Analysis on IGBT Developments

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***Abstract*— Silicon based high power devices continue to play an important role in modern high power systems, especially in the fields of traction, industry and grid applications. Today, approximately 30 years after its invention, a Bipolar-MOS "BiMOS" controlled switch referred to as the Insulated Gate Bipolar Transistor IGBT is the device of choice for the majority of power electronics converters with power ratings ranging from few kWs to beyond the 1GW mark. Following a brief introduction into power devices and applications in general, this paper will provide an overview of the development history and recent advancements of the IGBT. More importantly the future technology trends purely from the device design viewpoint will be discussed, including the predicted performance impact such technology platforms will have at the system level especially in the high power range.**

Keywords*— *Bipolar MOS Controlled, IGBT, gain, ON state resistance

I. INTRODUCTION

The Insulated Gate Bipolar Transistor (IGBT) is a minority-carrier device with high input impedance and large bipolar current-carrying capability. Many designers view IGBT as a device with MOS input characteristics and bipolar output characteristic that is a voltage-controlled bipolar device. To make use of the advantages of both Power MOSFET and BJT, the IGBT has been introduced. It's a functional integration of Power MOSFET and BJT devices in monolithic form. It combines the best attributes of both to achieve optimal device characteristics [1]

II. PERFORMANCE

The Insulated Gate Bipolar Transistor also called an IGBT for short, is something of a cross between a conventional *Bipolar Junction Transistor* and a *Field Effect Transistor*, making it ideal as a semiconductor switching device. The *IGBT transistor* takes the best parts of these two types of transistors, the high input impedance and high switching speeds of a MOSFET with a lower saturation voltage of a bipolar transistor, and combines them together to produce another type of transistor switching device that is capable of handling large collector-emitter currents with virtually zero gate current drive. IGBT uses the insulated gate (hence the first part of its name) technology of the MOSFET with the output performance characteristics of a conventional bipolar transistor. The result of this hybrid combination is that the "IGBT Transistor" has the output switching and conduction characteristics of a bipolar transistor but is voltage-controlled like a MOSFET. The advantage gained by the insulated gate bipolar transistor device over a BJT or MOSFET is that it offers greater power gain than the standard bipolar type transistor combined with the higher voltage operation and lower input losses of the MOSFET. In effect it is an FET integrated with a bipolar transistor in a form of Darlington type configuration as shown in Fig. 1.

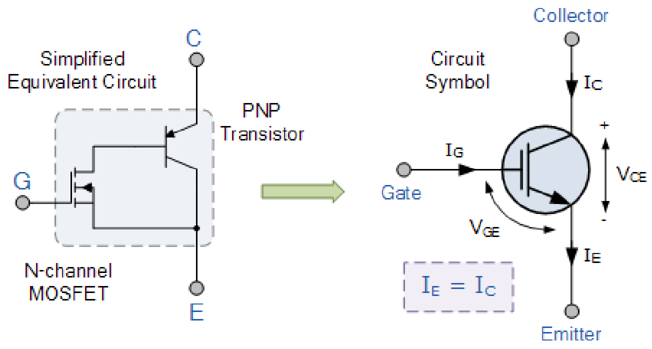


Fig.1. MOSFET Configuration.

The IGBT has a much lower "on-state" resistance, R_{ON} than an equivalent MOSFET. The forward blocking operation of the IGBT transistor is identical to a power MOSFET. When used as a static controlled switch, the insulated gate bipolar transistor has voltage and current ratings similar to that of the bipolar transistor. However, the presence of an isolated gate in an IGBT makes it a lot simpler to drive than the BJT as much less drive power is needed. It has the high voltage capability, low ON-resistance, ease of drive, relatively fast switching speeds and combined with zero gate drive current makes it a good choice for moderate speed, high voltage applications such as in pulse-width modulated (PWM) solar powered DC-AC inverter and frequency converter applications operating in the hundreds of Kilohertz range.

Table1: Comparison between different transistors

Device Characteristic	Power BJT	Power MOSFET	IGBT
Voltage Rating	High <1kV	High <1kV	Very High >1kV
Current Rating	High <500A	Low <200A	High >500A
Input Drive	Current 20-200 h_{FE}	Voltage V_{GS} 3-10V	Voltage V_{GE} 4-8V
Input Impedance	Low	High	High
Output Impedance	Low	Medium	Low
Switching Speed	Slow (uS)	Fast (nS)	Medium
Cost	Low	Medium	High

III. BASIC STRUCTURE

The basic schematic of a typical N-channel IGBT based upon the DMOS process is shown in Fig. 2. This is one of several structures possible for this device. It is evident that the silicon cross-section of an IGBT is almost identical to that of a vertical Power MOSFET except for the P+ injecting layer. It shares similar MOS gate structure and P wells with N+ source regions. The N+ layer at the top is the source or emitter and the P+ layer at the bottom is the drain or collector. It is also feasible to make P-channel IGBTs and for which the doping profile in each layer will be reversed. IGBT has a parasitic thyristor comprising the four-layer NPNP structure. Turn-on of this thyristor is undesirable.

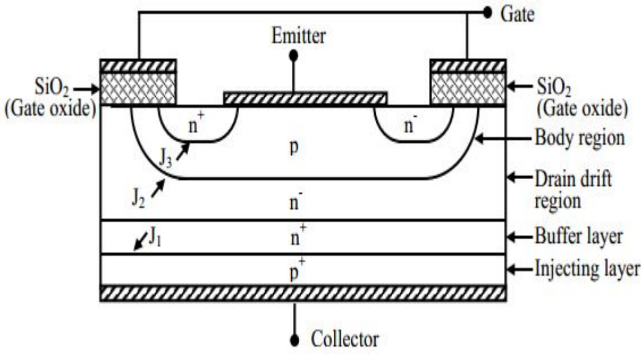


Fig. 2. IGBT

IGBT takes a parasitic thyristor includes the 4-layer NPN structures as shown in Fig. 2. The constituent p-n-p transistor, n-p-n transistor and the driver MOSFET are shown by dotted lines in this figure. There are some IGBs that are fabricated without the N+ buffer layer is called as NPT IGBTS non punch through), whereas some IGBTs are fabricated with the N+ buffer layer called as PT IGBTs (punch through). The performance of the device can considerably increase by exciting the buffer layer. The operation of an IGBT is faster to that of power BJT than a power MOSFET.

Fig. 3 shows the exact equivalent circuit of the IGBT cell structure. The top p-n-p transistor is formed by the p+ injecting layer as the emitter, the n type drain layer as the base and the p type body layer as the collector. The lower n-p-n transistor has the n+ type source, the p type the base of the lower n-p-n transistor is shorted to the emitter by the emitter metallization. However, due to imperfect shorting, the exact equivalent circuit of the IGBT includes the body spreading resistance between the base and the emitter of the lower n-p-n transistor. If the output current is large enough, the voltage drop across this resistance may forward bias the lower n-p-n transistor and initiate the latch up process of the p-n-p-n thyristor structure. Body and the n type drain as the emitter, base and collector respectively [2]

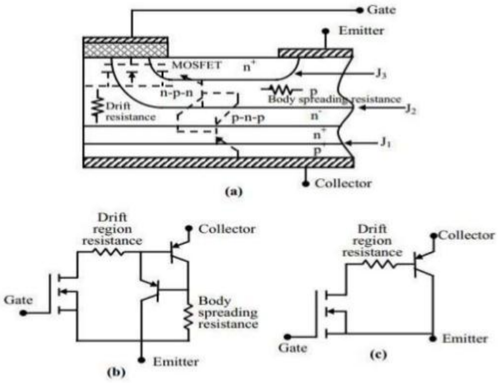


Fig. 3: Equivalent diagram of an IGBT

IV. OPERATING PRINCIPLE OF IGBT

1. From the input side the IGBT behaves essentially as a MOSFET.

2. Therefore, when the gate emitter voltage is less than the threshold voltage no inversion layer is formed in the p type body region and the device is in the off state.

3. The forward voltage applied between the collector and the emitter drops almost entirely across the junction J2.

4. Very small leakage current flows through the device under this condition.

5. In terms of the equivalent current of Fig.3(c), when the gate emitter voltage is lower than the threshold voltage the driving MOSFET of the Darlington configuration remains off and hence the output p-n-p transistor also remains off.

6. When the gate emitter voltage exceeds the threshold, an inversion layer forms in the p type body region under the gate.

7. This inversion layer (channel) shorts the emitter and the drain drift layer and electron current flows from the emitter through this channel to the drain drift region.

8. This in turn causes substantial hole injection from the p+ type collector to the drain drift region.

9. A portion of these holes recombine with the electrons arriving at the drain drift region through the channel.

The rest of the holes, cross the drift region to reach the p type body, where they are collected by the source.

V. CHARACTERISTICS OF IGBT

1. The V-I characteristics of an n channel IGBT are shown in Fig.4.
2. They appear qualitatively similar to those of a logic level BJT except that the controlling parameter is not a base current but the gate-emitter voltage.
3. When the gate emitter voltage is below the threshold voltage only a very small leakage current flows though the device while the collector – emitter voltage almost equals the supply voltage (point C in Fig. 4)

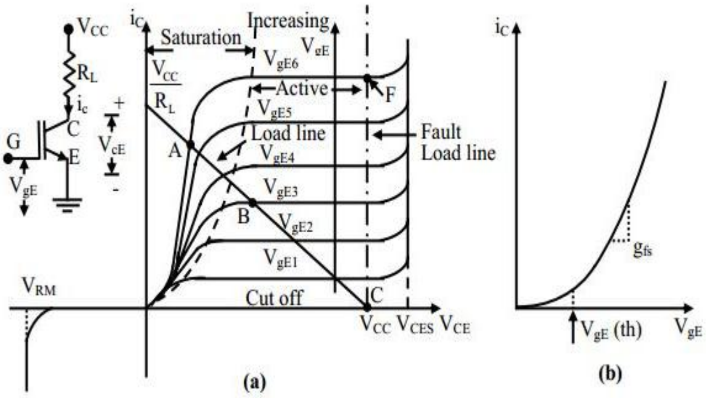


Fig. 4. V-I Characteristics of IGBT

The device, under this condition is said to be operating in the cut off region.

1. The maximum forward voltage the device can withstand in this mode (marked V_{CES} in Fig.5) is determined by the avalanche break down voltage of the body – drain p-n junction.

2. Unlike a BJT, however, this break down voltage is independent of the collector current as shown in Fig.5.

3. IGBTs of Non-punch through design can block a maximum reverse voltage (V_{RM}) equal to V_{CES} in the cut off mode.

4. However, for Punch through IGBTs V_{RM} is negligible (only a few tens of volts) due the presence of the heavily doped n+ drain buffer layer.

5. As the gate emitter voltage increases beyond the threshold voltage the IGBT enters into the active region of operation.

6. In this mode, the collector current i_c is determined by the transfer characteristics of the device as shown in Fig. 4.b.

7. As the gate emitter voltage is increased further i_c also increases and for a given load resistance (R_L) v_{CE} decreases.

8. At one point V_{CE} becomes less than V_{GE} – V_{GE}(th). Under this condition the driving MOSFET part of the IGBT (Fig. 4.a) enters into the ohmic region and drives the output p-n-p transistor to saturation.

9. Under this condition the device is said to be in the saturation mode.

10. In the saturation mode the voltage drop across the IGBT remains almost constant reducing only slightly with increasing V_{GE}.

11. If a short circuit fault occurs in the load resistance R_L (shown in the inset of Fig. 4.b). The fault load line is given by CF.

VI. OPERATING MODES

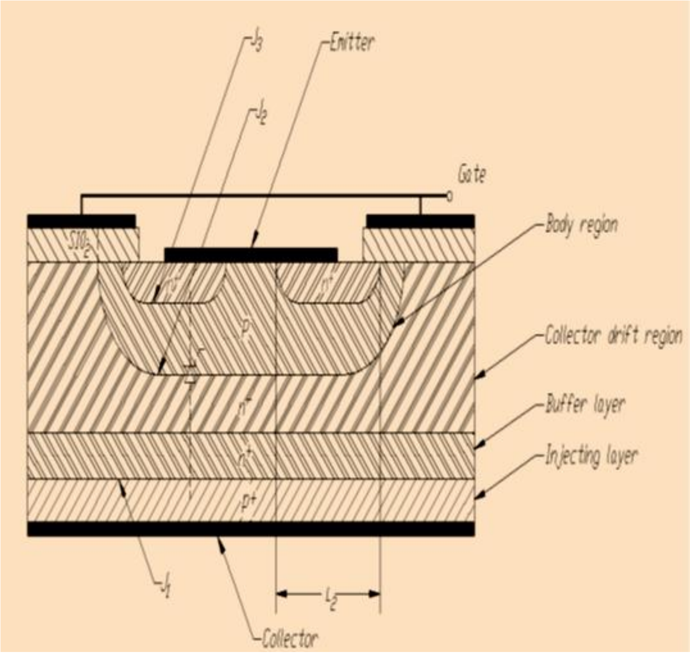


Fig. 5. Operating modes of an IGBT

A. *Forward Conduction Mode:*

An IGBT in the forward-blocking state can be transferred to the forward conducting state by removing the gate-emitter shorting and applying a positive voltage of sufficient level to invert the Si below gate in the P base region. This forms a conducting channel which connects the N+ emitter to the N- drift region. Through this channel, electrons are transported from the N+ emitter to the N- drift
Result: conductivity modulation.

B. *Reverse blocking mode:*

When a negative voltage is applied across the collector-to-emitter terminal, the junction J1 becomes reverse-biased and its depletion layer extends into the N- drift region. The break down voltage during the reverse-blocking is determined by an open-base BJT formed by the P+ collector/ N- drift/P base regions. The device is prone to punch-through if the N-drift region is very lightly-doped. The desired reverse voltage capability can be obtained by optimizing the *resistivity and thickness of the N- drift region.*
Reverse blocking IGBT is rare and in most applications, an anti - parallel diode (FRED) is used.

C. *Reverse-Blocking IGBT:*

The reverse-blocking IGBT is a new device with reverse withstands voltage performance that is not possible with conventional IGBTs. Fig. 6 shows a bidirectional switch with a conventional IGBT and a bidirectional switch with a reverse-blocking IGBT. When the reverse blocking IGBT is used in direct linked type converter such as matrix converters, the diodes required for obtaining reverse withstand voltage in conventional switch are no longer necessary. Elimination of the diodes should lead to the following benefits:
1. Lower cost and smaller packages because there are fewer chips.

2. Lower on-state voltage: About 4 V in conventional IGBTs + diodes, but about 2 V in reverse-blocking IGBT only.

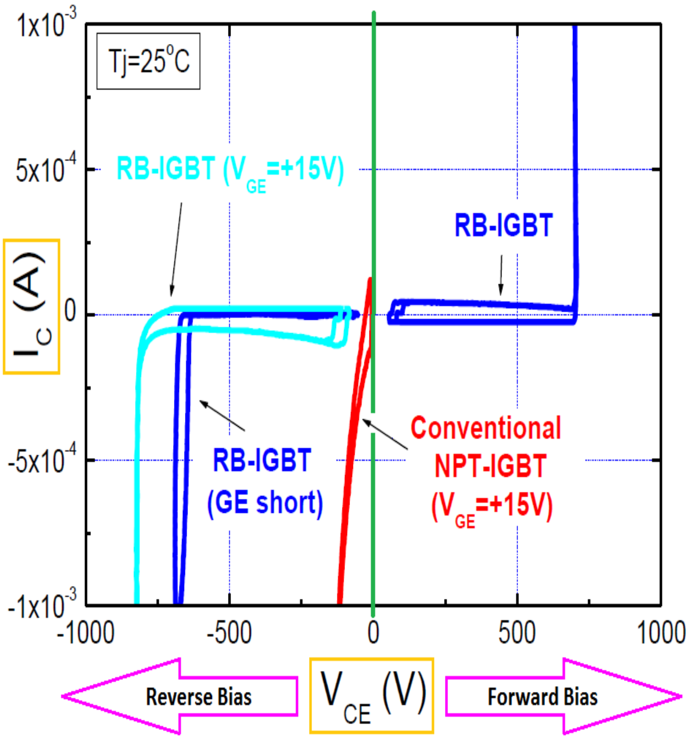
Described next is the reverse withstand voltage structure of a reverse-blocking IGBT. In the final stage of the chip manufacturing process, chips are cut out from the wafer (dicing process), leaving the side surfaces of the chips with crystal deformations and high density crystal defects. In a conventional IGBT, if a reverse bias is applied, the depletion layer extending from the p-n junction at the back surface - that is, a high electric field region - also appears on the dicing surface. Because carriers generated continuously from the crystal defects are transported by the electric field, resulting in a large leakage current, we could not obtain any reverse withstand voltage. In a mesa-type reverse-blocking IGBT, the chip periphery is etched through the n-layer to isolate the active area and dicing surface electrically. Because there is no electric field on the dicing surface, there is no leakage current. When a reverse bias is applied, the depletion layer extends from the p-n junction that appears on the etching groove surface. Because no silicon crystal deformation exists in this area, the leakage current is small. In addition, because the p-n junction has a positive bevel structure, the electric field is relaxed, preventing local enhancement of the electric field.

In an isolation type reverse-blocking IGBT, a very deep isolation region (p+) is formed from the wafer surface in advance so that an isolation region appears at the back surface after back lap of the wafer, and the dicing surface is completely covered with the isolation region. Next, formation of the p+ collector layer on the back surface extends the depletion layer along the adjacent collector layer at the back surface and the isolation region. Because it does not reach the dicing surface, generation of the leakage current can be prevented.

RB IGBT is a new device with reverse withstand voltage performance that is not possible with conventional IGBT**:**

1. Conventional IGBT
- Uni -directional
- Leakage current
- Non -Punch Through or Field Stop structure

2. True RB-IGBT
- Reverse Blocking capability
- NPT structure
- Isolation region
- Bi-directional switch (2x RB)



Biasing of IGBT

RB IGBT structure prevents leakage current generation:

1. Conventional IGBT
- NPT structure
- Mech Diced Side Wall
- Leakage Current

2. RB – IGBT
- Special Structure
- Isolation Region
- Well Designed
- Reliable for +/- Bias
- Mech Diced Side Wall

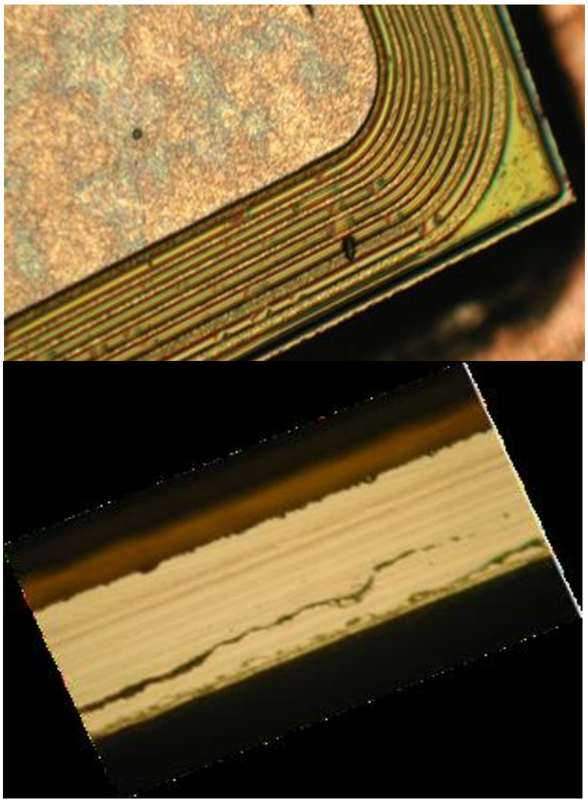


Fig. 6.-RB-IGBT main structure with RB capability

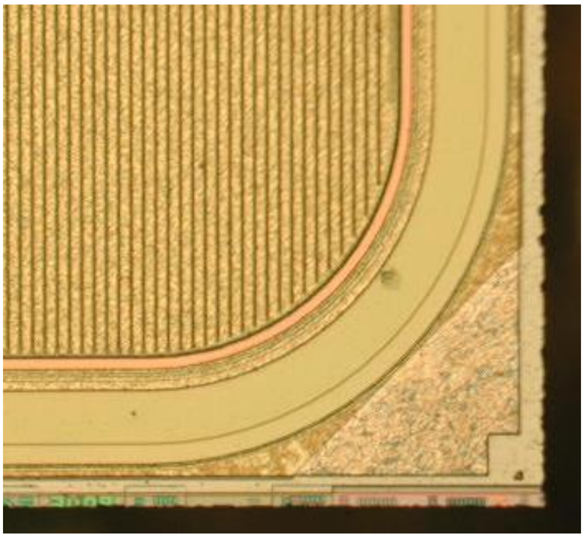


Fig. 7. IGBT isolation region without RB capability.

VII. REVERSE STATES OF THE IGBT

The use of the IGBT in inverter circuits does not come without its problems. During the switching cycle the signs of current and voltage applied to the switching device change temporarily caused by the inversion of the flux of energy between supply and load. The IGBT has no provision for carrying negative voltages; therefore it must be terminated with an anti-parallel or a series diode. However, it is not possible to completely suppress transient reverse states of the IGBT, which are caused by the transient behavior of the diode (which shows forward and reverse recovery) and are also due to parasitic inductance within the Circuit. Character and effect of these stresses are dependent on the trigger point and the electrical behavior of the switching scheme. But they are also influenced by the carrier densities inside the IGBT at the start of the commutation process. A further improvement of switching performance may be achieved by optimizing trigger points and substituting the supplementary diode in different NPT-IGBT applications. There is an immense risk in these schemes to expose the non-protected IGBT to a high reverse stress caused by changing driving and load conditions.

VIII. CLASSIFICATION OF REVERSE STATES

The reverse states can be distinguished by different parameters of the switching configuration. First of all the switching state allows to qualify the carrier density inside the IGBT at current zero crossing. The state is predicted by the drive only. Secondly the commutation is characterized by the derivatives of current and voltage at the device with respect to the time. The commutation rates determine the behavior of the circuit. A third parameter is based on the energy impressed into the IGBT [6].

A parameter summarizing the properties of the IGBT is the energy E_{REV}, which the inverter impresses into the IGBT during the reverse state:

$$E_{\mathrm{REV}} = \int \left| i_{rev} * v_{rev} \right| \partial t_{rev}$$

i_{REV} and v_{REV} the current through the collector and the voltage from collector to emitter during the whole time of reverse stress t_{REV}.

A parameter characterizing the IGBT is the energy E_{REV} (Q) which can be stored by displacement of charge until reverse breakdown at $V\mathrm{br}_{\mathrm{rev}}$:

$$E_{REV}(Q) = \int Q_{REV}(i, v) \partial\, v_{REV}$$

Q_{REV} is the charge displaced by the reverse stress until reverse breakdown. The ratio of the energies $E_{\mathrm{REV}}/E_{\mathrm{REV}}$ (Q) can be taken as an extension of the reverse stress of the IGBT. Whereas E_{REV} can be obtained recording v_{rev}, and i_{rev} the calculation for E_{REV} (Q) is more difficult. In the steady off-state only Q_{REV} reduces to the value of the fixed charges in the depleted region and is a function of v_{rev} alone. In the on-state Q_{REV} depends on the forward current and is expected to follow a square root law. The influence of the reverse bias appears more complicated. But mostly the commutation rates do not affect QREV due to the order of minority lifetime in common IGBTs.

IX. CONCLUSIONS

In an ever increasing power electronics applications market, the fundamental contribution power semiconductor devices have on the system level performance will ensure the continuous drive for improving both the device functionality and operational parameters. The paper presented a review of the recent advancements achieved in the field of Bipolar MOS controlled silicon devices with the main component under the spotlight being the IGBT. Conduction losses of an IGBT play an important role in the designing, development of the family. The new L5 IGBT [7] is a fresh example of this. The L5 in combination with the TO 247 4 pin package provides the lowest possible switching and conduction losses. Future developments will maintain similar past trends for the growing system demands in terms of increased power levels, improved efficiency, greater control and reliability.

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