Research on Electro-thermal Model Simulation of IGBT Switching Transient

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Abstract. The electro-thermal model of Insulated Gate Bipolar Transistor (IGBT) can be used to simulate the operating characteristics of devices at different temperatures. Considering the relationship between internal parameters, semiconductor physical constants and temperature, the electrical model of IGBT at a single temperature is extended to an electro-thermal model which can reflect the working characteristics at different temperatures. This model takes into account both simulation accuracy and simulation speed. Finally, the IGB model is selected, and the IGBT switching transient at different temperatures is verified by experiments.

1. Introduction

Insulated Gate Bipolar Transistor (IGBT) is a composite device which combines the structure of field effect transistor and bipolar transistor, and absorbs the advantages of both. It has high input impedance and fast switching speed. Low driving power, low saturation voltage, simple control circuit, large current bearing and so on. Widely used in new energy technology, energy-saving technology and other fields, it has gradually become the leading device of medium and high-power power electronic devices\textsuperscript{[1-2]}.

At present, there are two main methods to establish IGBT electro-thermal model\textsuperscript{[3-4]}. The first method is to obtain parameter values at different temperatures through a large number of test experiments, such as the classic Hefner model, and then substitute them into the model for calculation. Because there are many temperature-related parameters involved, the extraction process is complicated, which limits the improvement of accuracy. Another method is to use empirical formula for calculation, which is relatively simple and has limited application in actual device design. By adopting these two methods, both simulation accuracy and simulation speed can be taken into account.

In this paper, based on different types of IGBT mathematical models, considering the relationship between temperature and internal parameters of devices and semiconductor physical constants of materials, the IGBT mathematical model with single temperature is extended to an IGBT electro-thermal model that reflects the operating characteristics at different temperatures. Finally, the correctness of the electro-thermal model is verified by experiments.

2. Theoretical analysis

2.1. Mathematical model of IGBT

According to the physical theory of semiconductor and the structural characteristics of IGBT, the on-state model and switching transient model of NPT-type, PT-type and FS-type planar gate or trench gate IGBT are established by using some assumptions and modeling methods.
The switching transient of IGBT includes two kinds: on transient and off transient. Switching transient model describes the transient changes of IGBT port voltage, current and internal charge in these two processes. The basic method of establishing IGBT switching transient model is consistent with the on-state model. First, according to certain assumptions and boundary conditions, the excess carrier distribution in the base region is obtained by solving the carrier continuity equation, then the current expression is obtained by the current transport equation, and finally the relationship expression between current and voltage is deduced. However, the switching transient process is different from the on-state. IGBT is not in a relatively stable state, and its external port voltage and current are changing, and the corresponding internal carrier distribution and depletion layer width are also changing. Therefore, the establishment of IGBT switching transient model is more complicated than the on-state model. On the one hand, the continuity equation of transient model must consider the change of carrier distribution with time, and the time-related term must also be included; On the other hand, because the carrier concentration at the boundary of the base region is constantly changing and has dynamic boundary conditions, it is necessary to introduce another system variable besides the port voltage and current, that is, the total charge amount of the base region, and eliminate the intermediate variables appearing in the model derivation through the relationship between the boundary concentration and the total charge amount.

2.2. Electro-thermal model of IGBT switching transient

The electro-thermal model of IGBT can simulate the operating characteristics of devices at different temperatures, and expand the electrical model at a single temperature to an electro-thermal model that can reflect the operating characteristics of IGBT at different temperatures.

As the physical constants and internal parameters of semiconductor power IGBT devices, including carrier mobility, intrinsic carrier concentration, diffusion coefficient, excess carrier life, emitter electron saturation current, gate threshold voltage and transconductance, etc., will change with the change of temperature, resulting in the on-state voltage drop, switching speed, collector leakage current and other performance indicators of IGBT, so the operating characteristics of IGBT are greatly affected by temperature.

According to the internal simulation parameters of IGBT mathematical model, the temperature-related parameters can be divided into two categories. The first category is the internal parameters of the device, including excess carrier life, gate threshold voltage, transconductance and emitter electron saturation current, etc. References [5-6] give empirical formulas of these parameters changing with temperature:

\[
\begin{align*}
\tau(T_j) &= \tau(T_0) \times \left(\frac{T_j}{T_0}\right)^{1.5} \\
V_T(T_j) &= V_T(T_0) - 9 \times 10^{-3} (T_j - T_0) \\
K_p(T_j) &= K_p(T_0) \times \left(\frac{T_j}{T_0}\right)^{0.8} \\
I_{sne}(T_j) &= \frac{I_{sne}(T_0)(T_j/T_0)^{0.5}}{\exp\left(\frac{1}{T_j} - \frac{1}{T_0}\right) \times 1.4 \times 10^4}
\end{align*}
\]

Among them, \(\tau(T_0)\), \(V_T(T_0)\), \(K_p(T_0)\) and \(I_{sne}(T_0)\) represent the typical values of excess carrier concentration, gate threshold voltage, transconductance and emitter electron saturation current at \(T_0\) temperature; \(\tau(T_j)\), \(V_T(T_j)\), \(K_p(T_j)\) and \(I_{sne}(T_j)\) are parameter values at temperature \(T_j\), in which the coefficient of threshold voltage can be measured and extracted.

The other is the semiconductor physical constants of materials, including intrinsic carrier concentration, carrier mobility and diffusion coefficient. Among them, the relationship between intrinsic carrier concentration and temperature can be expressed as:
Where: \( N_c = 2.8 \times 10^{19} \text{cm}^{-3} \) is the effective state density of conduction band; \( N_v = 1.04 \times 10^{19} \text{cm}^{-3} \) is the effective state density of valence band; \( k = 8.62 \times 10^{-5} \text{eV} / \text{K} \) is Boltzmann constant; \( E_g \) is the band gap width of silicon material, and its relationship with temperature is:

\[
E_g(T) = E_g(0) - aT
\]

Where: \( E_g(0) = 1.206 \text{eV} \) is the forbidden band width at absolute zero; \( a = 2.7325 \times 10^{-4} \text{eV} / \text{K} \) is the scale factor; Substituting formula (3) into formula (2) can be obtained:

\[
n_i(T) = C \left( \frac{T}{300} \right)^{1.5} \exp\left( -\frac{1.206}{kT} \right)
\]

Where, \( C = 8.324 \times 10^{19} \text{cm}^{-3} \text{K}^{-1.5} \) is the proportional coefficient.

The relationship between intrinsic carrier concentration and temperature obtained by Mathcad mathematical calculation software simulation is shown in Figure 1.

![Figure 1. The relationship between intrinsic carrier concentration and temperature](image)

It can be seen from Figure 1 that the intrinsic carrier concentration changes little with temperature at low temperature (below 125°C), but increases exponentially with temperature at high temperature (above 125°C), which is a strong function of temperature.

Carrier mobility reflects the relationship between the average drift velocity of carriers and the electric field, which is related to temperature and doping concentration, and has great influence on the voltage drop in the quasi-neutral base region. The two scattering mechanisms affecting carrier mobility are lattice scattering and ionized impurity scattering. When the temperature is above room temperature, lattice scattering is the main scattering mechanism, and carrier mobility decreases with the increase of temperature, which is proportional to \( T^{-n} \); In addition, impurity atoms can control or change the properties of semiconductors. When the doping concentration increases, the mobility decreases. Both the absolute value and the relative value of carrier mobility have an important influence on the characteristics and working limits of semiconductor power devices, but it is very difficult to find these mobility values from the basic principle or by independent measurement. Because it is difficult to use mathematical model to describe the relationship between mobility and temperature and doping concentration, look-up table fitting method is used in simulation calculation. When the doping concentration of base region and buffer layer is of the order of \( 10^{14} \text{cm}^{-3} \) and \( 10^{17} \text{cm}^{-3} \) respectively, the mobility of silicon at each temperature point is found and fitted into a curve as shown in Figure 2.
In Figure 2, $\mu_n$ and $\mu_p$ are the electron and hole mobilities at the base doping concentration $10^{14}\, cm^{-3}$, $\mu_{n1}$ and $\mu_{p1}$ at the buffer doping concentration $10^{17}\, cm^{-3}$, respectively.

Carrier diffusion coefficient describes the movement of carriers in semiconductor under the action of concentration gradient, which is related to carrier mobility and satisfies Einstein relation between them:

$$D_n = D_p = \frac{kT}{e}$$  \hspace{1cm} (5)

Where, $D_n$ and $D_p$ are the electron and hole carrier diffusion coefficients, respectively.

The relationship between device internal parameters and semiconductor physical constants and temperature is substituted into IGBT mathematical model, which can be extended to IGBT electro-thermal model.

3. Experimental verification

Using the above IGBT electro-thermal model method, the transient process of IGBT switching at different temperatures is simulated. Select IGBT module with model FF200R06KE3, and calculate the related electrical parameters by using the numerical values in manual or empirical formula. The comparison between the measured and simulated waveforms of complete switching transients at temperatures of 50℃ and 100℃ is shown in Figure 3.
Figure 3. Comparison of simulated and measured waveforms at different temperatures

It can be seen from Figure 3 that the simulated waveforms at different temperatures are in good agreement with the measured waveforms, and the simulation results are in good agreement with the experimental phenomena. The turn-off process becomes slow with the increase of temperature, the current tail is prolonged, and the voltage spike drops, while the turn-on process is not greatly affected by temperature, thus verifying the accuracy of the conclusions and electro-thermal model method.

4. Summary
Considering the temperature variation characteristics of parameters in IGBT mathematical model, adopting the empirical formula of internal parameters changing with temperature and the accurate representation of semiconductor physical constants changing with temperature, IGBT mathematical model can be extended to IGBT electro-thermal model with reaction temperature, and this model has made a compromise between simulation accuracy and speed.

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