Available online at www.sciencedirect.com
SCIENCE DIRECT
Physica E 18 (2003) 116–117
PHYSICA E
www.elsevier.com/locate/physe

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

Vladimir A. Kulbachinskii[a,*], Roman A. Lunin[a], Vasili A. Rogozin[a], Boris N. Zvonkov[a], Dmitriy O. Filatov[a], Anne de Visser[b]

[a] *Low Temperature Physics Department, Physics Faculty, Moscow State University, 119992, GSP-2, Moscow, Russia*
[b] *Van der Waals-Zeeman Institute, University of Amsterdam, 1018 XE Amsterdam, The Netherlands*

**Abstract**

We have investigated the resistance in the temperature range $T = 0.4$–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-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.


*Keywords:* 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 QD 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 quantum Hall effect (qHe)–insulator transition of self-assembled InAs QD layers, grown on GaAs substrates.

## 2. Samples

The structures were grown by atmospheric pressure metal organic vapor phase epitaxy 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 10–12 layers, each contained: GaAs (thickness 0.1 μm), a Si $\delta$-doping layer for n-type samples (or C for p-type samples), a spacer layer (thickness 6 nm), an InAs QD layer, and to cap the structure a cladding layer of GaAs (thickness 0.1 μm) [2]. Here we show the results for three different samples. Samples 1 and 3 were n-type, with carrier concentration per layer of QDs $4.0 \times 10^{10}$ and $1.9 \times 10^{11}$ cm$^{-2}$ and Hall mobility 1000 and 5500 cm$^2$/V s, respectively ($T = 4.2$ K). Sample 2 was p-type with a hole concentration per layer of QDs $2.7 \times 10^{11}$ cm$^{-2}$ and a Hall mobility 100 cm$^2$/V s ($T = 4.2$ K).

The morphology of the QD layers was investigated by atomic force microscope (AFM) TopoMetrix® TMX-2100 Accurex™ in a contact mode. In Fig. 1, as an example, the AFM image of a QD layer after etching [3] for a sample prepared from the same wafer as sample 2 is shown. QDs with density $N_S \approx 2 \times 10^{10}$ cm$^{-2}$ are visible. In Fig. 2 the probability histogram of the radial distribution $W(r)$ of the quantum dot clusters is shown. (The probability $dP(r, \Delta r)$ to find a cluster in the ring $(r, r+\Delta r)$ is equal to $dP(r, \Delta r) = 2\pi r W(r)\Delta r$.)

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

1386-9477/03/$ - see front matter © 2003 Elsevier Science B.V. All rights reserved.
doi:10.1016/S1386-9477(02)01039-1

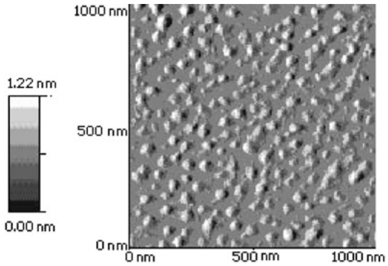


Fig. 1. Typical AFM image of an InAs QD layer surface after selective etching.

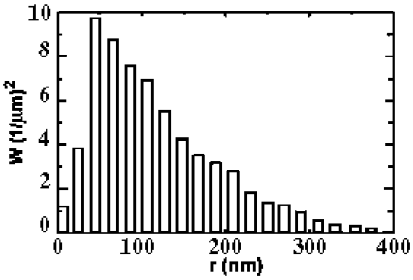


Fig. 2. The histogram of radial distribution of probability density $W(r)$ of quantum dot clusters.

## 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 inset 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 the value $T_0 \approx 17$ K, and hence the localization length is about 80 nm. This value correlates very well with the maximum of radial distribution of probability density $W(r)$ of quantum dot clusters (see Fig. 2).

In n-type samples with electron concentration $n > 10^{11}$ cm$^{-2}$ (for p-type samples $p > 5 \times 10^{11}$ 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 qHe–insulator transition. The transition takes place in the lowest Landau level (near $\nu \sim 0.75$). Notice that the data for $\rho_{xy}$ were corrected for resistance contributions by averaging over up and down field directions. 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 non-zero diagonal resistivity and the relatively high temperature at which data are taken. According to the theory [5] the value of $\rho_{xx}$ at the transition point is equal to $h/e^2$. In the case of QD layers with high density of dots the value of $\rho_{xx}$ 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 still be metallic. Above the critical point magnetic field dependence of the resistance obeys an exponential law up to the highest field $B \simeq 35$ T, like reported in Ref. [6].

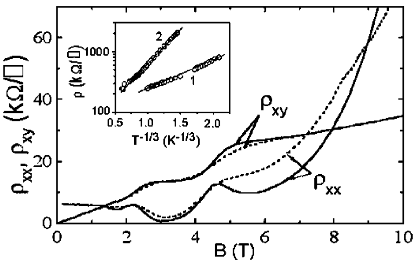


Fig. 3. Oscillations of the magnetoresistivity $\rho_{xx}$ and the Hall resistivity $\rho_{xy}$ at temperatures $T = 1.7$ K (solid lines) and $T = 4.2$ K (dashed lines) for sample 3. Inset show the temperature dependence of resistivity for samples 1 and 2.


## Acknowledgements

The work was supported by the Russian Foundation for Basic Research (Grants 00-02-17493, 01-02-16441) and CRDF (BRHE REC-001).


## References


[1] T. Noda, et al., J. Crystal Growth 127 (1993) 783.
[2] V.A. Kulbachinskii, et al., Physica B 266 (1999) 185.
[3] I.A. Karpovich, N.V. Baidus, B.N. Zvonkov, D.O. Filatov, et al., Phys. Low-Dimensional Struct. 3/4 (2001) 341.
[4] B.I. Shklovskii, A.L. Efros, Electronic Properties of Doped Semiconductors, Springer, Berlin, 1984.
[5] S. Kivelson, et al., Phys. Rev. B 46 (1992) 2223.
[6] D. Shahar, et al., Solid State Commun. 107 (1998) 19.