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An injection efficiency model to characterize the injection capability and turn-off speed for >10 kV 4H-SiC IGBTs

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ABSTRACT

This work analytically formulates the relationship among the followings for characterization purpose: (i) γ_E (injection efficiency), (ii) excess charge stored during on-state and (iii) charge extraction rate and voltage ramp before punch-through during the turn-off. Injection efficiency is expressed in terms of J_R (reference current density), J_b (buffer layer reference current), and J_T (terminal current). Both J_R and J_b are lumped parameters and can be extracted without any knowledge of parameters in the emitter and buffer layer. While γ_E is simply the ratio of minority to total current, injection capacity is defined mathematically in this work as an index of the tendency of the excess carriers being injected from emitter and then stored in the drift region. 4H-SiC p- and n-IGBT will be discussed side-by-side throughout the discussion. The adaptability of this injection efficiency model will be examined under different emitter conditions and buffer layer lifetimes. This work is also applicable to silicon devices.

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1. Introduction

10 kV-class 4H-SiC IGBTs have been fabricated and investigated in [1,2], aiming at the application in solid-state transformer for the future smart grid technology [3–5]. Before 10–20 kV IGBTs are widely commercialized, accurate device models in circuit simulators for application engineers are desirable to investigate the device in their application circuits. For the past two decades, silicon IGBT models [6–10] have been developed and implemented into circuit simulator such as Saber [13,14] and Spice [14–18]. Recently, 4H-SiC p-IGBT have also been modeled and implemented for circuit simulations [19].

To accurately extract the parameters for the model is equally important as the model itself [16,20,21]. Among all the parameters, injection efficiency is a critical one, for it largely determines the injection level during on-state and charge extraction rate in the drift region during turn-off. This is especially true for high-voltage 4H-SiC IGBT with relatively wide drift region. Different from median voltage silicon IGBTs, two distinctive phases of voltage ramp during turn-off for >10 kV 4H-SiC were observed [1–3]. In [22], a more detailed three-phase voltage ramp was discussed through simulations for 15–20 kV 4H-SiC IGBTs. By reducing the lifetime in the buffer layer, it is shown in [23] that the turn-off loss can be largely reduced due to the lowering of injection efficiency.

While efforts have been made to qualitatively explain [3,23] the relationship among γ_E, injection capability and turn-off speed, an analytical model to characterize this relationship is desired before resorting to computer-aid simulations for full switching wave form, especially for certain devices whose potential has not been fully tapped [24]. Most of the modeling works use either emitter recombination parameter h [8,9,14–17] or emitter saturation current I_{se} [6,11–13] to characterize the injection capability of silicon IGBTs. For 4H-SiC, I_{se} and the injection capability optimization for $p+$ emitter in modern bipolar devices were analytically discussed [24] without the presence of the buffer layer. Although sufficient for the modeling purpose, these two parameters are rather implicit in terms of indicating the injection capability of certain device. For example [6], I_{se} is used to relate the majority current, not the terminal current, to the boundary excess carrier density at drift region/emitter.

Fig. 1 summarizes the goal of this work – to analytically formulate the relationship among J_T, γ_E, injection capability, charge extraction rate, etc., for analytical characterization purpose. The goal of Section 2 is to show that boundary concentration can be directly calculated by using terminal current density J_T and

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Nomenclature

b the ratio of electron to hole mobility
D_n, D_p diffusivity for electron, hole in the drift region (cm^2/S)
D_{pE}, D_{nE} diffusivity of minority carrier in the emitter of p-, n-IGBT (cm^2/S)
h_n emitter recombination parameter for n-IGBT (cm^4/S)
h_p emitter recombination parameter for p-IGBT (cm^4/S)
I_{se} emitter saturation current for n-IGBT (A)
J_{Rp}, J_{Rn} injection efficiency reference current for p-, n-IGBT (A/cm^2)
J_{bp}, J_{bn} buffer layer reference current for p-, n-IGBT (A/cm^2)
J_T, J_T^- total current density in steady-state(A/cm^2)
J_T^+ total current density immediately after the gate turned off (A/cm^2)
L the ambipolar diffusion length in the drift region (cm)
L_{pE}, L_{nE} diffusion length of minority carrier in the emitter of p-, n-IGBT
n_W, p_W minority carrier density at the drift region/emitter boundary in the drift region (cm^{-3})
N_D, P_D doping concentration in the drift region p-, n-IGBT (cm^{-3})
N_E, P_E doping concentration in the emitter of p-, n-IGBT (cm^{-3})
n_{bL}, n_{bR} minority carrier density at the left, right edge in the buffer layer for p-IGBT (cm^{-3})
P_{bL}, P_{bR} minority carrier density at the left, right edge in the buffer layer for n-IGBT (cm^{-3})
P_b, N_b doping concentration in the buffer layer of p-, n-IGBT (cm^{-3})
p_E, n_E minority carrier density at the drift region/emitter boundary in the emitter region (cm^{-3})
Qe, Qh total minority charge density in the drift region for p-, n-IGBT (C/cm^2)
γ_{Ep}, γ_{En} injection efficiency for p-, n-IGBT
γ'_{Ep}, γ'_{En} effective injection efficiency for p-, n-IGBT
γ_{Epmin}, γ_{Enmin} Theoretical minimum injection efficiency for p-, n-IGBT
τ_{HL} high-level lifetime in the drift region (S)
τ_{buffer} lifetime in the buffer layer (S)
W ($W = W_B - W_d$) the length of quasi-neutral region (cm)
W_B the position of the end of the drift region (cm)
W_d the position of the end of depletion region (cm)

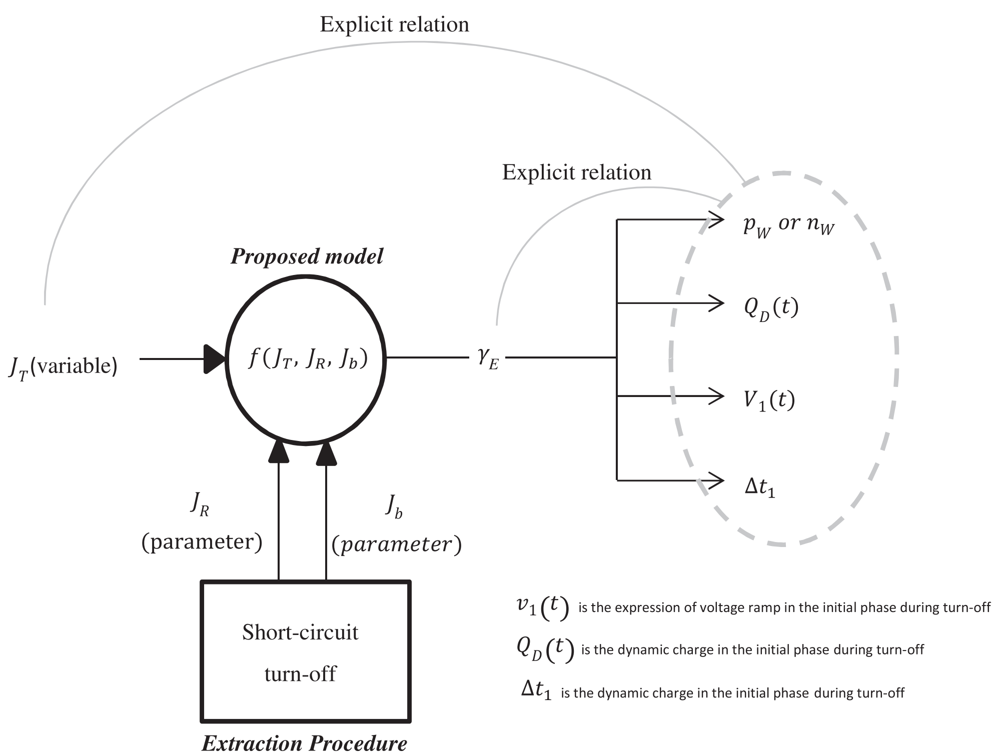

Fig. 1. The systematic depiction of this work. Once J_R and J_b are extracted for certain device, the characteristics shown in the right hand side can be analyzed in terms of either J_T or γ_E. Notice that γ_E can also be expressed in terms of J_T.

extractable parameters. Section 2.1 will discuss the relationship between γ_E and excess charge in the drift region during on-state. Section 2.2 will introduce an analytical model that predicts γ_E at given J_T. Section 2.3 will introduce a method of extracting parameters used in the injection efficiency model. Section 3.1 will directly compare the calculated results of γ_E and $n_W(p_W)$ in 4H-SiC p(n)-IGBT to the simulations in order to validate the model. An analytical model will also be derived in Section 3.2 to explain the relationship between γ_E and the turn-off speed (or charge extraction rate) in the initial phase before punch-through during clamped inductive load turn-off. Synopsys TCAD is used to validate the results predicted by the model, since the boundary quantities such as injection efficiency and boundary concentration can only be directly observed in the software. 4H-SiC p and n-IGBT will be