

Magnetic-field-induced quantum Hall effect - Hall insulator transition and hopping conductivity in InAs/GaAs quantum dot layers

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Abstract

We have investigated the resistance in the temperature range $T = 0.07 - 300$ K and magnetotransport in magnetic fields up to 35 T in InAs/GaAs quantum dot layers. In samples with a relatively high carrier concentration the quantum Hall effect (qHe) - to - Hall insulator transition was observed in high magnetic fields. Two-dimensional Mott variable range hopping conductivity has been observed at low temperatures in samples with low carrier concentration. The localization length correlates very well with the quantum dot cluster size obtained by Atomic Force Microscope (AFM).

Key words: quantum dots; insulator; localization

1. Introduction

In recent years, three-dimensional nanoscaled semiconductor islands have attracted significant attention due to their potential to act as quantum dot (QD) systems [1]. While the optical properties of quantum dot structures are currently under intense investigation, less attention has been given to the transport properties. In this work, we report on the hopping conductivity and qHe-insulator transition of self-assembled InAs quantum dot layers, grown on GaAs substrates.

2. Samples

The structures were grown by atmospheric pressure metal organic vapor phase epitaxy (AP-MOVPE) on semi-insulating (001) GaAs substrates misoriented

from the (001) plane towards the [110] direction. The samples consisted of 10-12 layers with the following sequence: GaAs (thickness $0.1\mu\text{m}$), a Si δ -doping layer for n-type samples (or C for p-type samples), a spacer layer (width 6 nm), an InAs quantum dot layer, and to cap the structure a cladding layer of GaAs (width $0.1\mu\text{m}$) [2]. Here we show the results for three different samples. Samples 1 and 3 were n-type, with carrier concentration per layer of quantum dots $4.0 \cdot 10^{10}\text{cm}^{-2}$ and $1.9 \cdot 10^{11}\text{cm}^{-2}$ and Hall mobility $1000\text{ cm}^2/\text{Vs}$ and $5500\text{ cm}^2/\text{Vs}$, respectively. Sample 2 was p-type with a hole concentration per layer of quantum dots $2.7 \cdot 10^{11}\text{cm}^{-2}$ and a Hall mobility $100\text{ cm}^2/\text{Vs}$.

The morphology of the quantum dot layers was investigated by AFM TopoMetrix®TMX-2100 Accurex™ in a contact mode. In fig. 1, as an example, the AFM image of a quantum dot layer after etching [3] for a sample prepared from the same wafer as sample 2 is shown. Quantum dots with density $N_S \approx 2 \times 10^{10}\text{ cm}^{-2}$ are visible. In fig. 2 the probability histogram of the radial distribution $W(r)$ of the quan-

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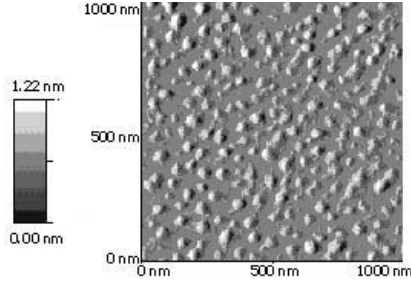


Fig. 1. Typical AFM image of an InAs quantum dot layer surface after selective etching.

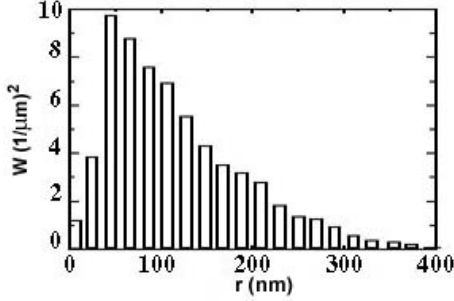


Fig. 2. The histogram of probability radial distribution $W(r)$ of quantum dot clusters.

tum dot clusters is shown. (The probability $dP(r, \Delta r)$ to find a cluster in the ring $(r, r + \Delta r)$ is equal to $dP(r, \Delta r) = 2\pi r W(r) \Delta r$).

3. Hopping conductivity and Quantum Hall - insulator transition

For samples 1 and 2 (low carrier concentration) the temperature dependence of the resistivity at low temperatures follows the law $\rho(T) = \rho_0 \exp(T_0/T)^{1/3}$ (Mott variable range hopping conductivity (VRHC) regime [4] (See insert in Fig. 3). The parameter T_0 is equal to $T_0 = C(g_{E_F} a^2)^{-1}$, where $C = 13.8$, g_{E_F} is the 2D density of states, and a is the localization length. For sample 2 $T_0 \approx 17$ K, and hence the localization length is about 80 nm. This value correlates very well with the maximum of the density of probability $W(r)$ radial distribution of quantum dot clusters (see fig. 2).

In n-type samples with electron concentration $n > 10^{11} \text{ cm}^{-2}$ (for p-type samples $p > 5 \times 10^{11} \text{ cm}^{-2}$) the SdH effect and qHe are observed. Magnetoresistance measured at different temperatures cross as shown in Fig. 3 for sample 3. We take this crossing point as the critical field for the quantum Hall effect-insulator transition. The transition takes place in the lowest Landau level (near $\nu \sim 0.75$). Notice that the data for ρ_{xy} were corrected for resistance contributions by averaging over up and down field directions.

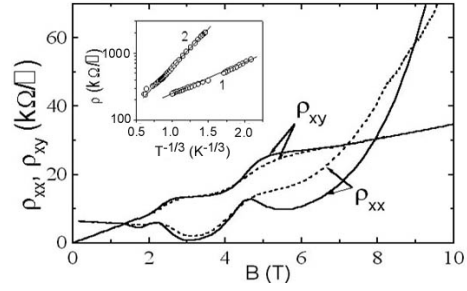


Fig. 3. Oscillations of the magnetoresistivity ρ_{xx} and the Hall resistivity ρ_{xy} at temperatures $T=1.7\text{K}$ (solid lines) and $T=4.2\text{K}$ (dashed lines) for sample 3. Insert show the temperature dependence of resistivity for samples 1 and 2.

The $\nu = 1$ plateau extends over a large field range beyond the crossing point. The departure from the value h/e^2 is due to the relatively high temperature at which the data are taken. According to theory [5] the value of ρ_{xx} at the transition point is equal to h/e^2 . In the case of quantum dot layers with high density of dots the value of ρ_{xx} in the transition point is about two times higher. This difference is explained by the morphology of the surface. 2D electrons are formed in the layer due to overlap of the electron wave functions in the dots. The density of 2D electrons fluctuates with a characteristic scale of about the cluster size (see Fig. 2). In magnetic field $B=1$ T the value of magnetic length $l=(\hbar/eB)^{1/2} \approx 28$ nm that is less than the cluster sizes. The current flows between clusters with maximal electron concentration. In this case the effective length of conducting paths may be longer and the width less than in the uniform 2D system. Thus the calculated sheet resistivity of sample in the qHe regime may exceed the value of h/e^2 , but the temperature dependence of the resistivity will be still metallic. Above the critical point magnetic field dependence of the resistance obeys an exponential law up to the highest field $B \simeq 30$ T, like reported in Ref. [6].

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