Research High Temperature Characteristics of 4.5kV New Power Semiconductor Device with Wave-based RC-GCT Structure

Bo Zhao, Xianghua Luo, Chuan Tang, Qingchao Song, Lifu Lu, Baobo Xu
Xi'an High Voltage Apparatus Research Institute Co., Ltd.; Qingdao Shang Ke High Voltage Apparatus Research Institute Co., Ltd.; Shandong Taikai Disconnectors Co., Ltd.; Shandong Taikai High Voltage Switchgear Co., Ltd.
Xi'an, China; Qingdao, China; Taian, China

e-mail: 438701854@qq.com

Abstract. In this paper, the effect of temperature change on the static and dynamic characteristics of power semiconductor devices is simulated by ISE-TCAD software with 4.5 kV power semiconductor device wavy base regions RC-GCT. The results show that the forward voltage drop UF of the device increases with the increase of temperature at high current density, the forward opening and turning off time of the device becomes longer, and the trailing current increases. The results of this study have certain reference value for the design and development of IGCT for new power semiconductor devices.

1. Introduction
IGCT is a new type of power electronic device developed at the end of the 20th century to improve the gate switchable thyristor (GTO) structure and control circuit. Since RC-GCT is based on GTO structure and power MOSFET, even at higher operating frequency, the unit area devices have higher current processing capacity. In order to break the foreign monopoly technology, the electrical properties of the RC-GCT structure with wavy base region at high temperature must be solved can carry out in-depth research to achieve the localization goal of RC-GCT.

In this paper, according to the concept of wave p base area IGCT, the idea of compound isolation area is also introduced, and the improved wave base area RC-GCT device structure model is established by software ISE-TCAD simulation. The electrical characteristics of the device at high temperature are studied by simulation, and the influence of temperature on the internal parameters and characteristics of the device is analyzed and summarized.

2. Characteristics of RC-GCT structure in wave base area
The basic structure of the CP-GCT and the wave base region RC-GCT with the composite isolation zone is shown in figures 1(a) and 1(b). The wave base region RC-GCT with the composite isolation zone compared to the CP-GCT is an inversely guided CP-GCT structure, which reverses a diode on the basis of the CP-GCT. In the RC-GCT structure, the anode region of diode and the p-base region of CP-GCT are formed at the same time, which are divided into two steps: high concentration p+ region
and low concentration p-region. The composite isolation region is also formed by etching in the case of n+ blocking.

3. Analysis of high temperature characteristic of RC-GCT in wave base region

3.1. Gate characteristics
Since the J3 junction in Figure 1 is a high-doped pn junction on both sides, it can be approximated as an n+p junction. Intrinsic carrier concentration

\[ n_i = 4 \times 10^{15} \left( \frac{m^*_p}{m_0^*} \right)^{3/4} \tau_0^{3/2} \exp \left( - \frac{E_g}{2kT} \right) \]  

(1)

M0 is the stationary mass of electrons, \( m^* \) and \( m^*_n \) is the effective mass of holes and electrons, \( E_g \) is the band gap.

Figure 2 is the avalanche breakdown characteristic curve of the gate at different temperatures. As can be seen from Figure 2, when the temperature rises from 300K to 380K, the avalanche breakdown voltage increases continuously, the leakage current also becomes larger, and the breakdown characteristic is hard. The intrinsic carrier concentration of silicon increases exponentially with the increase of temperature. When the temperature is higher than 380K, the intrinsic carrier generated by the excitation is much larger than the colliding ionized carrier, and the reverse current increases substantially, especially when both sides of J3 junction are heavily doped, the band \( E_g \) width becomes smaller. As can be seen from formula (1), the intrinsic carrier concentration increases more with temperature, at which point the breakdown characteristics of the J3 junction exhibit soft characteristics.

3.2. Forward blocking characteristics
Figure 3 shows the forward blocking characteristic curves of RC-GCT in wave basal regions at different temperatures from figure 3, it can be seen that when the temperature increases from 300 k to
420 k, the blocking voltage of the device increases continuously with the increase of temperature, and the size of the leakage current also increases with the increase of the operating temperature of the device. Unlike the gate, the gate is a high-doped pn junction on both sides, and the n-base region is a low-doped region, which is the one-thousandth of the carrier concentration at the j3 junction. although the width of the depletion layer at the forward blocking state is large, the number of space charge is less when the reverse bias is large, and the electron-hole pairs produced by the avalanche multiplication are less, at this time the current density is less than J3 junction when the impact current occurs.

![Figure 3. The forward blocking characteristic of different temperature for p-base RC-GCT](image)

3.3. Forward opening characteristics

Figure 4 shows the forward opening characteristic curve and the power consumption curve in the forward opening process of the wave base region RC-GCT at different temperatures. Where figure 4(a) is the forward opening characteristic curve at different temperatures and figure 4(b) is the forward opening power consumption curve at different temperatures. As can be seen from figure 4, with the increase of temperature, the gate trigger opening time of the wave base region RC-GCT increases and the device opening time becomes longer.

The opening time of the device consists of the delay time and the rise time. The delay time is the time when the gate current rises to 10% of its peak current and the anode blocking voltage drops to 90%. In this stage, the generation of the current is mainly the diffusion current of the carrier. The factor affecting the delay time is the transition time of the minority carrier in the p-base region. With the increase of temperature, the lattice vibration intensifies and the carrier is affected by with the increase of scattering and the decrease of mobility, the transition time and the delay time become longer. The rise time is the time that the forward blocking voltage decreases from 90% to 10%. In this stage, with the continuous recombination of carriers in the n-base region, the anode current begins to rise, and the rise time is controlled by the generation recombination of carriers. The relationship between the minority carrier life and temperature can be written as follows:

\[ \tau(T) = \tau_0 \left( \frac{T}{300} \right)^n \]

A is generally taken as 2.1. From formula (2), it can be seen that the minority carrier lifetime increases with the increase of temperature, making the rise time longer.
3.4. Forward turn-off characteristics

Figure 5 is the turn off characteristic curve and power consumption curve during the turn off process of RC-GCT in wavy base area at different temperatures, where figure 5 (a) is the forward turn off curve at different temperatures, and figure 5 (b) is the forward turn off power consumption curve at different temperatures. It can be seen from figure 5 (a) that with the increase of temperature, the shutdown time of the device becomes longer, in which the storage time and the falling time are both larger. The shutdown time of the device is generally longer at the beginning of shutdown with the increase of temperature. The influence of temperature on the shutdown characteristics is most obvious at the end of shutdown during the tailing current period. It can be seen from figure 5 (b) that the shutdown time is longer and the tailing current is directly increased this results in an increase in power consumption during shut down.

3.5. Reverse conduction characteristics

Figure 6 shows the high temperature characteristic curve of RC-GCT reverse conduction in wavy base area. It can be seen from Figure 6 that with the increase of temperature, the reverse conduction curve has an intersection point...Below the intersection point, the on resistance of the device decreases with the increase of temperature, showing a negative temperature coefficient. Above the intersection point, the on resistance of the device presents a positive temperature coefficient, and the voltage at the intersection of the curve is about 0.85v. At this time, the device just turned on, below the intersection point, the device is not in a small injection state, and the carrier concentration is not too high. With the increase of temperature, the carrier mobility increases, and the on state voltage drop decreases. With
the increase of voltage, the carrier injected into the N-region of the device reaches a large injection state. After the intersection point, the carrier concentration is very high. With the increase of temperature, the scattering effect on the carrier is strengthened with the decrease of mobility, the on state pressure drop increases with the increase of temperature.

**Figure 6.** The reverse on-state characteristic of different temperature for p-base RC-GCT

3.6. Commutation characteristics

Figure 7 shows the recovery characteristic curve of RC-GCT in wavy base from reverse on to off at different temperatures. When the device is in reverse on state, the reverse on resistance of the device in large injection state has a positive temperature coefficient. With the increase of temperature, the injection efficiency is greatly reduced, which makes the on state characteristics worse, but the greatly reduced injection efficiency also reduces the amount of charge stored in the device. In many cases, the recovery characteristics get better with the increase of temperature.

**Figure 7.** The recovery characteristic of different temperature for the diode part of p-base RC-GCT

4. Conclusion

RC-GCT is a new type of power semiconductor device based on the traditional reverse gate switching thruster (RC-GCT), which is formed by the integration of RC-GCT and gate hard drive circuits, which reduces the loss and cost of the circuit, reduces the volume of equipment and improves the performance of the device. Therefore, it is of great significance to study the electrical properties of the new RC-GCT structure at normal temperature and high temperature.

In this paper, the forward opening, the forward closing, the reverse opening and the reverse closing characteristics of the RC-GCT structure in 4.5 kV power semiconductor devices at room temperature and high temperature are simulated and analyzed by ISE-TCAD software. The results show that with the increase of temperature, the intrinsic excitation increases, the gate breakdown voltage and the forward blocking voltage increase, the leakage current increases, the scattering effect increases, the carrier mobility decreases, the forward opening and the forward closing time increases, the tailing current during the forward closing period increases, the tailing time becomes longer, the on state
voltage drops in the forward and reverse directions increase, and the reverse recovery characteristic of the diode is improved, it has certain guiding significance for the later RC-GCT design.

Acknowledgments
Thanks to the support and help from experts and friends.

References
[1] Steimer P, Apeldoorn O, Carroll E, et al. IGCT technology baseline and future opportunities [J]. IEEE/PES, 2001, 2(2): 1182-1187.
[2] E. D. Kim, C. L. Zhang, S. C. Kim, et al. Design of High-Power Reverse-Conducting Gate-Commutated Thyristor. 23th International Conference on Microelectronics[C], 2002 Vol.1: 147-150.
[3] Vemulapati U, Bellini M, Arnold M, et al. The concept of Bi-mode Gate Commutated Thyristor-A new type of reverse conducting IGCT. Proceedings of 2012 International Symposium on Power Semiconductor Devices & ICs[C], Bruges: 2012: 29-32.
[4] Yan Chen, Hongjuan Zhang. Study on IGCT performance of a new power semiconductor device [J]. Journal of Taiyuan university of technology, 2001, 32 (1): 75.
[5] Enke liu, Bingsheng Zhu et al. Semiconductor physics [M]. Xi 'an: xi 'an Jiao tong university press, 1998:100.
[6] IJEETC. International Journal of Electrical and Electronic Engineering & Telecommunications.ISSN: 2319-2518. Abstracting/Indexing: Scopus (since 2017), Google Scholar, Crossref, Citefactor, etc. http://www.ijeetc.com/
[7] H. Goebel, K. Hoffmann. Full dynamic power diode model including temperature behavior for use in circuit simulators [J]. Power Semiconductor Devices & ICs, (Tokyo), 1992:130-135.