Superlattices and Microstructures, Vol. 27, No. 5/6, 2000
doi:10.1006/spmi.2000.0866
Available online at http://www.idealibrary.com on IDEAL

Multistability, absolute negative conductivity and spontaneous current generation in semiconductor superlattices in large magnetic fields

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(Received 25 February 2000)

We discuss electron transport through a semiconductor superlattice subject to an electric field parallel to, and a magnetic field perpendicular to, the growth axis using a semi-classical balance equation model. We find that the current–voltage characteristic becomes multistable in a large magnetic field; furthermore, hot electrons display novel features in their current–voltage characteristic, including absolute negative conductivity and a spontaneously generated dc current at zero bias.

Key words: superlattice, miniband transport, nonlinear transport.

Semiconductor superlattices (SSLs) offer the exciting prospect of experimentally observing nonlinear transport and optical properties. The large period along the growth axis leads to narrow minibands; consequently, moderate electric and magnetic fields can accelerate electrons into the nonparabolic regions of the minibands before a scattering event occurs. Electrons which explore a significant portion of the miniband exhibit such nonlinear properties as negative differential conductivity (NDC) and Bloch oscillations; for an introduction, see [1].

We study a balance equation model for transport through a single miniband SSL with electric field, E, along the growth axis (the z-direction) and magnetic field, B, in the plane of the quantum wells (QWs) that form the SSL (the x-direction). These balance equations are derived from the semiclassical Boltzmann transport equation (BTE) which describes miniband transport in electric or magnetic fields not strong enough to localize electrons within a single period of the SSL. The balance equations for an electric field were first derived in [2], while the extension to include the magnetic field was discussed in [3, 4]; and we refer the reader to these references for the detailed derivation.

We assume a tight-binding miniband dispersion relation, $\epsilon(\boldsymbol{k}) = \hbar^2 k_y^2/2m^* + \Delta/2[1 - \cos(k_z a)]$, where

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m^* is the effective mass in the plane of the QWs, Δ is the miniband width, and a is the SSL period. The balance equations are

$$\dot{V}_y = -\frac{eB}{m^*c}V_z - \gamma_{vy}V_y \tag{1}$$

$$\dot{V}_z = -\frac{e}{m(\varepsilon_z)}\left[E - \frac{BV_y}{c}\right] - \gamma_{vz}V_z \tag{2}$$

$$\dot{\varepsilon}_z = -eEV_z + \frac{eB}{c}V_yV_z - \gamma_\varepsilon[\varepsilon_z - \varepsilon_{eq,z}], \tag{3}$$

where $-e$ is the charge of an electron and c is the speed of light. The average electron velocity, $\boldsymbol{V} = (V_y, V_z)$, is obtained by integrating the distribution function which satisfies the BTE over the Brillouin zone; γ_{vy} and γ_{vz} are the damping rates for these quantities, which follow from inelastic phonon scattering and elastic impurity and interface roughness scattering. Likewise, ε_z represents the average energy of motion along the growth axis; $\varepsilon_{eq,z}$ is its equilibrium value, and γ_ε is its relaxation rate due mainly to inelastic scattering. The balance equations contain the effective mass term $m(\varepsilon_z) = m_0/(1 - 2\varepsilon_z/\Delta)$, where $m_0 = 2\hbar^2/\Delta a^2$ is the effective mass at the bottom of the miniband. Owing to the nonparabolic dispersion relation, the effective mass for motion along the growth axis depends on the corresponding energy component; in contrast, the energy of motion within the QW does not enter the balance equations since the effective mass for this motion is constant. While the magnetic field does not change the total electron energy, it does transfer energy between the longitudinal and transverse directions, hence it affects the time dependence of ε_z.

The following scalings facilitate numerical studies: $v_y = ((m_0m^*)^{1/2}a/\hbar)V_y$, $v_z = (m_0a/\hbar)V_z$, $w = (\varepsilon_z - \Delta/2)/(\Delta/2)$, $w_0 = (\varepsilon_{eq,z} - \Delta/2)/(\Delta/2)$, $\mathcal{B} = eB/(m_0m^*)^{1/2}c$ and $\omega_B = eEa/\hbar$ (the Bloch frequency of the electric field). Accordingly, the set of balance equations becomes

$$\dot{v}_y = -\mathcal{B}v_z - \gamma_{vy}v_y \tag{4}$$

$$\dot{z}_z = \omega_B w - \mathcal{B}v_y w - \gamma_{vz}v_z \tag{5}$$

$$\dot{w} = -\omega_B v_z + \mathcal{B}v_y v_z - \gamma_\varepsilon(w - w_0). \tag{6}$$

With the time-independent electric field ω_B and magnetic field $\mathcal{B}$, the SSL current $I = -eNA(\Delta a/2\hbar)v_{z,ss}$, where N is the carrier concentration, A is the cross-sectional area, and $v_{z,ss}$ is the steady-state solution to eqn (5). Considering the steady-state solutions to eqns (4)–(6), we obtain a cubic equation relating $v_{z,ss}$ to the applied voltage, with $C = \mathcal{B}^2/\gamma_{vy}$

$$C^2v_{z,ss}^3 + 2C\omega_B v_{z,ss}^2 + [\gamma_{vz}\gamma_\varepsilon + \omega_B^2 - \gamma_\varepsilon w_0 C]v_{z,ss} - \gamma_\varepsilon w_0\omega_B = 0. \tag{7}$$

The current–voltage characteristic of an SSL exhibits a peak followed by NDC; and a magnetic field in the plane of the QWs increases the critical electric field at which the peak current is attained [5, 6]. As is evident in Fig. 1, the balance equations reproduce these well-known results; moreover, they predict the new result of multistability for a sufficiently large magnetic field (Fig. 1C). For the very low relaxation rates obtained in very recent experiments—$\gamma_{vy} = \gamma_{vz} = \gamma_\varepsilon = 1.5 \times 10^{13}$ s^{-1} for an SSL with $\Delta = 23$ meV and $a = 84$ Å [7]—this multistability may be observable at a modest magnetic field of a couple of Tesla.

The average energy for motion along the growth axis relaxes to its equilibrium value w_0 at the rate γ_ε; for thermal carriers, $w_0 \leq 0$. We now wish to discuss the situation where $w_0 > 0$; this occurs for 'hot' electrons which have a highly nonequilibrium distribution, even without applied fields, and requires a constant influx of energy. Experimentally, these hot electrons can be obtained by injecting electrons into the top half of the miniband of a finite SSL, as in the recent experiment described in [7]. Consider the situation in which there are no external fields: if electrons leave the SSL before relaxing to the bottom of the miniband, and new electrons replace them at the injection energy in the top half, then $w = w_0 > 0$. The energy to maintain $w_0 > 0$ comes from the steady injection of energetic electrons.

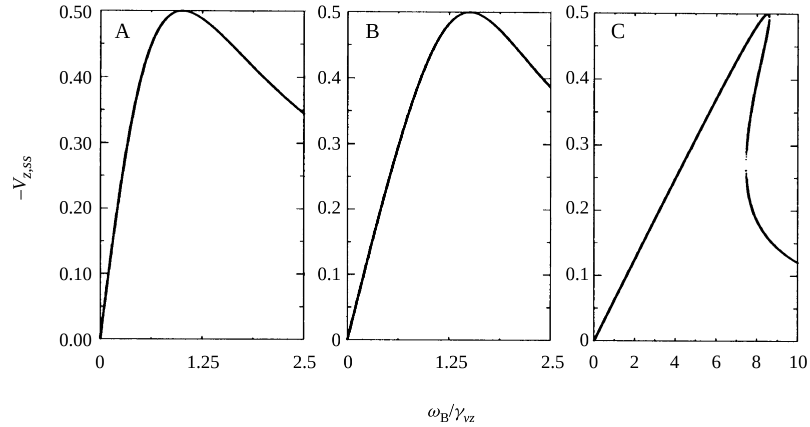

Fig. 1. Scaled current–voltage characteristic for an SSL with $w_0(\gamma_\varepsilon/\gamma_{vz})^{1/2} = -1$ and $C = 0$ (A), $C = \gamma_{vz}$ (B) and $C = 15\gamma_{vz}$ (C).

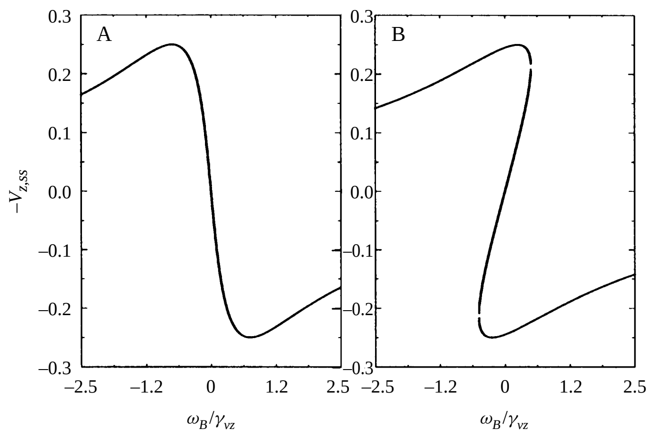

Fig. 2. Scaled current–voltage characteristic for hot electrons in an SSL with $w_0(\gamma_\varepsilon/\gamma_{vz})^{1/2} = 0.5$ and $C = \gamma_{vz}$ (A), and $C = 5\gamma_{vz}$ (B).

The balance equations predict two novel features in the current–voltage characteristic for hot electrons: absolute negative conductivity (ANC) and, for sufficiently large magnetic fields, spontaneous current generation at zero bias. Figure 2A illustrates the ANC, as a positive bias induces a negative current when $w_0 > 0$. For the larger magnetic field in Fig. 2B, multistability occurs at zero-bias; in fact, the zero bias–zero current solution is unstable and the SSL spontaneously developed a current across it. For ANC, the energy of the hot electrons supports a current against the applied bias; similarly, spontaneous current generation occurs when the hot electrons use their energy to maintain a current in the absence of any bias. Both effects may be observable through their influence on the current–voltage characteristics of high-quality samples [3].

Acknowledgements—We are grateful to Lawrence Eaves for stimulating discussions. FVK thanks the Department of Physics at the University of Illinois at Urbana-Champaign for its hospitality. This work received support from the NATO Linkage Grant NATO LG 931602, INTAS, RFBR and the NSF (grant NSF GER93-54978).

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