

A Fast Switching Insulated-Gate P-I-N Diode Controlled Thyristor Structure

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Abstract-- A new Insulated-Gate PIN Diode Controlled Thyristor (IGPDT) structure is reported. Its on-state and turn-off characteristics are studied using two-dimensional numerical simulations. Results show that the IGPDT achieves similar on-state characteristics compared to that of the trench BRT (Base Resistance Controlled Thyristor), and also provides gate turn-off capability up to current density of several hundred A/cm². However, resistive switching turn-off speed of the IGPDT is approximately 3 times faster than that of the trench BRT.

I. INTRODUCTION

Thyristor structures with high input impedance are of great interest for high voltage, high current power switching applications like HVDC transmission, traction drives, etc. In general, the principle of operation of these devices involves turning on and off of the thyristor through a MOS gate. And when the thyristor is on, an extremely low on-state resistance can be achieved. This type of device has the advantages of low forward drop and gate turn-off capability. The Base Resistance Controlled Thyristor (BRT) [1] is a good example of such a structure in which turn-on of the device is achieved by injection of electrons into the drift region via a DMOS channel formed in the p-base, resulting in injection of holes from the p+ anode and eventually turns on the thyristor. Turn-off of the structure is achieved by diverting the hole current away from the p-base using a p-channel MOSFET located adjacent to the p-base of the thyristor. However, during turn-off, the BRT may fail to divert the holes in the p-base quickly enough to turn-off the device owing to the large on-resistance of the p-channel MOSFET [2]. This results in low maximum controllable current and slow switching speed. Improvement on the performance of the BRT has been the focus of a lot of research, including the efforts of using trench gate and isolated p-base channel to achieve a better turn-off capability [3, 4].

In this paper, a new thyristor structure called the Insulated-Gate P-I-N Diode Controlled Thyristor (IGPDT) is reported. The new structure provides MOS gate control with low

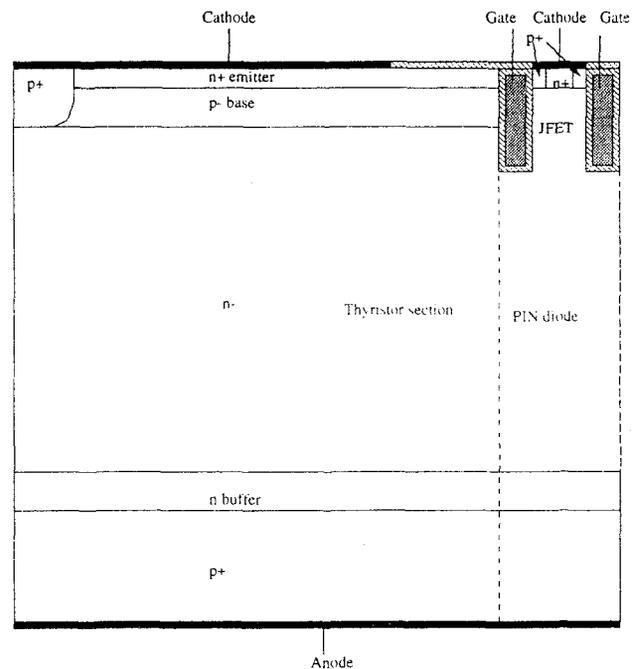


Fig.1. Cross-section of the IGPDT

forward voltage drop and good transient characteristics. The device structure and operation of the IGPDT is studied by using two-dimensional numerical simulations. Results on the on-state and switching characteristics of the structure are presented.

II. DEVICE STRUCTURE AND OPERATION

A cross-sectional view of the IGPDT structure is shown in Fig.1. It consists of a thyristor section and a combination region of a trench gate and a PIN diode with two p+ regions located at the cathode side of the diode separating the diode cathode with the trench side wall. When a positive gate voltage

is applied to the gate, an n+ accumulation layer is created at the bottom and along the side wall of the trench outside the p-base, and a DMOS channel is also produced along the trench side wall within the p-base. Current conduction at the diode cathode is enhanced by the drift of electrons through the accumulation layer. Majority of the electrons flow through the JFET region (Fig.1), and there are also electrons flow through the DMOS channel. All of these electrons flow from cathode to anode causes the anode p+/n diode to turn-on, resulting in hole injection from the anode. Since the JFET region resistance for hole current to flow into the p+ cathode is much larger than that for electron current to flow due to the transverse electric field, most of the holes are diverted to flow in the p-base. This causes the thyristor section to turn-on, and the on-state of the thyristor with a low forward drop is obtained. In device turn-off, due to the lower electron concentration at the trench sidewall and bottom regions of the IGPDT at the on-state, a negative voltage applied to the gate can easily create a p type inversion layer surrounding the trench gate in the n region. This creates a hole conduction path with much lower resistance compared to the channel resistance of the turn-off PMOS used in the BRT [3, 4]. Furthermore, due to the existence of the p inversion layer and a depletion layer formed in the JFET region, more holes can now flow from the p-base and the n drift region to the cathode via these paths. All of these make the turn-off of the IGPDT much faster than that of the BRT.

The p inversion layer is connected with the cathode through the p+ region of the PIN diode, forming a wide base PNP transistor with the n drift region and p+ anode. Holes in the p-base are collected by drifting through the p inversion layers and the JFET region to the diode p+ cathode regions. A depletion region is established in the JFET region because of the transverse electric field produced by the negative gate voltage. This creates a potential barrier to prevent electrons to flow from the n+ cathode to the n-drift region. The thyristor current path is therefore interrupted due to the decrease in electron supply from the cathode and the removal of holes in the p-base. After the JFET region is pinched-off and the n+ emitter/p-base junction is not turned on, the IGPDT is successfully turned off.

If the PIN diode p+ cathode regions do not exist, there is a high concentration electron-hole plasma present in the JFET region during device turn off. The high concentration plasma cannot be depleted by external application of a transversal electric field due to the fact that the plasma will prevent the penetration of the electric field to a few Debye lengths only [5]. The p+ cathode region provides an efficient path for holes to flow to the diode cathode, resulting in an obvious decrease in the electron-hole plasma concentration in the JFET region [6] at the initial of the turn-off period. Therefore, the IGPDT can be turned-off in a much faster speed. After the IGPDT is turned off, high voltage is supported by the wide base pnp transistor.

The IGPDT can also provide a much lower thyristor turn-on voltage due to the lower resistance in the JFET region

compared to that of the DMOS channel. This will result in a smaller turn-on "knee" in the forward conduction characteristics. Because of this, the length of the n+ emitter of the IGPDT can be considerably shorter than that of the BRT if the same turn-on voltage is required. Therefore, the IGPDT is more area efficient compared to the BRT. In addition, the smaller p-base resistance due to the shorter n+ emitter length will result in a more efficient removal of holes and a faster switching speed compared to the BRT.

III. NUMERICAL SIMULATIONS

The on-state and switching characteristics of the IGPDT were studied using the two-dimensional numerical simulator MEDICI [7]. In the simulations, the device structure shown in Fig.1 is used with a cell pitch of 35 μm . A trench gate with a gate oxide thickness of 500 \AA and a JFET region width of 1 μm are used. The thickness of the n- drift layer and n-buffer layer are 55 μm and 10 μm , respectively. The doping concentration of the n- drift layer and n-buffer layer are $1 \times 10^{14} / \text{cm}^3$ and $1 \times 10^{16} / \text{cm}^3$, respectively. The p-base region is with a surface concentration of $1 \times 10^{17} / \text{cm}^3$ and a junction depth of 3 μm . The n+ emitter length and depth are 25 μm and 1 μm , respectively. The trench gate depth is 5 μm .

A. Forward Conduction Characteristics

The forward conduction characteristics of the IGPDT

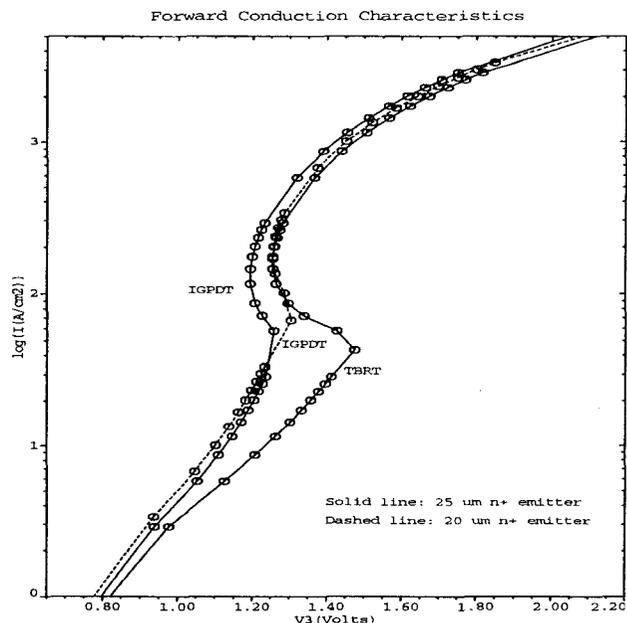


Fig.2 Comparison between the I-V characteristics of the IGPDT and the TBRT

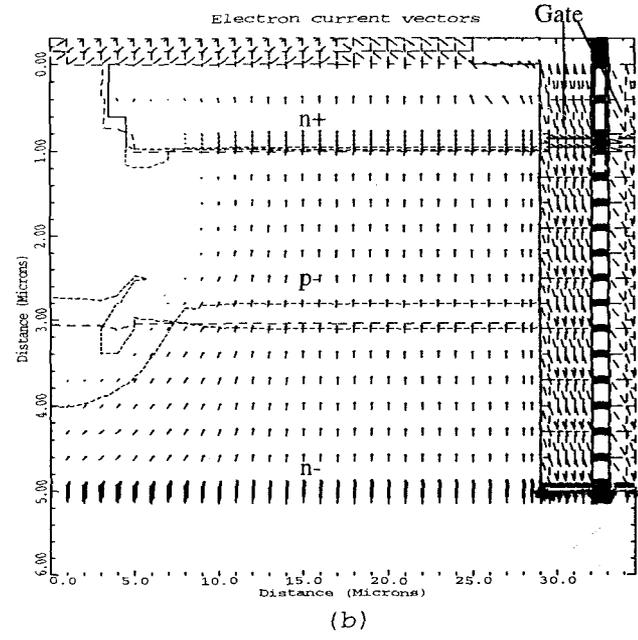
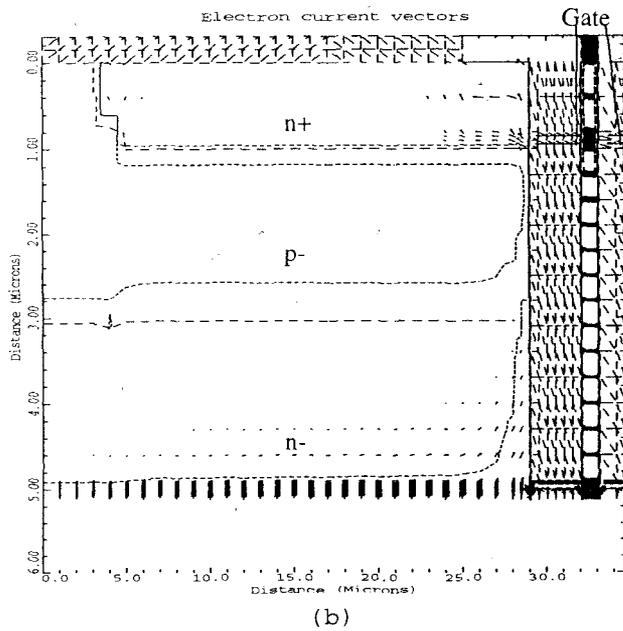
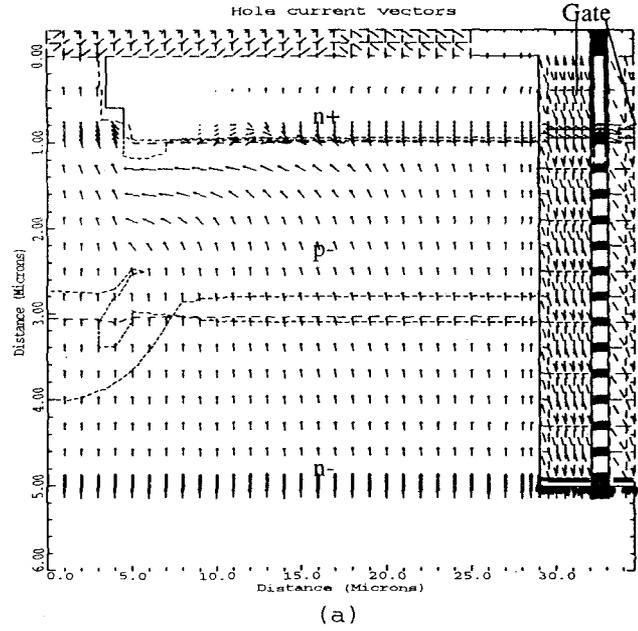
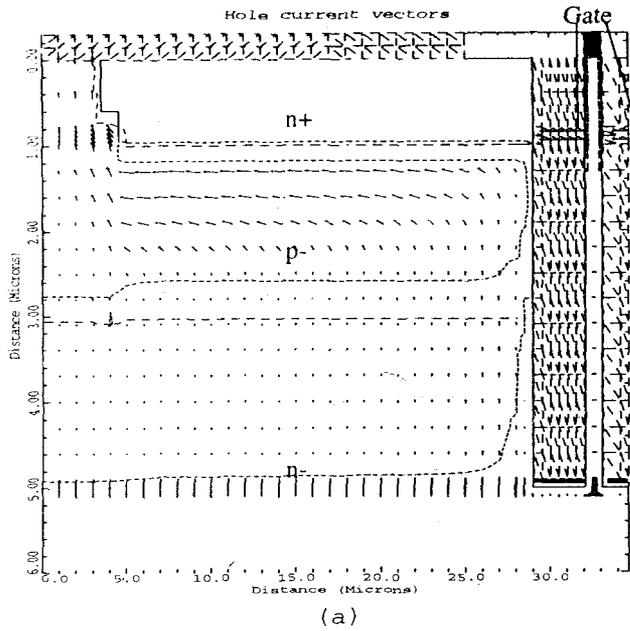


Fig.3 Hole (a) and electron (b) current vectors in the P-I-N diode mode of the IGPDT before thyristor turn-on

Fig.4 Hole (a) and electron (b) current vectors in the thyristor mode of the IGPDT after thyristor turn-on

obtained from simulations with different n+ emitter lengths are shown in Fig. 2. The forward conduction characteristics of the trench BRT (TBRT) [3] are also shown. The simulations are carried out at a gate bias of 10 V. From this figure, it can be seen that the IGPDT has approximately 17% smaller turn-on voltage compared to the TBRT. At a current density of 100 A/cm², the forward voltage drop of the IGPDT (1.16V) is approximately 10% smaller than that of the TBRT(1.29V). The latching and holding current of the IGPDT is determined

by the n+ emitter length and the amount of hole current flow underneath the emitter region. When the n+ emitter length of the IGPDT is reduced from 25 μm to 20 μm, the forward voltage of the IGPDT is about the same as that of the TBRT at 100 A/cm², and the turn-on voltage is about 0.2 V smaller. It is shown in latter section that a reduction of 5 μm in emitter length will result in a significant reduction in the turn-off time. The breakdown voltage of the IGPDT is found to be approximately 700 V. During turn-on and before the thyristor

latches on, the device operates like a PIN diode. The electron and hole current vectors of the IGPDT structure in forward PIN diode mode are shown in Fig.3. From Fig.3 (a) and (b), it can be seen that in the forward PIN diode mode most of the electrons and small part of the holes flow in the JFET region. However, most of the holes flow in the p-base region to trigger the thyristor to turn-on. After the thyristor latches on, the hole and electron vectors as shown in Fig.4 indicate that the n+ emitter injects electrons into the p-base and causes excessive hole concentration there. The IGPDT is now in its on-state.

B. Switching Characteristics

The resistive load turn-off characteristics of the IGPDT were investigated numerically. Turn-off transient simulations were performed at a current density of 340A/cm². The gate voltage was ramped down from 10V to -10 V in 10 ns. Fig. 5

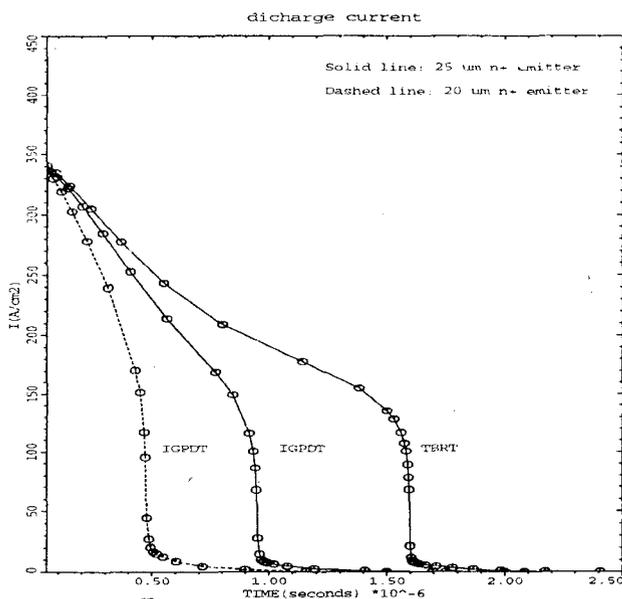


Fig.5. Turn-off transient simulations for the IGPDT and TBRT at 340 A/cm² current density.

shows a comparison of the turn-off characteristics of the IGPDT and TBRT. It can be seen that for an n+ emitter length of 25 μ m, the IGPDT turn-off time is less than 1 μ s. It is about 40% less than that of the TBRT (1.6 μ s). As discussed before, the fast turn off speed of the IGPDT is due to the lower resistance in the turn-off PMOS channel compared to that of the TBRT. As a result, the holes at the p-base can be drawn out quickly. This reduces the potential at the p-base and causes the electron injection from the n+ emitter to decrease drastically. Furthermore, the holes in the n- drift region can now flow in both the inversion layer and the depletion layer in the JFET region of the IGPDT. This makes the turn-off much quicker. When the n+ emitter length is reduced from 25 μ m to

20 μ m, the turn-off characteristics was further improved without compromising on the on-state characteristics (see Fig.2). From Fig.5, the turn-off time of the IGPDT is about 3 times smaller than that of the TBRT.

IV CONCLUSION

A fast switching Insulated-Gate PIN Diode Controlled Thyristor (IGPDT) structure was described. Using a trench gate PIN diode to control the turn-on and turn-off of the thyristor, better on-state and switching characteristics are obtained compared to that of the TBRT. Numerical simulations show that with proper design of the n+ emitter length, the IGPDT is 3 times faster than the TBRT and without compromising on the on-state and breakdown characteristics. These results show that the IGPDT is a promising device for high power switching applications.

ACKNOWLEDGEMENT

The authors would like to acknowledge the use of the MEDICI device simulator from Technology Modeling Associates, Inc. This work was supported by the RGC Competitive Earmarked Research Grant, Hong Kong Government, HKUST 194/93E

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