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HIGH SWITCHING SPEED IGBT MODULES

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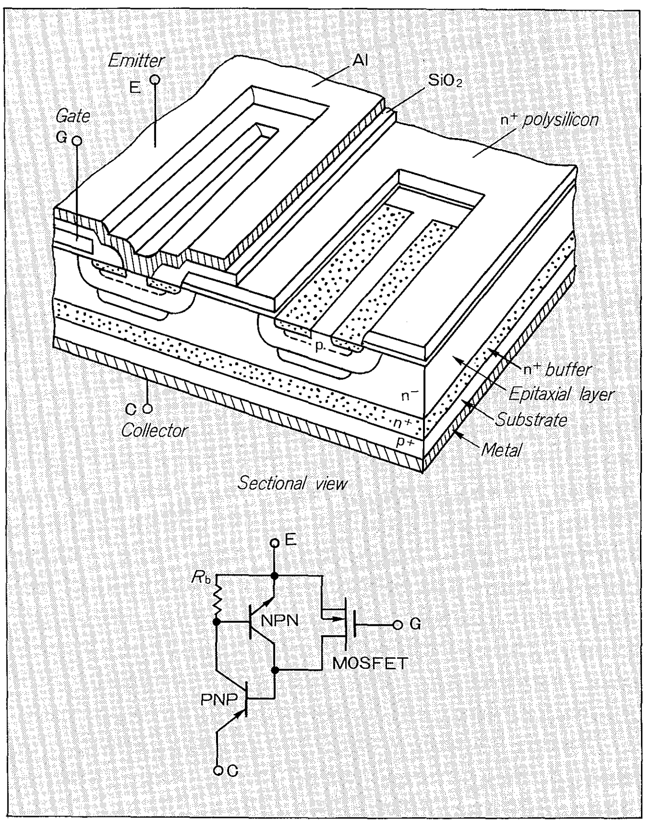
1. FOREWORD

The improvements being made in the performances of power converters is amazing. Of these, development of converters that are smaller, lighter, higher performance, more efficient, and quieter is advancing rapidly and their range of application is spreading quickly. The power device that has made this possible is the IGBT (Insulated Gate Bipolar Transistor). Fuji Electric developed an IGBT several years ago and introduced a 1st generation series of IGBT which are used in microwave ovens and inverters for motor control. Thereafter, it advanced development of a new low power loss series with a wide low power loss region as the target based on customer evaluation of and need for the 1st generation IGBT. High switching speed IGBT modules (L series) perfect for inverters for motor control, AC and DC servoamps, and uninterrupted power supplies has been developed and serialized. These IGBT modules are introduced.

Fig. 1 IGBT construction and equivalent circuit



2. TECHNICAL DEVELOPMENT OF LOW POWER LOSS IGBT

2.1 Development aims

Customer evaluation of the 1st generation IGBT showed that, depending on the application, they were not 100% satisfied with its power loss. For example, in inverter application, the power loss of the IGBT at 10 to 15kHz was not as low as expected compared to the power loss of the bipolar transistor at conventional carrier frequencies up to about 3kHz. This is thought to be due to the comparatively high on-state voltage (average 3.5V) and long fall time (average 0.5μs) of the 1st generation IGBT. Therefore, development of a 2nd generation high switching speed IGBT was promoted with a 30% or greater improvement in the on-voltage and fall time as the target based on customer needs.

2.2 Technical developments

2.2.1 Improvement of on-state voltage ($V_{CE\,(sat)}$)

The sectional construction and equivalent circuit of the IGBT are shown in *Fig. 1*. The on-state voltage of the IGBT is expressed by Ex. (1) below.

$$V_{CE(sat)} = V_{p^+\text{-}n^+} + V_{c,m} + I{\cdot}R_s + (R_{ch} + R_{acc} + R_{JFET}) \cdot I_{MOS} \qquad \text{..........} (1)$$

In short, the IGBT on-state voltage is determined by the $p^+ - n^+$ junction voltage $Vp^+ - n^+$, conductivity modulated n^- region voltage drop $V_{c,m}$, other series resistance voltage drops $I.R_s$, and the power MOS section channel resistance Rch and pinching resistance (R_{JFET}). The voltage drop components computed for that dropping voltage at an IGBT of a certain cell size are shown in *Fig. 2*. In this case, the voltage drops the MOS section are especially large and of these, the voltage drop across the pinching resistance is especially large. When the lifetime of the n^- base region is

Fig. 2 IGBT on-state voltage components (calculated)

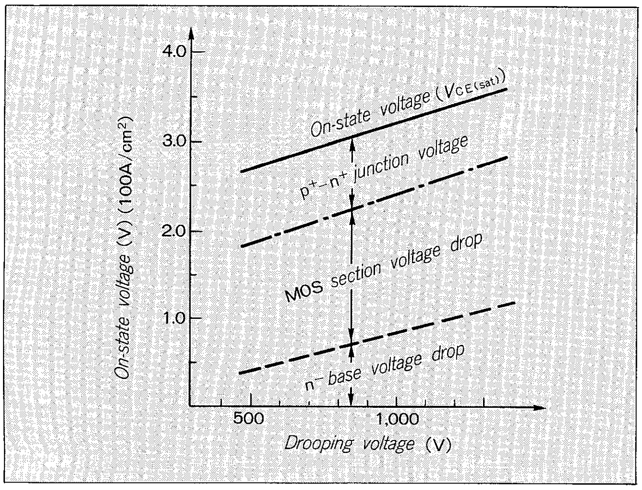
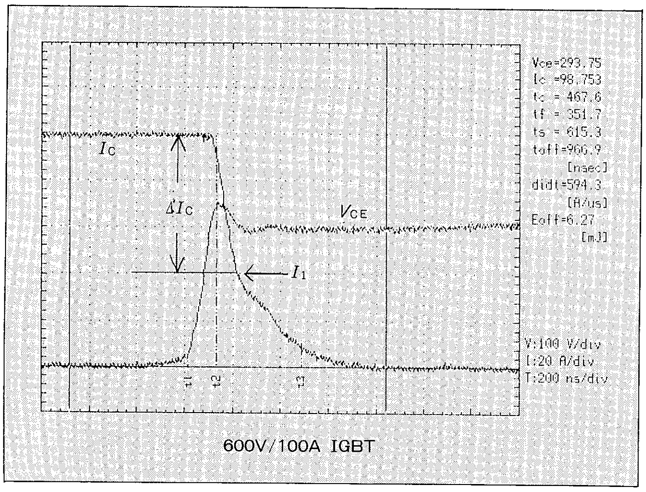


Fig. 3 Turn-off waveform of old type IGBT



lowered to realize higher speed, the voltage drop across the n^- base section increases suddenly like that of a PIN diode. From the results of such analysis, the following targets were set to lower the on-state voltage:

(1) Lowering MOS section resistance and increasing base current
(2) Improvement of on-state voltage and fall time trade-off by lifetime controlling technique

The main improvement contents are:

(1) Optimization of gate oxide film
(2) Cell size reduction and optimization
(3) Use of a new construction which lowers the pinching resistance
(4) Use of a new lifetime controlling technique

These technical developments lowered the on-state voltage approximately 30% compared to that of the old type IGBT.

2.2.2 Improvement of fall time (t_f)

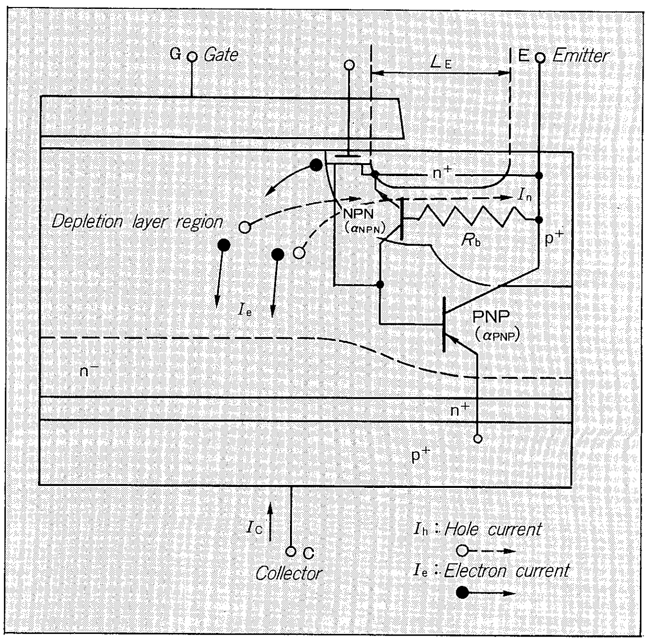
The turn-off waveforms of the old IGBT with L load are shown in *Fig. 3*. If it is assumed the current begins to drop when the gate voltage drop begins, a Cdv_{CE}/dt current, the so-called base current, is supplied by the inductance component, that is, the collector-emitter voltage rise, and a constant collector current flows continuously. However, when the V_{CE} voltage approaches a constant value, dv_{CE}/dt becomes very small and the Cdv_{CE}/dt current becomes zero and, therefore, a sudden collector current drop ΔI_C occurs. This ΔI_C is smaller than the normal on-state MOS current (I_{MOS}) because at turn-off, the effective β of the p^+ n^- – P^+ transistor becomes high due to spreading of the depletion layer. When the channel is closed and base current supplied to the n^- base becomes 0 like this, the collector current is eliminated over a comparatively long time by the extinction of recombination of the holes and electrons remaining in the n^- base at an attenuation constant determined by the carrier lifetime or back injection of the electron current to the p^+ collector, and other processes. Since most of the switching power loss of an IGBT is generated at this tail part, how to reduce this part is the main point. According to J. G. Fossum, as a result of applying the charge control method to the tail part of the IGBT, the tail current is given by the following equation:

$$I_c(t) \cong \frac{I_1 \exp(-t/\tau_H)}{1 + \dfrac{I_1 \cdot J_{NO} \cdot \tau_H}{A \cdot K_A \cdot q^2 \cdot n_i^2 \cdot D_p}\left[1 - \exp\left(-\dfrac{t}{\tau_H}\right)\right]} \quad \text{......(2)}$$

Where, τ_H shows the high level injection lifetime and J_{NO} shows the saturation current for recombination electron injection to the p^+ collector. If J_{NO} is low enough to be ignored, the tail current is related to τ_H only and is attenuated exponentially by that recombination process. However, if J_{NO} is increased, since an a new electron back injection to p^+ collector extinction process is added to the recombination process previously mentioned, the tail time can also be reduced substantially. The following fall time reduction targets were set based on these analyzes:

(1) Increase of J_{NO}

Fig. 4 Current flow at load short-circuit



(2) Establishment of a lifetime controlling technique which improves the switching time and on-state voltage tradeoff.

The main improvement contents are:

(1) Optimization of the n^+ buffer and p^+ collector layer density and thickness

(2) Use of a new lifetime controlling technique

These technical developments made it possible to lower the fall time about 30% without increasing the on-state voltage.

2.3.3 Improvement of short circuit and turn-off capabilities

When a short-circuit occurs at a PWM inverter or other main circuit, high withstand voltage and large current stress are applied simultaneously to the element. The IGBT must not be destroyed before the protection circuit operates when a short circuit occurs. In the state shown in *Fig. 4*, the parasitic thyristor is latched up at $\alpha_{NPN} + \alpha_{PNP} = 1$ and gate control is lost and the IGBT is destroyed. If it is assumed that latch up takes place when the $n^+ - p$ junction potential (emitter n^+ part and p channel part junction) 0.7V exceeds the voltage drop $V_A = I_h \cdot R_b$ generated by the hole current directly below the n^+ emitter, the latch up current in the normal state is:

$$I_L = \frac{0.7}{\alpha_{PNP} \cdot R_b} \qquad \text{......(3)}$$

Therefore, to increase the latch up capability, R_b, α_{PNP}, and I_h must be reduced. The following targets were set to improve the short circuit capability:

(1) Proportional increase of MOS electron current

(2) Reduction of R_b and α_{PNP}

The main improvement contents are:

(1) Increase of MOS electron current by reducing the cell dimension.

(2) Use of R_b reduction construction

(3) Optimization of n^+ buffer and p^+ collector layer

These improvements provide a short circuit capability (short circuit pulse width rms value 20μs or more, 125°C) of a level equal to that of the old IGBT while reducing the on-state voltage substantially. When the IGBT is turned off from a large current, a high voltage is applied by the wiring inductance component, etc. When a large current and a high voltage are applied simultaneously, the charge in the depletion layer in the n^-base increases and the electric field in the depletion layer is increased and its multiplication factor increases and, finally, avalanche breakdown occurs and the IGBT is destroyed. This mechanism was analyzed by device simulation and the device construction was improved and the turn-off capability increased.

3. ELECTRICAL CHARACTERISTICS OF HIGH SWITCHING SPEED IGBT (L SERIES)

3.1 The output characteristics and on-state voltage and fall time

The output characteristics and on-state voltage and fall time tradeoff relationship of the 600V, 1200V L series and the old IGBT are compared in *Fig. 5*. For the 600V series,

Fig. 5 Output characteristics and V_{CE} and t_f tradeoff comparison

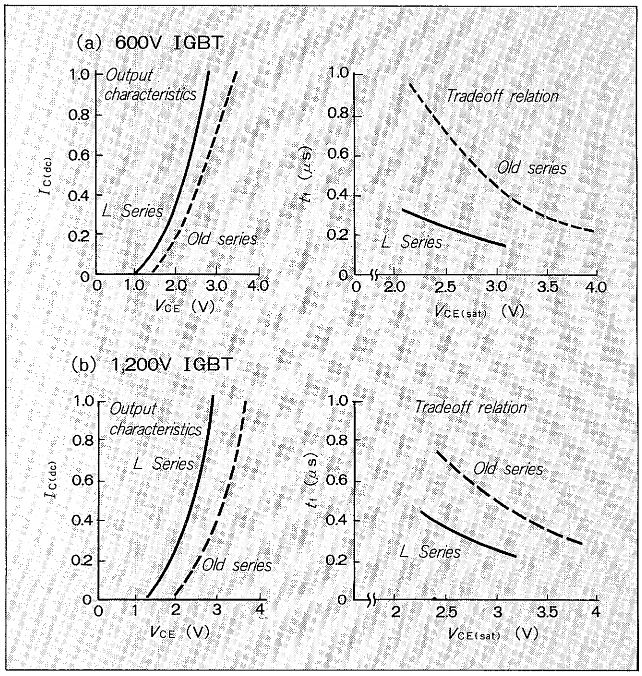


Table 1 Main electrical characteristics specifications of L Series

(a) 600V series

Item	Symbol	Conditions	Specification
Collector-emitter saturation voltage	$V_{CE(sat)}$	V_{GE} = 15V $I_C = I_{C(dc)}$	Max 3.5V
Turn-on time	t_{on}	V_{CC} = 300V $I_C = I_{C(dc)}$ V_{GE} = ±15V R_G = specified value	Max 0.8μs
	t_{off}		Max 1.0μs
	t_f		Max 0.35μs

(b) 1200V series

Item	Symbol	Conditions	Specification
Collector-emitter saturation voltage	$V_{CE(sat)}$	V_{GE} = 15V $I_C = I_{C(dc)}$	Max 3.5V
Turn-on time	t_{off}	V_{CC} = 600V $I_C = I_{C(dc)}$ V_{GE} = ±15V R_G = specified value	Max 0.8μs
	t_{off}		Max 1.5μs
	tf		Max 0.5μs

Fig. 6 Comparison of turn-off waveforms

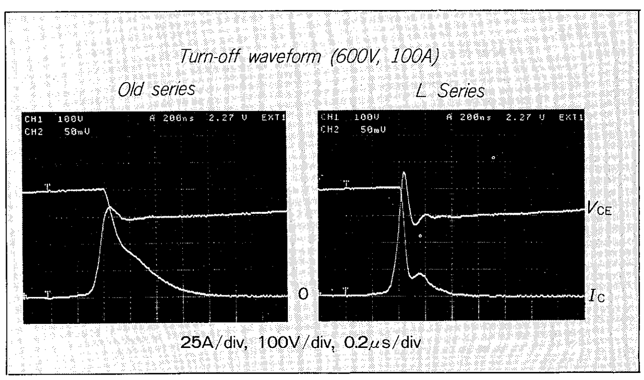


Fig. 7 Waveforms at load short circuit and turn-off capability measurement

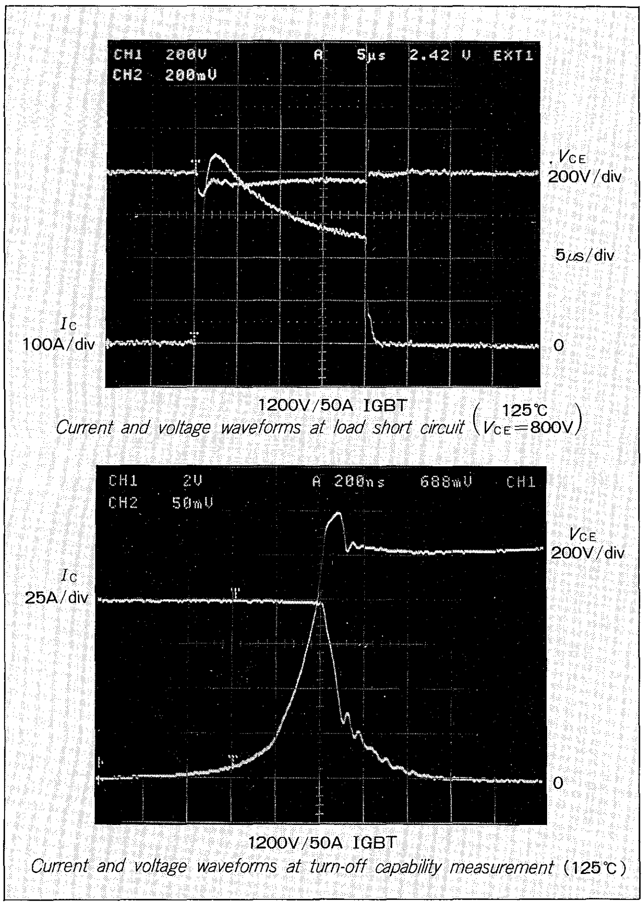
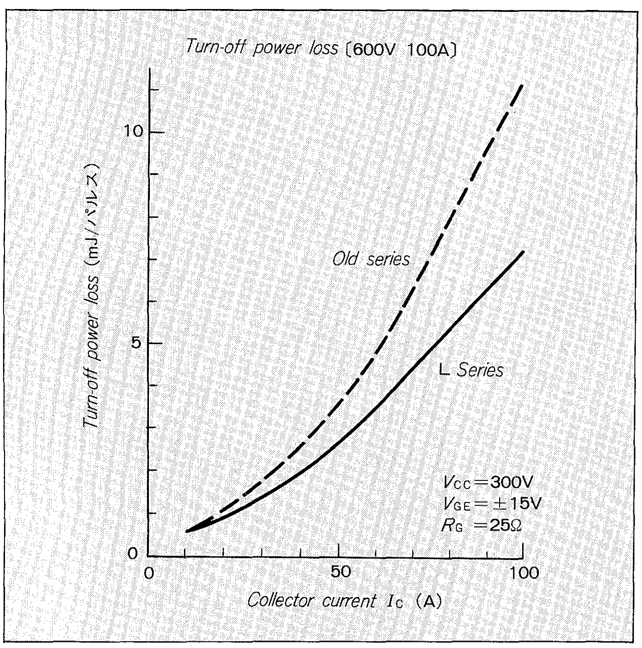
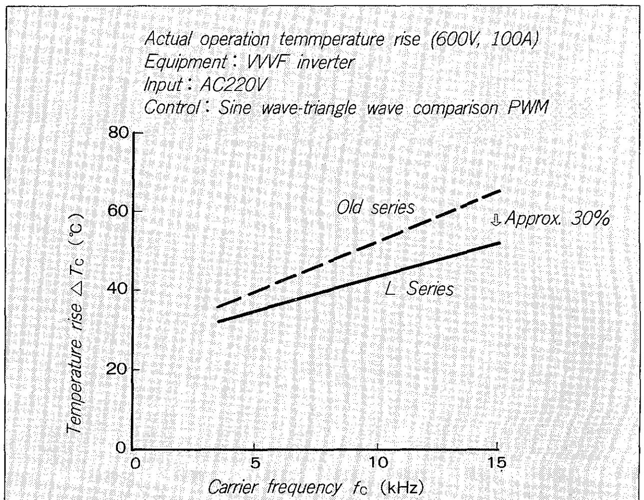


Fig. 8 Comparison of turn-off power loss



the average on-state voltage/fall time was improved from 3.5V/0.45µs to 2.8V/0.25µs and for the 1200V Series, the average on-state voltage/fall time was improved from 3.5V/0.45µs to 2.8V/0.35µs. The specifications of the main characteristics of the 600V and 1200V L series are shown

Fig. 9 Temperature rise at actual inverter operation



Specimen element	$V_{CE(sat)}$	t_f
Old series	3.25V	0.37µs
L Series	2.70V	0.26µs

Table 2 High switching speed IGBT modules series table

(a) 600V series

I_C (A)	Number of elements		
	6 pack	2 pack	1 pack
10	6MBI 10L-060		
15	6MBI 15L-060		
20	6MBI 20L-060		
30	6MBI 30L-060		
50	6MBI 50L-060	2MBI 50L-060	
75	6MBI 75L-060	2MBI 75L-060	
100	6MBI 100L-060	2MBI 100L-060	
150		2MBI 150L-060	
200		2MBI 200L-060	
300		2MBI 300L-060	1MBI 300L-060
400			1MBI 400L-060

(b) 1200V series

I_C (A)	Number of elements		
	6 pack	2 pack	1 pack
8	6MBI 8L-120		
15	6MBI 15L-120		
25	6MBI 25L-120	2MBI 25L-120	
50	6MBI 50L-120	2MBI 50L-120	
75		2MBI 75L-120	
100		2MBI 100L-120	
150		2MBI 150L-120	
200			1MBI 200L-120
300			1MBI 300L-120

Fig. 10 IGBT modules outline dimensions

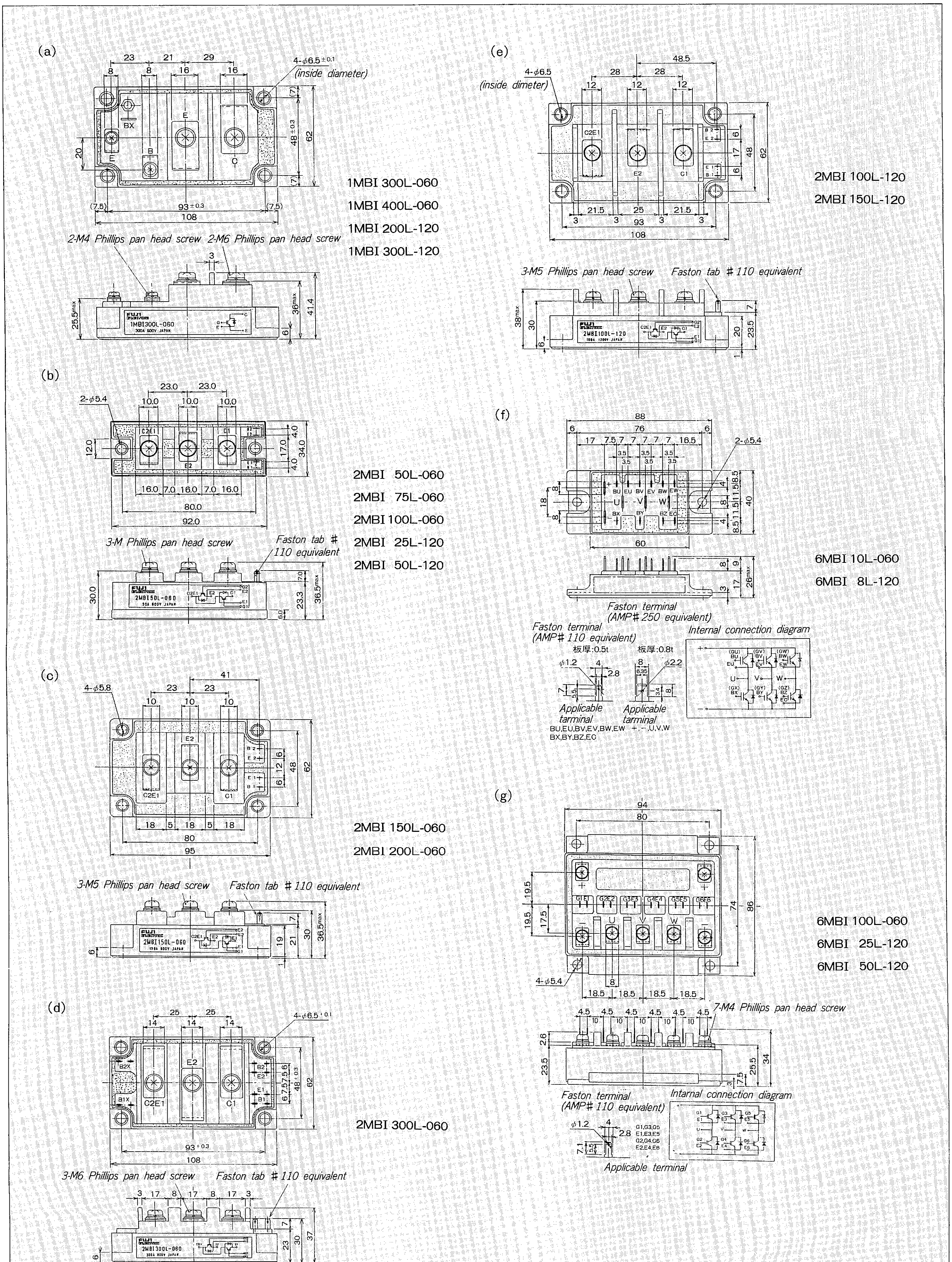
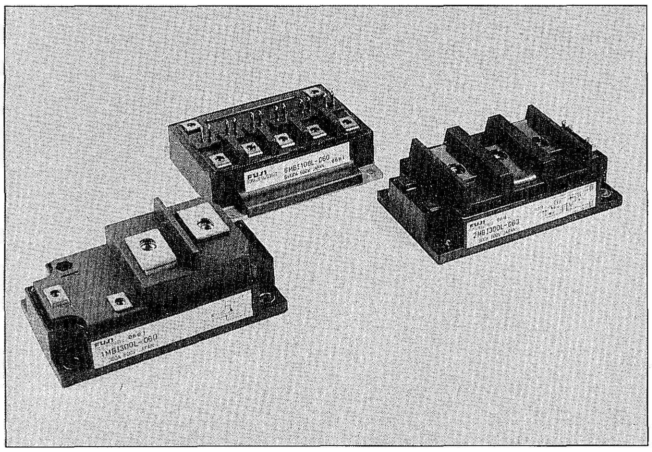


Fig. 11 IGBT module L Series



in *Table 1*. The 600V/100A turn-off waveforms are compared in *Fig. 6*. The IGBT module L Series can also reduce the turn-on power loss and switching power loss substantially compared to the old series. Especially, they are said to be the perfect IGBT modules for developing low acoustical noise, high performance, and small size inverters.

3.2 Short circuit and turn-off capability

The voltage and current waveforms of a 1200V/50A (L Series) IGBT module at a short circuit (T_C = 125°C) and turn-off capability (T_C = 125°C) measurement are shown in *Fig. 7*. The real short circuit time (V_{CC} = 800V, 125°C) is 20μs or more. Regarding the true gate turn-off capability (125°C) at a snubberless circuit the IGBT is not destroyed even by a current of double the collector rated current and a voltage stress of 1100V. The L Series has a sufficient breakdown capability even when abnormal.

3.3 Comparison of turn-off power loss and inverter operation power loss

The collector current and turn-off power loss relationship of a 600V/100A IGBT are compared in *Fig. 8*. The L Series can reduce the turn-off power loss about 30%. *Fig. 9* shows the relationship between the carrier frequency and IGBT module temperature rise at actual inverter operation. In the 10 to 15kHz high frequency region, the L Series can reduce the temperature rise approximately 30%. This is expected to make a large contribution to development of smaller and higher performance equipment.

4. HIGH SWITCHING SPEED IGBT MODULES SERIES

A table of the newly serialized high switching speed IGBT modules (L Series) series is shown in *Table 2*. The 600V series has been serialized from 10 to 400A and the 1200V series has been serialized from 8 to 300A. The outline dimensions of the package are shown in *Fig. 10*. The modules are shown in *Fig. 11*. We are confident that this abundant capacity series will meet the needs of the market.

5. CONCLUSION

The technical development points of the newly developed and serialized high switching speed IGBT modules (L Series) and there electrical characteristics features and the results of comparison at actual inverter operation were introduced above. These new L Series IGBT modules can reduced the total power loss approximately 30% compared to the old series. We are confident that they will meet the expectation of the inverter for motor control field which demands smaller size, higher performance, and lower acoustical noise equipment. We are also confident that they have performances which can be amply expected in the AC·DC servoamp, uninterrupted power supply, welder, and other switching mode power supply fields. Fuji Electric is already developing the next generation IGBT modules. In the future, we will accumulate technical innovations and pour our efforts into the development of high performance power devices matched to diverse market needs and contribute to the growth of the power electronics industry.