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The Carriers-Redistribution Phenomenon on Short-Circuit Oscillations of IGBTs

Rui Li[1], Keqiang Ma[1], Siliang Wang[1], Min Hu[1]

[1] Chengdu Semi-Future Technology Co., Ltd., China

Corresponding author: Siliang Wang, wangsl@fusemi.cn

Abstract

In this paper, the high-frequency short-circuit oscillations of IGBT are investigated. The short-circuit phenomenons of the 1.7-kV IGBT are simulated by TCAD. It is found that the carriers-redistribution (CR) phenomenon occurs in some areas of the device during the short-circuit phase. The CR phenomenon will cause the local electric field and the local capacitance to mutate, resulting in the *RLC* resonance condition being satisfied, and further lead to the high-frequency short-circut oscillations of the device during the short-circuit phase.

1 Introduction

The trench insulated gate bipolar transistor (IGBT) is an important switching device in power electronic applications [1]. IGBTs are moving towards higher power density and operating frequency [2][3]. In many industrial applications, IGBT chips are usually required to have the short-circuit capability. However, high-frequency short-circuit oscillations usually occurs during the short-circuit phase, which greatly affects the application reliability of the device [4]. In this paper, the mechanisms of the high-frequency short-circuit oscillations are investigated by TCAD simulations. In order to suppress short-circuit oscillations, the corresponding measures can be taken from the peripheral circuit and the device design.

2 Structure and Mechanism

Fig. 1 shows the schematic diagram of the 1.7-kV IGBT for short-circuit simulations. The period of the cell has been marked in Fig. 1, which contains 6 pitches. Both the gate trench (GT) and the dummy gate trench (DT) are connected to the V_{GG} through the gate resistance (R_G), and the emitter trench (ET) is shorted together with the emitter metal. There are no conductive channels on both sides of the DT. The depth of the trench (T_1) is 5 μm, the total thickness of the device (T_2) is 180 μm, and the width of the pitch is 3 μm. In the *x* direction, the points A, B and C are all on the median line between the GT and the ET. In the *y* direction, the point A is 0.1 μm below the trench, the point C is 5 μm above the collector metal on the back, and the point B is at the midpoint between the point A and the point C.

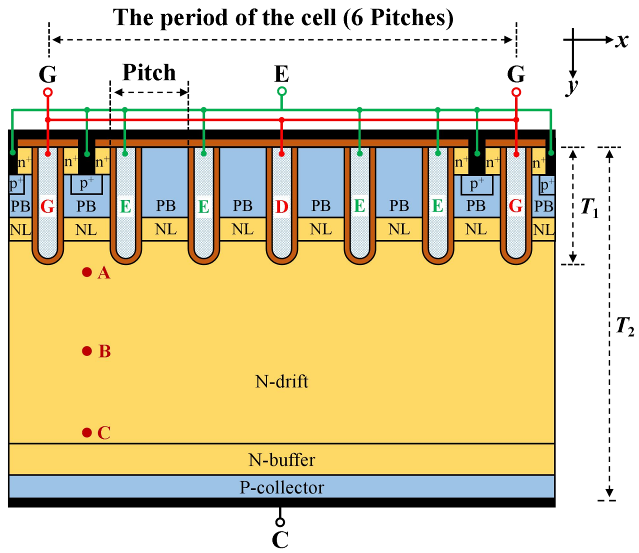

Fig. 1. Schematic diagram of 1.7-kV IGBT for the short-circuit simulations.

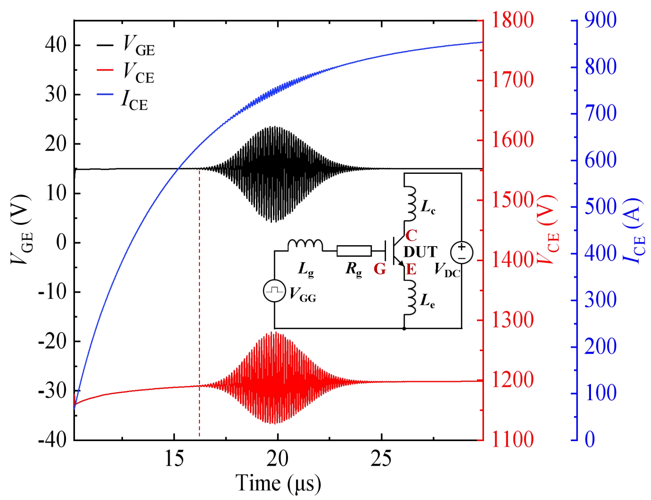

Fig. 2. Short-circuit simulation of the 1.7-kV IGBT at V_{DC} = 1200 V.

3 Test and simulation Results

Fig. 2 shows the short-circuit simulation of the 1.7-kV IGBT at V_{DC} = 1200 V. The inset in the Fig. 2 shows the TCAD simulation circuit for the short-circuit simulations. The gate resistance (R_g) and the gate inductance (L_g) are set to 1 Ω and 150 nH, respectively. The collector inductance (L_c) and the

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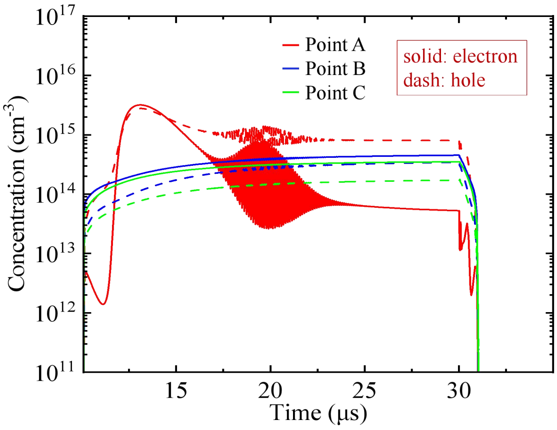

Fig. 3. The carrier concentrations at points A, B, and C during the short-circuit phase.

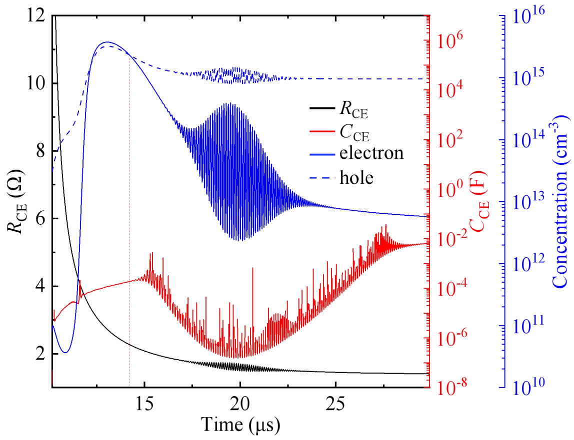

Fig. 4. Collector-emitter resistance (R_{CE}) and capacitance (C_{CE}) and the carrier concentrations at the point A during the short-circuit phase.

emitter inductance (L_e) are set to 200 nH and 30 nH, respectively. The device under test (DUT) in Fig. 2 is the 1.7-kV IGBT in Fig. 1. The short-circuit simulation starts at 10 μs and ends at 30 μs. The high-frequency short-circuit oscillations occurs at about 15.8 μs. The maximum amplitude of V_{GE} is about 11 V, and the maximum amplitude of V_{CE} is about 80 V. The oscillation of I_{CE} is obviously weaker than that of V_{GE} and V_{CE}. The oscillation waveforms of V_{GE} and V_{CE} show the spindle shape, and the time when the maximum amplitude appears is about 20 μs.

Fig. 3 shows the carrier concentrations at points A, B, and C during the short-circuit phase. The electron and hole concentrations at B and C don't oscillate. As time goes on, for points B and C, the electron concentrations (n_{PA}) are always greater than the hole concentrations (p_{PA}) during the short-circuit phase. The n_{PA} and the p_{PA} at point A also show spindle oscillations during the short-circuit phase. As time goes on, for the n_{PA} and the p_{PA} at the point A, (p_{PA}-n_{PA}) change from (p_{PA}-n_{PA}) > 0 to (p_{PA}-n_{PA}) < 0 and then to (p_{PA}-n_{PA}) > 0. This phenomenon at the point A is called the carriers-redistribution (CR) phenomenon.

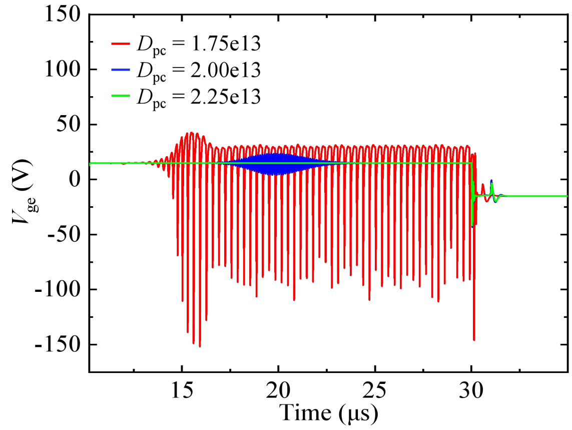

Fig. 5. The effect of the dose of p-collector (D_{pc}) on the short-circuit oscillations.

$$R_{CE} = \frac{V_{CE}}{I_{CE}} \tag{1-1}$$

$$C_{CE} = \frac{dQ_{CE}}{dV_{CE}} = \frac{dQ_{CE}/dt}{dV_{CE}/dt} = \frac{I_{CE}}{dV_{CE}/dt} \tag{1-2}$$

$$\frac{dE}{dx} = \frac{q}{\varepsilon}\cdot(p_{PA} - n_{PA} + N_D - N_A) \tag{1-3}$$

$$\lambda = \frac{R_{CE}}{2}\cdot\sqrt{\frac{C_{CE}}{L_C}} \tag{1-4}$$

Collector-emitter resistance (R_{CE}) and collector-emitter capacitance (C_{CE}) can be calculated according to equations (1-1) and (1-2). Fig. 4 shows the variation trend of R_{CE}, C_{CE} and the carrier concentrations at the point A during the short-circuit phase. V_{CE} and V_{GE} oscillate at about 15.8 μs, while C_{CE} oscillates at about 14.2 μs. In the entire short-circuit phase, C_{CE} oscillates first, and the oscillation center decreases first and then increases. For the point A, since the hole concentration (p_{PA}) begins to be greater than the electron concentration (n_{PA}) at 14.2 μs, at this moment (p_{PA}-n_{PA}) changes from (p_{PA}-n_{PA}) < 0 to (p_{PA}-n_{PA}) > 0. The positive and negative transformation of the device local (p_{PA}-n_{PA}) is the carriers-redistribution (CR) phenomenon. According to equations (1-2), (1-3) and (1-4), the CR phenomenon will lead to local electric field and capacitance mutations, which allows the local region to satisfy the *RLC* resonance condition (λ < 1). Local changes can lead to the global capacitance mutations and the high-frequency short-circuit oscillations.

Fig. 5 shows the effect of the dose of p-collector (D_{pc}) on the short-circuit oscillations. When the D_{pc} = 1.75×10^{13} cm^{-2}, the V_{ge} oscillates significantly, reaching a minimum value of -150 V and continuing until the end of the short circuit (at 30 μs moment). When the D_{pc} = 2.00×10^{13} cm^{-2}, the oscillation waveform of V_{ge} shows

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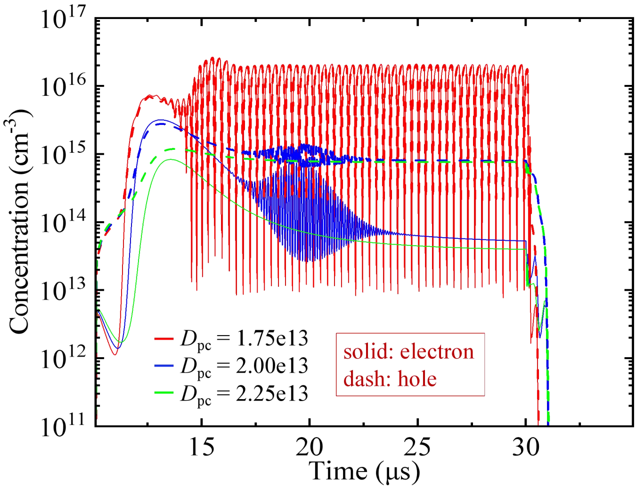

Fig. 6. The distributions of the carrier concentrations at the point A under different D_{pc}.

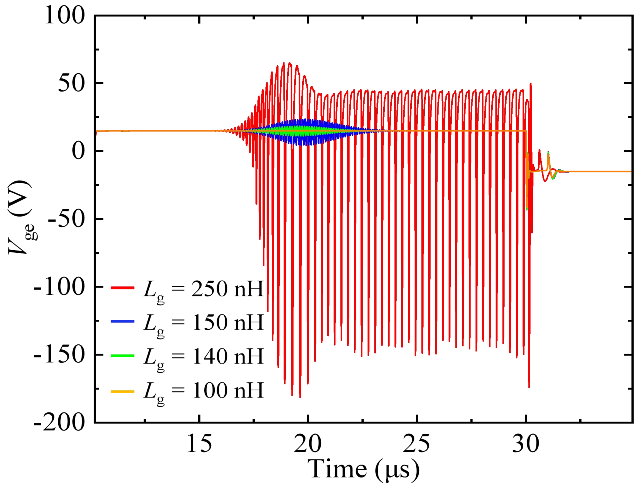

Fig. 8. The effect of the gate inductance (L_g) on the short-circuit oscillations.

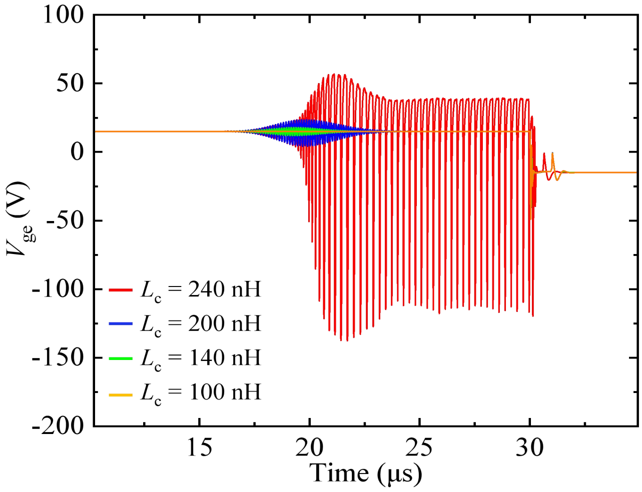

Fig. 7. The effect of the gate inductance (L_c) on the short-circuit oscillations.

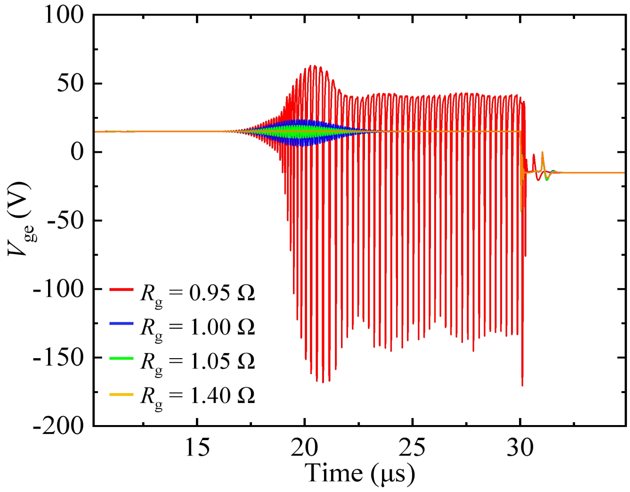

Fig. 9. The effect of the gate resistance (R_g) on the short-circuit oscillations.

a spindle shape, and the oscillations duration is significantly shorter than that when the D_{pc} = 1.75×10^{13} cm^{-2}. When the D_{pc} = 2.25×10^{13} cm^{-2}, the short-circuit oscillations does not occur. With the increase of D_{pc}, short-circuit oscillations can be significantly suppressed or even eliminated.

Fig. 6 shows the distributions of the carrier concentrations at the point A under different D_{pc} on the short-circuit oscillations. When the D_{pc} = 1.75×10^{13} cm^{-2} and 2.00 × 10^{13} cm^{-2}, local (p_{PA}-n_{PA}) positive and negative transitions will occur at the point A on the short-circut phase. When the D_{pc} = 2.25×10^{13} cm^{-2}, the hole concentration and electron concentration of the point A are always (p_{PA}-n_{PA}) > 0 during the duration of the short-circuit simulation. The CR phenomenon does not occur inside the device. With the increase of the D_{pc}, the number of the holes injected on the collector side of the device will increase, which will make (p_{PA}-n_{PA}) > 0. In this case, there is no CR phenomenon inside the device, and there is no short-circuit oscillations.

Fig. 7 and Fig. 8 show the effects of the collector inductance (L_c) and the gate inductance (L_g) on the short-circuit oscillations. Fig. 9 shows the effect of the gate resistance (R_g) on the short-circuit oscillations. With the decrease of L_c and L_g, it can be found that the short-circuit oscillations are significantly weakened. When L_c and L_g are reduced to a certain value, short-circuit oscillations can be completely eliminated. With the increase of R_g, it can be found that the short-circuit oscillations are significantly weakened. When R_g are increased to a certain value, short-circuit oscillations can be completely eliminated. Due to the decrease of inductance (L) and the increase of resistance (R) in the *RLC* resonant circuit, the damping coefficient λ will also increase, thus weakening the oscillations or even eliminating the oscillations.

4 Conclusion

The reasons of the short-circuit oscillations are not single, and are closely related to the peripheral circuit

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and the device design. For the peripheral circuit, reducing the parasitic inductance (L_g and L_c) and increasing the resistance (R_g) can effectively suppress the short circuit oscillations. For the device design, it is necessary to suppress the carrier redistribution (CR) phenomenon from the device design, that is to avoid the positive and negative transition of (p_{PA}-n_{PA}) in the short-circuit process. With the increase of the dose of p-collector (D_{pc}), the hole injection on the back can be increased, and the CR phenomenon inside the device can be effectively suppressed, so as to suppress the short circuit oscillations.

5 References

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