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TRANSPORT PROPERTIES OF A QUASI-TWO-DIMENSIONAL ELECTRON GAS IN InP/In$_{1-x}$Ga$_x$As/InP QUANTUM WELLS: CORRELATION AND MAGNETIC FIELD EFFECTS

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Received 01 May 2015
Accepted for publication 15 June 2015

Abstract. We investigate correlation and magnetic field effects on the mobility and resistivity of a quasi-two-dimensional electron gas in an InP/In$_{1-x}$Ga$_x$As/InP quantum well at arbitrary temperatures. We study the dependence of the mobility and resistivity on the carrier density, magnetic field, layer thickness and temperature for alloy disorder and impurity scattering using different approximations for the local-field correction. Multiple scattering effects and the possibility of a metal-insulator transition, which might happen at low density for unpolarized and fully polarized electron gas, are also considered.

Keywords: quantum well, magnetoresistance, exchange-correlation, temperature effect.

I. INTRODUCTION

The transport properties of a quasi-two-dimensional electron gas (Q2DEG) in the lattice matched InP/In$_{0.53}$Ga$_{0.47}$As/InP quantum well (QW) have been studied by several authors [1–5]. It is an attractive system for high-speed electronic device applications due to the negligible concentration of DX centers and dislocations on the InP donor layers [1]. Recently, we have studied the temperature effects on the mobility and resistivity of the unpolarized and fully polarized electron gas for interface-roughness, alloy disorder and impurity scattering [6]. We have used the Hubbard local field correction (LFC) to treat the exchange effects. In this paper, we generalize our results to the case of arbitrary spin-polarized EG and use analytical expressions of the LFC ($G_{GA}$) according to the numerical results obtained in Ref. [7] to include both exchange and correlation effects. We also consider multiple scattering effects (MSE) and discuss the possibility of a metal-insulator transition (MIT) for unpolarized and fully polarized EG.

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We assume that the EG, with parabolic dispersion determined by the effective mass $m^*$, is in the $xy$ plane with infinite confinement for $z < 0$ and $z > a$. For $0 \leq z \leq L$, the EG in the lowest subband is described by the wave function $\psi(0 \leq z \leq L) = \sqrt{2/a} \sin(\pi z/a)$ [6, 8, 9]. An applied parallel magnetic field induces a Zeeman splitting of spin-up and spin-down electrons and the EG can be spin polarized. At zero temperature the system is completely spin polarized for $B \geq B_s = 2E_F/(g\mu_B)$ where $g$ is the electron spin $g$-factor, $\mu_B$ is the Bohr magneton and $E_F$ is the Fermi energy. At finite temperatures, the spin-up and spin-down carrier densities $n_\pm$ can be determined using the Fermi distribution function [6, 9–11]. We have shown that the contribution of surface-roughness scattering to the mobility can be neglected for $a \sim 150 \text{ Å}$ and $n < 10^{12} \text{ cm}^{-2}$ [6]. Therefore, in this paper we consider only alloy disorder (A), remote (R) and homogenous background (B) doping as source of disorder. The expressions for the scattering time, mobility and magnetoresistance due to these scattering mechanisms can be found in our recent paper [6].

III. RESULTS AND DISCUSSION

In the following, we present our numerical calculations for the mobility and resistivity of a Q2DEG in an InP/In$_{1-x}$Ga$_x$As/InP QW using the following parameters [4, 6]: $N_B = 10^{16} \text{ cm}^{-3}$, $n_i = 10^{11} \text{ cm}^{-2}$, $\varepsilon_L = 13.3$, $x = 0.47$, $\delta V = 0.6 \text{ eV}$, $A = 5.9 \text{ Å}$ and $m^* = m_e = 0.041 m_0$ where $m_0$ is the vacuum mass of the electron.

The mobility of the unpolarized and fully polarized 2DEG is given by $\mu = e/m^* < \tau >$ where $< \tau >$ is the energy averaged transport relaxation time. The mobility $\mu$ limited by different scattering mechanisms versus electron density $n$ at $T = 0$ for a) $B = 0$ and b) $B = B_s$ for the well width $a = 150$ Å in two cases of $G_H$ and $G_{GA}$ (thick lines) is plotted in Fig. 1. It is seen from the figure that the difference between the results of $G_H$ and $G_{GA}$ model at low density is remarkable for unpolarized EG especially for alloy disorder scattering.
The resistivity of the polarized 2DEG is given 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 \( \sigma_\pm = n_\pm e^2 \langle \tau_\pm \rangle / m^* \) [10, 11]. We show in Fig. 2 the resistance ratio \( \rho(B_s)/\rho(B = 0) \) versus electron density for a QW of width \( a = 150 \, \text{Å} \) at \( T = 0 \) in two cases of \( G_H \) and \( G_{GA} \) (thick lines). We observe again that the difference between the results of \( G_H \) and \( G_{GA} \) model is remarkable for alloy disorder scattering and the ratio of total resistivities at low density. This behavior stems from the dependence of the screening function on the spin-polarization and from the fact that the random potential due to alloy disorder does not depend on wave vector \( q \) unlike the random potential due to impurity scattering [6].

In Fig. 3 we show our numerical results calculated without LFC for the magnetoresistance as a function of in-plane magnetic field for \( n = 5 \times 10^{11} \, \text{cm}^{-2} \) at \( T = 0 \). We find that the magnetoresistance increases strongly at \( B \approx B_s \) for all scattering mechanisms and electron densities considered in this paper. The total magnetoresistance shows a nonmonotonic dependence on the magnetic field for \( B < B_s \) because the magnetic field dependence for alloy disorder scattering is different from that for impurity scattering. For \( B \geq B_s \) the EG is fully polarized at \( T = 0 \) and the magnetoresistance becomes independent of magnetic field. Note that exchange and correlation effects are very small for \( n \geq 5 \times 10^{11} \, \text{cm}^{-2} \), as seen from Fig. 1 and from Figs. 3 and 4 of our recent paper [6].
The resistivity $\rho$ due to alloy disorder, remote and background impurity scattering versus the well width for $n = 10^{11} \text{ cm}^{-2}$ at $T = 0$ for a) $B = 0$ and b) $B = B_s$ is displayed in Fig. 4. The thin and thick lines correspond to the cases of $G(q) = G_H$ and $G(q) = G_{GA}$, respectively. The figure indicates that the differences between the results of two $G(q)$ models are notable for the wide range of QW width for both unpolarized and fully polarized EG.

Fig. 4. Resistivity $\rho$ due to alloy disorder, remote and background impurity scattering versus the well width for $n = 10^{11} \text{ cm}^{-2}$ at $T = 0$ for a) $B = 0$ and b) $B = B_s$. The thin and thick lines correspond to the cases of $G(q) = G_H$ and $G(q) = G_{GA}$, respectively.
In Figs. 5 and 6 we show the resistivity \( \rho \) due to alloy disorder, remote and background impurity scattering as a function of the temperature for \( a = 150\text{Å} \) and \( B = 0 \) in two \( G(q) \) models. We observe a notable difference between the results of two \( G(q) \) models for both \( n = 10^{10} \text{ cm}^{-2} \) and \( n = 10^{11} \text{ cm}^{-2} \). We find that the resistivity shows strong low-temperature dependence at low density in both \( G(q) \) models.
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ACKNOWLEDGMENT

This research is funded by the Vietnam National Foundation for Science and Technology Development (NAFOSTED) under grant number 103.01-2014.01.

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