ELECTRON MOBILITY IN QUANTUM WIRES AT HIGH TEMPERATURES

N. Mori, H. Momose, T. Ezaki and C. Hamaguchi
Department of Electronic Engineering, Osaka University
2 1, Yamada-oka, Suita City, Osaka 565, Japan

Abstract

Self-consistent calculation of quasi-one dimensional electron channel formed in GaAs/AlGaAs heterojunction is performed to study the gate voltage dependence of optical-phonon limited mobility at high temperatures. One-dimensional form factor which determines the magnitude of electron mobility is evaluated by using the results of self-consistent calculations. The calculated form factor is found to differ by a factor 2 to 3 from that obtained by the simple analytical results reported previously.

1. INTRODUCTION

Much attention has been placed on electron transport in quantum wires, where electrons confined in a plane are constricted in a narrow channel. At low temperatures, it is pointed out that the elimination of small-angle scattering by impurities in quantum wires can considerably enhance the mobility [1]. At high temperatures, however, the electron mobility is expected to be affected strongly by the optical phonon scattering in structures made of III–V compound semiconductors. Electron-phonon interaction in such a system has not yet been investigated in detail. The resonant inter-subband scattering is expected to occur when the spacing between two subbands approaches the longitudinal optical (LO) phonon energy [2]. The weak ergodic nature of the system results in anomalous carrier cooling and extremely high mobility [3]. Under high magnetic fields, resonant scattering of electrons by LO phonons between the Landau levels results in extrema in the magnetoconductivity, which is called magnetophonon resonances (MPR). Our calculations have shown that the feature of the MPR in a narrow channel is quite different from the MPR in three- or two-dimensional systems and that additional conduction caused by the confinement potential plays an important role [4]. In the present work, we are interested in obtaining electronic states in quantum wires by solving Poisson and Schödinger equations self-consistently [5 9] to study how the mobility limited by LO phonon scattering depends on the gate voltage or the channel width at high temperatures.

2. SELF-CONSISTENT CALCULATION

Many theoretical studies have been devoted to investigating the electron states in quantum wires. In the present calculations, we assumed quasi-one dimensional electron channel formed in GaAs/AlGaAs heterojunction, where the confinement of electrons in narrow channel is achieved by Al electrodes formed on a cap layer of GaAs on AlGaAs layer. We consider a quantum wire shown in Fig. 1 [10]. The device geometry consists of an unintentionally p-doped GaAs layer ($N_A = 1 \times 10^{14}\,\mathrm{cm}^{-3}$), followed by an undoped AlGaAs spacer ($d = 10\,\mathrm{nm}$) having an aluminum concentration of 35% and a doped AlGaAs layer ($d = 10\,\mathrm{nm}$, $N_D = 1.2 \times 10^{18}\,\mathrm{cm}^{-3}$) and a GaAs cap layer

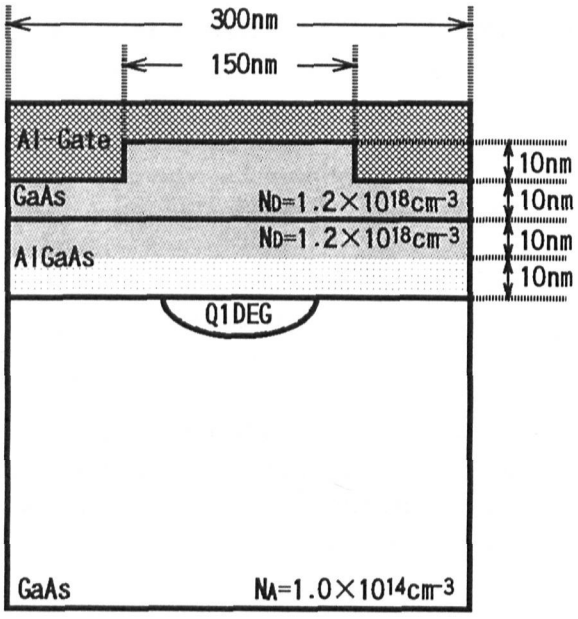

Figure 1: Schematic view of a quantum wire structure.

($N_{\mathrm{D}} = 1.2 \times 10^{18}\,\mathrm{cm}^{-3}$). In the calculations we take the coordinates such that the y and z axes are along parallel and normal directions to the GaAs/AlGaAs interface, respectively.

The electrostatic potential is calculated by solving two-dimensional Poisson equation with suitable boundary conditions, and Schrödinger equation for the envelope function (effective mass approximation). Schottky barrier between Al electrode and GaAs is assumed to be 0.7 eV and the conduction band offset is assumed to be 270 meV. The Poisson and Schrödinger equations were discretized by using nonuniform mesh (121×101 for Poisson mesh and 99×41 for Schrödinger mesh). Energy eigen values and eigen vectors up to 20 subbands are obtained. In Fig. 2 we show the gate voltage dependence of the energy levels E_i measured form the lowest subband level E_0 at $T = 300\,\mathrm{K}$. The subband indexes i are expressed by the numbers of nodes along the y and z directions, *i.e.* $i = (Ns)$ where N is the number of nodes along the y direction and s is that along the z direction. In Fig. 2, solid circles represent $E_i - E_0$ for $i = (N0)$, open circles for $i = (N1)$ and triangles for $i = (N2)$. The energy separation between two levels having the same s becomes smaller with increasing gate voltage. Figure 2 demonstrates that inter-subband resonance can occur at several points from the energy separation point of view, however, the resonant structure is expected to be weak because of the narrowness of separation.

3. ELECTRON MOBILITY

Under high electric fields, an organization effect in k-space makes the use of Boltzmann distribution function unsuitable [3]. At sufficiently low electric field, however, we can safely utilize the usual Boltzmann transport equation assuming the Boltzmann distribution function. In the case of weak electron-phonon interaction, the electron mobility is given by the following equation,

$$\mu = \frac{e}{kT} \sum_{ik} \left(\frac{k}{m}\right)^2 \frac{1}{W_{ik}} f(E_{ik}) \Big/ \sum_{ik} f(E_{ik}), \tag{1}$$

where $f(\varepsilon)$ is the distribution function, k is the electron wave vector along the wire, and W_{ik} is the scattering rate. We calculate W_{ik} by using the Fermi's golden rule with phenomenological

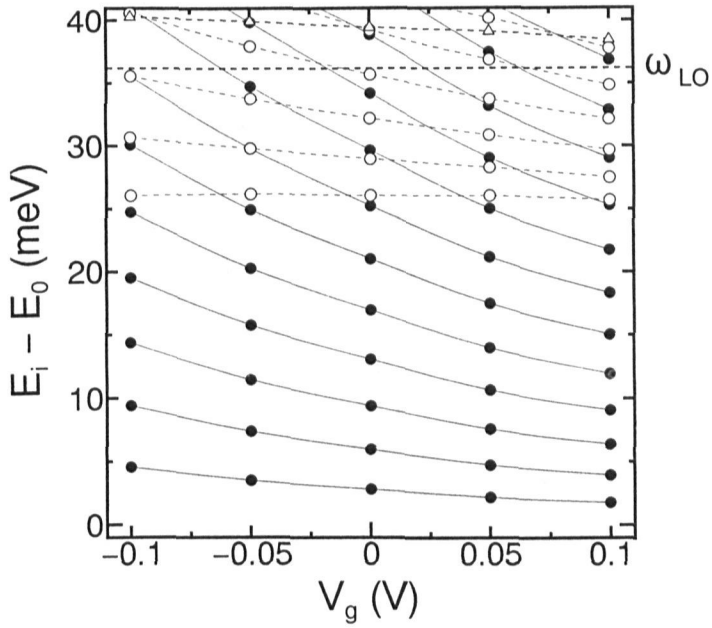

Figure 2: The gate voltage dependence of the energy levels E_i measured form the lowest subband level E_0 at $T = 300$ K.

broadening of the density of states and by making use of small wave vector limit, and then we have $\mu = e\tau/m$ with

$$\tau = \sum_i \frac{1}{W_i} \mathrm{e}^{-E_i/kT} \Big/ \sum_i \mathrm{e}^{-E_i/kT}, \tag{2}$$

and

$$W_i = 2\alpha\omega_0 N_0 \sum_{i'} G_{ii'}(k_{ii'}) \Re \sqrt{\frac{\omega_0}{\omega_0 - (E_{i'} - E_i) + i\Gamma}}, \tag{3}$$

where α is the Fröhlich coupling constant, ω_0 is the LO phonon frequency, N_0 is the distribution function of LO phonons, $k_{ii'} = (2m(\omega_0 - (E_{i'} - E_i)))^{1/2}$ and the one-dimensional form factor $G_{ii'}(q_x)$ is expressed by the i-th electron wave function $\Psi_i(\rho)$ ($\rho \equiv (y, z)$) and the modified Bessel function of order zero, K_0, as follows:

$$G_{ii'}(q_x) = \int d\rho_1 d\rho_2 \Psi_{i'}(\rho_1)\Psi_i(\rho_1)\Psi_{i'}(\rho_2)\Psi_i(\rho_2)\,\mathrm{K}_0(q_x|\rho_1 - \rho_2|). \tag{4}$$

Once we evaluate the one-dimensional form factor of Eq. (4), we are able to evaluate the electron mobility from Eqs. (2) and (3). The difference in the mobility between the numerical results obtained by using the self-consistent calculations and the simple analytical results [4] arises mainly from the value of $G_{ii'}$. In Fig. 3, we show $G_{(00)(N0)}(k_{(00)(N0)})$ (solid circles) as a function of applied gate voltage together with the approximated values of $G_{(00)(N0)}(0) \sim 1/2N$ [4] (diamonds), where the values of $G_{(00)(N0)}$ are obtained for the subscript, N, for the nearest resonance condition. We find that the present results of numerical calculations differ by a factor 2 to 3 from the simplified analytical results. It suggests that the form factor plays an important role in determining the electron mobility quantitatively. The plot $G_{0i}(k_{0i})$ vs $E_i - E_0$ is also shown in Fig. 4, where solid circles represent the calculated values for $i = (N0)$ and open circles for $i = (N1)$. As seen in the figure, the form factor becomes smaller for higher values of N, while $G_{(00)(01)}$ has got a large value. This can be explained as the wave function associated with $G_{(00)(01)}$ along the y direction is not orthogonal. Therefore we can expect a strong resonance when the levels of $(0, 0)$ and $(0, 1)$ is tuned to a LO phonon energy.

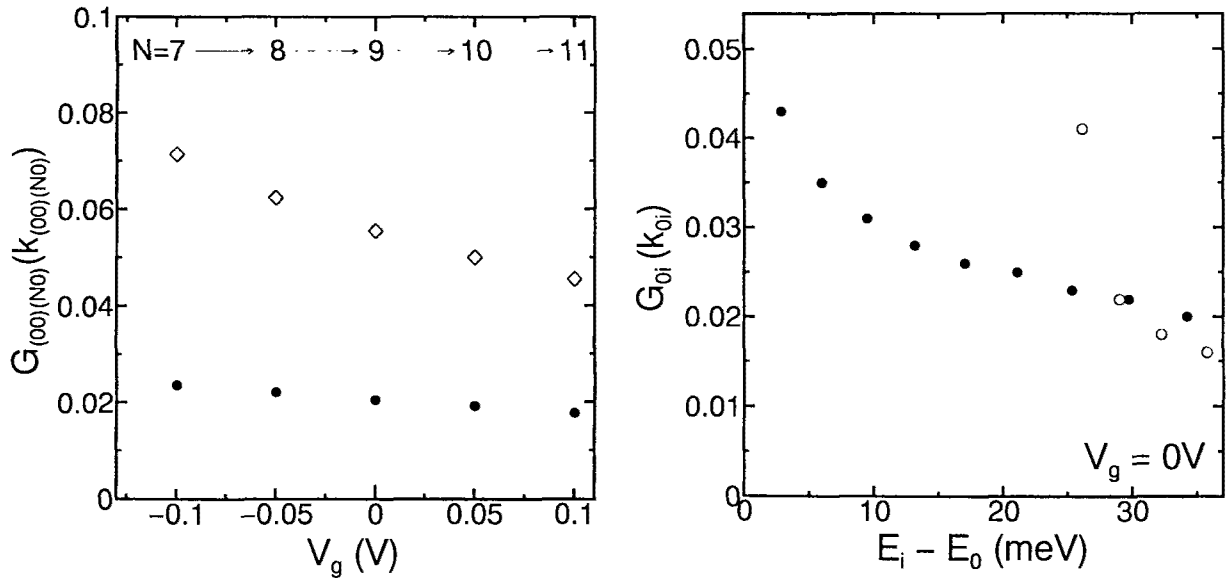

Figure 3: [left] The one-dimensional form factors $G_{(00)(N0)}(k_{(00)(N0)})$ obtained by using the self-consistent calculation (solid circles) as a function of applied gate voltage together with the approximate results of $G_{(00)(N0)} \sim 1/2N$ (diamonds).

Figure 4: [right] The energy separation dependence of the form factors $G_{0i}(k_{0i})$ for $V_g = 0$ V.

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