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Transport Properties in Samples Containing InAs Self-Assembled Dots and Dashes

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We report transport measurements of a two-dimensional electron gas (2DEG) formed in a GaAs/AlGaAs quantum well, in which InAs has been inserted into the centre of the GaAs quantum well. Depending on the capping layers, the InAs forms either self-assembled quantum dots or dashes, and due to the resulting strain fields repulsive short-range scattering is experienced by the conduction electrons in the 2DEG. The single electron transport is through a dot or dash isolated using a pair of split-gate deposited on the sample surface. By application of a source-drain voltage we investigate the energies of a dot or dash that is trapped within the one dimensional channel defined by the range 0.5-2 meV. We speculate that the dot and dash are formed by strain modulation of the conduction of the conduction band in the GaAs quantum well.

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I. INTRODUCTION

The electronic and structural properties of self-assembled quantum dots have attracted a great deal of interest, both for investigating fundamental physics [1–3] and device applications such as lasers [4,5], single electron transistors [6,7], optical memory devices [8], and infrared photodetectors [9,10]. While a great deal of work has been undertaken on the structural and optical properties of the self-assembled quantum dots, little work has been reported on their electron transport properties.

In this paper experimental data are presented on magnetotransport and single electron transport in samples containing InAs self-assembled quantum dots and dashes. The dots and dashes were incorporated in a GaAs quantum well in a modulation doped GaAs/AlGaAs heterostructure. We performed magnetotransport measurements to investigate insulator-quantum Hall transitions. In particular, we show that Shubnikov-de Haas oscillations arising from Landau quantization can exist in the insulating phase, suggesting that the temperature-independent point in longitudinal resistivity dose not correspond to a crossover localization to a strong reduction of the conductivity when Landau quantization becomes dominant.

The single electron transport was studied by a pair of split gates deposited on the surface of the dot and dash samples. By varying the source-drain bias voltage we measure the charging energy of the dot that is trapped within the one dimensional (1D) channel defined by the split gates. We discuss whether the measured single electron tunneling comes from the bound states of the self-assembled dots and dashes or they are related to the strain modulation of the conduction band of the GaAs quantum well.

II. EXPERIMENT

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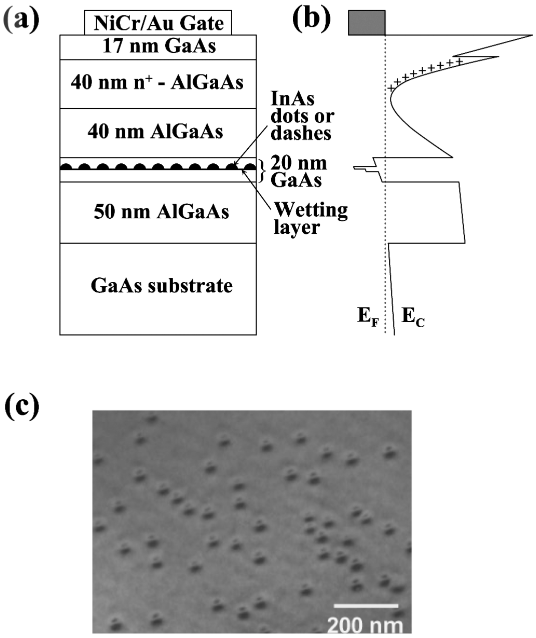

Fig. 1. (a) Structure of the samples. (b) Schematic of the conduction-band profile in the growth (z) direction, at the site of InAs deposition. (c) Plan view TEM image of self-assembled InAs dots (sample A).

Figure 1(a) shows a cross sectional schematic illustration of a molecular beam epitaxial grown n-AlGaAs/GaAs heterojunction on an undoped GaAs (100) substrate. The structure consists of a 20 nm wide GaAs/$Al_{0.33}Ga_{0.67}As$ quantum well that is modulation doped on one side using a 40 nm spacer layer. The growth of the GaAs quantum well was interrupted at its center, and the wafer was cooled from 580 °C to 525 °C. The shutter over the indium cell was opened for 80 sec, allowing growth of 2.15 monolayers (ML) of InAs. A cap layer of GaAs was grown at 530 °C, before the substrate temperature was raised to 580 °C for the remainder of the growth. The thickness of the GaAs capping layer over the InAs determines the dimensions and shape of the InAs structures [11]. A bias applied to the gate affects the conduction band in Fig. 1(b) varying the carrier density n in the two-dimensional electron gas (2DEG). In this sample A, the 2.15 ML of InAs were capped by a 5 nm GaAs layer, and self-assembled InAs quantum dots were formed. The dots have a density of 3×10^9 cm^{-2}, and are 4 nm in height and 28 nm in mean diameter [11] as shown in plan view of the transmission electron microscope image in Fig. 1(c) which was taken from the same measured wafer. In sample B, 2.15 ML of InAs were capped with 1 nm of GaAs. The dashes have a density of 2×10^8 cm^{-2} and are estimated 500 nm × 60 nm and elongated in the [011] direction [12].

Four-terminal longitudinal (ρ_{xx}) and transverse (ρ_{xy}) resistivity measurements were performed on Hall bars aligned in the [011] direction in a fridge, using an excitation current of 2 nA at 14 Hz. The two dimensional (2D) carrier density n was reduced by applying a negative gate voltage V_g to a gate covering the Hall bar. Two-terminal AC conductance $G = dI/dV$ of the split gate was measured in a ^{3}He cryostat using an excitation voltage of 0.1 mV at 31 Hz. The wafers were processed into Hall bar samples of dimensions 80 μm × 720 μm and, after definition with electron beam lithography, split gates of length 0.1 μm and width 0.3 μm were deposited on the sample surface. These 1D devices are shorter than those normally used to observe 1D ballistic transport; we use the shortest possible length so as to capacitively couple to just one dot.

III. RESULTS AND DISCUSSIONS

Figure 2 shows measurements of ρ_{xx} and ρ_{xy} traces over the temperature range T = 20-300 mK at $V_g = -0.252$ V. ρ_{xx} (B) traces have well developed at filling factor $\nu = 1, \nu = 2$, and $\nu = 4$, which are accompanied by Quantum Hall (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 $\nu = 1$ and $\nu = 2$, and insulating phase. The high field transitions are identified by a temperature independent ρ_{xx} at B=0.99 and 4.46 T (labeled C_2 and C_1). 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 $\nu = 4$ and $\nu = 6$ are clearly observed.

If there are an equal number of positively and negatively charged impurities, the QH plateaus in ρ_{xx} (B) are expected to be centered about the classical value $\rho_{xy} = B/en$. Haug *et al.* [13] showed that when repulsive or attractive scattering centers are deliberately introduced close to a 2DEG, the centers of the QH plateaus

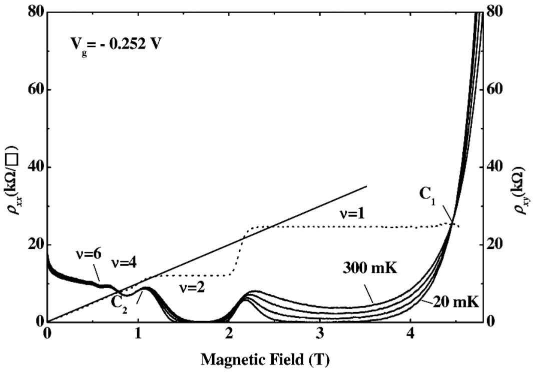

Fig. 2. (a) ρ_{xx} as a function of magnetic field at temperatures 20, 140, 220, and 300 mK. The doted line shows ρ_{xy} at T=300 mK for sample A. The straight solid line is extended from low ρ_{xy}.

are shifted to higher or lower magnetic fields, respectively. The Hall resistivity ρ_{xy} is shown as a line in Fig. 2, and the shift of both the ν=1 and 2 plateaus to magnetic fields greater than the classical value show that there is repulsive scattering, as observed by Ribeiro *et al.* [14]. A comparison of the upshift of the ν=1 plateaus in dot and dash sample at similar carrier densities, show there is stronger repulsive scattering in the dot samples than in the dash samples.

Figure 3 shows the conductance versus gate voltage measurement at different temperatures for sample B. The traces are offset in the y-direction for clarity. The peaks are numbered as 1, 2, 3, etc with respect to the pinch off voltage. With increasing temperatures, the peak positions shift towards lower gate voltages and the peaks height for last few peaks initially increases and then decreases. An increase in peak amplitude with increasing temperature can be explained as due to the thermal overlap with an adjacent state with a higher transmission [15]. A decrease in amplitude with increasing temperature is expected when the thermal broadening in the lead exceeds the intrinsic width of the resonance state. From the temperature dependence of the full width of the half maximum (FWHM) of a peak, one can determine the scaling factor $\alpha = C_g/C$. Figure 3 (b) shows the temperature dependence of FWHM for peak 2. It can be seen that the FWHM increases monotonically.

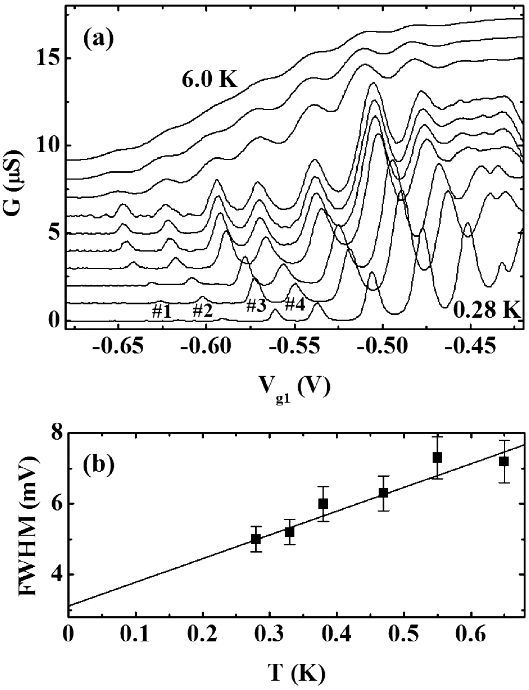

Fig. 3. (a) Differential conductance G versus gate voltage V_g at different temperatures 0.28, 0.33, 0.38, 0.47, 0.55, 0.65, 1.11, 3.64, 4.75, and 6.0 K for sample B. The sweeps are offset for clarity. The peaks are numbered as 1, 2, 3, and 4 with respect to the pinch off voltage. (b) The full width at half maximum of peak 2 at different temperatures.

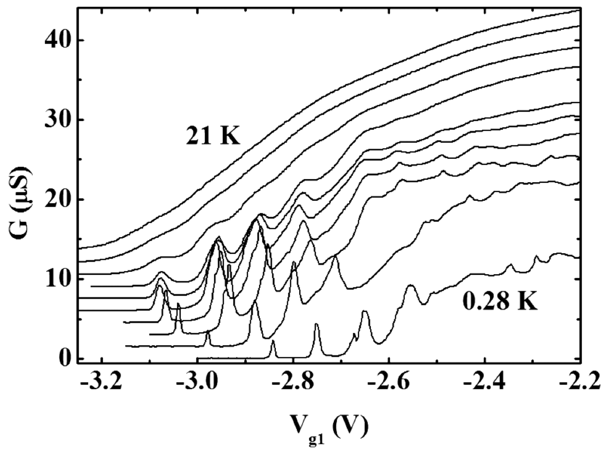

Fig. 4. Conductance versus gate voltage plot at different temperatures 0.28, 0.48, 0.75, 1.42, 2.85, 3.9, 7, 14, 18, 21 K for sample A.

To a first approximation, the FWHM is given by Ref.15 $(\alpha e)^{-1}(\Gamma_0 + 3.5k_BT)$ where Γ_0 is the intrinsic FWHM and from the data we obtain $\alpha = 0.05 \pm 0.01$. The value of ΔV_g between peaks 2 and 3 is 28 meV which gives addition energy of $\Delta E_p + e^2/C \approx 1.5$ meV.

Figure 4 shows the temperature dependence of Coulomb blockade oscillations observed in sample A. The traces are vertically offset for clarity. The conductance resonances can be seen up to 18 K as observed by Horiguchi *et al.* [16]. With increasing temperatures, the peak positions shift towards lower voltages and the peak amplitude for the last two peaks initially increases and then decreases as observed in the samples containing dashes. However, the FMHW monotonically increases with temperature. The Coulomb blockade characteristics in Figs. 3 and 4 shows lateral tunneling through a quantum dot and dash that is associated with a self-assembled InAs structure and we speculate that the conduction band is modulated by strain field from InAs/GaAs 7 % mismatched lattice. The dot diameter d is calculated from the self-capacitance of the dot ($C = 4\pi\epsilon\epsilon_0 d$) measured from the charging energy. From $e^2/C = 3$ meV, the dot diameter is estimated to be 370 Å, in rough agreement with transmission electron microscope measurements [11].

IV. CONCLUSIONS

We have demonstrated magnetotransport and single electron transport measurements on a gated GaAs electron gas in which self-assembled InAs quantum dots and dashes have been inserted into the centre of the quantum well. The two transport results, quantum Hall transitions and Coulomb blockade, can both be explained by assuming that the self-assembled InAs structures introduce repulsive scattering.

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