AN4503

An Introduction To IGBT Operation

Application Note

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The power semiconductor devices available on the market can be categorised into three groups viz.,

1) The devices such as diodes which are turned on and off by the action of the circuit;

2) Devices like thyristors and triacs which can be turned on by the gate control but require separate circuit implementation to turn them off.

3) Those devices such as bipolar transistors, gate turn-off thyristors (GTOs) and power MOSFETs which can be turned on and off by the gate signal.

The final group of devices are preferred in power electronics as they simplify circuitry, but they all have their advantages and disadvantages. For example GTOs are available in high-voltage and high current ratings but limited to lower frequencies (less than a few kHz) and require high power gate control. Bipolar junction transistors (BJTs) offer simpler driving than GTOs but they are limited to lower voltages (<1500V), while MOSFETs offer high speed operation (100kHz typical) and are very easy to drive but are limited to lower voltages and currents.

Over the past decade a new group of power devices which combines bipolar and mosfet technologies became commercially viable. MOS controlled bipolar devices such as IGBTs (Insulated Gate Bipolar Transistors) and MCTs (MOS Controlled Thyristors) belong to this group. These types of devices offer the best features of bipolar and MOSFETs devices. The aim of this note is to give an introduction to IGBTs outlining the device structures, mode of operation, ratings and characteristics so that the device can be used optimally by the power circuit designer.

1. IGBT STRUCTURES

All IGBTs on the market have either a punch-through structure (PT) or non-punch-through structure (NPT).

Fig.1 shows the vertical cross section through one of the elements of the PT and NPT IGBT structures. In practice an IGBT chip consists of many such elements connected in parallel. The NPT structure is the most basic one for an IGBT. It consists of a four layer sandwich of n+pn-p+, very similar to a thyristor structure except the gate consists of a polysilicon layer which is separated by an oxide layer grown on the top surface of the silicon wafer. The polysilicon layer is arranged such that it overlaps the n+ and n- regions. On the top, the emitter contact is made by aluminium which overlaps the n+ and p regions. On the other side of the wafer the collector contact is made by aluminium contact on the p+ region.

can be grown and so this type of structure is limited to voltages less than 1200V.

The NPT structure is fabricated by starting with a uniformly doped (n-) silicon wafer. The emitter and MOSFET are formed by diffusion on the top side of the wafer and the p+ collector is formed by an implantation method on the other side of the wafer. With the NPT structure it is currently possible to achieve forward blocking voltages as high as 4.5kV. The static and dynamic characteristics of the PT and the NPT IGBTs are different and these will be discussed later.

The reverse breakdown voltage between emitter and collector is characterised by the reverse breakdown of the un-terminated collector to base junction (n+ in PT structure and n- in NPT structure). This has a typical value of 10V. In many applications an anti parallel diode is used with an IGBT switch and so it has to withstand only the forward voltage drop of this diode in the reverse breakdown mode. However the transient forward voltage drop of a diode can be significantly higher than the steady state value and it is likely that this junction is broken down transiently by the diode's transient forward voltage. This has no serious detrimental effect as long as the duration is short and the magnitude of the resultant transient power is within the device avalanche power rating.

2. DEVICE OPERATION

In the normal mode of operation, the collector is made positive with respect to emitter and if gate is at zero potential with respect to emitter, no main current flows from collector to the emitter (apart from blocking current). When gate potential is made positive with respect to emitter, electrons are attracted in the p region below the gate oxide and eventually inverting the polarity of p type to n type. This inversion layer hence provides an n-channel from the n+ layer to the n- layer. Electrons are injected from the n+ emitter contact into the n- region thus lowering the potential of this region and forward biasing the p+ n- junction from the collector side. Hence holes are injected from the collector into the n- layer (Fig.2).

The excess holes and electrons in the n- region reduces the resistivity of this region. This is known as conductivity modulation which reduces the on-state resistance of the device. This is

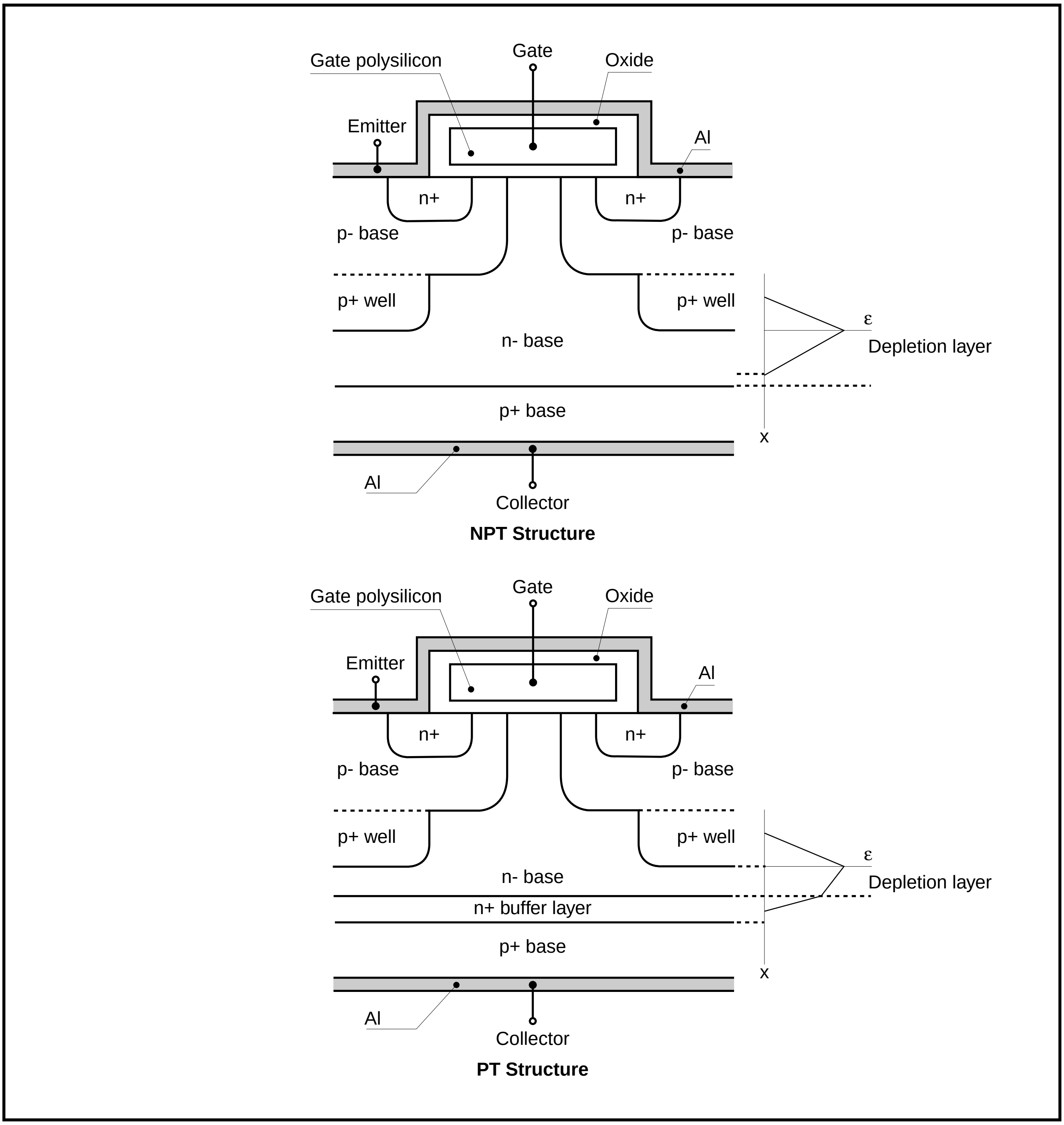

Fig.1 The structure of IGBTs

The main difference between the two structures is the lack of n+ buffer layer in the NPT structure. Those who are familiar with the power MOSFET will recognise that the PT IGBT structure is similar to the power MOSFET structure except an additional p+ layer has been added to the drain side of the MOSFET. When blocking voltage is applied between the collector and the emitter, most of this is supported by the n- region.

In the case of PT-structure, the extension of the depletion region punches through the n+ layer before break down of the junction occurs. One of the functions of the n+ buffer layer is to pin down the expansion of the depletion region to the n+ layer. Thus the main blocking junction of the PT IGBT has a classical p-i-n diode structure. The p-i-n structure has a thinner n- thickness compared with a pn structure for the same blocking voltage capability and this helps to improve the dynamic characteristics of the PT IGBT.

In an NPT-structure, the resistivity and the thickness of the n- layer is chosen such that, when the junction breaks down, the width of the depletion region does not reach through to the p+ collector layer. Hence the main blocking junction in the NPT IGBT has a pn diode structure. The electric fields associated with these structures are also illustrated in the Fig. 1.

The PT IGBT is fabricated by growing the n+ and then the n- epitaxial layers on the p+ substrate. The emitter and MOSFET are formed by double diffusion. The forward blocking voltage is a function of n- base-width and the resistivity of the n- epi layer. There is a practical limit for the thickness of the epi layer which

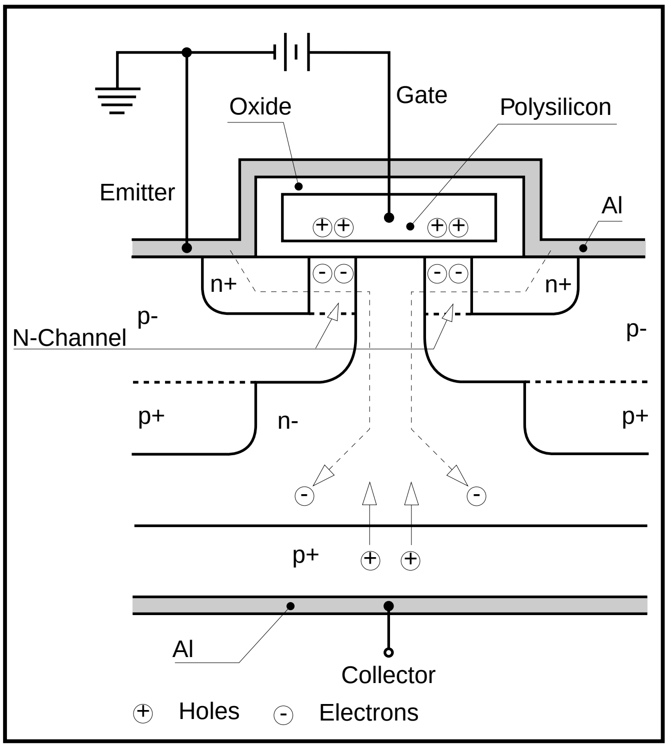

Fig.2 Turn-on process in IGBTs

why for a similar voltage design, an IGBT has a lower on-state resistance than a power MOSFET which does not exhibit conductivity modulation. In the PT structure, the injected holes from the p+ collector have to cross over the n+ buffer layer to reach n- base. Some of these holes are lost in the buffer layer due to recombination process, consequently the injection efficiency of the p+ is reduced. This has a marked influence on the dynamic characteristics of the IGBT.

3. IGBT EQUIVALENT CIRCUIT

Fig. 3a and 3b shows an equivalent circuit of an IGBT representing its internal structure.

As mentioned before the IGBT has a four layer (p-n-p-n) thyristor-like structure which may be represented by PNP and NPN transistors and because the middle n- region is common to both, the base of each transistor is effectively connected to the collector of the other.

The power MOSFET is then connected across the base and the collector of the PNP transistor. RMOD represents n- base resistance which is heavily modulated. RB is the lateral resistance of the emitter p-base diffusion.

If the loop gain of the PNP and NPN transistors combination is greater than one, then the

IGBT will latch on and behave like a thyristor with loss of gate control. Such a situation could be destructive to the device and various design features are included in the IGBT design to prevent it, such as:

i) Minimising the value of RB by diffusing a p+ well.

ii) Inclusion of an n+ buffer layer as in the PT structure which allows the gain of the PNP transistor to be controlled.

iii) Control of the gain of the PNP transistor by electron irradiation.

The NPN transistor is thus disabled and since RB is made insignificant, one can ignore these two components in the modified equivalent circuit as shown in Fig. 3c. The final combination of a PNP transistor and an N-channel power MOSFET behaves like an NPN transistor with a voltage driven base: hence the circuit symbol for the IGBT.

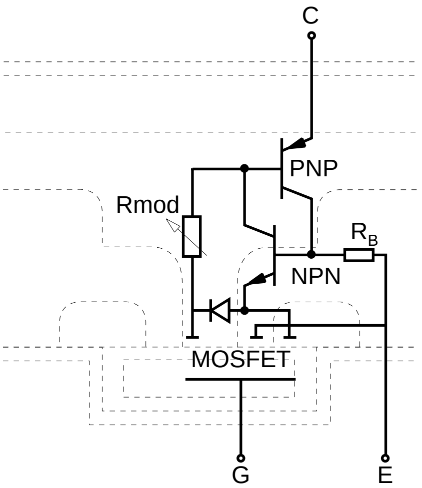

Fig.3a Equivalent circuit

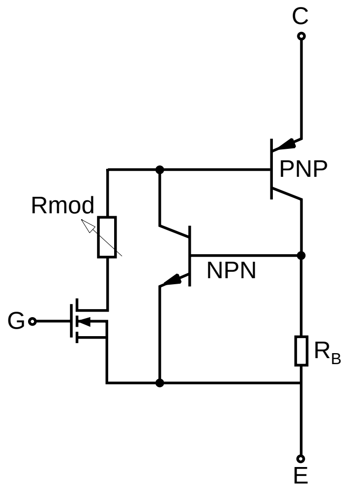

Fig.3b Equivalent circuit

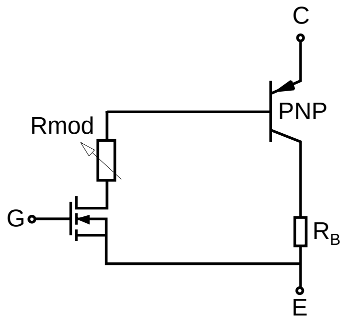

Fig.3c Equivalent circuit

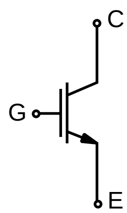

Fig.3d Circuit symbol

Fig. 3 IGBT equivalent circuit

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