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Self-assembled InAs quantum dots to investigate the tunneling between edge states in an AlGaAs/GaAs double quantum well system

E.S. Kannan[a], Gil-Ho Kim[a,*], I. Farrer[b], D.A. Ritchie[b]

[a]School of Information and Communication Engineering and Sungkyunkwan Advanced Institute of Nanotechnology,
Sungkyunkwan University, Suwon 440-746, Republic of Korea
[b]Cavendish Laboratory, University of Cambridge, Madingley Road, Cambridge CB3 0HE, UK

Abstract

Self-assembled InAs quantum dots (QDs) embedded close to the tunnel barrier in the upper well of the double quantum well system act as a sensitive probe to investigate the tunneling between the edge states. In the monolayer configuration, when the tunnel interaction between the edge states was absent, the Hall resistance exhibited well-developed and quantized Hall plateaus at integer filling factors. However, in bilayer configuration, no Hall plateaus were seen and an abrupt increase in the resistance was observed at $B = 2.1\,\mathrm{T}$, whereas no such anomalies were found in the control sample. This behavior appears to have its origin from the interaction between the edge state electrons and QDs as they tunnel across the barrier due to the difference in chemical potential between the upper and lower well.

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1. Introduction

Tunneling in double quantum well structures has been studied extensively ever since its practical realization was made possible by the development of high-quality epitaxial growth systems such as molecular beam epitaxial (MBE). Several theoretical and experimental studies were carried out to study the tunneling and coupling of two dimensional electron gases (2DEG) [1]. In a strongly coupled double quantum well (DQW) system, interactions between the 2DEG lead to the observation of various physical phenomena such as inter- and intra-layer coulomb interaction [2], new types of fractional quantum Hall effects [3], and a novel electron transport mechanism [4]. Interestingly, as the distance between the quantum wells is increased, the DQW system was found to undergo a phase transition giving rise to even denominator filling factors for $\nu > 1$, influenced by the presence of disorder and electron–electron interaction [5].

Apart from these studies, on the effect of tunneling in the bulk Landau levels, attempts were made to study the transport properties in edge channels (EC) by fabricating a DQW sample with unique gate and ohmic patterning [6]. Ohno et al. [6] and Yoshioka et al. [7] carried out experimental and theoretical studies on EC transport in a separately contacted double-layer quantum well system. Hall resistances (R_{xy}) of such separately contacted DQW system on resonance increased twofold at the filling factor $\nu = 2$, and the corresponding longitudinal magnetoresistance exhibited non-zero values. However, no such increase in R_{xy} traces was reported when contacts to both the quantum wells were re-established [7]. These features are interpreted in terms of the coupling of the EC electrons in two layers due to the difference in chemical potential.

2. Experiment

In the present work, we investigated the tunneling in edge states for a range of carrier densities in the DQW

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*Corresponding author. Tel.: +823 1290 7989.
E-mail addresses: kannan1@skku.edu (E.S. Kannan), ghkim@skku.edu (G.-H. Kim).

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system by embedding self-assembled InAs QDs at a distance of 40 Å from the tunnel barrier (sample B). Sample B was grown on a GaAs substrate by the MBE system. The DQW has a width of 180 Å, separated by a 100 Å AlGaAs barrier. The electrons were provided by the Si doping layer on each side of the quantum wells. The doping layers were separated from the quantum wells by AlGaAs layers with a thickness of 500 Å. The control sample A without the self-assembled InAs quantum dots in the upper well has a similar structure as that of sample B. The electron densities in the quantum wells are controlled by applying a bias through the front gate. Magnetoresistance measurements were taken in the four terminal configurations as a function of the gate voltage using the standard lock-in detection technique at 1.5 K. We employed a standard Hall bar geometry for our measurement, with the contacts established to both quantum wells.

3. Results and discussion

In our DQW system, the 100 Å wide AlGaAs barrier restricts the interaction between the neighboring 2DEG, resulting in the wavefunction being localized within the individual wells. The study was then carried out by selectively depleting the 2DEG in the upper well, and the tunnel interactions between the neighboring wells were monitored from the changes in the magnetoresistance traces as the DQW slowly evolves from monolayer to bilayer configuration. The presence of the InAs quantum dots, apart from acting as short-range scattering centers, increases the overall resistance in sample B [8]. The presence of short-range scattering centers between the quantum wells enhances the back-scattering effect of electrons when they attempt to tunnel across the barrier [9]. This would result in the abrupt increase in Hall resistance, which can be identified from the magnetoresistance traces. Hence, the embedded QDs tend to act as a sensitive probe to detect the tunneling between the quantum wells.

In Fig. 1, longitudinal and Hall magnetoresistance traces were plotted for samples A and B at a gate voltage of $-0.5\,\mathrm{V}$ corresponding to the carrier density of $1\times10^{11}\,\mathrm{cm}^{-2}$. At this gate voltage, only the lower quantum well is populated with electrons (monolayer configuration). The frequency of the Shubnikov–de Hass oscillation (SdH) is the same for both samples as their carrier densities are equal. However, their characteristics are completely different. Sample B is characterized by a very high zero field longitudinal resistivity (ρ_{xx}) in contrast to sample A, due to the presence of the short-range scattering potential of QDs. The sharp decrease in ρ_{xx} values as magnetic field is increased from 0 T (Fig. 1) is due to the suppression of electron back scattering by the magnetic field [10].

Moreover, in sample B, the Hall resistance has a nonzero value at 0 T. This may be due to the mixing of the fraction of zero field ρ_{xx} value with R_{xy}. Ideally, Hall bar geometry does not involve the mixing of ρ_{xx} and R_{xy}, but it can occur in some cases, and when ρ_{xx} is very large, as in the present case, it can appear in R_{xy} measurements. However, as the magnetic field is increased, well-developed plateaus were seen at filling factor $\nu = 4$ and 2 for both samples. As the gate voltage is gradually increased from -0.5 to $-0.42\,\mathrm{V}$, the upper well begins to populate, while the carrier density in the lower well remains constant. The population of the upper 2DEG increases the inter-layer electron interaction and a broad peak is clearly seen in the inset of Fig. 2 around $-0.5 < V_g < -0.44\,\mathrm{V}$. Further

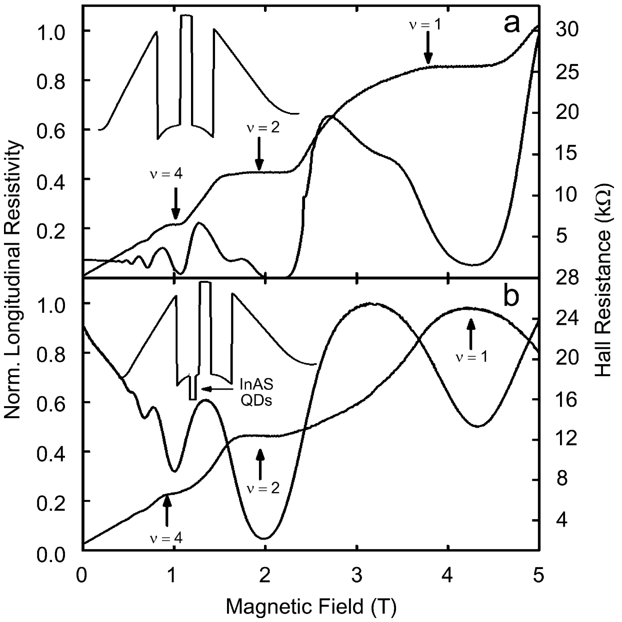

Fig. 1. (a) Longitudinal and Hall magnetoresistance traces for sample A at $-0.5\,\mathrm{V}$ in monolayer configuration. Inset: Sketch of the conduction band profile around the quantum well for sample A. (b) Longitudinal and Hall magnetoresistance traces for sample B at $-0.5\,\mathrm{V}$ in monolayer configuration. Inset: Sketch of the conduction band profile around the quantum well for sample B.

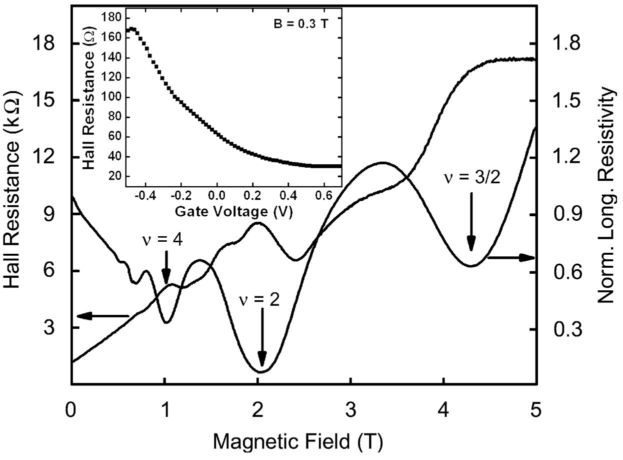

Fig. 2. Longitudinal and Hall magnetoresistance traces for sample B at $-0.42\,\mathrm{V}$ in bilayer configuration. Inset: Hall resistance as a function of gate voltage (V_g) at 0.3 T.

increase in the gate voltage decreases the R_{xy} value as the screening effect of the 2DEG increases with the carrier density. In this bilayer configuration at −0.42 V, the plateau corresponding to the integer filling factor is absent in the Hall traces for $B<4\,\mathrm{T}$, indicating the presence of dissipation inside the sample (Fig. 2). The dissipation could be due to the scattering of edge-state electrons by the InAs quantum dots. (The filling factors mentioned in the graph were calculated by using the formula $v = nh/eB$, where n is the carrier density obtained by Fourier transforming the SdH oscillation, h is the Planck's constant, e is the electronic charge, and B is the magnetic field.)

To gain further insight into this phenomenon, R_{xy} is plotted as a function of magnetic field for single-layer, bilayer and resonance configuration for samples A and B in Figs. 3a and b, respectively. Sample A exhibits well-developed Hall plateaus for all the three configurations; the detailed discussion of this phenomenon is presented elsewhere [11,12]. Sample B, on the other hand, shows an interesting behavior. For single-layer configuration, well-developed Hall plateaus are seen at $v=4$ and 2, but when the carriers are populated in both the wells (double layer) peaks are observed in R_{xy} for $B<4\,\mathrm{T}$. A close analysis of Fig. 3b reveals that a peak in R_{xy} is seen exactly at the point when the filling factor in the lower well reaches $v = 2$, indicated by the dashed line (Fig. 3b). Such peaks in R_{xy} also appear for $v = 4$, but with less intensity at 1.2 T.

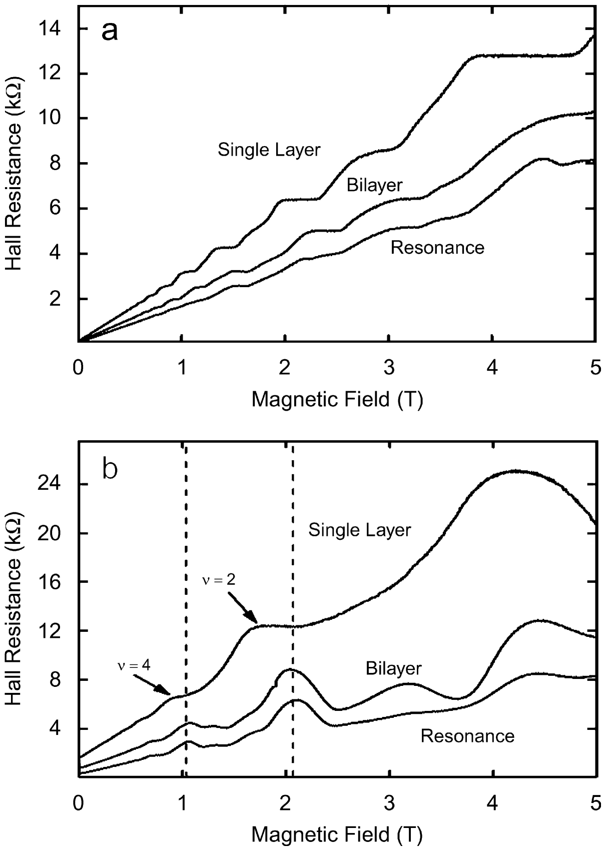

Fig. 3. (a) Hall resistance for single-layer, bilayer, and resonance condition for samples A (a) and B (b). The resonance condition corresponds to the case when the quantum wells have equal carrier density. The dashed line in (b) corresponds to the peak in Hall resistance when the filling factors are $v = 2$ and 4 in the lower well.

We present here a plausible explanation for the peaks in R_{xy} based on the theoretical model proposed by Barnes et al. [1]. In a DQW system with two parallel 2DEG of different mobility and carrier density, the Fermi energies of both wells oscillate independently. Due to this, an electric field is generated in proportion to the difference in chemical potential between the wells. The wider the barrier, the larger difference in the chemical potential that can be supported. The expression

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

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 across the device $V_\mathrm{l} - V_\mathrm{u}$ [1]. In the above expression, a represents the inter-layer 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, as the magnetic field is swept keeping the gate voltage constant, all parameters except $E_\mathrm{l} - E_\mathrm{u}$ remain constant. As the magnetic field is increased, Fermi energies of both wells move relative to each other. When the Fermi energy in one of the wells, differ significantly from that in the other, $\Delta E_\mathrm{lu} = E_\mathrm{l} - E_\mathrm{u}$ 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 tunneling of EC electron from one well to the other well across the barrier.

The extent of inter-edge state tunneling of electrons depends upon the magnitude of the difference in chemical potential between the EC channels [7]. 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 is greater compared to Zeeman and symmetric–asymmetric energy gaps. Therefore, R_{xy} peaks in sample B at filling factors $v = 4$ and 2 (lower well) are attributed to the scattering of EC electrons by the QDs when they tunnel across the barrier as the Fermi level passes through the cyclotron gaps. This explains the reason behind the much pronounced peak at $v = 2$ compared to $v = 4$ as the cyclotron energy gap at $v = 2$ is greater than at $v = 4$. The possible presence of random potential due to InAs QD that would destroy the momentum conservation for the inter-edge state tunneling does not influence our results because for EC tunneling momentum conservation does not hold good [6].

Finally, in the region of $B>4\,\mathrm{T}$, the Hall resistance in sample A at −0.5 and −0.42 V exhibits a strange behavior (Fig. 2 and 3). A hump in the Hall trace is observed at filling factor $v=1$ at −0.5 V, whereas a well-developed plateau is observed at −0.42 V corresponding to the filling factor of $v=1.5$. The anomalous behavior of R_{xy} in the high magnetic field region may be related to spin–flip processes involving electrons in the QDs and the nearby 2DEG [13]. But the exact physical phenomenon governing the magnetoresistance behavior at high magnetic field is not clearly understood.

4. Conclusion

In summary, we investigated the inter-edge state tunneling in the DQW system embedded with quantum dot. The Hall resistance exhibited peaks when the filling factor in the lower well reached $v = 2$ and 4. This behavior is attributed to the result of interaction between the QDs and the 2DEG as the electron tunnel through the barrier. The tunneling is assisted by the electric field gradient arising due to the abrupt change in chemical potential of the lower well when the Fermi level passes through the cyclotron gaps. Hence, the QDs act as a sensitive probe for studying the tunnel interaction between the 2DEG in the double quantum system.

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