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Physica E 12 (2002) 658– 661

PHYSICA E

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Insulator–quantum Hall liquid transitions in a two-dimensional electron gas using self-assembled InAs dots

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Abstract

We investigate the transport properties of two-dimensional electron gases (2DEG) formed in a GaAs/AlGaAs quantum well, where self-assembled InAs quantum dots were grown at the center of the GaAs well. Due to the resulting strain fields repulsive short-range scattering is experienced by the conduction electrons in the 2DEG. In a perpendicular magnetic field, there are transitions between quantum Hall liquids at filling factors $\nu = 1$ and 2 and the insulating phase. We show that the boundary of insulator–Quantum Hall transitions can be identified either by analysing the temperature-independent points in ρ_{xx} or from the peaks in σ_{xx} at low temperatures and both methods give similar results. © 2002 Elsevier Science B.V. All rights reserved.

PACS: 73.40.Hm; 72.10.Fk; 74.25.Fy

Keywords: Self-assembled quantum dots; Quantum Hall effect; Spin splitting

In a perpendicular magnetic field B, a two-dimensional electron gas (2DEG) exhibits the quantum Hall (QH) effect. There are localised states in the Landau level (LL) tails and extended states at the LL centres, and when the magnetic field B is decreased at a fixed carrier density (n), the localised and extended states alternately move down through the Fermi energy. It is believed [1,2] that at zero field a 2DEG becomes insulating, and therefore the extended states at the centre of each LL “float” up in energy as $B \to 0$.

Measurements [3–5] of disordered 2DEGs in GaAs show a transition with increasing B from a strongly localised zero-field insulating phase into a QH liquid of filling factor $\nu = 2$, and at higher B there is a transition back to the insulating phase. The observation of these insulator–QH liquid transitions enables one to construct the phase diagram in $n - B$ space which looks like the theoretically expected global phase diagram proposed by Kivelson et al. [6]. However in later measurements [8,9], transitions were observed with increasing B from an insulator $\to$ $\nu = 2$ QH liquid $\to$ $\nu = 1$ QH liquid $\to$ insulator (0–2–1–0) as B was increased, and not the expected (0–1–2–1–0) transitions. Pioneering experimental results on a Si electron gas show (0–6–0) and (0–2–0–1–0) transitions which are also not consistent with the global phase diagram [7].

In this paper, we present a new 2D system for observing insulator–QH transitions. We show that the

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PII: S1386-9477(01)00429-5

boundary of insulator–QH transitions can be identified either by analysing the temperature-independent points in ρ_{xx} or from the peaks in σ_{xx} at low temperatures and both methods give similar results.

The sample investigated was grown by molecular beam epitaxy. The structure consists of a 0.6 μm thick undoped GaAs buffer layer, followed by a 500 Å undoped $Al_{0.33}Ga_{0.67}As$ barrier, a 200 Å undoped GaAs quantum well, a 400 Å undoped $Al_{0.33}Ga_{0.67}As$ spacer layer, a 400 Å Si-doped ($1 \times 10^{18}\ cm^{-3}$) $Al_{0.33}Ga_{0.67}As$ layer, and finally a 170 Å GaAs capping layer. During a growth interrupt an InAs layer with a coverage of 2.15 monolayers (ML) was grown (Stranski–Krastanov growth) into the central part of the GaAs quantum well. In sample C1335, 2.15 ML of InAs were followed by a 50 Å GaAs capping layer; the InAs formed self-assembled quantum dots, having a density of $3.0 \times 10^9\ cm^{-2}$. We find the average dimension of the dots to be ∼ 280 Å wide and ∼ 40 Å high in this sample. All dots show strain contrast, and very few show loss of coherency, as observed [10]. For this sample, the ratio of the transport to quantum lifetime is approximately five, which is a consequence of short-range scattering from InAs dots [11].

Fig. 1(a) and (b) show longitudinal magnetoresistivity traces $\rho_{xx}(B)$ over the temperature range $T = 20 - 580$ mK, for two different gate voltages V_g. As V_g is made less negative, the effective disorder decreases and the zero-filed resistivity drops from being greater than 60–20 kΩ. As in previous studies [5], the temperature independence of $\rho_{xx}(B)$ at a particular magnetic field and gate voltage V_g, is used to identify the boundaries between different QH liquids at $\nu = 1$ and 2, and the insulating phase (0). Fig. 1(a) shows 0–2–0 transitions at $V_g = -0.278$ V, which are identified by temperature independent $\rho_{xx}(B)$ at $B = 1.2$ and 1.7 T (labelled C_2 and C_*), at which $\rho_{xx} \approx h/2e^2$. The ρ_{xx} minimum at a magnetic field of $B \simeq 1.4$ T correspond to the spin-degenerate filling factor $\nu = 2$. At the higher carrier density, $V_g = -0.260$ V [Fig. 1(b)], proper zeros in the low temperature $\rho_{xx}(B)$ traces have developed at filling factors $\nu = 1$ and 2, which are accompanied by QH plateaus in $\rho_{xx}(B)$. The 0–2 transition (C_2) at $B = 1.1$ T, and the 1–0 transition (C_1) at 3.8 T are clearly defined because they separate phases of opposite temperature dependence.

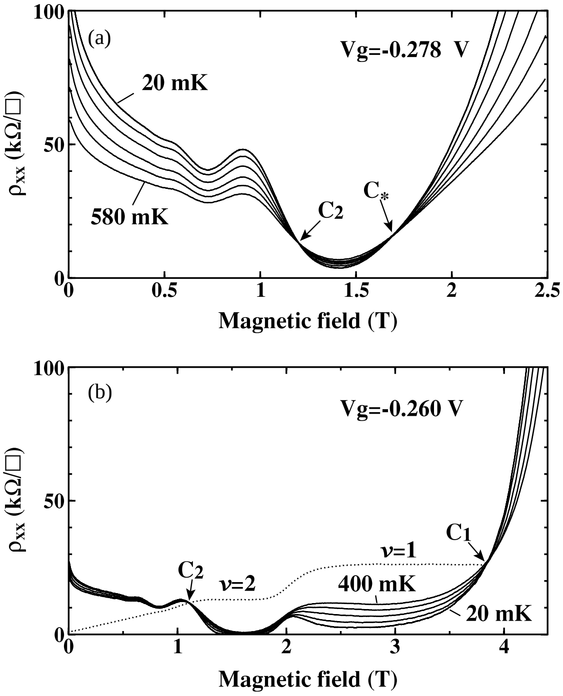

Fig. 1. ρ_{xx} as a function of magnetic field at temperatures 20 mK $\leqslant T \leqslant$ 580 mK. The dotted line in (b) shows ρ_{xy} at $T = 297$ mK.

In Fig. 2 we plot the magnetic field dependence of the conductivities σ_{xx} (solid lines) and σ_{xy} (dotted lines) for a range of negative gate bias at 20 mK. At the most negative bias, $V_g = -0.284$ V [Fig. 2(a)] the peaks in σ_{xx} have almost merged into a single feature. At $V_g = -0.280$ V [Fig. 2(b)] and $V_g = -0.276$ V [Fig. 2(c)], σ_{xx} has split into two peaks, the minimum between corresponding to the $\nu = 2$ spin-degenerate quantum Hall state. By $V_g = -0.272$ V [Fig. 2(d)] one begins to see the development in σ_{xx} at higher magnetic fields of the spin-polarised $\nu = 1$ state whilst σ_{xy} has a well-quantised plateau $2e^2/h$ at $\nu = 2$. At a bias of $V_g = -0.264$ V [Fig. 2(e)] we observe the maxima (delocalised states) in σ_{xx} and strong quantised plateaus at $2e^2/h$ and e^2/h in σ_{xy}.

Transition points on the phase boundaries in Fig. 3(a) were obtained from the temperature-independent points in the ρ_{xx} data. As may be seen, all of the states are insulating at zero field. The second phase diagram utilises the fact that the peaks in σ_{xx} are a signature for the delocalised states [12]. Fig. 3(b) shows the phase diagram which derived from the conductance peaks in σ_{xx} at 20 mK. The

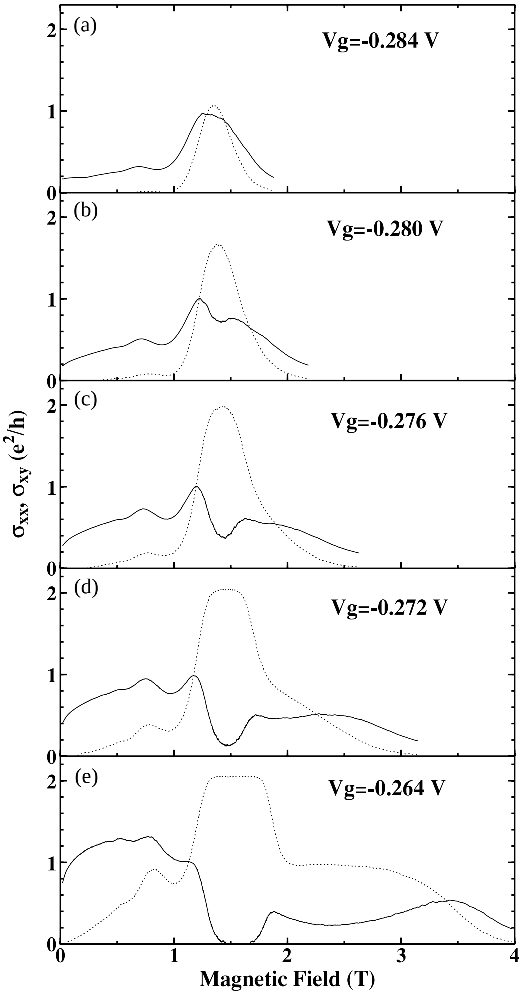

Fig. 2. σ_{xx} (solid lines) and σ_{xy} (dotted lines) as function of magnetic field for various gate voltages at 20 mK. The conductivities σ_{xx} and σ_{xy} are calculated from the resistivity ρ_{xx} and ρ_{xy} via the matrix relation.

exception being the closed triangle data points which were obtained at a temperature of 1.2 K.

Fogler and Shklovskii [13] have recently proposed that the collapse of spin splitting in the quantum Hall effect is due to the disorder-induced broadening of Landau levels. Fig. 3(b) shows the disorder-induced collapse of spin splitting. The similarity of Fig. 3(a) and (b) show that the phase boundary can be identified either by analysing the temperature-independent points in ρ_{xx} or from the peaks in σ_{xx} at low temperatures (< 300 mK).

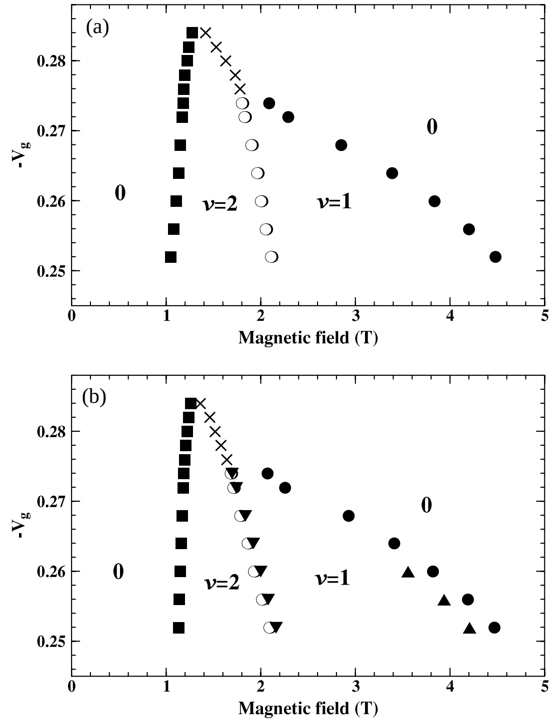

Fig. 3. The phase diagram determined from (a) temperature-independent points in ρ_{xx} traces and (b) peaks in σ_{xx}. Symbols indicate transitions from (i) 0–2 (solid squares), (ii) 2–0 (crosses), (iii) 2–1 (open circles), (iv) 1–0 (solid circles), and (v) peaks in σ_{xx} at 1.2 K (solid triangles).

In summary, transport measurements of InAs self-assembled quantum dot samples show insulator–QH transitions. The transport result of the quantum Hall transitions can be explained by assuming that the self-assembled InAs structures introduce strong scattering in the two-dimensional electron gas. For the first time, we have shown that phase diagrams in the QH effect can be constructed either by analysing the temperature-independent points in ρ_{xx} or from the peaks in σ_{xx} at low temperatures (< 300 mK). We note that both methods indeed give similar phase diagrams.

The authors wish to thank the EPSRC UK for supporting this work. Gil-Ho Kim acknowledges support from the Arkinson Fund, Clare College, Cambridge and the Korean Ministry of Information and Communication. C.-T. Liang is grateful for financial support from the NSC, Taiwan.

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