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POWER TRANSISTORS

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I. INTRODUCTION

A complete series of Fuji power darlington transistors, high capacity transistors up to 50 A, high-speed switching transistors, high gain ultra-high-β transistors, and BBT 100 A class moulded transistors featuring the superior characteristics of the planar construction has already been commercialized through the adoption of triple diffused planar techniques.

Generally, power electronics applied equipment can be grouped by function into sensor, controller, driver, and power sections. The rapid technological advances made in recent years have been accompanied by tremendous advances in the integration and modularization of controllers, but integration and simplification of the power section and its peripheral circuitry has been slow.

The characteristics and applications of the various multiple transistors commercialized as one approach to meeting the demand for simplification of the power section and the power MOS FET commercialized to meet the same demands by symplifying the drive stage through the adoption of planar technology by Siemens are introduced.

II. SIMPLIFICATION OF POWER SECTION AND ITS PERIPHERAL CIRCUITRY

On the practical level, there are the following three methods of simplifying the power section and its peripheral circuitry:

(1) Combining power elements
(2) Combining power elements and accessory elements
(3) Eliminating the drive stage

(1) is a combination of the same or different kind of power elements, e.g. thyristors transistors, diodes, and is called a power module, power unit, etc., (2) applies to the addition of protection elements, etc. and (3) corresponds to power elements containing the drive stage inside the power section or which do not need a drive stage.

This article introduces the power transistor and Darlington power transistor module with a built-in fast recovery diode as typical of (1), power transistor with built-in protection zener diode as typical of (2), and a power MOS FET that can be driven directly by a microcomputer or LSI output as typical of (3).

III. POWER TRANSISTOR WITH FAST RECOVERY DIODE FOR MOTOR CONTROL

Because the selfcommutating characteristics and switching speed of power transistors are better than those of thyristors, they have gained attention in the motor control field together with improvements in the control characteristics of motors and the appearance of high performance, high power transistors. Power transistors are used in motor control as a pair with fast recovery diode because the load is inductive and of the relationship with power regenerating operation.

1. Equivalent circuit

Three types of power transistors, ET127 (100A), 2SD1056 (50A), and 2SD1067 (30A), have been added to our current power transistor line. *Fig. 1* shows the exterior of these transitors and *Fig. 2* shows the equivalent circuit.

Fig. 1 Exterior view of power transistors including fast recovery diode

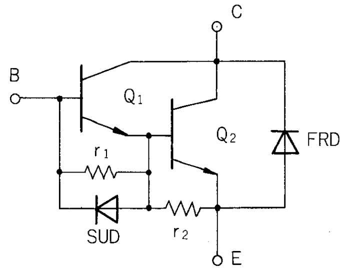

Fig. 2 Equivalent circuit of power transistor including fast recovery diode

The elements connected in anti-parallel from the emitter to the collector of the transistor.

In the figure, the element connected in anti-parallel from emitter to collector is a fast recovery diode and the diode between the drive-stage transistor base and emitter is a so-called speed-up diode to shorten the transistor turn-on time.

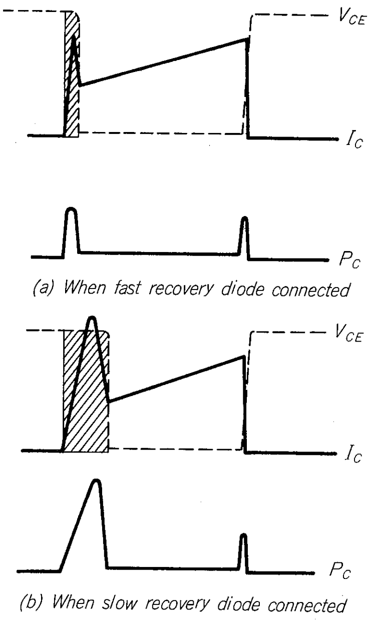

Fig. 4 Comparison of turn on losses

2. Need for the fast recovery diode

The PWM (pulse width modulation) transistor inverter output section and its operating waveforms are shown in *Fig. 3.* If,

Q_1 : Off
Q_2 : On
Q_3 : PWM operation
Q_4 : Off

During time t_1, current i_{t1} flows through the path B → Q_2 → M → Q_3 → B and during time t_2, i_{t2} flows through the path M → D_1 → Q_2 → M_2. Since forward current i_{t2} flows in D_1 during time t_2, at the end of t_2 and the beginning of t_3, a reverse recovery current flows in D_1. Because this current is superimposed on the collector current of Q_3, the transistor turn-on loss increased.

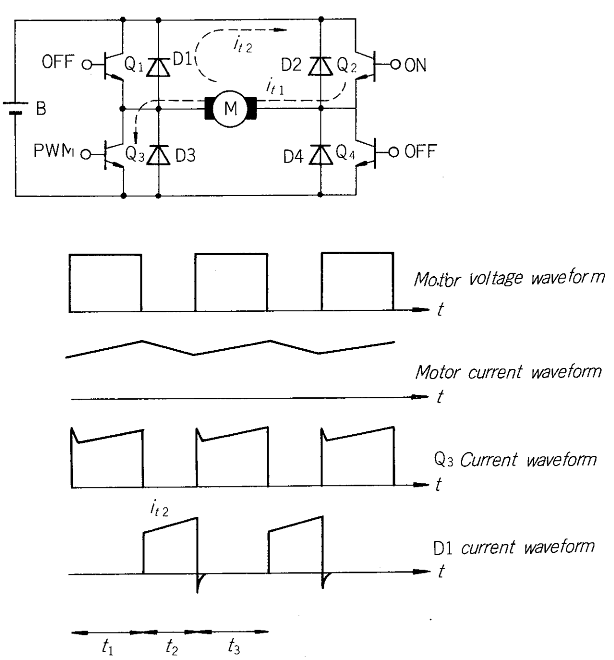

Fig. 3 Output circuits and their operating wave forms of transistor inverter

The turn-on loss of Q_3 when a fast recovery diode is used at D_1 and when a slow recovery diode is used at D_1 is compared in *Fig. 4.* D_1 must be a fast revovery diode to reduce the turn-on loss. Similarly, D_2, D_3, and D_4 should also be fast recovery diodes.

3. Characteristics of fast recovery diode

In order to apply this kind of transistor to the motor control field, special consideration was given to an internal fast recovery diode in the following points:

(1) $V_{RRM} = V_{CBO}$: The maximum reverse repetitive voltage of the fast recovery diode was made the same as V_{CBO} of the power transistor.

(2) $I_{F\,max} = I_{C\,max}$: Since a current over the current that flows in the transistor does not flow in the fast recovery diode, the current capacity of both the transistor and diode was made the same.

(3) t_{rr} = 0.3 μs: As previously described, the reverse recovery time t_{rr} is important in governing the turn-on loss of the transistor and a short t_{rr} level for a 600 V class unit was realized. Of course, a balance of t_{rr} was taken by considering the diode forward voltage drop and reverse leakage current.

4. Ratings and characteristics

Table 1 shows the main ratings and characteristics of the three types. The special features of the characteristics of this series are a safe operating area, especially a large reverse bias SOA, and a fast switching speed.

The h_{FE}-I_C curve of the ET127 is shown in *Fig. 5*, its switching characteristics are shown in *Fig. 6*, and the

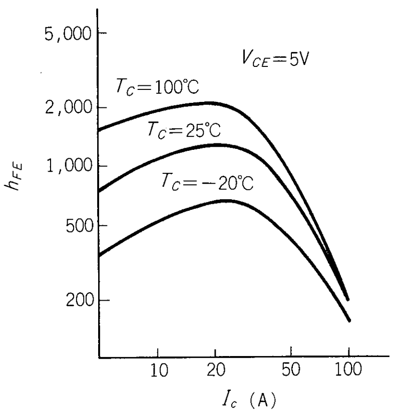

Fig. 5 h_{FE}-I_C characteristics of ET 127

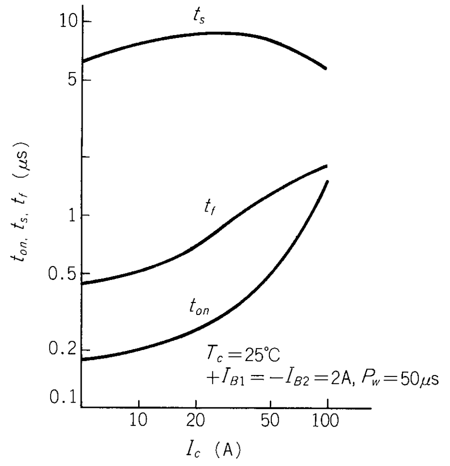

Fig. 6 Switching time of ET 127

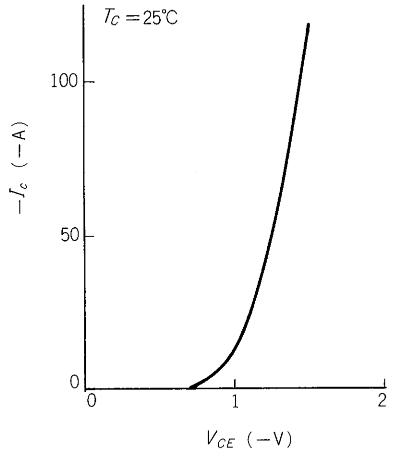

Fig. 7 Forward characteristics of fast recovery diode in ET 127

Table 1 Rating and characteristics of power transistors including fast recovery diode

Type		2SD 1067	2SD 1056	ET 127
Construction		Darlington	Darlington	Darlington
Maximum ratings	V_{CBO} (V)	600	600	600
	V_{CEO} (V)	600	600	600
	$V_{CEO(sus)}$ (V)	450	450	450
	V_{EBO} (V)	6	6	6
	I_C (A)	30	50	100
	$-I_C$* (A)	30	50	100
	P_C (W)	200	400	770
	T_j (°C)	+150	+ 150	+ 125
Electrical characteristics (T_C=25°C)	h_{FE} [V_{CE},I_C]	100 [5V,30A]	100 [5V,50A]	100 [5V,100A]
	$V_{CE(sat)}$ (V) [I_C,I_B]	2.0 [30A,0.6A]	2.0 [50A,1A]	2.0 [100A,2A]
	$V_{BE(sat)}$ (V) [I_C,I_B]	2.5 [30A,0.6A]	2.5 [50A,1A]	3.0 [100A,2A]
	t_{on} (μs) [I_C,I_{B1}]	3.0 [30A,0.6A]	3.0 [50A,1A]	4.0 [100A,2A]
	t_{stg} (μs) [I_C,I_{B1},I_{B2}]	12.0 [30A,0.6A,-0.6A]	12.0 [50A,1A,-1A]	10.0 [100A,2A,-2A]
	t_f (μs) [I_C,I_{B1},I_{B2}]	4.0 [30A,0.6A,-0.6A]	4.0 [50A,1A,-1A]	3.0 [100A,2A,-2A]
	Package	MD-18	MD-18	BBT

(Note) $-I_C$: Internal fast recovery diode current capacity

forward characteristics of the fast recovery diode are shown in *Fig. 7* as typical examples.

IV. DARLINGTON POWER TRANSISTOR MODULE

The power transistor including a fast recovery diode described in the preceding section is actually used more as a unit than a combination of multiple elements such as shown in *Fig. 3*. Therefore, the common parts can be unitized and operation increased for rationalization in actual applications.

The series of power transistor modules containing two Darlington power transistors and two fast recovery diodes in a moulded package and having a 600 V voltage rating and 30 A, 50 A, 75 A and 100 A current ratings are briefly described.

1. Exterior of power transistor module

Exterior views of the power transistor module are shown in *Fig. 8*.

The power transistor and fast recovery diode chip are brazed to the heat sink through an insulation plate.

This is the so-called isolated collector type. All electrodes are arranged on the same plane.

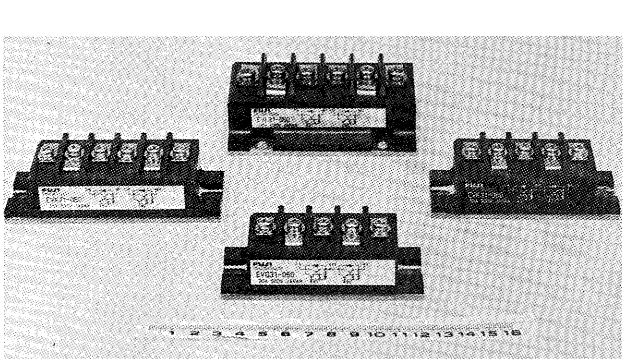

Fig. 8 Exterior view of power unit

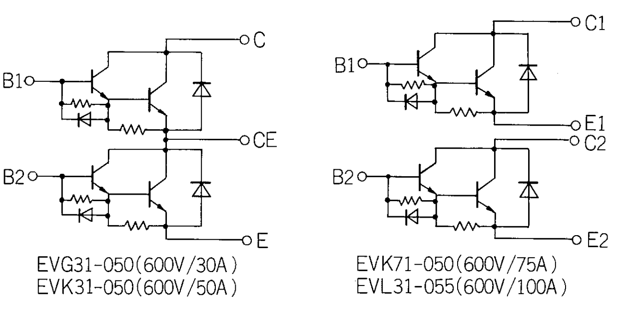

Fig. 9 Equivalent circuits of power transistor modules

Table 2 (a) Maximum ratings of Fuji power transistor modules

Rating	Symbol	Cond.	EVG31-050	EVK31-050	EVK71-050	EVL31-055	Unit
Collector-Base Voltage	V_{CBO}		600	600	600	600	V
Collector-Emitter Voltage	V_{CEO}(sus)		450	450	450	500	V
Emitter-Base Voltage	V_{EBO}		6	6	6	6	V
Collector Current	I_C	DC	30	50	75	100	A
Base Current	I_B	DC	2	3	4.5	6	A
Power Dissipation	P_C	T_C=25°C	200 x 2	300 x 2	350 x 2	500 x 2	W
Junction Temperature	T_j		150	150	150	150	°C
Strage Temperature	T_{stg}		−40~+125	−40~+125	−40~+125	−40~+125	°C

(b) Electrical characteristics of Fuji power transistor modules

Characteristics	Symbol	EVG31-050		EVK31-050		EVK71-050		EVL31-055		Unit
Collector-Emitter Voltage	V_{CEO}(sus)	≧450 (I_C=1A,R_{BE}=∞)		≧450 (I_C=1A, R_{BE}=∞)		≧450 (I_C=1A, R_{BE}=∞)		≧500 (I_C=1A, R_{BE}=∞)		V
Collector-Emitter Voltage	V_{CEX}(sus)	≧500 I_C=30A,I_B=+0.6A,-3A V_{CE}=500Vpeak,V_{EB}=6V		≧500 I_C=50A,I_B=+1A,-5A V_{CE}=500Vpeak,V_{EB}=6V		≧500 I_C=75A,I_B=+2A,-2A V_{CE}=500Vpeak,V_{EB}=6V		≧550 I_C=100A,I_B=+3A,-3A V_{CE}=550Vpeak, V_{EB}=6V		V
Collector Cutoff Current	I_{CBO}	≦1.0 (V_{CBO}=600V)		≦1.0 (V_{CBO}=600V)		≦1.0 (V_{CBO}=600V)		≦1.0 (V_{CBO}=600V)		mA
Emitter Cutoff Current	I_{EBO}	≦200 (V_{EBO}-6V)		≦200 (V_{EBO}-6V)		≦200 (V_{EBO}=6V)		≦300 (V_{EBO}=6V)		mA
DC Current Gain	h_{FE}	≧100 (I_C=30A, V_{CE}=5V)		≧100 (I_C=50A, V_{CE}=5V)		≧70 (I_C=75A, V_{CE}=5 V)		≧70 (I_C=100A, V_{CE}=5V)		
Collector-Emitter Saturation Voltage	V_{CE}(sat)	≦2.0 (I_C=30A,I_B=0.6A)		≦2.0 (I_C=50A,I_B=1A)		≦2.0 (I_C=75A,I_B=2A)		≦2.0 (I_C=100A,I_B=3A)		V
Base-Emitter Saturation Voltage	V_{BE}(sat)	≦2.5 (I_C=30A,I_B=0.6A)		≦2.5 (I_C=50A,I_B=1A)		≦2.5 (I_C=75A,I_B=2A)		≦2.5 (I_C=100A,I_B=3A)		V
Resistive Switching Time	t_{on}	I_C=30A I_B=±0.6A R_L=10Ω P_W=50μs	≦ 3.0	I_C=50A I_B=±1A R_L=6Ω P_W=50μs	≦ 3.0	I_C=75A I_B=±2A R_L=5Ω P_W=50μs	≦ 2.0	I_C=100A I_B=±3A R_L=4Ω P_W=50μs	≦ 2.0	μs
	t_{stg}		≦12.0		≦12.0		≦10.0		≦12.0	μs
	t_f		≦ 4.0		≦ 4.0		≦ 2.5		≦ 3.0	μs

2 . Ratings and characteristics of power transistor module

The circuit construction of the EVG31-050, EVK31-050, EVK71-050, and EVL31-055 power transistor modules is shown in *Fig. 9.* The ratings and characteristics are given in *Table 2*.

V. TRANSISTOR INCLUDING ZENER DIODE FOR IGNITION CIRCUIT

The use of electronic ignition circuits for automobiles and motorcycles, etc. has been advancing for several years in conjuntion with exhaust gas restrictions and maintenance-free operation. The power transistor used in this application must, of course, be highly reliable and must have a low saturation voltage characteristic and high secondary break-down capacity ($E_{s/b}$) for cold starting. It is well known that the secondary breakdown capacity can be increased and the transistor can be protected against surge voltages by connecting a zener diode between the collector and base. The 2SD706 power transistor with a discrete zener diode chip integrated on the same package (TO-3) as the power transistor has already been developed for this purpose and is highly praised by the market. In recent year, a demand has arisen for a moulded package to make the package smaller and cut costs. However, mounting a discrete power transistor chip and zener chip together on a TO-220 moulded package is difficult because of the problem of space.

Therefore, the 2SD1071 that contains a zener diode on the same chip as the power transistor was developed.

1. Equivalent circuit and necessity of zener diode

Fig. 10 is the equivalent circuit of the 2SD1071. The special feature of this unit is that a zener diode is connected between the collector and base of the power transistor.

The power transistor in a full transistor ignition circuit is operated by the voltage and current waveforms shown in *Fig. 11.* When an input signal is applied to the base at the state in which the transistor is blocking the power supply voltage V_{cc}, the transistor turns on and the collector current increases. When the base current is cutoff, the energy stored in the primary side of the ignition coil generates a high kick-back voltage onto the transistor.

The operating point at this time when a zener diode is included and when a zener diode is not included is compared in *Fig. 12.* As can be seen from *Fig. 12,* when a

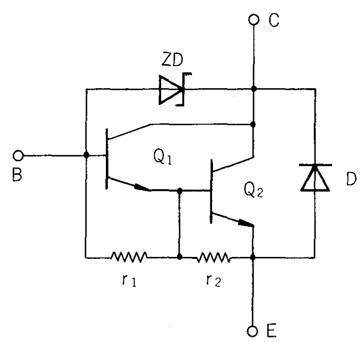

Fig. 10 Equivalent circuit of 2SD 1071

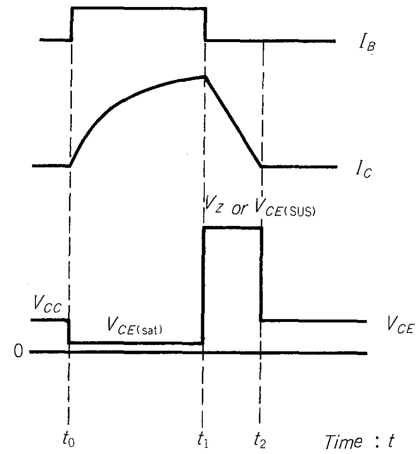

Fig. 11 Operating wave forms of full transistor ignition system

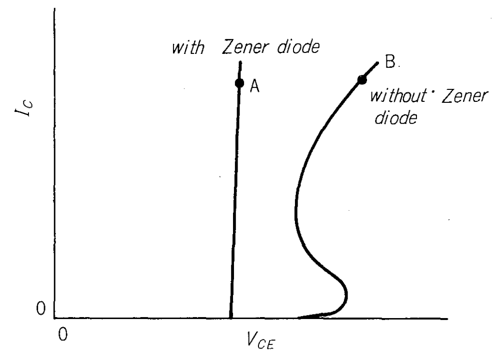

Fig. 12 Operating locus of transistor for ignition

zener diode is included, the operating voltage is low (point A) and when a zener diode is not included, the operating voltage is high (point B) and it can be seen that operating locus exceeds the safe operating area.

Therefore, it can be seen that the zener diode is important as a power transistor protection element.

2. Ratings and characteristics

Table 3 shows the ratings and characteristics of the 2SD1071. The following points have been given special consideration as a transistor including a zener diode chip:

1) Zener voltage (V_Z)

(1) Upper limit: 450V because of the relationship with the transistor secondary breakdown capacity.

(2) Lower limit: 300V because of the relationship with the ignition coil secondary side voltage at low temperature.

2) Zener diode avalanche capacity

Table 3 Ratings and characteristics of 2SD1071

	Item	Units	Ratings and characteristics		
Maximum rating	V_{CBO}	V	(450) *1		
	V_{CEO}	V	(450) *1		
	V_{EBO}	V	6		
	I_C	A	6		
	I_E	A	6		
	P_C	W	40		
	T_j	°C	+150		
Electrical characteristics (T_C= 25°C)			Condition	min	max
	V_Z *2	V	I_Z=100μA	300	450
	h_{FE}	–	I_C=4A V_{CD}=2V	500	
	V_{CE} (sat)	V	I_C=4A		1.5
	V_{BE} (sat)	V	I_B=15mA		2.0
	V_{ECO} *3	V	I_E=6A		1.5
	Package		EIAJ: SC-46,JEDEC: TO-220AB		

Notes) *1: Unmeasurable because a zener diode.
*2: Zener voltage
*3: V_F characteristics of internal reverse diode

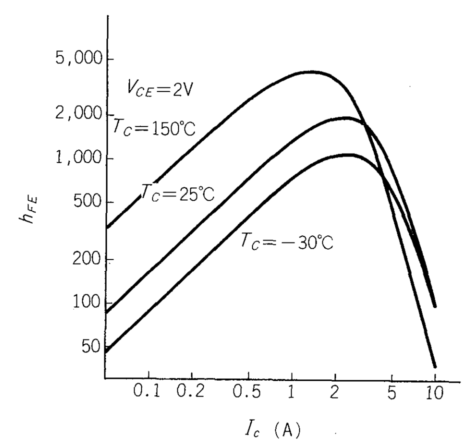

Fig. 13 h_{FE}-I_C characteristics of 2SD 1071

The avalanche capacity was designed not only to amply withstand the coil primary kickback voltage, but to also withstand the kickback voltage from the secondary side when the secondary side is open and to have high reliability.

3) Zener diode construction point

For good heat dissipation and to eliminated at the bulk part.

4) Internal reverse diode

To minimze the calorific value at battery reverse connection, the internal reverse diode current rating (I_E) was made 6 A and the forward voltage drop (V_{ECO}) was made a maximum 1.5 V.

The h_{FE}-I_C characteristics of the 2SD1071 are shown in *Fig. 13* and the characteristics of the zener diode are shown in *Fig. 14* as typical characteristic curves.

3. Application example

Fig. 15 shows the example of an igintion circuit when the 2SD1071 was applied to four wheel and two vehicles.

VI. SIPMOS TRANSISTOR

Advances made in the use of microcomputers and LSI

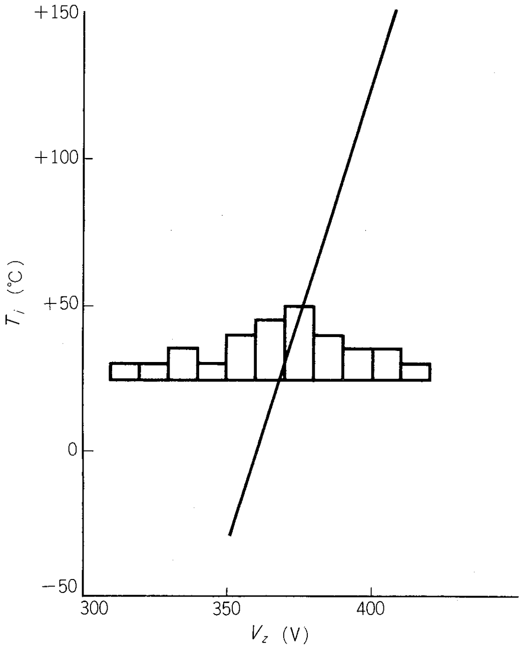

Fig. 14 Characteristics of Zener diode

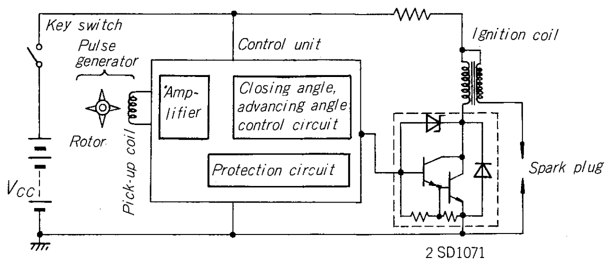

Fig. 15 Example of ignition circuit

process controllers has been accompanied by an increase in the need to replace mechanical switches with higher sensitivity semiconductor switches.

Thyristors, triacs, and bipolar transistors need higher input power than the power which is directly supplied by a microcomputer or LSI. When connecting both, an amplifier is generally necessary. This has hindered their growth from the standpoints of cost and volume.

The MOS transistor is already well known as a switching device that can be driven directly by a microcomputer and LSI. Siemens has developed a power MOS transistor with improved on resistance that is both easier to use and cheaper. This transistor is called the SIPMOS power transistor.

1. Construction and operation of the SIP MOS power transistor

Fig. 16 shows the construction of the SIP MOS power transistor. This transistor is a so-called DMOS FET.

The n^+ polysilicon which covers the surface of the chip in the form of a grid is insulated from the source bulk silicon region directly below it and the aluminum metallized

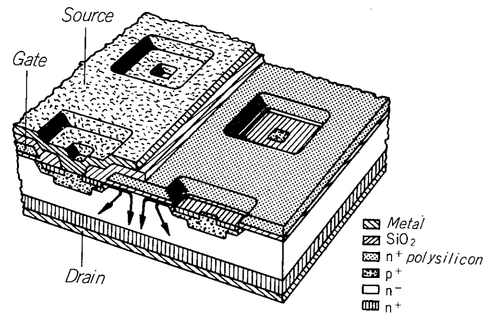

Fig. 16 Chip structure of SIP MOS power transistor

source electrode by a silicon oxide film. The source electrode aluminum lay connects to the source element through holes between the gate grid. The gate grid forms about 3000 cells on a 4 mm x 4 mm chip, for instance.

If an amply high voltage is applied between the source and gate and a plus voltage is applied to the gate, a thin negative charge layer is produced at the p^+ region directly below the gate. This is the conduction channel between the source and drain. (*Fig. 16*) and forms a state which causes current to flow vertically between the source and the drain at the bottom.

When a zero or minus bias is applied between the gate source contacts, a conduction channel is not formed and the electrons cannot cross the p^+ barrier. Consequently, the device is in the blocked state and current does not flow. Since a positive charge is injected at the n^- region by applying a reverse bias of $V_{DS}<0$ to the p^+n^- junction, the transistor operates as a diode.

2. Features of the SIPMOS transistor

The transistor announced so far as power MOS FET commonly called vertical or horizontal types. The vertical type is grouped into devices with the surface grooved to a V-shape as typified by the so-called VMOS and flat type devices, or so-called DMOS. The SIPMOS belongs to the DMOS type.

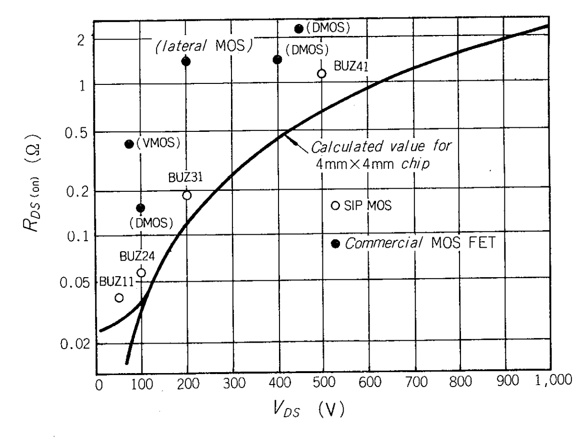

Fig. 17 Theoretical and actual on-resistance of MOS FET

Table 4 Line-up of SIPMOS power transistors

Type		BUZ 10...	BUZ 20...	BUZ 30...	BUZ 40...	BUZ 50...
V_{DS}	(V)	50	100	200	500	1,000
I_{DS}	(A)	12~40	8~28	5.5~14	1.7~7.8	2.1~4.7
R_{DS} (on)	(Ω)	0.1~0.03	0.2~0.08	0.75~0.2	4.5~0.6	5~2
t_{on}	(ns)	40	30	100	150	200
t_{off}	(ns)	100	95	200	550	600

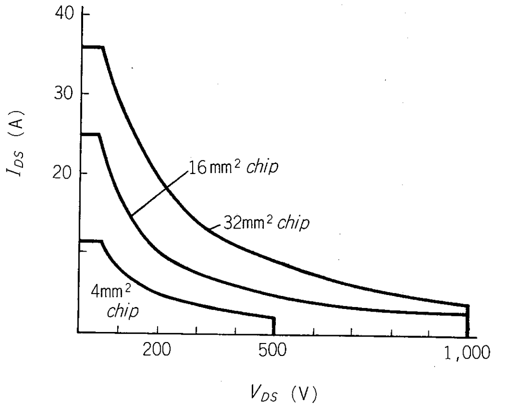

Fig. 18 I_{DS} vs. V_{DS} of SIPMOS power transistors

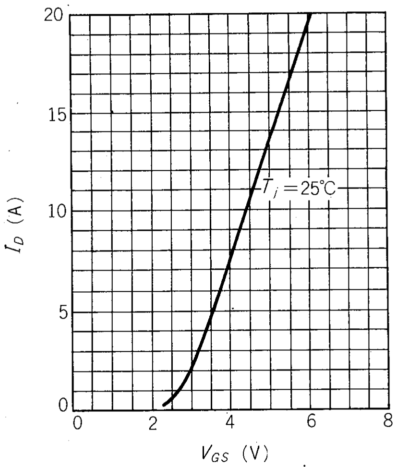

Fig. 19 Transmission characteristic of 100V, 15A type SIPMOS

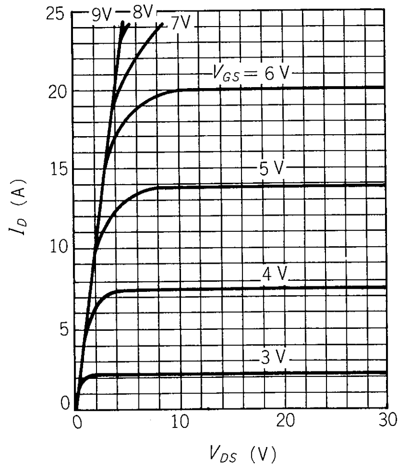

Fig. 20 Output characteristics of 100V, 15A type SIPMOS

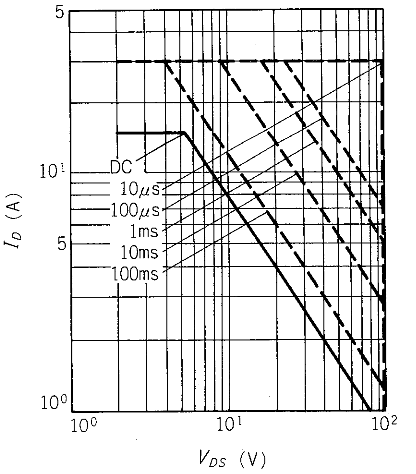

Fig. 21 Permissible operating range of 100V, 15A type SIPMOS

The SIPMOS transistor was made as small as possible by pursuing the on resistance $R_{DS(on)}$, to its theoretical limit. *Fig. 17* shows the relationship between the theoretical $R_{DS(on)}$ realized with a 4 mm square chip and the breakdown voltage. The characteristics of the MOS FET announced up to the present are plotted on this theoretical curve.

3. SIPMOS transistor series and characteristics

Three types of SIPMOS transistors having chip areas of 4 mm², 16 mm², and 32 mm² are available. *Fig. 18* shows the current and breakdown voltage of each type.

Table 4 shows the SIPMOS transistor type series. A complete series of transistors having voltage ratings from 50V to 500 V are available.

The transfer characteristic of the 100 V, 15 A type is shown in *Fig. 19*, its output characteristics are shown in *Fig. 20*, and its maximum safe operating area is shown in *Fig. 21* as typical examples.

4. Application of SIPMOS transistor

Similar to other MOS FET, compared with bipolar transistors, the SIPMOS features:

(1) Low drive power.
(2) High power gain.
(3) Fast switching speed making it advantageous in RF operation.
(4) No secondary breakdown and high breakdown capacity.
(5) High thermal stability.
(6) Simple parallel operation.

Consequently, its application to the following fields is expected:

Power electronics	: Switching power supply, Motor control
Automotive electronics	: Regulator, Ignition relay
Data equipment	: Printer, Stepping motor, Plotter

VII. CONCLUSION

The direction of power transistor technology and product development is toward larger unit capacity, higher voltage rating, higher speed, higher gain, higher breakdown capacity, and other higher performance on the one hand and toward more composite elements and simplier circuits. Some of these were introduced here. Since users are clearly demanding easier to use power elements, further improvements over a wide field are necessary.