Vol 17 No 4, April 2008
1674-1056/2008/17(04)/1410-05

Chinese Physics B

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Electrothermal simulation of the self-heating effects in 4H-SiC MESFETs*

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(Received 24 June 2007; revised manuscript received 5 November 2007)

A thermal model of 4H-SiC MESFET is developed based on the temperature dependences of material parameters and three-region $I-V$ model. The static current characteristics of 4H-SiC MESFET have been obtained with the consideration of the self-heating effect on related parameters including electron mobility, saturation velocity and thermal conductivity. High voltage performances are analysed using equivalent thermal conductivity model. Using the physical-based simulations, we studied the dependence of self-heating temperature on the thickness and doping of substrate. The obtained results can be used for optimization of the thermal design of the SiC-based high-power field effect transistors.

Keywords: 4H-SiC, MESFET, self-heating, analytic model
PACC: 7340S, 7220J

1. Introduction

Silicon carbide is a very promising candidate for high temperature, high power, high frequency, relatively low noise and radiation hardness applications due to its excellent physical properties such as a wide bandgap, high breakdown voltage, high thermal conductivity, and high saturation electron drift velocity. With excellent figure of merits compared with other types of SiC, 4H-SiC metal semiconductor field effect transistor (MESFET) is a potential candidate for the applications in HDTV systems, phased array radars and next generation mobile communication base station.[1]

For high-power microwave applications, dissipation of heat flow has been always problematical and the device output power is reduced due to self-heating effect.[2] Despite the high thermal conductivity of the material, SiC power devices may suffer from severe self-heating when operating at very high power levels. As lattice temperature increases, the concentration, generation/recombination, mobility and many other physical parameters of carriers will change accordingly. To illustrate this fact, SiC MESFETs operating at $V_{\rm D}$=50V has been measured by Royet[3] and the temperature increment in device has estimated to be up to 100K. The thermal characteristics of S-band silicon carbide monolithic microwave integrated circuits (MMICs) have been investigated by Mittereder[4] with high resolution atomic force thermal microscopy measurements and infrared measurements and the maximum temperature near the channel area of the device reached 445 K. It is necessary to develop an analytical model for 4H-SiC MESFETs, which is clear in device mechanism description and simple in calculation to be suitable for the design and optimization of thermal issues of 4H-SiC devices.[5]

In this paper, the temperature characteristics of SiC material is investigated first and the self-heating effect in 4H-SiC MESFET is analysed using an equivalent thermal conductivity model. The influence of the substrate thickness on device performance is estimated with this model. The simulation results agree well with the published experimental data.

2. Thermal properties of the material

2.1. Effective mass and carrier concentration

The experimentally determined electron effective masses for 4H-SiC are $m(M\Gamma) = 0.58 \pm 0.01 m_0$,

*Project supported by the National Natural Science Foundation of China (Grant No 60606022) the State Key Development Program for Basic Research of China (Grant No 51327010101) and Xi'an Applied Materials Innovation Fund, China (Grant No XA-AM-200702).

$m(MK) = 0.31 \pm 0.01 m_0$, $m(ML) = 0.33 \pm 0.01 m_0$.[6] Compared with 3C- and 6H-SiC, the relatively smaller electron effective mass of 4H-SiC is better for electronic applications. The electron density-of-states (DOS) effective mass of 4H-SiC becomes

$$m_c = (3^2 m(M\Gamma) m(MK) m(ML))^{1/3} m_0 = 0.76 m_0. \quad (1)$$

The top of the valence bands of 4H-SiC consists of three separate bands and their DOS effective mass are m_{v1}=0.81m_0, m_{v2}=0.79m_0 and m_{v3}=0.78m_0 respectively. The DOS effective mass of holes becomes

$$m_v(T) = \left[0.84^{3/2} + 0.79^{3/2} \exp\left(-\frac{0.009}{kT}\right) + 0.78^{3/2} \exp\left(-\frac{0.073}{kT}\right)\right]^{2/3} m_0. \quad (2)$$

The effective DOS in the conduction and valence bands of 4H-SiC can be evaluated as

$$N_c = \frac{4\pi m_c kT}{h^2} \quad \text{and} \quad N_v = \frac{4\pi m_v kT}{h^2}.$$

The intrinsic carrier concentration at thermal equilibrium is given by

$$n_i = (N_c N_v)^{1/2} \exp\left(-\frac{E_g(T)}{2kT}\right). \quad (3)$$

Donors in 4H-SiC have two energy levels corresponding to two different crystal sites, hexagonal site and quasi-cubic site. Since the ionization energy levels are too large for complete ionization at room temperature, 4H-SiC shows incomplete ionization phenomena at low temperature (< 350 K). In the effective-mass approximation, the multivalley band structure induces a valley–orbit splitting. Taking into account the two inequivalent lattice sites and the valley-orbit splitting at the hexagonal site, the ionized shallow donor concentration can be obtained

$$N_D^+ = \frac{N_{D1}}{1 + g_c \exp\left(\frac{E_F - E_{D1}(x) - \Delta E}{kT}\right)} + \frac{N_{D2}}{1 + g_c \exp\left(\frac{E_F - E_{D2}(x) - \Delta E}{kT}\right)}, \quad (4)$$

$$\Delta E = q\sqrt{\frac{qE_0}{\pi\varepsilon\varepsilon_0}}, \quad (5)$$

where g_c=2 is the donor degeneracy factor, ΔE the reduction of the ionization energy due to the Frenkel–Pool effect. N_{D1} is the hexagonal site concentration with E_{D1}=0.066 eV, and N_{D2} is the quasi-cubic site concentration with E_{D2}=0.124 eV. Figure 1 shows the calculated ionization ratio as a function of temperature in 4H-SiC with N_D=1.15×10^{17}cm^{-3}. It can be seen that the ionization ratio increases with increasing temperature and electric field obviously.

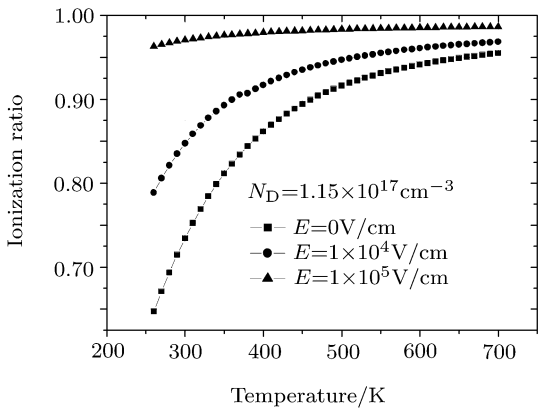


Fig.1. The calculated ionization ratio as a function of temperature for different electric fields applied.

2.2. Mobility & velocity-field dependence

At low electric fields, the following scattering processes are considered: acoustic phonon scattering, polar optical phonon scattering, zero- and first- order optical intervalley phonon scatterings, and ionized impurity scattering. The widely used empirical model as a function of impurity and temperature is

$$\mu_0 = \mu_{min} + \frac{\mu_{max}\left(\frac{T}{300}\right)^x - \mu_{min}}{1 + \left(\frac{T}{300}\right)^y \left(\frac{N_D^+}{N_{ref}}\right)^\alpha}, \quad (6)$$

where N_D^+ is the ionized impurity concentration, μ_{max} and μ_{min} and N_{ref} are fitting parameters. X and y are parameters indicate the influence of temperature on mobility.

To describe the electron mobility as a function of electric field $\mu(E) = v(E)/E$, a multiparameter model is developed for the velocity-field characteristic.

$$v(E) = \frac{\mu_1 E + \mu_0 E\left(\frac{E}{E_0}\right)^\theta + v_{sat}\left(\frac{E}{E_1}\right)^\eta}{1 + \left(\frac{E}{E_0}\right)^\theta + \left(\frac{E}{E_1}\right)^\eta}, \quad (7)$$

where the parameters μ_1, E_0, E_1, θ and η are influence factors on peak velocity, peak electric field and the steepness of $v(E)$ in the saturation region. Their fitting values are shown in Table 1.

Table 1. Parameters in mobility models.

Low field model	Velocity-field model
μ_{max} = 40(cm^2/Vs)	μ_1 =μ_0×0.17(cm^2/Vs)
μ_{min} = 950(cm^2/Vs)	E_0 = 3.05×10^4(V/cm)
N_{ref} = 2×10^{17}(cm^{-3})	E_1 =2.8×10^5(V/cm)
x=–2.4	θ =–1.95

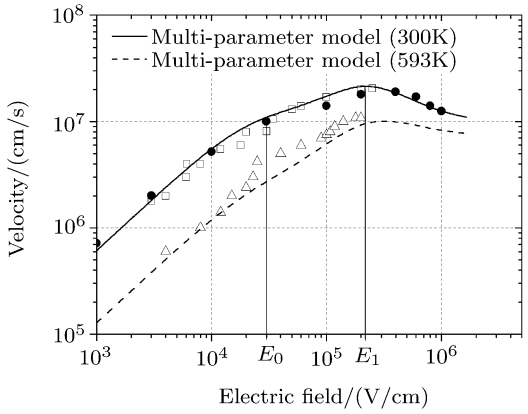


Fig.2. The velocity-field characteristic from Multi-parameter modelling, experiment and MC modelling.

Figure 2 shows that the modelling results reproduce a general behaviour of the velocity-field characteristics obtained by both the experiment measurements[7] and the Monte Carlo (MC) electron transport simulation results.[8]

2.3. Thermal conductivity

Generally, the thermal conductivity of SiC exceeds that of copper, silver and Al_2O_3. This is mainly due to the phonon dispersion distribution in SiC. The temperature-dependent thermal conductivities of 4H-SiC can be described as

$$K(T) = K_0(T/300)^{-1.5}, \tag{8}$$

where K_0 is a fitting coefficient depending on the doping concentration.

$$K_0 = a_0 + a_1 \log Nd + a_2(\log Nd)^2. \tag{9}$$

The simulation results using the above model agree well with the published experimental data[9] (in Fig.3).

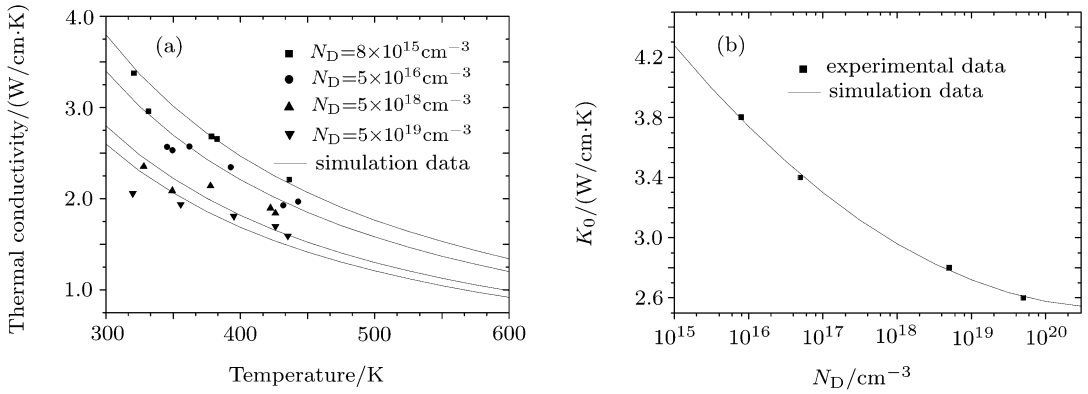


Fig.3. The dependence of the calculated thermal conductivity on temperature and carrier concentration (a) and the fitted K_0 as a function of carrier concentration (b).

3. Device self-heating model

Previous publications have developed a three-region model for 4H-SiC MESFET $I-V$ characteristics.[10] Based on this model and the above material properties, a self-heating model can be presented here. When thermal conducts in a single material, the temperature shows a linear distribution.[11] The temperature in the device between the region of the heat generation and the thermal sink is

$$T(y) = T_0 + y\frac{\Delta T}{t_{sub}}, \tag{10}$$

where y is the distance from the top of the substrate down to the backside contact, t_{sub} is the thickness of the substrate, T_0 is the room temperature and ΔT is the temperature difference between the device and the backside. The equivalent thermal conductivity is

$$\bar{K} = \frac{\int_0^{t_{\rm sub}} K(T)\mathrm{d}y}{t_{\rm sub}} = K_0 \frac{300}{0.5\Delta T}\left(\sqrt{\frac{300}{T_0}} - \sqrt{\frac{300}{T_0+\Delta T}}\right). \quad (11)$$

The quantity of power P_0 is

$$P_0 = \frac{\pi K(T_0) W T_0}{\ln(8t_{\rm sub}/\pi L)}. \quad (12)$$

With Kirchoff's transformation, ΔT is given by

$$\frac{\Delta T}{T0} = \frac{1-(1-P_{\rm diss}/4P_0)^4}{(1-P_{\rm diss}/4P_0)^4}, \quad (13)$$

where $P_{\rm diss}$ is power dissipation in the device. The increment of the temperature is assessed by solving iteratively the $I(V_{\rm DS}, V_{\rm GS})$ and ΔT. First, the drain current is calculated assuming a device temperature at T_0. Then, the corresponding power dissipation is inserted into Eq.(13). This gives a new device temperature which is used to calculate a new current value. This calculation process is iterated until a satisfactory convergence is reached.

The $I-V$ characteristics and self-heating temperature ΔT in 4H-SiC MESFET are shown in Fig.4 where the lines describe the calculated results and the symbols denote the experimental data from Ref.[3]. For a high dissipated power, the differential conductance $g_{\rm d}$ is clearly negative. This could be ascribed to the self-heating effects rather than trapping effects. The influence on the $I-V$ characteristics in our results is stronger at higher drain voltage while the trapping effects will disappear with increasing drain voltage.[12]

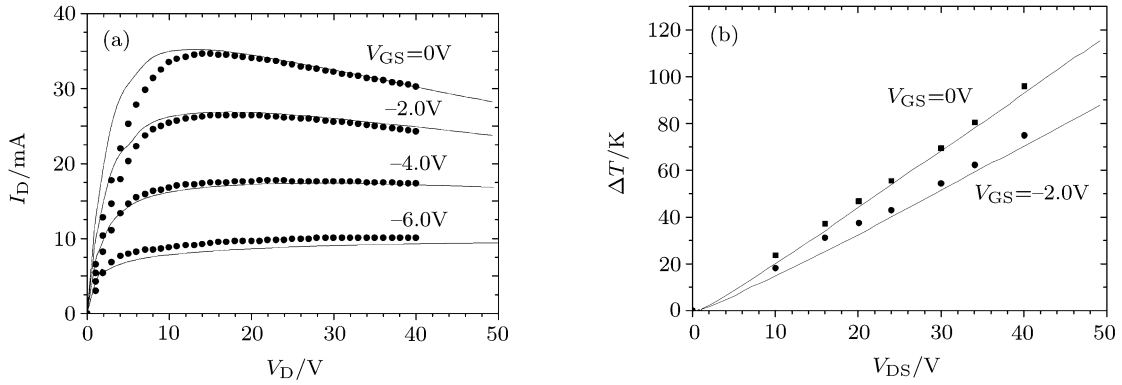


Fig.4. The $I-V$ characteristics (a) and self-heating temperature (b) in 4H-SiC MESFET.

The model can also be used to predict the influence of various physical or geometrical parameters. The variation of ΔT with the substrate thickness and doping concentration are simulated for a MESFET with a geometry similar to that of the experimental devices.[3] It can be seen from Fig.5 that substrate thinning should provide an improvement with respect to the current drive capability. With the $t_{\rm sub}$ varying from 400 μm down to the 50 μm, ΔT decreases from 150 to 125 K ($N_{\rm sub}$=1×10^{16}cm^{-3}). Also we can see from this figure, the self-heating effects are suppressed by using lightly doped substrate. This is due to the correlation between the equivalent thermal conductivity and the carrier concentration.

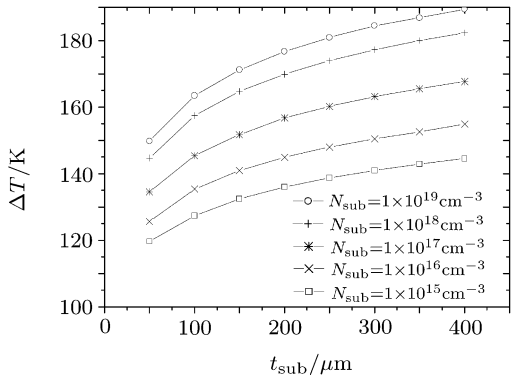


Fig.5. The dependence of ΔT on substrate thickness.

4. Conclusion

A physics-based model of large-signal $I-V$ characteristics of 4H-SiC MESFET is presented in this paper. The model incorporated the equivalent thermal conductivity and multi-parameter mobility for self-heating simulation. The calculated results are in excellent agreement with the experimental data.

The influence of the substrate thickness and doping concentration on device high-power performance are analysed. Significant improvement in device electrical and thermal characteristics is observed for thinner and lightly doped substrate.

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