Effects of Optical and Acoustic Phonon Scattering on Hot Electron Transport in Quantum Wires

N. Mori, H. Momose, S. Miyahara and C. Hamaguchi

Department of Electronic Engineering, Osaka University
2-1, Yamada-oka, Suita City, Osaka 565, Japan

Abstract

Transport responses of hot electrons in quantum wires at high temperature are calculated including both optical and acoustic phonon scatterings to study how the average electron energy and the drift velocity depend on the applied electric field. The average electron energy is found to increase monotonically with the applied electric field showing no anomalous carrier cooling. The calculated results of drift velocity at lower electric fields agree well with the results obtained by solving linearized Boltzmann transport equation. The contribution of acoustic phonon scattering to the transport response is also discussed.

I Introduction

In recent years, mesoscopic structures, such as quantum wires and dots, have been designed to investigate new phenomena and to explore high speed devices. In quantum wires, momentum space is limited to a single dimension, and the carrier density of states (DOS) shows some singularities resulting in changes in the nature of particle collisions. It is pointed out that at a moderate electric field anomalous carrier cooling of electrons in quantum wires enhances the transport response due to the conversion of thermal energy into drift motion [1]. In the present work, we are interested in obtaining transport responses of hot electrons in quantum wires at high temperature including both optical and acoustic phonon scatterings to study how the average electron energy and the drift velocity depend on the applied electric field. We adopt the Rees's iterative method [2] to evaluate hot electron distribution function, since the method provides a consistent treatment of the divergence of DOS of electrons and the scattering probability [3].

II Model

We employ a simple model for a quantum wire in which a two-dimensional electron gas in xy-plane is confined by narrow gates or split gates, and electrons are free along only the x direction. We assume that the wave function associated with quantized z motion is expressed by the Fang-Howard variational function ($\xi_0(z) = (b^3/2)^{1/2} z \exp(-\frac{1}{2}bz)$) and the confinement in the y direction is characterized by a parabolic potential of frequency Ω ($V(y) = \frac{1}{2}m\Omega^2 y^2$). We consider only the ground subband, *i.e.* the strong confinement case. Furthermore, number of electrons is assumed to be so small that their distribution is given by the Boltzmann distribution function in thermal equilibrium.

III Method

We evaluate the electron distribution function by using the iterative method proposed by Rees [2] accounting the Fermi's golden rule to calculate the scattering probability. In this study, we consider bulk longitudinal optical phonon scattering and acoustic deformation potential scattering, while other scattering processes are ignored for simplicity. The distribution function $f(k)$ is calculated by the iterative process as follows:

$$f_{n+1}(k) = \Gamma \int_0^\infty g_n(k - eEt) e^{-\Gamma t}\, dt, \tag{1}$$

$$g_n(k') = \sum_k f_n(k) \frac{S(k,k')}{\Gamma}, \tag{2}$$

where $S(k,k')$ is the scattering probability per unit time from k to k' and Γ is the total scattering rate including self-scattering process which is positive constant and determines the convergence of the iteration. $S(k,k')$, which includes self-scattering process, is evaluated from *real* scattering probability $W(k,k')$ as follows:

$$S(k,k') = W(k,k') + S(k)\delta_{k,k'} \tag{3}$$

with $S(k)$ being the self-scattering rate. $W(k,k')$ is given by the sum of optical and acoustic phonon scattering probabilities:

$$\begin{aligned} W(k,k') = &\sum_{\eta=\pm 1} 4\pi\alpha\omega_0 \left(\frac{\omega_0}{k_0}\right) (N_0 + \tfrac{1}{2} + \tfrac{1}{2}\eta)\, G(k'-k)\, \delta(\varepsilon_{k'} + \eta\omega_0 - \varepsilon_k) \\ &+ 8\pi\beta\omega_0 \left(\frac{\omega_0}{k_0}\right)\left(\frac{kT}{\omega_0}\right) f_y\, f_z\, \delta(\varepsilon_{k'} - \varepsilon_k) \end{aligned} \tag{4}$$

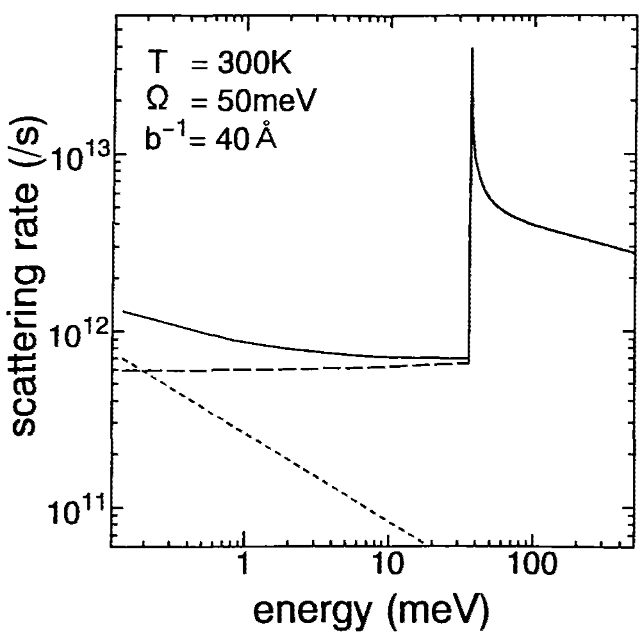

Figure 1: Total scattering rates in a GaAs quantum wire (solid line). $1/b = 40$ Å, $\Omega = 50$ meV and $T = 300$ K. Dashed line : rates for optical phonon scattering. Dotted line : rates for acoustic phonon scattering.

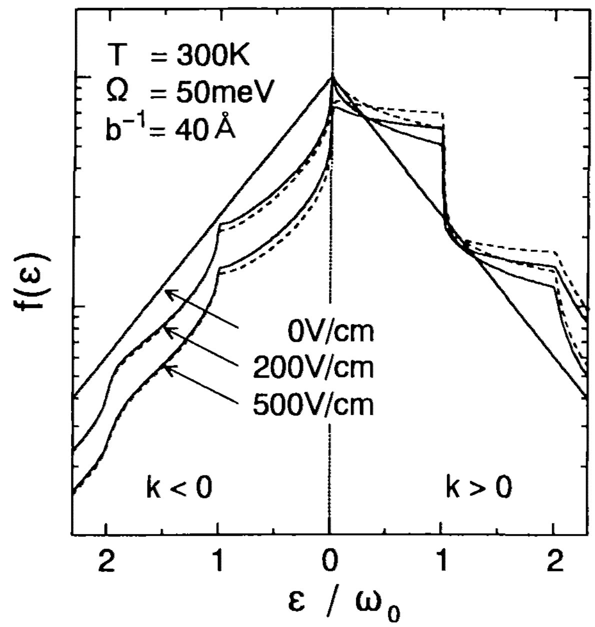

Figure 2: Distribution functions $f(k)$ as a function of electron energy $\varepsilon_k = k^2/2m$ with applied electric fields (0, 200 and 500 V/cm) switched on for 100 ps. $1/b = 40$ Å, $\Omega = 50$ meV and $T = 300$ K. Solid lines represent $f(k)$ including both optical and acoustic phonon scatterings, and dotted lines are $f(k)$ without acoustic phonon scattering.

with

$$G(q_x) = \int_{-\infty}^{+\infty} dq_y \, \frac{1}{2Q} e^{-(q_y/K)^2} F(Q), \quad F(Q) = \iint |\xi_0(z_1)|^2 |\xi_0(z_2)|^2 e^{-Q|z_1-z_2|} dz_1 dz_2, \quad (5)$$

where α is the Fröhlich coupling constant, ω_0 is the optical phonon energy, N_0 is the occupation number of optical phonons, $\beta = D^2 m k_0 / 2\rho s^2$, D is the deformation potential, ρ is the density of the material, s is the sound velocity, $f_y = (K/k_0)/(2\sqrt{\pi})$, $f_z = (3/16)(b/k_0)$, $K = (2m\Omega)^{1/2}$, $k_0 = (2m\omega_0)^{1/2}$ and $Q = (q_x^2 + q_y^2)^{1/2}$. Note that non-elastic effects of acoustic phonon scattering are ignored in the present calculation.

Calculated scattering rates of a GaAs quantum wire are shown in Fig. 1. Scattering rates by acoustic phonons are larger than those of optical phonons for low energy electrons because of the singularity of DOS at the bottom of subband.

IV Results

Figure 2 shows calculated results of distribution functions with applied electric fields (0, 200 and 500 V/cm) switched on for 100 ps. In the case of zero applied electric field, the distribution function coincides with the Boltzmann distribution function. This clearly indicates that the iterative method is valid for evaluating transport responses of one-dimensional electron gases.

In Fig. 3 we show the calculated average electron energy $\varepsilon_{\rm ave}$ in a quantum wire of GaAs as a function of applied electric field E. We find that $\varepsilon_{\rm ave}$ increases monotonically with E and an anomalous carrier cooling does not occur. The calculated result of drift

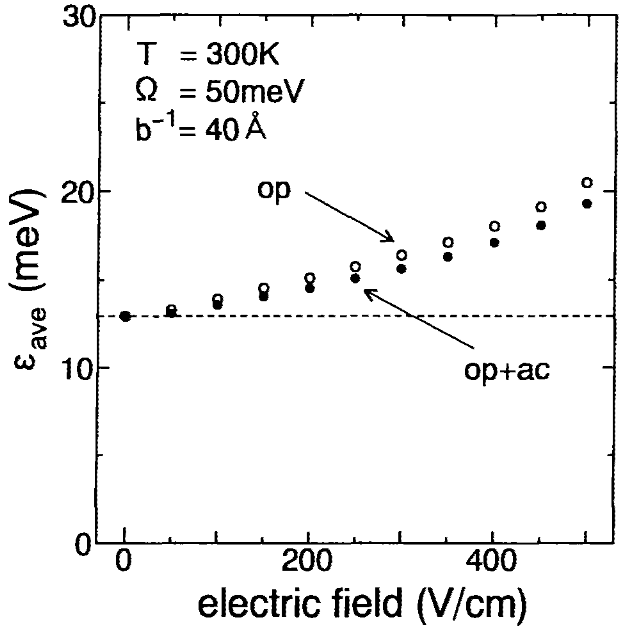

Figure 3: Average electron energy $\varepsilon_{\rm ave}$ in a GaAs quantum wire as a function of applied electric fields. Thermal kinetic energy ($\frac{1}{2}kT$) is represented by dotted line. $1/b = 40\,\text{Å}$, $\Omega = 50\,\text{meV}$ and $T = 300\,\text{K}$. Solid circles indicate $\varepsilon_{\rm ave}$ including both optical and acoustic phonon scatterings, and open circles are $\varepsilon_{\rm ave}$ without acoustic phonon scattering.

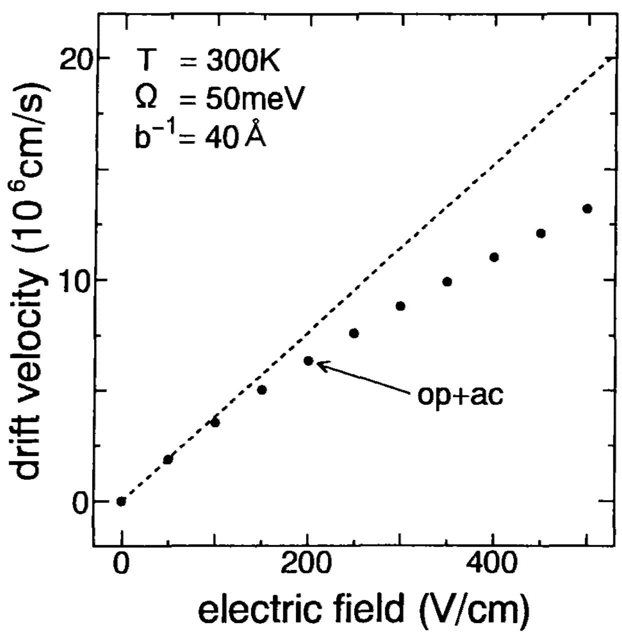

Figure 4: Electron drift velocity in a GaAs quantum wire as a function of applied electric fields (solid circles), compared with the results obtained by solving linearized Boltzmann transport equation (dotted line). Both optical and acoustic phonon scatterings are considered. $1/b = 40\,\text{Å}$, $\Omega = 50\,\text{meV}$ and $T = 300\,\text{K}$.

velocity is also shown in Fig. 4. The drift velocity at lower electric fields agrees well with the results obtained by solving linearized Boltzmann transport equation At higher electric fields, the drift velocity saturates as the electron temperature increases. Although electron energy and drift velocity are influenced only a little by acoustic phonon scattering in the case of $1/b = 40\,\text{Å}$ and $\Omega = 50\,\text{meV}$, it is not too small to be neglected.

Figure 5 shows a contribution of acoustic phonon scattering to the drift velocity. The contribution, η_{ac}, is defined as follows:

$$\eta_{\text{ac}} = 1 - \frac{v_{\text{op+ac}}}{v_{\text{op}}} \tag{6}$$

where $v_{\text{op+ac}}$ is the drift velocity calculated by including both optical and acoustic phonon

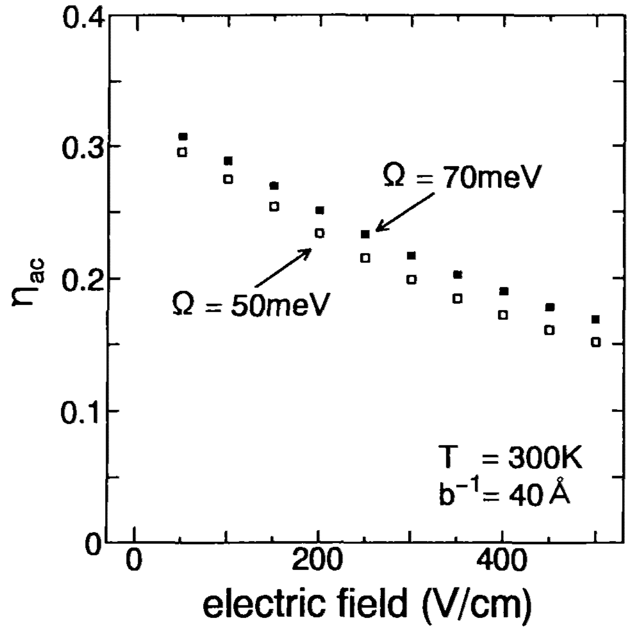

Figure 5: Contribution of acoustic phonon scattering to the drift velocity for $\Omega = 50$ and $70\,\text{meV}$. The contribution, η_{ac}, is defined in the text. $1/b = 40\,\text{Å}$ and $T = 300\,\text{K}$.

scatterings, and v_{op} is that without acoustic phonon scattering. The contribution of acoustic phonon scattering becomes larger in the case of low applied electric field E or strong confinement Ω.

References

[1] J.P. Leburton and D. Jovanovic, Semicond. Sci. Technol. **7** (1992) B202.

[2] H.D. Rees, J. Phys. Chem. Solids **30** (1969) 643.

[3] N. Mori and C. Hamaguchi, in *Extended Abstracts of the Second International Symposium on New Phenomena in Mesoscopic Structures*, Maui, Dec. 7–11, 1992, pp. 28–31.