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Transport properties of the two-dimensional electron gas in wide AlP quantum wells: The effects of background charged impurity and acoustic phonon scattering

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ABSTRACT

We present the theoretical results of the mobility and diffusion thermopower for the quasi-two-dimensional electron gas (Q2DEG) in a GaP/AlP/GaP quantum well (QW) for interface-roughness, remote and homogenous background charged impurity, and acoustic (AC) phonon scattering. We study the dependence of the mobility and diffusion thermopower on the temperature T, carrier density n and QW width L. The exchange and correlation effects are taken into account using different approximations for the local-field correction (LFC). It is shown that, for the values of parameters employed and wide QWs with $L > 125$ Å, the AC phonon scattering is dominant for $T > 35$ K and the effects of homogenous background charged impurity scattering (BIS) on the thermopower are remarkable. For thin QWs with $L < 55$ Å, the mobility and diffusion thermopower are mainly determined by interface-roughness scattering (IRS). At low density and temperatures the exchange and correlation effects considerably modify the thermopower.

1. Introduction

GaP/AlP/GaP QW structures, where the electron gas is located in the AlP, have been studied recently both experimentally [1–5] and theoretically [6–10]. In this structure, due to biaxial strain in the AlP and confinement effects in the QW, the electron gas has valley degeneracy $g_v = 1$ for well width $L < L_c = 45.7$ Å, and valley degeneracy $g_v = 2$ for well width $L > L_c$ [1,2,6,7]. Gold and Marty have calculated the transport scattering time, single-particle relaxation time and the magnetoresistance for a GaP/AlP/GaP QW at zero temperature [6,7]. The authors of this paper have extended the work of Gold and Marty to the finite temperature case [8,9] and calculated the diffusion thermopower taking into account the IRS and remote charged impurity scattering (RIS) [10]. Our calculations, however, are valid only for very pure samples and low temperatures. For real samples and high temperatures we have to include other scattering mechanisms such as BIS and AC phonon scattering. In addition, it was predicted in theory [7,11] that IRS is the dominant scattering mechanism in thin QWs. Therefore, in this paper, we consider the wide GaP/AlP/GaP QW with $L > L_c$ and calculate the mobility and diffusion thermopower of the Q2DEG realized in AlP for IRS, RIS, BIS and AC phonon scattering.

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2. Theory

We consider a 2DEG, with parabolic dispersion determined by the effective mass m^*, moving in the xy plane with infinite confinement for $z < 0$ and $z > L$. We assume that electrons are only in the lowest subband and described by the wave function $\psi(z) = \sqrt{2/L}\sin(\pi z/L)$ for $0 \leq z \leq L$ [8,9,11]. The mobility μ and the diffusion thermopower S^d, in Boltzmann transport formalism under relaxation time approximation, are given by Refs. [12–14],

$$\mu = e < \tau > / m^* \tag{1}$$

$$S^{\mathrm{d}} = (1/eT)[-E_{\mathrm{F}} + \langle E\tau(E)\rangle / \langle \tau(E)\rangle] \tag{2}$$

with

$$\langle x\rangle = \int_0^\infty x(-\partial f_0/\partial E)E\mathrm{d}E \Big/ \int_0^\infty (-\partial f_0/\partial E)E\mathrm{d}E \tag{3}$$

Here $\tau(E)$ is the relaxation time of the electrons with energy E, $f_0(E)$ is the Fermi-Dirac distribution function and E_F is the Fermi energy.

The relaxation time is given in the Boltzmann theory by Ref. [11],

$$\frac{1}{\tau(k)} = \frac{1}{2\pi\hbar E}\int_0^{2k} \frac{\langle|U(q)|^2\rangle}{[\in(q)]^2}\frac{q^2\mathrm{d}q}{\sqrt{4k^2-q^2}} \tag{4}$$

where

$$\varepsilon(q,T) = 1 + \frac{2\pi e^2}{\in_L}\frac{1}{q}F_C(q)[1-G(q)]\Pi(q,T) \tag{5}$$

$$\Pi(q,T) = \frac{\beta}{4}\int_0^\infty \frac{\Pi^0(q,\zeta')}{\cosh^2\frac{\beta}{2}(\zeta-\zeta')}d\zeta' \tag{6}$$

$$\Pi^0(q,\zeta') = \Pi^0(q) = \frac{g_\nu m^*}{\pi\hbar^2}\left[1-\sqrt{1-\left(\frac{2k_F}{q}\right)^2}\,\Theta(q-2k_F)\right] \tag{7}$$

$$F_C(q) = \frac{1}{4\pi^2+L^2q^2}\left(3Lq + \frac{8\pi^2}{Lq} - \frac{32\pi^4}{L^2q^2}\frac{1-e^{-Lq}}{4\pi^2+L^2q^2}\right) \tag{8}$$

with $\beta = (k_BT)^{-1}$, $E = \hbar^2k^2/(2m^*)$ and $\in_L$ denotes the background static dielectric constant (for AlP we use $\in_L = 9.8$ [5]). Here $k_F = (2\pi n/g_v)^{1/2}$, $E_F = \hbar^2k_F^2/(2m^*)$, $\mu = \ln[-1 + e^{\beta E_F}]/\beta$ and $\Pi(q,T)$ is the 2D Fermi wave vector, Fermi energy, chemical potential and polarizability of 2DEG, respectively. G(q) is the LFC describing the exchange-correlation effects [11,15] and $\langle|U(q)|^2\rangle$ is the random potential which depends on the scattering mechanism [11].

For IRS the random potential is given by

$$\langle|U_{IRS}(q)|^2\rangle = 2\left(\frac{2\pi}{L^2}\right)\left(\frac{m^*}{m_z}\right)^2\left(\frac{\pi}{k_FL}\right)^4(E_F\Delta\Lambda)^2e^{-q^2\Lambda^2/4} \tag{9}$$

where Δ represents the average height of the roughness perpendicular to the 2DEG, Λ represents the correlation length parameter of the roughness in the plane of the 2DEG and m_z is the effective mass perpendicular to the xy-plane.

For RIS, the random potential has the form

$$\langle|U_{RIS}(q)|^2\rangle = N_{RIS}\left(\frac{2\pi e^2}{\in_L}\frac{1}{q}\right)^2[F_{RIS}(q,z_i)]^2 \tag{10}$$

where N_{RIS} is 2D impurity density, z_i is the distance of the impurity layer from the QW edge at $z = 0$, and