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Crossover from negative to positive magnetoresistance in the double quantum well system with different starting disorder

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Abstract
Magnetotransport measurements were performed in two widely separated double quantum well systems with different starting disorders. In the weak magnetic field regime, a crossover from negative to positive magnetoresistance in the longitudinal resistivity was observed in the system with weak disorder when the electron densities in the neighboring wells were significantly unbalanced. The crossover was found to be the result of the exchange-energy-assisted interactions between the electrons occupying the lowest subbands in the neighboring wells. In the case of the system with strong disorder short range scattering dominated the scattering process and no such transition in longitudinal resistivity in the low magnetic field regime was observed. However, at high magnetic fields, sharp peaks were observed in the Hall resistance due to the interaction between the edge states in the quantum Hall regime.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Double quantum well systems provide a suitable platform for studying the interlayer electron–electron interaction. This interaction gives rise to various exotic many-body effects such as the Coulomb drag effect, the Coulomb screening effect, and resonant and non-resonant tunneling effects [1]. In heterostructures with weak interlayer interaction, the electrons carry current independently in their respective quantum wells resembling two-band electron transport [2]. In such a scenario, if electrons in the two subbands have different mobilities, the transport is dominated by the two-dimensional electron gas (2DEG) with the highest mobility. As a result, the Hall field can no longer compensate for the magnetic-field-induced drift for the 2DEGs individually and a positive magnetoresistance will appear at weak magnetic fields due to the scattering between the subbands [3]. This is commonly observed in a single quantum well system with a two subband population and also in an asymmetric double quantum well (DQW) system [4–6]. In this physical picture, the roles of other long and short range scattering mechanisms are either overlooked or given little attention. It is not clear exactly under what conditions intersubband scattering gains dominance over short and long range scattering effects. In other words, when does a crossover from negative to positive magnetoresistance at weak fields take place? It is the purpose of this paper to provide a detailed insight into these intriguing problems by investigating the magnetotransport in the DQW system. Since the DQW has two 2DEGs occupying the lowest subbands in their respective quantum wells, it offers a suitable platform to study the comparative strength of scattering between the subbands with the long and short range scattering potentials. Moreover, from the application point of view, the importance of this study can be gauged from the fact that the heterostructures

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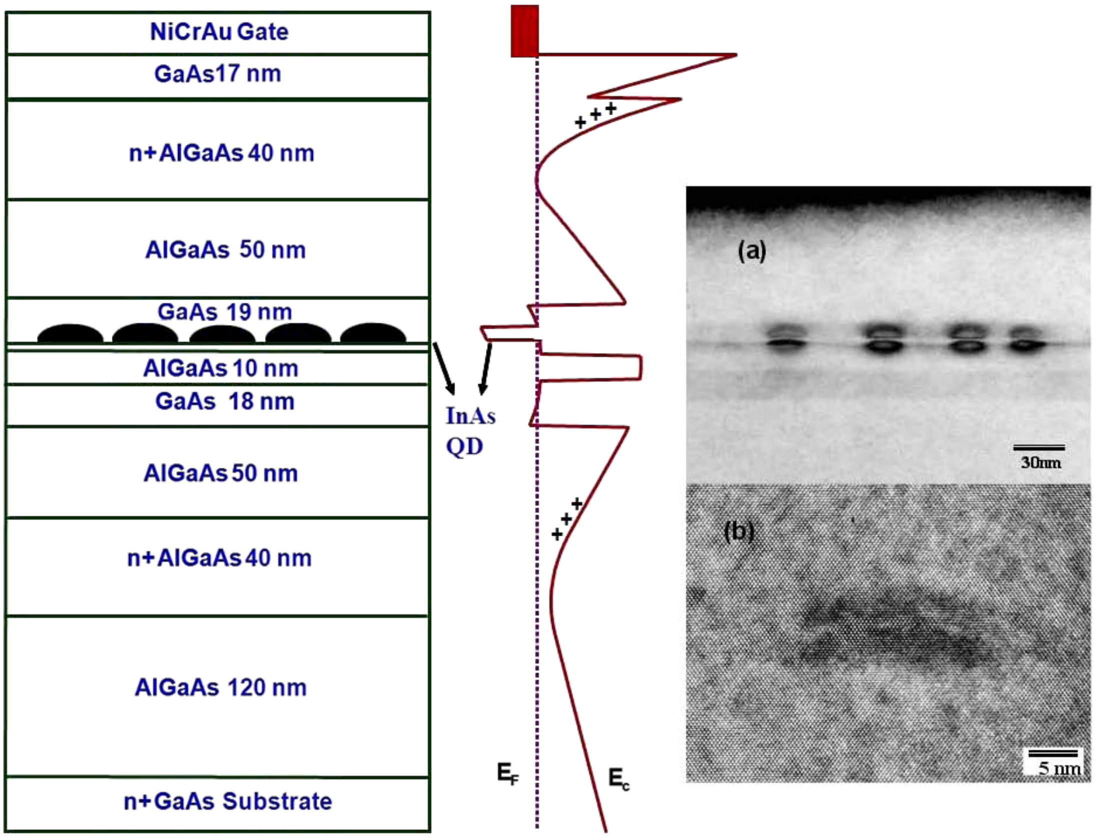

Figure 1. Schematics of the structure of sample B. (a) Transmission electron microscope image of sample B and (b) HRTEM image of a quantum dot embedded in the upper well of sample B.

based on the DQW system forms the important building block for designing the novel optical and electrical devices such as quantum cascade lasers, terahertz generators, variable mobility transistors and high power field effect devices [7–10]. Therefore it is of primary importance to understand the role of different scattering mechanisms in the DQW heterostructures to optimize the performance of these devices.

To investigate the relative strength of intersubband scattering with the long and short range scattering potentials, two double quantum well systems (samples A and B) with different starting orders have been fabricated. Comparison with long range scattering potential was studied in sample A, which is a modulation-doped symmetric DQW system. In sample B, self-assembled quantum dots (QDs) were embedded in one of the quantum wells. Since QDs are well known for their strong short range scattering effects, the relative strength of intersubband and short range scattering can be studied in sample B [11].

2. Experimental details

The two samples (samples A and B) used for this study were fabricated on a GaAs substrate by a molecular beam epitaxial system. Sample A consists of two GaAs quantum wells, each of width 180 Å separated by a 100 Å AlGaAs layer. The electrons were provided by the Si-doped AlGaAs layer grown on each side of the quantum wells with a doping density of 1.1×10^{17} cm^{-3}. Sample B is similar in structure to sample A with the exception that self-assembled InAs QDs were embedded in the upper well at a distance of 40 Å from the AlGaAs barrier (figure 1). The doping layers were separated from the quantum wells by a 50 nm spacer layer. Hall bars were fabricated using a standard photolithographic technique. Magnetoresistance measurements were performed in a pumped liquid helium cryostat at a temperature of 1.2 K using a superconducting magnet capable of producing a magnetic field of 7 T. During the entire measurement process the channel current is maintained at 95 nA. The electron densities in the quantum wells were controlled by applying voltage bias through the front gate (V_g).

Figure 1(a) shows the cross-sectional transmission electron microscope (TEM) image of the QDs embedded in sample B. The dark shades represent the strain induced by the dots in the GaAs quantum well. The variation in the strain contrast is due to the different size of the dots. From the high resolution transmission electron microscope (HRTEM) image (figure 1(b)), the embedded QDs were found to be 15 nm wide and 8 nm in height. By comparison with the samples grown in similar conditions, the dot density in the sample could be approximately 3×10^9 cm^{-2} [11].

3. Results and discussion

Before discussing the experimental results, we briefly discuss the characteristics of samples A and B. Due to the wide separation between the quantum wells (10 nm AlGaAs barrier),

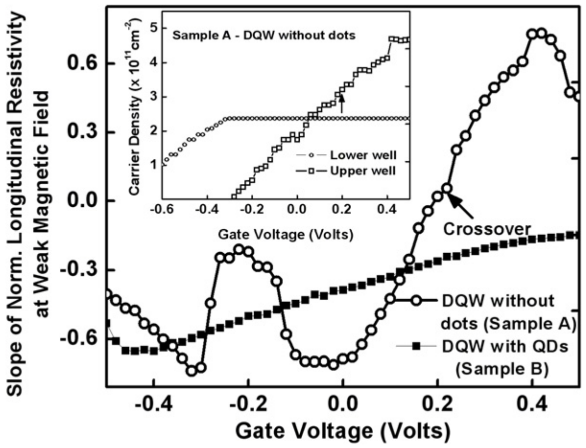

Figure 2. Slope of weak field normalized longitudinal magnetoresistivity as a function of gate voltage for samples A and B. Inset: plot of carrier density versus gate voltage for sample A.

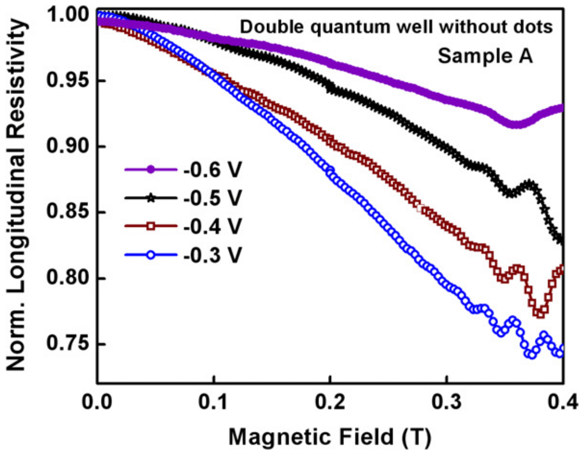

Figure 3. Longitudinal resistivity as a function of magnetic field for $V_g = -0.6, -0.5, -0.4$ and -0.3 V.

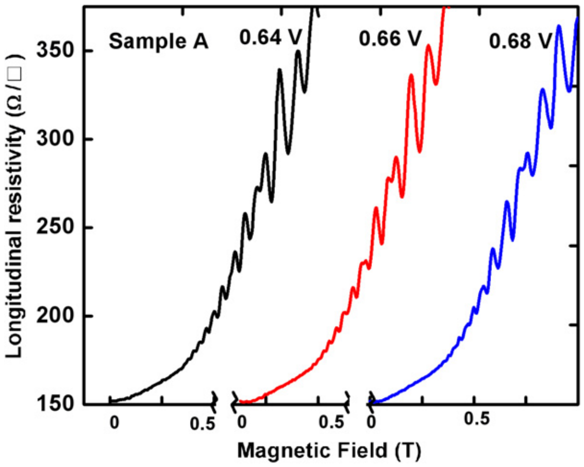

Figure 4. Positive magnetoresistance observed for sample A when the electron densities in the quantum wells are highly unbalanced. Longitudinal magnetoresistance traces are shown for $V_g = 0.64, 0.66$ and 0.68 V.

the transport in this heterostructure can be regarded as two-band electron transport. The electrons in the upper and lower quantum wells carry current independently. In sample A the two quantum wells are symmetric with more or less equal mobility at zero bias. However, in the case of sample B the repulsive short range scattering potential caused by the strain fields of the self-assembled dots in the upper well will give rise to localized states in the energy spectrum of the 2DEG. These localized states will significantly increase the resistivity of 2DEGs in both wells. Even a weak interlayer electron interaction will render the 2DEG in this heterostructure highly insulating [12]. This is due to the fact that an electron tunneling between the quantum wells of different mobilities will experience different potential landscapes and have a higher probability of finding a different localized state whenever it tunnels across the barrier.

The samples (A and B) under investigation were initially depleted of carriers in the upper well by applying a negative bias to the front gate. This is done in order to completely eliminate interlayer electron–electron interaction so that the 2DEGs in sample A will experience only the scattering potentials from the long range potential of the ionized donors and the electrons in sample B will be strongly influenced by the short range scattering potentials of InAs QDs. The change in the electron density (which was calculated from the slope of the Hall resistance between 0 and 0.4 T) with respect to gate bias in sample A is clearly shown in the inset of figure 2. The carrier density in the lower well ceases to increase when the electrons start to populate the upper well. This effect is due to the screening of the gate electric field by the electrons in the upper 2DEG. The variation in the strength of the long and short range scattering potentials with respect to the scattering between the electrons occupying the lowest subbands was then studied by monitoring the variation in the slope of the weak field longitudinal magnetoresistance (ρ_{xx}) as the DQW system was gradually taken from the single-layer (electrons are confined only in the lower well) to the bilayer (electrons present in both the wells) configuration by gradually increasing the voltage bias applied to the gate. The slope of the magnetoresistance curves was calculated by taking the ρ_{xx} values between 0.05 and 0.3 T which are the respective fields for the complete suppression of the weak localization effect and the onset of Shubnikov–de Haas oscillation.

As is clearly evident from figure 2, a negative slope in the ρ_{xx} at weak magnetic fields was observed throughout the single-layer configuration in sample A due to the magnetic-field-induced delocalization of electrons. The magnetoresistance traces at $V_g = -0.6, -0.5, -0.4$ and -0.3 V shown in figure 3 clearly shows this effect. However, when the 2DEG density in the upper well starts to deviate significantly from the lower well ($V_g > 0.2$ V), the slope of ρ_{xx} undergoes a transition from negative to positive value (figure 2). The magnetoresistance curves above the crossover regime are shown in figure 4 for three different V_g. In the case of sample B, no such crossover was observed and magnetoresistance was negative for all gate voltages (figures 2 and 5). This behavior arises due to the random distribution of QDs which causes spatial fluctuations in the potential

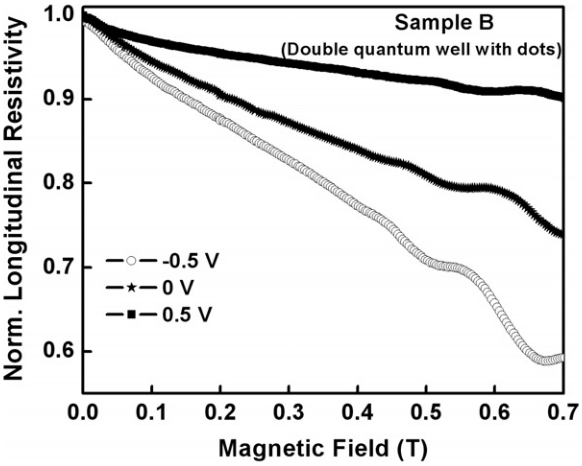

Figure 5. Normalized longitudinal resistivity as a function of magnetic field for $V_g = -0.5$, 0 and 0.5 V.

landscape leading to backscattering of electrons. At zero field, when these backscattered electrons undergo interference, its wavefunction will be completely localized, yielding an insulating behavior for all values of electronic density. As the magnetic field is increased, the wavefunction of electrons traversing different trajectories will acquire a certain phase change which in turn decreases the probability of interference of the backscattered electrons. Therefore the resistance of 2DEG decreases as the magnetic field is increased. This negative magnetoresistance arising due to magnetic-field-induced delocalization of electrons is significantly different from the one observed due to edge state formation in the sense that the former is usually observed in a weak magnetic field regime and the later at high magnetic fields.

Investigation by Russ *et al* on the nature of the interaction between the 2DEG and InAs quantum dots separated by a tunnel barrier revealed that the quantum dots act as uncorrelated scattering centers and enhance the scattering by strongly interacting with the 2DEG [13]. The quantum lifetime of electrons calculated from the Dingle plot for sample B was found to vary between 0.37 and 0.5 ps in the range of gate voltages studied. This value is almost two times lower than the value of the quantum lifetime (0.6–1 ps) calculated for sample A. Since quantum lifetime is a measure of the strength of the short range scattering potential it is clear that the influence of the short range scattering effect on the 2DEG in sample B is stronger when compared to sample A and no positive magnetoresistance was observed [14].

On the other hand, the positive magnetoresistance observed in sample A (figure 4) at weak magnetic fields can be explained by the following simple physical arguments. Earlier studies clearly suggest that, at magnetic fields not strong enough to induce Landau quantization, there exists a finite probability for the electrons to tunnel from the well with lower density to the one with higher density. This happens when the 2DEG density in the DQW is highly imbalanced [15]. In the regime of positive magnetoresistance (for $V_g > 0.2$ V), the upper 2DEG which is closer to the gate has a higher density. It then will exhibit negative compressibility which tends to deplete some of the electrons from the lower 2DEG. In addition to this, the exchange and correlation energy of an electron also tends to favor the transfer of an electron from the quantum well with lower density to the one with higher density [16]. The exchange energy ($\varepsilon_{\mathrm{ex}}$) for an electron in the quantum well is a direct function of carrier density (n) and is given by the relation

$$\varepsilon_{\mathrm{ex}} = -\frac{4\pi}{3}\left(\frac{2}{\pi}\right)^{1/2}\frac{e^2}{\varepsilon}n^{3/2}, \qquad (1)$$

where ε is the dielectric constant of the GaAs/AlGaAs system [17]. From the above relation it is clear that the upper well has more $\varepsilon_{\mathrm{ex}}$ owing to the higher electron density than the lower well. This facilitates the transfer of some of the electrons from the lower well across the tunneling barrier. Due to this tunneling process there will be a change in the total energy of the system, which is a function of kinetic energy (first term), Hartree energy (second term) and the exchange energy (third term) as shown below:

$$E_{\mathrm{total}} = \frac{1}{2}D^{-1}[(n-\Delta n)^2 + (n+\Delta n)^2] + \frac{2\pi e^2}{\varepsilon}d\Delta n^2 - \frac{4\pi e^2}{3\varepsilon}\sqrt{\frac{2}{\pi}}[(n-\Delta n)^{3/2} + (n+\Delta n)^{3/2}], \qquad (2)$$

where D is the two-dimensional density of states, Δn is the fraction of electrons that are transferred and d is the distance between the centers of the quantum well [18]. Clearly the tendency for the electron to tunnel across the barrier relies on the negative exchange energy being larger than the positive kinetic and Hartree energies. Hence the tunneling of electrons in sample A will occur at a critical value of V_g (in this case at $V_g = 0.2$ V) in which the exchange interaction starts to dominate. In this regime the resistance of the 2DEG is bound to increase due to the scattering induced by electron–electron interaction between the lowest subbands of the neighboring wells [19]. This exchange-interaction-assisted intersubband scattering gives rise to positive magnetoresistance in the ρ_{xx} measurement.

At high magnetic fields, instead of quantum Hall plateaus small peaks were observed in the Hall resistance (R_{xy}), at integer filling factors for sample A (figure 6). Similar characteristics were also observed for sample B but with more pronounced peaks. Since exchange-driven interactions will be suppressed in the high magnetic field regime, we present here a plausible explanation for the peaks in R_{xy} based on the theoretical model proposed by Barnes *et al* [16]. In a DQW system with two parallel 2DEGs of different mobility and carrier density, the Fermi energies of both wells oscillate independently. Due to this an electric field proportional to the difference in the chemical potential between the wells will be generated. The wider the barrier the larger is the difference in the chemical potential that can be supported.

The expression

$$(n_{\mathrm{l}} - n_{\mathrm{u}})e^2 d/\varepsilon = e(V_{\mathrm{l}} - V_{\mathrm{u}}) - (1 + 2d/a)(E_{\mathrm{l}} - E_{\mathrm{u}}) \qquad (3)$$

relates the difference in the Fermi energies of the lower (l) and upper (u) well ($\Delta E_{\mathrm{lu}} = E_{\mathrm{l}} - E_{\mathrm{u}}$) to the difference in carrier density of the layers $\Delta n_{\mathrm{lu}} = n_{\mathrm{l}} - n_{\mathrm{u}}$ and the potential difference

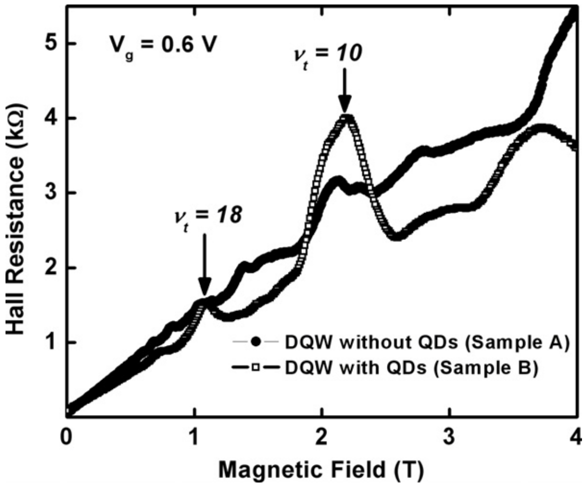

Figure 6. Hall resistance for samples A and B at $V_g = 0.6$ V. ν_t represents the total filling factor of the upper and lower well.

across the device $V_l - V_u$. In the above expression, a represents the interlayer separation between the center of the quantum wells (280 Å) and ε is the permittivity of GaAs. From the above expression, it is clear that with a time-varying magnetic field at constant gate voltage, all parameters except $E_l - E_u$ remain constant. On increasing the magnetic field, the Fermi energies in both the wells move relative to each other. When the Fermi energy in one of the wells differs significantly from the other, then $\Delta E_{lu} = E_l - E_u$ becomes quite large and to maintain the equilibrium there will be a transfer of electrons from one well to the other. This would cause the electrons in the edge channel of one quantum well to tunnel across to the other well. The extent of inter-edge state tunneling of electrons depends upon the magnitude of the difference in chemical potential between the edge channels (EC). This in turn depends upon the energy difference between the Landau levels through which the Fermi level passes. Hence, we expect R_{xy} peaks to appear when the Fermi level passes between cyclotron energy gaps whose energy gaps are greater compared to the Zeeman and symmetric–asymmetric energy gap. Therefore, R_{xy} peaks occurring at total filling factors (combined filling factor of lower and upper well) $\nu_t = 10$ and 18 can be attributed to the scattering of EC electrons when they tunnel across the barrier as the Fermi level passes through the cyclotron gaps. In sample B, the presence of InAs QDs adds to the strength of the scattering potential and hence the peak in R_{xy} is more pronounced.

4. Conclusions

From our study, it is clear that a crossover from negative to positive longitudinal magnetoresistance was observed due to exchange-energy-driven interlayer electron interaction. The onset of intersubband electron scattering occurs in the DQW system when the exchange interaction dominates over the interlayer Coulombic interaction. Such behavior was not observed in the system with strong disorder due to the dominating effect of short range scattering induced by InAs quantum dots. This is a clear indication that the intersubband scattering can only be observed in a system with weak disorder. The difference in the mobilities of the neighboring 2DEGs has little or no role to play in the crossover behavior of the DQW system, in sharp contrast to the 2DEG occupying two subbands in the single quantum well system. In the high magnetic field regime, the exchange-induced interaction gave rise to peaks instead of quantum Hall plateaus at integer filling factors.

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