Ultra High Switching Speed 600 V Thin Wafer PT-IGBT Based on New Turn-Off Mechanism

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Abstract ----- A new turn-off mechanism for 600V thin wafer PT-IGBTs has been found, and ultra high speed switching has been demonstrated, for the first time, in this paper. The new turn off process makes it possible to operate IGBTs in a quasi-MOSFET mode in the turn-off transient, realizing ultra high speed switching. Most of the stored carriers in the n-drift region can be automatically removed, without any additional means, in the storage time period, before the voltage recovery process. This results in extremely low dissipated power loss and substantially eliminates tail current. Furthermore, this paper described the results of numerical investigation and measured characteristics on the sustaining mode operation. When a p-emitter efficiency of thin wafer PT-IGBTs was decreased, the sustaining voltage was larger than the static breakdown voltage and most of the current was supplied by impact ionization due to poor pnp transistor action. Thin wafer PT-IGBTs with reduced p-emitter efficiency behaves like a quasi-MOSFET.

INTRODUCTION

In the course of vertical IGBT development, two typical design concepts of PT (Punch Through) IGBTs and NPT (Non Punch Through) IGBTs have been proposed [1][2]. Recently, the new device concept of thin wafer PT-IGBT with a low dose n-buffer and a transparent p-emitter has been attracting interest, since it has been verified the excellent trade-off relation between the device on-state voltage and the switching speed [3][4]. This new thin wafer PT-IGBT has the high carrier lifetime. Then the carrier densities in the n-drift layer are much higher than those of the conventional PT-IGBT and the extremely low on-state voltage is realized. On the other hand, the on-state voltage of NPT-IGBT is not sufficiently low in spite of high carrier lifetime, because the n-drift layer is relatively thick. In this thin wafer PT-IGBT, the n-drift layer can be reduced for stopping the electric field by the n-buffer layer. Furthermore, the fast switching speed is achieved without a lifetime control by the low efficient emitter. Especially, the fast speed switching without the tail current was realized if a p-emitter efficient was very small. However, the details of the turn-off mechanism have not been analyzed yet.

In this paper, we report a new turn-off mechanism for 600V thin wafer PT-IGBTs and experimentally demonstrate the ultra high speed switching. Then turn-off process on the sustaining mode operation was also illustrated.

DEVICE STRUCTURE AND CHARACTERISTICS

Fig.1 shows the schematic cross section of thin wafer PT-IGBTs in this numerical investigation and the measurement. This PT-IGBT has trench gates, a low dose n-buffer layer and a low dose anode p-emitter. The switching speed was controlled by changing the dose of the anode p-emitter with an optimally doped n-buffer layer. The lifetime in the drift layer is kept high, preventing the degradation of switching speed in

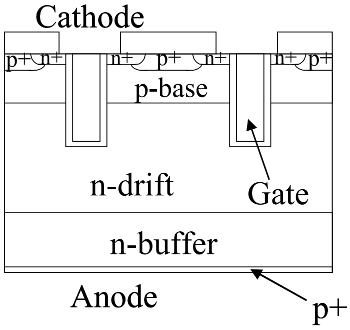

Fig. 1 Cross Section of thin wafer PT-IGBT with trench gate and transparent p-emitter

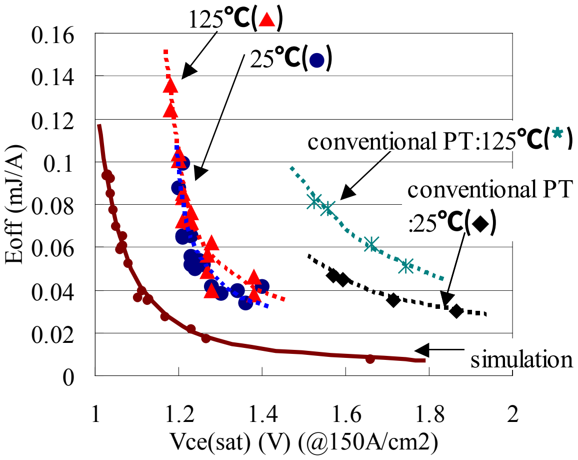

Fig. 2 Measured and simulated trade off relation between on-state voltage drops and turn-off losses for thin wafer PT-IGBTs.

an elevated temperature.

Fig.2 shows the measured and the simulated trade-off relation between the device on-state voltages and the turn-off losses for 600V PT-IGBT, when the dose of p-emitter changes. The measurement was made at the drain current of 150A. The excellent trade-off relation for 600V thin wafer PT-IGBT can be confirmed in spite of the severe measurement condition of 150A of drain current.

TURN-OFF CHARACTERISTICS

The design principle to realize the ultra high speed IGBT is the following. An IGBT with a low p-emitter efficiency of less than 0.27 ($=\mu_p/(\mu_n+\mu_p)$) realizes a linearly decreasing carrier distribution from cathode to anode in the n-drift region, as illustrated by in Fig.3 (look at the curve t1). In a turn-off process, the channel electron current initially decreases by the decrease in the gate voltage. Because the emitter efficiency of the p-emitter is small enough, the magnitude of the electron current must be maintained in the same level in the anode side. The stored carriers in the drift region have to be removed to compensate the decrease in the channel current. Thanks to the special carrier density gradient in the n-drift region, carriers throughout the drift region must be removed uniformly. This process can remove most of the stored carriers in the n-drift region in the storage time period (please refer to the curve t2 in Fig.3). The rest of the turn-off process is quite similar to that of MOSFET, realizing high speed switching in the Fig.4. In this case, the simulated fall time is only 23nsec and the power loss is 0.0099mJ/A.

On the other hand, in the conventional thin wafer PT-IGBT with a p-emitter efficiency of more than 0.27, most of the store carriers remains in the drift region, as illustrated in Fig.5. In this case, the p-emitter efficiency is 0.355. The carriers must be removed in the voltage recovery process by a developing depletion region, creating a large power loss and a tail current in Fig.6. In this case, the simulated power loss is

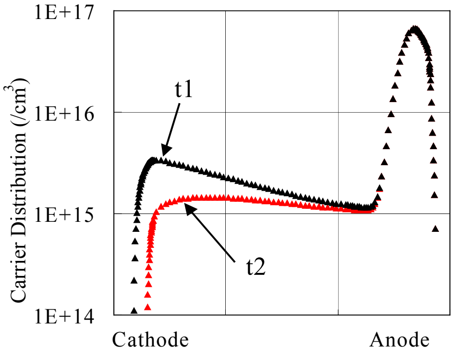

Fig. 3 Simulated electron carrier distributions for high switching speed PT-IGBTs. Current density is 188A/cm^2 at time step t1 and t2 in Fig.4.

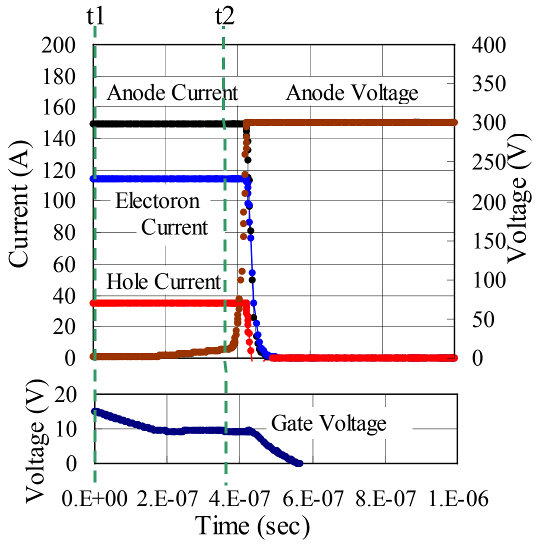

Fig. 4 Simulated turn-off waveforms for high switching speed thin PT-IGBTs. Initial current is 150A(188A/cm^2). Fall time is only 23nsec and power loss is 0.0099mJ/A. P-emitter efficiency is 0.238.

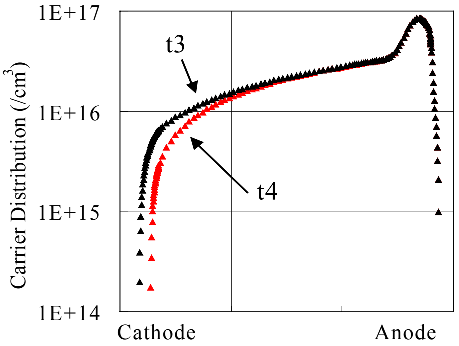

Fig. 5 Simulated electron carrier distributions for conventional thin PT-IGBTs. Current density is 188A/cm^2 at time step t3 and t4 in Fig.6.

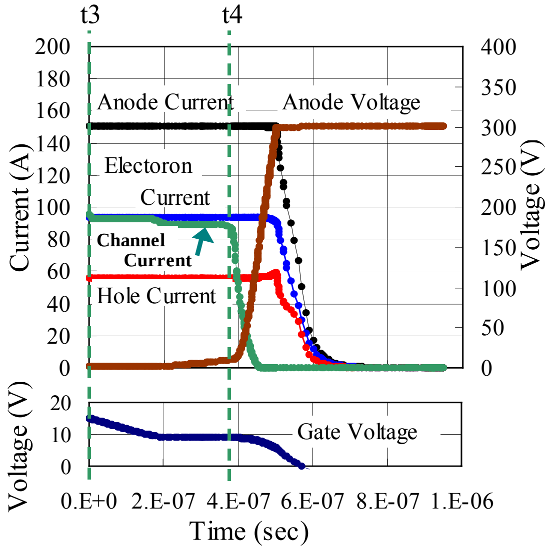

Fig. 6 Simulated turn-off waveforms for conventional thin PT-IGBTs. Initial current is 150A(188A/cm^2). Fall time is 101nsec and power loss is 0.0320mJ/A. P-emitter efficiency is 0.355.

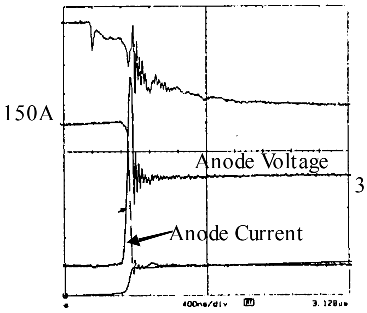

Fig. 7 Measured turn-off waveforms for ultra high switching speed 600V thin wafer PT-IGBTs is demonstrated. Fall time is 55nsec even for large current 150A(188A/cm^2). Tail current is eliminated.

0.0320mJ/A.

Fig.7 shows typical turn-off waveforms for ultra high speed 600V thin wafer PT-IGBT with a low p-emitter efficiency. The fall time is only 55nsec even for large current of 150A and the tail current is eliminated. The real circuit inevitably includes the stray inductance, the turn-off time and the turn-off increased a little compared with the simulated values.

SUSTAINING MODE OPERATION

The sustaining mode operation of a thin wafer IGBTs has been studied by numerical simulation and measurement. Fig.8 shows the simulated sustaining waveforms of the conventional thin PT-IGBTs. The initial current was 300A and the load inductance was $2\mu H$. In this turn off process, the channel electron current began to decrease as the gate voltage decreased. Then, the impact ionization occurred and the avalanche current (= $\int q \cdot G\, dx$, q:magnitude of electron charge, G:impact ionization rate) began to flow because the total current was forced to maintain the initial value for the large inductive load. In the initial stage, the current was supplied by the large amount of stored carriers and the depletion layer developed slowly. After the removal of the storage carriers, the current was supplied by the pnp transistor, where the base current is solely supplied by impact ionization. Fig.9 shows the carrier densities in the sustaining mode. It is noted that the magnitude of the hole density is larger than that of the electron density.

On the other hand, for the ultra high switching PT-IGBT with γ of 0.26, the current by the stored carriers hardly flowed because the carrier density was very small in the initial state. The avalanche current increased quickly and occupied 70% of the total current, shown in Fig.10.

Using 1-D Poisson's equation, the value of

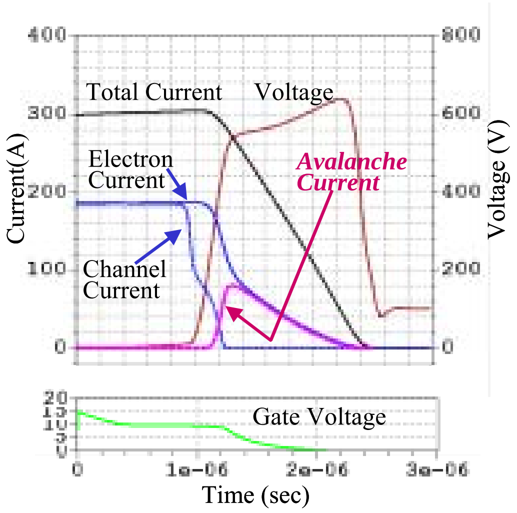

Fig.8 Simulated sustaining waveforms of conventional thin PT-IGBTs. P-emitter efficiency is 0.38.

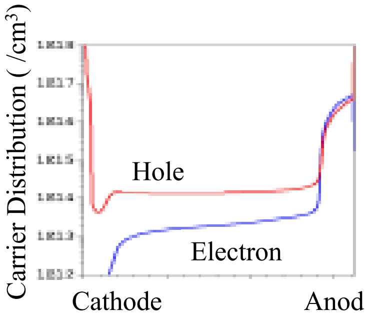

Fig.9 Simulated carrier distributions in sustaining mode at the time step of 1.35e(-6)sec in Fig.8. Hole density is larger than electron density.

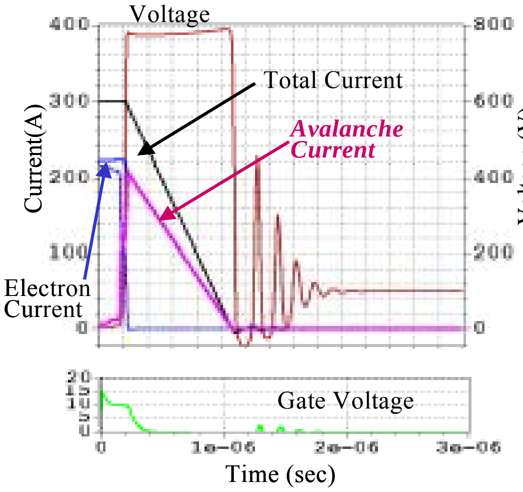

Fig.10 Simulated sustaining waveforms of high speed thin PT-IGBTs. P-emitter efficiency 0.26.

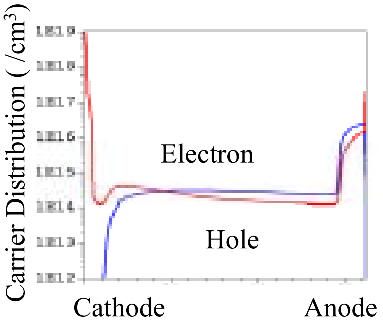

Fig.11 Simulated carrier distributions in sustaining mode at the time step of 0.21e(-6)sec in Fig.10. Electron density is larger than hole density.

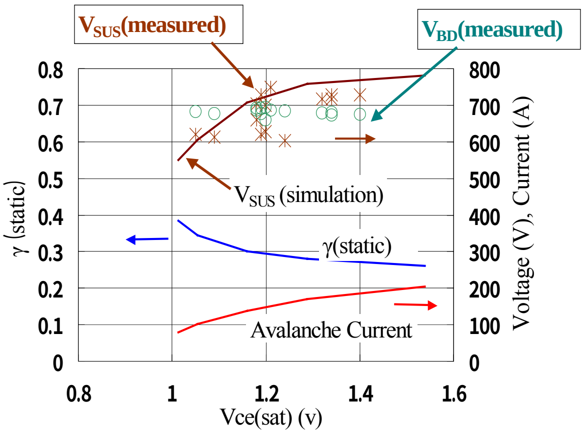

Fig.12 Simulated peak avalanche current and sustaining voltage (Vsus) when 300A(376A/cm^2) of current is turned-off under 2μH unclamped inductive load. Plotted data are measured sustaining voltage (Vsus(measured)-*) and measured static breakdown voltage (V_{BD}(measured)-o). When p-emitter efficiency is small , sustaining voltage is larger than static breakdown voltage.

n-base (n-drift region) space charge is given by

$$\text{<n-base space charge>} = N_D + J_p/qv_p - J_n/qv_n$$
$$= N_D - ((1-\gamma)/v_n - \gamma/v_p)J/q\text{------Eq(1)}$$

,where $\gamma = J_p/(J_p+J_n) = J_p/J$, N_D is the donor concentration in the n-base and v_p,v_n are hole and electron saturation velocities respectively. γ denotes a p-emitter efficiency [5]. Theoretically, it is shown that the n-base space charge density becomes lower than N_D in the sustaining mode of operation if γ is less than 0.5 (assuming $v_n = v_p$). This increases the sustaining voltage over the static breakdown voltage if γ is less than 0.5.

From Fig.11, it is seen that the electron carrier density is larger than the hole carrier density in the depletion layer in the sustaining mode for the device of Fig.10, resulting in the decrease in the total space charge density. This means that the sustaining voltage is larger than the static breakdown voltage.

Fig.12 shows the simulated avalanche current and the sustaining voltage. The measured sustaining voltage and the static breakdown voltage are also plotted in the same figure. As the p-emitter efficiency decreased, the sustaining voltage monotonically increased and finally exceeded the static breakdown voltage. The simulated sustaining voltages agreed with the measurements.

Fig.13 shows the breakdown characteristics for thin PT-IGBTs. If γ decreases, the negative resistance in the current range of 1e3A disappears and the V-I characteristics become similar to that of MOSFETs.

CONCLUSION

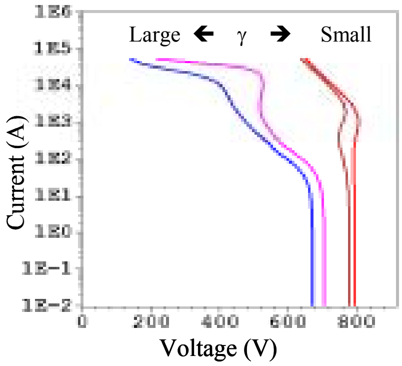

Fig. 13 Simulated breakdown characteristics. Negative resistance doesn’t appear for IGBT with a very low p-emitter efficiency. Chip area size is 0.8cm^2.

We have analyzed the new turn-off mechanism for 600V thin wafer PT-IGBT. This PT-IGBT with a low p-emitter efficiency of less than 0.27 behaves like a quasi-MOSFET in the turn-off transient. An extremely high speed switching was realized, for the first time, for 600V/150A IGBTs.

The sustaining mode operation of the thin wafer PT-IGBTs has been reproduced by the numerical simulations. If the p-emitter efficiency is small, the sustaining voltage is larger than the static breakdown voltage and most of the current is supplied by the impact ionization current.

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