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EFFECT OF NONEQUILIBRIUM PLASMONS ON ELECTRON–PLASMON INTERACTIONS IN SEMICONDUCTORS

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The effect of nonequilibrium plasmons on the steady-state high-dc-field response of electron gas in n-GaAs is numerically studied via iterative procedure using the Monte Carlo simulation algorithm for hot-electron transport and the Boltzmann equation for plasmons. The electron population inversion in wave vector space along the electric field is predicted to exist for fields in excess of about 10 kV/cm. The plasmon distribution disturbances leave the steady-state velocity at low fields almost unaffected but lead to reduction of that up to 10% for fields around and above the maximum of the velocity-field characteristics.

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In earlier works [1, 2] it was shown that the account for the electron–plasmon scattering in Monte Carlo simulation affects substantially the hot-electron energy distribution function and transport properties in n-GaAs under high electric field application. Note that the reservoir of plasmons was assumed to be in thermal equilibrium with the semiconductor lattice in those works. Such an assumption is justified only when electron–plasmon scattering rates are much less than the nonelectronic relaxation rate of the plasmons. However, this situation can be hardly conceived and the plasmon distribution may be in fact significantly disturbed.

In this paper we study the effect of nonequilibrium plasmons on the electron–plasmon scattering rates and steady-state high-dc-field response of electron gas in n-GaAs using the conventional Monte Carlo simulation algorithm for hot-electron transport and the Boltzmann equation for plasmons

$$\frac{\partial N_q(q,t)}{\partial t} = \frac{\partial N_q(q,t)}{\partial t}\bigg|_{\text{pl-e}} + \frac{\partial N_q(q,t)}{\partial t}\bigg|_{\text{pl-ph}}. \qquad (1)$$

The two terms in the right-hand side of Eq. (1) describe the variations of $N_q(q,t)$ produced by plasmon–electron (pl–e) and plasmon–phonon (pl–ph) scattering processes.

The first term in Eq. (1) can be written as

$$\frac{\partial N_q(q,t)}{\partial t}\bigg|_{\text{pl-e}} = [N_q(q,t)+1]W_e(q) - N_q(q,t)W_a(q),$$

where $W_e(q)$ and $W_a(q)$ are the pl–e scattering rates for emission and absorption of the plasmon with a given wave vector q by electrons, respectively. From the Fermi golden rule we have

$$W_{e,a}(q) = \frac{2\pi}{h}\int \frac{\Omega}{(2\pi)^3}\mathrm{d}kM_{mq}^2\delta[E_{kmq} - E_k \pm h\omega_P(q)]f(k)[1 - f(kmq)], \quad (2)$$

where the matrix element of the pl–e interaction M_{mq} is given by [2, 3], where E_k is the energy of electron with wave vector k, $f(k)$ is the electron distribution function in k-space, $\omega_P(q)$ is the dispersion relation for plasmons, and Ω — the real-space volume. Here and further the upper signs in formulae refer to the plasmon emission, whereas the lower ones do to the plasmon absorption processes and we will assume $\omega_P(q) = \omega_P = \sqrt{e^2N_e/(\varepsilon m^*)}$.

The second term in Eq. (1) is treated in a simple approximation

$$\left.\frac{\partial N_q(q,t)}{\partial t}\right|_{\mathrm{pl-ph}} = \frac{N_q(q,t) - N_L}{\tau_L},$$

where N_L is the Bose–Einstein distribution for plasmons at the lattice temperature T, and τ_L is a phenomenological relaxation time.

We obtain the steady-state solution of Eq. (1) by iterative procedure. The hot-electron momentum distribution function entering Eq. (2) is extracted from the Monte Carlo simulation with electron–plasmon scattering rates taken by [2]

$$W_{e,a}(k) = \frac{2\pi}{h}\int \frac{\Omega}{(2\pi)^3}\mathrm{d}qM_{mq}^2\delta[E_{kmq} - E_k \pm h\omega_P(q)]\left[N_q(q) + \frac{1}{2} \pm \frac{1}{2}\right], \quad (3)$$

where $N_q(q)$ is the stationary plasmon distribution function given by Eq. (1).

Integrals in Eqs. (2), (3) have been computed in spherical coordinates with a polar axis along the electric field. Cylindrical symmetry of the problem with respect to the electric field direction has been taken into account. The integration bounds are defined by the energy and momentum conservation requirements for the scattering processes involving electrons with $k \leq k_{\max}$, where $k_{\max}$ is chosen such that no electrons with $k > k_{\max}$ appear during simulation time.

The electron and plasmon distribution functions were iteratively adjusted to each other after every run of the Monte Carlo simulation.

Here we present results obtained for n-GaAs with $N_e = 10^{18}$ cm^{-3} at $T = 77$ K with $\tau_L = 10^{-12}$ s. Apart from pl–e scattering other standard electron scattering mechanisms with characteristic parameters listed in [2] were incorporated into all Monte Carlo simulations.

It follows from Fig. 1 that the electron population inversion in k-space along the electric field is predicted to exist at electric field strengths above 10 kV/cm. The physical reason for this phenomenon is that wave vector space regions around $k_{\parallel} = -2 \times 10^6$ cm^{-1} and $k_{\parallel} = 4 \times 10^6$ cm^{-1} become depleted of electrons since pl–e scattering rates, both with plasmon emission and absorption, have maxima at those electron wave vectors. No such inversion results if the plasmons are assumed to be in thermal equilibrium with the crystal lattice.

Plasmon distribution function in q-space is tremendously (by several orders of magnitude in N_q) disturbed from thermal equilibrium and becomes strongly anisotropic with respect to the electric field direction at electric field strengths in

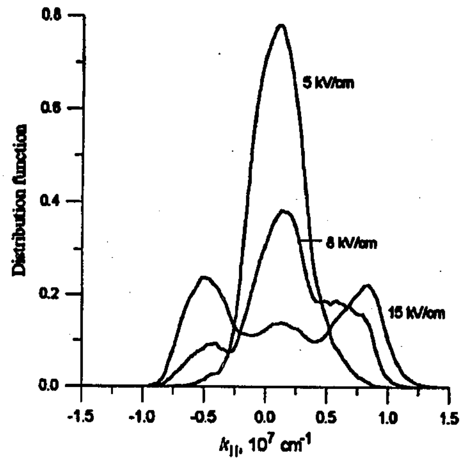

Fig. 1. Plots of the distribution function in k-space along line through $k = 0$ parallel to the electric field at various electric field strengths; $k_{\parallel}$ is the longitudinal component of the electron wave vector with respect to the electric field direction.

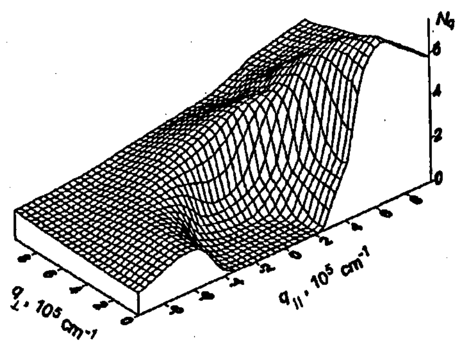

Fig. 2. Nonequilibrium plasmon distribution function in $\{q_{\parallel}, q_{\perp}\}$ plane at the electric field 15 kV/cm; $q_{\parallel}$ and $q_{\perp}$ are the longitudinal and transverse components of the plasmon wave vector with respect to the electric field direction.

excess of about 5 kV/cm (see Fig. 2). A valley with $N_q \approx N_{\mathrm{L}}$ in a small-q region remains undisturbed since, in keeping with the energy and momentum conservation requirements, the plasmons with so small q can interact only with very-high-k electrons and there is scarcely any such electron to appear during simulation time.

It is seen from Fig. 3 that the plasmon disturbances leave the steady-state velocity at low electric fields almost unaffected but lead to reduction of that up to 10% for fields around and above the maximum of the velocity-field characteristics. As a result, the velocity-field characteristics become closer to that calculated without taking into account the electron–plasmon scattering.

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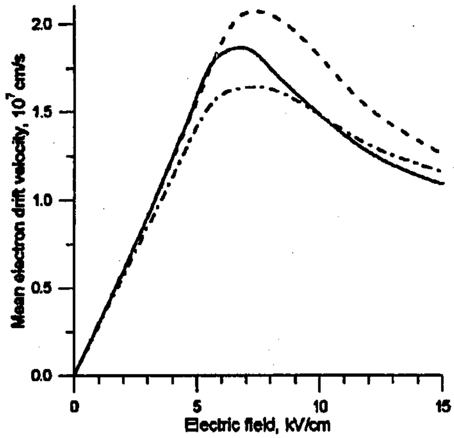

Fig. 3. Mean electron drift velocity as a function of electric field, calculated with regard to the pl–e scattering for nonequilibrium (solid line) and equilibrium (dashed line) plasmons, and without pl–e scattering (dashed-point line).

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