AC Hot Carrier Transport in 3C– and 6H–SiC in the Terahertz Frequency and High Lattice Temperature Regime

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Received on 23 April, 2001

The complex mobility of electrons in 3C– and 6H–SiC subjected to intense high frequency electric fields is calculated taking into account effects of band nonparabolicity. The electric field, given by a *dc* component plus an *ac* component in the frequency range 0.1-100 THz, is applied along the [0001] ([111]) direction in the hexagonal (cubic) polytype. The real electron mobility presents a characteristic maximum peaking around 6–8 THz, while the imaginary electron mobility is structured, with characteristic minimum and maximum around 2–3 THz and 20–30 THz, respectively. These mobilities are seen to smooth down for higher temperatures in both polytypes.

Silicon carbide (SiC) polytypes have attracted attention due to their promising applications in the field of high power, high temperature and high frequency devices. High power SiC-based devices, for instance, rectifiers, power MOSFETs, thyristors, static induction transistors, MESFETs, as well as sensors operating in hostile environment conditions, are being developed and tested with success [1]. The SiC breakdown electric field and thermal conductivity is, respectively, about ten times greater than in Si and GaAs, and its bandgap (near to 3 eV) is almost three times greater than Si [1]. On the other hand, the calculated difference in the total energy per atom among the 3C–, 2H–, 4H–, and 6H–SiC polytypes is a few meV [1, 2]. However, further fundamental research work is still necessary for a better understanding of some basic properties of the silicon carbide polytypes, which is particularly true in the case of their *ac*–transport phenomena.

The electron transport characteristics of the various SiC polytypes were studied in the past years, including the investigation of the steady-state regime [3-12], high-frequency transport properties [13], and the ultrafast transient response [14-16]. Effects of an intense electric field were computed using Monte Carlo simulations and equations based on quantum and classical transport theories. Mickevičius and Zhao [8] studied electron transport in 6H–, 4H–, and 3C–SiC for the steady state (at 300 K and 600 K) and transient regime (only at 300 K), which was shown to be shorter than 0.2 ps. They pointed out the possibility of an overshoot in the electron drift velocity, which was more pronounced in the 3C– polytype. In a recent work, Caetano *et al.* [14], using balance transport equations in the relaxation time approximation, showed that there is an overshoot in the electron drift velocity for electric fields higher than 150 kV/cm. Weng and Lei [13] have calculated the room temperature terahertz complex mobility under low *ac+dc* fields ($<$ 50 kV/cm) for electrons in 6H–SiC, showing the existence of frequency dependent peaks in the complex mobility appearing around 1–5 THz.

The purpose of this work is to study the influence of the lattice temperature on the terahertz hot electron complex mobility in 6H– and 3C–SiC subjected

to a high *ac+dc* electric fields applied along the [0001] and [111] directions, respectively. These polytypes were chosen because of their high saturation velocities. The frequency dependent carrier drift velocity and energy are calculated for lattice temperatures 300, 673, and 1073 K, and shows a high nonlinear behavior. They allow to calculate the complex mobility behavior of the carriers in the 0.1 – 100 THz *ac* frequency range. For higher lattice temperatures, the 6H– and 3C–SiC mobilities are shown to be very close, which is a surprising result if we take into account the difference between the physical properties of the polytypes.

The electron energy $\epsilon(\omega,t)$ and drift velocity $v(\omega,t)$ are found solving numerically the following balance transport equations:

$$\frac{d\epsilon(\omega,t)}{dt} = qv(\omega,t)E(\omega,t) - \frac{\epsilon(\omega,t)-\epsilon_L}{\tau_\epsilon(\epsilon,E)}, \quad (1)$$

$$\frac{dv(\omega,t)}{dt} = \frac{qE(\omega,t)}{m_c} - \frac{v(\omega,t)}{\tau_p(\epsilon,E)}, \quad (2)$$

where $\epsilon(\omega,t)[=3k_BT(\omega,t)/2]$ is the average electron energy, which depends on the frequency ω of the *ac* field component; $T(\omega,t)$ is the electron temperature, and k_B is the Boltzmann constant. The electric field, applied along the [0001] (hexagonal structure) and [111] (cubic structure) directions, is given by $E(\omega,t) = E_{dc} + E_{ac}cos(\omega t)$. In the calculations here performed, E_{ac} is keep fixed at 200 kV/cm, and E_{dc}, the field dc component, varies in the 250 kV/cm – 800 kV/cm range. ϵ_L is the electron thermal energy at the lattice temperature T_L, q is the electron electric charge and m_c its effective mass, which for the 3C– and 6H–SiC polytypes were choosed here as those given in Weng and Cui [9]. We take into account the band nonparabolicity according the relation $\hbar^2k^2/2m_c = \epsilon(1+\alpha\epsilon)$, where α is $0.323\,eV^{-1}$ for 3C–SiC , and $\alpha = (1-m_c/m_0)^2$ for 6H–SiC, where m_0 is the free space electron mass. $\tau_\epsilon(\epsilon,E)$ and $\tau_p(\epsilon,E)$ are, respectively, the energy and momentum relaxation times, which are calculated through the steady-state relations $v_{ss}\times E_{dc}$ and $\epsilon_{ss}\times E_{dc}$ obtained by Weng and Cui [9] for 3C– and 6H–SiC at lattice temperatures T_L = 300, 673 and 1073 K.

The Fourier transform of the time-dependent electron mobility calculated in the time period T is the dynamic mobility:

$$\mu(\omega) = \mu_R(\omega) + i\mu_I(\omega) = \frac{1}{T}\int_\tau^{\tau+T} \frac{v(\omega,t)}{E(\omega,t)}e^{+i\omega t}dt, \quad (3)$$

where $\mu_R(\omega)$ and $\mu_I(\omega)$ are the real and imaginary parts of the complex electron mobility, respectively; T is the time period of the *ac* component of the electric field, and τ is the time necessary for both the electron drift velocity and energy to arrive at the steady state.

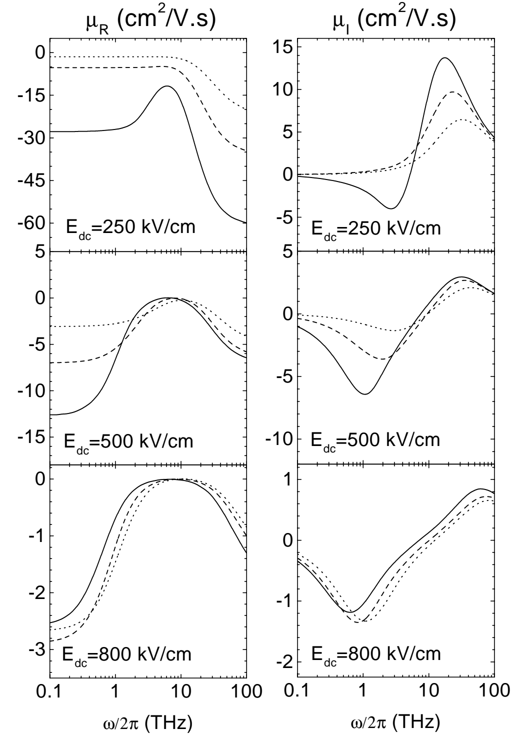

Figure 1. Real and imaginary mobilities of 3C–SiC for lattice temperatures 300 K (solid lines), 673 K (dashed lines), and 1073 K (dotted lines).

The behavior of $\mu_R(\omega)$ and $\mu_I(\omega)$ at terahertz frequencies is shown, for 3C–SiC (6H–SiC) at temperatures of 300, 673 and 1073 K, in Fig. 1 (Fig. 2). At 300 K, $\mu_R(\omega)$ presents a peak around $\omega/2\pi \approx$ 6-8 THz for E_{dc} = 250 kV/cm. The maxima in $\mu_R(\omega)$ are strongly smoothed when E_{dc} is increased, and practically disappear for E_{dc} = 800 kV/cm. Increasing lattice temperature considerably reduces the peak of the real mobility. The peak is very small when T_L = 673 K and disappears completely when T_L = 1073 K. In this case, $\mu_R(\omega)$ decreases continuously for high frequencies and low enough E_{dc}. The imaginary mobility $\mu_I(\omega)$ in 3C–SiC and 6H–SiC at low temperatures (300 K) presents a minimum and a maximum around 2–3 THz and 20–30 THz, respectively. These critical points are more pronounced in 3C–SiC than in 6H–SiC. Both the minima and the maxima are smoothed when the dc-component of the field increases. However, the maxima always exists in the dc-electric field intensity range investigated, while the minima almost disappears for E_{dc} = 250 kV/cm. When the lattice temperature increases,

the minima and maxima are considerably smoothed, the former more remarkably than the latter. For low dc-electric fields, a high lattice temperature can preclude the existence of minima in the imaginary component of the mobility. On the other hand, at high E_{dc} intensities the minima and maxima always exist at high lattice temperatures.

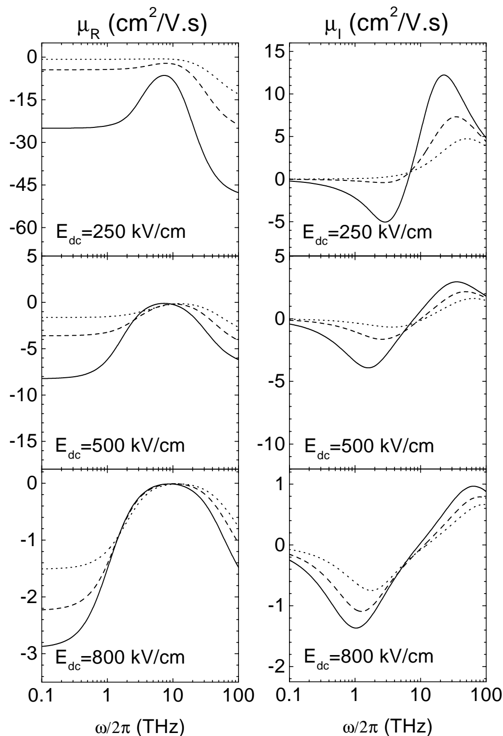

Figure 2. Real and imaginary mobilities of 6H–SiC for lattice temperatures 300 K (solid lines), 673 K (dashed lines), and 1073 K (dotted lines).

In conclusion, the complex mobility of hot electrons in 3C–SiC and 6H–SiC subjected to intense high frequency electric fields was studied. The overall effect of an increase in lattice temperature for the SiC polytypes was shown to smooth down the complex mobility features (maxima and minima). The modulus of the complex mobility for 3C-SiC was always larger than in 6H-SiC (except for $T_L = 300$ K and $E_{dc} = 800$ kV/cm), which is a consequence of a lower effective mass in 3C-SiC. However, at high enough temperatures the electron mobility behavior and its modulus are very close in both polytypes (except for $E_{dc} = 800$ kV/cm), and consequently the choice between 3C– and 6H–SiC for high temperature devices must be based on the suitability of other physical properties. Finally, one limitation of the present work is the fact that changes on the dielectric permitivity were not considered, even with the so high *ac*-frequency range investigated. However, the results should stimulate research on how the dielectric constant change (when the high-frequency ac electric field is applied to the semiconductor) to include this effect on the transport equations.

Acknowledgments

E. F. Bezerra and E. W. S. Caetano acknowledge the graduate fellowships they received from the Brazilian National Research Council (CNPq) at the Physics Department of the Universidade Federal do Ceará during the development of this work. V. N. F., J. A. P. C., and E. F. S. Jr. are thankful to the financial support from CNPq and the Ministry of Planning (FINEP) under contract FNDCT/CTPETRO-1190/00 #65.00.02.80.00.

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