Improvement of Cosmic Ray Robustness in IGBT with Deep-N layer

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***Abstract*— Single Event Burnout (SEB) is one of the issues causing the blocking instability of high voltage semiconductor devices. In this paper, we suggest introducing Deep N-buffer layer (DN) into IGBT for improvement of the robustness. By TCAD simulation, the destruction mechanism and the effect of the backside structure on SEB robustness were clarified. The result indicated that DN suppressed the temperature rising around P-collector and PNP bipolar action at the backside during the period of the event. The proposed IGBT with DN layer was fabricated and the SEB failure rate was evaluated. The experimental results showed that the proposed structure improved the robustness.**

Keywords—IGBT; Cosmic Ray Robustness; Single Event Burnout; Deep-N layer; Experiment; Simulation

I. INTRODUCTION

The power devices like Insulated Gate Bipolar Transistor (IGBT) have been widely applied for industrial applications such as hybrid vehicles, railway systems, and so on. These devices are usually used under high voltage, so highly stable blocking capability is required. One of the issues causing the blocking instability is Single Event Burnout (SEB). SEB mechanism has been researched for several decades on IGBT. The cause of the destruction is assumed that a lot of carriers are suddenly generated by cosmic rays, and these trigger bipolar action or thermal runaway under blocking state [1-3]. Fig. 1 is an example of the result of SEB failure rate dependence on the applied voltage with IGBTs having different Si thickness. The failure rate increases exponentially from a certain applied voltage, and the voltage becomes lower as the thickness becomes thinner. This result means that thinner Si IGBTs are vulnerable to SEB. Although modern IGBT's characteristics have been improved by using thin-Si-wafer technology [4, 5]. Therefore the solutions which improve loss characteristics without sacrificing the SEB robustness are desired.

As previous study [2] presented that the bipolar action in P-base / N-drift / P-collector should affect SEB, SEB robustness strongly depend on the backside structure of IGBT. In this paper, we investigated the failure mechanism of SEB for IGBT and the effect of the backside structure by TCAD simulation. We introduced Deep-N layer (DN) into IGBT at backside, and compared to the conventional structure (Fig. 2). We clarified that the suppression of the junction temperature contributes to the improvement of SEB robustness. We also fabricated proposed

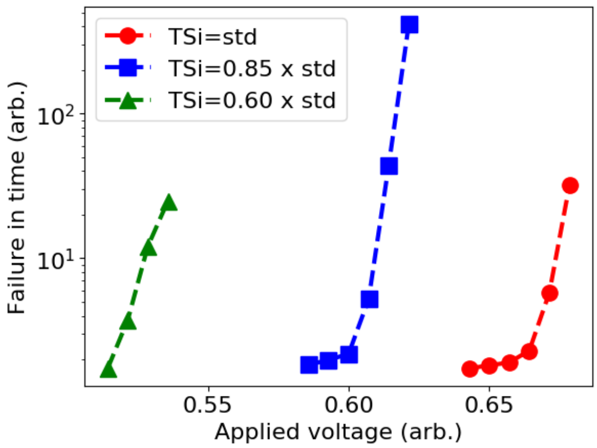


Fig. 1: The experimental result: Si thickness dependence of SEB robustness (failure in time), with respect to applied voltage. The y-axis is logarithmic scale. The red circle, blue square, and green triangle indicate wafer thickness: standard (std), 0.85 x std, and 0.60 x std, respectively. As the thickness becomes thinner, the destruction occurs faster.

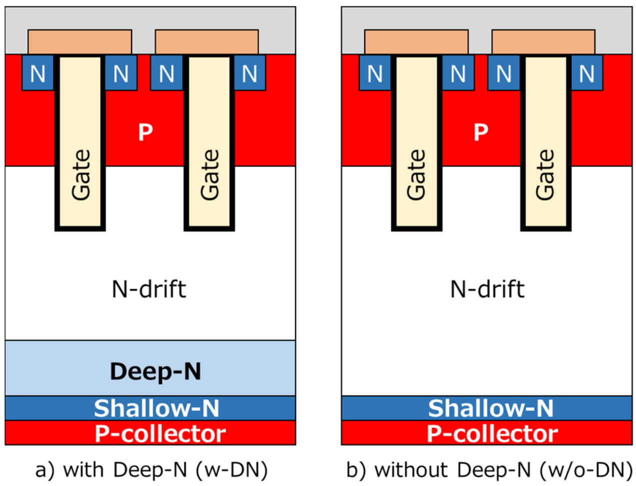


Fig. 2: IGBT structures: (a) w-DN (with Deep-N), that is proposed structure, (b) w/o-DN (without Deep-N).

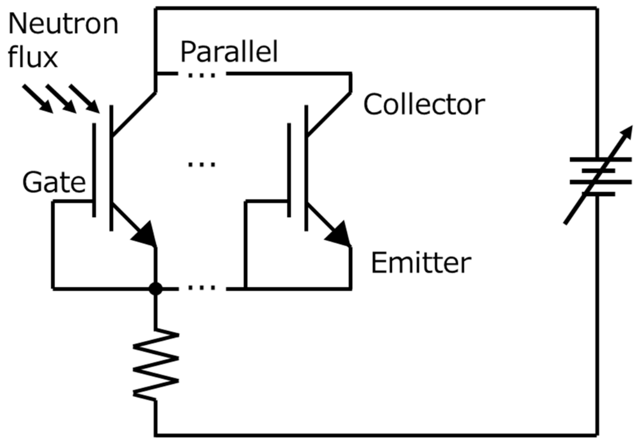


Fig. 3: Experimental circuit for SEB failure rate by irradiating white neutron beams which normalized energy spectra is similar to sea level.

IGBT with DN, and experimentally demonstrated improvement of the SEB robustness for the first time.

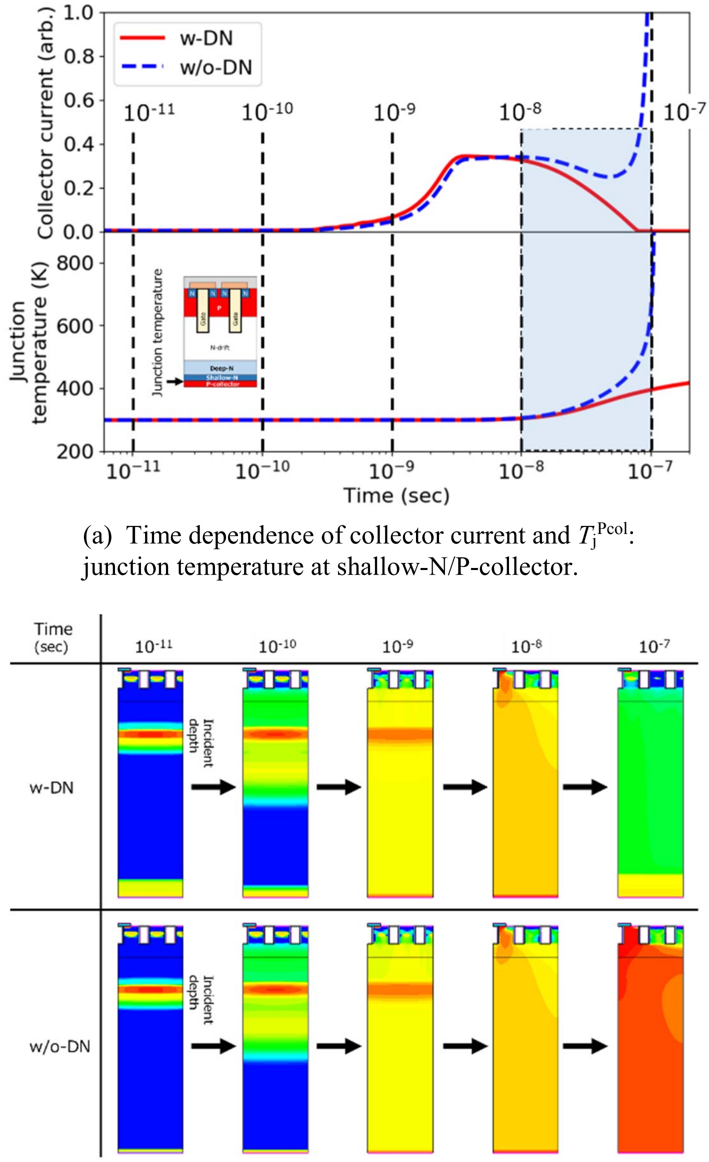
II. Simulation And Experimental Conditions

A. Simulation Condition

SEB process was modeled in TCAD framework by heavy ion model in which high energy particles transfer energy to the atoms and generate electron-hole pairs during penetrating through devices under reverse bias condition. In the model, SEB is attributed to collector current runaway. The model was used in the previous studies [3,6] and described the experimental results well. In this paper, we carried out the 2D device simulation using the model in Synopsys Sentaurus Device for IGBT with Deep-N layer (w-DN, Fig. 2(a)) and without DN (w/o-DN, Fig. 2(b)). In order to model the thermal runaway, we also took the self-heating effect during SEB transient into account. We analyzed the transient behavior of collector current, electron density distribution and impact ionization rate for fundamental realization of SEB process. We also analyzed lattice temperature, electric field and hole injection efficiency because previous studies indicated that PNP bipolar action is trigger of SEB[2, 3].

B. Experimental Condition

To examine SEB robustness by cosmic ray, we assumed that only neutron affects SEB phenomena because almost charged particle in cosmic ray should be decayed through atmosphere at sea level, and this assumption is same with previous studies [1-3, 6]. Therefore in order to measure the neutron-induced SEB failure rate, we used the facility of the Research Center for Nuclear Physics (RCNP) at Osaka University [7]. Schematic of the evaluation configuration is shown in Fig. 3. We fabricated IGBT both w-DN and w/o-DN, irradiated white neutron beams into a number of those devices at the same time under reverse bias voltage, monitoring leakage current for detecting failure devices.



(a) Time dependence of collector current and T_j^{Pcol}: junction temperature at shallow-N/P-collector.

(b) Time dependence of electron density distribution.

Fig. 4: (a) Time dependence of collector current (upper) and junction temperature at shallow-N / P-collector (lower). The depth of junction temperature is shown in inset. Red solid line and blue break line indicate w-DN and w/o-DN respectively.
(b) Time dependence of electron density for w-DN (upper) and w/o-DN (lower) at the time: 10^{-11}, 10^{-10}, 10^{-9}, 10^{-8}, 10^{-7} s (corresponding with the emphasized times in Fig. 3). Red and blue color indicate high and low electron density.

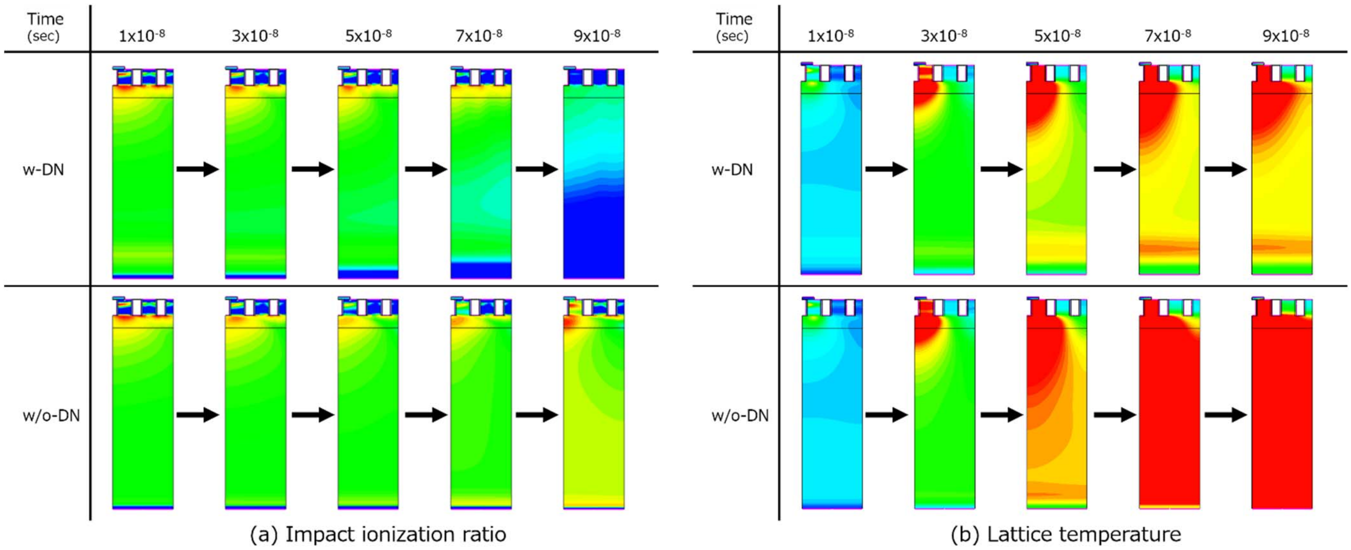


Fig. 5: (a) Time dependence of impact ionization rate and (b) lattice temperature for w-DN (upper) and w/o-DN (lower) at the time: 1, 3, 5, 7, 9 x 10^{-8} s (corresponding with the hatched period in Fig. 3). Red (blue) color indicate high (low) impact ionization rate and temperature at (a) and (b), respectively.

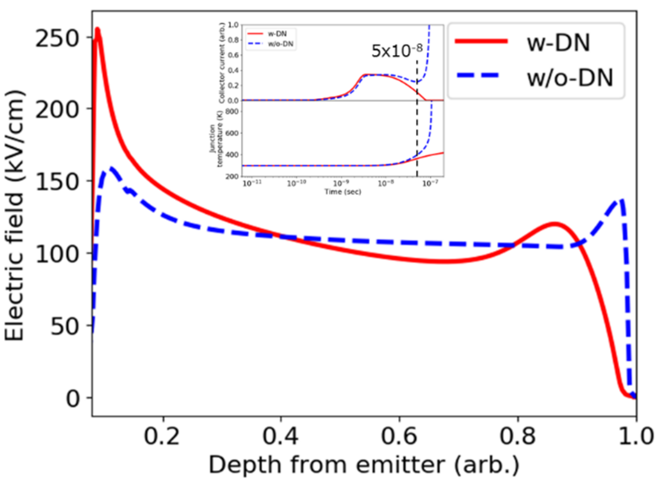


Fig. 6: Electric field with respect to depth from emitter to collector at the time the collector current starts to increase (5 x 10^{-8} s, see the inset which is corresponding to Fig. 4(a)). The red solid line and the blue break line indicate w/-DN and w/o-DN, respectively.

III. Results and Discussions

A. Simulation Results

In order to clarify the effect of introducing DN, we examined simulation results in detail. Fig. 5(a) shows the transient simulation result of the collector current and the junction temperature at shallow-N / P-collector (T_j^{Pcol}) after heavy ion irradiation under blocking state for w-DN and w/o-DN structures. Until 10^{-8} s, collector current and junction temperature are almost same with each structure, but after 10^{-8} s, while the collector current runaway for w/o-DN occurs when T_j^{Pcol} starts to rise, the collector current for w-DN decays and T_j^{Pcol} rising saturates at around 430K. This result indicates that the steep current rising strongly correlates with the junction temperature. To analyze more detail, we examined the time dependence of electron density distribution shown in Fig. 4(b). It is observed that electrons generated by the irradiation at 10^{-11} s spread along time, and fill the N-drift region until 10^{-8} s for both structures. However, at 10^{-7} s when generated carriers are detected as collector current (see Fig. 4(a)), there is a clear difference between w-DN and w/o-DN. Electrons are swept out in the case of w-DN, while these still increase in w/o-DN.

In order to explain the reason of the difference, we focused on the period between 10^{-8} s and 10^{-9} s corresponding to hatch in Fig. 4(a). As the device is exposed to reverse bias voltage with a lot of generated carriers, it is considered that impact ionization is a possible cause for the trigger of current runaway. Fig. 5(a) shows time dependence of impact ionization rate from 1 x 10^{-8} s to 9 x 10^{-8} s. Until the time of current rising for w/o-DN (7 x 10^{-8} s), the rate is almost same with each structure. This result attributes that impact ionization is not the trigger of current runaway. Fig. 5(b) shows time dependence of lattice temperature. Until 3 x 10^{-8} s, the temperature of both structures is similar. However, after 5 x 10^{-8} s, temperature in w/o-DN becomes higher than w-DN at emitter and collector side. While the temperature rising at emitter side might cause N-emitter / P-base / N-drift bipolar action, the rising at collector side might cause PNP bipolar action. To analyze which bipolar action is the trigger of current runaway, Fig. 6 shows the electric field under same voltage in both devices with respect to depth from emitter to collector at 5 x 10^{-8} s when the collector current starts to increase. Electric field in w-DN at emitter side is larger than in w/o-DN. However, collector current runaway did not occur in w-DN. This result is attributed that the electric field at emitter side, that might cause NPN bipolar action, is not the trigger of current runaway. On the other hand, electric field in w/o-DN around P-collector is larger than in w-DN because DN, that has

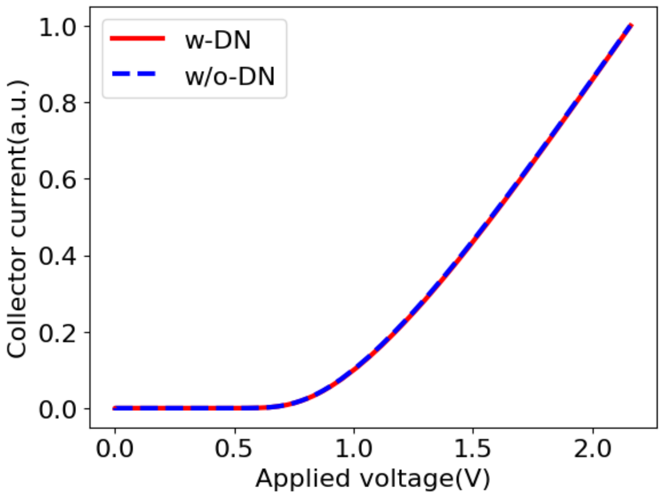


Fig. 7: Ic-Vce curve of w-DN (red solid line) and w/o-DN (blue break line).

more impurity concentration than drift layer, stop the depletion region expansion. As collector current density is same with each structure, local joule heat usually becomes higher under high electric field. As a result, low electric field at backside suppresses arising T_j^{Pcol} in w-DN structure and PNP bipolar action.

DN introduction at backside might affect the hole injection efficiency because PN junction profile might be changed by the addition. We checked the effect by simulating Ic-Vce curve (Fig.7). The two curves are identical, so the DN does not affect the injection efficiency. This is because dopant concentration of DN layer is much lower than shallow-N, and PN junction profile at shallow-N / P-collector is not changed much.

From these results, we concluded that collector current runaway in the simulation is caused by the temperature rise near backside PN junction and triggering PNP bipolar action. DN structure reduces the electric field and joule heat generation, and hence the bipolar action is successfully suppressed.

B. Experimental Result

Above simulation result indicates that DN structure is good candidate for improvement of SEB robustness. Fig. 8 shows the experimental data of the neutron-induced SEB failure rate with respect to reverse bias voltage between collector and emitter. This experimental result shows that introducing DN improve SEB robustness, and corresponding with our simulation result.

IV. Conclusion

We investigated the improvement of SEB robustness by introducing DN at backside of IGBT by heavy ion simulation and experiment in RCNP. The simulation shows that introduction of DN improve SEB robustness because of electric field relaxation, suppressing T_j^{Pcol} rise and PNP bipolar action. We also fabricated IGBT with DN and succeeded to confirm good agreement with simulation result. We conclude that introducing DN is the one of solutions for improvement of cosmic ray robustness.

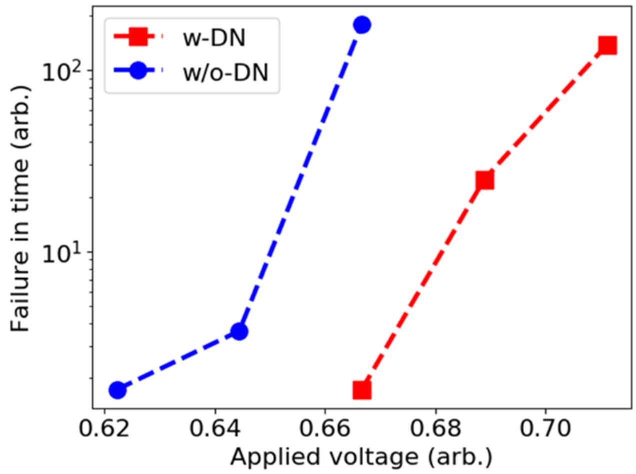


Fig. 8: The experimental result: DN (Deep-N) dependence of SEB robustness with respect to applied voltage. The y-axis is logarithmic scale. The red square and blue circle indicate w-DN and w/o-DN, respectively. The improvement of SEB robustness is realized by introducing w-DN.

Acknowledgment

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