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MOS GATE BIPOLAR TRANSISTOR (MBT)

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1. FOREWORD

Recently, inverters for motor drive for machine tools, air conditioners and robots, as wellas uninterruptible power supplies for OA equipments and medical equipments have been required to be low-noisy, high efficient, small, and lightweight.

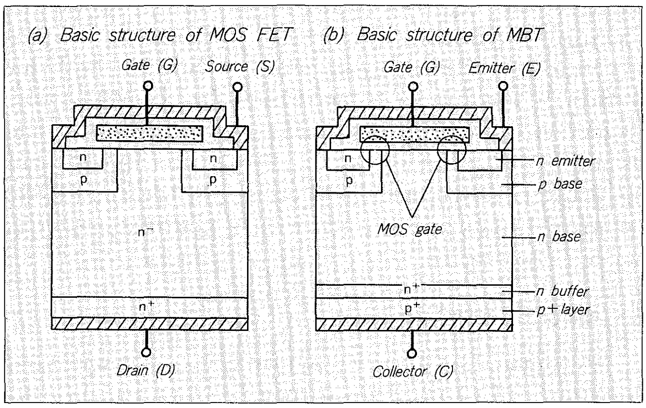
In the past, the semiconductor devices widely used in this field were the bipolar power transistor and power MOS FET, etc.. The bipolar power transistor has a withstand voltage of 1,000V or more and can switch a high current of 100A or greater, but has a low switching frequency of a few kHz. On the other hand, the power MOS FET can operate at a high switching frequency of several ten to several hundred kHz, but when its withstand voltage becomes high (about 1,000V) the current which can be conducted becomes very low (several A).

The newly developed MOS gate bipolar transistor (MBT) is a device that can handle high withstand voltages and large currents and can also cover a switching frequency range from several kHz to a few ten kHz higher than the bipolar power transistor. In other words, it is a new type of composite device with the features of both the bipolar power transistor and power MOS FET. The structure, operation, design and rated characteristics of the MBT are described below.

2. STRUCTURE

A comparison of the basic structure of the newly developed MBT and the MOS FET is shown in *Fig. 1*. Basically, the MBT is analogues to a MOS FET with a single p^+ layer at the drain side. *Fig. 1* shows the unit structure of the MBT. The actual device consists of many of these unit structures integrated together. The three electrodes of the MBT are named gate (G), emitter (E), and collector (C), as shown in *Fig. 1*. This MBT has a structure equivalent to that of an insulated gate bipolar transistor (IGBT), and is the same as devices called IGT, COMFET, and bipolar MOS FET.

Fig. 1 Comparison with MOS FET and MBT



3. OPERATION

Operation of the MBT is devided into a turn-on period, on-state period, and turn-off period as shown in *Fig. 2* and described for an inductive load circuit (*Fig. 3*.)

3.1 Turn-on period (Fig. 4(a))

When a positive voltage is applied to the gate (G) in the state in which the emitter (E) is made earth potential and a positive voltage is applied to the collector (C) as

Fig. 2 Operation period of MBT

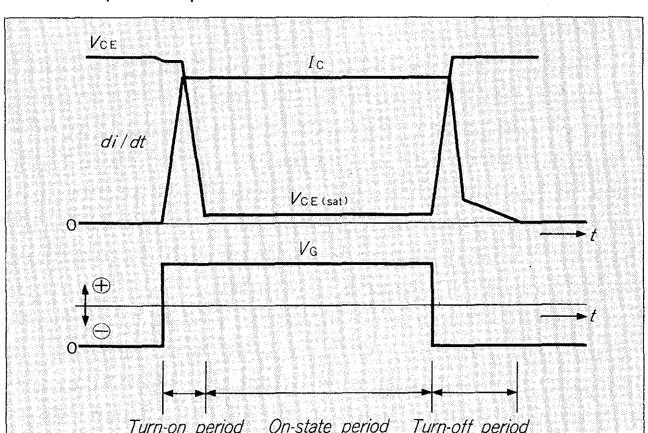


Fig. 3 Inductive load circuit

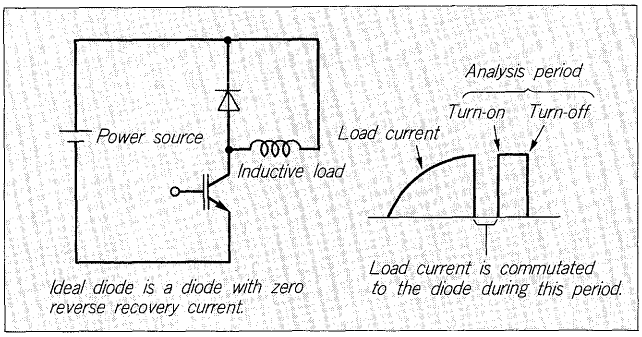
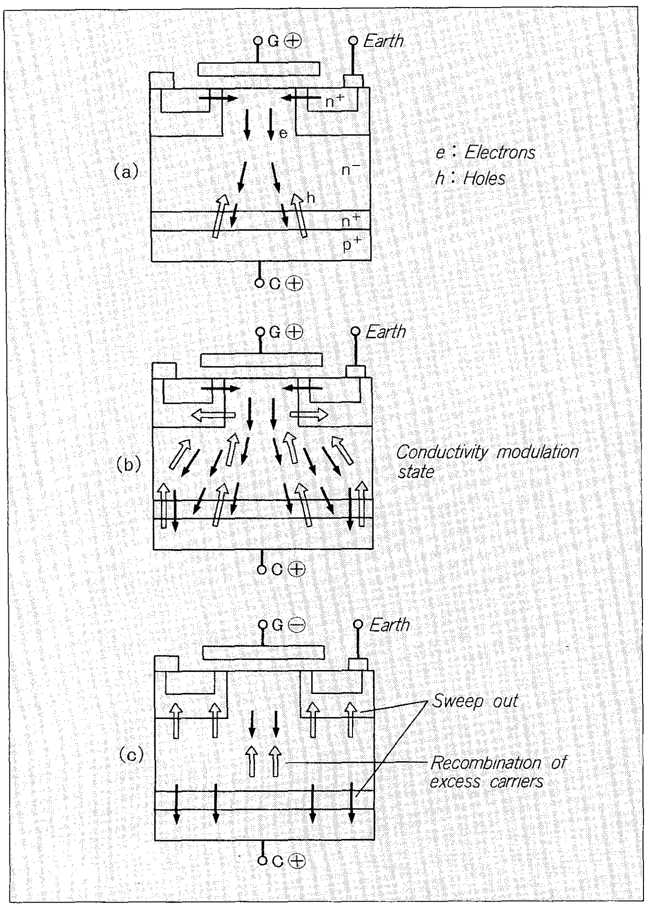


Fig. 4 Operation of MBT



shown in *Fig. 4*(a), a channel is formed at the MOS gate and electrons are injected into the n base layer from the n emitter. The electrons stored in the n layer start injection of holes from the collector side p^+ layer to the n base layer. The density of electrons and holes in the n base layer increases abruptly, and conductivity modulation is inducted. Therefore, the collector current suddenly rises to the load current. From this point, the collector-emitter voltage drops abruptly to an extremely low value of a few volts. This period is the turn-on period.

3.2 On-state period (Fig. 4(b))

The period during which the a low collector-emitter voltage ($V_{CE(sat)}$) of a few volts is maintained even when conductivity modulation in the n base layer is sufficient and a large load current flows is called the "on-state period".

3.3 Turn-off period (Fig. 4(c))

Next, when the gate is made zero or a negative voltage relative to the emitter, the channel disappears and injection of electrons from the n emitter stops. By the rise of the collector-emitter voltage (V_{CE}) applied from an external power source, the holes stored in the n base layer are swept out at the emitter side and the electrons are swept out at the collector side. The inductance effect is also added and load current continues to flow. This period is the storage time and a collector current drop is not seen.

When the collector-emitter voltage of the MBT reaches the external power source voltage, the sweep-out current flow stops and the collector current drops suddenly. This is the fall time.

The excess carriers of the electrons and holes remaining in the n base layer are reduced by recombination until the electron and hole density reaches to that at the thermally equilibrium state. This period is the tail period. These three periods are combined and called the turn-off period.

4. MBT DESIGN

As previously described, the MBT is a device with the same, or better, current and voltage ratings as a bipolar power transistor and can operate at a higher switching frequency region thatn the bipolar power transistor.

Therefore, the following features are desired:

(1) Short switching time and low switching loss
(2) Low on-state voltage (collector-emitter saturation voltage) and on-state loss.
(3) High withstand value for load short (wide safety operation area)

To realize (1) to (3) above, the following innovations were made at device design:

(a) To improve the trade-off relationship between switching characteristics and collector-emitter saturation voltage, the gate spacing, channel length, n base layer thickness, n buffer layer density, and p^+ layer density were optimized and the best lifetime killer doping conditions were selected.

(b) To increase the withstand value for load short, the device was constructed so that the latch-up phenomenon does not occur. The latch-up phenomenon lowers the turn-off ability by operating a parastic thyristor when a large current flows. This problem was solved by optimizing the depth and density of the p base and reducing the depth and width of the n emitter. This minimized the voltage drop generated by the hole current that flows in the p base layer under the n emitter layer which flows in at turn-off as shown in *Fig. 5* and prevented the parastic thyristor turn-on phenomenon.

Fig. 5 Latch-up phenomenon at turn-off time

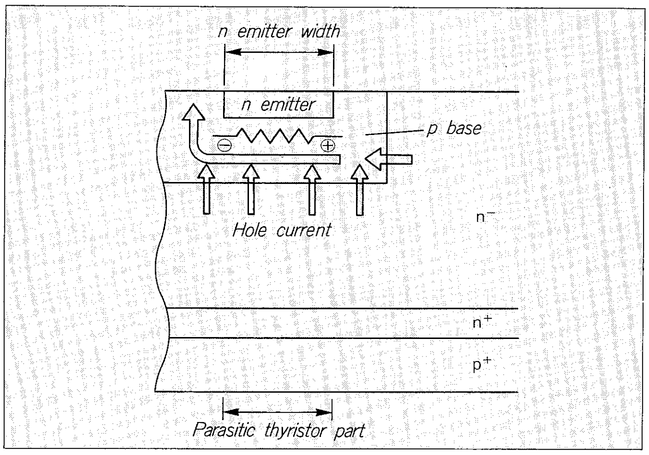
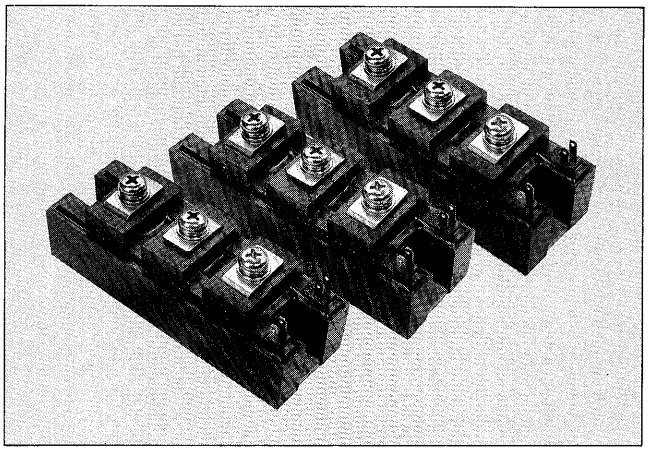


Fig. 6 Outline of MBT



These innovations made it possible to commercialize 600V/25A, 500V/50A, and 1,200V/25A MBTs without the latch-up phenomena. Outlines of these MBTs are shown in *Fig. 6*.

5. MBT RATINGS AND CHARACTERISTICS

The main ratings and characteristics of the 600V/25A, 600V/50A, and 1,200V/25A MBT are shown *table 1*.

The dependency of the various parameters is introduced by taking the 1200V/25A MBT as an example.

5.1 Turn-on characteristic

The relationship between *di/dt* and collector current at turn-on is shown in *Fig. 7*. At I_c=25A, *di/di* has a value of 200A/μs or greater.

The relationship between the turn-on loss and gate resistance is shown in *Fig. 8*. When the gate resistance is made large, since the turn-on loss increases, the gate resistance must be selected carefully when using the MBT.

5.2 Forward characteristics

The relationship between collector-emitter saturation voltage ($V_{CE(sat)}$) and collector current (I_c) is shown in *Fig. 9*. The collector current is increased by a gate voltage increase, but is saturated in the region at which the collector current is higher than a certain value. At V_{GE}=15V, and I_c=25A, $V_{CE\ (sat)}$=3.5V.

The relationship between the collector current (I_c) and gate voltage (V_{GE}), with the case temperature (T_c) as a parameter, is shown in *Fig. 10*. When the case temperature rises, collector current flow is difficult.

The voltage and current waveforms when the withstand capacity for load short was tested are shown in *Fig. 11*.

At V_{CE}=15V, V_{CE}=800V, and I_c=300A, a conduction pulse width of 10μs was obtained.

Table 1 Main ratings and characteristics

Item	Unit	600V 25A	600V 50A	1,200V 25A
Collector-emitter breakdown voltage	V	600	600	1,200
Gate-emitter voltage	V	±20	±20	±20
Collector current	A	25	50	25
Gate threshold voltage	V	3~6	3~6	3~6
Collector-emitter saturation voltage	V	5	5	5
Turn-off time	μs	1.0	1.0	1.0
Junction temperature	°C	150	150	150

Fig. 7 *di/dt* vs. collector current

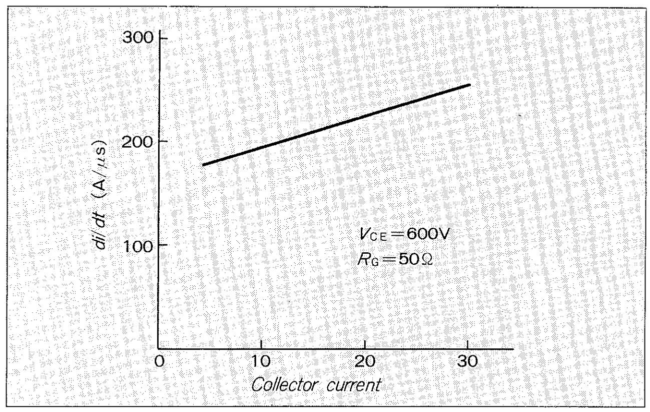
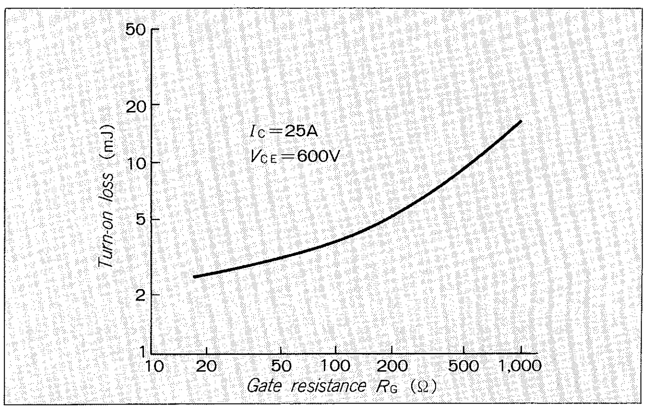


Fig. 8 Turn-on loss vs. gate resistance



5.3 Turn-off characteristics

The relationship between turn-off time (t_{off}) and collector-emitter saturation voltage ($V_{CE(sat)}$) is shown in *Fig. 12*. A t_{off} of 0.7μs at $V_{CE(sat)}$=3.5V is obtained

Fig. 9 Collector current vs. collector voltage

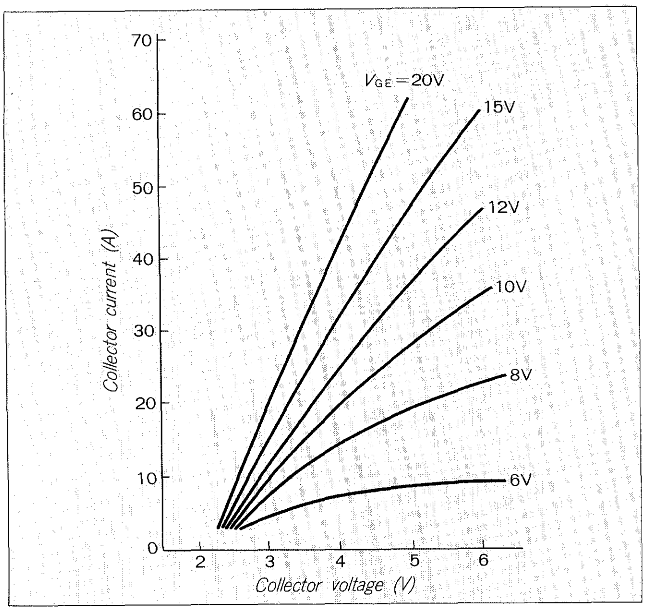


Fig. 10 Collector current vs. gate voltage

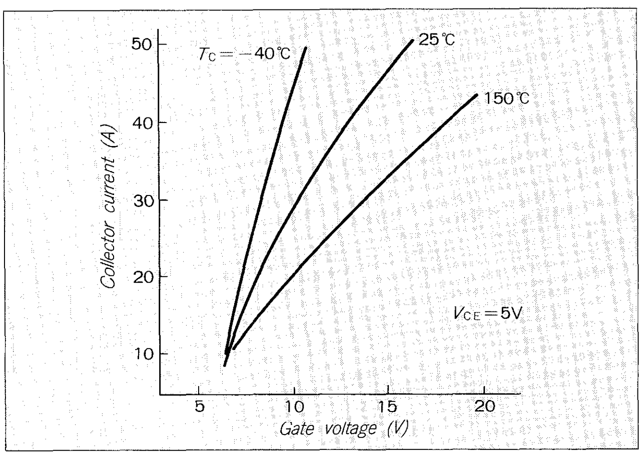
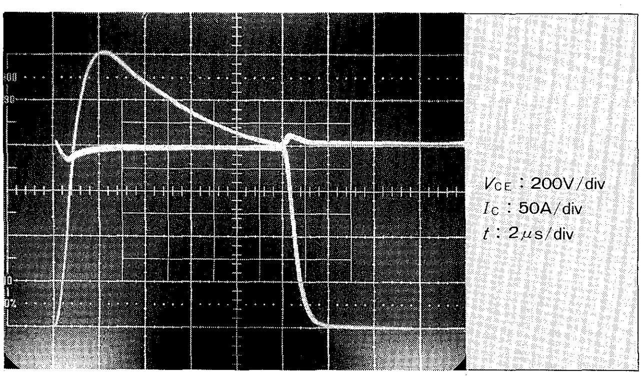


Fig. 11 Voltage and current waveform at a load short circuit



by optimizing the design parameters.

The relationship between turn-off loss (E_{off}) and collector current (I_c) is shown in *Fig. 13*.
At I_c=25A, E_{off}=3mW or less.

The turn-off waveforms when I_c=25A was conducted are shown in *Fig. 14*.

Fig. 12 Turn-off time vs. collector-emitter saturation voltage

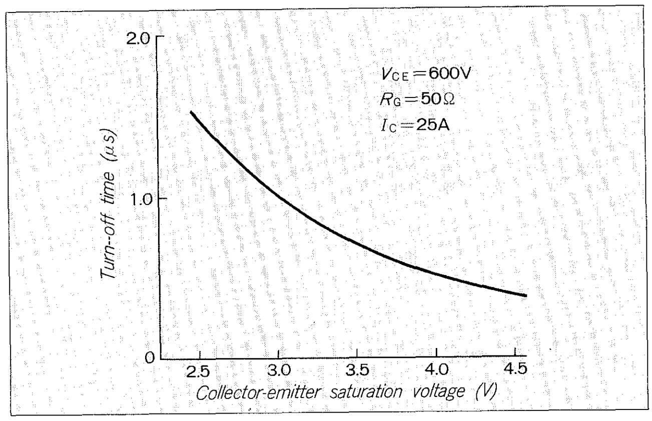


Fig. 13 Turn-off loss vs. collector current

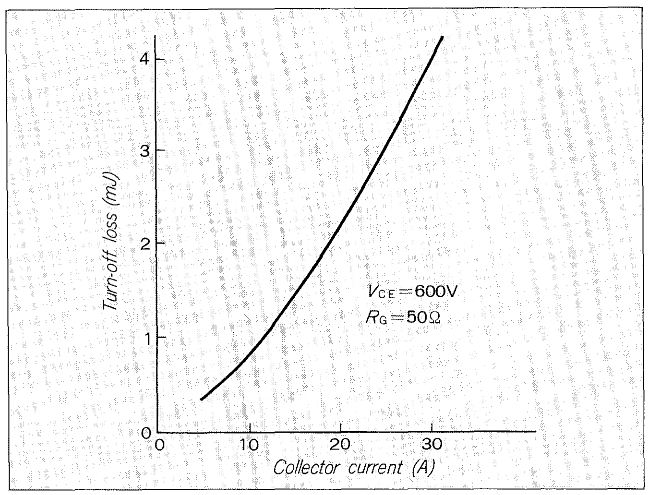
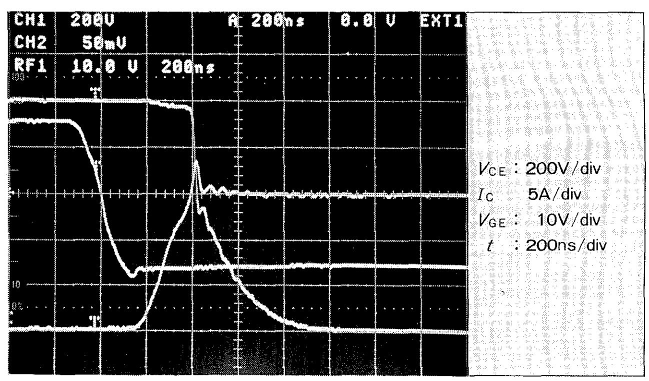


Fig. 14 Turn-off waveforms of MBT



6. CONCLUSION

The newly developed MBT is a new composite device which can be used at a higher switching frequency than the bipolar power transistor while having the same voltage and current ratings as the bipolar power transistor obtained by optimizing the design parameters.

This MBT will contribute to making various PWM inverter quieter and switching power supplies smaller and lighter and is expected to be used in various converters in the future by expansion of the series.