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Analysis for Rapid Tail Current Decay in IGBTs with Low Dose p-Emitter

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Abstract— **A new theory is developed to correctly describe the turn-off mechanism in IGBTs. We found that the p-emitter efficiency (α) in IGBTs dramatically reduces during the fall-time. The hole current component of the tail current in IGBTs with low α instantly decays to zero at the onset of the fall-time, because α becomes negative during the fall-time and the stored holes are removed towards the collector electrodes. An abnormal hole diffusion current flows in the n-drift toward the p-emitter because the decreasing carrier density gradient toward the p-emitter is created. The magnitude of the stored carriers (p_n) at the n-drift near the p-emitter is universally determined by the forward bias (V_{Fp}) between the p-emitter and the n-drift even in the turn-off transient. It is found that the initial V_{Fp} is decided only by the p-emitter dose (d_P). Consequently, the turn-off tail current in IGBTs is decided by d_P because V_{Fp} in the fall-time and the stored carriers in the n-drift in the fall-time are decided by d_P. It is difficult to correctly describe the phenomenon with conventional IGBT models because the models assume that the α does not change in the fall-time period.**

Keywords- IGBT; turn-off; tail current; current component; high-speed; p-emitter; collector dose; fall-time

I. INTRODUCTION

It is essential to reduce the turn-off tail current in Insulated Gate Bipolar Transistors (IGBT) for achieving low switching power loss. The tail current occurs due to the remaining stored carriers in the n-drift during the turn-off fall-time period. It was shown [1] that an IGBT with low p-emitter (collector) efficiency of less than 0.27 is effective in order to reduce the tail current because a lot of stored carriers are removed in storage-time period. Fig.1 shows experimentally obtained turn-off waveforms of a Field-Stop (FS) IGBT. Generally, the tail current of FS-IGBT with low p-emitter efficiency is smaller than that of so-called PT-IGBTs.

In this paper, we show that the low p-emitter efficiency benefits reducing the stored carriers during not only the storage-time but also the fall-time. This benefit relates to the reduction in p-emitter efficiency during the fall-time. Conventional IGBT models that assume constant p-emitter injection efficiency cannot correctly describe the IGBT turn-off phenomenon. The tail current in FS-IGBTs has been tried to be described with a fitting-parameter, which is a time constant of the carrier life-time [2]. We propose a new theory that correctly describes the IGBT turn-off mechanism.

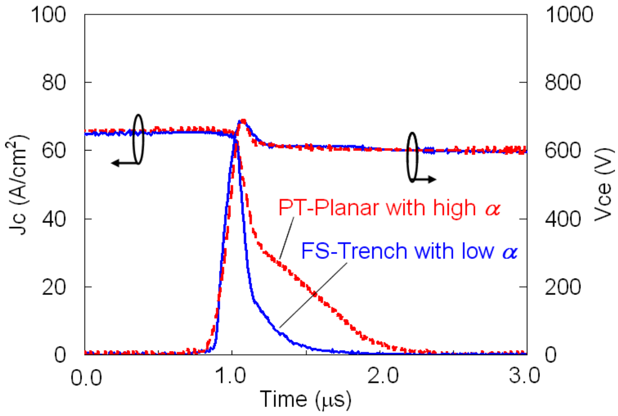

Fig. 1: Measured turn-off waveforms of a FS-Trench IGBT with low p-emitter efficiency (α) and PT-Planar IGBT with high α

II. ANALYSIS AND DISUCUSSION

The hole and the electron current components of the collector tail current are simulated for a switching under an inductive load [3] and are shown in Fig. 2. The tail current in the FS-IGBT rapidly decays in the fall-time. The electron current occupies almost all of the tail current because the hole current component instantly decays. For simplifying the analysis, the turn-off waveforms were analyzed for the two Non-Punch-Through (NPT) IGBTs, having low and high p-emitter doses (d_P) as shown in Fig. 3. Analogous to the FS-IGBT, the hole current component of the tail-current in the NPT-IGBT with low d_P also reduces to zero instantly. Therefore, d_P is considered to be an important parameter that influences the tail current behavior. As shown in Fig. 4, the p-emitter efficiencies (α) in the two NPT-IGBTs with different d_P rapidly decrease during the fall-time. It should be noted that the negative α period exists in the NPT-IGBT with the low d_P. In this period, hole current flows in the reverse direction, which means that holes are removed from the n-drift toward the collector electrodes. After the fall-time, the values of α in the both IGBTs are reaching the values in steady off-state.

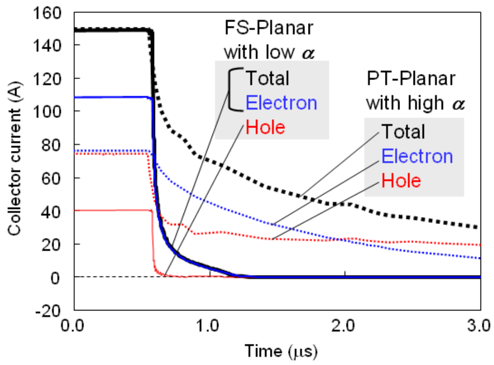

Fig. 2: Simulated hole and electron current components of turn-off waveforms for FS-IGBT with low p-emitter efficiency (α) and for PT-IGBT with high α. In FS-IGBT, hole current component is instantaneously turned-off in fall-time, and the tail current flows only by electrons.

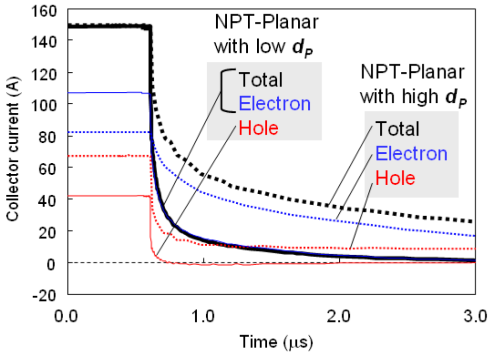

Fig.3: Simulated hole and electron current components of turn-off waveforms for two NPT-IGBTs with p-emitters of high d_P and low d_P

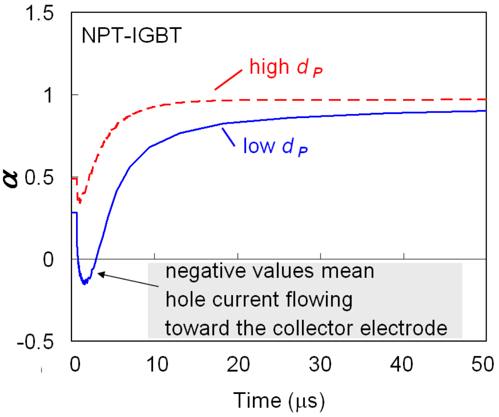

Fig. 4: Simulated injection efficiency of p-emitter (α) during turn-off as a function of time for NPT-IGBTs with high d_P and low d_P.

For further analyzing the reverse hole current, the hole and electron currents are divided into the diffusion and the drift components. These in the two IGBTs at the time, when the total current equal to just 13% of the rated current in the fall-time period, are shown in Figs.5 and 6. The horizontal axis indicates the depth from the emitter electrode. In the NPT-IGBT with low d_P, the hole diffusion current near the p-emitter flows toward the collector electrode (in the direction opposite to the drift current) in spite of the positive forward-bias across the PN junction between the p-emitter and the n-drift. On the other hands, the hole drift current flows in normal direction. The total hole current near the p-emitter flows to the collector electrode from the n-drift because of the large abnormal hole diffusion current. Moreover, in the NPT-IGBT with low d_P, the large electron diffusion current flows in the same direction as the electron drift current. Therefore, a huge total electron current flows as seen in Fig. 7. The total tail current is occupied almost by the electron current. This is the reason for a negative α during the fall-time and the rapid tail current decay of IGBTs with low d_P.

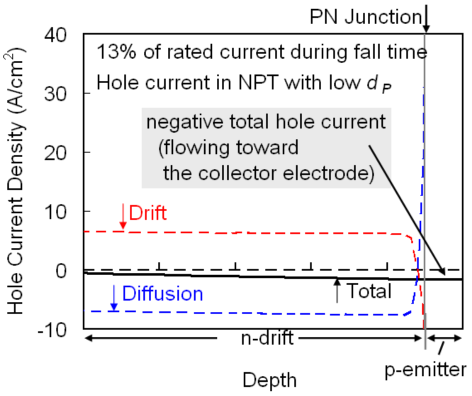

Fig. 5: Simulated total, diffusion and drift hole current components for NPT-IGBT with low d_P as a function of depth from surface at the time when total collector current is 20A (13% of rated current) during fall-time. As the hole diffusion current flows into p-emitter, total hole current becomes negative at p-emitter.

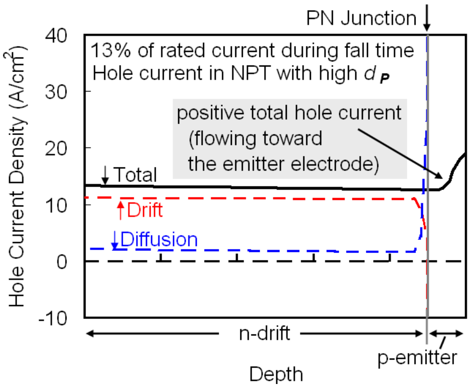

Fig. 6: Simulated total, diffusion and drift hole current components for NPT-IGBT with high d_P as a function of depth from surface at the time when total collector current is 20A (13% of rated current) during fall-time.

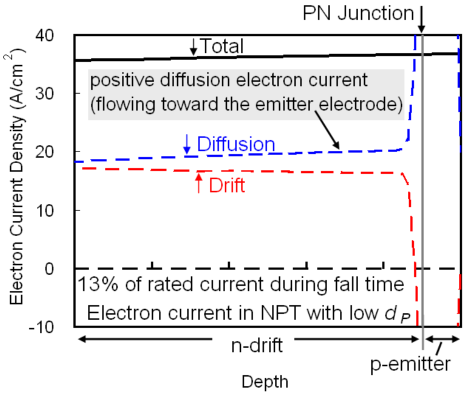

Fig. 7: Simulated total, diffusion and drift electron current components for NPT-IGBT with low d_P as a function of depth from surface at the time-step when total collector current is 20A (13% rated current) during fall-time.

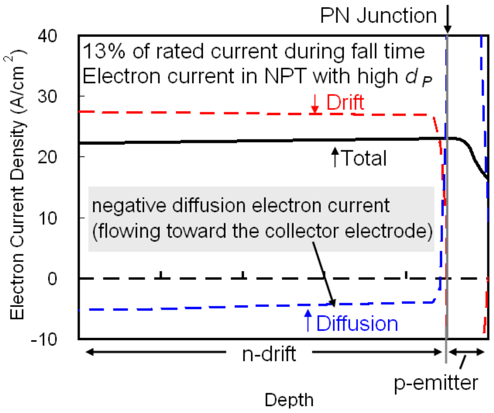

Fig. 8: Simulated total, diffusion and drift electron current components for NPT-IGBT with high d_P as a function of depth from surface at the time-step when total collector current is 20A (13% rated current) during fall-time.

For analyzing the abnormal diffusion current in IGBTs with low d_P, we investigate the forward bias (V_{Fp}) applied to the p-emitter/n-drift junction, as shown in Fig. 9. V_{Fp} starts to decrease immediately after the onset of current falling. In order to understand why hole current flows from the n-drift toward the p-emitter in the IGBT with low d_P, the stored hole density (p_n) is plotted as a function of V_{Fp} in Fig. 10, for each time step when the collector current takes the value of 150A (initial value), 100A, 50A, 20A or 10A, respectively. It is clearly seen that the magnitude of p_n is universally dependent on the magnitude of V_{Fp}. For analyzing that phenomenon, the band diagram is shown in Fig. 11. Because the electron density (n_n) is equal to the hole density (p_n) in high injection state to fulfill charge neutrality, the difference (V_i) of the hole quasi-Fermi potential (ϕ_{Fp}) from the band gap center and the difference of the band gap center from the electron quasi-Fermi potential (ϕ_{Fn}) are the same. Since V_i and V_{Fp} are almost equal to each other, ϕ_{Fp} and, thus, p_n or the stored carriers in the n-drift near the p-emitter is decided by V_{Fp}. Therefore, p_n reduces during the fall-time as V_{Fp} decreases as shown in Fig. 10.

In the fall-time period, as V_{Fp} decreases, the stored carriers become excessive, in other words, the stored carriers exceed the amount that the positive forward-bias of the p-emitter/n-drift junction can afford to supply. The condition is unstable and is not in equilibrium state, and, thus, the stored carriers must decrease to the amount that the forward-bias can afford to supply. This is the main reason for the reverse hole diffusion current and the reduction in α.

It was found by simulations that the initial stored carrier density in the n-drift near the p-emitter in the initial steady on-state or the initial V_{Fp} is determined by the p-emitter dose (d_P). The stored carrier density in the n-drift reduces according to the universal line in Fig.10 in the turn-off transient. Thus, it is suggested that the whole turn-off process and the tail current is decided only by the p-emitter dose (d_P).

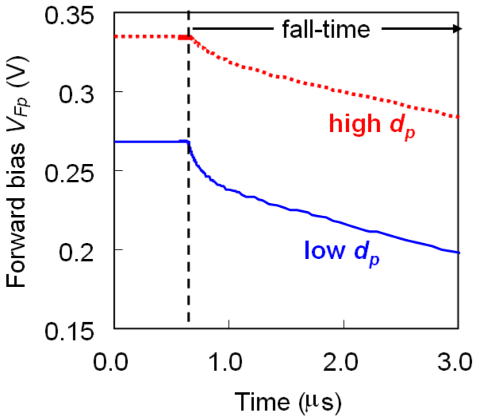

Fig.9 Forward bias (V_{Fp}) applied to p-emitter/n-drift junction is plotted as a function of time during fall-time.

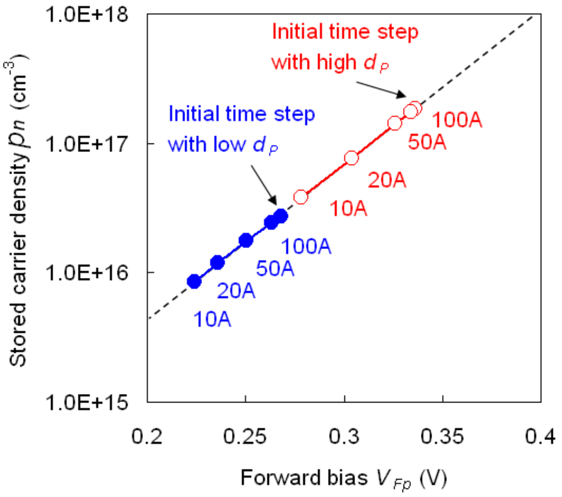

Fig.10 Stored hole density is plotted as a function of forward bias, V_{Fp}, for each time-step when collector current takes the value of 150A (rated current), 100A, 20A or 10A, respectively, in fall-time. All plotted points for both IGBTs with high and low d_P appear on the same straight line. This means that stored holes are uniquely determined by V_{Fp}, during fall-time or tail current period.

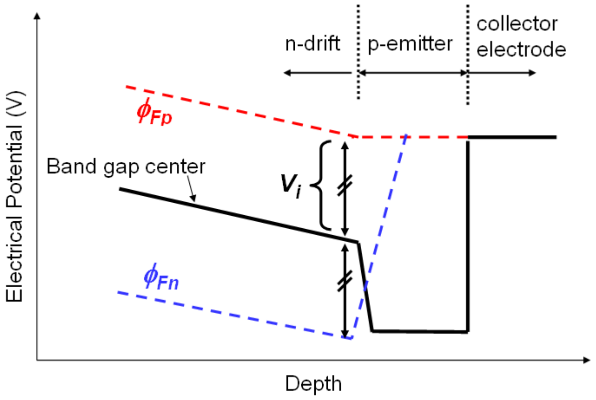

Fig.11 Illustration of band gap center and quasi-Fermi potential of hole (ϕ_{Fp}) and electron (ϕ_{Fn}) near the p-emitter in high injection state. The differences of band gap center and ϕ_{Fp} (V_i) and ϕ_{Fn} are equal to each other to fulfill a charge neutral condition.

Because a large amount of electrons are removed from the p-emitter in the NPT-IGBT with low d_P, the decreasing hole density gradient from the n-drift toward the p-emitter is created in the n-drift near the p-emitter in the fall-time, as seen in Fig.12. The hole density gradient is easily formed in the NPT-IGBTs with low d_P since the initial carrier distribution is almost flat due to the initial low V_{Fp}. A large hole diffusion current flows toward the p-emitter because of the created hole density gradient. On the other hand, for NPT-IGBT with high d_P, electrons are relatively difficult to be removed from the p-emitter because of the high built-in voltage. Moreover, a large increasing hole density gradient from the n-drift toward the p-emitter exists in the initial time-step, as seen in Fig. 13. Thus, it is difficult to reverse the initial hole density gradient by removing electrons from the p-emitter.

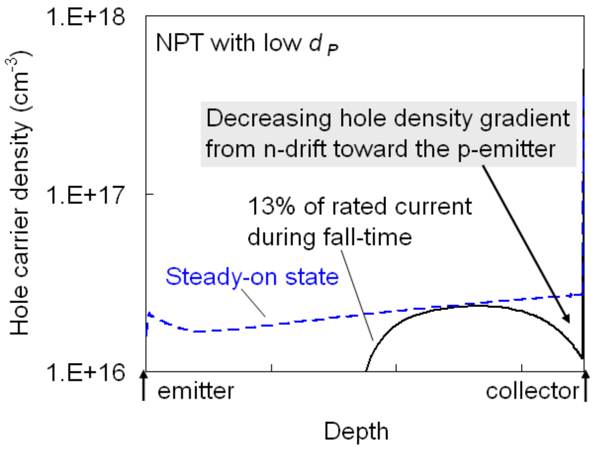

Fig.12 Hole density distributions for NPT-IGBT with low d_P as a function of depth for initial time-step (steady on-state) and for time step when collector current is 20A (13% rated current) during fall-time.

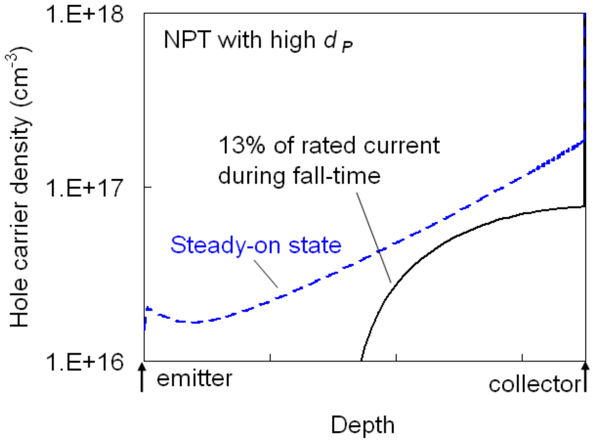

Fig.13 Hole density distributions for NPT-IGBT with high d_P as a function of depth for initial time-step (steady on-state) and for time step when collector current is 20A (13% rated current) during fall-time.

In summary, it is found that the turn-off tail current in IGBTs is decided by d_P because V_{Fp} during the fall-time and the initial stored carriers in the n-drift near the p-emitter are decided by d_P. As long as d_P is the same, the turn-off waveforms are almost the same even if the other device structures are different. For the verification, the turn-off waveforms are calculated and shown in Fig.14 for IGBTs that have an additional N buffer layer or have a trench-gate structure with retaining the same d_P. The turn-off tail currents for these IGBTs are closely the same.

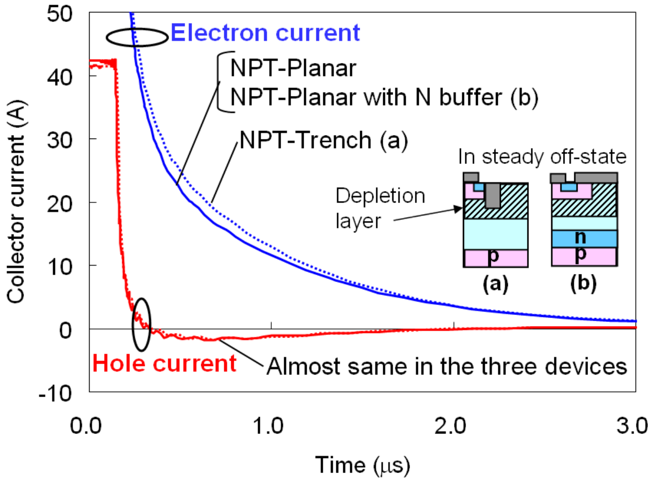

Fig. 14 Simulated hole and electron current components of turn-off waveforms for NPT-Planar IGBT, NPT-Trench IGBT and NPT-Planar IGBT with N buffer, while d_P are the same. The two solid lines completely coincide with each other.

III. CONCLUSION

IGBT turn-off behavior is investigated in detail. We propose a new theory correctly describing the turn-off mechanism of IGBTs with low p-emitter dose (d_P). The stored carrier density (p_n) at the n-drift near the p-emitter decreases in non-equilibrium condition as the forward bias (V_{Fp}) decreases. A large abnormal hole diffusion current flows to collector electrode (in the direction opposite to drift current), which results in negative α. Thus, the hole current instantly decays to zero in the fall time period. The tail current becomes small and almost consists of electron current only. It was found that the turn-off tail current in IGBTs is decided by d_P because V_{Fp} during the fall-time and the initial amount of the stored carriers at the n-drift near the p-emitter are decided by d_P.

REFERENCE

[1] T. Matsudai and A. Nakagawa, "Ultra High Swiching Speed 600V Thin Wafer PT-IGBT Based on New Turn-off Mechanisum", ISPSD'02 Proceeding., pp.285-288, 2002.

[2] B. J. Baliga, "Fundamentals of Power Semiconductor Devices" , Springer, pp.896-904, 2008.

[3] Synopsys, Inc. "Sentaurus device User Guide" ver. F-2011.09.