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Influence of non-parabolicity on hot electrons in n-type gallium arsenide

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Abstract. Hot-electron transport in n-type GaAs has been investigated in the crossed applied DC electric field and DC magnetic field. The energy band structure of conduction electrons is taken to be a non-parabolic band and the dominant interaction between hot electrons and lattices is assumed to be the deformation-potential coupling. Results show that the dissipative current density increases nonlinearly with the applied electric field owing to the non-parabolic band structure of electrons in semiconductors. In the lower electric field region, the dependence of the current density on temperature does not appear to follow a regular trend. It is also shown that the current density depends strongly on the magnetic field.

1. Introduction

When electron transport is caused by an electric field, electrons are continuously supplied with energy from the source of the electric field at a rate $\boldsymbol{J}\cdot\boldsymbol{E}$, where $\boldsymbol{J}$ is the current density and $\boldsymbol{E}$ is the applied electric field. It would appear that the total energy of the system should go on increasing indefinitely. This, however, does not happen as the gain of energy is balanced by the transfer of energy to lattice atoms through the process of collisions. As the electric field increases, the difference between the electron temperature and the lattice temperature becomes significant. In very high electric fields, the electron temperature may become an order higher than the lattice temperature. A factor which influences the nature of the current flow and the properties of diode structures could be the non-parabolicity of carriers in semiconductors [1–3]. In our present work, we shall study the quantum nonlinear effect of hot electrons in the crossed static electric and magnetic fields due to the non-parabolicity of electrons in non-degenerate semiconductors. The dominant interaction between hot electrons and the lattice is assumed to be the deformation-potential coupling. Some numerical results for n-type GaAs are presented and a brief discussion about our numerical analysis is given.

2. Theory of hot electrons in non-degenerate semiconductors

For the non-parabolic model, the eigenfunctions and eigenvalues for electrons in the applied electric field $\boldsymbol{E}$ directed along the x-axis and the magnetic field $\boldsymbol{B}$ directed along the z-axis are given by

$$\Psi_{kn}(\boldsymbol{r}) = \exp(\mathrm{i}k_y y + \mathrm{i}k_z z)\Phi_n\left(x - \frac{\hbar c}{eB}k_y + \frac{eE}{m^*\omega_c^2}\right) \tag{1}$$

and

$$E_{kn} = -\tfrac{1}{2}E_g\left\{1 - \left[1 + \left(\frac{4}{E_g}\right)\left((n+\tfrac{1}{2})\hbar\omega_c + \frac{\hbar^2 k_z^2}{2m^*} + \frac{\hbar cE}{B}k_y - \frac{e^2E^2}{2m^*\omega_c^2}\right)\right]^{1/2}\right\} \tag{2}$$

respectively, where m^* is the effective mass of electrons, E_g is the energy gap between the conduction and valence bands, $\omega_c = |e|B/m^*c$ is the cyclotron frequency of the electrons, Φ_n is the harmonic-oscillator wavefunction, and k_y and k_z are the components of the electron wave vector in the y and z directions respectively.

From Liouville's theorem,

$$\frac{\mathrm{d}\rho}{\mathrm{d}t} = \frac{\partial\rho}{\partial t} + \frac{1}{\mathrm{i}\hbar}[\rho, H] = 0 \tag{3}$$

with $\rho = \rho_0 + \rho_1$ and $H = H_0 + V(\boldsymbol{r})$; it can be shown that the transition probability due to the effect of collisions in a high DC electric field is given by

$$W_{kk'} = \frac{2\pi}{\hbar}|\langle k'n'|V(\boldsymbol{r})|kn\rangle|^2\delta(E_{k'n'} - E_{kn}) \tag{4}$$

where ρ_0 is the unperturbed density operator, ρ_1 is the perturbation operator due to the scattering potential $V(\boldsymbol{r})$ between electrons and lattices in semiconductors, and H_0 is the unperturbed Hamiltonian. The current density can

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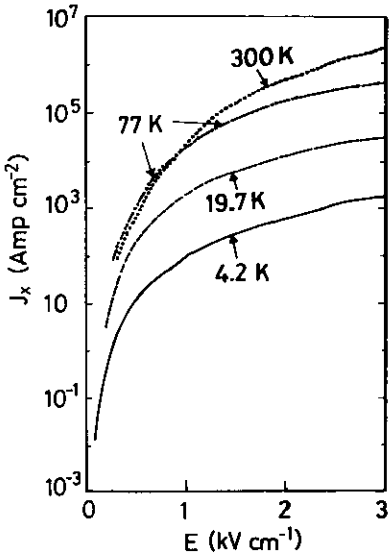

Figure 1. Current density in n-type GaAs as a function of the electric field at $B = 1.5$ kG.

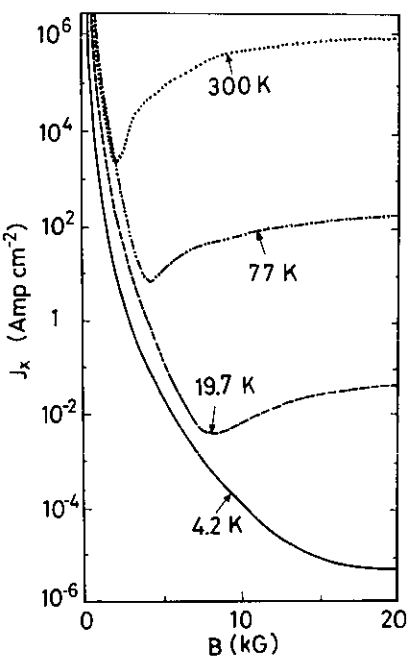

Figure 2. Current density in n-type GaAs as a function of the magnetic field at $E = 900\,\mathrm{V\,cm^{-1}}$.

be obtained from

$$\boldsymbol{J} = \mathrm{Tr}(\rho \cdot \boldsymbol{J}_{\mathrm{op}}) = \sum_{kk'nn'} \langle k'n'|\rho|kn\rangle\langle kn|\boldsymbol{J}_{\mathrm{op}}|k'n'\rangle \tag{5}$$

where the current-density operator is given by

$$\boldsymbol{J}_{\mathrm{op}} = \frac{|e|}{2}\left[\frac{\mathrm{d}\boldsymbol{r}}{\mathrm{d}t}, \delta(\boldsymbol{r} - \boldsymbol{R})\right]_+ \tag{6}$$

where $[,]_+$ denotes the anticommutator.

From equations (4)–(6), one may obtain the current density as [4, 5]

$$J_x = \frac{2\pi|e|}{\hbar}\sum_{kk'nn'}(f_{k'n'} - f_{kn})|\langle k'n'|V(\boldsymbol{r})|kn\rangle|^2\delta(E_{k'n'} - E_{kn}) \tag{7}$$

where $f_{kn} = \langle kn|\rho_0|kn\rangle$ is the Maxwell–Boltzmann distribution, since we have assumed a non-degenerate semiconductor. In high electric fields, it is assumed that $V(\boldsymbol{r})$ is slowly varying compared with the lattice positions such that

$$V(\boldsymbol{r}) = C\sum_j \delta(\boldsymbol{r} - \boldsymbol{R}_j) \tag{8}$$

where $\boldsymbol{R}_j$ is the position vector of lattice atoms and C is the deformation potential.

3. Numerical analysis and discussion

As a numerical example, we shall consider the current density due to the nonlinear effect of hot electrons in the high magnetic field region for the non-parabolic energy band in n-type GaAs. The relevant values of physical parameters for n-type GaAs are taken to be [6]: $m^* = 0.07m_0$ (m_0 is the mass of a free electron), n_0 (electron concentration) $= 1.73 \times 10^{15}\,\mathrm{cm^{-3}}$, $E_g = 1.51$ eV, and $C = 7$ eV. In figure 1 we plot the current density as a function of the applied electric field in n-type GaAs at $B = 1.5$ kG. It can be seen that the current density increases nonlinearly with the electric field due to the non-parabolic band structure of electrons in semiconductors. It is also shown that, in the lower electric-field region, the dependence of the current density on temperature does not appear in a regular trend. However, in high electric fields the current density increases with increasing temperature. In figure 2 it can be seen that the current density in n-type GaAs at $E = 900\,\mathrm{V\,cm^{-1}}$ decreases monotonically with increasing magnetic field at $T = 4.2$ K. When the temperature increases, a minimum point can be observed. The minimum point will be shifted to lower magnetic field with increasing temperature. From our numerical results, it can be seen that the non-parabolicity of energy bands in semiconductors will increase the effect of hot electrons due to the nonlinear property of energy bands in the crossed electric and magnetic fields. Moreover, the nonlinear effect of energy bands in semiconductors will become much more significant as the magnetic field reaches a high field region [6].

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