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Analytical model of electron transport characteristics for 4H-SiC material and devices*

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Based on 4H-SiC material parameters, three different analytical expressions are used to characterize the electron mobility as the function of electric field. The first model is based on simple saturation of the steady-state drift velocity with electric field (conventional three-parameter model for silicon). The second GaAs-based mobility model partially reflects the peak velocity in high electric fields. The third multi-parameter model proposed in this paper is more realistic since it well reproduces the drift velocity–field characteristics obtained by Monte Carlo calculations, revealing the peak drift velocity with subsequent saturation at higher electric fields. Thus, the drift velocity model presented in this paper is much better for device simulation. In this paper, the influence of mobility model on DC characteristics of 4H-SiC MESFET is calculated and the better accordance with the experimental results is presented with multi-parameter model.

Keywords: SiC, mobility, velocity–field characteristics, MESFET
PACC: 7210, 7220, 7280, 6185

1. Introduction

Because of its excellent properties, 4H-SiC is considered as one of the most promising materials for high-power, high-temperature and high-frequency applications.[1,2] To achieve reliable simulation and modelling for SiC-based electron devices, the mobility and velocity–field relationship are the most important parameters, which have great influence on the I–V characteristics, switch speed and frequency property of devices. In a recent report, Khan and Cooper presented the measurement of velocity of electrons in 6H- and 4H-SiC at room temperature and elevated temperatures using the conductance technique.[3] Nilsson *et al* investigated the high field transport properties using full band MC models and presented reliable data at higher field.[4] Roschke and Schwierz [5] and Huang *et al*[6] have established numerical and analytical models for the SiC MESFET.

The reported models have not taken the high field velocity and its influence on I–V characteristics into account. Since SiC power devices are designed to work at up to 50 volts, simple and accurate high field transport models consistent with other device models are demanded. In this paper, the empirical expressions for electron mobility as a function of electric field are summarized and a new multi-parameter model is presented for 4H-SiC material. With the Matlab program, the fitting parameters in the model are extracted and implemented into a MESFET device model. The influence of transport models on 4H-SiC MESFET is simulated with the present model.

2. Low-field mobility models

At low electric field, the following scattering processes are considered: acoustic phonon scattering, polar optical phonon scattering, zero and first order optical intervalley phonon scattering, and ionized impurity scattering. A widely used empirical expression as a function of impurity and temperature has been given as

$$\mu_0 = \mu_{\min} + \frac{\mu_{\max}\left(\dfrac{T}{300}\right)^{x} - \mu_{\min}}{1 + \left(\dfrac{T}{300}\right)^{y}\left(\dfrac{N_{\rm D}^{+}}{N_{\rm ref}}\right)^{\alpha}}, \qquad (1)$$

where $N_{\rm D}^{+}$ is the ionized impurity concentration, and $\mu_{\max}$, $\mu_{\min}$, $N_{\rm ref}$ and α are fitting parameters. x and y are parameters reflecting the influence of temperature on mobility. The values of the parameters for 4H-SiC material are shown in Table 1.

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Table 1. Low-field mobility model parameters.

$\mu_{max}/(cm^2/(V\cdot s))$	$\mu_{min}/(cm^2/(V\cdot s))$	N_{ref}/cm^{-3}	x	y	α
40	950	2×10^{17}	−2.4	1.05	0.76

With the above model, we obtain the dependence of mobility on impurity as shown in Fig.1. The mobility is decreasing with high doping due to the increasing number of impurity scatterings. The simulated mobility is in good accordance with the mobility measured.[7−9] With the increasing temperature, the mobility decreases for two reasons: the increasing carrier energy and the number of phonons. This results in an increase in the number of scatterings and the scattering energy. The mobility therefore decreases with increasing temperature. Figure 2 shows the comparison of the modelling results and the experimental data from Refs.[7, 8] and MC results from Ref.[9]. Bulk mobility in materials with three different doping concentrations shows a decreasing trend when temperature increases.

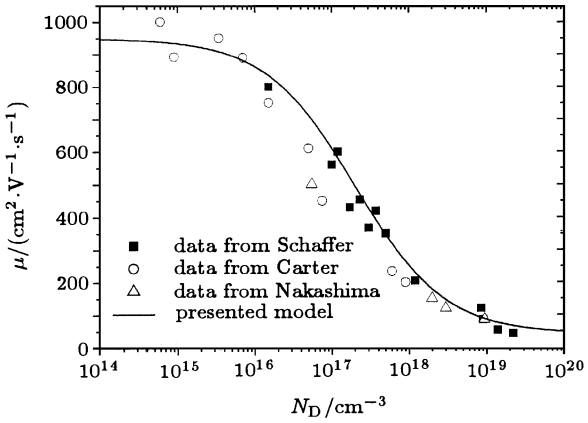


Fig.1. The dependence of mobility of 4H-SiC on doping concentration (at 300K).

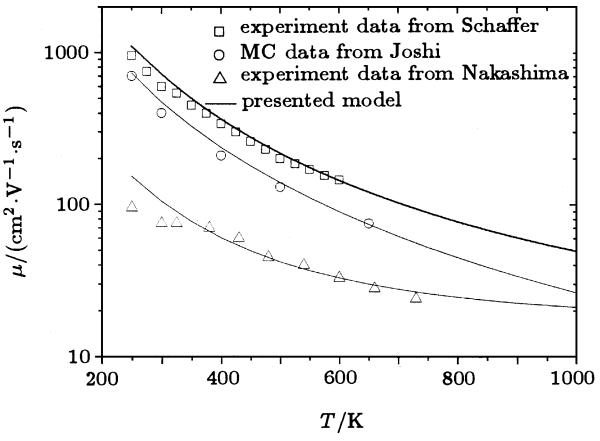


Fig.2. The dependence of bulk mobility of 4H-SiC with different doping concentration on temperature.

3. High field mobility model

To describe the electron mobility as a function of electric field $\mu(E) = v(E)/E$, we use three analytical expressions for the velocity–field characteristics $v(E)$:

$$v(E) = \mu_0 E\left[1+\left(\frac{\mu_0 E}{v_{sat}}\right)^{\beta}\right]^{-1/\beta}, \tag{2}$$

$$v(E) = \frac{\mu_0 E + v_{sat}\left(\frac{E}{E_{on}}\right)^4}{1+\left(\frac{E}{E_{on}}\right)^4}, \tag{3}$$

$$v(E) = \frac{\mu_1 E + \mu_0 E\left(\frac{E}{E_0}\right)^{\theta} + v_{sat}\left(\frac{E}{E_1}\right)^{\eta}}{1+\left(\frac{E}{E_0}\right)^{\theta}+\left(\frac{E}{E_1}\right)^{\eta}}. \tag{4}$$

The validity of applying this mobility model is based on the fact that it well reproduces the experimentally measured mobility field characteristics. Equations (2) and (3) are three-parameter mobility models, which are purely empirical and conventionally used in the simulation of electron devices using narrow bandgap materials such as Si and GaAs. They can reproduce the mobility field characteristics at low field and high field respectively, but neither of them can reflect the linear characteristics at low field and peak velocity at high field simultaneously (Figs.3 and 4).

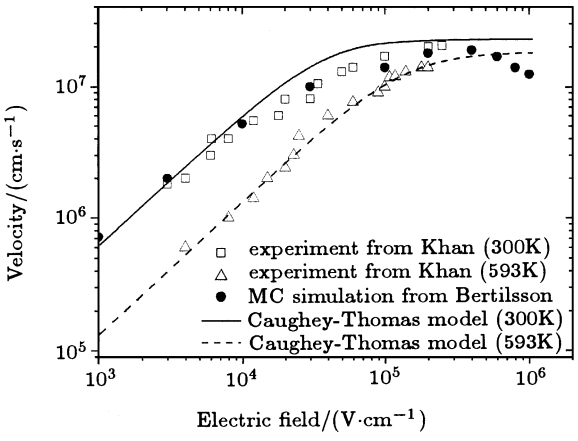


Fig.3. The velocity–field characteristic calculated with the Caughey–Thomas model.

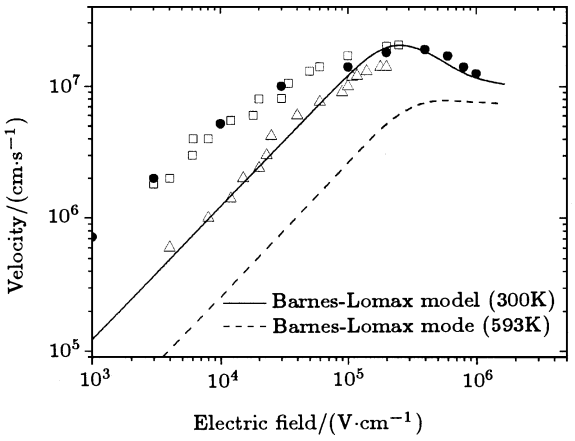


Fig.4. The velocity–field characteristic calculated with the Barnes–Lomax model.

In contrast, for the wide bandgap semiconductor SiC, the multi-parameter model given by Eq.(4) is better justified, since it reproduces a general behaviour of the velocity–field characteristics obtained by experiment measurements and the MC electron transport simulation results (Fig.5). The latter reveals the presence of a velocity peak, which is higher than the saturation velocity, at least at room temperature (300K) and at typical doping level of 10^{17}cm^{-3}.

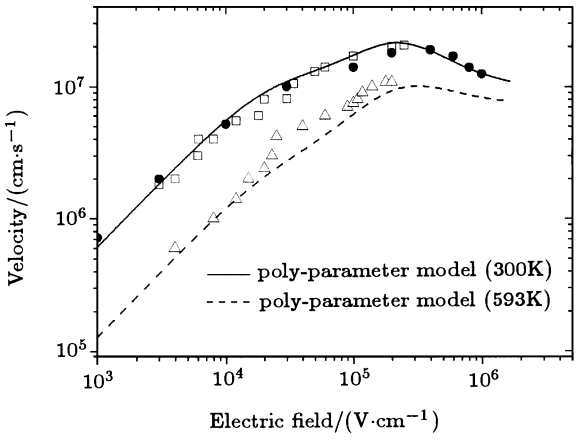


Fig.5. The comparison of the velocity–field characteristic from multi-parameter model with experiments and MC result.

Table 2. Parameters in multi-parameter model.

μ_1/(cm^2/(V·s))	E_0/(V/cm)	E_1/(V/cm)	θ	η
μ_0×0.17	3.05×10^4	2.8×10^5	–1.95	3

The parameters μ_1, E_0, E_1, θ and η are influencing factors on peak velocity, peak electric field and the steepness of $v(E)$ in the saturation region. Their fitting values are shown in Table 2. Figure 5 shows the velocity–field characteristics $v(E)$ generated by expression (4). With the increasing electric field (1×10^3–2×10^{5}V/cm), drift velocity increases monotonically (7×10^5–2.1×10^{7}cm/s). At high electric field of 2.5×10^{5}V/cm, drift velocity reaches it peak value 2.18×10^{7}cm/s. When the electric field increases further (2.8×10^5–1×10^{6}V/cm), the drift velocity decreases from 2.18×10^7 to 1.3×10^{7}cm/s. Thus, the MC transport data can be well fitted by Eq.(4) for a subsequent device simulation.[10]

Figure 6 shows the experimentally measured[11] and calculated DC current–voltage (I–V) characteristics for a 4H-SiC MESFET at gate-source voltage of V_{gs}=0V. In the current–voltage curves calculated with three electron field-dependent mobility models, an appreciable difference can be observed. At about V_{ds}=28V, there is a crossing point of the I–V curves calculated with (2)–(4). The higher drain current for mobility model (2) up to the drain-source voltage of 28V can be explained by a larger initial slope of the velocity–field characteristics compared to that of the mobility model (3) and (4). For higher drain-source biases the drift velocity of model (4) exceeds the saturation level and crossing of the I–V curves occurs. These results show that the simulation of 4H-SiC FETs require not only precise values of the low-field mobility and the saturation velocity, but also the actual shape of the velocity–field characteristics over the whole range of electric field.

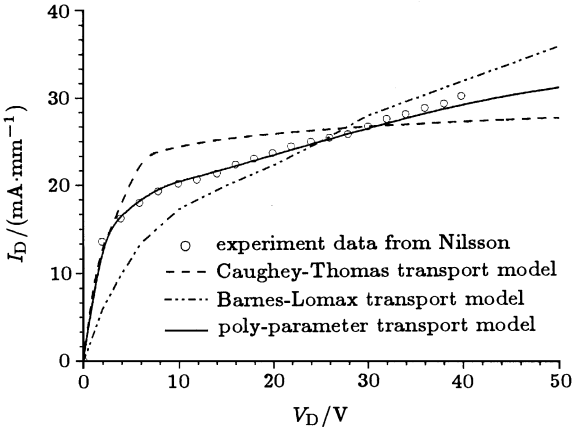


Fig.6. The experimentally measured and calculated I–V characteristics of 4H-SiC MESFET.

4. Conclusion

For 4H-SiC material and devices, three different analytical models and velocity–field characteristics are presented. Compared to the experimental Caughey–Thomas and Barnes–Lomax models, the multi-parameter model presented in this paper can well reproduce the drift velocity–field characteristics

obtained by experiments and Monte Carlo calculations, accurately reflecting the transport property of 4H-SiC at high as well as low electric field. The analytical model can be implemented in the device model directly to simulate 4H-SiC FETs over the whole range of applied voltage and electric field.

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