Automotive Smart MOSFETs

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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.

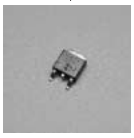
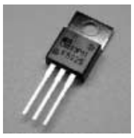
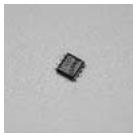
2.2 Characteristics

(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
	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 mm^2 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.

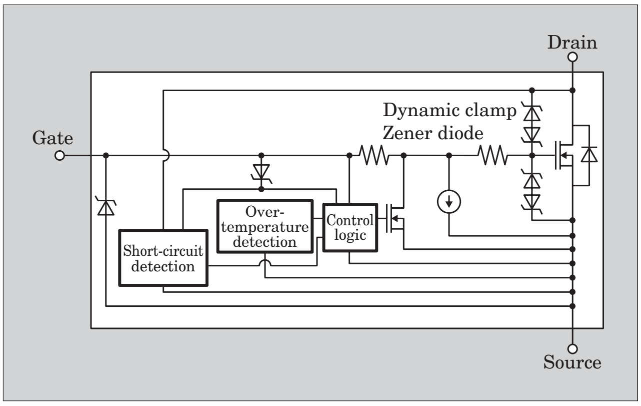
The intelligent power MOSFET is designed for auto-restart upon returning from an operating sequence of short-circuit and overtemperature detection. Moreover, compared to the case where the temperature sensor is located next to the active part of the power

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

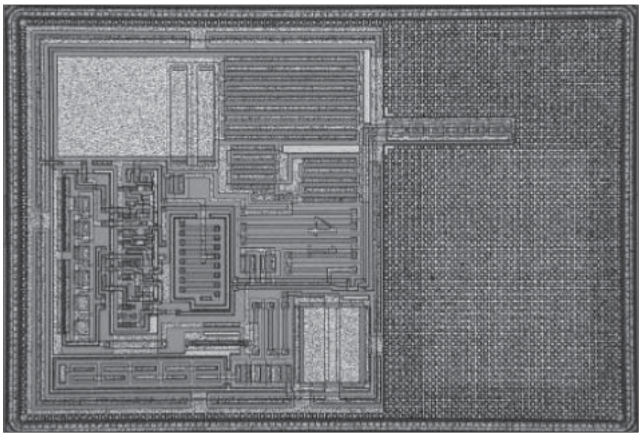


Fig.3 F5041 waveform at time of short-circuit detection, current limiting, and overtemperature detection

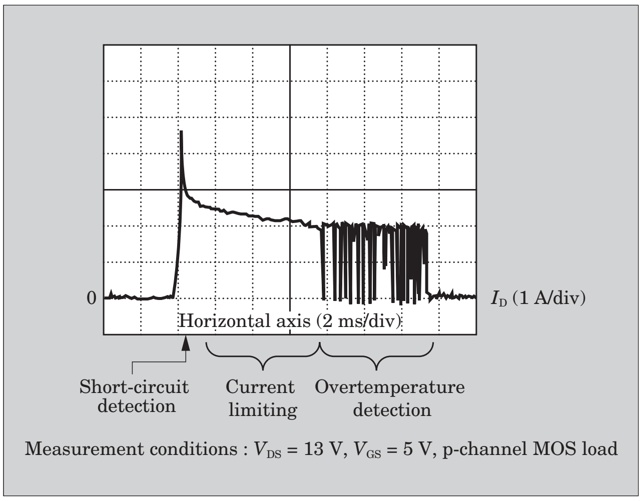
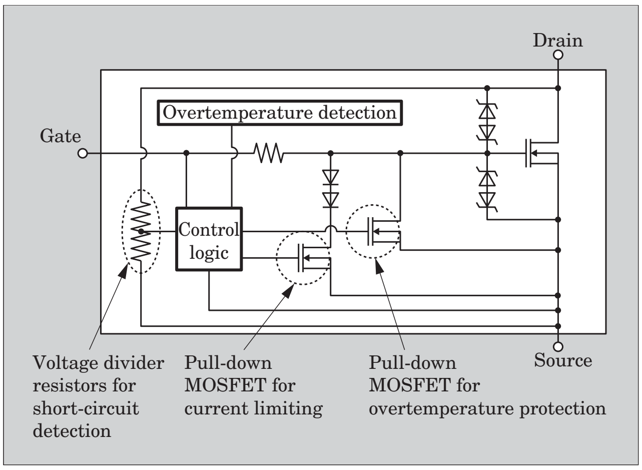


Fig.4 F5041 circuit for short-circuit detection, current limiting and overtemperature detection



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

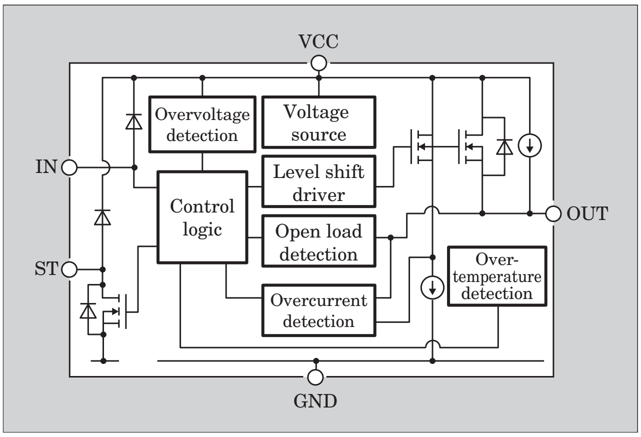


Fig.6 F5044H chip die photo

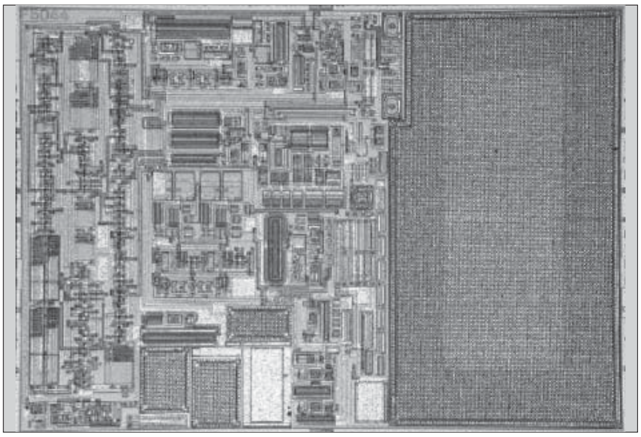


Fig.7 F5044H waveform during sequence from overcurrent detection to output switching mode

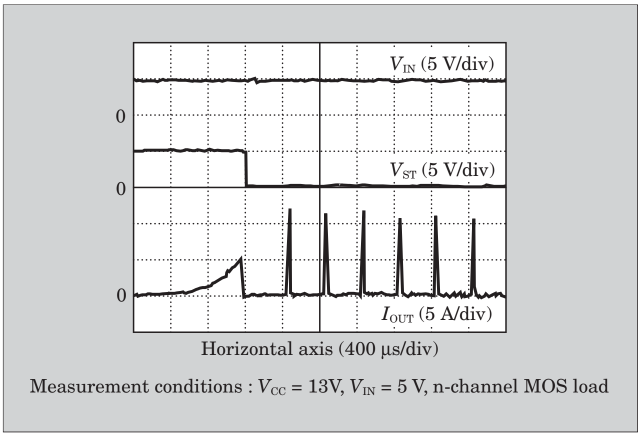


Fig.8 Comparison of mounting area and acceptable conduction capacity of the TO-220F-5 package IPS and SOP-8 package IPS

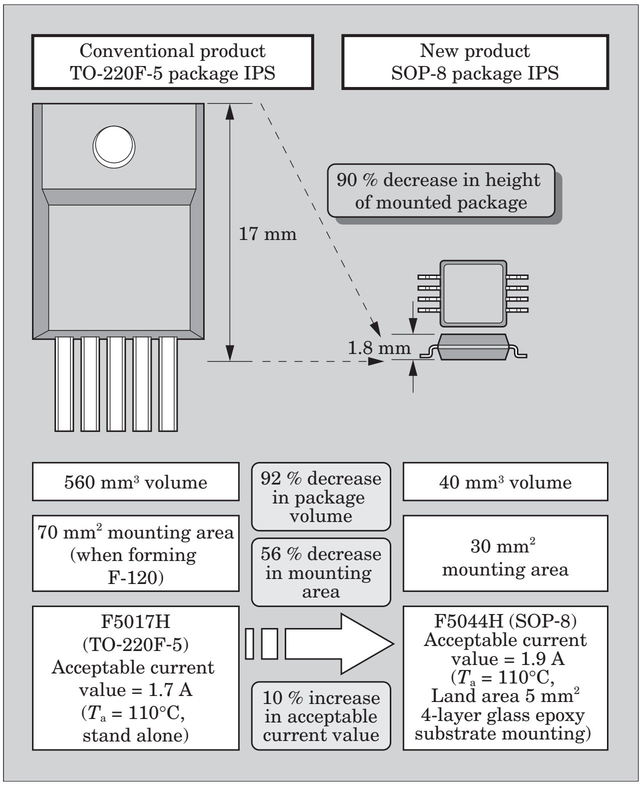
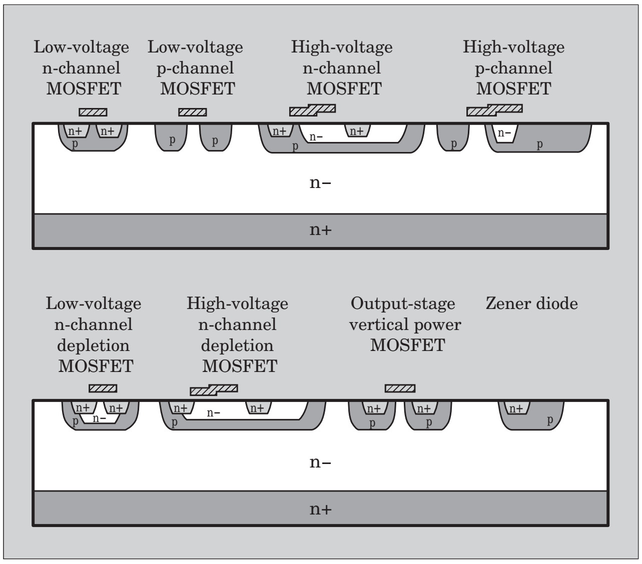


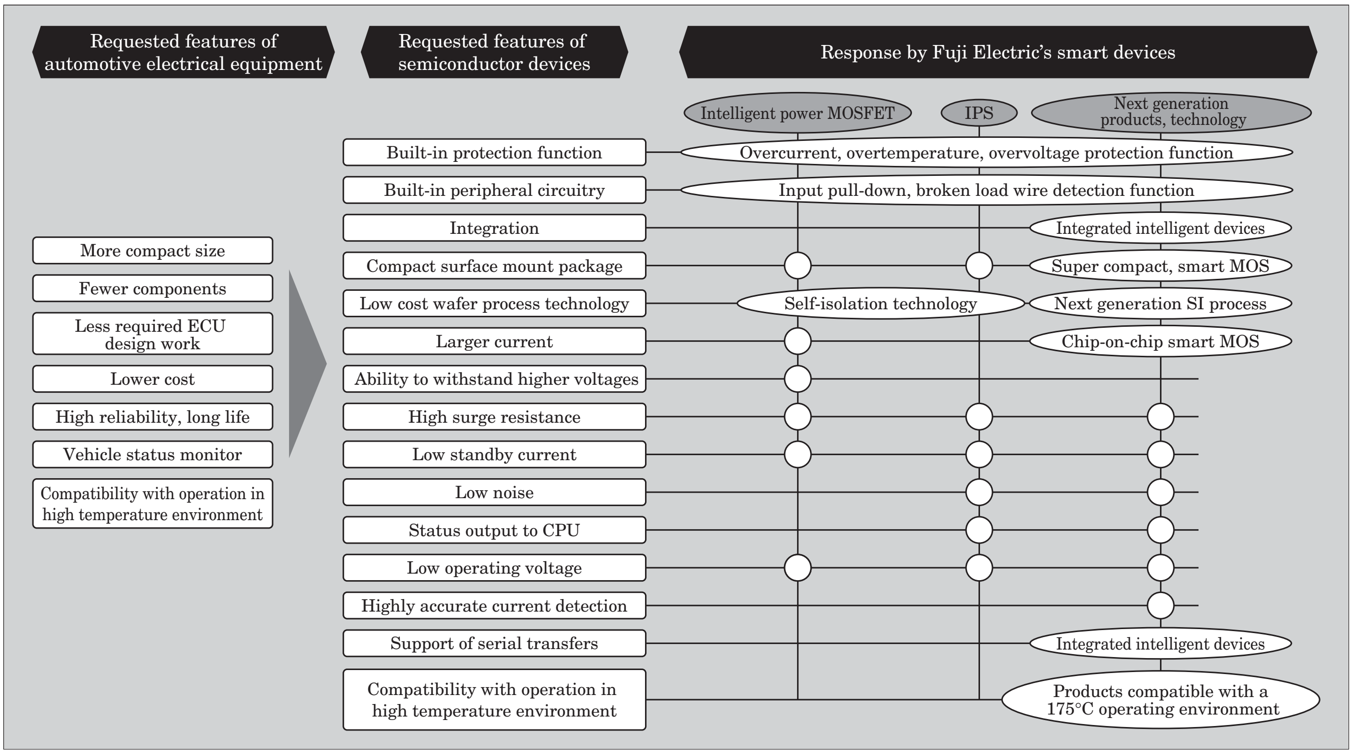
Fig.9 Cross-section of self-isolation structure (IPS)



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.