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High dV/dt Controllability of 1.2kV Si-TCIGBT for High Flexibility Design with Ultra-low Loss Operation

ABSTRACT

High dV/dt controllability of IGBT is an important factor for flexible design as well as low switching loss in power electronics systems. However, Dynamic Avalanche (DA) phenomenon poses a fundamental limit on their dV/dt control range, operating current density, turn-off power loss as well as reliability. Overcoming this phenomenon is essential to ensure their safe operation in emerging electric transport. In this work, detailed analysis of 1.2 kV trench gated IGBTs is undertaken through experiments and calibrated TCAD simulations to show the fundamental cause of the low dV/dt controllability of conventional IGBTs and a method to achieve DA free design by Trench Clustered IGBT (TCIGBT). The potential of TCIGBT for ultra-high current density operation with high dV/dt controllability is also presented.

INTRODUCTION

Trench Insulated Gate Bipolar Transistor (TIGBT) is a key component in power electronics applications today, and its performance has been improved by new approaches [1]-[5]. The improvements in the switching loss (E_{off}) and on-state voltage drop ($V_{ce(sat)}$) trade-off have resulted in not only low loss operation but also increases in current density and improvement in cost performance of TIGBT modules. Low E_{off} (high dV/dt) reduces the system size by shrink of passive component with high frequency operation. Since high dV/dt induces EMI noise, the dV/dt must be adjusted by the external gate resistance to compromise both the power efficiency and the noise in the system design. However, high current density and high dV/dt during switching can induce DA and the dV/dt controllability is therefore limited [6]. During turn-off transient, expanding depletion layer is obstructed by stored carriers as depicted in Figure 1. DA will take place if the resulting electric field exceeds the critical electric field ($E_{critical}$), which can occur even at a voltage well below the static breakdown voltage. Therefore, DA poses a fundamental limit on the operating current density, turn-off power loss [7] as well as reliability [8].

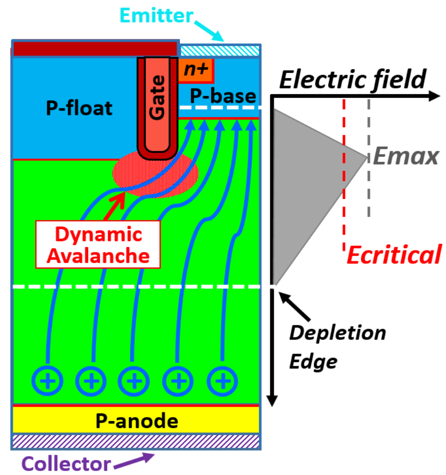

Figure 1: Schematic of DA in the turn-off of TIGBT.

In this paper, an in-depth analysis of the TIGBT switching behavior focusing on the DA is presented and a DA free turn-off operation is demonstrated in a Trench Clustered IGBT (TCIGBT) [9], through in both simulation and experiment. Moreover, the impact of TCIGBT on dV/dt controllability at high current density operation is evaluated in detail.

dV/dt Limitation by Dynamic Avalanche

To analyze the DA in silicon TIGBTs, the 3D Sentaurus Device [10] is utilized to simulate the switching behavior, with a circuit configuration for mix-mode simulation. The dependence of switch-off characteristics of a 1.2 kV TIGBT in Field-Stop (FS) technology on gate resistance (R_g) is shown in Figure 2(a). In practice, smaller R_g should induce large dV/dt; however, the DA decreases the dV/dt, which results in decrease in surge voltage even with small R_g conditions, as shown in Figure 2(b). This clearly indicates that DA occurs in the cases of R_g<20 Ω and the dV/dt is limited by DA.

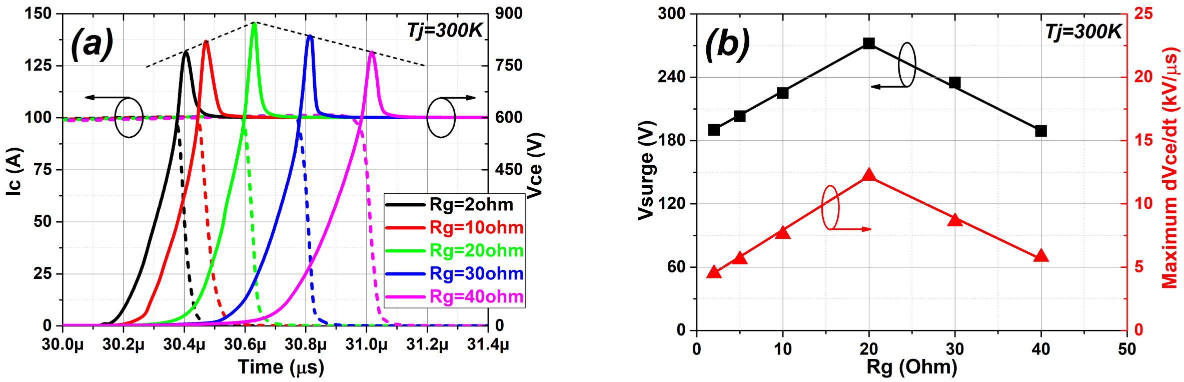

Figure 2: Influence of R_g on (a) switch-off characteristics, and (b) surge voltage (V_{surge}) and maximum dV/dt of a conventional TIGBT. (V_{DC}=600V, I_c=100A at J_c=200A/cm^2, V_g=±15V, and L_{stray}=100nH)

DA FREE SOLUTION - dV/dt CONTROLLABILITY BY TCIGBT

As a fundamental solution towards the DA removal, the TCIGBT as shown in Figure 3(a) is attractive because of its design for electric field management and does not suffer from DA. The TCIGBT device features a MOS-gated thyristor structure, which consists of P-anode, N-drift, P-well and N-well. Its turn-on mechanism has been explained in [9].

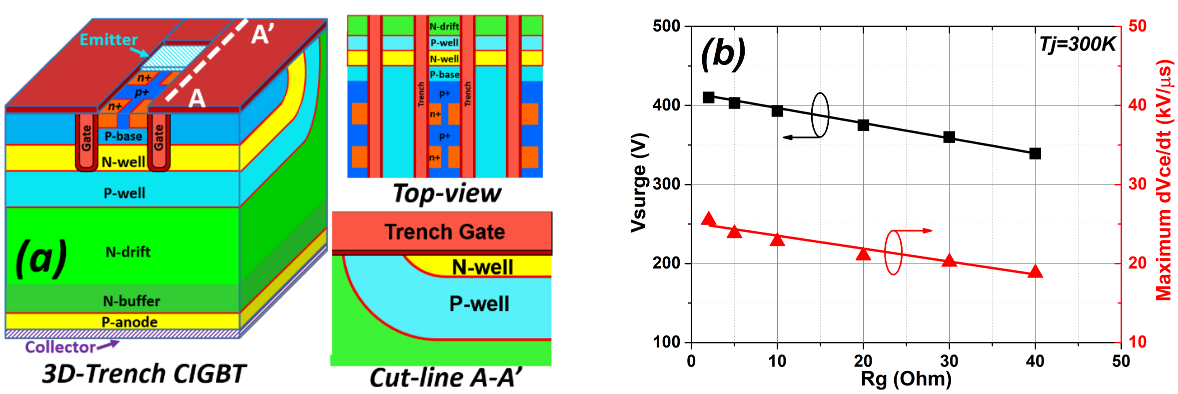

Figure 3: (a) 3-D cross-sectional view of TCIGBT, and (b) V_{surge} and maximum dV/dt during turn-off of the TCIGBT. (V_{DC}=600V, I_c=100A at J_c=200A/cm^2, V_g=±15V, and L_{stray}=100nH)

During turn-off transient, the accumulation layers formed along the sidewall of trench gates connect the P-well layer with P-base region (PMOS). Together with its salient self-clamping feature, such design provides a direct evacuation path for excess holes to be collected within emitter region as well as shift maximum electric field away from the trench regions. This results in effective control of the DA and dV/dt as depicted in Figure 3(b). Figure 4(a) compares the electric field distributions when V_{ce} increases to 600 V during turn-off between TIGBT and TCIGBT under R_g=0.1 Ω and identical $V_{ce(sat)}$ (on-state carrier density) conditions. As can be seen, the TCIGBT shows a linear decrease of E_{off} as R_g reduces, as shown in Figure 4(b). Absence of the DA in TCIGBT is clearly evident from the experimental results of the switching waveforms and maximum dV/dt of 1.2 kV, 40 Ampere devices [11] as a function of R_g as shown in Figures 5(a) and (b), respectively. The dV/dt can be controlled even at low R_g conditions. Although the demonstrated devices were made in Non Punch-Through (NPT) technology, moving from NPT technology to a thinner FS technology has no impact on the DA.

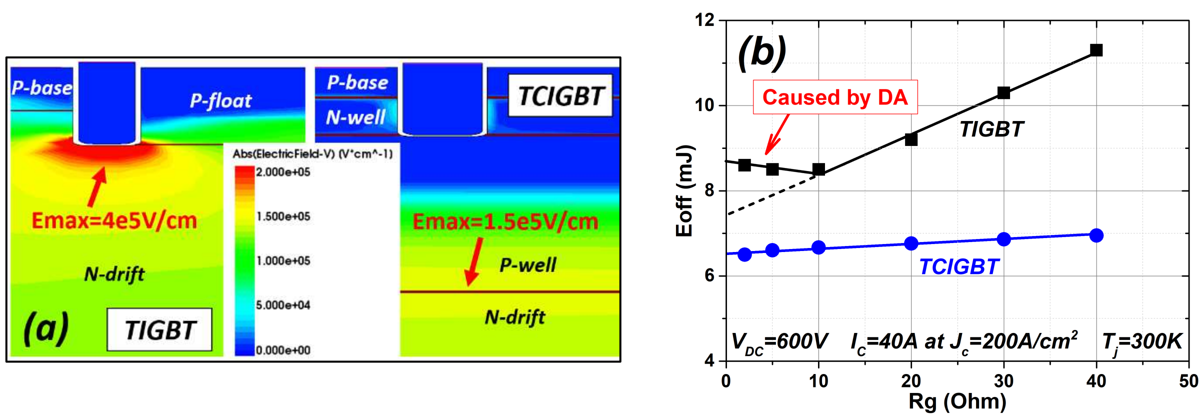

Figure 4: Comparison of (a) electric field distribution when V_{ce} raises to 600V during turn-off (R_g=0.1 Ω), and (b) E_{off} dependence on R_g between TIGBT and TCIGBT. (V_g=±15V)

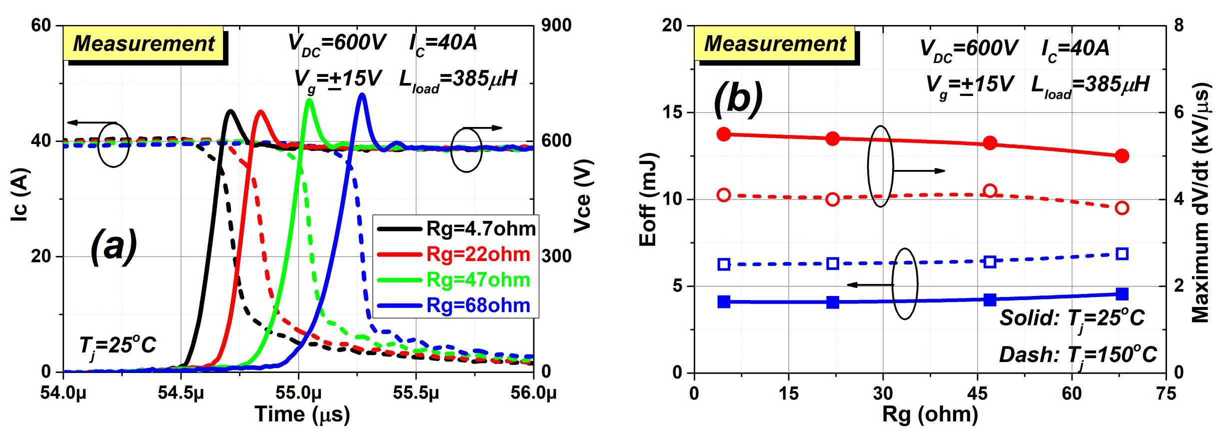

Figure 5: Experimental results of (a) turn-off characteristics and (b) V_{surge} and maximum dV/dt dependence on R_g of a 1.2kV, 40A TCIGBT in NPT technology.

POTENTIAL OF HIGH CURRENT DENSITY OPERATION AND LOW LOSS OPERATION

Figure 6(a) shows TCIGBT does not show DA even at high current density of 800 A/cm^2. Although limitation of maximum dV/dt is reduced at high current density operation, absence of DA in TCIGBT can be maintained. In addition, it can be expected that low $V_{ce(sat)}$ condition induces DA due to high carrier concentrations in the on-state operation. However, Figure 6(b) shows that DA is absent in TCIGBT even at a low $V_{ce(sat)}$ of 1.75 V at J_c=500 A/cm^2. This confirms that TCIGBT can provide high design flexibility with ultra-high current density operation as well as very low power losses.

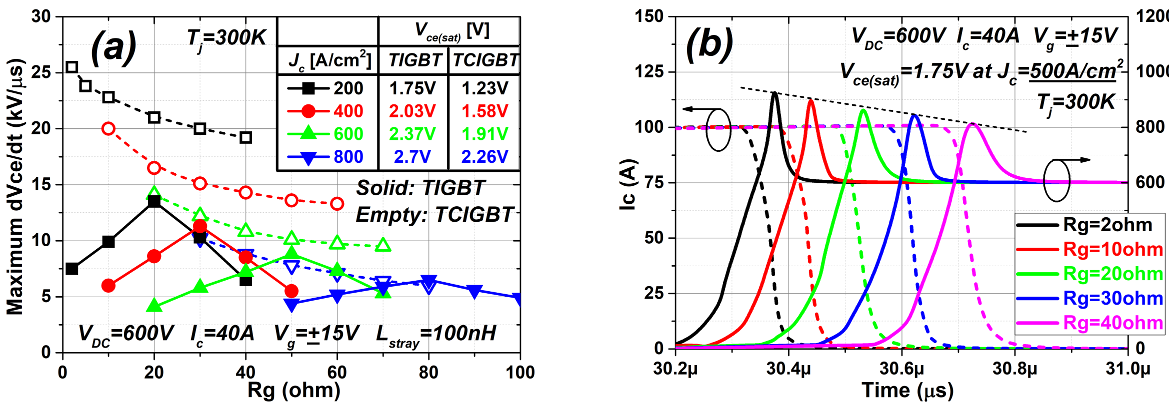

Figure 6: (a) Comparison of maximum dV/dt dependence on current density (J_c) and R_g of TIGBT and TCIGBT (Same P-anode dose), and (b) switch-off characteristics of TCIGBT at J_c=500A/cm^2.

CONCLUSIONS

The 1.2 kV trench IGBT switching behavior focusing on the DA was analyzed through 3D TCAD models for the first time. Management of the electric field beneath the trench gate is the most critical to minimize the DA. Moreover, a DA free turn-off operation is demonstrated in a TCIGBT through in both simulation and experiment. As a MOS controlled thyristor device, TCIGBT can be operated with very low power losses and at high current densities without DA and provides high design flexibility for power electronics systems by high dV/dt controllability.

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