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Magnetic-field-induced quantum Hall—insulator transition and persistent photoconductivity in InAs/GaAs quantum dot layers

Vladimir A. Kulbachinskii[a,*], Roman A. Lunin[a], Vasili A. Rogozin[a], Vladimir G. Kytin[a], Boris N. Zvonkov[b], Sergey M. Nekorkin[b], Dmitriy O. Filatov[b], Anne de Visser[c]

[a] *Low Temperature Physics Department, Physics Faculty, Moscow State University, GSP-2, Moscow, 119899, Russia*
[b] *Physicotechnical Research Institute, University of Nizhny Novgorod, 603600, Nizhny Novgorod, Russia*
[c] *Van der Waals-Zeeman Institute, University of Amsterdam, 1018 XE Amsterdam, The Netherlands*

Abstract

We have investigated the temperature dependence of resistance in the temperature range $T = 0.07$–300 K and in magnetic field up to 35 T in InAs/GaAs quantum dot layers. In samples with relatively high carrier concentration quantum Hall effect—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 length of localization correlates very well with the quantum dot cluster size obtained by atomic force microscope. In all samples a positive persistent photoconductivity was observed.

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1. Introduction

In order to probe quantum Hall effect (qHe)—insulator transition it is essential to carry out experiments on samples where there are different scattering mechanisms. In this work, we report on qHe—insulator transition in self-assembled InAs quantum dot (QD) layers, grown on GaAs substrates. We observed also the hopping conductivity in samples with low carrier concentration and persistent photoconductivity at low temperatures.

2. Samples

The structures with QD layers were grown by atmospheric pressure metal organic vapor phase epitaxy (AP-MOVPE) on semi-insulating (0 0 1) GaAs substrates misoriented from the (0 0 1) plane towards the [1 1 0] direction. The samples consisted of a 10–12 layers: of GaAs 0.1 μm thickness, a δ-doping layer of Si for n-type samples (or δ-carbon layer for p-type samples), a spacer layer (thickness 6 nm), an InAs QD layer.

3. Quantum Hall effect—insulator transition

2D electrons are formed in QD layer due to overlapping of the electron wave functions in dots. In samples

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[*] Corresponding author. Tel.: +7-095-939-1147; fax: +7-095-932-8876.
E-mail address: kulb@mig.phys.msu.su (V.A. Kulbachinskii).

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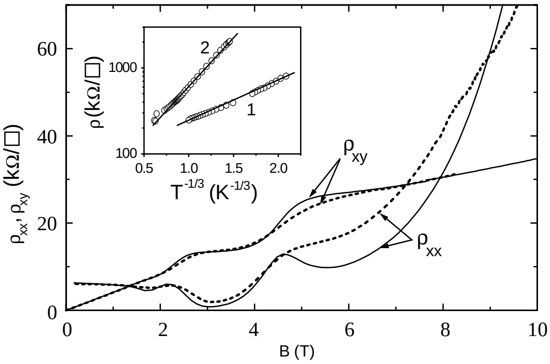

Fig. 1. Oscillations of the magnetoresistivity ρ_{xx} and the Hall resistivity ρ_{xy} at temperatures $T = 1.7$ K (solid lines) and $T = 4.2$ K (dashed lines) for sample with $n = 1.9 \times 10^{11}$ cm^{-2}. Inset shows the temperature dependence of resistivity for samples with $n = 4 \times 10^{10}$ cm^{-2} (1) and $p = 2.7 \times 10^{11}$ cm^{-2} (2).

with relatively high carrier concentration conventional qHe is observed. Moreover, magnetoresistance measured at different temperatures crosses. In the crossing point derivative $d\rho_{xx}/dT$ changes the sign and qHe—insulator transition is observed. Filling factors in this point is about $\nu \approx 0.8$. The qHe plateau is very long and visible behind the crossing point (Fig. 1). The slope of the plateau is due to relatively high temperature of measurements. Theoretically the value of ρ_{xx} in the transition point is equal to h/e^2 [1]. In QD layers with high density of dots ($\approx 2 \times 10^{10}$ cm^{-2}) the value of ρ_{xx} in the transition point is higher. Morphology of the surface was investigated by atomic force microscope (AFM) in a contact mode. Clusters of QD with characterisitic size of 80 nm are visible. The density of 2D electrons fluctuates with the characteristic scale of about the cluster size. 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. The 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.

Two-dimensional Mott variable range hopping conductivity has been observed at low temperatures in samples with low carrier concentration ($n < 10^{11}$ cm^{-2} for n-type and $p < 5 \times 10^{11}$ cm^{-2} for p-type samples, see inset in Fig. 1). The length of localization (80 nm) correlates very well with the QD cluster size obtained by AFM.

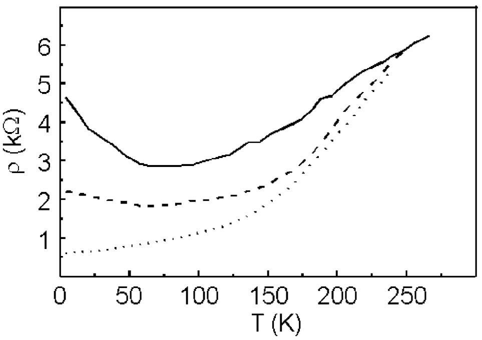

Fig. 2. Temperature dependence of the resistivity in dark ($n = 3 \times 10^{11}$ cm^{-2}, solid line) and after illumination at $T = 4.2$ K by $\lambda > 1120$ nm (dash line) or $\lambda = 791$ nm (dotted line).

4. Persistent photoconductivity

The conductivity of structures was studied as a function of illumination with $\lambda > 1120$ nm and $\lambda = 791$ nm. All samples exhibited a positive persistent photoconductivity (PPC) at $T < 250$ K. The resistivity of all samples decreases after both types of illumination (Fig. 2). For all samples the Hall density and Hall mobility obtained after illumination $\lambda = 791$ nm are higher than the ones obtained after illumination $\lambda > 1120$ nm.

In the case of illumination by light with $\lambda > 1120$ nm, PPC is attributed to the ionization of donor Cr atoms in the GaAs substrate. The electrons excited from the Cr level in substrate move to the QD layer. In the saturation case, the conduction band in the GaAs buffer layer (between the substrate and the QD layer) becomes flatter. In the case of illumination by light with $\lambda = 791$ nm, the effect of PPC can be explained by photogeneration of electron–hole pairs. The electrons flow towards the QD layer, and the holes flow towards the substrate or recombine with the electrons trapped at the surface states.

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