Analysis of Reverse Recovery Characteristics of Anti-parallel Diode

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Abstract. Insulated gate bipolar transistor (IGBT) is widely used in various renewable green energy systems such as wind power generation and solar power generation at present. High-power IGBT modules usually include IGBT chips and anti-parallel diodes, and the transient characteristics of anti-parallel diodes will affect the external port characteristics of IGBT modules. Based on semiconductor physics and diode basic structure, this paper analyzes four stages of diode reverse recovery process, and describes the change process of turn-off time and stored charge by a step recovery process. Finally, the voltage and current waveforms of diode reverse recovery process are simulated and verified for a certain IGBT module.

1. Introduction
Insulated gate bipolar transistor (IGBT) is a kind of composite device which integrates the structure of power field effect transistor (MOSFET) and bipolar transistor (BJT), and absorbs the advantages of both[1]. It has the advantages of high input impedance, fast switching speed, low driving power, reduced saturation voltage, large current bearing, etc, and has been widely used in various power electronic conversion devices. IGBT has rapidly expanded its application fields and become the leading device of medium and high-power power electronic devices, which are not only used in power systems, but also widely used in general industries, transportation, communication systems, computer systems and new energy systems[2,3].

High-power IGBT modules usually adopt an integrated package structure of IGBT chip and anti-parallel diode, in which the anti-parallel diode plays a role in providing energy dissipation in the switching process, so as to prevent overvoltage generated when the inductive load circuit is turned off hard. Therefore, the reverse recovery characteristics of freewheeling diodes have an increasing influence on switching losses and power electronic devices. Existing research mainly focuses on the steady-state reverse recovery characteristics of freewheeling diodes, analyzes and models the influence of diode switching behavior on performance, and analyzes the stored charge during diode reverse recovery[4-6]. It is necessary to analyze the reverse recovery process of diode in order to accurately grasp the reverse recovery voltage spike and current variation law of diode in free-wheeling state.

In this paper, based on the common PIN structure power diodes, the forward recovery characteristics and reverse recovery characteristics of diodes are analyzed from the perspective of semiconductor physics, and a step recovery process is used to analyze the change of carrier concentration and reverse recovery process when the diodes are turned off. Finally, the simulation is carried out.
2. Theoretical Analysis

2.1. Introduction of IGBT Structure
High-power IGBT devices used in power electronic devices are generally packaged in a modular way. One IGBT module contains one or more parallel IGBT single chips, freewheeling diodes, connecting wires, substrates, backplane, driving terminals, power connection terminals and other structural components. Figure 1 is a schematic structural diagram of IGBT module.

![Figure 1. Internal structure of IGBT module](image1)

IGBT module is characterized by three ports of collector, emitter and gate. As shown in figure 2, it is an IGBT cell structure. IGBT module is usually composed of several such cell structures. The mathematical model of IGBT module includes IGBT chip and anti-parallel diode. Different mathematical models are applied in different working stages of IGBT module, and diode switching transient will affect IGBT switching transient.

![Figure 2. IGBT cell structure](image2)

2.2. Analysis of reverse recovery characteristics
During the transition from blocking state to conducting state, the diode will be accompanied by the peak overshoot of anode voltage, which is called forward recovery; During the transition from conducting state to blocking state, the stored charge must be extracted before the drift region can withstand high voltage, and a large reverse current is generated, which is called reverse recovery.

The causes of diode reverse recovery are as follows: when the P-i-N diode is switched from conduction mode to blocking mode, the drift region needs to extract free carriers to form a depletion
region that can withstand high voltage. In the case of inductive load, the diode current can not drop to zero immediately, but a large peak reverse current appears, and then gradually decreases to zero.

Figure 3 shows typical voltage and current waveforms during the reverse recovery process of P-i-N diode. According to the changes of current and voltage, the reverse recovery process is divided into four sections for analysis. Assuming that the carrier concentration in the drift region can be linearized, a step recovery process can be used to analyze the reverse recovery process at turn-off, as shown in figure 4.

![Figure 3. Current and voltage waveforms of diode reverse recovery](image)

![Figure 4. Carrier concentration in reverse recovery process](image)

It is approximately replaced by the linear part between the average value of the drift region and the concentration \( n(0) \) at the drift region \( x = 0 \):

\[
\begin{align}
n(0) &= \frac{J_T \tau}{2qL} \left[ \cosh\left(\frac{W_L}{2L}\right) - \frac{\sinh\left(\frac{W_L}{2L}\right)}{2 \cosh\left(\frac{W_L}{2L}\right)} \right] \\
&= \frac{J_T \tau}{2qL} n_u
\end{align}
\]

Where: \( J_T \) is the current density, \( W_L \) is the base width, \( L \) is the bipolar diffusion length and \( q \) is the electron quantity.

In the turn-off transient process, the current at any time is determined by the carrier diffusion rate at the edge of the P+/N junction:

\[
J_T = 2qD \frac{dn}{dx} \bigg|_{x=0}
\]
2.2.1. The first stage of shutdown
In the first stage of the turn-off process, the diode current decreases from the on-state current to zero, and the change of the stored charge in the drift region is obtained from the region in the figure 4.

\[ Q_1 = \frac{q}{2} b(n(0) - n_s) \]  
\[ (3) \]

The amount of charge is obtained by current integration:

\[ Q_1 = \int_0^{t_1} J_T(t)dt = \int_0^{t_1} (J_T - at)dt = J_T t_0 - \frac{at_0^2}{2} \]  
\[ (4) \]

The distance obtained simultaneously is:

\[ b = \frac{J_T^2}{qa(n(0) - n_s)} \]  
\[ (5) \]

The time of \( t_0 \) is:

\[ t_0 = \frac{J_T}{a} \]  
\[ (6) \]

2.2.2. The second stage of shutdown
In the second stage of the turn-off process, the current changes from zero to voltage, and the carrier concentration distribution extends from zero concentration at the junction to the average concentration at the distance \( b \) from the junction. After the time \( t_1 \), the carrier concentration at a certain distance from the junction is zero, and a depletion layer is formed.

The charge extracted in this time period is represented by the following areas in the figure 4:

\[ Q_2 = \frac{q n_s b}{2} \]  
\[ (7) \]

The amount of charge is obtained by current integration:

\[ Q_2 = \int_0^{t_1} J_T(t)dt = \int_0^{t_1} (at)dt = \frac{a}{2}(t_1^2 - t_0^2) \]  
\[ (8) \]

Simultaneous acquisition time \( t_1 \) is:

\[ t_1 = \sqrt{\frac{q n_s b}{a} + \frac{J_T^2}{a^2}} \]  
\[ (9) \]

2.2.3. The third stage of shutdown
In the third stage of the turn-off process, the voltage borne by the diode starts to increase continuously, and the formed space charge region expands outward, further extracting the charge stored in the drift region, and the reverse current continues to increase.

The extracted charge is obtained from the area \( Q_3 \) in the figure 4:

\[ Q_3(t) = q n_s W_{SC}(t) \]  
\[ (10) \]

The amount of charge is obtained by current integration:

\[ Q_3(t) = \int_s^{t} J_T(t)dt = \int_s^{t} (J_T - at)dt = J_T(t - t_1) - \frac{a}{2}(t^2 - t_1^2) \]  
\[ (11) \]

The width of space charge region is a function of time, which is the largest in time \( t_2 \) and is determined by the external voltage:
\[ W_{SC}(t_2) = \frac{2\varepsilon_i V}{qN_i} \tag{12} \]

Combine the above formulas:
\[ \frac{a}{2qn_a} (t_2^2 - t_1^2) - \frac{J_R}{qn_a} (t_2 - t_1) = \frac{2\varepsilon_i V}{qN_i} \tag{13} \]

The time \( t_2 \) and the corresponding extracted charge \( Q_R(t_2) \) can be obtained by solving the above formula.

2.2.4. The fourth stage of shutdown

In the fourth stage of the turn-off process, the reverse bias current decreases at a constant rate and the voltage remains constant.

At the moment \( t_2 \), the peak reverse current \( J_R \) flows, and the relationship between the current and the carrier concentration distribution is:
\[ J_R = 2qD \frac{dn}{dx} = 2qD \frac{n_a}{h} \tag{14} \]

Stored charge at time \( t_4 \):
\[ Q_4 = qn_a (W - W_{SC} - h) \tag{15} \]

The charge extracted in the fourth stage is:
\[ Q_R = \frac{1}{2} J_R (t_3 - t_2) \tag{16} \]

The stored charge and the extracted charge are equal, and the reverse current extraction time is as follows:
\[ t_3 - t_2 = \frac{2qn_a}{J_R} (W - W_{SC} - h) \tag{17} \]

Through the above analysis of the four stages of the reverse recovery process of the anti-parallel diode inside the IGBT module, the charge amount and time of each stage are obtained.

3. Simulation Analysis and Verification

The IGBT model selected is GD50HFL120C1S, which is a soft through two-cell half-bridge module. The electrical parameters of the anti-parallel diode are calculated by parameter manual or extracted by experiments. The simulation parameters are set as follows: DC voltage is 300V, load inductance is 1mH, load resistance is 12 ohms, and DC steady-state current is 25 A. The simulated waveform of the reverse recovery process of the internal anti-parallel diode is shown in figure 5.
Figure 5. Simulation waveform of diode reverse recovery process

Comparing figure 5 with figure 3, it can be seen that the simulation and analysis of voltage and current waveforms during diode reverse recovery are basically the same, thus verifying the analysis in this paper.

4. Conclusion
Based on the movement mechanism of semiconductor physical carriers, the reverse recovery of PIN diode is divided into four stages from the change of reverse recovery residual stored charge, and a step recovery process is used to describe the reverse recovery process when the diode is turned off. The reverse recovery process of the anti-parallel diode in a certain IGBT module is simulated, and the correctness of the theoretical analysis is verified.

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