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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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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 discolations 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.

II. THEORY

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 $0 \leq z \leq a$, 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, μ_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 $a \sim 150$Å and $n < 10^{12}$ 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/$In_{1-x}Ga_xAs$/InP QW using the following parameters [4,6]: $N_B = 10^{16}$ cm^{-3}, $n_i = 10^{11}$ cm^{-2}, $\varepsilon_L = 13.3$, $x = 0.47$, $\delta V = 0.6$ eV, A $= 5.9$Å and $m^* = m_z = 0.041 m_o$ where m_o is the vacuum mass of the electron.

The mobility of the unpolarized and fully polarized 2DEG is given by $\mu = \frac{e}{m^*} < \tau >$ where $< \tau >$ is the energy averaged transport relaxation time. The mobility μ 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.

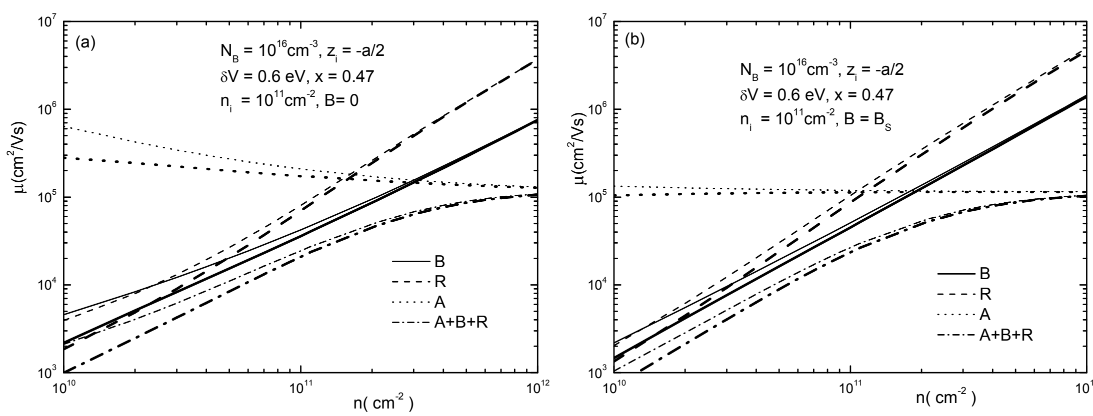

Fig. 1. Mobility μ limited by different scattering mechanisms versus electron density n at $T = 0$ for a) $B = 0$ and b) $B = B_s$ for the well width $a = 150$ Å in two cases of G_H and G_{GA} (thick lines)

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 $a = 150$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].

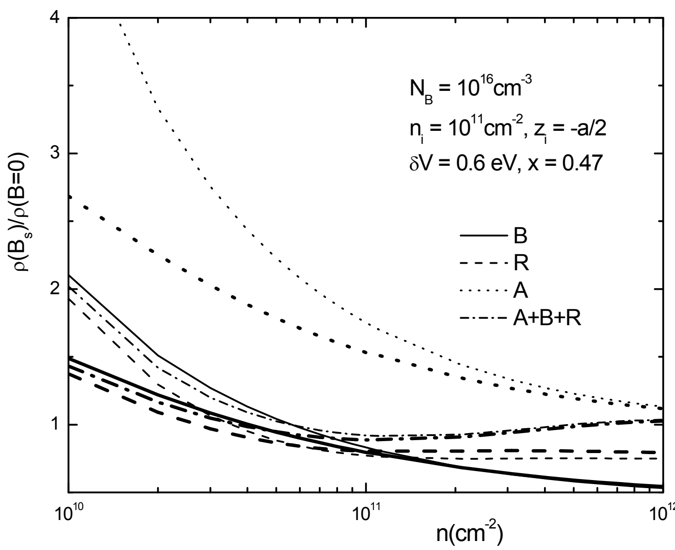

Fig. 2. Resistance ratio $\rho(B_s)/\rho(B=0)$ versus electron density for a QW of width $a = 150$Å at $T = 0$ in two cases of G_H and G_{GA} (thick lines).

In Fig. 3 we show our numerical results calculated without LFC for the magnetoresistance as a function of in-plane magnetic field for $n = 5 \times 10^{11}$ 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 non-monotonic 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 $n \geq 5 \times 10^{11}$ cm^{-2}, as seen from Fig. 1 and from Figs. 3 and 4 of our recent paper [6].

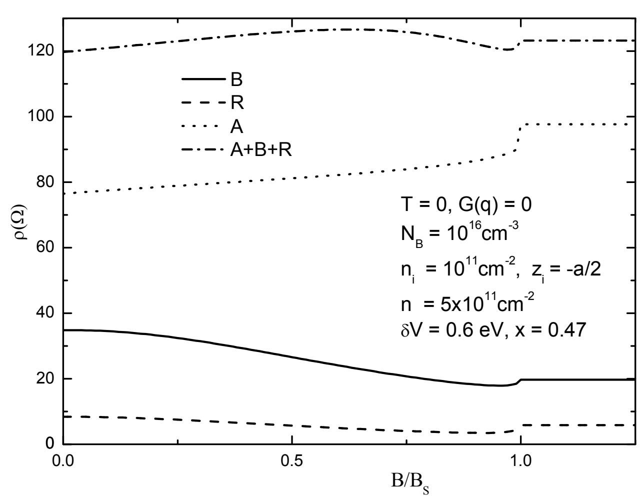

Fig. 3. Magnetoresistance calculated without LFC as a function of in-plane magnetic field for $n = 5 \times 10^{11}$ cm^{-2} at $T = 0$.

The resistivity ρ due to alloy disorder, remote and background impurity scattering versus the well width for $n = 10^{11}$ 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.

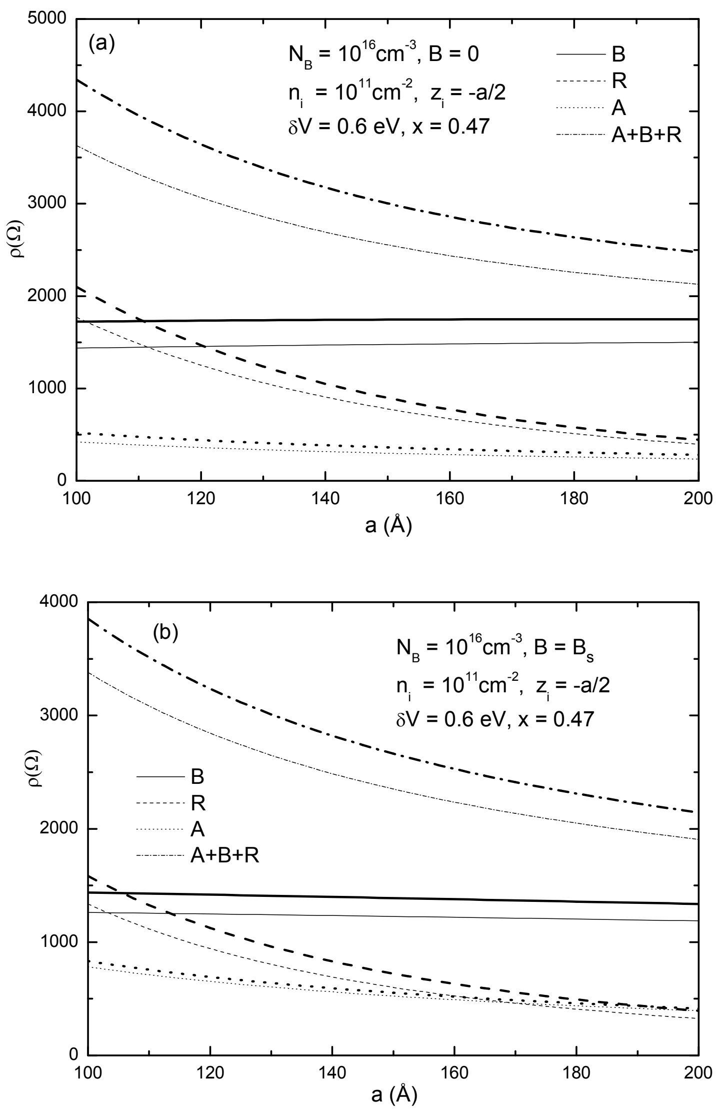

Fig. 4. Resistivity ρ due to alloy disorder, remote and background impurity scattering versus the well width for $n = 10^{11}$ cm^{-2} at $T = 0$ for a) $B = 0$ and b) $B = B_s$. The thin and thick lines correspond to the cases of $G(q) = G_H$ and $G(q) = G_{GA}$, respectively.

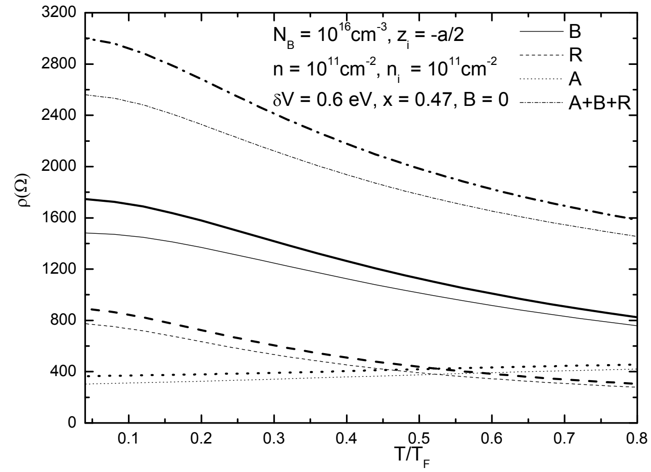

Fig. 5. Resistivity ρ due to alloy disorder, remote and background impurity scattering as a function of the temperature for $a = 150$Å, $n = 10^{11}$ cm^{-2} and $B = 0$ for $G(q) = G_H$ and $G(q) = G_{GA}$ (thick lines).

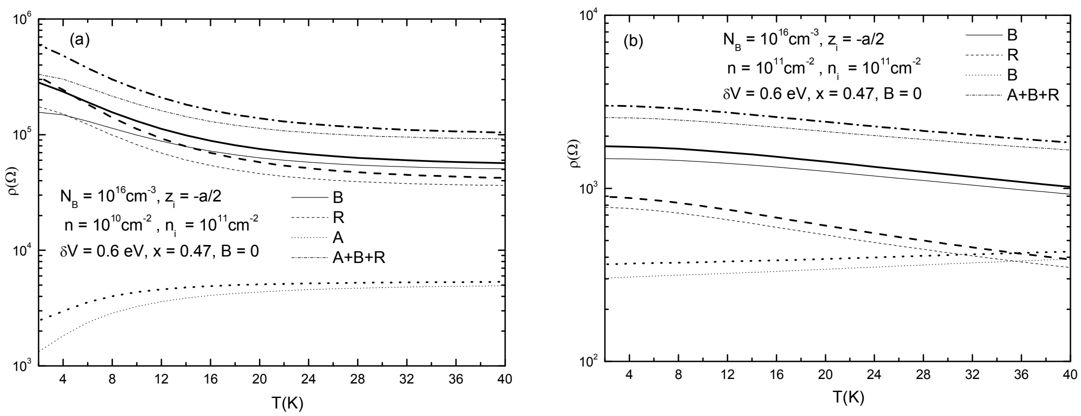

Fig. 6. Resistivity ρ due to alloy disorder, remote and background impurity scattering as a function of the temperature for $a = 150$Å and $B = 0$ for a) $n = 10^{10}$ cm^{-2} and b) $n = 10^{11}$ cm^{-2}. The thin and thick lines correspond to the cases of $G(q) = G_H$ and $G(q) = G_{GA}$, respectively.

In Figs. 5 and 6 we show the resistivity ρ due to alloy disorder, remote and background impurity scattering as a function of the temperature for $a = 150$Å and $B = 0$ in two $G(q)$ models. We observe a notable difference between the results of two $G(q)$ models for both $n = 10^{10}$ cm^{-2} and $n = 10^{11}$ cm^{-2}. We find that the resistivity shows strong low-temperature dependence at low density in both $G(q)$ models.

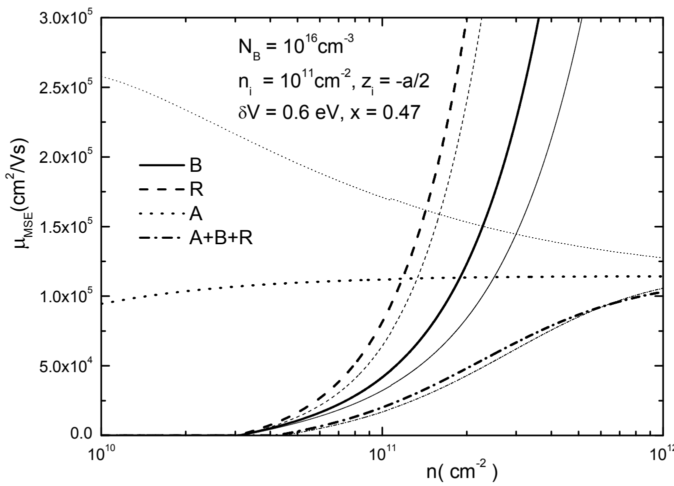

Fig. 7. Mobility calculated with the LFC G_{GA} as a function of electron density n for alloy disorder, remote and background impurity scattering for $a = 150$Å and $T = 0$ in two cases $B = 0$ and $B = B_s$ (thick lines).

It was shown that MSE can account for a MIT at low electron density where interaction effects become inefficient to screen the random potential created by the disorder [12-13]. When the MSE are included, the mobility can be calculated as $\mu_{\text{MSE}} = \mu(1-A)$ where the parameter A is given in Refs. [4,9]. At the MIT, $A = 1$, $n = n_c$ and the EG is in a metallic phase for $n > n_c$ and in an insulating phase for $n < n_c$. In Fig. 7 we show the mobility calculated with the LFC G_{GA} as a function of electron density n for alloy disorder, remote and background impurity scattering for $a = 150$Å and $T = 0$ in two cases $B = 0$ and $B = B_s$ (thick lines). We see considerable magnetic field effects on the mobility, especially in the case of alloy disorder scattering. The critical density n_c for the fully polarized EG is somewhat less than that for the unpolarized EG. We have also found that exchange-correlation effects described by the LFC G_{GA} increase the critical density n_c appreciably, compared to exchange effects alone.

IV. CONCLUSION

To sum up, we have calculated the mobility and resistivity of a Q2DEG in an InP/In$_{1-x}$ Ga$_x$As/InP QW as a function of the carrier density, magnetic field, layer thickness and temperature for alloy disorder and impurity scattering in two $G(q)$ models. We have shown that the difference between the results of G_H and G_{GA} model at low density is remarkable for wide range of the carrier density, layer thickness and temperature. At low temperature, the magnetoresistance increases strongly at $B \approx B_s$ for all scattering mechanisms and the total magnetoresistance shows a nonmonotonic dependence on the magnetic field for $B < B_s$. We have also included MSE and found that correlation effects increase considerably the critical density n_c for a MIT at low density. We hope that our results maybe of help in getting information about the scattering mechanisms and many-body effects in InP/In$_x$Ga$_{1-x}$As/InP QW structures.

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