International Journal of Modern Physics B
Vol. 21, Nos. 8 & 9 (2007) 1502–1506
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HALL RESISTANCE AND MANY-BODY EFFECTS IN A PARABOLIC WELL.

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Received 30 July 2006

We report on Hall effect measurements in 1000-4000 Åwide $Al_xGa_{x-1}As$ parabolic wells with quasi-two-dimensional electrons and holes in the presence of a perpendicular magnetic field. Above a critical magnetic field $B > 3T$, the Hall resistance is found to increase when temperature decreases. We attribute such an enhanced Hall slope to the variation of the carrier density. The Hartree and exchange-correlation terms produce a strong variation of the potential well shap: the width of the electronic and hole slabs shrinks as magnetic field increases, which in turn leads to a charge redistribution between the well and impurity layer.

Keywords: Hall effect; parabolic well; many-body effects.

1. Introduction

Remotely doped parabolic quantum wells (PQWs) have been initially proposed as a system where it might be possible to observe broken- symmetry ground states for three-dimensional electron system in the presence of a strong magnetic field [1]. In such PQWs, the electrons are spatially separated from the dopant atoms. This reduces the electron-impurity scattering and provides an excellent opportunity to study interacting electron systems. The incorporation of the electron-electron interaction leads to a variety of unusual electronic phases in a two and quasi-two dimensional systems in the presence of a magnetic field.

It is worth noting that, among all of the many-body effects in a wide electronic slab, some of them might be robust against electron impurity scattering. In particular, previous numerical computation of the charge distribution and potential-well shapes as a function of magnetic field demonstrated that the Hartree and exchange correlation terms are equally important as the bare potentials in the Schrodinger equation [2]. In particular, as the magnetic field is increased, the width of the electron slab shrinks and the minima of the self-consistent potential near the edges of the electron slab are shifted to the center of the well. It may lead to a decrease of the electron density n_s in the well, since n_s is very sensitive to the well-potential shape.

In this paper, we report on the measurements of the Hall resistance in wide electronic and hole parabolic wells in the presence of a perpendicular magnetic field. We found that, above a critical magnetic field, the Hall slope in hole systems is strongly enhanced in comparison with their low-field Hall coefficient. We attribute this effect to the decrease of the carrier density due to the shrinking of the slab width in the wide bare parabolic potential.

2. Experimental results

Assuming that Z-axis is the growth direction and taking Z=0 as the center of the parabolic well, we consider an effective harmonic potential $V_0(z) = m\Omega^2 z^2/2$ with $\Omega = a(2/m)^{1/2}$ and effective mass m, when a composition profile $x(z) = az^2$ is achieved. The characteristic bulk density is given by the expression $n_+ = \frac{\Omega_0^2 m^* \varepsilon}{4\pi e^2}$. The effective thickness of the electronic slab can be obtained from expression $W_e = n_s/n_+$, where n_s is the two-dimensional density. The dimensionless interelectron spacing in the 3D case is given by $r_s = \frac{4\pi^2 m^* e^2}{\varepsilon h^2}\left(\frac{3}{4\pi n_+}\right)^{1/3}$. Since r_s is usually much larger in **p-type** parabolic quantum wells due to the heavy effective mass, many-body effects are expected to be more pronounced in three-dimensional hole systems. The dimensionless parameter $r_s \approx 15$ for $3000\mathring{A}$ wide PQWs with holes $(m^* = 0.4m_0)$ whereas its value is around 3.3 for electronic $4000\mathring{A}$ - wide wells.

The p-type PQW samples were grown by molecular-beam epitaxy on a semi-insulating GaAs(311)A substrate. Their width varied between $1000\mathring{A}$ and $3000\mathring{A}$ and each of them was symmetrically delta doped with silicon spike located at 150 or $200\mathring{A}$ from the border of the well (depending on the width of the PQW). N-type

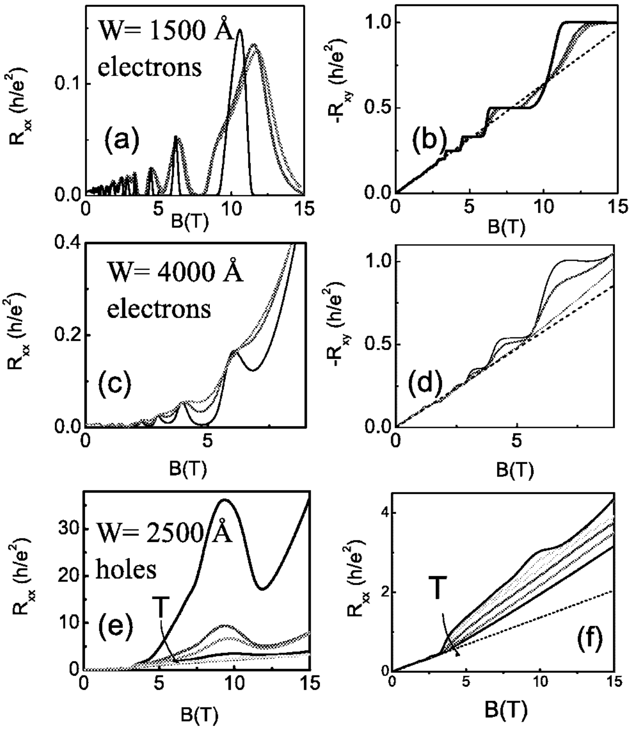

Fig. 1. R_{xx} (a) and R_{xy} (b) for a n-type $1500\AA$ - wide PQWh as a function of the perpendicular magnetic field for different temperatures T (mK): 850 (red), 650 (blue), 50 (black). R_{xx} (c) and R_{xy} (d) for a n-type $4000\AA$ - wide PQW as a function of the perpendicular magnetic field for different temperatures T (mK): 950 (red), 450 (blue), 50 (black).R_{xx} (e) and R_{xy} (f) for a p-type $2500\AA$ - wide PQW versus B for different temperatures T (mK) (1 K - 50 mK). The dashed line corresponds to the linear extrapolation of the low-field Hall resistance.

samples identical to the p-type sample were simultaneously obtained by placing a GaAs(100) substrate close to the GaAs(311)A substrate. The effective thickness of the hole slab was $W_h = p_s/p_+ \approx 800\AA$ for the $2000\AA$ PQW and $W_h \approx 500\AA$ for the $W = 1000\AA$ sample. The hole mobility was of the order of $(30 - 60) \times 10^3 cm^2/Vs$ at T=1.4 K and increased up to $100 \times 10^3 cm^2/Vs$ at T=50 mK. The transport measurements were performed using a Hall-bar geometry with the current flow along the $[\bar{2}33]$ and $[01\bar{1}]$ directions for p-type and n-type structures, respectively. In Fig.1 we show plots of the longitudinal R_{xx} (a) and Hall R_{xy} (b) resistances for the $1500\AA$ - wide electronic PQW and of R_{xx} (c) and R_{xy} (d) for the $4000\AA$ - wide PQW versus the perpendicular magnetic field for three different temperatures. We can see that the n-type samples demonstrate a conventional quantum Hall effect (QHE) behaviour: a wide plateau in the Hall resistance accompanied by a deep minima in R_{xx}. Note that the Hall resistance in the 1500$\AA$ PQW is linear with the magnetic field and that the centers of the Hall plateaus are coincident with the minima in R_{xx}. For the $4000 - \AA$ PQW, the Hall resistance also varies linearly with magnetic field at low B, but, at higher field, its slope increases. Note that the extrapolation of the low-B Hall resistance intersects the Hall plateaus at magnetic field higher than the the value corresponding to the centers of the plateaus. Such an anomalous behaviour is observed only at low temperature.

In general, parabolic wells with holes demonstrate a similar behaviour, but an enhanced Hall slope is usually observed in samples with a smaller effective width. Figures 1(e,f) illustrate the dependence of the Hall resistance for a 2500$\AA$ - wide p-type parabolic well. The figure clearly shows the pronounced high field excess Hall resistance in p-type samples. Note that the Hall slope changes abruptly at a critical magnetic field $B_c \approx 3.2$ T and can not be accounted for by the simple gradual magnetic freeze-out picture. The Hall slope $R_H = \Delta R_{xy}/\Delta B$ gradually increases when temperature decreases, and becomes 2 times larger at T= 50 mK than at low field and high temperature.

It is well known that the presence of multiple carrier types (i.e. in different subbands) with different mobilities can cause changes in the Hall coefficient. However, in that case, the Hall slope at low field is larger than the Hall slope in a stronger magnetic field, which disagrees with our observations. Therefore, we may conclude here that the change in the Hall slope due to multiple subband occupancy and subbands depopulation can not provide a conventional explanation for the larger Hall slope observed in PQWs.

We attribute the enhanced R_H to the variation of the carrier density. Since the potential profile and the shape of the wave function along the z direction are very sensitive to the electron-electron interactions, and may be tuned by a strong magnetic field, the result is a redistribution of the charges between the well and the dopant layers. The evolution of the shape of the electron gas slab in the presence of a magnetic field have been studied in papers [2,3].

3. Self-consistent calculations

We mostly focus on the dependence of the electronic slab width on the magnetic field, which is assumed to be robust against band nonparabolicity and other details of the spectrum. We found that the magnetic field strongly modifies the potential profile and carrier density distribution: the width of the electronic slab shrinks with magnetic field and the height of the central maximum of the self-consistent potential increases. These observations agree with previously published calculations of the self consistent potential and energy spectrum of a PQW in the presence of a magnetic field [2,3]. We extended these calculations in order to determine the electron density in a wide PQW in the presence of a magnetic field. For this aim, we used the balance equation previously developed for square quantum wells [4]. First we calculated the variation of the electron density as a function of the quantum well width W and

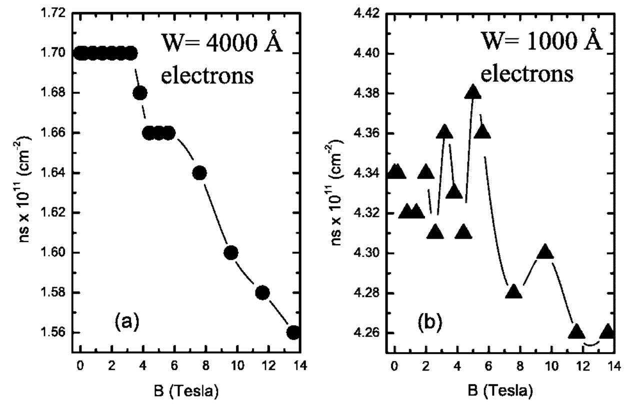

Fig. 2. Variation of the electron density as a function of magnetic field for a 4000Å (a) and 1000Å (b) - wide electronic parabolic wells.

the spacer thickness L_s. For a wide PQW, the calculated density decreases with increasing W and L_s and agree with with the value of n_s extracted form the Hall measurements at low magnetic field. Fig.2 shows the carrier density as a function of magnetic field for the 4000Å and 1000Å- wide electronic parabolic wells. We can see a 9% decrease of the density with B in the widest parabolic well and a small ($\sim$ 1%) oscillation of the density in narrowest well. Note that in the 4000Å - wide well the density is almost constant for $B < 4T$, which agrees with our observation. We did not calculate the energy spectrum for the p-type PQWs because of the complexity of the valence band. However, we expect a stronger Hall-slope change due to the larger value of parameter r_s. It is worth noting that our calculations can not explain completely the enhanced value of R_H in n and p-type PQWs because of the limitation of the Hartree approximation. However, we believe that this model catches the main features of the behaviour of the parabolic quantum wells in a strong magnetic field.

Acknowledgments

Support of this work by FAPESP and CNPq (Brazilian agencies) is acknowledged.

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