High temperature characterization of double base epilayer 4H-SiC BJTs*

Zhang Qian(张倩)†, Zhang Yuming(张玉明), Zhang Yimen(张义门), and Wang Yuehu(王悦湖)

(Key Laboratory of Semiconductor Wide Band-Gap Materials and Devices, School of Microelectronics, Xidian University, Xi’an 710071, China)

Abstract: Based on the material characteristics and the operational principle of the double base epilayer BJTs, and according to the drift–diffusion and the carrier recombination theory, the common emitter current gain is calculated considering four recombination processes. Then its performance is analyzed under high temperature conditions. The results show that the emitter injection efficiency decreases due to an increase in the base ionization rate with increasing temperature. Meanwhile, the SiC/SiO2 interface states and the quality of the passivation layer will affect the surface recombination velocity, and make an obvious current gain fall-off at a high collector current.

Key words: 4H-SiC; bipolar junction transistors (BJTs); current gain; carrier recombination; high temperature
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1. Introduction

With the increasing demand for devices of superior high-power, high-frequency performance and the ability to operate in rigorous environments, such as in high-temperature conditions, silicon carbide (SiC) has been recognized as one of the potential choices for application to different devices due to its high thermal conductivity (4.5 W/cm·K). In comparison with power MOSFETs, 4H-SiC bipolar junction transistors (BJTs) offer higher current densities at lower offset voltages, higher operating temperature and better reliability. In order to reduce the driving loss, the common-emitter current gain (βCE) is very important among all of the performance parameters. Much work has been done to increase β by optimizing the emitter geometry[1,2], by improving the passivation layer[3] and by improving the base epilayer process[4]. In our previous work, we put forward a novel structure of a bipolar transistor with double base epilayers[5]. This structure can not only avoid the ion implantation process but also reduce the base transit time. However, the temperature dependence of its working performance has not been unambiguously determined yet.

In the present work, we focus on the DC characteristics at an elevated temperature and calculated in terms of models including (1) surface recombination; (2) recombination in the emitter–base space charge region (SCR); and (3) incomplete ionization. Then the expression of βCE is solved, and is validated by the two-dimensional simulation tools. The calculation results show that βCE performs the negative temperature coefficient at elevated temperature. Also, the SiC/SiO2 interface states and the quality of the passivation layer can affect the surface recombination velocity to decrease βCE.

2. Device structure and modeling

A schematic cross-sectional view of the fabricated 4H-SiC BJTs is shown in Fig. 1. The base was grown as a two-layer structure with Al doping: 0.35 μm with 1 × 1017 cm−3, followed by 0.15 μm with 4.6 × 1018 cm−3 on top. This configuration can accelerate the carriers by the built-in electric field in the base region and reduce the base transit time. Also, it can avoid the ion implantation process and reduce the defects introduced by the high-temperature annealing.

2.1. Physical models analysis

The physical models considered in this research include Shockley-Read-Hall (SRH) recombination, Auger recombination, surface-recombination mechanisms, mobility models and incomplete ionization models when carriers are injected from emitter transport through the base region. In the latter analysis, we ignore the bulk resistor of the semiconductor and the electrode contact resistance, and assume the base width constant, that is to say, we do not consider the Early effect, which is a good approximation for the low doped collector region.

2.1.1. SRH recombination

The interface states are located at the base-emitter junction and the SiC/SiO2 interface, as shown in Fig. 1. Both of them recombine through deep levels in the bandgap. The SRH recombination rate $R^{SRH}$ can be defined as

$$R^{SRH} = \frac{2}{\tau_{i} n_{i}}$$

where $\tau_{i}$ is the lifetime of the carriers.

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† Corresponding author. Email: zq_xacom@163.com
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Fig. 2. Distribution of the surface state in the forbidden band.

Fig. 3. Relationship between the excess carrier concentration and the surface distance.

\[ R_{\text{SRH}} = \frac{np - n_i^2}{\tau_p \left( n + n_i \exp \left[ \frac{E_{\text{trap}}}{kT} \right] \right) + \tau_n \left( p + n_i \exp \left[ -\frac{E_{\text{trap}}}{kT} \right] \right)} \]

where \( \tau_n \) and \( \tau_p \) are the electron and hole lifetimes, which depend on temperature, dopant type and defect concentration. They are in the range of 0.1–2 \( \mu \)s. In our calculation process, we assume \( \tau_n = 5 \tau_p \).

2.1.2. Auger recombination

Auger recombination is important at high carrier concentrations. The band-to-band Auger recombination rate \( R_A \) is given by

\[ R_A = (C_n n + C_p p)(np - n_i^2), \]

where \( C_n \) and \( C_p \) denote the Auger coefficients of electrons and holes. For 4H-SiC, \( C_n = 5 \times 10^{-31} \text{ cm}^{-6}\text{ s}^{-1} \). \( C_p = 2 \times 10^{-31} \text{ cm}^{-6}\text{ s}^{-1} \).

2.1.3. Surface recombination

As Figure 2\(^7\) shows, there exists the distribution of the permitted energy states in the forbidden band region. It can be proved that the defect density at the device surface is larger than that in the bulk of the material. Therefore, as Figure 3\(^7\) shows, the excess carrier in the material will diffuse from the interior to the surface. For an extrinsic semiconductor, the surface recombination rate can be expressed as

\[ R_s = \frac{\delta_{ps}}{\tau_{ps}}, \]

where \( \tau_{ps} \) is the lifetime and \( \delta_{ps} \) is the concentration of the excess minority carrier located at the surface.

2.1.4. Incomplete ionization

Unlike Si, the donor \( (E_D) \) and acceptor \( (E_A) \) levels in SiC are relatively deep compared to the thermal energy at room temperature, so the dopants in SiC are not fully ionized, even at high temperature. The concentration of the ionized impurity atoms is given by\(^8\)

\[ N_{D}^{+} = \frac{N_D}{1 + g_e \exp \left[ \frac{E_{F_D} - E_D}{kT} \right]} \]
\[ N_{A}^{-} = \frac{N_A}{1 + g_v \exp \left[ \frac{E_A - E_F}{kT} \right]} \]

where \( N_D \) and \( N_A \) are the doping concentrations of the donor and acceptor, and \( E_D \) and \( E_A \) are the donor and acceptor energy level, respectively. For nitrogen donor levels in 4H-SiC, a dopant ionization energy \( E_C - E_D = 65 \text{ meV} \) and \( g_e = 2 \), the p-type doping can be achieved with Al acceptors with ionization energy \( E_A - E_V = 191 \text{ meV} \) and \( g_v = 4 \). Figure 4\(^{10}\)
shows the ionization rate of Al in 4H-SiC as a function of doping concentration and temperature. From this figure we can see that the Al ionization rate increases with increasing temperature and decreasing doping concentration.

2.2. Common-emitter current gain

The common-emitter current gain $\beta_{CE}$ is an important parameter that is defined as the ratio of the collector current density and the base current density. In order to indicate the influence of the temperature on $\beta_{CE}$, the following recombination mechanism is taken into account: (1) recombination in the emitter junction space charge region (SCR); (2) surface recombination; (3) recombination in the emitter; and (4) recombination in the double base epilayer, as shown in Fig. 1.

The current gain $\beta_{CE}$ can be expressed as

$$\beta_{CE}^{-1} = \beta_{SCR}^{-1} + \beta_{sr}^{-1} + \beta_{E}^{-1} + \beta_{T}^{-1}. \quad (5)$$

The recombination current density $J_{SCR}$ caused by the recombination in the SCR of the emitter junction is given by

$$J_{SCR} = J_{sr} \exp \left( \frac{q V_{BE}}{2kT} \right), \quad (6)$$

where $J_{sr}$ is the recombination saturation current, $q$ is the electron charge and $V_{BE}$ is the external voltage across the BE junction.

The emitter current density $J_{E}$ can be expressed as

$$J_{E} = J_{od} \exp \left( \frac{q V_{BE}}{kT} \right), \quad (7)$$

$$J_{od} = \frac{q D_{ab} n_{B}^{0}}{W_{B}}, \quad (8)$$

where $D_{ab}$ is the diffusion coefficient of the minority carrier in the base and $n_{B}^{0}$ is the equilibrium electron density in the p-base.

Combining Eqs. (6)–(8), $\beta_{SCR}$ is expressed as

$$\beta_{SCR}^{-1} = \frac{J_{SCR}}{J_{E}} = \frac{J_{sr}}{J_{od} \exp \left( \frac{q V_{BE}}{2kT} \right)} = \frac{J_{sr}}{J_{od} \exp \left( \frac{q V_{BE}}{2kT} \right)} \sqrt{J_{E}/J_{od}}. \quad (9)$$

Secondly, $\beta_{sr}$ is the current gain related to the surface recombination and it is defined as

$$\beta_{sr}^{-1} = \frac{J_{sr}}{J_{od}} \exp \left( \frac{q V_{BE}}{kT} \right). \quad (10)$$

$$J_{sr} = \frac{n_{s}^{2}}{Q_{B}} \exp \left( \frac{q V_{BE}}{kT} \right), \quad (11)$$

$$J_{od} = \frac{q D_{ab} n_{B}^{0}}{W_{B}}, \quad (12)$$

$$Q_{B} = \int_{0}^{W_{B}} N_{B}(x) \, dx, \quad (13)$$

$$N_{B}(x) = \begin{cases} \frac{N_{1}}, & 0 < x < W_{a} \\ \frac{N_{2}}, & W_{a} < x < W_{B} \end{cases} \quad (14)$$

Combining Eqs. (10)–(14), $\beta_{sr}$ is described as

$$\beta_{sr}^{-1} = \frac{s Q_{B}}{D_{ab} N_{B}(0)}, \quad (15)$$

where $s$ is the surface recombination velocity.

Thirdly, $\beta_{E}$ is limited by the decrease in the injection coefficient at high-injection levels and is given by

$$\beta_{E}^{-1} = \frac{J_{pd}}{J_{E}} \approx \frac{D_{PE} j_{E} W_{B}^{2}}{q D_{P}^{2} N_{E} V_{pE}}, \quad (16)$$

where $D_{PE}$ and $L_{PE}$ are the hole diffusion coefficient and hole diffusion length in the emitter, and $D_{P}$ is the ambipolar carrier diffusion coefficient in the base, which can be expressed by

$$D_{P} = \frac{2 D_{ab} D_{ pb}}{D_{ab} + D_{pb}}, \quad (17)$$

Finally, $\beta_{T}$ is defined as the ratio of the electron current density injected into the base region from the emitter junction with recombination current density in base region, as shown by

$$\beta_{T}^{-1} = \frac{J_{B}}{J_{ne}}, \quad (18)$$

$J_{B}$ is calculated by Eq. (18) due to a built-in electrical field existing in the base region, which consists of two epilayers with different doping concentrations,

$$J_{B} = \frac{q}{\tau_{ne}} \int_{0}^{W_{B}} \Delta n_{B}(x) \, dx = \frac{q}{\tau_{ne}} \int_{0}^{W_{B}} \left[ n_{B}(x) - n_{B}^{0} \right] \, dx, \quad (19)$$

where $n_{B}(x)$ is the minority-carrier concentration profile in the base. When neglecting $n_{B}^{0}$ and substituting the expression of $n_{B}(x)$[5] into Eq. (18), the recombination current in the base is obtained,

$$J_{B} = \frac{q}{\tau_{ne}} I_{OE} \int_{0}^{W_{B}} n_{B}(x) \, dx = \frac{I_{OE}}{\tau_{ne} D_{ab}} \int_{0}^{W_{B}} n_{B}(x) \frac{1}{N_{B}(x)} \int_{0}^{W_{B}} N_{B}(x) \, dx \, dx = \frac{L_{2}}{2} \left[ \frac{1}{2} L_{1} + \frac{N_{2}}{N_{1}} L_{1} L_{2} + \frac{N_{1}}{N_{2}} L_{2} \left( L_{1} - \frac{1}{2} L_{2} \right) \right] + L_{2} \left[ \frac{W_{a}}{N_{1}} + \frac{W_{B} - W_{a}}{N_{2}} \right], \quad (20)$$

where $N_{1}$ and $N_{2}$ are the doping concentrations of the P+ and P layer, $L_{1} = W_{a}$ and $L_{2} = W_{B} - W_{a}$.

3. Results and discussions

The temperature dependent DC performance is calculated using the models outlined above with the help of the DESSIS-ISE software. The material and device parameters used in the calculation are summarized in Table 1.

In order to validate the correction of the calculation model, a simulation for a device that has only one base epilayer is made to compare with the measured results. Figure 5 shows a comparison of the experimental[13] and simulation results at $T =$
Table 1. Material and device parameters used in the calculation.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Device parameter</td>
<td></td>
</tr>
<tr>
<td>Emitter doping concentration/thickness</td>
<td>$3 \times 10^{19}$ cm$^{-3}$/0.5 μm</td>
</tr>
<tr>
<td>Base doping concentration/thickness (top)</td>
<td>$4.6 \times 10^{18}$ cm$^{-3}$/0.15 μm</td>
</tr>
<tr>
<td>Base doping concentration/thickness (bottom)</td>
<td>$1 \times 10^{17}$ cm$^{-3}$/0.35 μm</td>
</tr>
<tr>
<td>Collector doping concentration/thickness</td>
<td>$5 \times 10^{15}$ cm$^{-3}$/25 μm</td>
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<tr>
<td>Material parameter</td>
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<tr>
<td>Bandgap energy ($E_g$)</td>
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<tr>
<td>Donor energy level</td>
<td>0.065 eV</td>
</tr>
<tr>
<td>Acceptor energy level</td>
<td>0.191 eV</td>
</tr>
<tr>
<td>$\mu_n$</td>
<td>$1110$ cm$^2$/V·s$^{-1}$[12]</td>
</tr>
<tr>
<td>$\mu_p$</td>
<td>$65$ cm$^2$/V·s$^{-1}$</td>
</tr>
<tr>
<td>Surface recombination velocity</td>
<td>$2 \times 10^6$ cm/s</td>
</tr>
</tbody>
</table>

300 K. It shows that the presented model for calculation is reasonable.

Figure 6 illustrates the space charge profile in the base region at room temperature. In this figure, it can be seen that there exists a space charge region in the bulk of the base. The P$^+$ side is negative charge and the P side is the accumulation of the hole carrier, which has no obvious boundary. Also, we can find that the Al dopants in the base region are not fully ionized. The hole concentration will grow with increasing temperature, which will strongly affect the emitter-injection efficiency and base transport factor.

Figure 7 shows the dependences of the common-emitter current gain $\beta_{CE}$ on the collector current density at four different temperatures. With increasing temperature, the ionization rate of the Al dopants in the base region increase and they cause a substantial decrease in emitter injection efficiency. Therefore, the common-emitter current gain decreases rapidly at a higher temperature. Overall, the current gain decreases rapidly at a higher temperature. This is very different from power silicon BJTs and makes the device attractive for paralleling and thermal run-away suppression. Figure 8 illustrates the temperature dependence of the common-emitter current gain. As Figure 7 shows, $\beta_{CE}$ performs the negative temperature coefficient.

Figure 9 shows the forward $I–V$ characteristics at room temperature and together with those at $T = 500$ K. From this figure it is observed that there is an obvious degradation in the device performance at elevated temperature. That is mainly because, with increasing temperature, the surface recombination at the SiC/SiO$_2$ interface becomes aggravating, which ultimately increases the SRH recombination rate and base recombination current. This confirms that the SiC/SiO$_2$ interface plays an important role in the BJT’s performance. Thus, an improvement in the passivation layer quality is necessary.

Figure 10 shows the DC current gain over a wide range of emitter–base voltage for the transistors with two different temperatures, while the collector–base voltage is kept constant...
4. Conclusion

The high-temperature performance of a double base epi-layer 4H-SiC BJT is demonstrated in this paper. By solving the analytical expression of the common-emitter current gain considering recombination process, the $\beta_{CE} - I_C$ dependences are determined at elevated temperature based on models including recombination, incomplete ionization, bandgap narrowing and a built-in field in the base region. The simulation results show that the current gain has a negative temperature coefficient. This makes the device attractive for paralleling and thermal runaway suppression. Meanwhile, the SiC/SiO$_2$ interface states and the quality of the passivation layer will affect the surface recombination velocity, and make a current gain fall-off at a high collector current.

References


