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Design Concept for Key Parameters of Reverse Conducting GCT

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Abstract: Presented is design concept for key parameters of the reverse conducting gate commutated thyristor (RC-GCT), such as the thickness and concentration of n-base region and the transparent anode region, and the width of separation region between asymmetric GCT and PIN diode. A structure model of the RC-GCT is set up based on the design concept and its characteristics are analyzed. The simulation results show the design concept is reasonable.

Key words: power semiconductor device; reverse conducting gate commutated thyristor; transparent anode; separation region

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1 Introduction

In new power semiconductor devices, integrated gate commutated thyristor (IGCT) has been a key device for the transportation systems and other high-power applications[1]. The IGCT is the combination of the GCT device and a low inductance gate unit. The GCT is the die of IGCT, in which successfully combines the merits of thyristor and transistor characteristics, while fulfilling the additional requirements of manufacturability and high reliability. IGCT shows many advantages in applications, but the theoretical concept of design basis for the GCT still needs to be worked on. In this paper, for example, as a 2500V/2000A reverse conducting GCT (RC-GCT), the design concept for key parameters of the RC-GCT device is given by investigating its characteristics. A RC-GCT's structure model is set up based on the design concept and its blocking characteristic, conducting characteristic, and the reverse characteristic of gate-cathode junction are analyzed by using the Avanti-MEDICI simulator. The results show that the design concept is reasonable.

2 RC-GCT structural and operational features

The vertical structure of the RC-GCT derived from the reverse conducting gate turn off thyristor is composed of a $p^+nn^-pn^+$ five layers thyristor (called asymmetric GCT) and a PIN diode anti-paralleled integrated in single wafer as shown in Fig. 1[2]. The key techniques of the RC-GCT include (1) the anode is a transparent emitter; (2) the introduction of a n-buffer layer between n^- base region and p^+ transparent anode region; (3) a reverse conducting technique. These improved structures enable the GCT to possess high blocking characteristic, fine conducting characteristic, and quick switching characteristic at the same time.

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Therefore, the power dissipation during conducting and turn off is very low.

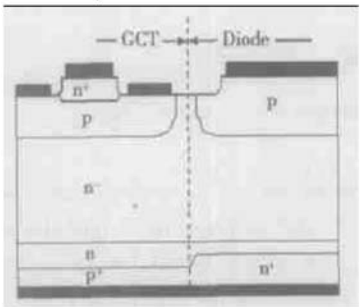

Fig. 1 Basic structure of the RC-GCT

The operation of the RC-GCT is conducting at both directions of forward and backward. When the RC-GCT operates at forward bias, its characteristic is similar to gate turn-off thyristor (GTO) during blocking and conducting but differs to GTO during turn off. It behaves like an open-base pnp transistor at turn-off. When the RC-GCT operates at backward bias, its characteristic is similar to PIN diode. Thereby it has the common advantages of GTO, insulated gate bipolar transistor (IGBT), and PIN.

3 Design concept of key parameters of RC-GCT

Based on above analysis, the design method for the key structure parameters of the RC-GCT can be described from three aspects as below.

3.1 Design of the n^- base region

The n^- base region determines the device's blocking characteristic and conducting characteristic. In order to compromise the relation of breakdown voltage and the forward voltage drop, the concentration and thickness of n^- base region must be optimized. Because the n buffer layer exists in the RC-GCT, a punch through (PT) type endurance voltage structure with $p^+nn^-pn^+$ five layers is adopted in the design. Compared with a non-punch through (NPT) structure, it can obtain higher breakdown voltage at same thickness of n^- base region. Based on analyzing the breakdown voltage for PT type structure[3], the breakdown voltage U_{BR} can be expressed as

$$U_{BR} = E_{BR}W_{n^-} - \frac{qN_BW_{n^-}^2}{2\epsilon_0\epsilon_r} \quad (1)$$

where E_{BR} is the critical breakdown field, which is related to the doping concentration of n^- base region and expressed as[4]

$$E_{BR} = 4010N_B^{1/8} \quad (2)$$

Substituting (2) into (1), the calculation formula of RC-GCT's breakdown voltage U_{BR} is derived

$$U_{BR} = 4010N_B^{1/8}W_{n^-} - \frac{1}{2}\times\frac{qN_BW_{n^-}^2}{\epsilon_0\epsilon_r} \quad (3)$$

where W_{n^-} is the thickness of the n^- base region, and N_B is the doping concentration of the n^- base region.

In practice process, in order to reduce the device's cost, the original material resistivity is as low as possible. Based on the formula (3), 180Ω·cm and 200μm are chosen for the resistivity and thickness of n^- base region respectively for 2500V/2000A RC-GCT, which off-state non-repetition peak voltage is about 2800V.

3.2 Design of transparent anode region

The transparent anode region is a key of the RC-GCT. The anode region doping profile is determined by the hole injection during conducting and the rate-of-rise of anode voltage during turn-off. The thicker and higher doping of the anode region is helpful to the conducting characteristic, but turn-off characteristic is deteriorated. Therefore, the design of the transparent anode region must take account of the device's conducting characteristic and turn-off characteristic at the same time.

Because conducting GCT behaves like PIN diode, the carrier concentration or voltage drop during conducting is determined by the doping concentration and thickness of the p^+ transparent anode region and n^+ cathode region. Reducing the p^+ transparent anode region impurity dose (Q_P) is helpful to control the hole number injected into n^-

base region to shorten turn-off time, but too small Q_P will result in the bulk voltage drop increasing. Therefore, the thickness and doping concentration of the p^+ transparent region must be optimized based on analysis of the conducting characteristic of PIN diode, and the relation of the thickness and the impurity dose of the transparent anode region must fulfill the formula[5]:

$$d_E \leqslant 1.7 \times 10^{-9} Q_P^{2/5} \tag{4}$$

where d_E is the thickness of anode region and its unit is μm; Q_P is impurity dose of the p^+ transparent anode region and its unit is cm^{-2}, which determines the doping concentration of the anode region after redistribution.

Based on above design concept, the doping concentration and thickness of the p^+ transparent anode region for 2500V/2000A RC-GCT is about $10^{18}cm^{-3}$ and 5μm, respectively.

3.3 Design of separating region

Because the RC-GCT is composed of an asymmetric GCT and a PIN diode anti-paralleled integrated in single wafer, a separation exists between the asymmetric GCT and PIN diode. The design of the width of separation region in the RC-GCT is very important. In particular, during the commutating of the RC-GCT, that is, from the conducting of the PIN diode to the blocking of the asymmetric GCT, if the width of separation region is too small, it will lead to commutating failure; if the width of separation region is too large, it will lose effective cathode areas. So special design must be taken at the boundary between the asymmetric GCT and the PIN diode. In this paper, a pnp separation region is adopted. The advantages of the pnp separation region are very low negative gate currents and high blocking stability; and the area consumed by the pnp separation structure is very small, resulting in an optimized use of the wafer area. This structure is implemented by a complete separation of both p-diffusion. The resulting pnp structure is designed to a blocking voltage in each direction, preventing any significant current between the asymmetric GCT's gate and the PIN diode's anode.

Based on above analysis, the calculation formula of the width of separation region (W_S) is given by us:

$$W_S = W_D + L_P + 2L_J \tag{5}$$

where W_D is the width of the depletion layer in n^- base at breakdown voltage of the gate-cathode junction; L_P is the diffusion length of minority carrier, which is about 1/3 of W_D; L_J is the lateral diffusion depth of p-type impurity, which is about 80% of its junction depth.

The width of separation region is about 200μm for 2500V/2000A RC-GCT based on above design concept.

4 Simulation results and analysis

Based on above analysis results, a RC-GCT's structure model is schemed as shown in Fig. 2. Seen from this figure, the asymmetric GCT with 6-ring cathode units is located in the inner of wafer and the PIN diode is located in the external of wafer. So does this design for two reasons, one is to ensure the GCT's cathode surface uniformly enduring press; another is to simplify the bevelling required to terminate protection, in which only a bevel angle needs to be done. In order to obtain same current during forward and backward conducting, the GCT cathode's effective area is designed to be same with the PIN anode's area. The doping distribution of the RC-GCT used in simulation is shown in Fig. 3.

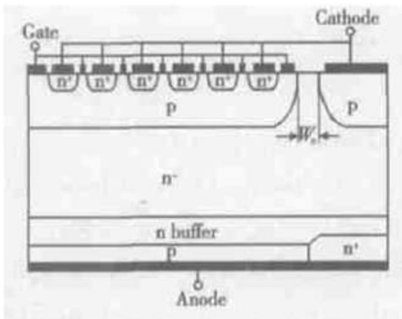

Fig. 2 Profile of the RC-GCT structure model

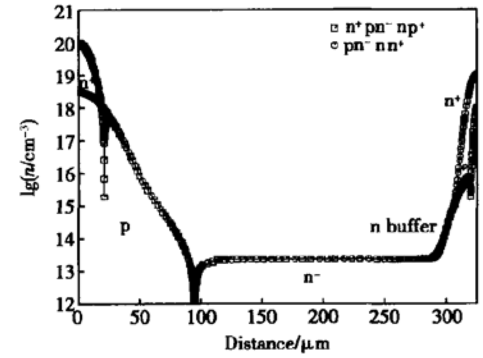

Fig. 3 Doping profile used in simulation

Based on structure model above, the RC-GCT forward blocking characteristic, conducting characteristic, and the reverse characteristic of gate-cathode junction are analyzed using MEDICI simulator[6] in which the electrons and holes current-continuity equations and Poisson equation are solved simultaneous with the finite element method.

4.1 Blocking characteristic

The blocking characteristic curves of the RC-GCT and PIN diode are shown in Fig. 4 and Fig. 5, respectively. From two figures, the forward break-

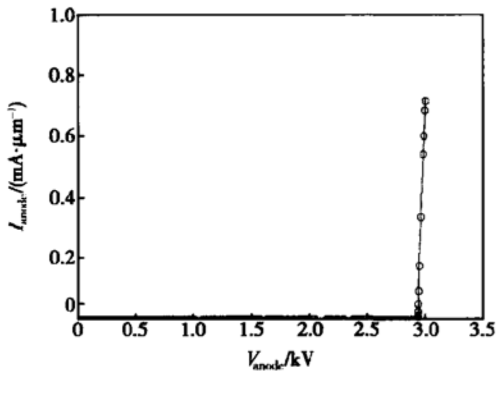

Fig. 4 Forward blocking characteristic of the RC-GCT

down voltage of the RC-GCT can be reached to 2800V, and the backward breakdown voltage of PIN diode can be also reached to 2800V. This is because the parameters of n^- base region are the same for the asymmetric GCT and the PIN diode. Thereby, the simulation results show that the design for n^- base region is reasonable.

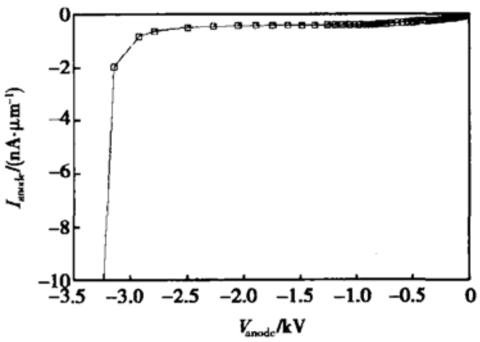

Fig. 5 Backward blocking characteristic of the PIN diode

4.2 Conducting carrier distribution

In order to analyze the effect of the transparent anode region on the conducting characteristic of the RC-GCT, the carrier distribution during forward conducting is shown in Fig. 6 and the carrier distribution during backward conducting is shown in Fig. 7. Comparing two figures, it is seen that the carrier distribution of the RC-GCT after turning on

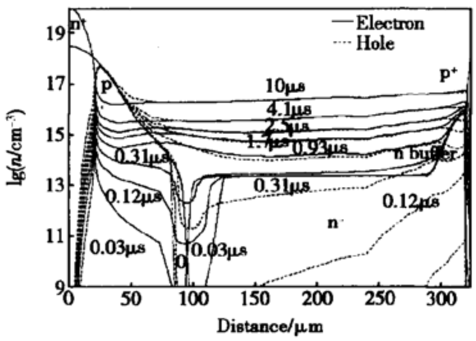

Fig. 6 Carrier distribution of the RC-GCT during conducting

about 1μs is similar to that of a conducting PIN diode, and the carrier concentration located in transparent anode is lower and the carrier concentration located in the center n^- layer for GCT is obviously higher than that of PIN diode during conducting. This shows that the conducting characteristic of the RC-GCT is better than that of PIN diode and the lower carrier concentration located in transparent anode is helpful to the device's turn off. So the transparent anode used in practice RC-GCT device is helpful to improve conducting characteristics and turn off characteristics at the same time. Thereby, the design that conducting GCT is equivalent to PIN diode is reasonable.

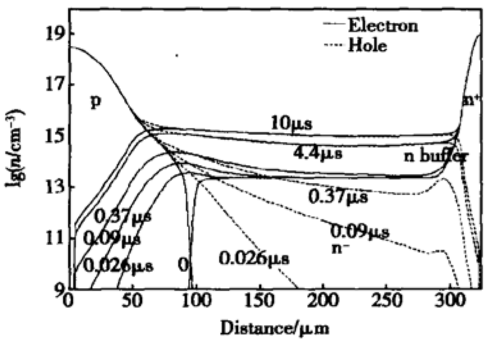

Fig. 7 Carrier distribution of the PIN diode during conducting

4.3 The gate-cathode junction′s reverse characteristic

To demonstrate the performance of the pnp separation region, the reverse characteristic of the gate-cathode junction of the RC-GCT is simulated, the result is shown in Fig. 8, in which the gate current is expressed in milliampere per micrometer the width of device. Seen from this figure, as described in above section, there is no resistive contribution

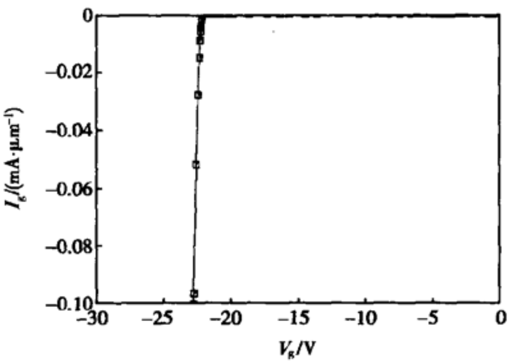

Fig. 8 Reverse characteristic of gate-cathode junction of the RC-GCT

from the separation region. The leakage current is very low at the avalanche breakdown of the gate cathode junction, which is about 22V. Thereby, the result shows that the design for the width of separation region of the RC-GCT is reasonable.

5 Conclusion

In this paper, the RC-GCT′s structure and operating principle is analyzed briefly; the design concept of its key structure parameters is presented. A structure model of the RC-GCT is set up based on the design concept, and the forward blocking characteristics, conducting characteristics, and the gate-cathode junction′s reverse characteristic of the RC-GCT device are analyzed by using MEDICI simulator. The simulation results verify the correctness of the design concept.

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逆导型 GCT 关键参数的设计考虑

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摘要: 提出了逆导型门极换流晶闸管(RC-GCT)中几个关键参数, 如 n^- 基区和透明阳极的厚度和浓度及隔离区的宽度等参数的设计方法. 根据该设计方法建立了 RC-GCT 的结构模型, 利用 MEDICI 模拟器对其正向阻断特性、导通特性及门-阴极的反向特性进行了模拟分析, 结果证明这些设计考虑是合理的.

关键词: 电力半导体器件; 逆导型门极换流晶闸管; 透明阳极; 隔离区

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