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Physica E 17 (2003) 292–293
PHYSICA E
www.elsevier.com/locate/physe

Insulator-quantum Hall transitions in two-dimensional electron gas containing self-assembled InAs dots

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Abstract

We present a study of magnetotransport properties in two-dimensional electron gases formed in a GaAs/$Al_{0.33}Ga_{0.67}As$ quantum well, where self-assembled InAs quantum dots have been inserted into the centre of the GaAs well. In a perpendicular magnetic field there are transitions between quantum Hall liquids at filling factors $v = 2$ and 1 and the insulating phase from temperature independent points. In the insulating regime we observe $v = 4$ and 6 quantum Hall states due to Landau quantisation. We are able to construct a phase diagram in which Shubnikov–de Haas oscillations and insulating behaviour coexist.

PACS: 73.61.−r

Keywords: Self-assembled quantum dots; Quantum Hall effect; Phase diagram

Recently there has been a great renewal of interest in transitions from an insulating state to integer quantum Hall (QH) states [1,2]. The evolution of electronic states from being extended at strong magnetic field B to being weakly localised at zero B was first explained by Khmelnitskii [3] and Laughlin [4]. To date, an interesting but unsettled issue is that whether a direct transition from a high Landau level (LL) filling factor $v \geqslant 1$ to an insulator can occur. Existing experimental results show that such a transition [5–9] can occur, and a numerical study appears to support this picture [10]. On the other hand, it is argued that the observed low-field transition can be identified as a crossover due to localisation and a strong reduction of the conductivity when Landau quantisation becomes dominant [11]. A very recent theoretical work has shown that a narrow phase may exist between an integer QH state and an insulating phase when inter-LL mixing of opposite chirality is taken into account [12].

In this paper, we report new experimental results on QH—insulator transitions. Our results fall into three categories. (i) We show that Shubnikov–de Haas (SdH) oscillations arising from Landau quantisation can exist in the insulating phase, suggesting that the temperature-independent point in ρ_{xx}

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doi:10.1016/S1386-9477(02)00805-6

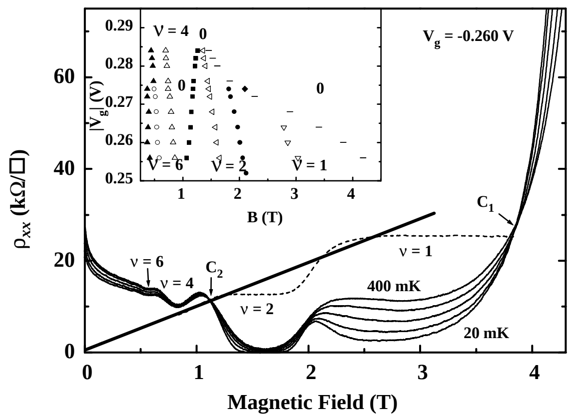

Fig. 1. ρ_{xx} as a function of magnetic field $T = 20, 140, 220, 300$, and 400 mK. The dotted line is show ρ_{xx} at $T = 300$ mK. The Solid line is extended from low ρ_{xy}. The inset shows the experimental phase diagram determined from temperature independent points and maxima and minima in ρ_{xx} traces.

does not correspond to a crossover due to localisation, and a strong reduction of the conductivity when Landau quantisation becomes dominant. (ii) By tracing the minima in ρ_{xx} and the temperature-independent points, we are able to construct a "new" phase diagram in which SdH oscillations and the insulating phase coexist. (iii) Scaling behaviour was observed on both sides of the temperature-independent point in ρ_{xx} and the onset of the SdH oscillations causes deviation from the scaling effect. Our experimental results challenge conventional understanding of Landau quantisation and phase transitions in two dimensions, and thus urge further experimental and theoretical studies on these areas.

Fig. 1 shows measurements of longitudinal resistivity ρ_{xx} and Hall resistivity ρ_{xy} traces over the temperature range $T = 20$–400 mK at $V_g = -0.260$ V. ρ_{xx} (B) traces have well developed at filling factor $v = 1$ and 2, which are accompanied by QH plateaus in ρ_{xy} (B). The temperature independence of ρ_{xx} at a particular magnetic field and gate voltage V_g, is used to identify the boundaries between different QH liquid at filling factor $v = 1$ and 2, and insulating phase. The high field transitions are identified by a temperature independent ρ_{xx} at $B = 1.11$ and 3.84 T (labelled C_2 and C_1) at which $\rho_{xy} = B/2e^2$ and $\rho_{xy} \approx B/e^2$, respectively. In low magnetic field, below the critical field C_2 the resistivity ρ_{xx} increases with decreasing temperature, and hence the sample is always in the insulating phase, nevertheless the filling factors $v = 4$ and 6 are clearly observed.

The inset of Fig. 1 shows the experimental phase diagram. The quantum Hall-insulator transitions can be identified by a temperature-independent ρ_{xx} as labelled by squares and diamonds. Open symbols correspond to minima in ρ_{xx} at various filling factors. The triangles correspond to the onset of the SdH oscillations. We can clearly see that $v = 6$ and 4 quantum Hall states due to Landau quantisation.

Our experimental results show that the SdH oscillations can be observed in the insulating phase and we are able to construct a new phase diagram. The scaling behaviour observed at both low-field insulator quantum Hall transition and high-field quantum Hall-insulator transition strongly suggest they are genuine phase transitions.

This paper was supported by Faculty Research Fund, Sungkyunkwan University, 2002.

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