# Theoretical investigations on IGBT snubberless, self-clamped drain voltage switching-off operation under a large inductive load

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## ABSTRACT

This paper describes the results of numerical investigations on IGBT snubberless switching-off operation under a large inductive load (so-called sustaining mode operation). A simulation of this kind has not previously been performed because it involves severe convergence problems. However, the authors have successfully analyzed this phenomenon for the first time by using a device simulator TONADDE2C which implements a rapid device/circuit solving algorithm (1)(2).

## 1. INTRODUCTION

The insulated gate bipolar transistor (IGBT) has been widely used for many applications since it has many advantages over Darlington bipolar transistors: high input impedance and high speed operation like a MOSFET and a larger safe operating area (SOA) (3)(4).

IGBTs are frequently used in an inductive load switching circuit, and they suffer the condition of both high current density and high voltage. Fig.1 shows experimentally obtained snubberless 110 ampere switching-off waveforms under a 5 $\mu$H inductive load. The drain voltage was self-clamped at the rated device voltage of 650 V for about 0.5$\mu$s time duration with a high drain current. This kind of switching-off operation is the so-called sustaining mode operation, and the self-clamped drain voltage is called sustaining voltage Vsus.

It is important to study the mechanism of the sustaining mode operation from the device design viewpoint because the device voltage rating is substantially determined by the value of the self-clamped drain voltage for such an operation and the static breakdown voltage is generally greater than the self-clamped drain voltage.

This paper describes the results of the authors' analysis on the sustaining operation mechanism of an IGBT by using a device simulator TONADDE2C.

## 2. SIMULATION RESULTS

The simulated device structure and the external circuit are shown in Fig.2. A 600 V vertical type IGBT with an n-buffer was analyzed. The actual static breakdown voltage BV of this device structure was 700 V. The initial current density was 350 A/cm$^2$. The carrier lifetimes for both electrons and holes were assumed to be 150 ns. The load inductance and resistance values were determined as 5 $\mu$H and 1 ohm, respectively, according to the actual measurement circuit constants. A 51 ohm gate circuit resistance was inserted between the gate voltage source and the gate electrode.

Fig.3 shows the calculated waveforms for the above simulation system. The results agreed very well with the experiment shown in Fig.1. The self-clamping phenomenon of the drain voltage was successfully reproduced.

The turn-off process proceeded in the following way. First, the channel electron current began to decrease as the gate voltage decreased. However, the total drain current was forced to maintain the initial value because of the nature of a large inductive load. This means that the electron current flowing into the

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p-emitter had to be maintained at the same level while the channel electron current decreased. This situation was solved by increasing the device forward voltage, developing a depletion layer under the p-base. The amount of stored carriers under the p-base was swept away by the high electric field, creating the depletion layer. The swept away electrons increased the electron current flow so that the net electron current flow into the p-emitter was maintained at the same level.

As time proceeded, the maximum field in the depletion region reached the critical field causing impact ionization, and the electron current due to this impact ionization began to increase. Finally, it reached the situation that most of the electron current was supplied by impact ionization, neither by the channel electron current nor by depletion layer development. Under this situation, the device voltage was clamped at the so-called sustaining voltage by the device itself.

Fig.4 shows the waveforms in a magnified time scale where the electron current through the n-MOS channel and the amount of generated electrons per unit time due to the impact ionization in the n-base region are also shown in addition to the drain current and the drain voltage waveforms. The generated electrons were forced to increase rapidly as the channel electron current decreased as the gate voltage decreased because the net electron current could not change rapidly due to the nature of a large inductive load.

Figs.5(a) and 5(b) show a bird's eye view of the electron density distribution before and during the sustaining operation, which correspond to the time steps of 0.5 μs and 0.7 μs in Fig.3. At the 0.5 μs time step (Fig.5(a)), the electrons were injected into the n-base through the n-channel. However, at the 0.7 μs time step(Fig.5(b)), the channel electron current was interrupted completely, and the electron current was supplied by impact ionization. Thus, the electron distribution was localized into the center of the n-base where most of the impact ionization occurred. Fig.6 represents a bird's eye view of the carrier generation rate due to the impact ionization during the sustaining operation (0.7 μs time step). A large amount of impact ionization occurred in the part of the deepest p-base n-base junction. Figs.7(a)(b) show the electric field along the symmetry axis, going through the center of the p-base. At the 0.5 μs time step (Fig.7(a)), the electric field of the region where the electrons were generated was about 2.0E5 V/cm (Fig.7(b)), and at the 0.7 μs time step it reached about 2.5E5 V/cm, which was sufficient to cause impact ionization.

The current flow lines in the IGBT for 0.5 μs time step and 0.7 μs time step are shown in Figs.8(a) and 8(b), respectively. A severe current concentration into the center of the p-base was observed in the sustaining mode operation. The hole current flows laterally under the $n^+$diffusion region as shown in Fig.9. The amount of the lateral hole current flow decreases in a sustaining operation.

Similar simulated waveforms for an IGBT with a larger carrier lifetime of 1 μs is shown in Fig.10. The sustaining voltage decreased to 450 V when the carrier lifetime was increased from 150 ns to 1 μs.

## 3. DISCUSSIONS

Fig.5(b) shows that the IGBT does not latch-up during the sustaining operation. In a sustaining operation, the lateral hole current density in the p-base flowing under the n+diffusion region decreases, as shown in Fig.9. This is because impact ionization occurs in the part of the deepest p-base n-base junction, and most of the hole current flows directly into the p-base. This leads to the conclusion that device failure in the sustaining mode operation is likely caused by localized impact ionization and not by parasitic thyristor latch-up.

In order to calculate the sustaining voltage as an estimate, a 1-D Poisson's equation was solved in the depletion layer by using some assumptions as follows:

1)The electron and the hole currents Jn and Jp consist of only the drift current and the ratio does not change in the depletion layer.

2)The electron and the hole velocities are approximately equal to the saturation velocities $v_{sn}$ and $v_{sp}$.

Thus, the 1-D Poisson's equation is given by

$$\frac{dE}{dx}=-\frac{q}{\epsilon}\left[N_D+\frac{J}{q}\left\{\alpha_{pnp}\left(\frac{1}{v_{sn}}+\frac{1}{v_{sp}}\right)-\frac{1}{v_{sn}}\right\}\right] \quad ...(1)$$

where $N_D$ is the donor concentration in the n-base which is constant, and $\alpha_{pnp}$ is the p-n-p transistor part common-base current gain. Solving equation (1) for the following two cases gives the voltage drop across the depletion layer, which approximately equals to the sustaining voltage:

a) $W_d \leqq W_b$: the depletion layer does not reach the n-buffer:

$$V_{sus}=\frac{\epsilon E_{crit}^2}{2q\left[N_D+\frac{J}{q}\left\{\alpha_{pnp}\left(\frac{1}{v_{sp}}+\frac{1}{v_{sn}}\right)-\frac{1}{v_{sn}}\right\}\right]}. \quad ...(2)$$

b) $W_d > W_b$: the depletion layer reaches the n-buffer:

$$V_{sus}=W_bE_{crit}-\frac{qW_b^2}{2\epsilon}\left[N_D+\frac{J}{q}\left\{\alpha_{pnp}\left(\frac{1}{v_{sp}}+\frac{1}{v_{sn}}\right)-\frac{1}{v_{sn}}\right\}\right], \quad ...(3)$$

where Vsus is the sustaining voltage, and Wd is the width of the depletion layer , Wb is the thickness of the n-base, and Ecrit is the maximum electric field initiating the impact ionization.

From equations (2) and (3), it can be understood that the sustaining voltage depends on $\alpha_{pnp}$ besides the other characteristic parameters of the device. Vsus depends on the carrier lifetime $\tau$ through $\alpha_{pnp}$

## 4. CONCLUSIONS

A sustaining mode operation of an IGBT has been completely reproduced by numerical simulations. The simulated results have revealed the following: all of the electron current is supplied by impact ionization during the sustaining mode; the drain voltage is self-clamped at the sustaining voltage by electrons due to impact ionization. The sustaining voltage is considered to be a function of $\alpha_{pnp}$ and the structure parameters, and it can be controlled by the carrier lifetime through $\alpha_{pnp}$

## ACKNOWLEDGMENTS

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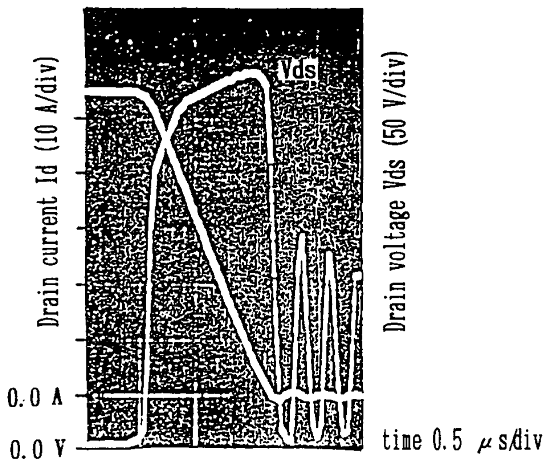


Fig. 1 Experimentally obtained sustaining waveforms of 600 V IGBT turn-off with snubberless inductive load L

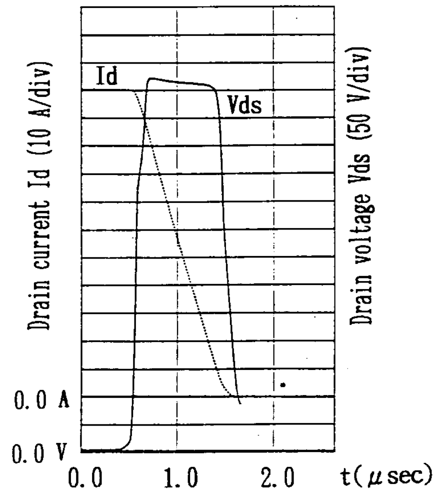


Fig. 3 Simulated turn-off characteristic under the same condition as Fig. 1 (The MOS gate voltage source Vgg was ramped from 18 V to -15 V in 1 ns. n-base carrier lifetime was 150 ns.)

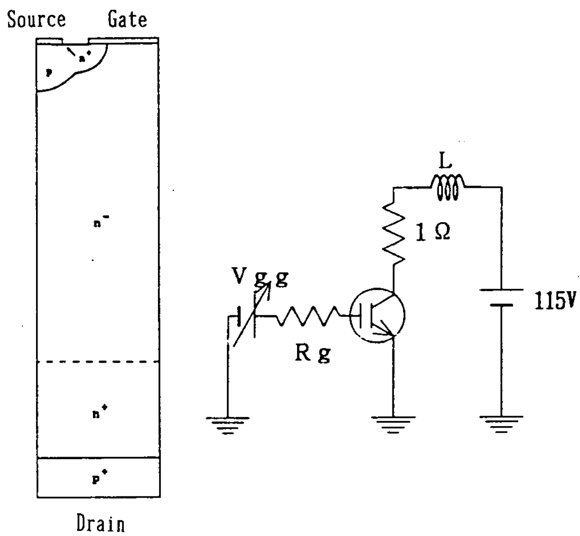


Fig. 2 Simulated device structure and its circuit

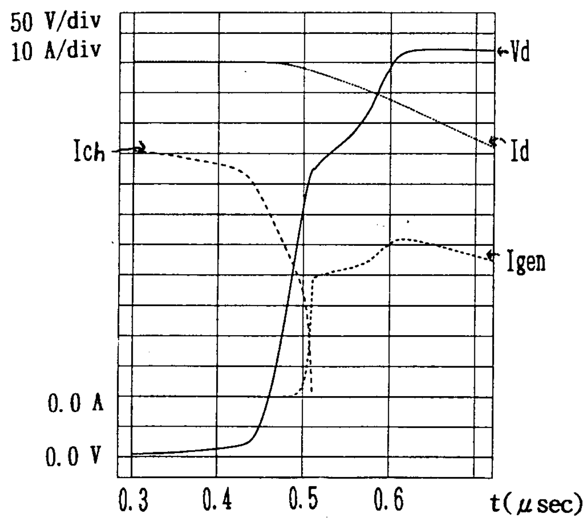


Fig. 4 Simulated waveforms in a magnified time scale of Fig. 1 (The electron current through the n-MOS channel Ich and the amount of generated electrons per unit time due to impact ionization in the n-base region Igen are also shown in addition to the drain current Id and the drain voltage Vds waveforms.)

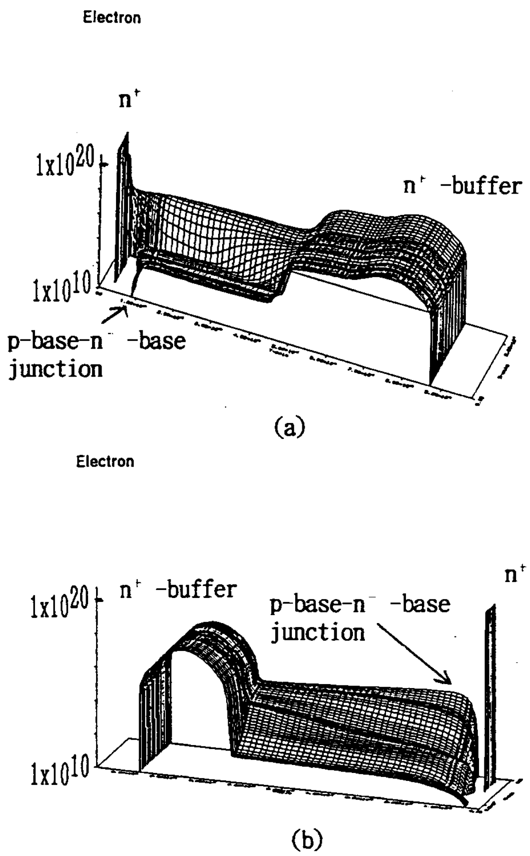


Fig.5 Electron density distribution
(a) Electron density at t=0.5 $\mu$s;
(b) electron density at t=0.7 $\mu$s.

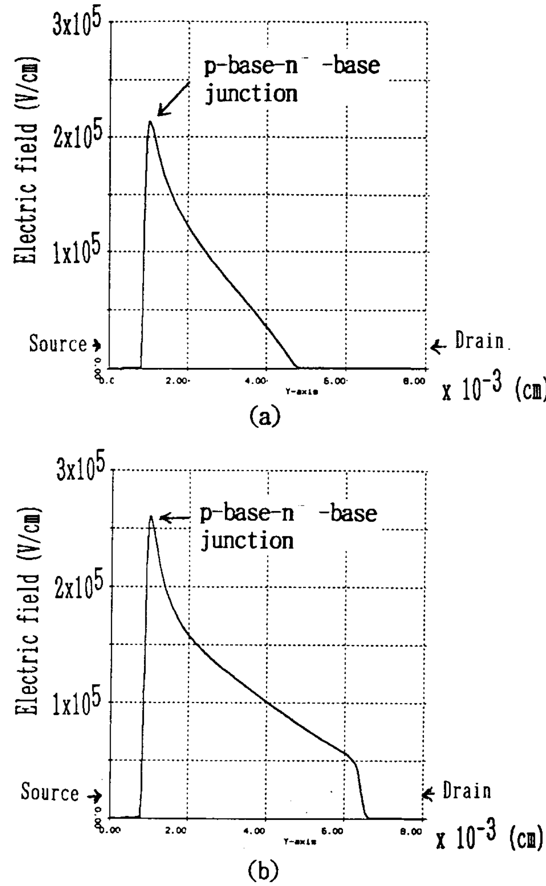


Fig.7 Electric field along symmetry axis
(a) At t=0.5 $\mu$s; (b) at t=0.7 $\mu$s.

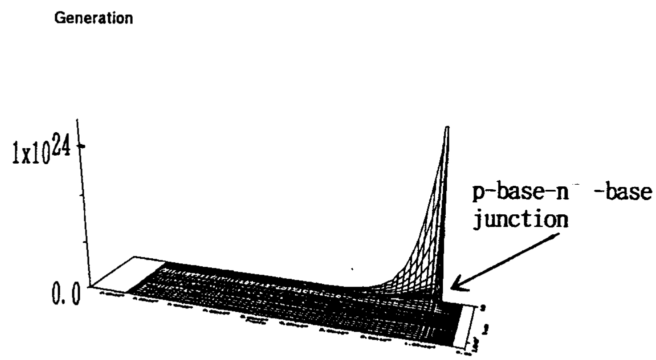


Fig.6 Generation rate due to impact ionization at
t=0.7 $\mu$s in sustaining mode

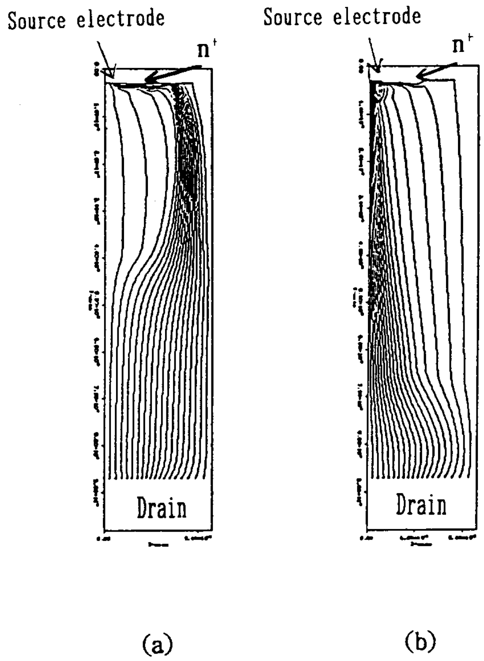


Fig. 8 Current flow lines during turn-off
(a) Current flows normally at initial stage ($t=0.5$ μs); (b) current concentrates into the center of the p-base layer ($t=0.7$ μs).

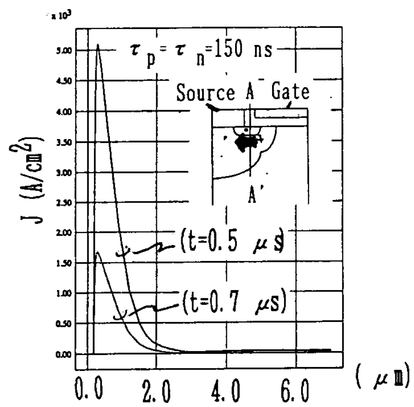


Fig. 9 Lateral hole current flowing under $n^+$diffusion region for the time steps of 0.5 μs and 0.7 μs

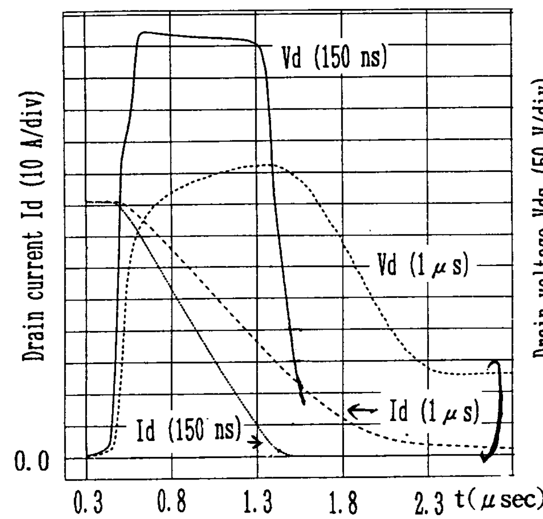


Fig. 10 Simulated waveforms with a larger carrier lifetime of 1 μs in comparison with the case of 150 ns