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High-magnetic-field effects on the terahertz mobility of hot electrons in *n*-type InSb

E. W. S. Caetano, E. A. Mendes, and V. N. Freire*
Departamento de Física, Universidade Federal do Ceará, Caixa Postal 6030, Campus do Pici, 60455-760 Fortaleza, Ceará, Brazil

J. A. P. da Costa
Departamento de Física Teórica e Experimental, Universidade Federal do Rio Grande do Norte, Caixa Postal 1641, 59072-970 Natal, Rio Grande do Norte, Brazil

X. L. Lei
Shanghai Institute of Metallurgy, Chinese Academy of Sciences, 865 Changning Road, Shanghai 200 050, China
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We study the high-frequency behavior of hot-electron transport in *n*-type InSb subjected simultaneously to parallel high electric (dc plus ac) and magnetic fields. It is shown that the magnetic field reduces the real and imaginary components of the hot-electron mobility in *n*-type InSb, reducing or even eliminating the hump in the low-frequency side (around 0.1 THz) of the imaginary mobility. [S0163-1829(98)01919-5]

The understanding of high-frequency hot-electron magnetotransport in *n*-type InSb is of technological interest since its main possible device applications are in the fields of high-frequency electronics and magnetic-field sensors.[1] The electron transport properties in this narrow-gap semiconductor can be strongly modified under the action of a magnetic field as a consequence of its small electron effective mass ($m=0.0014\,m_0$, with m_0 being the free-electron mass) and the population of Landau subbands. If the applied magnetic-field intensity is high enough (>30 T, as indicated by Weng and Lei[2]), only the lowest Landau subband is populated (the extreme quantum limit) and all electrons move in the same circular orbit. Otherwise, several Landau subbands are occupied and since the electrons can move in several circular orbits and their interband scattering time is estimated to be much smaller than 4 ps,[3] it is thus necessary to consider high-lying Landau subband filling when calculating magnetotransport in *n*-type InSb.[2,4]

Electron scattering, which plays a major role in the determination of magnetotransport properties in *n*-type InSb, changes with the order and filling of Landau subbands. High-lying Landau subband filling can modify both the stationary[2] and the transient[4,5] characteristics of the high-field electron magnetotransport in *n*-type InSb. In the former case, a high magnetic field may suppress the occurrence of the negative differential resistivity,[2] while in the latter case the overshoot in the electron drift velocity decreases considerably by the action of the magnetic field.[4,5]

Recently, calculations of the hot-electron high-frequency mobility in wide- (SiC) and narrow-gap (GaAs and InAs) semiconductors were performed in the absence of a magnetic field.[6] It is showed that the imaginary component of the InAs frequency-dependent mobility exhibits a maximum and a minimum around 1 THz and 0.01 THz, respectively. The minimum of the imaginary component of the mobility, however, does not occur in the case of GaAs and SiC.[6] These results indicate that the effect of nonparabolicity has to be taken into account in the calculation of high-field transport in semiconductors such as InSb and InAs.

When *n*-type InSb is subjected simultaneously to parallel high dc plus ac electric ($E\sim 1$ kV/cm) and magnetic fields ($B\sim 1$ T), very interesting phenomena can emerge due to the competition between the electron-phonon scattering (mean collision time $\sim 1-100$ ps), the electron heating induced by the high-frequency ($\omega\sim 1$ THz) electric field, and the Landau intersubband transitions (relaxation time ~ 1 ps). Among interesting highly nonlinear phenomena that take place in these conditions, the present theoretical study focuses on how a strong magnetic field applied parallel to the high dc plus ac electric field can change the terahertz mobility of electrons in *n*-type InSb.

For the purpose of demonstrating the possible phenomena rather than offering accurate results, we start from transport equations for the electron energy ε and the drift velocity v, which are derived from the Boltzmann equation in the approximation of momentum and energy relaxation times τ_p and τ_ε, respectively.[7–9] These relaxation times are field dependent, i.e., $\tau_p=\tau_p(E,B)$ and $\tau_\varepsilon=\tau_\varepsilon(E,B)$, and can be obtained using the steady-state relations between the electron drift velocity and energy $v_s(E,B)$ and $\varepsilon_s(E,B)$, respectively, for each value of E and B.[4,5] The steady-state results of Weng and Lei[2] for hot-electron magnetotransport in *n*-type InSb are used to calculate the relaxation times $\tau_\varepsilon(E,B)$ and $\tau_p(E,B)$. Consequently, high-lying Landau subband filling, nonparabolicity of the *n*-type InSb band energy, and electron scattering due to ionized impurities and acoustic and polar optical phonons are considered during the numerical solution of the coupled transport equations.

The electric field has the form $E(t)=E_0+E_1\cos(\omega t)$ and is assumed to be parallel to the magnetic field B. The time evolution of the drift velocity $v(t)$ is obtained numerically for $B=2$, 10, and 25 T, respectively, in the case of an ac electric-field strength $E_1=0.5$ kV/cm and a dc electric-field intensity in the range 0.5 kV/cm$<E_0<$2.5 kV/cm. We have chosen not do deal with large ac fields as an attempt to connect somehow our theoretical study with recent advances in experiments. Due to the development of the free-electron

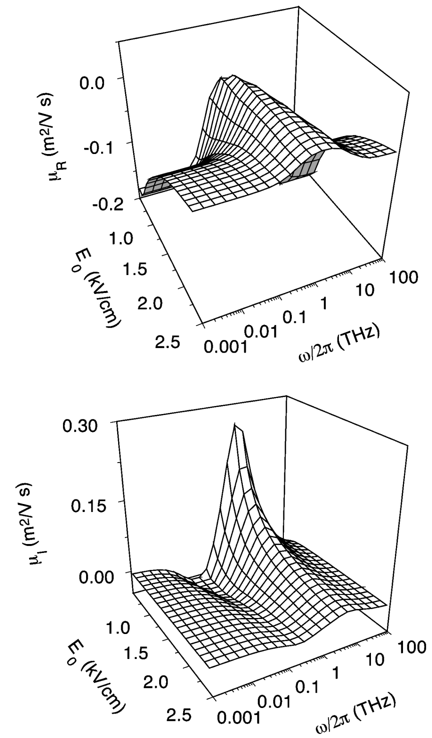

FIG. 1. Real (top) and imaginary (bottom) components of the electron mobility in n-type InSb subjected to a magnetic field intensity $B=2$ T and an ac electric-field intensity $E_1=0.5$ kV/cm.

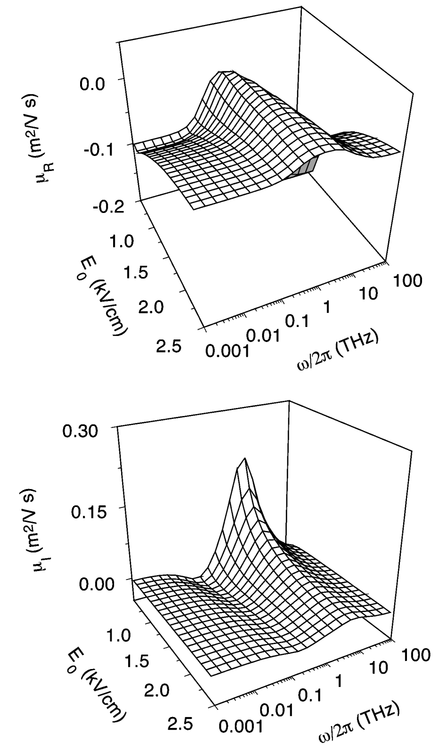

FIG. 2. Real (top) and imaginary (bottom) components of the electron mobility in n-type InSb subjected to a magnetic field intensity $B=10$ T and an ac electric-field intensity $E_1=0.5$ kV/cm.

laser, the effect of an intense terahertz field on electron transport has become a focus of many experimental studies, in which the intensity of the high-frequency electric field can be as high as 10 kV/cm.[10] In the numerical calculation, the n-type InSb electron density is 10^{16} cm^{-3} and the thermal bath temperature is 42 K. Under these conditions, the time-dependent electric field $E(t)$ remains in the same direction and never vanishes. Thus we can define a mobility $\mu(t)$ at time t as the ratio of the drift velocity $v(t)$ to the electric field $E(t)$. The complex Fourier spectrum $\mu(\omega)$ of the time-dependent mobility may represent the dynamic mobility of the system under a high dc plus ac electric field. It is calculated in the time period T by performing the Fourier transform of the electron drift velocity after its arrival at the steady state at the time τ according to

$$\mu(\omega)=\mu_R(\omega)+i\ \mu_I(\omega)$$
$$=\frac{1}{T}\int_{\tau}^{\tau+T}\frac{v(t)}{E_0+E_1\cos(\omega t)}e^{+i\omega t}\,dt. \qquad (1)$$

The frequency dependence of the real $\mu_R(\omega)$ and imaginary $\mu_I(\omega)$ components of the complex mobility is presented in Figs. 1, 2, and 3 for magnetic-field intensities of 2, 10, and 25 T, respectively. A reduction of both $\mu_R(\omega)$ and $\mu_I(\omega)$ can be observed when B increases. This result is a direct consequence of the magnetic-field cooling effect,[6] which is due to the increase of the electron scattering rate when high-lying Landau subbands become less populated.[4] Measurements performed by Song *et al.*[1] showed that the Hall mobility in n-type InSb films decreases when the magnetic field increases, essentially in agreement with the results obtained here. Nevertheless, more experiments are still needed to confirm directly the magnetic-field dependence of the n-type InSb mobility predicted in this work. Additional theoretical calculations based on transport equations beyond

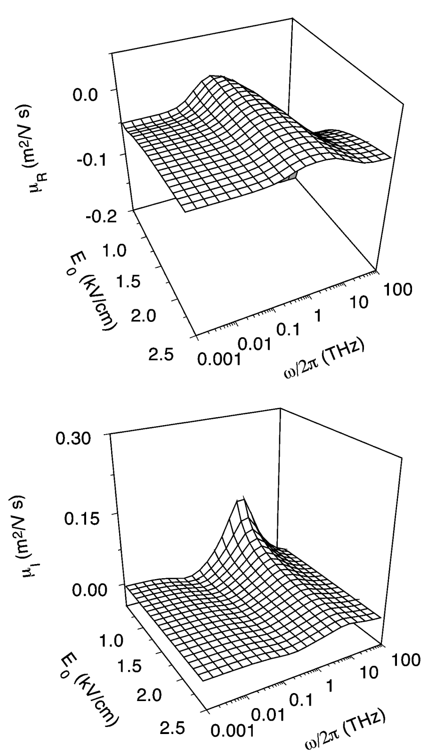

FIG. 3. Real (top) and imaginary (bottom) components of the electron mobility in n-type InSb subjected to a magnetic field intensity $B=25$ T and an ac electric-field intensity $E_1=0.5$ kV/cm.

the relaxation time approximation are also needed to confirm and to improve the accuracy of our results.

While $\mu_I(\omega)$ exhibits only one maximum around 1 THz in the frequency range investigated, $\mu_R(\omega)$ has a maximum around 0.1 THz and a minimum around 10 THz. By inspecting Figs. 1–3, one can see that there is a shift to high frequencies in all maxima and minima of $\mu_R(\omega)$ and $\mu_I(\omega)$ when the intensity of the dc electric field becomes higher. The increase of the magnetic-field intensity makes smaller or even eliminates the hump in the low-frequency side of $\mu_I(\omega)$. On the other hand, when the magnetic field is maintained constant, the variation of $\mu_R(\omega)$ or $\mu_I(\omega)$ with the dc electric field is highly frequency dependent.[11] At a frequency ω of the order of 1 THz, both $\mu_R(\omega)$ and $\mu_I(\omega)$ decrease monotonically with increasing electric field, the former smoothly and the latter more sharply. At very low ($\omega \sim 0.001$ THz) or very high ($\omega \sim 100$ THz) frequencies, $\mu_R(\omega)$ varies monotonically with the electric field, while $\mu_I(\omega)$ almost vanishes, indicating the fact that in the former case the electrons closely follow the time variation of the electric field, while in the latter case the electrons become completely idle in response to the fast changing of the electric field. The study of the frequency dependence of the electron mobility in narrow-gap semiconductors was pioneered by Rees[11] using a Monte Carlo simulation for a weak ac field response in GaAs without a magnetic field.

In conclusion, we have studied effects of high magnetic fields on the terahertz mobility of hot electrons in n-type InSb when both a high electric (dc plus ac) field and a parallel magnetic field are simultaneously applied. The behavior of the real and imaginary components of the mobility was shown to be highly dependent on the magnetic-field intensity and on the frequency of the ac component of the applied electric field. A high magnetic field (~ 25 T) can eliminate the hump otherwise occurring on the low-frequency side (around 0.1 THz) of the imaginary mobility.

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*FAX: 55 (85) 2874138. Electronic address: valder@fisica.ufc.br

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