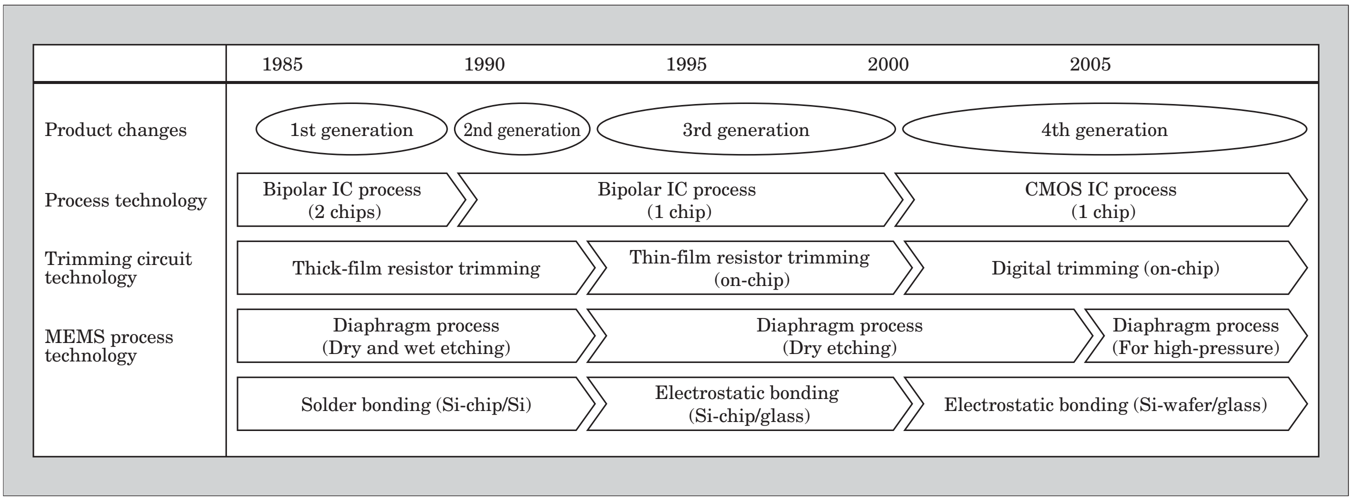


Fig.5 Roadmap of Fuji Electric's pressure sensors



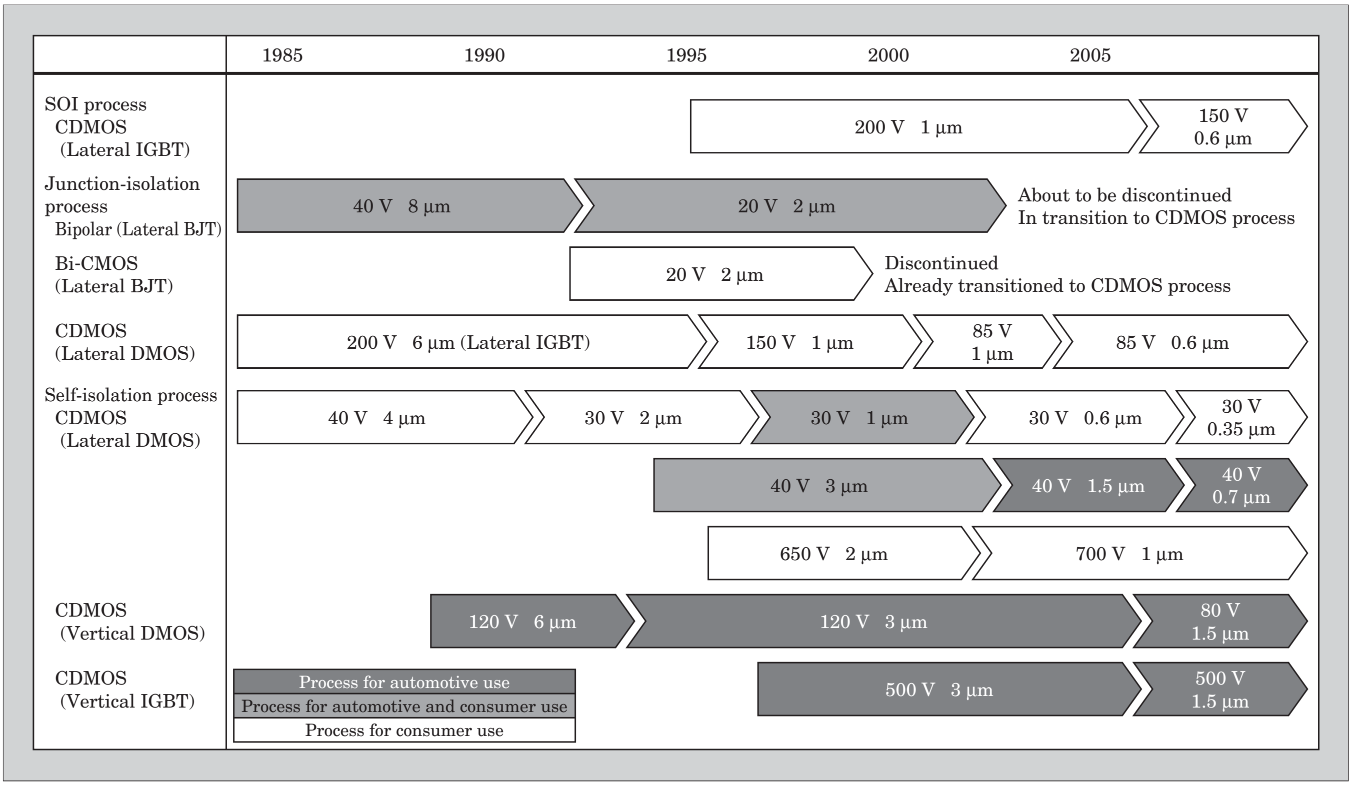
semiconductor component for precisely controlling the amount of air intake.

In 1984, Fuji Electric began to supply pressure sensors for engine control applications as mass-produced silicon diaphragm type sensors that used the piezo effect of a resistor. Because they are installed in environments of harsh temperature, heat, magnetic noise and the like, automotive pressure sensors are required to be highly reliable (and to retain their accuracy).

As can be seen from the pressure sensor roadmap of Fig. 5, Fuji Electric has addressed these requirements by promoting the development and improvement of high-precision concave processing technology, technology for adjusting temperature dependence and amplification linearity, sensor structures highly resistant to static electricity and magnetic noise, protection devices and the like. Moreover, in response to requests for lower cost, technology such as plastic-mold packages for replacing high-cost can packages, technology for integrating the sensor and adjustment circuitry and the like onto a single chip, and digital trimming technology that utilizes an EPROM (electrically programmable ROM) instead of the thin-film trimming method have been developed and applied to commercial products.

The 4th generation pressure sensor, which has been mass produced since 2002, integrates a pressure transducer gauge resistor, CMOS amplifier circuit, digital adjusting circuit, EMI filter, surge protection device and the like into a single chip that is housed in a compact plastic mold package and achieves higher precision and twice the EMI immunity as 3rd generation products. Moreover, in the prior manufacturing method, a stress relaxation glass chip was bonded individually to each sensor chip, but Fuji Electric has developed and applied a technology for bonding electrostatically a glass plate directly to the "wafer-size" 6-inch silicon wafer on which ICs are fabricated and the application of this technology enables products to be

Fig.6 Roadmap of Fuji Electric's power IC process



made with smaller size, lighter weight, higher precision, higher reliability and lower cost.

At present, Fuji Electric is mass-producing automotive pressure sensors for use in engine control and motorcycle EFI (electronic fuel injection) systems. In addition to these low-pressure applications, 4th generation pressure sensor technology will be capable of expanding its range of applications to include high-pressure applications as well. In the future, Fuji Electric plans to apply high-pressure diaphragm technology, for which development has been completed, in order to provide a single-chip pressure sensor solution for such high-pressure applications as air conditioners, CVTs (continuously variable transmissions), brake oil pressure systems and the like.

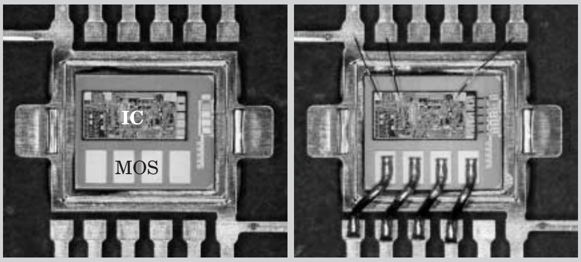
7. Future Outlook

The present status and trends of Fuji Electric's automotive semiconductor products have been discussed above. Awareness of the importance of protecting the global environment and requests for safety, comfort and convenience have increased year-by-year, and accordingly, the use of electronic components and systems in automobiles is expected to continue to accelerate. As the rate of semiconductor usage per automobile increases further, higher reliability, smaller size and lower price are requested of those automotive semiconductor products. Fuji Electric is moving steadily to develop technology that complies with those requests.

Figure 6 shows the roadmap of Fuji Electric's power IC process. As an overall trend, due to improvements in CMOS analog precision and operation frequency and in DMOS current drive capability, bipolar and Bi-CMOS processes have been discontinued and production is now concentrated on CDMOS process technology. The three isolation processes of an SOI (silicon on insulator) process for high-voltage multi-channel applications, a junction-isolation process for medium-voltage multi-channel applications, and a self-isolation process for low-voltage multi-channel and high-voltage single-channel applications will be retained and used selectively according to the application.

One recent focus of automotive processes is a 40 V 1.5 μm self-isolated CDMOS process (having a lateral MOS output stage), which is an integrated power IC process for achieving smaller size of the ever-increasing power switch and peripheral circuitry by integrating multiple channels of low-current circuitry into a single chip. This 40 V 1.5 μm self-isolated CDMOS process is still in the start-up stage but mass production is slated to begin in 2004. The CDMOS process will become Fuji Electric's basic automotive power IC process, and in the future, micro-fabrication techniques will be advanced and established technology will be applied to develop this process into a vertical output self-isolated CDMOS process. One such example is an 80 V 1.5 μm CDMOS process (vertical MOS output) that will contribute to the smaller size and lower ON-resistance of medium-current range smart MOSFETs, and another example is a 500 V 1.5 μm CDMOS

Fig.7 Internal view of chip-on-chip high-current smart MOSFET



After die bonding of the MOS and IC — After bonding of 300 μm and 50 μm aluminum wire

process (vertical IGBT output) that will contribute to the higher performance of single-chip igniters.

In order to provide smart functionality to lower the failure rate of high-current power MOSFETs and to eliminate failures by using semiconductor-based relays, Fuji Electric is endeavoring to advance the development of COC smart MOSFET technology, an example of which is shown in Fig. 7, and plans to commercialize this technology in 2004. A 40 V 1.5 μm CDMOS process is used to fabricate a control power IC on top of a low ON-resistance trench-gate MOSFET chip at the output stage, and the MOSFET and IC are connected by aluminum wire bonding to realize both small size and high reliability. Because these devices will be replaced by 2nd generation trench-gate MOSFET chips in the future, even lower ON-resistance and larger current capacity will be achieved.

Fuji Electric is also advancing the development of automotive IPMs for even larger current applications, which are mainly for the motor drive system of hybrid electric vehicles and fuel cell electric vehicles. By leveraging Fuji Electric's world-leading IGBT chip technology and industrial IPM technology, and by developing and adding new technology such as solder bonding technology, DCB (direct copper bonding) substrate technology, circuit technology for imbedding more sophisticated functions and the like to realize high reliability at a low cost as required for automotive applications, Fuji Electric plans to begin mass production of automotive IPMs in 2005.

For automotive pressure sensors, there has been progress in the development of technology for high-pressure applications. Fuji Electric intends to expand its line of products for high-pressure applications and plans to support 2 MPa applications by 2005 and 20 MPa applications by 2008.

Restrictions on the use of hazardous substances that will be enforced in Europe beginning in 2005 are hastening the adoption of measures to counteract environmental problems, and all components and materials used in semiconductor products, except for some high-temperature solder, are required to be lead-free. Fuji Electric is steadily preparing for compliance with this regulation. Our power module products such as IPMs already use lead-free solder below the silicon chip portion of the module, and we plan to complete the transition to lead-free solder in the outer pins, printed circuit board and the DCB substrate by Spring 2005. Discrete products and power IC products in axial-leaded and stand-alone packages have been shipped lead-free since the 1st half of 2003 and SMD discrete products have been shipped lead-free since the 2nd half of 2003. We are preparing to make our hybrid ICs and pressure sensors lead-free compliant as of 2004.

8. Conclusion

Sufficient caution and pre-verification is necessary when using these remarkably innovative semiconductor products in automotive applications. Fuji Electric has maintained the high quality of its designs by adopting a cross-functional team approach to its design and control procedure, in which both the quality assurance and production departments participate from the initial design stage in order to work toward a good quality design that is easy to manufacture while maintaining an appropriate process capacity, and by using quality-function-deployment, design FMEA (failure mode and effect analysis), process FMEA and other techniques to verify that a design is appropriate for a customer's particular usage environment and usage method. Fuji Electric will continue to provide quality leading-edge products, even for new applications, that satisfy user requirements with reliable technology and management based on careful design verification.

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Automotive Diodes

Taketo Watashima
Shoji Kitamura
Hiroaki Furihata

1. Introduction

Environmental problems and the need to conserve energy are powerful factors that have advanced the development of electric vehicles and hybrid electric vehicles in the automotive field. In particular, because hybrid electric vehicles require only a supply of fuel and do not need special charging equipment (eco-stations), the quantity of production and range of model types of hybrid vehicles have been increasing year-by-year. A hybrid vehicle is equipped with, in addition to an engine, a motor, a high-voltage high-power battery to drive that motor, and a DC-DC converter to convert the voltage from a main battery and to supply that voltage as a low voltage source to conventional electronic autoparts. It is important that DC-DC converters for hybrid electric vehicles have high efficiency, small size and high reliability, and because DC-DC converters that handle large currents are likely to become a source of noise, it is also important that consideration be given to anti-noise capability.

This paper introduces Fuji Electric's high-voltage, low loss and low noise product line of diodes that have been developed for use in DC-DC converters in accordance with the growing use of electronic control units (ECUs) due to the increasing use of electronic components and systems in automobiles, and also introduces a high-voltage highly reliable diode that is being used in distributorless ignition systems (DLIS), an increasingly popular form of electronic ignition systems.

2. High-voltage SBD

2.1 Overview

Fuji Electric's newly developed Schottky barrier diode (SBD) is considered to be the ideal diode for power supply rectification and especially well suited for high voltage output rectification. Low-voltage SBDs (30 V and 45 V) are being used in 3.3 V and 5 V low-voltage output circuits, and high-voltage LLDs (low loss fast recovery diodes) (200 V, 300 V and 400 V) have been used in 12 V and higher high-voltage output circuits. In order to support requests for larger capacity, smaller size and lower noise of 12 V and higher high-voltage outputs, reduction of the generated loss by improvement of the forward voltage (V_F) and reduction of the generated surge voltage and switching noise by improvement of the reverse recovery characteristic are required of diodes used in power supply rectification applications. An analysis of the loss occurring in a 12 V output stage diode in a power supply (250 W) that uses a 200 V LLD reveals that at least 90 % of loss is due to V_F. Moreover, to suppress the surge voltage applied to a diode during switching and to suppress the noise generated by the steep dv/dt characteristic, additional components such as snubber circuits and EMI-suppressing beads have been used, but doing so increases the part count and leads to higher cost.

The LLDs used previously were pn junction diodes and there was a limit to the extent which their V_F could be lowered. Also, there was a general tradeoff relation (reverse correlation) between soft recovery characteristics and V_F, and it was extremely difficult to realize both low V_F and soft recovery. Therefore, in recognition of the low V_F and soft recovery characteristics of SBDs, by using a high-voltage SBD instead of the high-speed pn diode that had conventionally been used in high-voltage output circuits, lower loss and lower noise due to the soft recovery characteristics could be achieved simultaneously. Accordingly, the new high-voltage SBD targeted output stage applications ranging from 12 V to 48 V and, in contrast to the existing high-speed pn diode, was developed to:

(1) ensure lower V_F characteristics,
(2) ensure a soft recovery, and
(3) have a V_{RRM} (or working voltage) of 120 to 250 V.

2.2 Chip design

(1) Chip edge design

Figure 1 shows the structure of a high-voltage SBD chip. The chip edge design utilizes a guard ring process. The breakdown voltage of the device is determined by the resistivity ρ and thickness t of the epitaxial layer (n-layer). Figure 2 shows the dependency of breakdown voltage (V_{BR}) on resistivity ρ and thickness t. Higher resistivity ρ and a greater thickness t of the epitaxial layer were designed to achieve a higher breakdown voltage. Furthermore, the desired working voltage was secured by optimizing the concentration and diffusion depth of the guard ring.

(2) Selection of barrier metal

Based on the considerations of paragraph (1) above, in order to secure a working voltage range of 120 to 250 V, it was necessary to increase the resistivity and to achieve an epitaxial layer thickness of at least 10 µm. Assuming the same type of unipolar operation as a low-voltage SBD, V_F would be expected to become considerably larger than that of a pn diode, however the injection of minority carriers (holes) from Schottky contacts and the guard ring acts to suppress V_F. Below we shall verify how the selection of barrier metal changes the forward characteristics. Figure 3 shows the simulated results of the forward characteristics for three types of barrier metals a, b and c (having barrier heights of a<b<c) fabricated in 40 V, 150 V and 250 V epitaxial layers. For the 150 V and 250 V epitaxial layers, in the region of high current flow, V_F decreased as barrier height increased (and the plotted curves intersected between 0.7 and 0.8 V). Hole injection from the Schottky contacts increased as the resistivity and/or barrier height of the epitaxial layer increased. Figure 4 shows the relation between V_F and I_R (V_F-I_R characteristics obtained by varying the barrier height for each voltage class) based on the results of Fig. 3. The 40 V class exhibits the usual V_F-I_R characteristic tradeoff, but at 150 V and 250 V, V_F decreases as barrier height increases. It is thought that the characteristics at 120 V are similar to those at 150 V. Moreover, in a 250 V SBD, a barrier height of metal b or higher is required to achieve a lower V_F

Fig.1 Cross-section of SBD chip structure

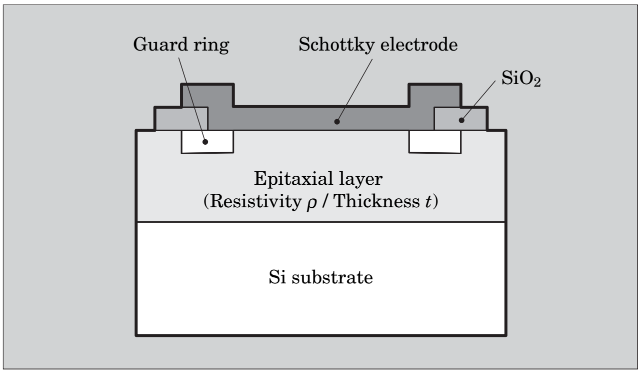


Fig.2 Relation between epitaxial layer thickness and breakdown voltage

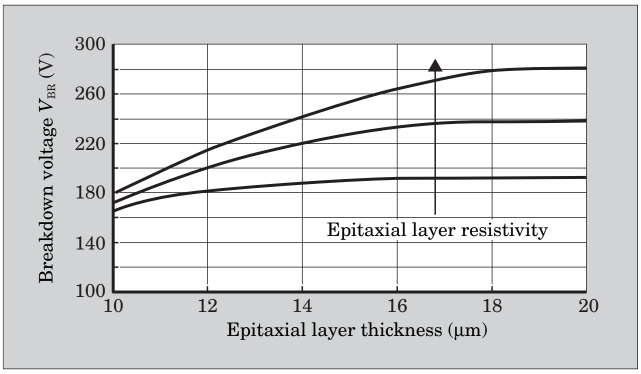


Fig.4 Relation between forward voltage and reverse current

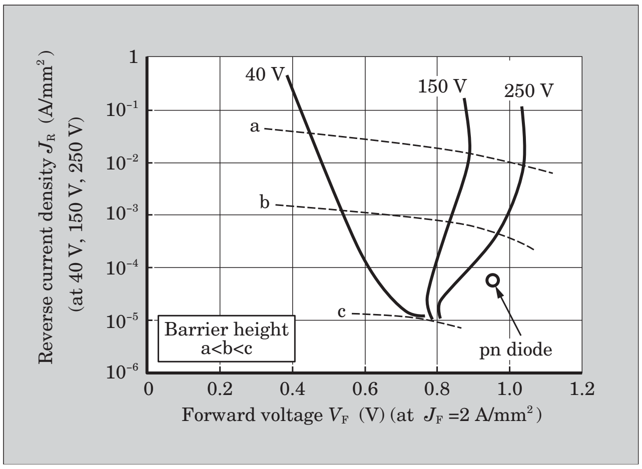


Fig.3 Simulated forward characteristics

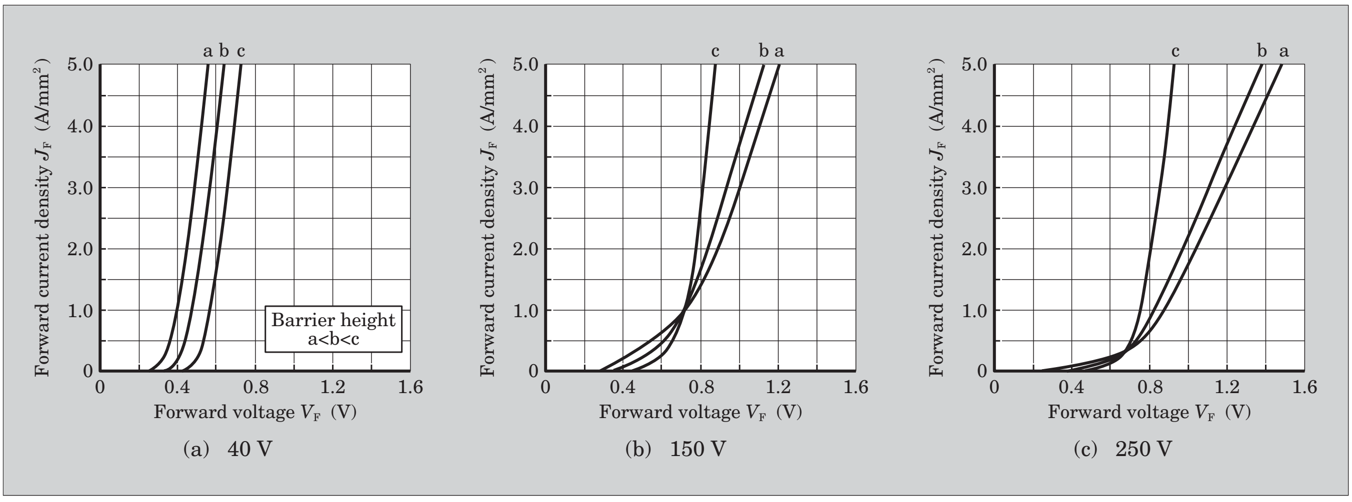


Fig.5 Forward and reverse characteristics of 120 V SBD (trial product)

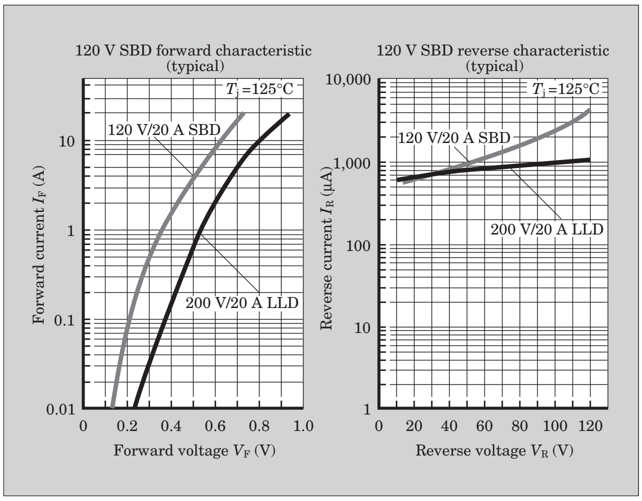
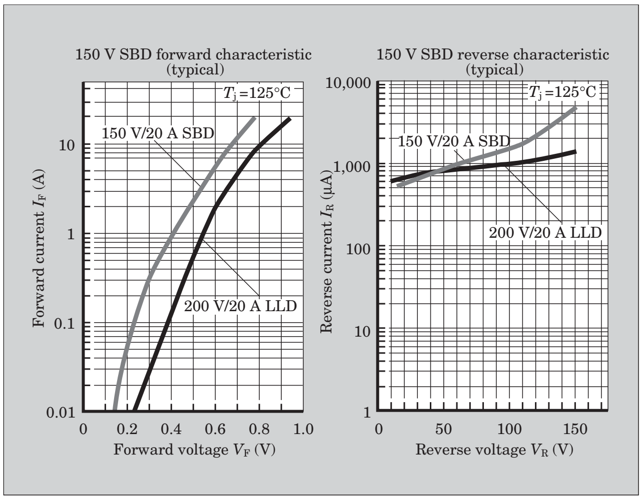


Fig.6 Forward and reverse characteristics of 150 V SBD (trial product)



characteristic than that of a pn diode.

2.3 Electrical characteristics

Based on the above considerations, we manufactured 120 V, 150 V and 250 V SBDs (having a rated current of 10 A). Figure 5 shows the forward and reverse characteristics of the 120 V SBD and Fig. 6 shows the forward and reverse characteristics of the 150 V SBD (where $T_j = 125°C$). Fuji Electric's 200 V LLD is shown for comparison. Both the 120 V and 150 V SBDs have lower V_F than the LLD. The low V_F is particularly noticeable in the low current region. Figure 7 shows a comparison of the reverse characteristics of a 150 V SBD and a 200 V LLD. It can be seen that the SBD has somewhat lower reverse peak current (I_{RP}) and has a softer recovery.

2.4 Actual circuit test results

Figure 8 shows a comparison of the diode waveforms in a 250 W 12 V output power supply test circuit using a 200 V LLD and also in the case of using a 150 V SBD. Figure 8(a) shows the evaluation circuit, and Figs. 8(b) and (c) show the forward waveforms of the diode. It can be seen that the SBD dramatically reduces surge voltage. A comparison of the loss calculated at the secondary-side diode in each of these cases is shown in Fig. 9. The SBD achieves an 18.3 % reduction in loss. 24 V and 48 V power supplies are expected to have similar results and an approximate

Fig.7 Reverse recovery characteristic (trial product)

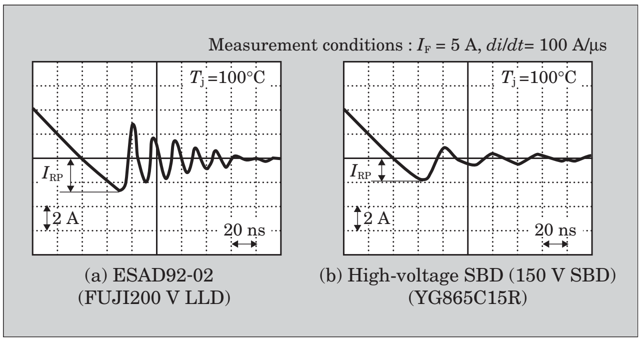


Fig.8 *V* and *I* waveforms of diode operation in 12 V output power supply circuit

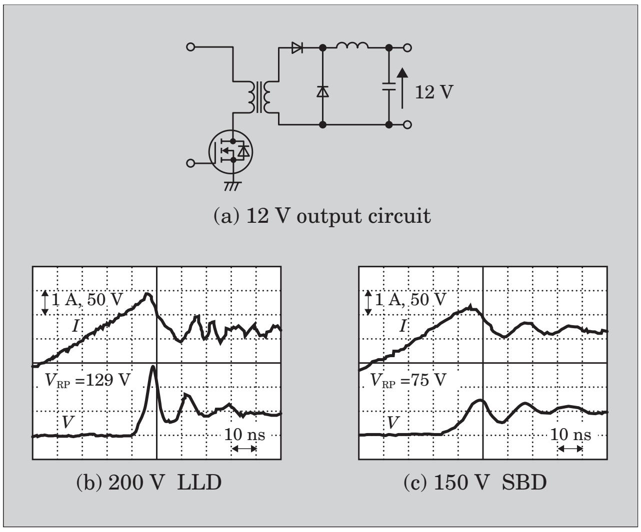


Fig.9 Loss comparison of 12 V output power supply secondary side diodes (simulated results)

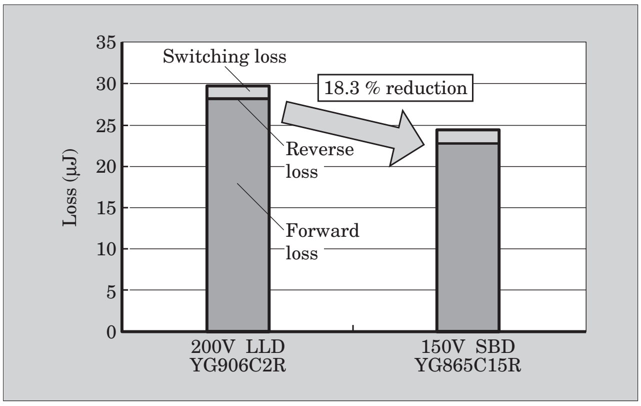


Table 1 High-voltage SBD product line

Model number	Package	Maximum rating			Electrical characteristic	
		V_{RRM} (V)	I_O (A)	I_{FSM} (A)	V_{FM} (V) $I_{FM}=0.5\times I_O$ (T_j = 25°C)	I_{RRM} (μA) $V_R=V_{RRM}$
YA862C12R	TO-220	120	10	75	0.88	150
YG862C12R	TO-220F	120	10	75	0.88	150
TS862C12R	T-Pack	120	10	75	0.88	150
YA865C12R	TO-220	120	20	150	0.88	150
YG865C12R	TO-220F	120	20	150	0.88	150
TS865C12R	T-Pack	120	20	150	0.88	150
YA868C12R	TO-220	120	30	225	0.88	200
YG868C12R	TO-220F	120	30	225	0.88	200
TS868C12R	T-Pack	120	30	225	0.88	200
YA862C15R	TO-220	150	10	75	0.90	150
YG862C15R	TO-220F	150	10	75	0.90	150
TS862C15R	T-Pack	150	10	75	0.90	150
YA865C15R	TO-220	150	20	150	0.90	150
YG865C15R	TO-220F	150	20	150	0.90	150
PH865C15	TO-247	150	20	150	0.90	150
TS865C15R	T-Pack	150	20	150	0.90	150
YA868C15R	TO-220	150	30	225	0.90	200
YG868C15R	TO-220F	150	30	225	0.90	200
PH868C15	TO-247	150	30	225	0.90	200
TS868C15R	T-Pack	150	30	225	0.90	200
YA862C25R	TO-220	250	10	75	1.08	150
YG862C25R	TO-220F	250	10	75	1.08	150
TS862C25R	T-Pack	250	10	75	1.08	150
YA865C25R	TO-220	250	20	150	1.08	150
YG865C25R	TO-220F	250	20	150	1.08	150
PH865C25	TO-247	250	20	150	1.08	150
TS865C25R	T-Pack	250	20	150	1.08	150
YA868C25R	TO-220	250	30	225	1.08	200
YG868C25R	TO-220F	250	30	225	1.08	200
PH868C25	TO-247	250	30	225	1.08	200
TS868C25R	T-Pack	250	30	225	1.08	200

20 to 30 % reduction in loss is anticipated.

2.5 Product lineup

Table 1 shows the high-voltage SBD product line-up. I_o ratings are 10 A, 20 A and 30 A and available packages are the TO-220, TO-220F, TO-247 and T-Pack (SMD).

3. High-voltage Diodes for DLIS-use

3.1 Overview

DLIS is a highly efficient system for electrically delivering a high voltage to individual spark plugs based on control signals from an electronic control unit (ECU), and is used to overcome the following disadvantages of the conventional distributor ignition system (in which a mechanical contact point rotates to deliver a high voltage to each spark plug):

(1) burnout and energy loss caused by sparks at the point of contact,
(2) the difficulty of achieving precise control at high rotational speeds, and
(3) the generation of electromagnetic noise and loss of ignition energy due to sparks at the point of contact and the use of a high tension ignition cable.

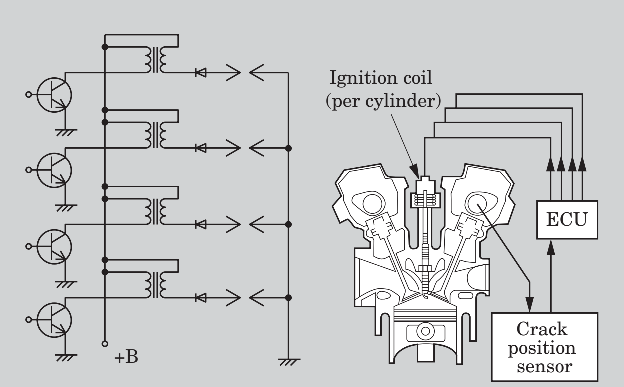
Figure 10 shows a circuit diagram of the coil distributed independent spark-type DLIS, which is the mainstream DLIS, and also shows a diagram of the ignition system. Below, the high-voltage diodes used in this coil distributed independent spark-type DLIS will be described.

3.2 Role of the high-voltage diode in a DLIS system and future challenges

In order to achieve high output voltage at the secondary coil, the abrupt change in magnetic flux in the coil caused by the turnoff of a primary-side ignition transistor is utilized. However, a voltage is naturally generated in the secondary coil while the transistor is in the on-state, and this voltage which is also applied to the spark plug may cause pre-sparking to occur at times other than the optimal sparking interval. A high-voltage diode may be used to prevent this on-state voltage and pre-sparking, however.

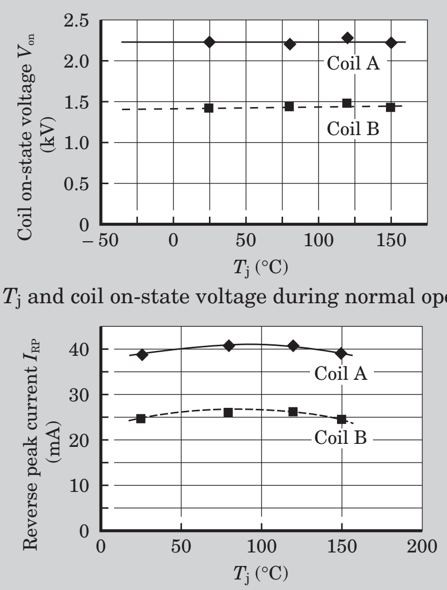
For this reason, a high-voltage diode is incorporated in the ignition coil close the spark plug in an engine block. In order to ensure reliability, it is important that the design has been made heat-resistant. It is also necessary to consider the surge voltage in the case of misfiring, and the provision of the device with surge-proof capability is an important challenge for the future.

Fig.10 Coil distributed spark-type DLIS



(a) Independent spark-type (b) Ignition systems diagram

Fig.11 Relation between T_j and V_{on} at normal operation and relation between T_j and I_{RP} at abnormal (open) operation



(a) T_j and coil on-state voltage during normal operation

(b) T_j and reverse peak current during open operation

3.3 Device design

(1) Breakdown voltage design

As an example of the results of an investigation of the voltage generated at the secondary side of the ignition coil during on-state operation of the transistor, Fig. 11(a) shows the relationship between diode junction temperature (T_j) and the voltage generated at the secondary side when I_c = 9 A. Based on these findings, the actual voltage is assumed to be 2.5 kV or less.

Next, we simulated an abnormal operating condition in which the spark plug was assumed to be open-circuited and examined the electrical stress of an HVD (high-voltage diode). When the plug is open-circuited, a high reverse bias of several tens of kV is applied to the high-voltage diode and loss is generated due to the avalanche voltage and reverse current.

Figure 11(b) shows the relationship between the peak value of reverse current and T_j during open operation. The pulse width of the reverse current was 100 µs or less. In the design stage, it has been proposed to make the V_{RRM} (or working voltage) of an element higher than the voltage generated at the secondary coil during open plug operation, but this is impractical because a large voltage of several tens of kV would be applied to the entire system in the case of an abnormal operation. Additionally, a design that increases the breakdown voltage would lead to greater forward loss and the generation of heat, and as such, is not the best solution.

On the other hand, decreasing the breakdown voltage leads to lower loss, and in consideration of safety as well, the optimal design would be one in which the specified breakdown voltage is reduced to the extent possible and reverse surge withstand capability is ensured. Such a design is capable of achieving a drastic reduction in the heat generated by a high-voltage diode and is well suited for realizing a high

Fig.12 Relation between pulse width and avalanche current withstand capability

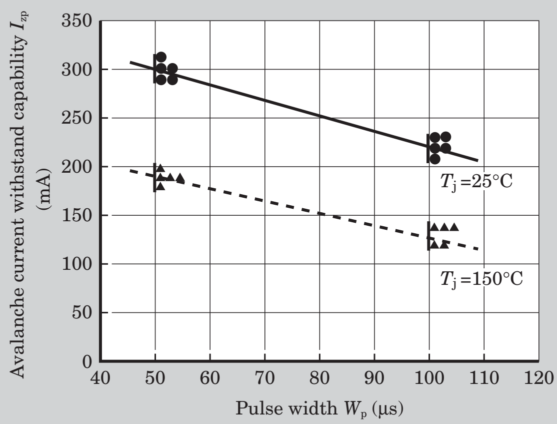


Table 2 Absolute maximum ratings and electrical characteristics of EJA28-02S, ESJA28-03 and ESJA27-02S

(a) Absolute maximum ratings

Item	Symbol	Rating			Unit	Condition
		ESJA28-02S	ESJA28-03	ESJA27-02S		
Repetitive peak reverse voltage	V_{RM}	2.2	2.7	2.2	kV_{peak}	Ignition pulse
Non-repetitive peak reverse voltage	V_{RSM}	2.5	3	2.5	kV_{peak}	Ignition pulse
Average forward current (half sine-wave average)	I_o	10	10	10	mA	f = 60 Hz, sine half-wave rectification
Non-repetitive peak forward current (10 ms)	I_{surge}	1	1	1	A_{peak}	f = 60 Hz, sine-half wave, 1 cycle
Junction temperature	T_j	150	150	150	°C	—
Storage temperature	T_{stg}	– 40 to +150	–40 to +150	–40 to +150	°C	—
Package size	—	ϕ2.5 × 6.5	ϕ2.5 × 6.5	ϕ2.5 × 6.5	mm	—

(b) Electrical characteristics

Item	Symbol	Rating			Unit	Measurement condition (at T_j = 25°C)
		ESJA28-02S	ESJA28-03	ESJA27-02S		
Forward voltage	V_F	≤7	≤8.4	≤7	V	I_F = 10 mA
Reverse current	I_{R1}	≤5	≤5	≤5	µA	– 02S : V_R = 2.2 kV – 03 : V_R = 2.7 kV
Reverse current	I_{R2}	≤10	≤10	≤10	µA	– 02S : V_R = 2.5 kV – 03 : V_R = 3.0 kV
Avalanche breakdown voltage	V_{av}	2.7≤	3.3≤	2.7≤	kV	I_{av} = 100 µA

heat-resistant design.

(2) Design for reverse surge withstand capability

The ability to withstand reverse surges is necessary because of the sudden reverse voltage that exceeds the avalanche voltage and is applied during open plug operation. To achieve high surge withstand capability with a sufficient margin to withstand surge currents during open operation, this product incorporates such measures as:

① optimized chip resistivity, chip area and insulation layer thickness,
② uniform silicon (Si) resistivity,
③ technology for achieving uniform p^+ and n^+ diffusion depths, and
④ technology for achieving uniform shape of the chip surface

and also reduces and equalizes the electric field intensity when an overvoltage is applied. Figure 12 shows the relationship between pulse width and avalanche current withstand capability.

(3) Design for high temperature operation

The quality of materials, structure of the mold resin, chip surface passivation and the like are important factors for usage in high temperature environments such as this application and in usage environments where the temperature differential is large and causes high thermal stress. Accordingly, Fuji Electric has achieved a high-temperature-resistant design by implementing such measures as:

① assessing the degradation in material properties over time by testing the properties of resin materials in a high temperature storage test,
② using the optimal external resin packaging based on heat shock tests, high temperature reverse bias tests and the like, and
③ adopting technology to ensure a proper and uniform thickness of the passivation layer.

3.4 Product introduction

Table 2 lists the maximum ratings and main electrical characteristics of Fuji Electric's DLIS pre-spark prevention high-voltage diode product line.

4. Conclusion

An overview of Fuji Electric's automotive diodes has been presented. Based on the products and technologies introduced herein, Fuji Electric intends to further expand its product line and is committed to advancing the development of even higher-grade products for the future.

Automotive Power MOSFETs

Koji Horiuchi
Yasuhiko Arita
Takeyoshi Nishimura

1. Introduction

As the automobile industry has increasingly used electronic components and systems in recent years for the purpose of making car bodies that are lighter in weight and achieving better fuel efficiency, the use of electronic control units (ECUs) has advanced.

In particular, the transition from power steering systems that use conventional oil pressure control to DC motors that use electronic control (hereafter referred to as electric power steering ECUs) has been particularly rapid, and similarly, headlights are transitioning from conventional halogen bulbs to discharge bulbs that use electronically controlled ballast devices.

Additionally, environmental problems such as global warming have led to the commercialization of products one-after-another such as hybrid vehicles, electric vehicles and fuel-cell vehicles. In accordance with the trends in these automotive fields, there is strong demand for the improved performance of power MOSFETs which are used as the switching devices in ECUs.

Fuji Electric has responded to the trend of increased usage of electronic components and systems in automobiles by developing and commercializing various power MOSFETs.

This paper will introduce the product line, features and future development trends of Fuji Electric's automotive power MOSFETs.

2. Fuji Electric's Product Line of Automotive Power MOSFETs

Table 1 lists Fuji Electric's product line of automotive power MOSFETs and Fig. 1 shows the external appearance of those packages. As MOSFETs for electric power steering ECUs, Fuji provides a 60 V product line for 12 V battery-use and provides a partial lineup of 75 V products capable of supporting the upcoming changeover to 42 V power sources (36 V battery voltage) in the future. Fuji also has a line of 100 to 200 V MOSFETs for use in the DC-DC converter of hybrid vehicles and a line of 500 to 600 V MOSFETs for use in the electronic ballast circuits for discharge bulbs.

3. Features of Fuji Electric's Automotive Power MOSFETs

3.1 Features of MOSFETs for electronic power steering systems

Electric power steering ECUs mainly use 60 V MOSFETs, but the upcoming changeover to a 42 V power source has led to requests for 75 V products.

These 60 V and 75 V MOSFET products utilize trench structure technology to realize lower ON-resistance and smaller package size. Features of the electric power steering MOSFETs are introduced below.

(1) Low ON-resistance chip structure and high gate reliability

Figure 2 shows a cross-sectional comparison of the conventional planar chip structure and the trench chip structure.

A characteristic of the trench chip structure is a concave structure fabricated at the gate by means of precision controlled etching. This structure enables the channel resistance component to be decreased, which had been difficult to achieve with the conventional planar chip construction, and also drastically reduces the resistance component due to a JFET effect. Figure 3 shows a comparison of the ON-resistance components of a 60 V conventional planar chip and a trench chip.

Fuji Electric has optimized the trench shape, uniform gate oxidation layer and the polysilicon layer that forms the gate electrode to achieve gate reliability capable of maintaining a high gate voltage (V_{GS} = 30 V) simultaneously with low ON-resistance.

(2) Optimization of the gate threshold voltage

The MOSFETs used in electric power steering ECUs are selected based on their low ON-resistance characteristics, and because the chip design involves a tradeoff between ON-resistance characteristics and gate threshold voltage, MOSFETs having a low gate threshold voltage of approximately 1 to 2 V are commonly used. However, a low gate threshold voltage is susceptible to malfunction caused by noise and the

Table 1 Fuji Electric's product line of automotive power MOSFETs

Targeted application such as ECUs	Model number	Main product specification V_{DSS} (V)	I_D (A)	$R_{DS(on)}$ (Ω)	Package	Remark
ECUs for electric power steering	2SK3270-01	60	80	6.5 m	TO-220AB	
	2SK3271-01	60	100	6.5 m	TO-3P	
	2SK3272-01L, S	60	80	6.5 m	D^2-Pack	
	2SK3273-01MR	60	70	6.5 m	TO-220 full-mold	
	F1519	60	80	6.0 m	D^2-Pack	Under development
	2SK3730-01MR	75	70	8.5 m	TO-220 full-mold	
Hybrid electric vehicles, Electric vehicles, DC-DC converters, Electronic ballast for discharge bulbs (DC-DC converter/ inverter units)	2SK3804-01S	75	70	8.5 m	D^2-Pack	Under development
	F1515	75	80	8.5 m	TO-247	Under development
	2SK3644-01	100	30	44 m	TO-220AB	
	2SK3645-01MR	100	30	44 m	TO-220 full-mold	
	2SK3646-01L, S	100	30	44 m	D^2-Pack	
	2SK3590-01	150	40	41 m	TO-220AB	
	2SK3591-01MR	150	40	41 m	TO-220 full-mold	
	2SK3592-01L, S	150	40	41 m	D^2-Pack	
	2SK3594-01	200	30	66 m	TO-220AB	
	2SK3595-01MR	200	30	66 m	TO-220 full-mold	
	2SK3596-01L, S	200	30	66 m	D^2-Pack	
	2SK3504-01	500	14	0.46	TO-220AB	
	2SK3505-01MR	500	14	0.46	TO-220 full-mold	
	2SK3450-01	600	12	0.65	TO-220AB	
	2SK3451-01MR	600	12	0.65	TO-220 full-mold	

Fig.1 External appearance of packages

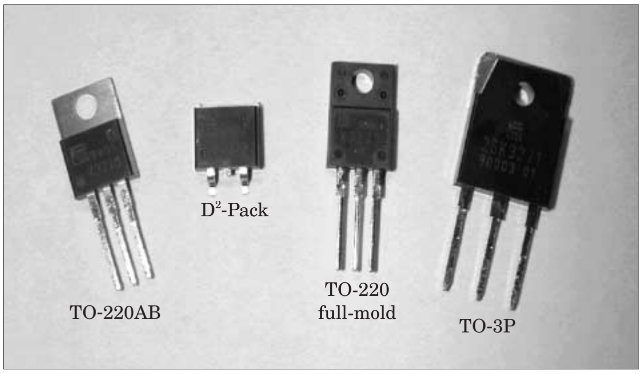


Fig.2 Planar chip structure and trench chip structure

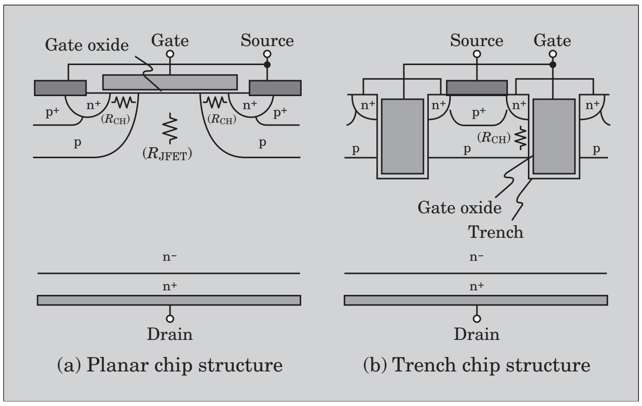
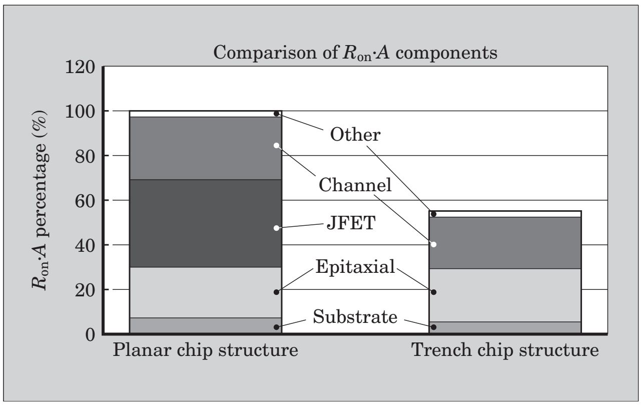


Fig.3 Comparison of the ON-resistance components of a 60 V conventional planar chip and a trench chip (60 V) [per unit area: $R_{on} \cdot A$]



like.

Fuji Electric's MOSFETs for electric power steering applications have an optimized gate threshold voltage of 3 V (typical value) and therefore the target circuitry can easily be configured to include anti-noise measures to prevent malfunction due to noise generated in the interconnects to gate peripheral circuitry.

(3) Highly reliable package compatible with large currents

An ECU system for electric power steering use as shown in Fig. 4 must have a highly reliable package capable of withstanding instantaneous large currents due to: 1) a load short-circuit of the DC motor, 2) a short-circuit to ground in the wiring harness that connects the DC motor and ECU, 3) an arm short-circuit between upper and lower devices that comprise of an H bridge or a 3-phase bridge, and so forth.

Figure 5 shows the internal structure of Fuji Electric's trench power MOSFET. When an electric power steering ECU operates at maximum torque (motor current of approximately 30 to 65 A), the large current flow causes power loss to occur in the chip and is dissipated as thermal energy and an even larger emission of thermal energy is dissipated in the lead wiring that connects to external pins. In consideration of the above problem, Fuji Electric has optimized the chip design by, (1) increasing the diameter of the internal connecting wire, and (2) by using multiple internal connecting wires.

Provided with the above features, Fuji Electric's electric power MOSFETs are being used in a wide range of applications in addition to those listed above.

(4) 75 V MOSFET product line

Although a battery voltage of 12 V is used at present, in order to support the future transition to a 42 V power source (36 V battery), Fuji Electric also provides a 75 V product line. Table 2 shows the main ratings and Table 3 shows the electrical characteristics of the 75 V product line. This product line is characterized by a high voltage of 75 V and by low ON-resistance (8.5 mΩ maximum).

Fig.4 Equivalent circuit of electric power steering ECU system (3-phase motor control)

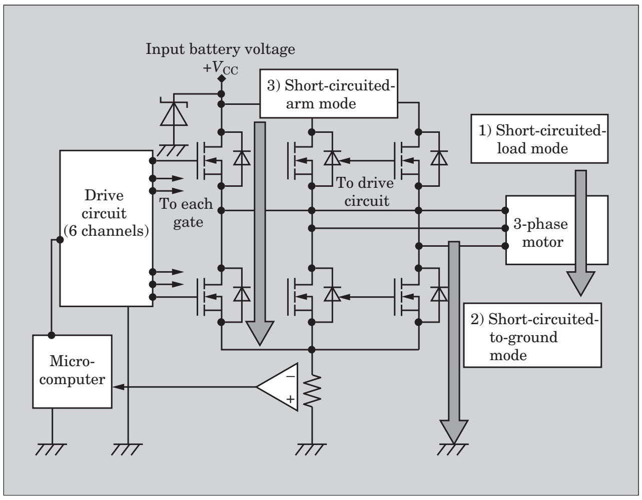
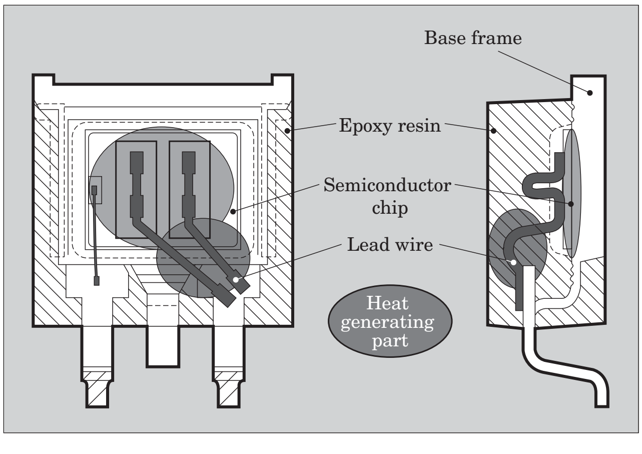


Fig.5 Internal structure of Fuji Electric's trench power MOSFET (surface mount type)



3.2 Features of Fuji Electric's MOSFETs for use in DC-DC converters and electronic ballast circuits

Figure 6 shows a ballast device system for controlling a discharge bulb. 100 to 200 V MOSFETs are used in DC-DC converters to boost the battery voltage and 500 to 600 V MOSFETs are used in inverter units to generate a high voltage for a discharge bulb. A DC-DC converter requires a MOSFET capable of high-frequency switching operation in order to realize a compact and lightweight step-up transformer, and an inverter requires a high-voltage and high-speed MOSFET capable of withstanding the high voltage during the bulb unloaded output state of approximately 380 V and the high dv/dt at the beginning of bulb discharge. In response to these requests, Fuji Electric provides the SuperFAP-G product line which has high speed and low ON-resistance. This SuperFAP-G product line incorporates the new technology of a quasi-planar junction (QPJ) shown in Fig. 7 and achieves a high level of performance that is only 10 % less than the theoretical performance limit of silicon (Si).

Features of this product line are listed below (in comparison to the conventional 600 V product line.

(1) 75 % decrease in turn-off loss
(2) 60 % decrease in gate charge
(3) High avalanche withstand capability
(4) Package product line that includes various surface mount packages

By providing the above SuperFAP-G product line, Fuji Electric is able to supply MOSFETs that are ideally suited for DC-DC converter and electronic ballast applications.

Table 2 Main ratings of Fuji Electric's 75 V automotive power MOSFET (T_C = 25°C)

Item	Symbol	Rating	Unit	Remark
Drain-source voltage	V_{DS}	75	V	
	V_{DSX}	40	V	V_{GS}= −20 V
Continuous drain current	I_D	±70	A	
Pulsed drain current	I_{DP}	±280	A	
Gate-source voltage	V_{GS}	+30/−20	V	
Maximum avalanche energy	E_{AV}	443.8	mJ	L= 84.5 µH, V_{CC}= 48 V
Maximum power dissipation	P_D	162	W	
Operating temperature range	T_{ch}	175	°C	
Storage temperature range	T_{stg}	−55 to +175	°C	

Table 3 Electrical characteristics of Fuji Electric's 75 V automotive power MOSFET (T_C = 25°C unless specified otherwise)

(a) Static characteristics

Item	Symbol	Measurement condition	Standard value			Unit
			Min.	Typ.	Max.	
Drain-source breakdown voltage	BV_{DSS}	I_D = 1 mA V_{GS} = 0 V	75	–	–	V
	BV_{DSX}	I_D = 1 mA V_{GS} = – 20 V	40	–	–	V
Gate threshold voltage	$V_{GS\,(th)}$	I_D = 10 mA V_{DS} = V_{GS}	2.5	3.0	3.5	V
Zero gate voltage drain current	I_{DSS}	V_{DS} = 75 V, V_{GS} = 0 V, T_{ch} =25°C	–	1.0	100	μA
		V_{DS} = 75 V, V_{GS} = 0 V, T_{ch} =125°C	–	10	500	μA
Gate-source leakage current	I_{GSS}	V_{GS} = +30 /–20 V_{DS} = 0 V	–	10	100	nA
Drain-source ON-state resistance	$R_{DS\,(on)}$	I_D = 35 A V_{GS} = 10 V	–	6.4	8.5	mΩ

(b) Dynamic characteristics

Item	Symbol	Measurement condition	Standard value			Unit
			Min.	Typ.	Max.	
Forward transconductance	g_{fs}	I_D = 35 A V_{DS} = 10 V	25	50	–	S
Input capacitance	C_{iss}	V_{DS} = 25 V V_{GS} = 0 V f = 1 MHz	–	7,500	–	pF
Output capacitance	C_{oss}		–	1,050	–	
Reverse transfer capacitance	C_{rss}		–	500	–	
Turn-on time	$t_{d\,(on)}$	V_{cc} = 38 V V_{GS} = 10 V I_D = 70 A R_G = 10 Ω	–	50	–	ns
	t_r		–	90	–	
Turn-off time	$t_{d\,(off)}$		–	150	–	
	t_f		–	90	–	
Total gate charge	Q_g	V_{cc} = 38 V I_D = 70 A V_{GS} = 10 V	–	150	–	nC
Gate-source charge	Q_{gs}		–	30	–	
Gate-drain charge	Q_{gd}		–	45	–	

(c) Parasitic diode characteristics

Item	Symbol	Measurement condition	Standard value			Unit
			Min.	Typ.	Max.	
Avalanche withstand capability	I_{AV}	L = 84.5 μH T_{ch} = 25°C	70	–	–	A
Diode forward ON-voltage	V_{SD}	I_F = 75 A V_{GS} = 0 V T_{ch} = 25°C	–	1.3	1.65	V
Reverse recovery time	t_{rr}	I_F = 35 A V_{GS} = 0 V $-di/dt$ = 100 A/μs T_{ch} = 25°C	–	95	–	ns
Reverse recovery charge	Q_{rr}		–	0.30	–	μC

(d) Thermal characteristics

Item	Symbol	Measurement condition	Standard value			Unit
			Min.	Typ.	Max.	
Thermal resistance	$R_{th\,(ch\text{-}c)}$		–	–	0.926	°C/W
	$R_{th\,(ch\text{-}a)}$		–	–	75.0	°C/W

Fig.6 Ballast device system

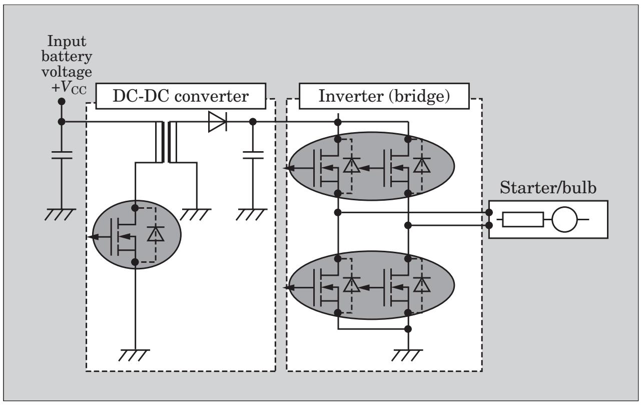
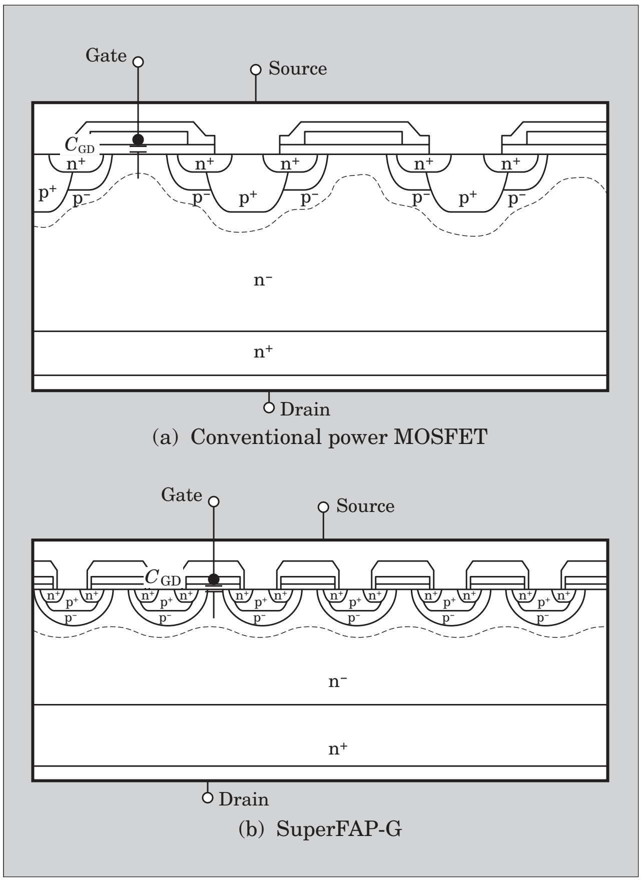


Fig.7 Chip structure of SuperFAP-G product line



(a) Conventional power MOSFET

(b) SuperFAP-G

4. Future Development Trends

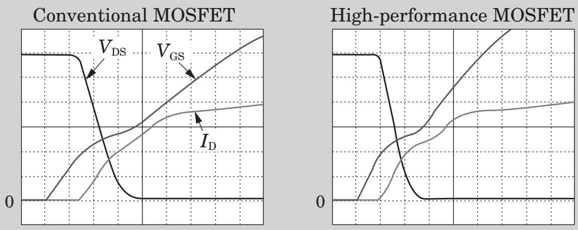
In addition to Fuji Electric's existing 60 V product line that has a track record of successful use in electric power steering application and the new 75 V product line, we are also endeavoring to develop high performance products that utilize next generation technology.

The design goals for these high performance products, for which development and commercialization being advanced, are listed below.

(1) Product voltage V_{DS}: 60 V, 75 V

Fig.8 Comparison of switching characteristics (gate charge) of a conventional 60 V MOSFET and a new high-performance 60 V MOSFET

Measurement conditions (V_{DS} = 30 V, I_D = 80 A, V_{GS} = 10 V)

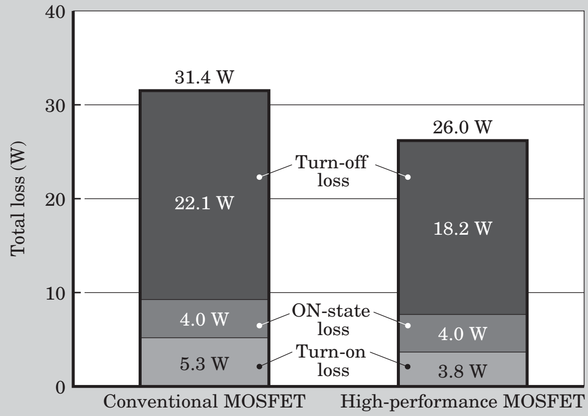


Sample	Q_g (nC)	Q_{gs} (nC)	Q_{gd} (nC)
Conventional MOSFET	126	38	37
High-performance MOSFET	88	32	22

V_{DS} : 5 V/div
I_D : 20 A/div
V_{GS} : 2 V/div
T : 2 µs/div

Fig.9 Comparison of loss generated by a conventional 60 V MOSFET and a new high-performance 60 V MOSFET (simulated results)

Measurement conditions (I_D = 80 A, V_{DS} = 30 V, V_{GS} = 10 V, R_g = 100 Ω, f_C = 20 kHz, Duty = 50 %)



(2) Rated current I_D: 70 to 80 A
(3) Gate threshold voltage: 2.5 to 3.5 V
(4) ON-resistance, $R_{on} \cdot A$: 20 % less than conventional products
(5) Input capacitance C_{iss}: 30 % less than conventional products
(6) Package lineup: Stand-alone packages (as typified by the TO-220) and surface mount packages

Figure 8 shows a comparison of the switching waveforms (gate charge) for a 60 V engineering sample of a product presently under development and a conventional MOSFET and Fig. 9 compares the results of a simulation of loss generation for these two devices assuming use as in an electric power steering application and a carrier frequency of 20 kHz.

According to these comparative results, an approximate 40 % improvement in gate charge quantity (Q_g), effective in reducing loss during gate driving, and an approximate 18 % in loss generation at 20 kHz are achieved.

Based on the above results, by endeavoring to improve the various main specifications and to enhance performance, higher performance can be achieved not only as a MOSFET for electric power steering applications, but by developing other product lines, higher performance can be achieved for additional applications as well.

5. Conclusion

Fuji Electric has developed and commercialized various automotive power MOSFETs including those described herein. We are committed to continue developing and providing distinctive products to satisfy the needs for electronic parts and systems and to expand the field of automotive electronics.

Reference

(1) Yamazaki, T. et al. Low Q_{gd} Trench Power MOSFETs with Robust Gate for Automotive Applications. PCIM2003.

Automotive Smart MOSFETs

Shin Kiuchi
Minoru Nishio
Takanori Kohama

1. Introduction

In the automotive electrical equipment industry, based on the goals of improving the environment, safety and comfort, electronic systems have grown in complexity in order to realize more advanced vehicle control technology and enhanced combustion technology for reducing gas emissions and increasing fuel efficiency, and these trends have led to increasingly sophisticated electronic control units (ECUs) year-after-year. Furthermore, because the space for installation of an ECU is limited, the temperature of the environment in which ECUs operate has also been increasing year-by-year. Because of these circumstances, system manufacturers desire to make ECUs more compact in size and to increase their reliability in a high temperature environment. As semiconductor devices well suited for realizing small size and highly reliable ECUs, attention is focused on smart power devices that integrate a power semiconductor, peripheral protection circuits, a status output circuit, a drive circuit and the like into a single device. Applications of these smart power devices are steadily growing.

Fuji Electric has integrated power semiconductors and the abovementioned peripheral circuits into single chip solutions and has developed semiconductor products that are compatible with the smaller size, higher performance and higher reliability of ECUs. This product family includes high-side and low-side type intelligent power MOSFETs, IPSs (intelligent power switches) and single chip igniters. A common characteristic of these products is the integration of a power device with control circuitry, circuitry to protect against current, voltage and ESD (electrostatic discharge) surges, self-diagnosis circuitry and the like. This integration of electronic components into a single chip achieves lower cost and higher reliability than in the conventional case where the abovementioned circuits were added separately by system manufacturers. This paper introduces the intelligent power MOSFET and IPS which are typical smart MOSFETs and representative of the abovementioned semiconductor products.

2. Intelligent Power MOSFETs

2.1 Overview of product line

Table 1 lists Fuji Electric's product line of smart MOSFETs. The F5048 and F5045P have been newly added to the line of intelligent power MOSFET products. The F5048 is an 80 V product and has the advantage of eliminating the need for a 30 V power Zener diode that had conventionally been attached to the ECU to absorb the load dump surge (an excessive high energy surge of, for example 80 V for a period of $\tau = 0.25$ s, generated when the battery lead becomes open-circuited for some reason). The F5045P is the first high-side element in the intelligent power MOS FET product line. To enable operation directly from a battery power source, this product has a minimum operating voltage of 3 V and a standby current (I_{cc}) of 90 µA (typical value at $T_j = 25$°C).

As a representative device of the intelligent power MOSFET product line, main specifications of the F5041 are listed in Tables 2 and 3, and a circuit block diagram and chip die photo are shown in Figs. 1 and 2, respectively.

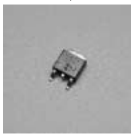
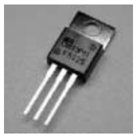
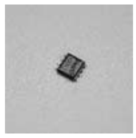
2.2 Characteristics

(1) Short-circuit protection

Intelligent power MOSFETs contain a built-in short-circuit detection circuit to protect the system, load and device itself in case the load impedance in a system decreases and causes the current flow to become excessively large. As an example, Fig. 3 shows the operating waveform of the F5041 over the course of the sequence from short-circuit detection to current limiting and then to overtemperature detection.

This operating waveform was obtained by using a p-channel MOS as the load and gradually increasing the drain current from 0 A to verify operation of the F5041's protection function from short-circuit detection to current limiting and then to overtemperature detection. Figure 4 shows the short-circuit and overtemperature detection circuit. This detection circuit contains an internal resistor for monitoring the ON-voltage of the output-stage power MOSFET. A drain-source voltage monitoring circuit detects when the drain

Table 1 Fuji Electric's product line of smart MOSFETs

Type	High-side					Low-side																			
	IPS							IGBT	Intelligent power MOSFET																
Model number	F5016H	F5017H	F5038H	F5044H	F5045P	F6008L	F5025	F5024	F5020	F5022	F5018	F5042	F5019	F5043	F5023	F5026	F5027	F5029	F5030	F5031	F5032	F5028	F5033	F5041	F5048
Package	TO-220F-5			SOP-8		TO-220			K-Pack				T-Pack		TO-220		T-Pack	TO-220	T-Pack	K-Pack		T-Pack	SOP-8		T-Pack
Package		TO-220F-5 						K-Pack (D-Pack) 					T-Pack (D^2-Pack) 					TO-220 					SOP-8 		
Rating: Voltage (V) *1	60	60	50	50	50	370	370	410	40	70	40		40			40		40		40	40	40	40		80
Rating: Current (A) *2	3	6	3	3	1	8.5	8.5	10	3	3	8		12			52		18		14	6	28	1 A (2in1)		15
Max. ON-state resistance, $R_{DS(ON)}$ (Ω)	0.16	0.16	0.16	0.12	0.6	V_{sat} 1.3 V Typical value	V_{sat} 1.3 V Typical value	V_{sat} 1.3 V Typical value	0.4	0.55	0.14		0.14			0.02		0.07		0.07	0.2	0.04	0.6		0.125
Function: Overcurrent detection	○	○	○	○	○	○	○		○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
Function: Over-temperature detection	○	○	○	○	○	○			○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
Function: Overvoltage detection	○	○	○	○																					
Function: Open load detection	○	○	○	○																					
Function: Status output	○	○	○	○																					
Function: Induced voltage clamping	○	○	○	○	○	← Drain-gate clamping Zener diode →																			
	(Typical value −11 V)		(Typical value −42 V)																						
Low standby current					○																				○
Low noise (in output switching mode at time of overcurrent detection)			○	○	○																				
Remarks												* 3		* 3											

* 1 : Voltage limited by drain-gate Zener diode
* 2 : Current limited by built-in protection circuit
* 3 : Turn-off time (50 µs or less) is shorter than for F5018 and F5019

Table 2 F5041 maximum ratings (T_j = 25°C)

Item	Symbol	Rating	Measurement conditions	Unit
Drain-source voltage	V_{DSS}	40	DC	V
Gate-source voltage	V_{GSS}	−0.3 to +7.0	DC	V
Drain current	I_D	1		A
Max. power dissipation	P_D	1.5	See note below.	W
Junction temp.	T_j	150		°C
Storage temp.	T_{stg}	−55 to +150		°C

Note : When mounted on a 1,000 mm² glass epoxy substrate and 2 channels are ON simultaneously

current flowing to that resistor exceeds the short-circuit current detection value, and in such a case, functions to limit the output current by lowing the value of the gate voltage of the output-stage power MOSFET to a specific voltage value. Moreover, if the continuation of this current-limiting operation causes the device's junction temperature (T_j) to rise above a certain value, an overtemperature detection circuit will operate to turn-off the output current.

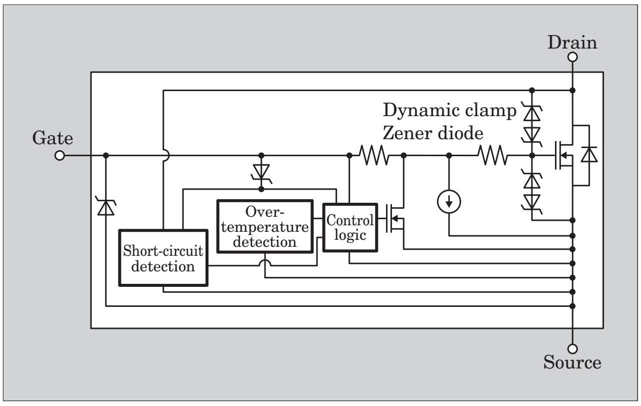
The intelligent power MOSFET is designed for auto-restart upon returning from an operating sequence of short-circuit and overtemperature detection. Moreover, compared to the case where the temperature sensor is located next to the active part of the power

Table 3 F5041 electrical characteristics (T_j = 25°C)

Item	Symbol	Measurement condition	Standard value Min.	Standard value Max.	Unit
Drain-source voltage	V_{DSS}	I_D = 1 mA, V_{GS} = 0 V	40	60	V
Gate threshold voltage	$V_{GS\,(th)}$	I_D = 1 mA, V_{DS} = 13 V	1.53	2.8	V
Drain current at zero gate voltage	I_{DSS}	V_{DS} = 16 V		15	μA
		V_{DS} = 30 V		35	μA
Drain current at negative gate voltage	$I_{DS\,(-VGS)}$	V_{DS} = 16 V, V_{GS} = −1.5 V, R_G = 100 Ω		12	μA
		V_{DS} = 30 V, V_{GS} = −1.5 V, R_G = 100 Ω		30	μA
Gate-source current	$I_{GS\,(n)}$	V_{GS} = 5 V (Note 1)		250	μA
	$I_{GS\,(un)}$	V_{GS} = 5 V, T_j >150°C (Note 2)		350	μA
ON-state resistance	$R_{DS\,(on)}$	V_{GS} = 5 V, I_D = 0.5 A		600	mΩ
Overcurrent detection	I_{OC}	V_{GS} = 5 V	1.5		A
Over-temperature detection	T_{trip}	V_{GS} = 5 V	150		°C
Switching time	t_{on}	V_{DS} = 13 V, I_D = 0.5 A, V_{GS} = 5 V		50	μs
	t_{off}			50	μs
Dynamic clamping energy dissipation	E_{CL}	T_j = 150°C	25		mJ

Note 1 : Normal operation when the protection function is not active
Note 2 : When the protection function is operating (in the load short circuit, overcurrent detection, or overtemperature detection modes)

Fig.1 F5041 circuit block diagram



MOSFET cell, the adoption of a layout in which the overtemperature detection sensor is positioned directly above the active part of the power MOSFET cell enables an overtemperature detection response speed that is approximately 10 times quicker and greater detection accuracy and enhanced protection functions to be obtained.

(2) Dynamic clamping function

In automobile systems where there are many inductive loads such as solenoid valves, there is a

Fig.2 F5041 chip die photo

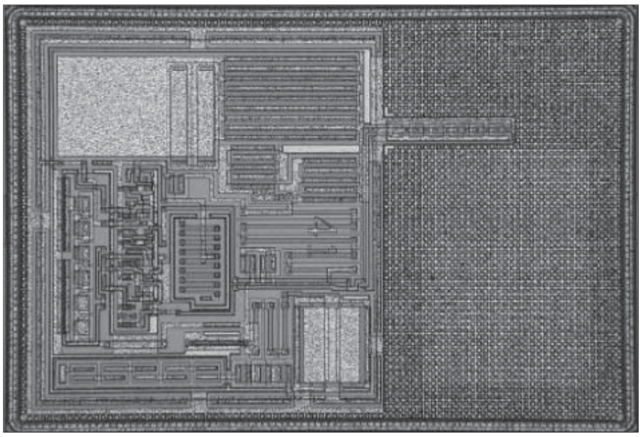


Fig.3 F5041 waveform at time of short-circuit detection, current limiting, and overtemperature detection

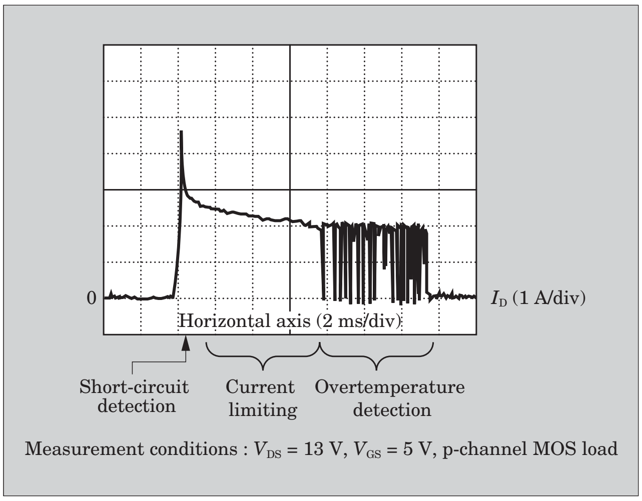
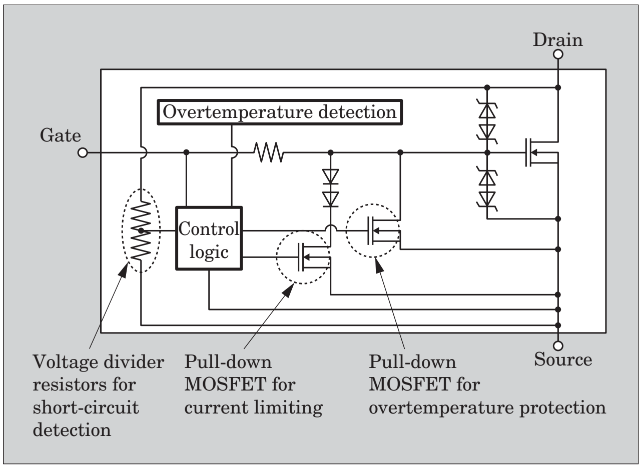


Fig.4 F5041 circuit for short-circuit detection, current limiting and overtemperature detection



problem of dealing with the $LI^2/2$ energy accumulated in the inductive loads.

The intelligent power MOSFET contains a dynamic clamping circuit that clamps the surge voltage generated when an inductive load turns off and absorbs the energy accumulated in the inductive load with the power MOSFET itself. This dynamic clamping circuit eliminates the need for external components such as a snubber circuit.

(3) High ESD capability

The intelligent power MOSFET has been carefully designed to be capable of withstanding surge voltages in the harsh surge environment of automobiles. Specifically, the construction of the Zener diode for surge absorption and the circuit layout have been optimized and the operating resistance decreased to ensure that ESD capability between the drain and source is at least 25 kV (at 150 pF, 150 Ω and T_a = 25°C).

3. IPSs

3.1 Overview

Fuji Electric's line of IPS products is listed in Table 1. As a representative device from this product line, main specifications of the F5044H are listed in Tables 4, 5 and 6, and a circuit block diagram and chip die photo are shown in Figs. 5 and 6, respectively

3.2 Characteristics

(1) Overcurrent protection

The IPS is equipped with an overcurrent protection function for protecting the system, load and device itself when an excessive current flows into the output-stage power MOSFET. As an example, Fig. 7 shows the operating waveform of the F5044H over the course of the sequence from overcurrent detection to the current switching mode. With the F5044H, the peak current value during the output switching mode is clamped at approximately 12 A (prior products had a peak current of 30 A). Even under abnormal conditions when the current flow is excessively large, the noise generated by the device during output switching is suppressed to a low value. Moreover, this reduction in peak current is advantageous for the trends toward use of thinner wiring for ECUs and thinner and lighter wire for wire harnesses.

(2) Dynamic clamping function

As in the case of intelligent power MOSFETs, the handling of energy stored in an inductive load is also a problem for IPSs.

Similar to the intelligent power MOSFET, the IPS incorporates a dynamic clamping function that clamps the surge voltage generated when an inductive load turns off and absorbs the energy accumulated in the inductive load with a power MOSFET.

(3) Low loss

In contrast to the conventional IPS fitted in a TO-220 full-mold 5-pin package (TO-220F-5), the F5044H is fitted in an SOP-8 package to achieve a more compact size. The largest problem encountered in making the package size smaller was in maintaining the conduction capacity and acceptable loss, but this was resolved by lowering the ON-state resistance to 120 mΩ (max.). Figure 8 compares the mounting area and acceptable conduction capacity of the TO-220F-5 and SOP-8 package IPSs.

Table 4 F5044H maximum ratings (T_j = 25°C)

Item	Symbol	Rating	Measurement conditions	Unit
Supply voltage	V_{CC}	33/50	DC/0.25 s	V
Output current	I_{OUT}	3	Internally limited value	A
Input voltage	V_{IN}	−0.3 to V_{CC}+0.3	DC	V
Status current	I_{ST}	5		mA
Operating junction temp.	T_j	150		°C
Storage temp. range	T_{stg}	−55 to +150		°C

Table 5 F5044H electrical characteristics (T_j = 25°C)

Item	Symbol	Measurement conditions	Standard value		Unit
			Min.	Max.	
Operating voltage	V_{CC}		6	28	V
Standby current	I_{CC}	V_{CC} = 13 V R_L = 10 Ω V_{IN} = 0 V		3	mA
Input voltage	$V_{IN(H)}$	V_{CC} = 13 V	3.5		V
	$V_{IN(L)}$	V_{CC} = 13 V		1.5	V
Input current	$I_{IN(H)}$	V_{CC} = 13 V V_{IN} = 5 V		12	μA
ON-state resistance	$R_{DS(on)}$	V_{CC} = 13 V I_{out} = 1.25 A		0.12	Ω
Overcurrent detection	I_{OC}	V_{CC} = 13 V	3	6	A
Over-temperature detection	T_{trip}	V_{CC} = 13 V	150	200	°C
Overvoltage detection	V_{OV}		28	33	V
Turn-on time/ turn-off time	t_{on} / t_{off}	V_{CC} = 13 V R_L = 10 Ω		120/40	μs
Output clamp voltage	V_{clamp}	V_{CC} = 13 V L = 10 mH	−(50−V_{CC})	−(60−V_{CC})	V
Open load detection	R_{LOPEN}	V_{CC} = 13 V V_{IN} = 0 V	6	36	kΩ

Table 6 F5044H logic table

Item	IN	ST	OUT	Remark
Normal operation	L H Open	L H L	L H L	
Open load	L	H	H	Auto-restart
Overcurrent	L H	L L	L L	Switching mode Auto-restart
Overtemperature	L H	L L	L L	Auto-restart
Overvoltage	L H	L H	L L	Auto-restart

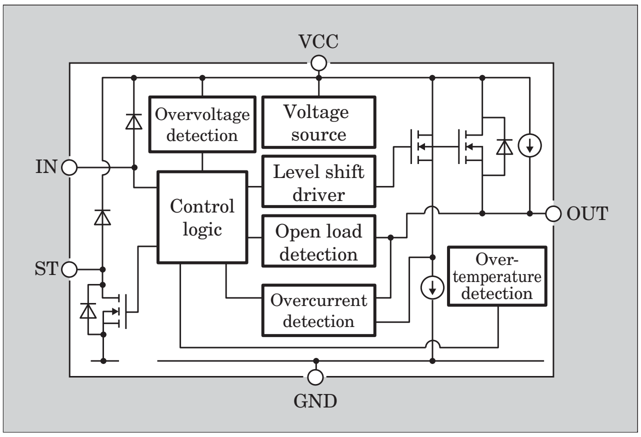


Fig.5 F5044H circuit block diagram

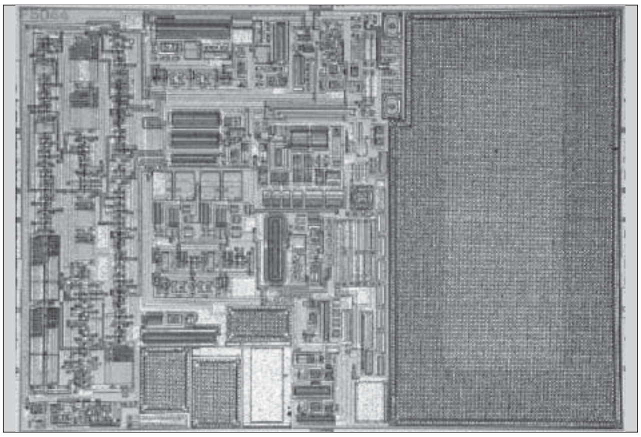


Fig.6 F5044H chip die photo

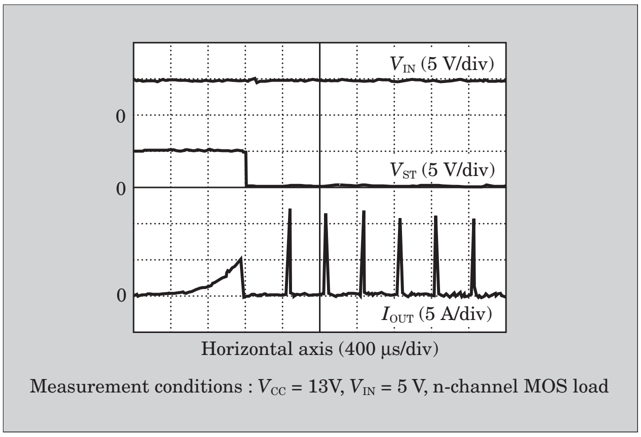


Fig.7 F5044H waveform during sequence from overcurrent detection to output switching mode

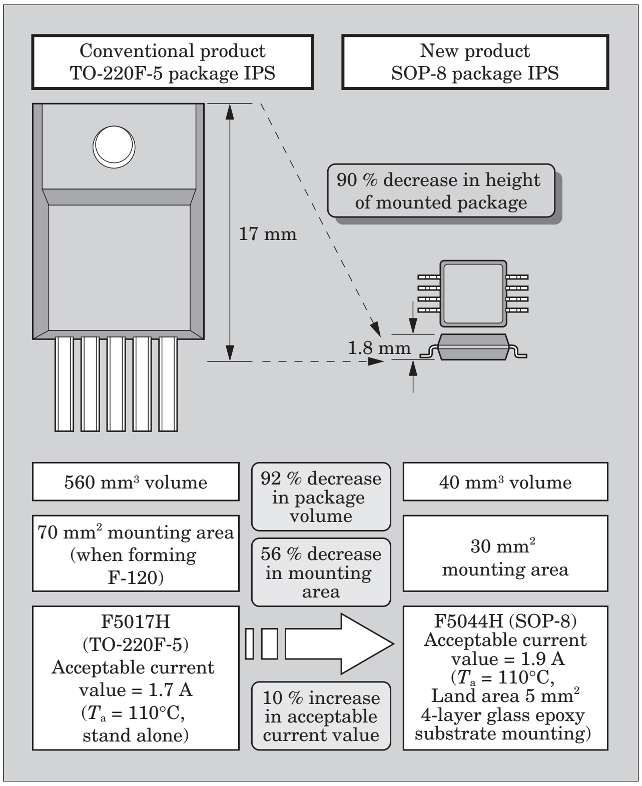


Fig.8 Comparison of mounting area and acceptable conduction capacity of the TO-220F-5 package IPS and SOP-8 package IPS

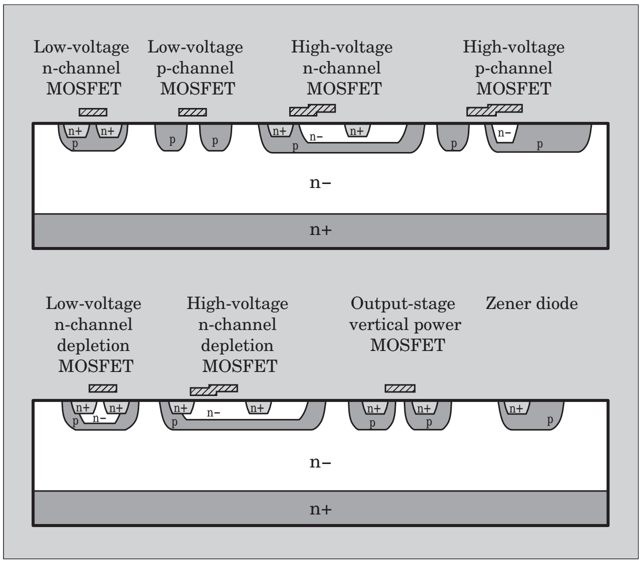
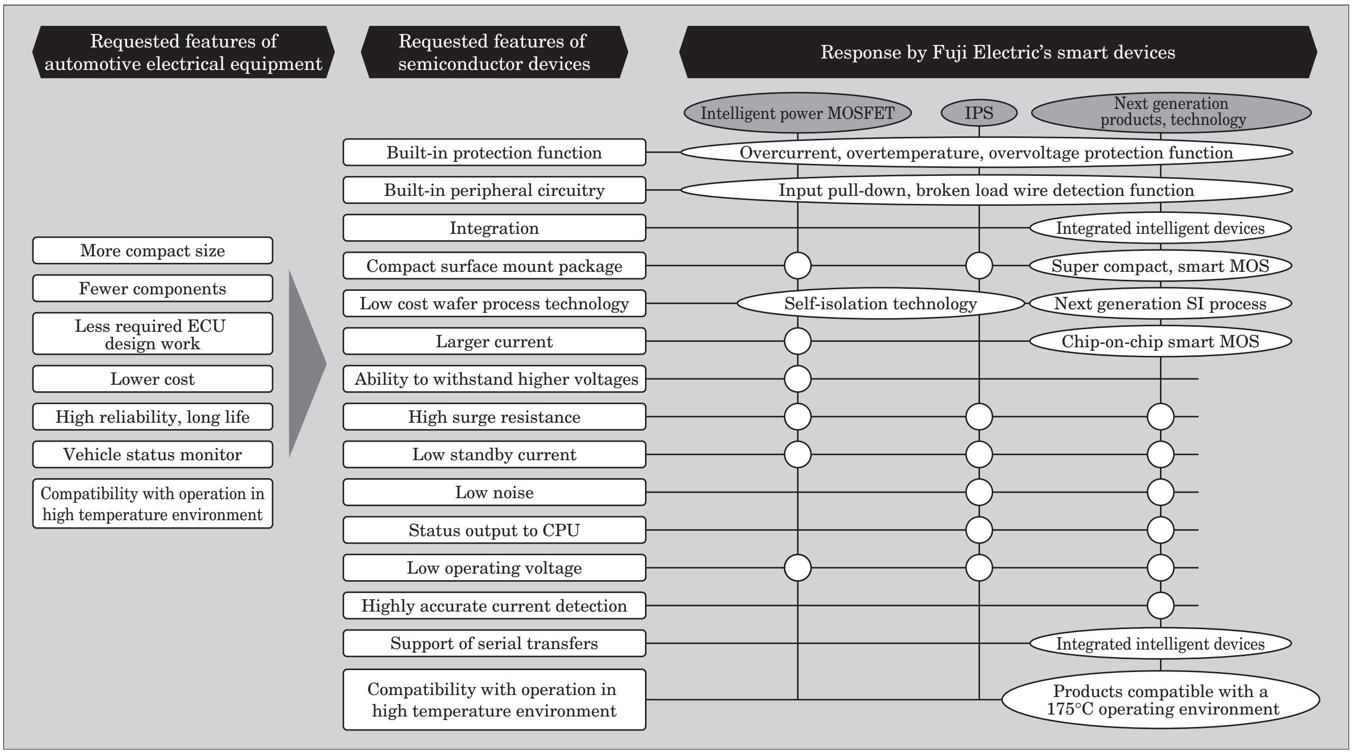


Fig.9 Cross-section of self-isolation structure (IPS)

4. Self-isolation Technology

In the case of a device such as a smart MOSFET that integrates a vertical power MOSFET and control IC into a single chip, isolation of the structures is important. Fuji Electric uses self-isolation CMOS/DMOS (complementary MOS/diffusion MOS) technology in its line of smart MOSFET products. Figure 9 shows a cross-section of the IPS series as a representative example of the smart MOSFET product line. Fabricated on the same silicon substrate as the power MOSFET, the self-isolated structures consist of low and high-voltage CMOS devices, a Zener diode and the like separated by each device's own p-n junction and integrated together with the power MOSFET. This self-isolation technology can realize low cost structures since it requires fewer processes than junction-isola-

Fig.10 Requested features of semiconductor devices for the automotive electrical equipment market and the response by Fuji Electric's smart devices



tion technology or silicon-on-insulator technology, and the silicon wafer does not require special processing. Moreover, by making full use of self-isolation CMOS/DMOS technology based on a vertical power MOSFET process, commercialization can be achieved by adding approximately 3 to 6 mask steps and processes.

5. Conclusion

Figure 10 shows the features requested of semiconductor devices for the automotive electrical equipment market and the conformance to those requests by smart devices. Fuji Electric has responded to the customer and marketplace requests listed in Fig. 10 by introducing intelligent power MOSFETs and IPSs in its new line of smart MOSFET products. In the future, Fuji Electric intends to develop integrated devices such as ICs equipped with a surge absorption function for applications that require the integration of systems and circuits, chip-on-chip smart MOSFETs for applications that require small-size power devices having a large current capacity, and super-small smart MOS FETs for applications in which further miniaturization of 1-channel smart MOSFETs is required. Additionally, as a wafer process, we are developing next generation self-isolation technology that integrates lateral power devices and control ICs in order to achieve multi-channel capability. While continuing to promote the above-described technology and product development to leverage the advantages of conventional smart MOSFETs, Fuji Electric intends to contribute to making ECUs more compact in size and to achieving overall cost reductions.

A Self-isolated Single-chip Igniter (F6008L) for Automobiles

Mitsutoshi Yamamoto
Kenichi Ishii
Yoshiaki Toyoda

1. Introduction

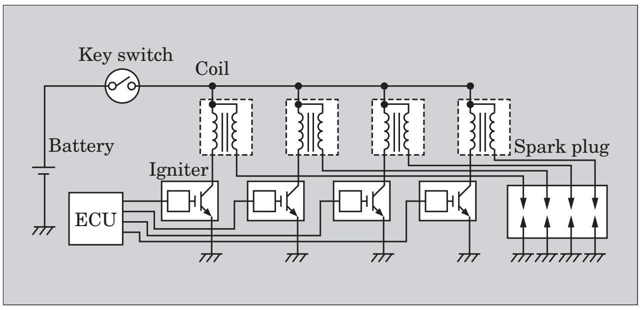
Driving by concerns for preventing atmospheric pollution and global warming caused by gas emissions, the automobile industry has, in recent years, aggressively promoted the development of vehicles capable of achieving dramatically lower fuel consumption and reducing the amount of hazardous substances in gas emissions. These capabilities are also in demand for automotive parts.

Regarding the ignition control sub-assembly of a gasoline engine control system, there are also strong demands for more stable ignition coil voltage and more precise control in order to achieve higher fuel efficiency and lower gas emissions. Consequently, instead of the conventional distributor method in which a mechanical mechanism is used to distribute a high voltage to an ignition spark plug for each cylinder, the use of an individual ignition method has increased in popularity in recent years. In the individual ignition method, a coil and switch are provided for each ignition spark plug and the ignition interval is adjusted according to the operational timing of each cylinder. Figure 1 shows an example block diagram of an individual ignition system for each cylinder.

In response to requests for higher performance, Fuji Electric commercialized the world's first single-chip igniter (F5025) that incorporated an IGBT having a self-isolation structure, and has been mass-producing this device since 1998.

This paper introduces the newly developed F6008L, which adds an overtemperature protection function to Fuji Electric's popular F5025 product line of single-chip igniters.

Fig.1 Example configuration of the individual ignition system



2. Overview

An igniter device is used in the central part of the engine drive system and because device failure would likely cause the engine to stop operating, extremely high

Fig.2 F6008L schematic diagram

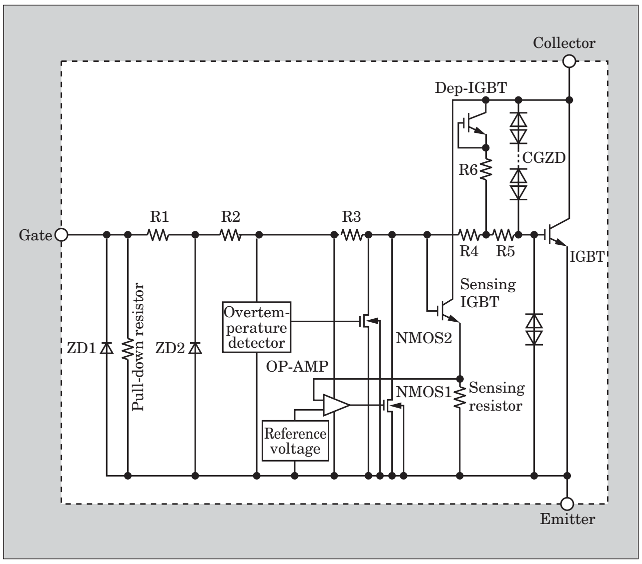
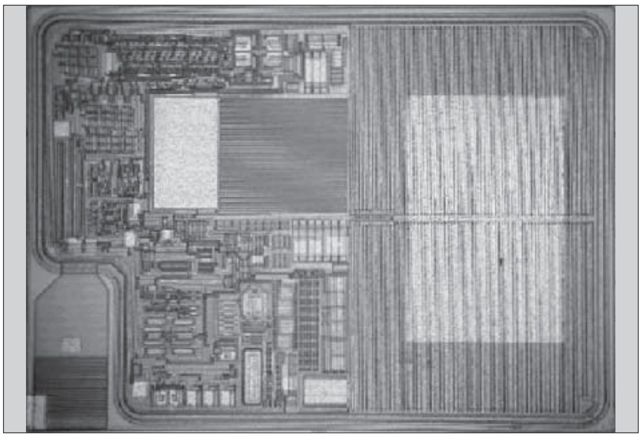


Fig.3 F6008L chip die photo



reliability is required. The F6008L has the following features and capabilities to satisfy such requirements.

(1) The F6008L achieves high system reliability by incorporating current-limiting and overtemperature protection functions.
(2) The F6008L realizes the same high surge withstand capability, high inductive load protection, high electromagnetic noise immunity and high resistance to adverse environmental conditions as the F5025, and additionally is provided with an overtemperature protection function.
(3) The F6008L integrates an igniter device and overtemperature protection function into the same TO-220 compact package as used to house the F5025.

A block diagram of the internal circuitry of the F6008L is shown in Fig. 2 and a chip die photograph is shown in Fig. 3.

3. Characteristics and Functions

Main electrical specifications and specific features of the F6008L are described below.

3.1 Electrical characteristics

Table 1 lists main electrical characteristics of the F5025 and F6008L. Electrical characteristics of the newly developed F6008L basically inherit those of the F5025, allowing easy device substitution without requiring additional circuit modification.

The collector-emitter voltage is determined by the Zener diode connected between the collector and gate, and the gate-emitter voltage is determined by the value of the surge protection Zener diode (ZD1). Because a current detection resistor is not used in the emitter line, the collector-emitter saturation voltage is low as same as the usual IGBT saturation voltage.

3.2 Overtemperature protection function

If a gate signal is input to the igniter device for a longer than usual duration, because the igniter load is a coil, the load current will reach an overcurrent state and device temperature will rise. In this case, the igniter device will activate its current-limiting function that is able to self-protect the device for a certain period of time. During normal operation, the duration of the gate signal input does not extend for a longer period of time than a certain presumed duration. But, for whatever reason, in the case where the duration of the ON signal exceeds this duration interval or the ambient temperature rises to an abnormal level or the like, the chip will generate an abnormal amount of heat that exceeds the design temperature, and this generated heat may cause damage to the chip.

For cases such as the above when an abnormally high temperature is reached, the F6008L is provided with an overtemperature protection function that operates to protect the chip from heat damage by forcibly turning off the IGBT collector current when the chip temperature reaches a certain value.

Figure 2 shows a schematic diagram of the overtemperature protection circuitry that is built into the chip. The F6008L integrates an IGBT power circuit and a control circuit into a single chip. An overtemperature detection unit built into the IGBT power circuit and a decision unit provided in the control circuit operate to detect and determine the temperature of the chip, and when a specific temperature is reached, the IGBT's gate is pulled-down to cutoff the collector current.

Features of the F6008L's overtemperature protection function are described below.

(1) High precision temperature detection using trimming technology

The F6008L uses Zener-zap trimming technology to suppress fluctuation in the overtemperature detection threshold temperature. Because the F6008L has overtemperature sensor and detection functions built into a single chip, temperature trimming can be

Table 1 Electrical characteristics of the F5025 and F6008L

Item	Symbol	Measurement condition	F5025		F6008L	
			Min.	Max.	Min.	Max.
Collector breakdown voltage	V_{CE}	I_C = 10 mA *	370 V	460 V	Same as at left	
Gate breakdown voltage	V_{GE}	I_{GE} = 10 mA	6 V	10 V	Same as at left	
Limiting current	I_{CL}	V_{GE} = 3.5 V * V_{CE} = 5 V	8.5 V	—	Same as at left	
Collector-emitter saturation voltage	$V_{CE\,(sat)}$	V_{GE} = 3.5 V * I_C = 6 A	—	1.7 V	Same as at left	
Gate-emitter threshold voltage	$V_{CE\,(th)}$	V_{CE} = 16 V * I_C = 3 mA	0.7 V	—	Same as at left	
Gate leakage current	I_{CES}	V_{CE} = 300 V	—	500 µA	Same as at left	
Gate pull-down current	I_{GES}	V_{GE} = 3.5 V *	2 mA	3.5 mA	2 mA	4 mA
Turnoff time	T_d T_f	V_{GE} = 3.5 V * I_C = 6 A	— —	35 µs 15 µs	Same as at left	
Overtemperature detection	T_{trip}	—	—		175°C	205°C

* T_j = –40 to +150°C (otherwise T_j = 25°C)

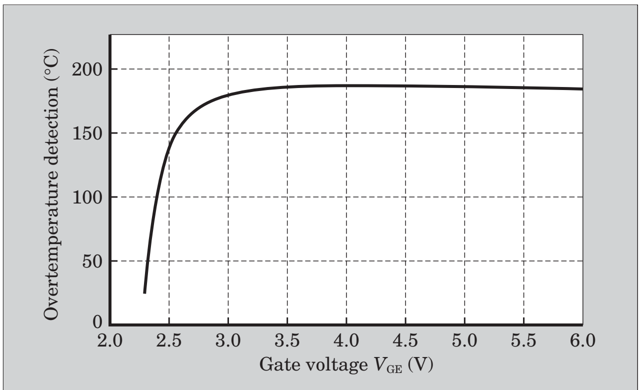
implemented by directly comparing fluctuations of both these characteristics. In the wafer probing process, both characteristics are compared and a selector is used to select the optimal detection value and correct the detection temperature. This technology has enabled the realization of high precision temperature trimming with an NMOS circuit.

(2) Realization of an overtemperature protection function using a 3-pin configuration

The F6008L is constructed such that the control circuit is provided with power via the gate input pin, and this enables overtemperature protection to be realized with the same 3-pin configuration as a stand-alone IGBT or F5025, without requiring the provision of an additional power supply pin, thereby achieving package interchangeability with the F5035. However, fluctuation in the characteristics of the overtemperature detection circuit (detection temperature fluctuation) due to fluctuation of the gate voltage (fluctuation of the power supply voltage for the control circuit) is a problem. The voltage of the gate signal from an electronic control unit (ECU) is typically in the range of 4.0 to 5.0 V, but an igniter device must be designed with the assumption that gate voltage will be lowered to 3.0 V or less. For an overvoltage detection circuit constructed from NMOS circuitry, the constituent circuitry will have a large fluctuation in detection temperature characteristics in this range of power supply voltage, and accordingly, the detection temperature will have a large dependency on gate voltage. To address this problem, the F6008L adds a circuit to correct for the fluctuation in characteristics caused by gate voltage, thereby making the detection temperature less dependent on gate voltage. Furthermore, so that the overtemperature detection threshold temperature does not rise above the maximum value of 205°C while the gate voltage is low, the F6008L has been designed such that its overtemperature detection threshold temperature will decrease together with the decrease in gate voltage.

These measures have dramatically decreased the fluctuation of detection temperature due to gate voltage fluctuation and have realized a mechanism that safely halts igniter operation when the gate voltage decreases. Figure 4 shows the gate voltage (circuit voltage) dependency of the overtemperature detection threshold temperature.

Fig.4 Overtemperature characteristics



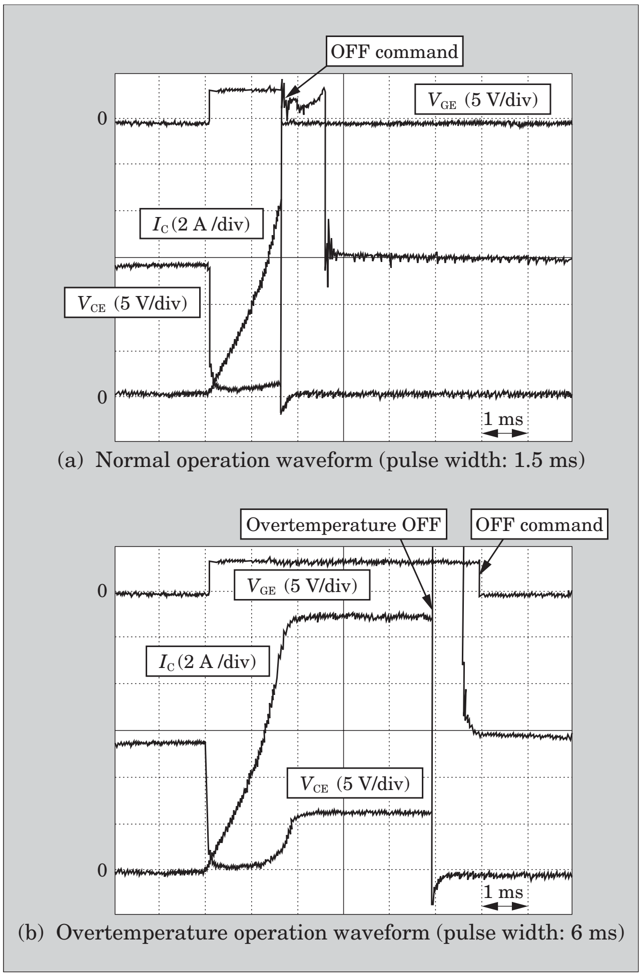
3.3 Current-limiting function

Because the igniter has a coil as its load, if the ON signal from the ECU continues for a long time, the collector current will increase up to the value determined by the battery voltage and the circuit inductance and resistance, and in the worst case scenario, the igniter will be damaged by an overcurrent. To prevent this from happening, it is critically important to add a current-limiting function.

Fuji Electric's single-chip igniter utilizes a current detection and limiting method based on sensing IGBT technology. Because this method does not require a current-detecting shunt resistor to be connected directly in series with the main IGBT, there is no voltage drop due to the flow of collector current through a shunt resistor, and therefore $V_{CE(sat)}$ can be reduced.

Also, to prevent the surge in collector-emitter voltage generated at the start of the current-limiting operation (which would generate an unnecessary voltage at the secondary coil and could potentially cause

Fig.5 F6008L operating waveforms



(a) Normal operation waveform (pulse width: 1.5 ms)

(b) Overtemperature operation waveform (pulse width: 6 ms)

Fig.6 Dynamic clamping characteristics

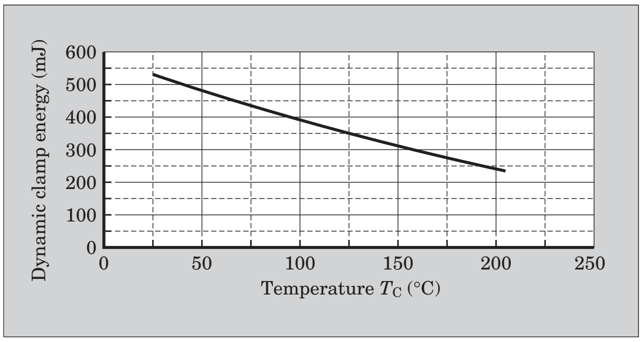
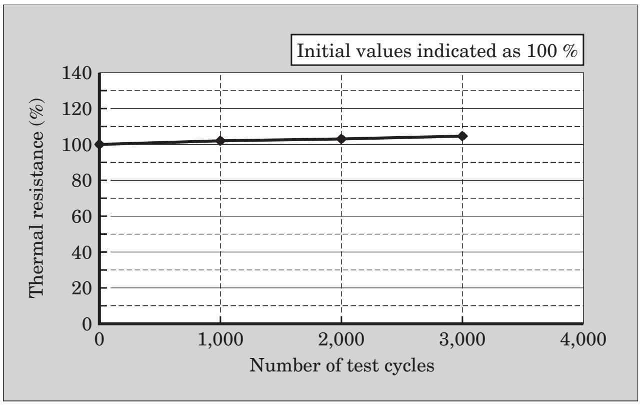


Fig.7 Thermal shock test results



unintentional ignition sparking), our single-chip igniters also utilize Fuji Electric's proprietary technology for preventing oscillation during current limiting, thereby resolving a problem which had been difficult to handle with only IGBT-based technology.

Waveforms during normal operation and in the case where current-limiting and overtemperature detection functions are active are shown in Fig. 5(a) and 5(b), respectively. Waveforms are shown assuming operation in the two cases where an ON signal is input for the usual ON duration (approximately 2 ms) and for a longer-than-usual ON duration (approximately 6 ms, where the ambient temperature was 170°C so that overtemperature detection would be easy to activate). It can be seen that the current-limiting function is not activated for the usual ON duration, but in the case of an extended ON duration, after current-limiting is activated, the overtemperature protection function acts to turn off the current even before an OFF signal is input.

3.4 Dynamic clamping

If the igniter device misfires, the device must be able to process the inductive load energy stored in the ignition coil. The amount of such energy is usually in the range of several tens of mJ to 100 mJ. Since the F6008L is specified for overtemperature detection in the range from 175°C to 205°C, a dynamic clamping capability of 100 mJ is guaranteed at the overtemperature detection threshold temperature.

Figure 6 shows typical dynamic clamping characteristics of the F6008L. It can be seen that the F6008L has sufficient capability even at the maximum overtemperature detection threshold temperature of 205°C.

3.5 Electromagnetic noise immunity

Electromagnetic noise immunity of the F6008L was verified using the TEM-cell method. We verified that in an electric field of 200 V/m and frequency range of 10 MHz to 1 GHz, there were no operational anomalies during current-limiting, overtemperature detection or ON-OFF switching operation.

Also, based on the assumption that noise will be input from the ignition coil or elsewhere to the gate pin, we performed a test in which an ESD (electrostatic discharge) surge (150 pF, 150 Ω, 5 to 25 kV) was applied between the gate and emitter pins as noise, and then verified that there was no anomaly in the operation of the overtemperature detection circuit under these conditions.

3.6 Resistance to environmental conditions

There is demand for igniter systems to be made smaller in size or packaged together with a coil in order to eliminate the high-tension lead between a coil and igniter device, and Fuji Electric is considering an integrated package as it continues to develop single-chip igniter technology. In the case of integration with a coil, because the resultant device will be mounted directly on an engine, it must be highly resistant to adverse environmental conditions in order to withstand the extreme temperature fluctuations in an engine compartment. Fuji Electric's single-chip igniter uses low-stress high-density resin and stress-resistant solder. As a result, after 3,000 cycles of a thermal shock test (– 55 to +150°C, ΔT_C = 205 K) the change in thermal resistance, which is an indicator of deterioration, was suppressed to 5 % or less, thereby verifying the strong resistance to environmental conditions. Figure 7 shows a graph of the thermal shock test cycle and change in thermal resistance.

4. Conclusion

Similar to the requirements automotive systems, ignition systems are also expected to require smaller size, greater functionality, higher performance and higher reliability in the future. In response to those requirements, Fuji Electric intends to promote the development of new small-size, multi-function, single-chip igniter products as successors to the F5025 and F6008L.

Reference

(1) Yoshida, K. et al. A Self-Isolated Intelligent IGBT for Driving Ignition Coils. Proceedings of the 10th ISPSD 1998, p.105-108.

Automotive Pressure Sensors

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Kazunori Saito
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1. Introduction

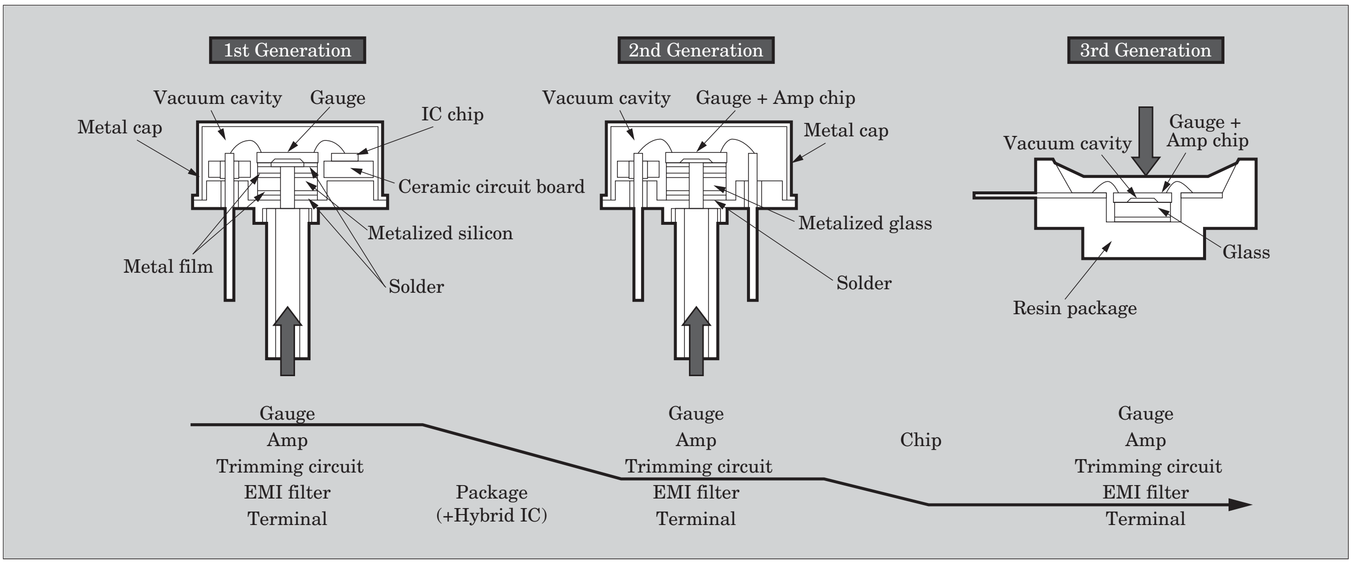
As the automotive industry moves to comply with global environmental regulations in Europe, North America, Asia and elsewhere, the industry is promoting efforts to boost the efficiency and to achieve higher control accuracy of engine systems. For the control of gasoline engines and diesel engines, a higher degree of accuracy is being required in pressure sensors in order to accurately monitor (measure) conditions such as the air volume and the exhaust gas pressure of the EGR (exhaust gas recirculation) system and to increase efficiency. Moreover, due to an increase in pressure sensor applications, such as the use of a barometric pressure sensor to perform altitude correction when driving at high-altitudes, automotive-use pressure sensors are required to have high accuracy and a low price.

In response to these requirements, Fuji Electric has developed an automotive pressure sensor with digital trimming that is fabricated using a CMOS (complementary MOS) process. Product development was based on the concept of providing an “all in single chip solution” and the commercialization of products was promoted with the goal of realizing the lowest possible product failure rate at low cost. This paper introduces Fuji Electric’s product lineup and future outlook for automotive pressure sensors.

2. Special Features

Figure 1 shows the technical trends of pressure sensor cell in Fuji Electric’s automotive pressure sensor cells. Fuji Electric’s first generation of mass-produced automotive pressure sensors in 1984 used pressure sensor chips equipped with only a gauge function, and other functions such as an amplifier circuit, trimming resistor and EMI filter were provided by packaging the sensor together with a hybrid IC. Subsequently, as of the second generation, a thin film trimming resistor for trimming was built-in to the chip. In the newly developed pressure sensor as the third generation, a vacuum cavity is fabricated by means of anodic bonding of glass and silicon, and the device construction consists of connection terminals and a resin package housing a sensor chip and its built-in functions only. The material for the resin package was selected based on considerations such as

Fig.1 Technical trends of pressure sensor cell



adhesion to the connection terminals and temperature stability.

2.1 Pressure sensor chip

The pressure sensor chip developed by Fuji Electric is shown in Fig. 2. This chip was realized using Fuji Electric's proprietary MEMS (micro-electronics and mechanical system) technology and is provided with the following functions.

1) A function for converting pressure into strain
2) A function for providing a vacuum cavity
3) A function for converting a change in resistance into an electrical signal

Fig.2 Pressure sensor chip

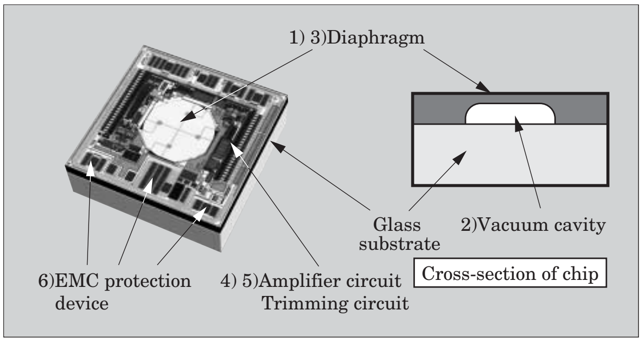


Table 1 Absolute maximum ratings

Item	Symbol	Unit	Standard specification
Overvoltage	V_{max}	V	<16.5 V
Storage temperature	T_{sto}	°C	−40 to +135
Proof pressure	P_{max}	%F.S.	200
Burst pressure	P_{burst}	%F.S.	300
International EMC standards	JASO D00-87, CISPR25, ISO11452-2, ISO7637		

Table 2 Standard specifications

Item	Symbol	Unit	Standard specification
Operating voltage	V_{cc}	V	5±0.25
Operating current	I_{cc}	mA	<10
Operating temperature	T_{op}	°C	−40 to +135
Output voltage	V_{out}	V	0.5 to 4.5
Measurement pressure range*1	P_{op1}	kPa	10 to 120
	P_{op2}	kPa	20 to 250
	P_{op3}	kPa	50 to 300
	P_{op4}	MPa	up to 20 *2
Sink current	I_{sink}	mA	1
Source current	I_{source}	mA	0.1
Pressure error	V_{per}	%F.S.	<1.0
Temperature error	V_{ter}	%F.S.	<1.5

*1 : The pressure range can be set to an arbitrary value with the diaphragm thickness.
*2 : 20 MPa high-pressure products are presently under development.

4) A function for amplifying electrical signals
5) A function for adjusting electrical signals to specific characteristic values and then maintaining that adjustment
6) A function for protecting electrical signals from external noise

In particular, compared to a conventional bipolar process, the use of a CMOS process enables this pressure sensor chip to achieve a higher degree of EMC protection (such as overvoltage, ESD, EMI, and surge protection), as is required of automotive-use devices.

Figure 2 shows the pressure sensor chip developed by Fuji Electric. A diaphragm that realizes the abovementioned functions 1) and 3) is formed in the center of the silicon chip. Also, technology for anodic bonding to the glass substrate provides the abovementioned function 2), and ensures high reliability by maintaining a high vacuum condition for an extended period of time. Moreover, an amplifier circuit and trimming circuit for supplying functions 4) and 5) are provided at the periphery of the diaphragm. The absolute maximum ratings and standard specifications for a pressure sensor that uses this chip are shown in Tables 1 and 2, respectively.

2.2 Concept of the product lineup

Fuji Electric's automotive pressure sensors are based on the concepts shown in Fig. 3 and this product

Fig.3 Concept of pressure sensors

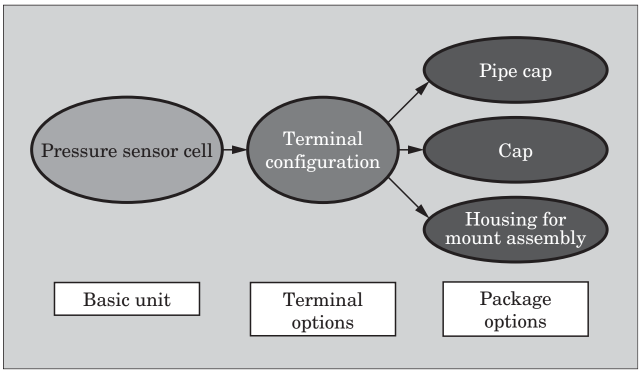
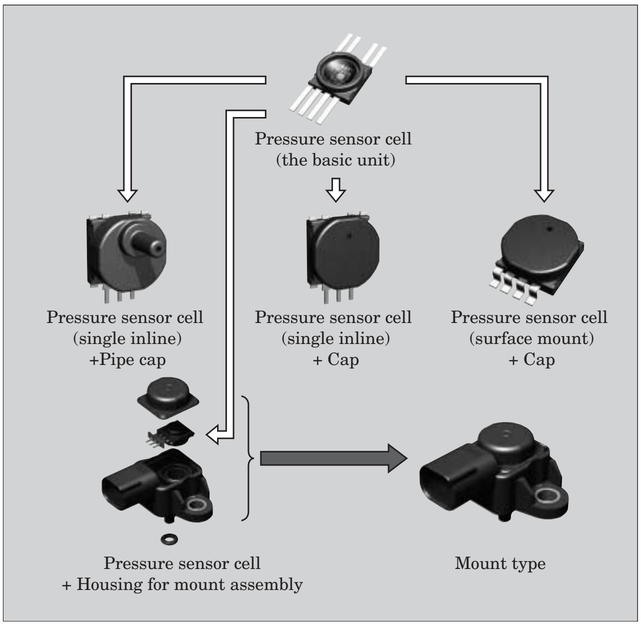


Table 3 Examples of automotive pressure sensor applications

Application		Pressure range	Remark
Engine	Manifold pressure	120 kPa	Commercial production
	Turbocharged pressure	250 kPa	
	Diesel	300 kPa	
	EGR	250 kPa	
	Barometric pressure	120 kPa	
Air conditioner	R134a	5 MPa	Under development
	CO_2	20 MPa	
Oil actuator	Brake system	5 MPa	Under development
	Power steering	5 MPa	
CVT		10 MPa	Under development

Fig.4 Packages for Fuji Electric's lineup of pressure sensors



lineup is configured from the combination of a pressure sensor cell, terminal configuration and package option. Table 3 lists example applications of automotive pressure sensors.

(1) Pressure sensor cell

A pressure sensor cell houses the pressure sensor chip and provides the capability for outputting sensor signals from the pressure sensor chip to the exterior. The pressure sensor cell is the most basic unit in Fuji Electric's pressure sensor products. The package material was selected based on assumed usage in such automotive applications as the measurement of intake manifold suction, EGR exhaust gas pressure and the like, and chemical compatibility with materials such as gasoline, diesel gasoline, lubricant and the like. This pressure sensor cell forms the basis of Fuji Electric's standard package lineup of pressure sensor products. Even among products of different terminal configurations, final package shapes and pressures ranges, because all pressure sensor cells are manufactured on the same production line, a significant reduction in production cost is achieved.

(2) Terminal configuration

The terminal configuration of the pressure sensor cell can be selected to support a particular application in which the pressure sensor chip will be mounted. Figure 4 shows examples of Fuji Electric's standard specifications. Single inline, surface mount and other types of terminal configurations can be supported.

(3) Package options

In response to various requests from customers, the pressure sensor cell package supports the attachment of hardware for the mechanical interface (pipe, cap, mount type) to a particular application. Figure 4 shows Fuji Electric's standard product series. The pipe and cap type are examples of applications in which the pressure sensor will be mounted on a printed circuit board, and the mount type is an example suitable for installation on an engine. A new high-voltage package is currently under development.

3. Conclusion

This paper has described the product concept behind Fuji Electric's automotive pressure sensor products and introduced the product lineup that has been developed.

Environmental and safety regulations of various countries throughout the world are expected to lead to increasingly severe requirements for the accuracy, quality and price of automotive pressure sensors in the future, and Fuji Electric remains committed to the development of world-class automotive pressure sensor technology and products.

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