Impact ionization coefficients of 4H silicon carbide

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doi: 10.1063/1.1784520
Impact ionization coefficients of 4H silicon carbide

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(Received 2 March 2004; accepted 21 June 2004)

Among many wide band-gap semiconductor materials, 4H silicon carbide (4H-SiC) has great potential for use as the material for power devices, owing to its crystal maturity and superior electrical properties, such as nearly isotropic mobility and high breakdown electric field. Impact ionization coefficients are important material properties for power devices, because the avalanche breakdown of a power device is caused by the impact ionization phenomena, and the physical model of an impact ionization coefficient is indispensable for the device simulation of power devices. However, the reports of measurements of the impact ionization coefficient of 4H-SiC are few, and they are not in agreement with one another.\(^1\,\,^2\) Recently, it was shown that a significant reduction of the breakdown field in 4H-SiC occurs when the electric field is applied perpendicular to the c-axis, but the impact ionization coefficients were not reported.\(^3\) In order to predict the breakdown voltage of a real power device precisely, we have to consider the anisotropy of impact ionization coefficients, because the direction of the electric field at the field crowding part is not necessarily parallel to the c-axis when the reverse bias is applied, even if the device is fabricated on a (0001) 4H-SiC wafer.

In this letter, we present the impact ionization coefficients of 4H-SiC for (0001) and (1\(\bar{1}\)20) directions that reproduce avalanche breakdown behavior of \(p^+n\) diodes on (0001) and (1\(\bar{1}\)20) epitaxial 4H-SiC wafers. We also discuss the origin of anisotropy of the impact ionization coefficient of 4H-SiC, based on the microscopic description of the impact ionization and the transport physics under high electric field.

The breakdown voltages as a function of doping density and the multiplication factors of a leakage current were obtained using \(p^+n\) diode fabricated on (0001) and (1\(\bar{1}\)20) epitaxial 4H-SiC wafers. The substrates used in this work were heavily doped \(p\)-type (0001) and (1\(\bar{1}\)20) 4H-SiC wafers purchased from Cree Research, Inc. The epitaxial layers on a (0001) wafer were grown by Cree Research, Inc., and those on a (1\(\bar{1}\)20) wafer were grown in a horizontal hot-wall chemical-vapor deposition reactor using SiH\(_4\) and C\(_3\)H\(_8\) as source gases and H\(_2\) as a carrier gas.\(^*\) The inset of Fig. 1 shows a cross section of the \(p^+n\) diode and the measuring system for multiplication factors. The \(p^+n\) junction of a diode is located between a \(p^+\)-type epitaxial layer, on a \(p^+\)-type substrate and an \(n\)-type epitaxial layer in order to exclude the effect of defects in the substrate. The doping concentration of the \(n\)-type epitaxial layer, was between \(3 \times 10^{16}\) and \(2 \times 10^{17}\) \(cm^{-3}\). Deep mesa for the isolation and termination of \(p^+n\) diodes was formed using inductively coupled plasma reactive ion etching in SF\(_6\) chemistries. Nickel was deposited for the contact area after the contact implantation and

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FIG. 1. Reverse leakage current of \(p^+n\) diodes on (0001) and (1\(\bar{1}\)20) wafers in the dark and in UV light. The inset shows a cross section of the \(p^+n\) diode and the measuring system for multiplication factors.
layer is the same. Thus, in designing the structure of power devices made of 4H-SiC, it is necessary to pay attention to the direction of the high electric field when the reverse voltage is applied.

The impact ionization coefficients are obtained by the combined fitting procedure of the multiplication versus voltage characteristics and breakdown voltage-doping density curve, as mentioned above. The impact ionization coefficient model commonly used in the device simulator is based on the model suggested by Chynoweth: \[ \alpha = a_0 \exp(-b_0/F), \quad \beta = a_0 \exp(-b_0/F), \] where \( F \) represents the magnitude of the electric field. Other parameters are fitting parameters. The calibrated parameters of the electron- and hole-impact ionization coefficients model are summarized in Table I. Figure 3 shows the obtained impact ionization coefficients in (0001) direction and those in \( <11\overline{2}0> \) direction. It can be seen that the ionization coefficients in \( <11\overline{2}0> \) direction are larger than those in (0001) direction. Further, the asymmetry of the electron and hole-ionization coefficients in \( <11\overline{2}0> \) direction is smaller than that in (0001) direction.

Now we discuss the origin of the anisotropy of the impact ionization coefficients of 4H-SiC from the physical and theoretical points of view. The impact ionization coefficient for electrons is expressed by the integral of the product of the impact ionization rate and distribution function,

\[
\alpha = \frac{1}{n_{v_i} \nu_{d}} \int_{0}^{\infty} dE w_{i}(E) f(E) \rho(E),
\]

where \( n_{v_i}, \nu_{d}, f(E), w_{i}(E), \) and \( \rho(E) \) denote electron density, drift velocity, distribution function, impact ionization rate, and density of states, respectively. Impact ionization for holes can be viewed as a mirror image of the impact ioniza-

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<th>Parameter</th>
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<th>(11\overline{2}0)</th>
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<tr>
<td>(a_0(\text{cm}^{-2}))</td>
<td>(1.76 \times 10^8)</td>
<td>(2.10 \times 10^9)</td>
</tr>
<tr>
<td>(b_0(\text{V/cm}))</td>
<td>(3.30 \times 10^7)</td>
<td>(1.70 \times 10^7)</td>
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<tr>
<td>(a_0(\text{cm}^{-2}))</td>
<td>(3.41 \times 10^8)</td>
<td>(2.96 \times 10^7)</td>
</tr>
<tr>
<td>(b_0(\text{V/cm}))</td>
<td>(2.50 \times 10^7)</td>
<td>(1.60 \times 10^7)</td>
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</table>
tion for electrons, and so we treat only the electron impact ionization. The Keldysh formula is assumed for the impact ionization rate

$$w_i(E) = C_i(E - E_{th})^\alpha,$$

(2)

where $E_{th}$ is a threshold energy and $C_i$ is a fitting parameter.\(^7\)\(^8\) The distribution function $f(E)$ is a solution of the Boltzmann transport equation (BTE), which includes microscopic physical properties, such as the band-structure and carrier scattering mechanisms. For easier comprehension, we first adopt the “hydrodynamic” model to introduce the mean quantities, such as carrier temperature and drift velocity, and their relation with impact ionization coefficients.\(^9\) The BTE is treated as a set of the kinetic equations for mean quantities in the hydrodynamic model. After we can figure out the relation between the mean quantities and impact ionization coefficients, we return to the discussion of the effect of microscopic physical properties, such as the band-structure and carrier scattering mechanisms. Monte Carlo studies of high-field transport in 4H-SiC have shown anisotropy of the carrier velocity, the carrier temperature and the impact ionization coefficients; the carrier velocity, the carrier temperature, and the impact ionization coefficients under the electric field parallel to the $c$ axis are much smaller than those under the electric field perpendicular to the $c$ axis.\(^10\)\(^\text{—}12\)

This is due to the highly anisotropic band structure of 4H-SiC, which is derived from a long period along the $c$ axis of the crystal structure of 4H-SiC.

The anisotropy of the saturation velocity can be estimated from anisotropy of the impact ionization coefficients based on Eq. (4), if we assume that the drift velocity shows saturation characteristics as for the electric field. The electron saturation velocity parallel to the $c$ axis is about 60% of that perpendicular to the $c$ axis. The hole saturation velocity parallel to the $c$ axis is about 80% of that perpendicular to the $c$ axis.

In conclusion, the electric-field dependence and anisotropy of the impact ionization coefficients of 4H-SiC are obtained. The obtained impact ionization coefficients show large anisotropy; the impact ionization coefficients in (1120) direction are larger than those in the (0001) direction and the asymmetry of the electron and hole-ionization coefficients in the (0001) direction is smaller than that in the (1120) direction. The anisotropy of the impact ionization coefficients is originated from the anisotropic electronic structure or crystal structure of 4H-SiC.

This work was performed under the management of FED as part of a Ministry of Economy, Trade and Industry (METI) Project (R&D Research and Development of Ultra-Low-Loss Power Device Technologies) supported by the New Energy and Industrial Technology Development Organization (NEDO).

8K. Hess, Monte Carlo Device Simulation: Full Band and Beyond (Klumer, Boston, 1991), Chap. 2.