Vol 12 No 1, January 2003
1009-1963/2003/12(01)/0089-05

Chinese Physics

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Theoretical investigation of incomplete ionization of dopants in uniform and ion-implanted 4H-SiC MESFETs*

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(Received 19 April 2002; revised manuscript received 24 September 2002)

The effects of incomplete ionization of nitrogen in 4H-SiC have been investigated. Poisson's equation is numerically analysed by considering the effects of Poole–Frenkel, and the effects of the potential on $N_{\rm d}^{+}$ (the concentration of ionized donors) and n (the concentration of electrons). The pinch-off voltages of the uniform and the ion-implanted channels of 4H-SiC metal-semiconductor field-effect transistors (MESFETs) and the capacitance of the gate are given at different temperatures. Both the Poole–Frenkel effect and the potential have influence on the pinch-off voltage $V_{\rm p}$ of 4H-SiC MESFETs. Although the C-V characteristics of the ion-implanted and the uniform channel of 4H-SiC MESFETs have a clear distinction, the effects of incomplete ionization on the C-V characteristics are not significant.

Keywords: silicon carbide, ion implantation, pinch-off voltage, C-V characteristics
PACC: 7155, 7155D, 7850G

List of symbols

a: channel depth (μm),
$g_{\rm C}$: degeneracy factor,
k: Boltzmann constant (J·K^{-1}),
m_n: effective mass of electron of 4H-SiC (kg),
n: concentration of electrons (cm^{-3}),
p: concentration of holes (cm^{-3}),
q: electronic charge (C),
$v_{\rm s}$: electron saturation velocity of 4H-SiC (cm/s),
x: direction along which ions are implanted (μm),
y: direction from source to drain along the channel (μm),
C: capacitance (F/cm^2),
E: field along which ions are implanted (V/cm),
$E_{\rm D}(E_{{\rm D}i})$: donor level (eV),
$E_{\rm F}$: Fermi level of 4H-SiC (eV),
$M_{\rm C}$: dimensionless quantity,
$N_{\rm a}(N_{\rm a}^{-})$: concentration of acceptor (cm^{-3}),
$N_{\rm d}(N_{\rm d}^{+})$: concentration of donors (cm^{-3}),
$N_{\rm A}$: acceptor concentration (cm^{-3}),
$N_{\rm C}$: density of states in the conduction band (cm^{-3}),
$Q(Q_{\rm i})$: implanted dose (cm^{-2}),
$R_{\rm p}(R_{\rm pi})$ implant range parameter (μm),
T: temperature (K),
V_y: channel voltage (V),
$V_{\rm A}$: applied bias voltage (V),
$V_{\rm D}$: build-in voltage of PN junction (V),
$V_{\rm p}$: pinch-off voltage (V),
W: depletion layer thickness under gate (μm),
α: dimensionless quantity,
β: activation rate of ions,
χ: electron affinity of 4H-SiC (eV),
χ_n: thickness of the depletion layer in the n-region (μm),
$\varepsilon_{\rm s}$: permittivity of 4H-SiC (F/cm),
$\sigma(\sigma_{\rm i})$: implant straggle parameter (μm),
μ: electron mobility of 4H-SiC (cm^2/Vs),
μ_0: low-field electron mobility (cm^2/Vs),
$\rho(x)$: effective carrier concentration at a distance x from surface (cm^{-3}),
ψ: potential (V),
$\Delta E_{\rm F}$: Fermi level difference between metal and 4H-SiC.

1. Introduction

Much attention has been given to silicon car-

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bide (SiC),[1,2] which possesses outstanding properties, such as wide bandgap, high breakdown field, and saturation–electron drift velocity, and has been used to fabricate high-temperature, high-power, and high-speed devices. On the energy point of view, the impurities in 4H-SiC (also 6H polytype) have relatively high value of ionization energies of N (45–127 meV),[3,4] Al (189–266 meV),[3,5] B (>300 meV).[3,5] So either donors or acceptors in 4H-SiC are not completely ionized at room temperature. The incomplete ionization of the impurities doped in SiC can affect the characteristics of metal-semiconductor field-effect transistors (MESFETs), such as the pinch-off voltage, and the capacitance of the gate. Accurate knowledge of the effects of incomplete ionization is vital to the design and performance of 4H-SiC MESFETs. Ion implantation of dopants has been recognized as a crucial means of selective area doping because thermal diffusion rates of most dopants are very slow in SiC at temperatures lower than 1800–2000°C. A number of experimental[6,7] and theoretical[8–10] investigations have been carried out by various workers, in which the effects of ion implantation on SiC device characteristics were studied. As one of the essential parts of fabrication technologies for SiC devices, it is urgent to study the effects of incomplete ionization on SiC MESFETs of ion-implanted channels.

In this paper we investigate the effects of incomplete ionization on the pinch-off voltages of SiC MESFETs in the uniform and ion-implanted channels. The capacitances of the gates of the uniform and ion-implanted channels are given comparatively. The effects of temperature are also considered.

2. Theory

2.1. Pinch-off voltage $V_{\rm p}$ and C-V characteristics

One-dimensional (1D) Poisson's equation can be written as

$$\frac{{\rm d}^2\psi}{{\rm d}x^2} = -\frac{q\rho(x)}{\varepsilon_{\rm s}}, \tag{1}$$

where

$$\rho(x) = N_{\rm d}^+ - n - N_{\rm a}^- + p. \tag{2}$$

Taking into account the effects of Poole–Frenkel and the potential on the ionization, the concentration of free electrons and the concentration of ionized donor are

$$n = N_{\rm C}\exp\left(-\frac{E_{\rm C}-E_{\rm F}}{kT}\right)\exp\left(\frac{q\psi}{kT}\right), \tag{3}$$

$$N_{\rm d}^+ = \frac{N_{\rm D1}}{1+g_{\rm C}\exp\left(\dfrac{E_{\rm F}-E_{\rm D1}}{kT}\right)\exp\left(-\dfrac{\Delta E_{\rm D}}{kT}\right)\exp\left(\dfrac{q\psi}{kT}\right)} + \frac{N_{\rm D2}}{1+g_{\rm C}\exp\left(\dfrac{E_{\rm F}-E_{\rm D2}}{kT}\right)\exp\left(-\dfrac{\Delta E_{\rm D}}{kT}\right)\exp\left(\dfrac{q\psi}{kT}\right)}, \tag{4}$$

where the change of activation energy of the Poole–Frenkel effect[11] is

$$\Delta E_{\rm A} = q\sqrt{\frac{qE}{\pi\varepsilon_{\rm s}}}. \tag{5}$$

With the boundary conditions $\psi(h)=0$ and $\dfrac{{\rm d}\psi}{{\rm d}x}(h)=0$, we can have $\psi(x)$. So the pinch-off voltage is

$$V_{\rm p} = \frac{\Delta E_{\rm F}}{q} - \psi(0)|_{h=a}. \tag{6}$$

The capacitance of Schottky barrier diodes of the gates is

$$C = \frac{\varepsilon_{\rm s}}{W}. \tag{7}$$

The voltage applied, from Eq.(1), can be written as

$$V_{\rm D} - V = \int_0^W \int_\xi^W \frac{q\rho(x)}{\varepsilon_{\rm s}}{\rm d}x{\rm d}\xi. \tag{8}$$

2.2. Concentration of donors $N_{\rm d}$

In order to obtain simulation results, we assume a triple-implanted 4H-SiC MESFET. Nitrogen ions are implanted at energies and doses of 55 keV and $1.07\times10^{13}\,{\rm cm}^{-2}$, 100 keV and $1.53\times10^{13}\,{\rm cm}^{-2}$, 160 keV and $1.95\times10^{13}\,{\rm cm}^{-2}$. The location of peak concentration and the longitudinal straggling of N are calculated using the Monte Carlo simulator TRIM.[12] The activation rate of N is assumed to be about 10%.

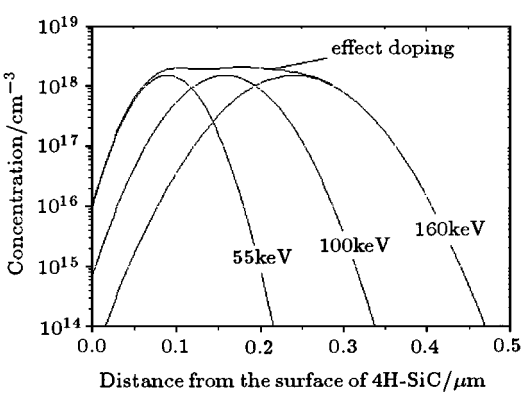


Fig.1. Simulated ion implantation profiles for N implanted into 4H-SiC.

Figure 1 shows the ion implantation profiles using the Gaussian model to express the ion implantation range, which is expected to result in an effective doping concentration of $1.5\times10^{17}\,\mathrm{cm}^{-3}$. The impurity concentration in the ion-implanted channel of the MESFETs after nitrogen activation by annealing can be given as

$$N_{\mathrm{d}} = \sum_{i=1}^{n} \frac{\beta Q_{\mathrm{i}}}{\sqrt{2\pi}\sigma_{\mathrm{i}}} \exp\left[- \left(\frac{x - R_{\mathrm{pi}}}{\sqrt{2}\sigma_{\mathrm{i}}} \right)^2 \right]. \tag{9}$$

The distance x_a from the SiC surface to the intrinsic point at which

$$qN_{\mathrm{A}} = \frac{q\beta Q_3}{\sqrt{2\pi}\sigma_3} \exp\left[- \left(\frac{x_a - R_{\mathrm{p3}}}{\sqrt{2}\sigma_3} \right)^2 \right] \tag{10}$$

can be calculated by

$$x_a = R_{\mathrm{p3}} + \sigma_3 \sqrt{2 \ln \frac{\beta Q_3}{\sqrt{2\pi}\sigma_3 N_{\mathrm{A}}}}. \tag{11}$$

PN junctions between the buffer (the epitaxial layer) and the channel of a MESFET is an abrupt junction. So the thickness of the depletion layer in the n-region is

$$x_n = \left[\frac{2\varepsilon_{\mathrm{s}} N_{\mathrm{A}}}{q(n + N_{\mathrm{D}})n} (V_{\mathrm{D}} - V_{\mathrm{A}}) \right]^{1/2}. \tag{12}$$

Thus the channel depth a is determined by

$$a = x_a - x_n. \tag{13}$$

2.3. Effects of temperature

The temperature dependence of the saturation velocity v_{s} is given as [13]

$$v_{\mathrm{s}} = \frac{v_{\mathrm{s}}(0)}{1 + 0.8\exp\left(\dfrac{T}{600} \right)}. \tag{14}$$

For 4H-SiC, $v_{\mathrm{s}}(0)$ is $5.8\times10^7\,\mathrm{cm/s}$ calculated from $v_{\mathrm{s}}(300)=2\times10^7\,\mathrm{cm/s}$.[14] The low-field drift mobility is modelled by the Caughey–Thomas equation[16,17]

$$\mu = \mu_{\min} + \frac{\mu_{\max} - \mu_{\min}}{1 + \left(\dfrac{N_{\mathrm{D}} + N_{\mathrm{A}}}{N_{\mathrm{ref}}} \right)^r} \left(\frac{T}{300K} \right)^{\alpha}, \tag{15}$$

where $\mu_{\min}=40\,\mathrm{cm}^2/\mathrm{Vs}$, $\mu_{\max}=800\,\mathrm{cm}^2/\mathrm{Vs}$, $N_{\mathrm{ref}}=4.0\times10^{17}\,\mathrm{cm}^{-3}$, and $\alpha=0.44$. The energy gap of 4H-SiC is written as[13,15]

$$E_{\mathrm{g}}(T) = E_{\mathrm{g}}(300) - 3.3\times10^{-4}(T - 300), \tag{16}$$

where $E_{\mathrm{g}}(300)=3.26\,\mathrm{eV}$. The electron affinity χ is[16]

$$\chi(T) = \chi(300\mathrm{K}) - \frac{1}{2}[E_{\mathrm{g}}(T) - E_{\mathrm{g}}(300)], \tag{17}$$

where $\chi(300)=3.7\,\mathrm{eV}$.

Temperature-dependent parameters are shown below without giving unnecessary details.[17]

$$n = N_{\mathrm{C}} \exp\left(- \frac{E_{\mathrm{C}} - E_{\mathrm{F}}}{kT} \right), \tag{18}$$

$$N_{\mathrm{C}} = 2M_{\mathrm{C}} \frac{(2\pi m_n kT)^{3/2}}{h^3}. \tag{19}$$

3. Simulation, results, and discussions

The concentration of donors N_{d} of the uniform channel is also $1.5\times10^{17}\,\mathrm{cm}^{-3}$ in order to make a comparison of other data. The concentrations of nitrogen for the cubic and hexagonal lattice sites N_{d1} and N_{d2} are equal. The ionization energies of them are 45 and 100 meV respectively.[4] Fig. 2 presents the concentrations of ionized donors N_{d}^+ and free electrons n as functions of the potential. From Eqs.(3) and (4) without Poole–Frenkel effect, n and N_{d}^+ at 300K are $1.1\times10^{17}\,\mathrm{cm}^{-3}$, corresponding to an ionization rate of 73%. The calculated concentrations of ionized donors N_{d}^+ and free electrons n as functions of the potential indicate that a complete ionization of donors can be achieved, and the free electrons are close to depletion at the potential higher than 0.1 V. So the depletion mode of Poisson's equation will induce errors when the impurities are incompletely ionized.

Considering the temperature-dependent parameters, we obtain the curves of the influence of Poole–Frenkel effect on the pinch-off voltages V_{p} of the ion-implanted and the uniform channels, as shown in Figs.3 and 4 respectively. The simulated values of the pinch-off voltage V_{p} with the Poole–Frenkel effect have been found to be lower than those without the Poole–Frenkel effect. From this point of view, the Poole–Frenkel effect cannot be ignored. With increasing temperature, the changes in the pinch-off voltages with and without the Poole–Frenkel effect decrease.

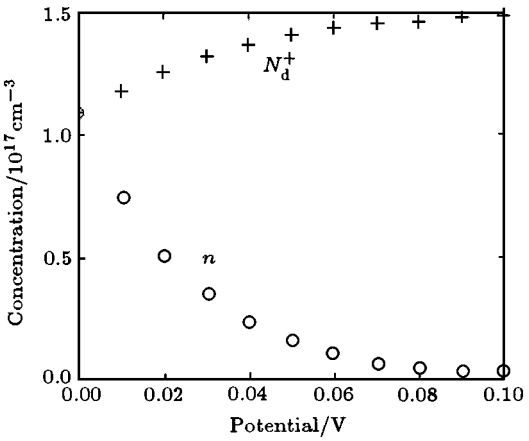


Fig.2. The effects of the potential on the concentrations of ionized donors N_d^+ and free electrons n.

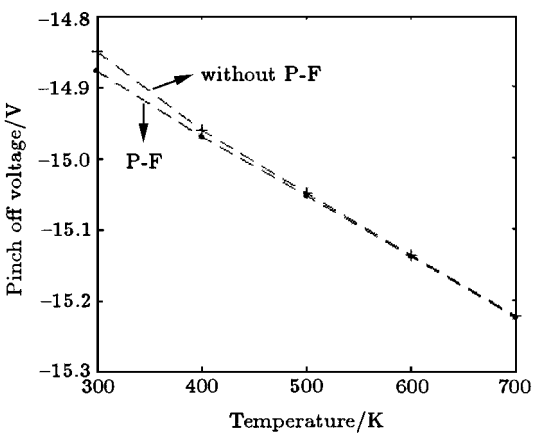


Fig.3. The pinch-off voltage V_p of 4H-SiC MESFETs in the ion-implanted channel versus temperature with and without the Poole–Frenkel effect.

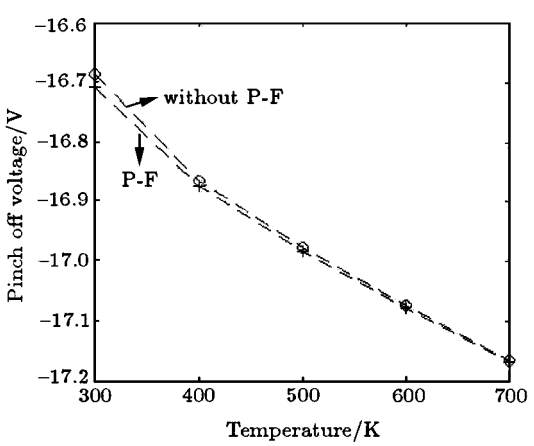


Fig.4. The pinch-off voltage V_p of 4H-SiC MESFETs in the uniform channel versus temperature with and without the Poole–Frenkel effect.

Figures 5 and 6 show the simulated pinch-off voltages V_p of the ion-implanted and the uniform impurity channels of 4H-SiC MESFETs, compared between incomplete and complete ionizations at different temperatures. As the changes are small, the incomplete ionization can be considered on the condition of an accurate mode.

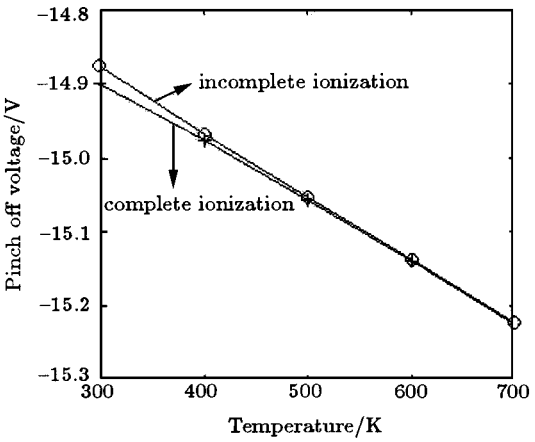


Fig.5. The pinch-off voltage V_p of 4H-SiC MESFETs in the ion-implanted channel versus temperature with effects of incomplete and complete ionizations.

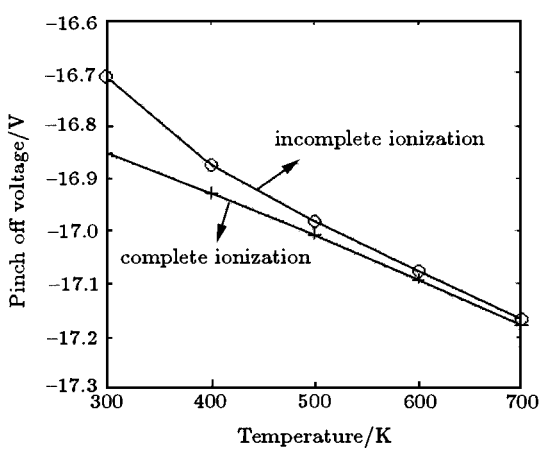


Fig.6. The pinch-off voltage V_p of 4H-SiC MESFETs in the uniform impurity channel versus temperature with effects of incomplete and complete ionizations.

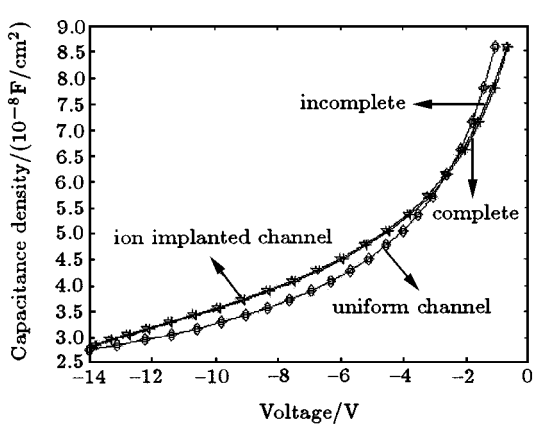


Fig.7. C-V characteristics of the gates of 4H-SiC MESFETs.

The capacitance of the gates of the ion-implanted and the uniform channels are significant, as shown in Fig.7. The effects of the incomplete ionization are not significant.

4. Conclusions

The effects of Poole–Frenkel and incomplete ionization on the pinch-off voltage V_p and C-V characteristics of 4H-SiC MESFETs have been studied. One-dimensional Poisson's equation is solved numerically, and a comparison between the ion-implanted and the uniform channels is carried out. The pinch-off voltages of the uniform and the ion-implanted channels of 4H-SiC MESFETs and the capacitance of the gate are given at different temperatures comparatively. The effects of incomplete ionization would be considered only when an accurate mode is needed. The capacitance of the gates of 4H-SiC MESFETs of the ion-implanted channel is different from that of the uniform channel.

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