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Growth of short-circuit current filament in MOSFET-Mode IGBTs

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***Abstract*—In this paper, a new theory of current filament formation in MOSFET-Mode IGBTs is presented, for the first time, based on large scale 3D & 2D TCAD simulations. It was found that current filaments appear because the total collector current increases while current filaments are growing. The total collector current of the state of filament is larger than that of the state of uniform current flow. Current filament grows because of positive feedback mechanism when the avalanche generation rate exceeds a critical value even when the collector emitter voltage is constant. Adoption of the lightly doped N-buffer reduces the maximum current density in the current filament and improves short-circuit withstanding capability of MOSFET-Mode IGBT.**

I. INTRODUCTION

The short circuit withstand capability is still a crucial topic in the course of development of MOSFET-Mode IGBTs[1-6] in order to realize high current density operation. In Ref.[7], we proved that the current filaments appear in MOSFET-Mode IGBTs when the devices are turned-on in short-circuit state and avalanche generation exceeds a critical value at the N-base N-buffer junction. It was also explained that there coexist two stable states as isothermal solutions: a state of uniform current flow and a state of current filaments. For example, these two states are represented by blue and red filled circles, respectively, in Fig. 2, where the locus curves of the total collector current and the maximum avalanche generation rate are plotted when the devices are turned-on in short-circuit state. The system moves from a state of uniform current flow (blue filled circle) to a state of current filament (red filled circle) when the maximum avalanche generation rate exceeds a critical value. However, the transition mechanism between the two states has not been completely clarified yet.

MOSFET-Mode IGBT is defined in such a way that the anode efficiency $\gamma (= J_p/J)$ is less than γ_{MOS}, which is defined as $\mu_p/(\mu_p+\mu_n)$. γ and γ_{MOS} are defined as the values at the N-base N-buffer junction. The γ_{MOS} value dynamically changes as the electric field or the lattice temperature changes inside the device because the mobility μ_p and μ_n are functions of the electric field and the lattice temperature.

The net charge ρ can be calculated by Eq.(1) for the high field region, using the donor density N_D and the electron and hole saturation velocities v_e and v_h.

$$\rho = N_D + p - n = N_D + \left(\frac{\gamma}{v_h} + \frac{\gamma - 1}{v_e}\right)\frac{J}{q}$$

$$= N_D + \left(\frac{v_h + v_e}{v_h v_e}\right)(\gamma - \gamma_{MOS})\frac{J}{q} \qquad (1)$$

$$\gamma_{MOS} = \frac{\mu_p}{\mu_p + \mu_n} \approx \frac{v_h}{v_h + v_e} \qquad (2)$$

For the high electric field case, γ_{MOS} is approximately given by Eq.(2). When the anode efficiency γ is less than γ_{MOS}, the second term in Eq.(1) is negative, and the net charge ρ becomes negative for sufficiently large current density J. Once the net charge becomes negative, the peak high electric field region appears in the anode side of the N-base as shown in Fig. 1.

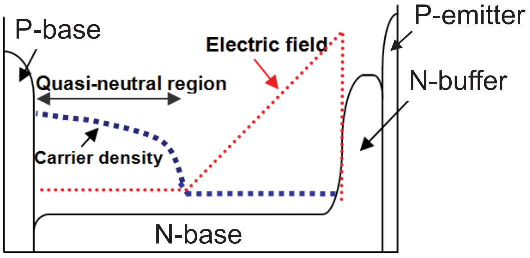

Fig. 1. Electric field distribution during short-circuit operation of MOSFET-mode IGBT. High electric field region appears in the anode side for high current density cases.

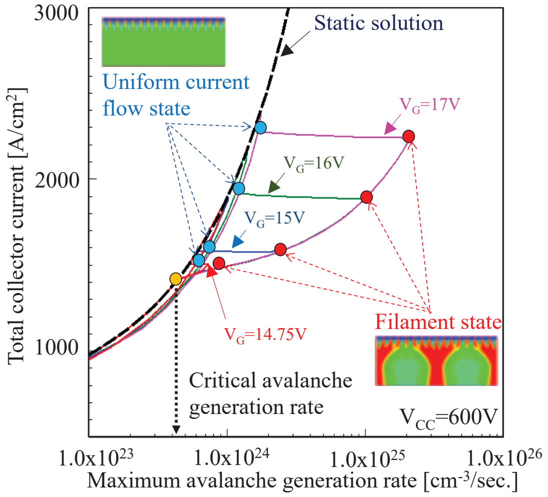

Fig. 2. Locus curves of the collector current vs. the maximum avalanche generation rate are plotted for the short-circuit waveforms when V_{CC}=600V and V_G=14.75V, 15V, 16V, 17V[7]. When $V_G \geq$14.75V, large avalanche generation occurs and the locus moves from the state of uniform current flow (blue filled circle) to the state of current filaments (red filled circle). For details, see Ref.[7].

In this paper, we present a new theory of current filament formation in MOSFET-Mode IGBTs, based on large scale 3D & 2D TCAD simulations. First, we discuss current filament growth by observing the transition from the state of uniform

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current flow to the state of the current filament. Then, we propose a new concept on lightly doped N-buffer, which suppresses formation of current filaments and improves short-circuit withstanding capability.

II. TCAD SIMULATION SETUP

The simulated IGBTs were 1.2kV rated and had the N-base thickness of 120um. The doping concentrations of the P-emitter and the N-buffer were set such that the anode efficiency was less than 0.27 at the rated current density (150A/cm^2) to realize MOSFET-Mode operation. The simulations included high field saturation and carrier-carrier scattering mobility models as well as the University of Bologna avalanche generation model. TCAD Sentaurus Device was used for all the simulations.

In order to analyze the filament formation mechanism, short-circuit transient isothermal simulations of the 2D structure without any circuit elements were performed, where the collector emitter voltage, V_{CE}, was always kept exactly at 600V. As shown in Fig.3, the gate voltage was ramped up to a specific value at the rate of 10V/us to initially create the state of uniform current flow. Next, the transient simulation was continued for 1 second with keeping the gate voltage at the specific value to observe the growth of the current filament toward a steady state. These simulations were performed for the range of the gate voltage of 14V to 17V for every 0.1V step. The 2D IGBT structure was 320um wide and had completely uniform identical 16 cells and meshes.

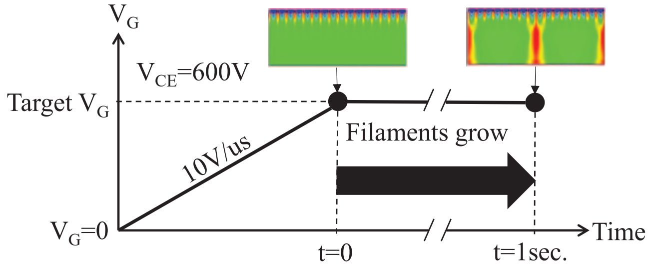


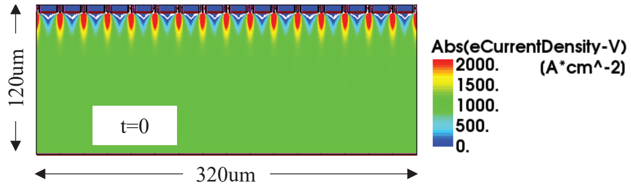
Fig. 3. Gate voltage chart for the transient simulations. Initially, the gate voltage is ramped up to a specific value at the rate of 10V/us to create the state of uniform current flow. Next, the transient simulation is continued for 1 second with keeping the gate voltage at the specific value to observe the growth of the current filament toward a steady state.

In order to confirm the new effect of the lightly doped N-buffer, an exact short-circuit simulation of a large scale 3D IGBT structure was performed with taking into account self-heating. The 3D IGBT structure was 160um in width and 160um in depth and completely uniform identical 8 cells and meshes. Self-heating was taken into account. The thermal resistance of 0.3K/W was set between the anode electrode and the heat-sink. The heat-sink temperature was 300K.

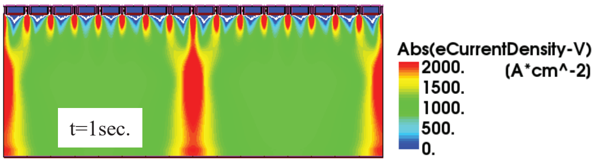
III. RESULTS AND DISCUSSION

A. *Current Filament Formation*

It is shown in Fig.4 that the current filament grows from small inhomogeneity of current flow, and that huge current density crowding occurs even when V_{CE} and the lattice temperature are kept constant. It is shown in Fig.5 and Fig.6 that the filament rapidly grows when the applied gate voltage is higher than the critical value of 14.7V. The peak current density inside the filament depends on the gate voltage. This means that the peak current density of the current filament at t=1sec. depends on the magnitude of the electron current supplied by the MOS gate. As most of the electron current concentrates into the filaments, the current density outside the filaments becomes very low value.



(a) Just after the gate voltage has been ramped up.



(b) 1 second after the gate voltage has been ramped up.

Fig. 4. Electron current density distributions are shown for the results of short circuit device simulation of Fig.3. Fig.4(a) shows the electron current density distribution at t=0 just after the gate voltage has been ramped up from 0V to 15.0V at 10V/us. Fig.4(b) shows the distribution at t=1 sec. after the gate voltage has been fixed at 15.0V. The current filament grows from small inhomogeneous current flow of Fig.4(a) to high current density filament of Fig.4(b) even when V_{CE} is always kept at 600V.

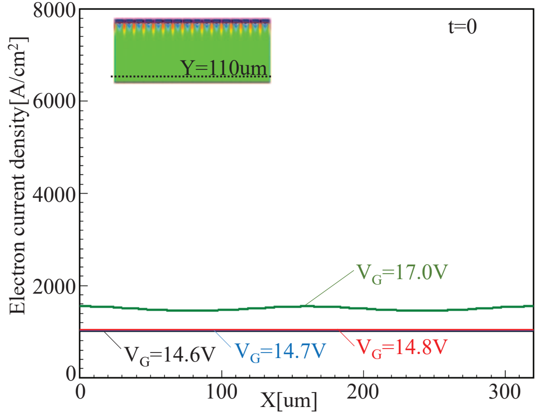


Fig. 5. Electron current density distributions are plotted along the cross section of Y=110um, at t=0, just after the gate voltage has been ramped up from 0V to the specific gate voltage values.

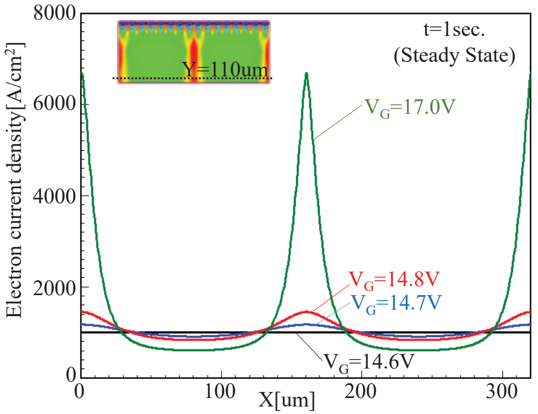


Fig. 6. Electron current density distributions are plotted along the cross section of Y=110um, at t=1 sec. after the gate voltage has been fixed at the each specific value. When $V_G \geq 14.7V$, the current filament rapidly grows even when V_{CE} is kept at 600V. The peak current density in the filament depends on the gate voltage. When $V_G < 14.6V$, no manifest current filament appears.

It is shown in Fig.7 that the total collector current, J_C, increases while the current filaments are growing. This suggests that the state of current filament is more stable than the state of uniform current flow, and the filament state will never goes back to the state of uniform current flow. Fig.7 also shows that the maximum avalanche generation rate increases while the filaments are growing. It is suggested that the cause of the transition to the filament state can be explained by the dependence of avalanche generation rate on the electric field because the avalanche generation rate is an exponential function of the electric field. The high electric field is created by the negative space charge density, which is induced by the electron current crowding into the filament. Fig.8 shows the negative space charge distribution along the center of the current filament. The large negative space charge is created by the large difference of γ and γ_{MOS}, according to Eq.(1). However, a part of negative electron charges is compensated by the holes created by impact ionization. The amount of the compensated negative charge is indicated by an arrow in the figure. The current created by impact ionization contributes to the increase in the total current of the state of current filament.

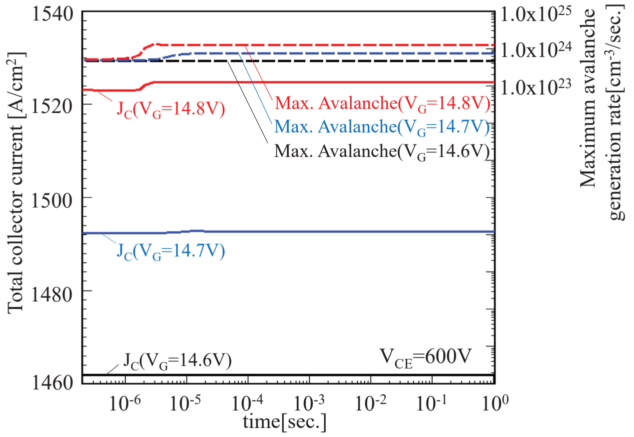


Fig. 7. The total collector current, J_C, and the maximum avalanche generation rate within the N-base are shown as a function of time after the gate voltage has been ramped up to 14.6, 14.7, 14.8V. For $V_G \geq 14.7$V, J_C, and the max. avalanche generation rate increase while the current filament is growing. The total collector current of the state of current filament is larger than that of the state of uniform current flow.

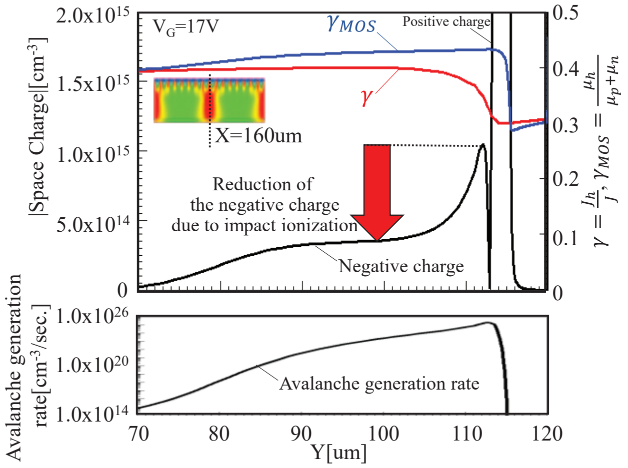


Fig. 8. Space charge distribution for the center of the current filament (X=160um) at t=1sec. when V_G=17.0V. The large negative space charge is created by the large difference of γ and γ_{MOS}. A part of negative electron charges is compensated by the holes created by impact ionization. The amount of the compensated negative charge is indicated by an arrow in the figure.

B. New N-buffer concept

It is suggested from Eq.(1) that higher anode efficiency reduces the strength of the electric field at the N-base N-buffer junction. In general, the anode efficiency for lower operating current density is designed to be low and is determined by both of the N-buffer and the P-anode doping concentrations. However, the anode efficiency increases and becomes large enough when the collector emitter voltage V_{CE} increases and exceeds several hundred volts if the doping concentration of the N-buffer is sufficiently low. This is because the applied high electric field in the N-base depletes a part of the N-buffer and reduces the N-buffer thickness. Thus, the peak electric field at the N-base N-buffer junction might reduce if the doping concentration of the N-buffer is sufficiently low. The reduction in the electric field at the N-base N-buffer junction prevents the transition from the state of uniform current flow to the state of the current filament due to the reduction in the avalanche generation at the N-base N-buffer junction. It increases the critical current level of current filament formation, and improves the short-circuit withstand capability. The switching speed of the proposed MOSFET-Mode IGBT with the lightly doped N-buffer is as fast as that of conventional MOSFET-Mode IGBTs as long as the anode efficiency for the rated current level is designed to be the same as that of conventional MOSFET-Mode IGBTs.

Fig.9 compares the dependency of the anode efficiency γ on V_{CE} between the two IGBTs with conventional N-buffer and the lightly doped N-buffer when V_G=15V. For the IGBT of lightly doped N-buffer, the anode boron doping is set such that the anode efficiency is the same as that of the conventional N-buffer IGBT at the rated current. Since the anode efficiency of the IGBT with the lightly doped N-buffer more rapidly increases as V_{CE} becomes larger, the calculated avalanche generation rate is significantly lower, as compared with the IGBT of conv. N-buffer, as is shown in Fig. 9. It follows that the IGBTs with the lightly doped N-buffer might not cause the transition from the state of uniform current flow to the state of the current filament at V_{CE}=600V and V_G=15V because the maximum avalanche generation rate at the N-base N-buffer junction is sufficiently lower than the critical value of 4.2x10^{23}cm^{-3}/sec., above which the current filament appears in conventional MOSFET-Mode IGBTs, as shown in Fig. 2.

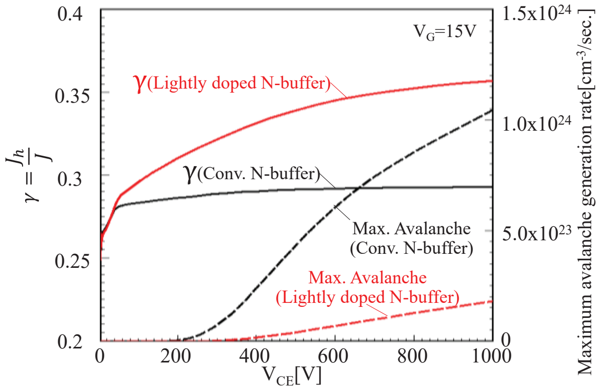


Fig. 9. Dependencies of anode efficiency γ and maximum avalanche generation rate at the N-base N-buffer junction on V_{CE} are compared for conventional N-buffer and the lightly doped N-buffer. The γ is set at 0.27 for low V_{CE}. As the IGBT with the lightly doped N-buffer (red lines) has higher anode efficiency γ when V_{CE} is high, the calculated maximum avalanche generation rate is significantly lower than that of IGBT with conv. N-buffer.

Figures 10 to 12 verify the effect of the lightly doped N-buffer by 3D simulations. In Figs.10 and 11, it is shown that the current filament is formed in the conventional MOSFET-Mode IGBT when V_G=15V. The maximum lattice temperature of conventional IGBT exceeds the silicon melting point of 1687K at t=2.0us. On the other hand, no manifest current filament is observed in the IGBT with the lightly doped N-buffer during the short-circuit operation for 10us under V_{CC}=600V and V_G=16V as seen in Figs.10 and 12. The structure of the lightly doped N-buffer significantly improves the short-circuit capability because the temperature increase is significantly reduced.

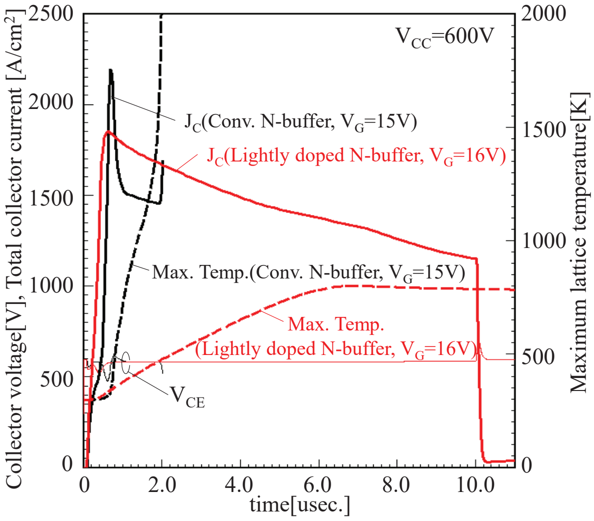


Fig. 10. Short-circuit 3D simulation waveforms of collector current density J_C, collector emitter voltage V_{CE} and the maximum lattice temperature are shown for two IGBTs with conv. N-buffer and lightly doped N-buffer when V_{CC}=600V.

It is clearly seen in Fig. 11 that the current filament appears in the center of the simulated conventional MOSFET-Mode IGBT, whose dimension is 160um in width and 160um in depth. The adopted IGBT cell structure is stripe. It is suggested that the current filament appears every 160um pitch both in width and in depth. The 160um pitch of current filament formation was also observed in 2D simulations as shown in Fig. 4(b).

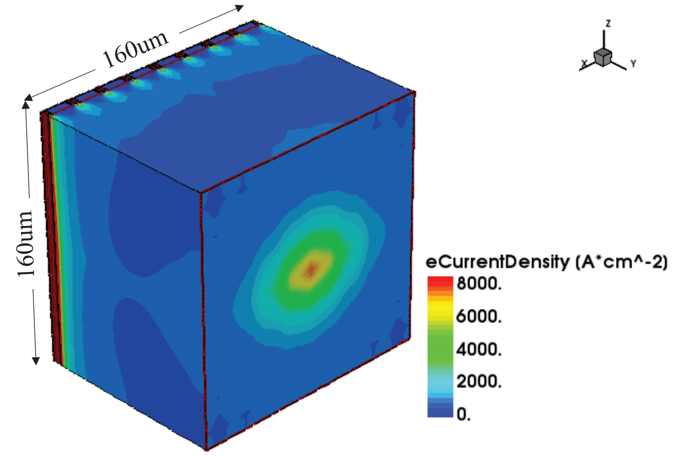


Fig. 11. Calculated electron current distribution of the 3D IGBT with conventional N-buffer at t=1.0us when short-circuit simulation is performed at the conditions of V_G=15V and V_{CC}=600V. The current filament appears in the center of the device even if the IGBT cells are stripe.

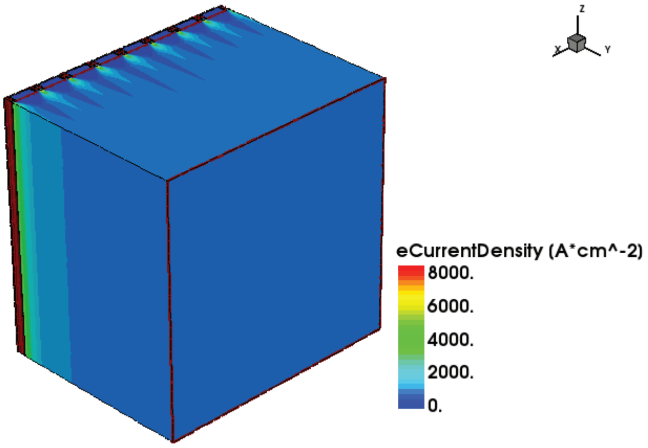


Fig. 12. Calculated electron current distribution of the 3D IGBT with the lightly doped N-buffer at t=9.0us when short-circuit simulation is performed at the conditions of V_G=16V and V_{CC}=600V. No manifest current filament appears in IGBTs with the lightly doped N-buffer.

IV. CONCLUSION

A new theory on the formation mechanism of current filaments is proposed. It was found that current filaments appear because the total collector current increases while current filaments are growing. The total collector current of the state of filament is larger than that of the state of uniform current flow. Current filament grows because of positive feedback mechanism when avalanche generation exceeds a critical value even when the collector emitter voltage is constant. The design of the lightly doped N-buffer reduces the electric field and the avalanche generation rate at the N-base N-buffer junction during the short-circuit operation. It prevents the transition from the state of uniform current flow to the state of current filament, thus, improving short-circuit withstanding capability of MOSFET-Mode IGBT while retaining the same high switching speed.

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