AIP Journal of Applied Physics

Onedimensional hotelectron transport in quantumwell wires of polar semiconductors

A. Ghosal, D. Chattopadhyay, and A. Bhattacharyya

Citation: Journal of Applied Physics **59**, 2511 (1986); doi: 10.1063/1.336998
View online: http://dx.doi.org/10.1063/1.336998
View Table of Contents: http://scitation.aip.org/content/aip/journal/jap/59/7?ver=pdfcov
Published by the AIP Publishing

One-dimensional hot-electron transport in quantum-well wires of polar semiconductors

A. Ghosal, D. Chattopadhyay, and A. Bhattacharyya
Institute of Radio Physics and Electronics, 92 Acharya Prafulla Chandra Road, Calcutta 700009, India

(Received 28 June 1985; accepted for publication 5 December 1985)

The velocity-field characteristics of hot electrons moving one dimensionally in the lowest subband of a polar semiconductor quantum-well wire are obtained on a drifted Maxwellian model and also by the Monte Carlo technique. No negative differential resistance is obtained in contradiction to a previous prediction. The size effects at low temperatures are found to be more significant in the drifted Maxwellian model. Our calculations show that the one-dimensional (1-D) mobility for large transverse widths may be higher than the 3-D mobility.

I. INTRODUCTION

Current progress in the growth of fine layers of semiconductors has produced quantum wells in which a smaller band-gap material is confined between the layers of a larger band-gap material. Recently, attempts have been made toward the realization of a "wire" semiconductor quantum-well structure in which the electron gas is quantized in two transverse directions.[1] Electron transport in these structures is essentially one dimensional (1-D) and takes place in the longitudinal direction. The effect of ionized impurity scattering on the quantum-well transport is significantly small, as "modulation doping" spatially separates the electrons from their parent donor atoms. The structures are therefore characterized by a high electron mobility, particularly at low temperatures. Mobility in the 1-D structures may be further enhanced owing to the reduced number of final states during a scattering process which consists of either forward or backward scattering.[2] Quantum-well wire structures thus show promise for application in high-speed devices. In this context, investigations of hot-carrier effects in these structures are of considerable importance.

The major scattering mechanism that needs attention is the polar optic (POP) scattering. The scattering rate in 1-D structures for the POP interaction has been derived by Riddoch and Ridley[3] using the momentum conservation approximation and by Leburton[4] without this approximation. We use Leburton's expressions here to obtain the hot-electron mobility in quantum-well wires. We employ a drifted Maxwellian distribution function[5] as well as the Monte Carlo technique.[6] The latter gives the features associated with the pure POP scattering, while the former gives the results for POP scattering coupled with strong electron-electron (e-e) interactions. Owing to the weakness of ionized impurity scattering, e-e interactions may dominate in energy and momentum exchanges in quantum wells for sufficiently large carrier concentrations to enforce a drifted Maxwellian distribution function characterized by a drift wave vector and an electron temperature. At a lattice temperature of 30 K such a dominance would occur for linear electron concentrations above 3×10^5 cm^{-1} over the field range of interest here. Photoluminescence studies in two-dimensional (2-D) structures have indeed indicated the establishment of an electron temperature.[7]

We also study here the effect of the size of the "wire" cross section on the electron mobility. Our results show that the 1-D mobility may be higher than that for the 3-D electrons. The possibility of the occurrence of a negative differential resistance (NDR) at low temperatures, as predicted by Riddoch and Ridley,[3] however, is contradicted.

II. MODEL AND METHOD

We use the infinite-well approximation and assume the extreme quantum limit condition (EQL), i.e., the electrons occupy the lowest subband. The electron energy is given by

$$E_t = E + E_0, \tag{1}$$

where

$$E = \frac{\hbar^2 k_x^2}{2m}, \tag{2}$$

and

$$E_0 = \frac{\hbar^2\pi^2}{2m}\left(\frac{1}{L_y^2} + \frac{1}{L_z^2}\right). \tag{3}$$

Here $\hbar$ is Planck's constant divided by 2π, k_x is the longitudinal component of the electron wave vector, m is the effective mass, and L_y and L_z are the transverse dimensions of the quantum-well wire.

The details of the drifted Maxwellian and the Monte Carlo methods used in our analysis are given below.

A. Drifted Maxwellian method

The electron temperature T_e and the drift wave vector d associated with the distribution function are determined from the energy and the momentum balance equations.[5] For the 1-D transport problem, these balance equations read

$$ev_dF + \frac{1}{\sqrt{\pi k_B T_e}}\int_0^\infty \left(\frac{\partial E}{\partial t}\right)_{\rm POP} \exp\left(\frac{-E}{k_B T_e}\right) E^{-1/2} dE = 0, \tag{4}$$

and

$$eF + \left(\frac{2m}{\pi}\right)^{1/2} \frac{v_d}{(k_B T_e)^{3/2}} \int_0^\infty \left(\frac{\partial p}{\partial t}\right)_{\rm POP} \times \exp\left(\frac{-E}{k_B T_e}\right) dE = 0, \tag{5}$$

where F is the electric field applied along the longitudinal direction of the wire structure, e is the electron charge, k_B is the Boltzmann constant, v_d is the drift velocity given by $v_d = \hbar d/m$, and $(\partial E/\partial t)_{\rm POP}$ and $(\partial p/\partial t)_{\rm POP}$ are the rates of change of electron energy and momentum due to the POP scattering.

If $\hbar\omega$ represents the optic phonon energy, we have[8]

$$\left(\frac{\partial E}{\partial t}\right)_{\rm POP} = \hbar\omega\left(\sum_{q_a}\frac{1}{\tau_a} - \sum_{q_e}\frac{1}{\tau_e}\right) \qquad (6)$$

and

$$\left(\frac{\partial p}{\partial t}\right)_{\rm POP} = \sum_{q_a}\hbar q_a\left(\frac{1}{\tau_a}\right) - \sum_{q_e}\hbar q_e\left(\frac{1}{\tau_e}\right), \qquad (7)$$

where τ_a^{-1} and τ_e^{-1} are the scattering rates out of the state k_x due to the absorption and emission of phonons with longitudinal wave vector components q_a and q_e, respectively; Σ denotes summation over the possible values of q_a and q_e. The detailed expressions of τ_a^{-1}, τ_e^{-1}, q_a, and q_e are obtained from Ref. 4.

B. Monte Carlo method

The Monte Carlo method follows the same general pattern as described by Fawcett *et al.*[6] Absorption and emission processes are treated separately and self-scattering is included. Random numbers are generated to determine the time of flight of the electron before scattering and the type of scattering terminating the flight. Once the type of scattering is selected, the longitudinal component of the phonon wave vector involved in the scattering and hence the final state after the scattering are automatically determined. This is different from the 3-D case where more random numbers need to be generated to determine the final state of the electron after the scattering.[5]

A singularity in the phonon emission rate is introduced at $E = \hbar\omega$ owing to the 1-D density of states.[3,4] Beyond this singularity, the emission rate drops off rapidly with increasing electron energy. The singularity is avoided in our calculations by assuming that the scattering rate in the energy range $E = \hbar\omega$ and $E = 1.07\ \hbar\omega$ is equal to that at $E = 1.05\ \hbar\omega$. The results are insensitive to this choice since a very strong emission rate in a small range of energy beyond $E = \hbar\omega$ is maintained.

III. COMPUTED RESULTS AND DISCUSSIONS

Calculations are done here using the material parameters of GaAs listed in Table I. Figure 1 shows the variation of the drift velocity with electric field. The drift velocities at the lattice temperature of 30 K are found to be larger than these at 300 K owing to the reduced electron-phonon interactions at a lower temperature. The drifted Maxwellian calculations yield drift velocities lower than those obtained by

TABLE I. Material parameters of GaAs.

Effective mass (m)	0.6103×10^{-31} kg
Optical phonon temperature (T_{po})	419 K
Static permittivity (ϵ_s)	1.133×10^{-10} Fm^{-1}
Optical permittivity (ϵ_∞)	0.9651×10^{-10} Fm^{-1}

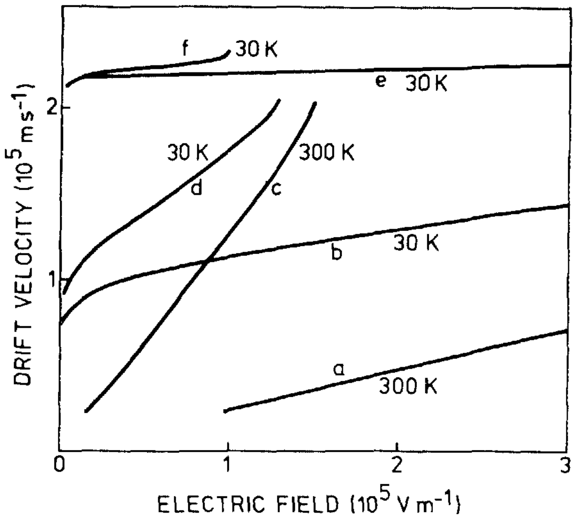

FIG. 1. Variation of drift velocity with electric field in a quantum-well wire at lattice temperatures of 300 and 30 K. Curves a through d are obtained in the drifted Maxwellian model and curves e and f are obtained in the Monte Carlo method. $L_y = L_z = L_0$ for curves a, b, and e; and $L_y = L_z = 5L_0$ for curves c, d, and f, where $L_0 = (\hbar/2m\omega)^{1/2}$.

the Monte Carlo method. In the Monte Carlo simulation the number of electrons falls off sharply above $\hbar\omega$ due to the emission of optic phonons.[6] In the drifted Maxwellian model, however, the sharing of energies due to the e-e interactions increases the number of electrons in the high-energy tail of the distribution function beyond $E = \hbar\omega$. As the scattering rates for such energies are greater than those for energies less than $\hbar\omega$, the velocities calculated in the drifted Maxwellian approximation are lower.

Riddoch and Ridley,[3] and Ridley[9] have predicted that an NDR may occur in 1-D and 2-D transport at low temperatures due to the differences in the scattering rates above and below the threshold for emission of polar optic phonons. Ridley[9] has estimated on the basis of a crude model that the threshold field for the NDR would be about 2 kV/cm. Previously two of us showed that no such NDR is obtained in 2-D transport.[10] We find here that also in the 1-D case an NDR is not obtained either in the drifted Maxwellian or in the Monte Carlo model. That the features of the pure POP scattering at low temperatures do not produce an NDR can be understood with the help of the following simple picture of 1-D transport.

At a low temperature the electron may be taken to be at the state $k_x = 0$ in the absence of an electric field. When a longitudinal electric field is applied, the electron is accelerated and does not suffer interactions with phonons so long as E remains less than $\hbar\omega$. This is because for $E < \hbar\omega$, only POP absorption is possible, but at low temperatures the probability of this process is very small. However, as soon as E reaches $\hbar\omega$, an optic phonon is emitted due to the extremely large emission probability.[4] The electron is then scattered back to the state $k_x = 0$, and the above process is repeated. The velocity of the electron in the beginning of its free flight is zero and that at the end is v_0, where $\frac{1}{2}mv_0^2 = \hbar\omega$. The average drift velocity is therefore $v_d = v_0/2 = (\hbar\omega/2m)^{1/2}$. Thus the drift velocity saturates rather than decreases with field. For the parameter values of Table I, the saturated value of v_d comes out as 2.18×10^5 ms^{-1}. The Monte Carlo results at 30 K agree very well with this simple picture. The slight differences between the two results are due to any deviation from the simple picture in practice.

The size effect may be studied by comparing the curves for $L_z = L_y = L_0$ and $L_z = L_y = 5L_0$, where $L_0 = (\hbar/2m\omega)^{1/2}$. Larger widths of the quantum well are not considered, as they will reduce the separation between the quantized levels; then intersubband scatterings will occur and the EQL cannot be maintained. For larger transverse dimensions, the drift velocities in the drifted Maxwellian model are considerably enhanced. The low-temperature Monte Carlo drift velocities, however, are not affected much. The answer is found in the simple picture of the 1-D transport presented above. The energy E hardly rises above $\hbar\omega$ in the 1-electron Monte Carlo simulation, while in the drifted Maxwellian model there is an appreciable number of electrons with $E > \hbar\omega$. As the emission rate for such electrons is lower at wider transverse dimensions,[4] the drifted Maxwellian drift velocities increase as the cross section of the quantum-well wire is increased. The lower scattering rates for wider transverse dimensions explain the nonsaturatory behavior of the curves (c) and (d) and also show that the velocity runaway would occur at a lower field for such dimensions.

Considering curve (c), it is found that the 1-D mobility for wider transverse dimensions may be larger than the 3-D mobility. The effects of screening would further increase the 1-D mobility. The potentiality of the quantum-well wires for use in high-speed devices is thus favored.

IV. CONCLUSION

The features of the POP scattering in the EQL do not produce an NDR in a quantum-well wire. The low-temperature Monte Carlo values of the drift velocity are larger than the drifted Maxwellian values. For larger transverse dimensions of the quantum well, the drift velocities are larger; at low temperatures this effect is more pronounced in the drifted Maxwellian model. Velocity runaway occurs at lower fields as the transverse dimensions of the quantum well are increased.

[1] P. M. Petroff, A. C. Gossard, R. A. Logan, and W. Wiegmann, Appl. Phys. Lett. **41**, 635 (1982).
[2] H. Sakaki, Jpn. J. Appl. Phys. **19**, L735 (1980).
[3] F. A. Riddoch and B. K. Ridley, *Proceedings of the 5th International Conference on Electronic Properties of 2-D Systems* (Oxford, England, 1983); Surf. Sci. **142**, 260 (1984).
[4] J. P. Leburton, J. Appl. Phys. **56**, 2850 (1984).
[5] R. Stratton, Proc. R. Soc. London Ser. A **246**, 406 (1958).
[6] W. Fawcett, A. D. Boardman, and S. Swain, J. Phys. Chem. Solids **31**, 1963 (1970).
[7] J. M. Carlson, S. A. Lyon, J. M. Worlock, A. C. Gossard, and W. Wiegmann, Bull. Am. Phys. Soc., March meeting, 1984, p. 213.
[8] E. M. Conwell, "High Field Transport in Semiconductors" in *Solid State Physics*, edited by F. Seitz, D. Turnbull, and H. Ehrenreich (Academic, New York, 1967), Suppl. 9, pp. 158–160.
[9] B. K. Ridley, J. Phys. C **15**, 5899 (1982).
[10] D. Chattopadhyay and A. Ghosal, J. Phys. C **16**, 2583 (1983).