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Advanced Junction Terminal Technology of Ultra High Voltage Thyristor

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Abstract

The advantages and disadvantages of traditional thyristor`s junction terminal technology are analyzed. Based on double negative angle modeling, a new technology is developed with radial variable doping and mesa shape modification. The technology minimized the chip thickness and the junction terminal structure length on chip, as well as maximized the effective conduction length of device. Three different samples of junction terminal structure technology were manufactured and tested. The results indicate that the samples using the new technology has a smaller leakage current (2.50mA) without reducing blocking voltage (⩾ 8000V) and a smaller on-state voltage drop (1.782V) under flowing the same on-state current (4500 A). Moreover, reverse recovery charge, dv/dt tolerance, di/dt tolerance and turn-off time get fully optimized. The 6-inch (1inch=2.54cm) ultra-high voltage thyristor (4500A/8500V) was successfully developed, and its dynamic characteristic and parameter consistency fulfill the design and application requirement.

Keywords: junction terminal; radial variable doping; mesa shape modification; blocking voltage; on-state current capacity; on-state voltage drop

1 Introduction

The ultra-high voltage thyristor [1] (4500A/85000V) is the key device of VSCs in the UHVDC transmission [2] project (± 800KV/7200MW) in China. The main technical targets of UHV thyristor include blocking voltage (≥8500V), on-state current capacity (≥4500A) and on-state voltage drop (≤1.75V).

The shape of junction in thyristor terminal [3] area is different from that in body. The shape of body junction is parallel plane. While the shape of terminal junction gets distorted due to the outside interruption. The distortion will cause the electric field of junction terminal area (known as surface electric field) to be concentrated. Then the surface breakdown voltage will drop. Therefore, the breakdown voltage of terminal junction is usually lower than that of body junction. To help solve this problem, many kinds of junction terminal modeling technology are specifically developed. These technologies try to make the breakdown voltage of the device close to the ideal breakdown voltage of parallel-plane junction. The improvement is related to process parameters control such as doping and molding of semiconductor devices. How to perform terminal doping and molding in a thyristor with multiple junctions, to obtain equal extremely high forward and reverse breakdown voltage, is an important issue in the study of UHV thyristors.

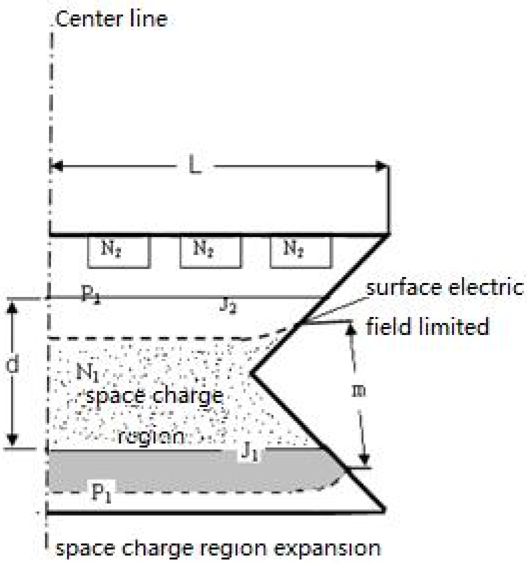
At present, there are several first-class junction terminal technologies of UHV thyristor in the world. Mitsubishi Corporation developed double positive angle junction terminal technology and created 6-inch UHV light-controlled thyristor (3600A/8000V), successfully applied in KII waterway DC transmission project; Infineon used positive and negative angle junction terminal technology to manufacture 5-inch light-controlled thyristor (3000A/7600V), successfully applied in Gui-Guang transmission project; ABB created 5-inch thyristor (3000A/7200V) through double negative angle junction terminal technology and it is successfully applied in the Three Gorges transmission project. This paper introduces a new junction terminal technology that overcomes the shortcomings of the technologies mentioned above. The test results of thyristors with different junction terminal techniques show the superiority of this technology. By adopting this technology， 6-inch UHV thyristors (4500A/8500V) were successfully developed and applied in the HVDC transmission project in China.

2 Analysis of Junction Terminal Modeling of Thyristors

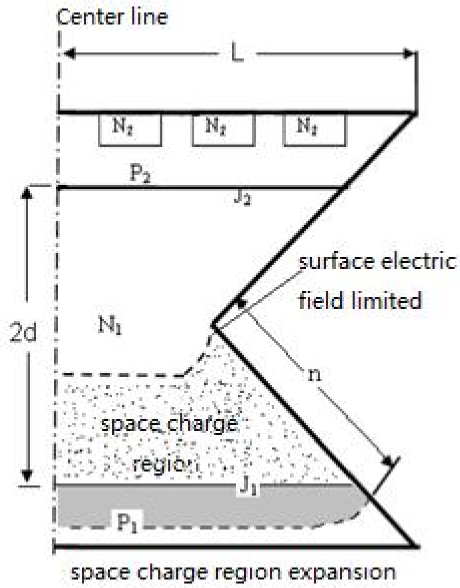
2.1 Double positive angle modeling

Double positive angle modeling [4] can increase the effective conduction area of the chip. However, according to the theory of semiconductor devices [5], the surface electric field of devices with double positive angle shape is limited in the middle of the long base region, causing the electric field concentrated and the blocking voltage decreased. Only when the long base region is doubled can the problem be eliminated. As a result, a wider long base region is required to keep the voltage constant, but the on-state current capacity is reduced due to thicker chip.

Figure 1 compares the space-charge regions of different long base regions under the same reverse voltage. In the pictures below: L is the radius of the effective conduction region; d is the width of the single long base region and 2d is the width of the double long base region; N2 is the cathode emission region; P1 is the anode emission region; P2 is the short base region; J1 and J2 are the PN junctions; N1 is the long base region; m is the space charge region expansion width of the junction terminal at a specific voltage when the long base region width of the device is d. n is that at the same voltage when the long base region width of the device is 2d. Mitsubishi Corporation adopted the junction terminal technology showed in Figure 1 (b), creating the 6-inch UHV light-controlled thyristor (3600A/8000V) [6].



(a) Single long base region width



(b) Double long base region width

Fig.1 Space charge region widening schematic diagram of different long base widths under the same reverse voltage

2.2 Positive and negative angle modeling

According to the theory of semiconductor devices, the boundary conditions of forward and reverse blocking junctions are different. Under the negative oblique angle condition, the width of the long base region determined by specific forward blocking voltage [7] is not enough to withstand the same reverse voltage under the positive oblique angle condition. The reason is that in the case of reverse blocking, due to the warpage of the space charge region boundary on the surface, the boundary gets closer to the junction J2 (shown in Figure 2), which increases the current amplification factor α_2 of $N_1P_2N_2$ and reduces the blocking voltage at the junction J2 terminal. In addition, the positive and negative oblique angle modeling [8] will reduce the effective conduction area cumulatively. To keep the forward and reverse voltage equal, the device needs additional long base width to reduce the influence of α_2. The increase of the thickness will also cause the decrease of the on-state current capacity. However, for the simple process, most 5-inch thyristors (below 6500V) are made based on this technology.

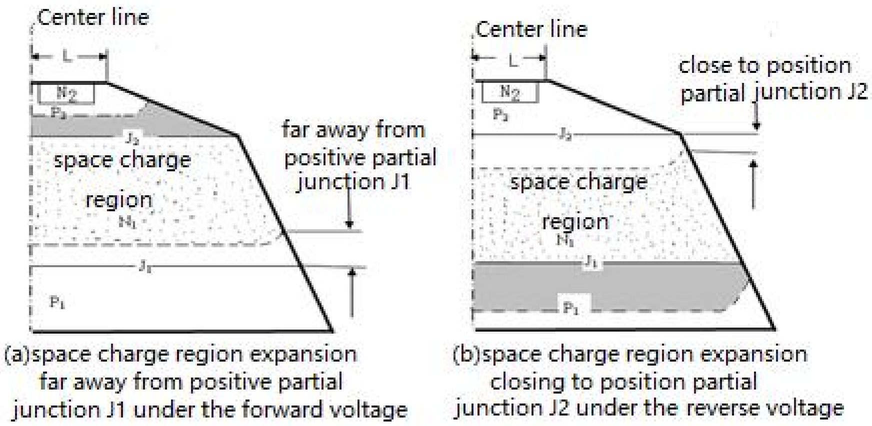


Fig.2 Space charge region widening schematic diagram of the position and negative angle modeling under the same forward and reverse voltage

2.3 Double negative angle modeling

It's known from the theory of semiconductor devices that only when the device have the double negative angle modeling [9], can the warpage of the space charge region boundary on the surface be far away from junctions J1 and J2 respectively under the forward and reverse blocking conditions (shown in Figure 3). And α_1 and α_2 are reduced (α_1 and α_2 are the current amplification factors on the surface of the transistors $P_1N_1P_2$ and $N_1P_2N_2$ respectively). The width of the long base required for the certain breakdown voltage is determined by the one-dimensional calculation, and the forward and reverse breakdown voltages are symmetric [10]. Therefore, this technology can be used to optimize the overall electrical characteristic parameters of thyristors. Swiss ABB adopts this technology to manufacture 5-inch thyristors (3000A/7200V)

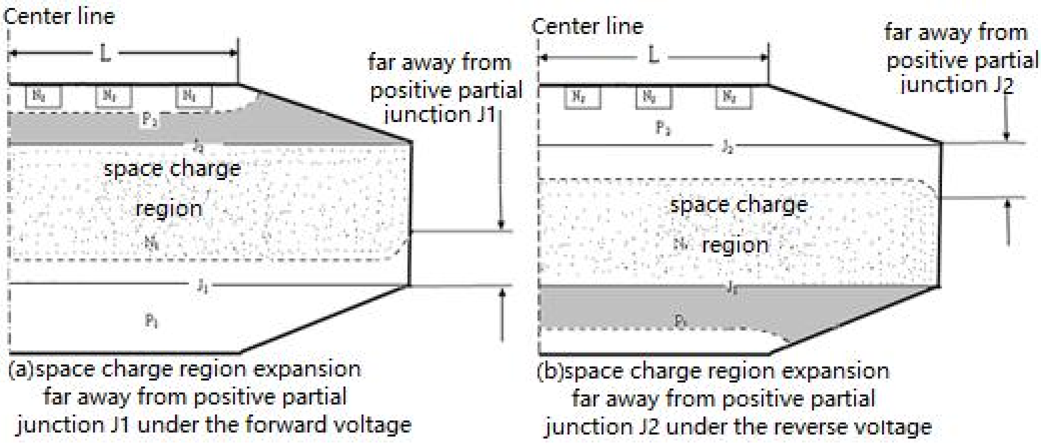


Fig.3 Space charge region widening schematic diagram of the double negative angle modeling under the same forward and reverse voltage

3 Radial Variable Doping Technology

According to the working principle of thyristors [11], the conduction region must be able to withstand high voltage and flow large current. Besides, other electrical dynamic characteristics, such as di/dt, dv/dt and recovery charge, also need to be taken into account. Therefore, there must be low-concentration P-type impurities of certain thickness (P_1 base region) in the conduction region to meet the high blocking voltage requirement in the body, and high-concentration P-type impurities of specific thickness on P_1 to form P_2 base region. And the sheet resistance of P_2 can match the gate, the amplified gate and the short-circuit point to meet the requirements of large on-state current and electrical dynamic characteristics.

The only requirement for the junction terminal is high blocking voltage, so the P-type impurity should be kept at rather low concentration by deep diffusion. The traditional doping technique is to diffuse high-concentration P-type impurities after deep diffusion of low-concentration P-type impurities. In this method, high-concentration doping impurities will cover the low-concentration doping ones. As a result, the width of the depletion layer is not wide enough to block certain voltage in the junction terminal (shown in Figure 4). In Figure 4, W_{OM} is the extended width of high-concentration side of the depletion layer at the junction terminal when the device is under a blocking voltage of 8500V; W_1 is the actual extended width (<W_{OM}) due to the cover of high-concentration P-type impurity at the junction terminal. Therefore, when the same voltage is applied, the electric field peak of W_1 is higher than that of W_{OM}, causing the breakdown voltage of W_1 lower than that of W_{OM}. In order to eliminate this effect, additional short P base depth (ΔW_P) is needed to ensure the junction terminal depletion layer width W_{OM}, then the device can block target voltage (8500V) capability. As a consequence, the device thickness is increased and the current-flow capacity is decreased. Moreover, the device loses the conduction length ΔL due to increased depth of the short P base region at the same negative angle, which is shown in Figure 5.

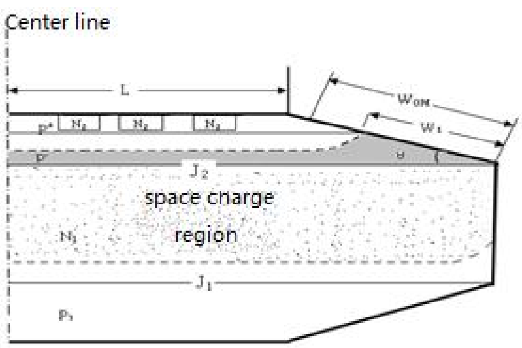


Fig.4 Space charge region widening schematic diagram under the forward voltage

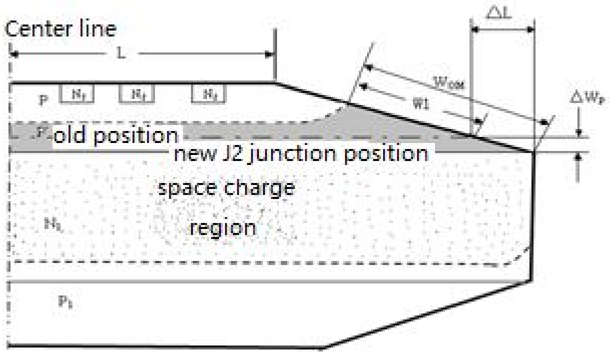


Fig.5 Conduction length loss schematic diagram under the forward voltage

In order to solve this contradiction effectively, the radial doping technique [12] was proposed based on the traditional double negative modeling junction terminal. This technique is to maintain low-concentration P-type deep diffusion doping impurities in the junction terminal without changing the doping structures in the body by a special doping method. Using radial doping technology, the device can block specific voltage (8500V) without the influence of high-concentration P-type impurities in the junction terminal, as shown in Figure 6.

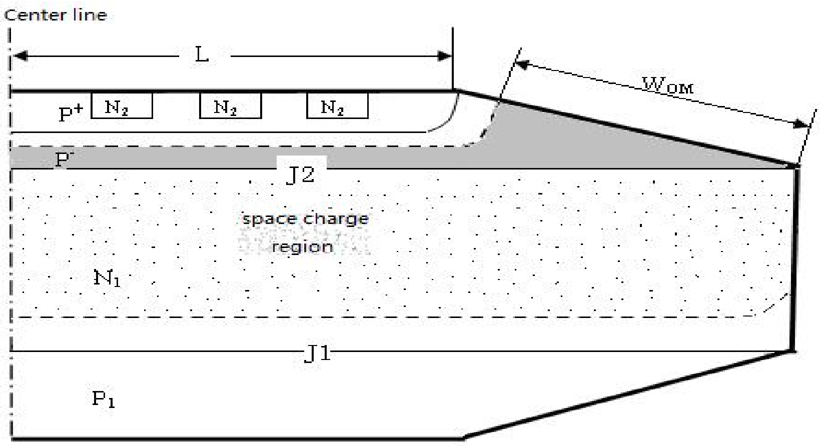


Fig.6 Space charge region widening schematic diagram of using radial variable doping technique under the forward voltage

Therefore, this structure helps the junction terminal maintain low-concentration P-type deep diffusion impurities, which satisfies the need of depletion layer expansion for high blocking voltage. Meanwhile the body possesses both high and low concentration P-type impurities. The low-concentration impurities are located in the lower layer, satisfying the need for the high blocking voltage in the body and the high-concentration impurities are located in the upper layer to coordinate with the characteristics of the gate, the amplified gate and the short-circuit point. Through the comparison between Figure 5 and Figure 6, it can be seen that under the same blocking voltage, the thickness of radial variable doping device is reduced by

ΔW_P and the effective conduction length is increased by ΔL, so that the on-state voltage drop is reduced and the on-state current capacity is improved.

4 Mesa Shape Modification

The negative bevel shape [13] can reduce the surface electric field effectively and restrict the breakdown of the body only when it is at a small angle between 3-5°. Despite the radial variable doping technique is implemented effectively, the traditional negative angle shaping still loses a large number of effective conduction lengths. To solve this problem, the negative angle modeling of the mesa is modified. This new kind of shaping is to keep the negative angle at a small angle in a local area, and then to increase it gradually. As shown in Figure 7, in this structure, the radial variable doping technology is firstly performed to ensure the low-concentration doping impurities in the junction terminal; and then the new kind shape of mesa is implemented, which guarantees the negative angle. This technique maximizes the effective conduction length at a specific blocking voltage (8500V) at the same time that it guarantees the depletion layer width W_{OM} required for charge extension in the junction terminal. Therefore, this kind of junction terminal shape is the best terminal structure of the UHV thyristors.

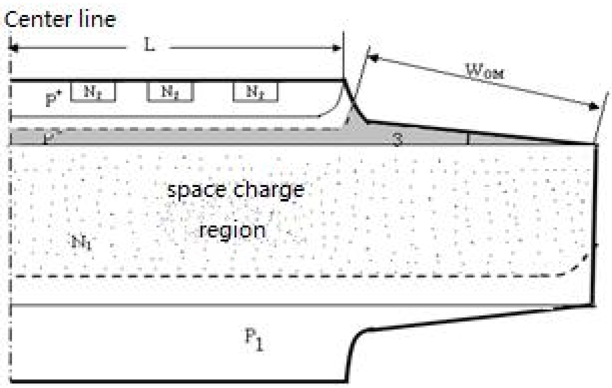


Fig.7 Space charge region widening schematic diagram of the mesa negative angle modeling under the forward voltage

5 Design and Verification

In order to verify the advantages of the techniques proposed, several kinds of 6-inch UHV thyristors (8500V) were manufactured using different junction terminal techniques. The schematic diagram of these thyristors made by different techniques is shown in Figure 8.

Figure 8(a) shows the schematic diagram of the thyristor using the positive and negative angle junction terminal technique (called A type); Figure 8(b) is the schematic diagram of the thyristor made by the double negative angle junction terminal technique (referred to as ABB type); Figure 8(c) presents the schematic diagram of the thyristor using the new proposed junction terminal technique (called PERI type).

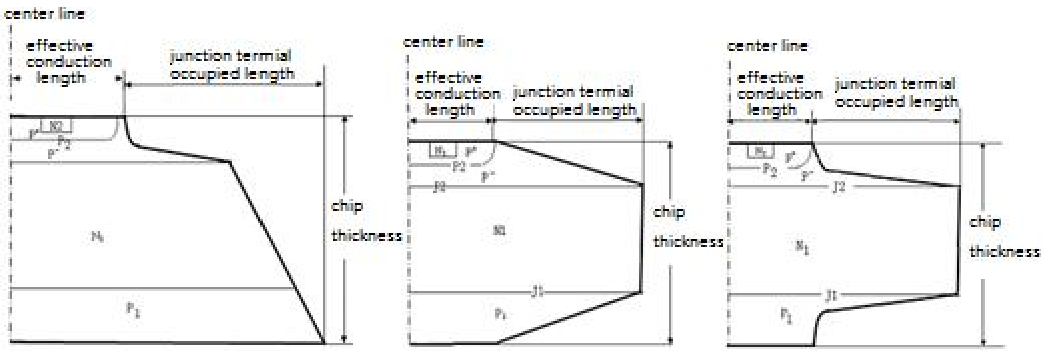


Fig.8 Diagrammatic cross-section of three different junction terminal techniques

Table 1 compares the technical parameters of different junction terminals of 6-inch UHV thyristors. From Table 1, it can be seen that the PERI type has the smallest junction terminal occupied length (8mm), the largest effective conduction length (137 mm) and the smallest chip thickness (1400 μm) among three types, under the same requirements (8500V/4500A/Ø145mm).

Table 1. Parameters comparison of 6-inch UHV thyristors with different terminal techniques

Junction terminal type	Chip thickness(um)	Chip diameter(mm)	Effective conduction length(mm)	occupation length (mm)
A Type	1450	145	130	15
ABB type	1430	145	135	10
PERI type	1400	145	137	8

The characteristics comparison of the three type of thyristors are shown in Table 2. In the table, V_{DRM} is the forward repeated peak off-state voltage, V_{RRM} is the repeated peak reverse voltage, I_{DRM} is the repeated peak off-state current repeat peak; I_{RRM} is the reverse current; V_{DSM} is the non-repetitive peak off-state voltage, and V_{RSM} is the non-repetitive peak reverse voltage, I_{TAV} is the on-state current capability, V_{TM} is the on-state peak voltage; Q_{RR} is the reverse recovery charge; t_q is the turn-off time; V_{GT} is the gate trigger voltage; I_{GT} is the gate trigger current.

Table 2. Electrical characteristics of 6-inch thyristors

Characteristics	A Type	ABB type	PERI type
V_{DRM}/V	≥8000	≥8000	≥8000
I_{DRM}/mA	8.90	5.80	2.50
V_{RRM}/V	≥8000	≥8000	≥8000
I_{RRM}/mA	8.40	7.20	2.50
V_{DSM}/V	≥8500	≥8500	≥8500
V_{RSM}/V	≥8500	≥8500	≥8500
I_{TAV}/A	4500	4500	4500
V_{TM}/V	2.213	1.952	1.782
Q_{RR}/μC	8074	7826	7731
t_q/μs	460	357	335
di/dt/(A/μs)	1338	1445	1589
dv/dt/(V/μs)	4546	4749	4976
V_{GT}/V	2.8	2.5	2.0
I_{GT}/mA	290	253	223

It can be seen from Table 2 that among the three types of samples, the PERI type sample has the best electrical characteristics, then the ABB type and the A type as followed. The reason is that under the same blocking voltage, the PERI-type sample chip has the smallest thickness, the smallest junction terminal occupation length and the largest effective conduction length. The thickness reduction of the chip only does harm to the blocking voltage, but it is beneficial to other electrical characteristics. The dynamic response of the chip is faster due to the smaller chip thickness; The on-state current capability is improved due to the increased effective conduction length; The surface leakage current is smaller due to the shorter junction terminal occupied length.

Figure 9 is a physical diagram of a 6-inch UHV thyristor (8500V/4500A) developed using the new kind of junction terminal technique (PERI type). The devices also passed the reliability experiments without failure and were successfully applied in the HVDC transmission project in China.

Fig.9 8500V/4500A UHV thyrisitor (PERI Type)

6 Conclusion

Based on the structure and working principle of thyristors, this paper compares and analyzes the advantages and disadvantages of various junction terminal techniques of UHV thyristors. And then a new kind of junction terminal technology including radial variable doping and mesa shape modification is proposed to improve the electrical characteristics of UHV thyristors. This technology can eliminate the additional thickness of the P-base region required for the traditional junction terminal technology, so that the chip is extremely thin. Under the same blocking voltage, the device has the minimized junction terminal occupied length, which maximizes the effective conduction length. It can also ensure the symmetry of the forward and reverse blocking voltages. The advantages can be seen obviously from the experiment results. Finally the 6-inch UHV thyristor (8500V/4500A) was manufactured and applied to the UHV DC transmission project in China successfully.

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