Physica E 67 (2015) 84–88

Contents lists available at ScienceDirect

Physica E

journal homepage: www.elsevier.com/locate/physe

Transport properties of the two-dimensional electron gas in wide AlP quantum wells including temperature and correlation effects

Vo Van Tai, Nguyen Quoc Khanh *

Department of Theoretical Physics, National University in Ho Chi Minh City, 227-Nguyen Van Cu Street, 5th District, Ho Chi Minh, Vietnam

HIGHLIGHTS

- The difference between the results of G_H and G_{GA} model is remarkable.
- The temperature effects are notable at very low temperature $T \sim 0.3T_F$.
- The correlation effects increase the critical density for a MIT considerably.

ARTICLE INFO

Article history:
Received 15 August 2014
Received in revised form
5 November 2014
Accepted 24 November 2014
Available online 26 November 2014

Keywords:
AlP quantum wells
Magnetoresistance
Scattering time
Temperature effect

ABSTRACT

We investigate the mobility, magnetoresistance and scattering time of a quasi-two-dimensional electron gas in a GaP/AlP/GaP quantum well of width $L > L_c = 45.7$ Å at zero and finite temperatures. We consider the interface-roughness and impurity scattering, and study the dependence of the mobility, the resistance and scattering time ratio on the carrier density and quantum well width for different values of the impurity position and temperature using different approximations for the local-field correction. In the case of zero temperature and Hubbard local-field correction our results reduce to those of Gold and Marty (Phys. Rev. B. 76 (2007) 165309) [3]. We also study the correlation and multiple scattering effects on the total mobility and the critical density for a metal–insulator transition.

1. Introduction

GaP/AlP/GaP quantum well (QW) structures, where the electron gas is located in the AlP, have been studied recently at low temperatures via cyclotron resonance, quantum Hall effect, Shubnikov de Haas oscillations [1] and intersubband spectroscopy [2]. In this structure, due to biaxial strain in the AlP and confinement effects in the quantum well of width L, 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 $L > L_c$ [3,4]. Recently, we have calculated the mobility, scattering time and magnetoresistance for a GaP/AlP/GaP QW with $L < L_c$ including the temperature and exchange-correlations effects [5]. In this paper, we present our calculation for the case of wide GaP/AlP/GaP QW with $L > L_c$. We consider interface-roughness and randomly distributed charged impurities as source of disorder. We investigate the dependence of the mobility, the resistance and scattering time ratio on the carrier density and QW width for different values of the impurity position and temperature. We also study the correlation and multiple scattering effects (MSE) [6] on the total mobility and the critical density for a metal–insulator transition (MIT) [6,7].

2. Theory

We assume that the electron gas (EG), with parabolic dispersion determined by the effective mass m^*, is in the xy plane with infinite confinement for $z < 0$ and $z > L$. For $0 \le z \le L$, the EG in the lowest subband is described by the wave function $\psi(0 \le z \le L) = \sqrt{2/L}\sin(\pi z/L)$ [5,8].

When the in-plane magnetic field B is applied to the system, the carrier densities $n_\pm$ for spin up/down are not equal [5,9,10]. At $T = 0$ we have

$$n_\pm = \frac{n}{2}\left(1 \pm \frac{B}{B_s}\right), \quad B < B_s$$
$$n_+ = n, \; n_- = 0, \quad B \ge B_s \tag{1}$$

Here $n = n_+ + n_-$ is the total density and B_s is the so-called saturation field given by $g\mu_B B_s = 2E_F$ where g is the electron spin g-

* Corresponding author. Fax: +84 8 38350096.
E-mail address: nqkhanh@phys.hcmuns.edu.vn (N.Q. Khanh).

http://dx.doi.org/10.1016/j.physe.2014.11.015
1386-9477/

factor, μ_B is the Bohr magneton and E_F is the Fermi energy. For $T>0$, $n_\pm$ is determined using the Fermi distribution function and given by [5,9]

$$n_+ = \frac{n}{2}t\,\ln\frac{1-e^{2x/t}+\sqrt{(e^{2x/t}-1)^2+4e^{(2+2x)/t}}}{2}$$
$$n_- = n - n_+ \tag{2}$$

where $x = B/B_s$ and $t = T/T_F$ with T_F is the Fermi temperature. The energy averaged transport relaxation time for the $(\pm)$ components are given in the Boltzmann theory by [5,8,9]

$$\langle\tau_\pm\rangle = \frac{\int d\varepsilon\,\tau(\varepsilon)\varepsilon[-(\partial f^\pm(\varepsilon)/\partial\varepsilon)]}{\int d\varepsilon\,\varepsilon[-(\partial f^\pm(\varepsilon)/\partial\varepsilon)]} \tag{3}$$

where

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

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

$$\Pi(q,T) = \Pi_+(q,T) + \Pi_-(q,T) \tag{6}$$

$$\Pi_\pm(q,T) = \frac{\beta}{4}\int_0^\infty d\mu'\frac{\Pi_\pm^0(q,\mu')}{\cosh^2(\beta/2)(\mu_\pm-\mu')}, \tag{7}$$

$$\Pi_\pm^0(q,E_{F\pm}) \equiv \Pi_\pm^0(q) = \frac{g_v m^*}{2\pi\hbar^2}\left[1-\sqrt{1-\left(\frac{2k_{F\pm}}{q}\right)^2}\,\Theta(q-2k_{F\pm})\right], \tag{8}$$

$$F_C(q) = \frac{1}{4\pi^2+a^2q^2}\left(3aq + \frac{8\pi^2}{aq} - \frac{32\pi^4}{a^2q^2}\frac{1-e^{-aq}}{4\pi^2+a^2q^2}\right), \tag{9}$$

with $\beta = (k_BT)^{-1}$, $\varepsilon = \hbar^2k^2/(2m^*)$ and $\in_L$ denotes the backg round static dielectric constant. Here $k_{F\pm} = (4\pi n_\pm/g_v)^{1/2}$, $E_{F\pm} = \hbar^2k^2_{F\pm}/(2m^*)$, $\mu_\pm = \ln[-1+\exp(\beta E_{F\pm})]/\beta$, and $\Pi_\pm(q,T)$ is the 2D Fermi wave vector, Fermi energy, chemical potential, Fermi distribution function and polarizability for the up/down spin state, respectively. $G(q)$ is the local-field correction (LFC) describing the exchange-correlation effects [8,11] and $\langle|U(q)|^2\rangle$ is the random potential which depends on the scattering mechanism [8]. For interface-roughness scattering (IRS) the random potential is given by [8]

$$\langle|U_{IRS}(q)|^2\rangle = 2\left(\frac{4\pi}{a^2}\right)\left(\frac{m^*}{m_z}\right)^2\left(\frac{\pi}{k_Fa}\right)^4(\varepsilon_F\Delta\Lambda)^2e^{-q^2\Lambda^2/4} \tag{10}$$

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 remote charged impurity scattering (CIS) the random potential has the form

$$\langle|U_{CIS}(q)|^2\rangle = N_i\left(\frac{2\pi e^2}{\in_L}\frac{1}{q}\right)^2F_{CIS}(q,z_i)^2 \tag{11}$$

where N_i is 2D impurity density, z_i is the distance between remote impurities and 2DEG, and $F_{CIS}(q,z_i)$ is the form factor for the electron–impurity interaction given in Ref. [8].

The mobility of the nonpolarized and fully polarized 2DEG is given by $\mu = e<\tau>/m^*$. The resistivity is defined by $\rho = 1/\sigma$ where $\sigma = \sigma_+ + \sigma_-$ is the total conductivity and $\sigma_\pm$ is the conductivity of the $(\pm)$ spin subband given by $\sigma_\pm = n_\pm e^2\langle\tau_\pm\rangle/m^*$ [9]. It was shown that multiple-scattering effects can account for the MIT at low electron density where interaction effects become inefficient to screen the random potential created by the disorder [6,7]. The MIT is described by parameter A, which depends on the random potential, the screening function including the LFC and the compressibility of the electron gas, and is given by [3,6,7]

$$A = \frac{1}{4\pi n^2}\int_0^\infty\frac{\langle|U(q)|^2\rangle[\Pi^o(q)]^2qdq}{[\in(q)]^2}. \tag{12}$$

For $n>n_{MIT}$, where $A<1$, the 2DEG is in a metallic phase and for $n<n_{MIT}$, where $A>1$, the 2DEG is in an insulating phase and the mobility vanishes.

3. Numerical results

For the case $L>L_c$ we use the following parameters [1–3,12]: $\in_L=9.8$, $g_v=2$, $m^*=0.52m_o$ and $m_z=0.3m_o$, where m_o is the free electron mass. The LFC is very important at low electron densities. In the Hubbard approximation, only exchange effects are taken into account and the LFC has the form $G_H(q) = q/[g_vg_s\sqrt{q^2+k_F^2}]$ where g_s is the spin degeneracy [3–5]. We also use analytical expressions of the LFC (G_{GA}) according to the numerical results obtained in Ref. [11] where both exchange and correlation effects are taken into account.

In Fig. 1, we show the mobility μ versus electron density n for a QW of width $L=60$ Å for IRS with $\Delta=3$ Å and $\Lambda=50$ Å for different temperatures in two $G(q)$ models. It is seen that correlation effects are very important for $n<10^{12}$ cm^{-2} and the mobility depends strongly on the approximation for LFC. The LFC reduces the screening, increases the effective scattering potential, and hence reduces the mobility. The temperature effect is remarkable for $T\sim0.3T_F$ (~1.6 K for $n=10^{11}$ cm^{-2}). We have chosen $\Delta=3$ Å and $\Lambda=50$ Å because, using these values, Gold and Marty [4] have calculated the mobility for thin AlP QW of width $L=40$ Å and obtained good agreement with experimental results. Furthermore, although there is not very much known about the parameters Δ and Λ, Δ values around 3 Å and Λ values between 60 and 10 Å seem to be most realistic [4,13]. Our results can be helpful for experimenters in determining the interface-roughness parameters Δ and Λ for GaP/AlP/GaP QW structures. The minimum in the

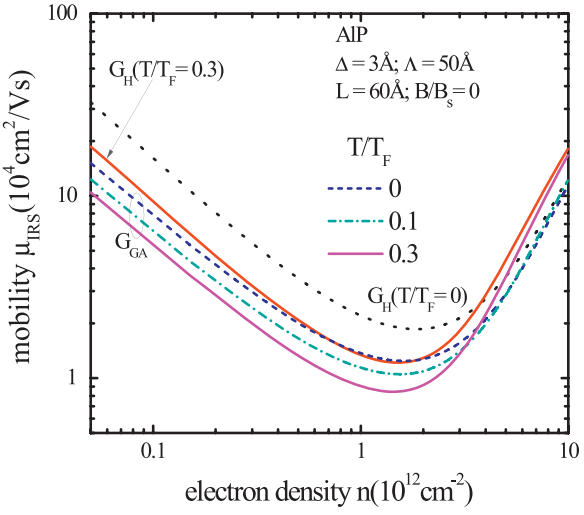

Fig. 1. Mobility μ versus electron density n for a QW of width $L=60$ Å for IRS with $\Delta=3$ Å and $\Lambda=50$ Å for different temperatures in two $G(q)$ models.