Chapter 1

Structure and Features

PREFACE

Power converters, such as variable-speed motor drives and uninterruptible power supplies for computers, were revolutionized with the introduction of bipolar power transistor modules and power MOSFETs. The demand for compact, lightweight, and efficient power converters has consequently also promoted the rapid development of these switching devices.

Bipolar transistor modules and MOSFETs however, cannot fully satisfy the demands of these power converters. For example, while bipolar power transistor modules can withstand high voltages and control large currents, their switching speed is rather slow.

Conversely, power MOSFETs switch fast, but have a low withstand voltage and current capacity.

Therefore, to satisfy these requirements, the insulated gate bipolar transistor (IGBT) was developed.

The IGBT is a switching device designed to have the high-speed switching performance and gate voltage control of a power MOSFET as well as the high-voltage / large-current handling capacity of a bipolar transistor.

1 Structure and features

Fig. 1-1 compares the basic structure of an IGBT and a power MOSFET. The IGBT is characterized by a p^{+-}-layer added to the drain side of the power MOSFET structure. It is this p^{+-}-layer that enables the various IGBT features explained in this manual

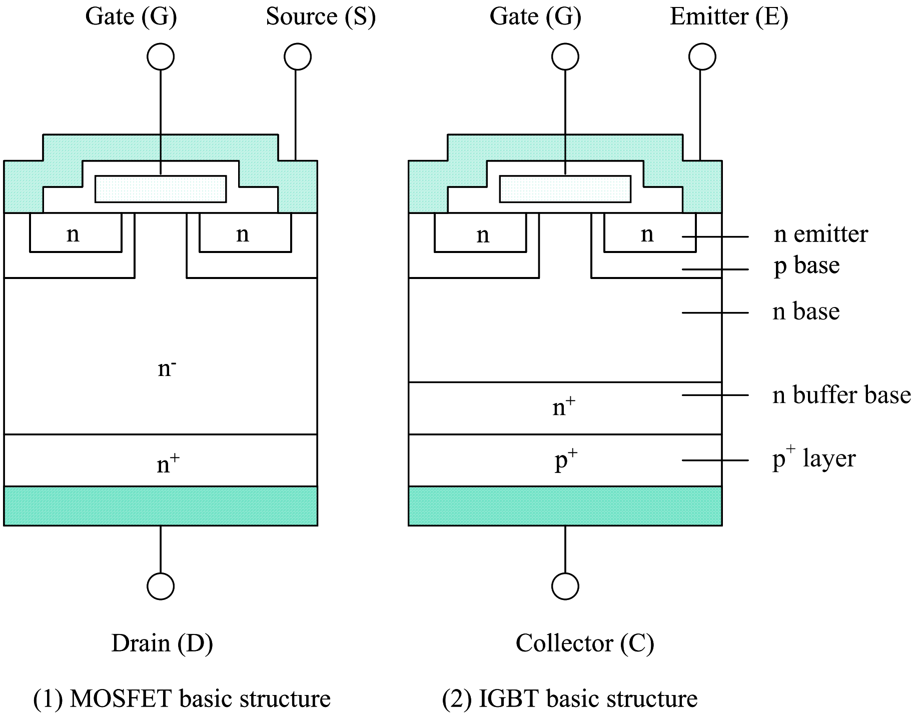


Fig. 1-1 Basic structure of MOSFET and IGBT

1.1 Voltage – controlled device

As shown in Fig. 1-2, the ideal IGBT equivalent circuit is a monolithic Bi-MOS transistor in which a pnp bipolar transistor and a power MOSFET are darlington connected. Applying a positive voltage between the gate and the emitter, switches on the MOSFET and produces a low resistance effect between the base and the collector of pnp transistor, thereby switching it on.

When the applied voltage between the gate and the emitter is set to "10", the MOSFET will switch off, causing the supply of base current to the pnp transistor to stop and thereby switching that off as well.

This means that an IGBT can be switched on and off using voltage signals in the same way as a power MOSFET.

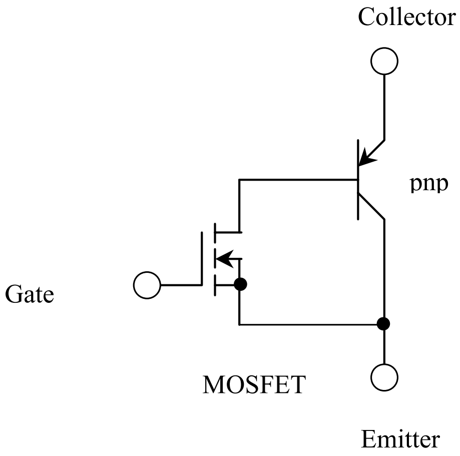


Fig. 1-2 Ideal equivalent circuit

1.2 Higher voltage and higher current switching capability than power MOSFETs

Like the power MOSFET, a positive voltage between the gate and the emitter produces a current flow through the IGBT, switching it on. When the IGBT is on, positive carriers are injected from the p^{+-}-layer on the drain side into the n-type bases layer, thereby precipitating conductivity modulation. This enables the IGBT to achieve a much lower on-resistance than a power MOSFET.

Explanation

The IGBT has a very low on resistance for the following reasons:

A power MOSFET becomes a single-layer semiconductor (n-type in the diagram) when it is in the on-state, and has resistor characteristics between the drain and the source. The higher the breakdown voltage and the device, the thicker the n-layer has to be, but this results in an increased drain-to-source resistance. Thus, as the breakdown voltage increases so does the on-resistance, making it difficult to develop large capacity power MOSFETs.

Unlike the power MOSFET, the n-base layer resistance of the IGBT becomes negligible due to the effect of the pn diode formed by the junction of the added p^{+-}-layer and n-type base layer when viewed from the drain side. As the ideal equivalent circuit in Fig. 1-2 shows, the IGBT is a monolithic cascade-type Bi-MOS transistor that consists of a pnp bipolar transistor and a power MOSFET connected in Darlington form.

The device can be compared to a hybrid cascade-type Bi-MOS transistor that consists of a bipolar transistor chip and a power MOSFET chip. The major difference is the on-resistance of the power MOSFET. The on-resistance is extremely small in the IGBT. Considering the chip for inter-chip wiring, the IGBT is superior to the hybrid cascade-type Bi-MOS transistor.

2 FUJI's IGBTs

Fuji Electric Device technology (FDT) began producing and marketing IGBTs (insulated gate bipolar transistors) in 1988 and has been supplying them to the market ever since. Fig. 1-3 is an overview of the development of, and technologies implemented in the first five IGBT generations. FDT succeeded in enhancing the characteristics of the first three IGBT generations, by using epitaxial wafers, optimizing the lifetime control techniques, and by applying fine patterning technology. The company was able to significantly enhance the characteristics of the fourth and fifth generations by switching from epitaxial wafers to FZ (floating zone) wafers. This achievement brought about a revolutionary transition in conventional approaches to IGBT design.

The basic design concept of epitaxial wafer-based IGBTs (the third and fourth generations rated at up to 600V, called "punch-through" (PT) IGBTs) is described below. These IGBTs were injected with a carrier at a high level from the collector side so that they would be filled up with the carrier to reduce the on voltage when they are turned on. In order to obtain this on voltage reduction, an n-buffer layer supporting a higher voltage was built in the FZ wafer to achieve a thinner n-layer. Moreover, a lifetime control technique was implemented to remove the carrier filling up the IGBTs so as to lessen the switching loss (Eoff) when they are turned off.

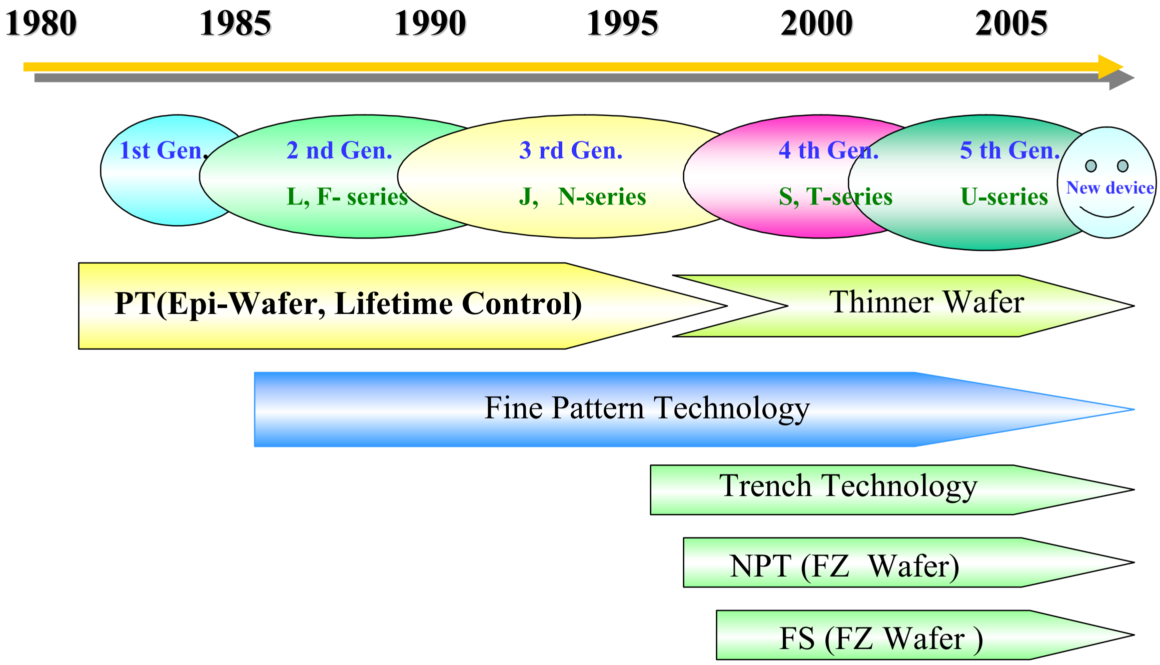


Fig. 1-3 Developments in technologies implemented in Fuji Electric IGBTs

Implementing lifetime control techniques led to increased on voltage because its effect (reduced carrier transport efficiency) persisted even in the regular on state. FDT initially worked around this problem by pursuing higher-level carrier injection. The basic design concept of epitaxial wafer-based IGBTs can be simply expressed in the wording "higher-level injection and lower transport efficiency." In contrast, FZ wafer-based IGBTs (fourth-generation 1200V IGBTs and later) implement the opposite approach to the basic design concept, such that carrier injection from the collector is suppressed to reduce injection efficiency and thus boost transport efficiency. The aforementioned design concept of higher-level injection and lower transport efficiency implemented in epitaxial wafer-based IGBTs had a limited effect in terms of characteristics enhancement as it took the illogical approach of using lifetime control techniques to suppress a carrier that had already been injected with a carrier. Moreover, the use of lifetime control resulted in certain effects that were detrimental to addressing the then growing need for the parallel use of IGBTs. One of these was increased variation in on voltage characteristics caused by lifetime control. The new FZ wafer-based non-punch through (NPT) IGBT (implemented from the fourth generation) and field stop (FS) IGBT (implemented from the fifth generation) were the result of technologies we developed to deal with these problems. The IGBTs are essentially designed to control the impurity level of the collector (p+ layer), without relying on lifetime controls, to suppress carrier injection efficiency. Yet, Fuji Electric had to work out an IGBT that withstood voltages as high as 1200V and that was as thin as one hundred and several tens of microns to achieve characteristics superior to those of an epitaxial wafer-based IGBT. (With a FZ wafer-based NPT or FS IGBT, the n-layer would approximate the chip (wafer) in thickness, and less thickness meant a lower on voltage.) In other words, the development of an FZ-wafer based IGBT has been a constant struggle for ever-thinner wafers.

FDT has launched a new line of NPT IGBTs that have evolved out of the fourth generation of 1200V IGBTs, as the S-series resolve these tasks. The company has made progress in developing 600V IGBTs requiring less thickness to such point that the market release of the 600V U series (fifth generation) is just around the corner. The U-series fifth generation of 1200V IGBTs has advanced from the NPT structure to the New FS structure to achieve enhanced characteristics that surpass the

S series. The FS structure, while adhering to the basic design concept of the lower-level carrier injection and higher transport efficiency with a lifetime control-free process, has an n-buffer layer supporting a higher voltage was built in the FZ wafer to achieve an IGBT structure that is thinner than the NPT structure. The company has completed preparations for putting on the market the resultant U-series of 1200V IGBTs which has an on voltage that is lower than that of the S-series. This technology is also implemented in a high withstand voltage line of 1700V IGBTs, which will soon be put on the market as well.

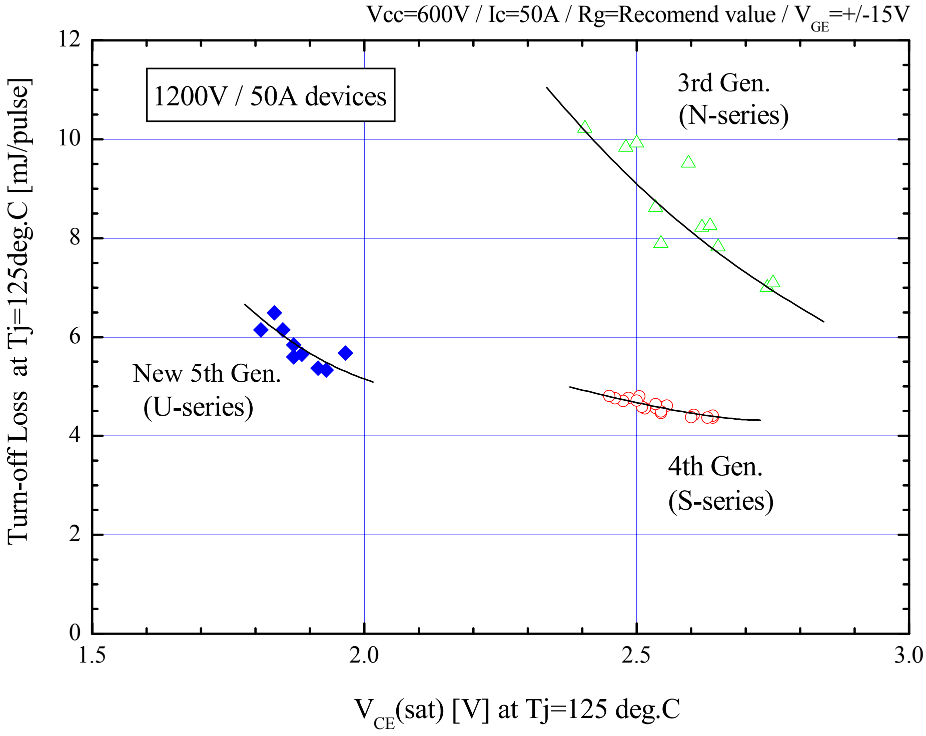


Fig. 1-4 Improved tradeoff characteristics

FDT has also pursued a finer-patterned surface structure as a technological prerequisite to enhancing IGBT characteristics. (Because an IGBT is made up of numerous IGBT blocks, fine patterning should allow a lower on voltage to be attained for more IGBT blocks.) FDT was able to realize more enhanced characteristics with the first four IGBT generations in terms of fine patterning in a planar structure (in which IGBTs are fabricated in a planar pattern). However, the company was able to dramatically enhance the characteristics with the fifth generation of the 1200V and 1700V lines of IGBTs, as a result of a technical breakthrough it made in fine pattern technology by drilling trenches in the Silicon (Si) surface. (Fig. 1-4 shows developments in the improvement of characteristics in the 1200V line.)

3 Gate controlled overcurrent protection

The most difficult challenge in producing an IGBT was making gate controlled protection possible. Differing from the ideal equivalent circuit shown in Fig. 1-2, the actual IGBT is a combination of thyristor and MOSFET as shown in Fig. 1-5.

The circuit design in Fig. 1-5 has one problem however, if the thyristor is triggered, then the IGBT cannot be turned off. This phenomenon, known as “latch-up”, may allow an overcurrent to destroy the device.

To prevent this “latch-up phenomenon”, the following techniques are used:

1) Reducing the base-emitter resistance makes the device less susceptible to latch-up.
2) Optimizing the thickness of the n^+ -buffer layer and the impurity concentration, allows the h_{FE} of the pnp transistor to be controlled.
3) Implementing a lifetime killer, allows the h_{FE} of the pnp transistor to be controlled.

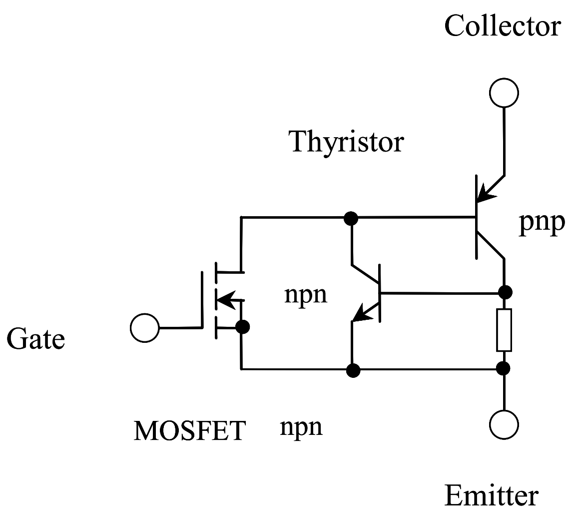


Fig. 1-5 Practical equivalent circuit

Using the above techniques, high speed, high voltage and high current IGBTs that don’t latch-up can be produced.

4 Overcurrent limiting feature

During operation, a load short-circuit or similar problem may cause an overcurrent in the IGBT. If the overcurrent is allowed to continue, the device may quickly overheat and be destroyed. The time span from the beginning of an overcurrent to the destruction of the device, is generally called the “short-circuit withstand capability time”.

The IGBT module has the ability limited to several times the devices current rating. In the event of a short circuit, the overcurrent is limited, giving the device a high short-circuit withstand capability.

5 Module structures

Fig. 1-6 and Fig. 1-7 show typical IGBT module structures. The module integrated with a terminal block shown in Fig. 1-6 has a case and external electrode terminals molded into a single unit to reduce the number of parts required and cut the internal wiring inductance. In addition, the use of a direct copper bonding (DCB) substrate makes for a high-reliability product that combines low thermal resistance and high transverse breaking strength.

The wire terminal connection structure module shown in Fig. 1-7 has main terminals bonded to the DCB substrate by wire, rather than by soldering, to simplify and downsize the package structure. This results in cuts in both thickness and weight, and fewer assembly person-hours.

Other design considerations implemented include an optimal IGBT and FWD chip layout to assure efficient heat distribution and the equal arrangement of IGBT devices in the upper and lower arms to equalize turn-on transient current balances and thus prevent increases in turn-on loss.

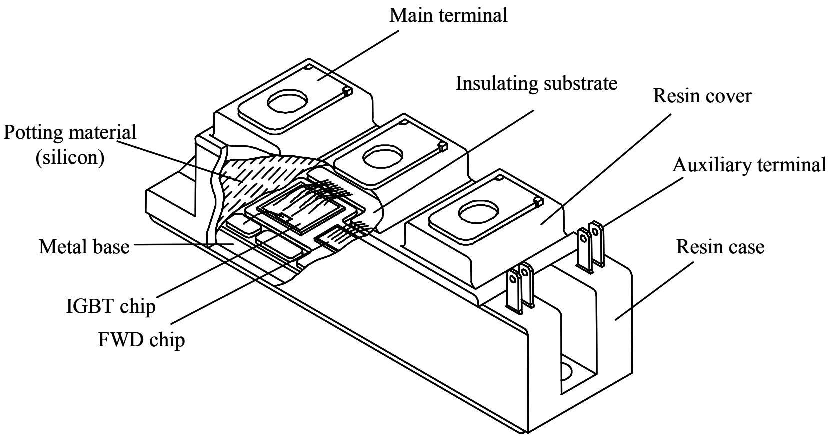


Fig. 1-6 Integrated with a terminal block type IGBT module

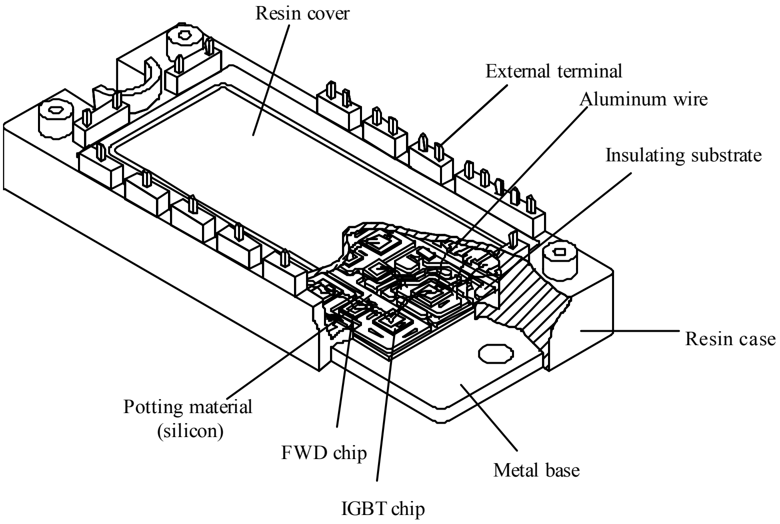
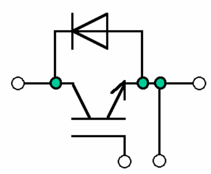
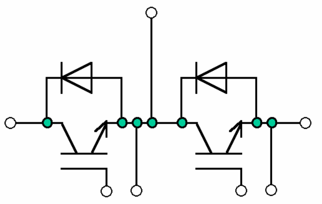
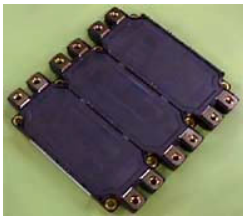
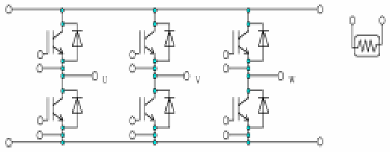
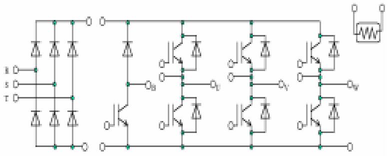


Fig. 1-7 Wire terminal connection structure type IGBT module

6 Circuit configuration of IGBT module

Table 1-1 shows typical circuit configuration of IGBT modules.
IGBT modules are configurationally grouped into four types: 1 in 1, 2 in 1, 6 in 1, and PIM (7 in 1). A circuit configuration is prescribed for each of these types. A summary description of the features of each type is also included in the figure to aid you in your device selection.

Table 1-1 Circuit configuration of IGBT modules

Type	Example of IGBT module		Features
	External view	Equivalent circuit	
1 in 1	 Example: 1MBI600S-120		Each product contains one IGBT chip and one FWD chip. Products having a high current rating are often connected in parallel in large capacity applications.
2 in 1	 Example: 2MBI450UE-120		Each product contains two IGBT chips and two FWD chips. Three units are generally used in a set to make up a PWM inverter. Otherwise, products having a high current rating are often connected in parallel.
6 in 1	 Example: 6MBI450U-120		Each product contains six IGBT chips and six FWD chips. Some variations contain a NTC. One unit is generally used alone to make up a PWM inverter.
PIM (7 in 1)	 Example: 7MBR75UB120		7 in1 contains seven IGBT chips and seven FWD chips in the inverter and brake section. PIM includes a converter section in addition to 7 in1. Some variations contain a NTC or a thyristor used for a electrolytic capacitor charging circuit.

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   - Safety devices

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