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Persistent infrared photoconductivity in InAs/GaAs structures with quantum dot layer

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Abstract

Persistent lateral infra-red photoconductivity has been observed and investigated in InAs/GaAs layers with quantum dots (QD) in the temperature range $4.2<T<300$ K. The relaxation of photoconductivity was logarithmic in a certain time range after switching off the light, while the rate of the decay of photoconductivity increases strongly when temperature increases.

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1. Introduction

Investigation of semiconductor structures with quantum dot (QD) layers is the subject of major ongoing research efforts due to fundamental interest [1] and because of their potential broad applications in semiconductor lasers, light emitting devices [2] and infrared photo-detectors [3–7]. Most of the experimental and theoretical works on the electronic properties of self-assembled QD's have concentrated on the heterosystem InAs/GaAs. QD-related transport has attracted a special attention. In particular, it has been found that InAs dots embedded in the vicinity of a two-dimensional 2D electron gas in selectively doped heterojunctions reduces the electron mobility, acting as controllable scattering centers [8,9]. A more interesting case is the 2D interdot coupling in the plane of the self-assembled QD layer. In high densities of InAs QD's formed on GaAs substrate 2D conductance was observed [10–12]. Due to the strong localization of QD-levels, hopping conduction was identified in the plane at low temperatures [13,14].

Quantum well infrared photodetectors are being used successfully for detecting infrared light in detectors, sensors, and imaging devices. However, a limitation of such detector is that, due to the transition selection rules, (i) they are not sensitive to normally incident light, and (ii) they typically only have a narrow response range in the infrared. QD infrared photodetectors are not suffer from the normal-incidence limitation because of the geometry with the carrier confinement in all three directions. Furthermore, they can have a broader infrared response range because the self-assembled QDs have several discrete states and tend to naturally grow with an inhomogeneous broadening and with intersublevel energies which are suitable for the long wavelengths [15–17]. Photodetectors based on zero-dimensional transitions are also expected to exhibit lower dark currents and have therefore been the subject of recent studies using self-assembled QDs. The electronic shell structure and the intersublevel energy spacing of InAs/GaAs self-assembled QDs can now be controlled to produce ensembles which display well

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resolved excited states in state-filling photoluminescence spectroscopy. It is therefore interesting to study the properties of devices, which have been fabricated with self-assembled QD ensembles having sharp electronic shells [18]. Later lateral intersubband photocurrent spectroscopy has also been carried out in order to investigate transitions between QD bound states and the wetting-layer subband. In this case, confined electrons are excited into the wetting layer subband and carrier transport takes place in the wetting layer or in the surrounding bulk GaAs due to subsequent thermal excitation out of the wetting layer [19,20].

Changing of conductivity under infra-red illumination and its relaxation to the initial value has a special significance for studying doped QD's energy spectrum. It's important to understand the nature of the processes of relaxation of conductivity at high and low temperatures. Mainly photoconductivity was studied on n-type samples of QD-layers [12,15–21].

In the present work the in-plane conductivity of p-type InAs/GaAs structures with QDs has been investigated in a wide range of temperatures in darkness and under infrared illumination. The relaxation of photoconductivity in p-type structures is compared with the same process in n-type structures. The theoretical model of the relaxation of photoconductivity was developed which has a good agreement with the experimental results.

2. Experimental

Investigated structures were grown by metal organic chemical vapor deposition (MOCVD) on semiinsulating (0 0 1) GaAs(Cr) vicinal substrates. p-type structures consisted of (from substrate to the top): 0.25 μm *i*-GaAs buffer layer; delta-layer of carbon (C); 11 nm *i*-GaAs spacer; a layer with InAs QD; 11 nm *i*-GaAs spacer, another delta layer of C; 0.1 μm cap layer of GaAs. The samples were grown at lowered temperature 520–550 °C. Similar QD structures with n-type conductivity are described elsewhere [14]. Depending on the doping level, we could obtain various concentrations of carriers in the samples.

The surface morphology of the samples was studied for the structures whose growth was immediately stopped after the appearance of QDs. The surface topography was studied using an Accurex TMX-2100 atomic-force microscope in the contact mode under the atmospheric pressure. The density of QDs in p-type samples was $2\times10^{10}\,\mathrm{cm}^{-2}$, their average base size was about 50 nm.

We studied in-plane (lateral) resistivity, the Hall effect and photoconductivity of QD layer. Hall effect and resistivity have been measured by a conventional four probe technique in the temperature range 4.2–300 K in a magnetic field B up to 6 T created by superconducting solenoid. Magnetotransport in p-type samples was also investigated in pulsed magnetic field up to 40 T. Concentrations and mobilities of carriers measured from Hall effect are listed in Table 1. In some samples Shubnikov-de Haas effect was measured which allowed independently evaluating concentrations of carriers (see Table 1). It is seen from Table 1 that the mobility of holes in QD layer non-monotonically depends on hole concentration. Lowest mobility was observed in samples P2 with lowest hole concentration. The hole mobility increases with increase of hole concentration in sequence of samples P2-P1-P6-P5-P4 from 230 cm^2/(V s) in sample P2 to 3000 cm^2/(V s) in sample P4. This tendency can be explained by the weaker influence of the random potential on hole transport for higher Fermi level due to screening effect. Further increase of hole concentration in sequence of samples P4-P3-P7 results in the decrease of hole mobility to 640 cm^2/(V s) in sample P7. This dependence can be due to increase of amplitude of random fluctuations of electrical potential caused by ionized impurities in C δ-layer. In Fig. 1 as an example we show Shubnikov de Haas effect and Quantum Hall effect in sample P4. Magnetotransport data in n-type samples have been published earlier in [14].

Samples were illuminated up to saturation of resistance by infrared light with a wavelength $\lambda > 1120$ nm using lamp and Si-filter or by LED with $\lambda = 950$ nm (in both cases the energy of photon is less than the energy gap of GaAs). Resistivity and its relaxation have been measured by

Table 1
P_{H}—Hall concentrations, P_{SdH}—Shubnikov-de Haas concentrations, μ—mobility of carriers at $T = 4.2$ K in darkness

Sample	P_{H} (10^{11} cm^{-2})	P_{SdH} (10^{11} cm^{-2})	μ (cm^2/Vs)
P1	2.7	—	330
P2	2.6	—	230
P3	13	10.5	1600
P4	8.4	6.0	3000
P5	7.4	6.15	2500
P6	3.8	3.1	1900
P7	540	44.0	640

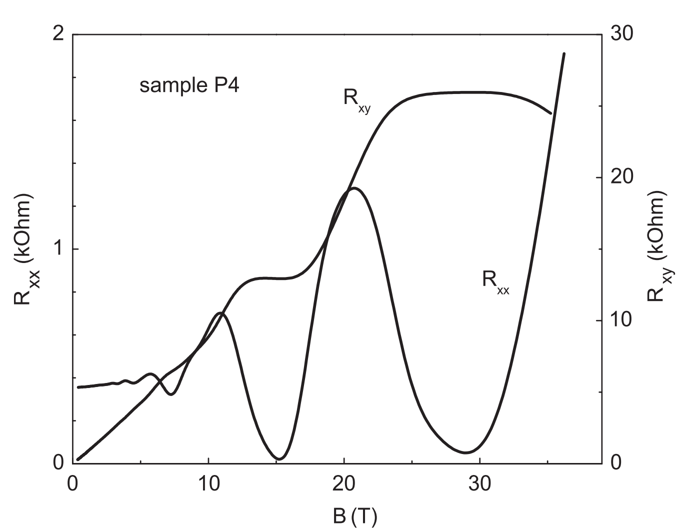

Fig. 1. Magnetoresistance and Quantum Hall Effect in sample P4.