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Optical and transport properties of short period InAs/GaAs superlattices

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Abstract. The photoluminescence, magnetoresistance, Shubnikov-de Haas and Hall effect have been investigated in modulation doped short period InAs/GaAs superlattices as a function of InAs layer thickness Q in the range $0.33 < Q < 2.7$ monolayer (ML). Large photoluminescence enhancement takes place when InAs layer thickness $Q = 0.33$ ML. When $Q > 2.7$ ML the quantum dots are formed. The anisotropy of resistivity and mobility of electrons depends not monotonically on the thickness Q of InAs layers.

Introduction

In recent years considerable attention has been focussed on the research of the self-organized ensembles of quantum dots, that is the quasi-zero-dimensional objects (with dimensions 5–20 nm) shaped during heteroepitaxial growth in case of misalignment of lattice parameters with a substrate [1–3]. While the mechanism of a nucleation and formation of quantum dots and optical properties of undoped structures with quantum dots have been widely studied, the optical and electrical properties of doped structures at initial stage of quantum dot formation have not been investigated enough. In the present work the investigation of a photoluminescence at the temperature 77 K, magnetoresistance and Hall effect in modulation doped shot period InAs/GaAs superlattices with very thin InAs layers in magnetic fields up to 8 T in the temperature range 0.4–4.2 K was conducted.

1. Samples

The structures were grown by MBE at 490 °C on semi-insulating (001) GaAs substrates. The samples consisted of 1 μm thick GaAs buffer layer, superlattice InAs/GaAs (with different periods and total thickness 14 nm), a 10 nm thick spacer layer $Al_{0.2}Ga_{0.8}As$, a 35 nm thick Si-doped layer $Al_{0.2}Ga_{0.8}As$ and a 6 nm thick GaAs cap layer. In investigated structures the effective thickness Q of InAs layers was changed from 0.33 ML up to 2.7 ML. The thickness of GaAs layers in superlattice was also proportionally changed to keep the mean composition of the superlattice equivalent to solid solution $In_{0.16}Ga_{0.84}As$. From the wafers double Hall bars were fabricated for anisotropy and magnetotransport experiments with the current (I) channel along [110] (pa-direction) and perpendicular (I parallel to $[\bar{1}10]$, pe-direction) in the same sample. Thus the anisotropy of resistance have been measured in the samples with single current channel bended to 90 degrees. The relevant parameters of the structures are listed in Table 1.

2. Photoluminescence

In Fig. 1 the photoluminescence spectra are shown for samples with InAs layer thickness Q from 0.33 up to 2.7 ML. The photoluminescence spectra of samples with thickness less than 2 monolayers showed two peacks: a low-energy peak with a maximum at photon energy 1.356–1.375 eV and a high-energy peak with a maximum at photon energy 1.406–1.434 eV (see Table 1). These two peaks correspond to optical transitions from the two occupied electronic subbands to hole subband [4] because in the case of undoped quantum well only optical transition from lowest subband is visible in PL spectra. Always the intensity of the peak with higher energy is higher (see Fig. 1). However, when the effective thickness of InAs layers equal to or exceeds 2.7 monolayers, the photoluminescence spectrum essentially transforms. A new broad and intensive photoluminescence peak with a maximum at 1.265 eV appears in long-wavelength region of the photoluminescence spectrum (Fig. 1(8)). As shown in Ref. [1–3], such change of photoluminescence spectrum may be ascribed to the phase transition from two-dimensional layer-by-layer growth to the formation of a vertically-stacked quantum dots. The second feature of the photoluminescence spectra is not monotonous dependence of the intensity I_{PL} on the InAs layer thickness Q. Maximal intensity was observed for $Q = 0.33$ ML. The maximal electron mobility was observed in this sample (see later).

Table 1. The InAs layer thickness Q in monolayers (ML), the energy $h\nu_{max}$ of the maximum of the photoluminescence spectra at $T = 77$ K, the Hall density n, and the Hall mobility μ, at $T = 4.2$ K for modulation doped InAs/GaAs superlattices.

Sample number	Q (ML)	$h\nu_{max}$ (eV)	n (10^{11} cm^{-2})	μ (cm^2/Vs)
1	solid solution $In_{0.16}Ga_{0.84}As$	1.434, 1.375	8.7	8100
2	0.33	1.419, 1.367	11.5	9400
3	0.67	1.411, 1.369	5.98	2060
4	1.00	1.411, 1.370	15.2	2450
5	1.33	1.418, 1.374	8.66	4220
6	1.58	1.404, 1.368	5.60	4910
7	2.00	1.406, 1.356	10.4	7060
8	2.70	1.390, 1.265	1.52	120

3. Magnetoresistance

A negative magnetoresistance was observed at low temperatures in magnetic fields $B <$ 0.1 T in all samples. In high magnetic fields the Shubnikov–de Haas effect and quantum Hall effect was observed (Fig. 2,3). The Hall electron concentration is equal to $(1.5-15) \times 10^{11}$ cm^{-2} in different samples at temperature 4.2 K and coincides with concentration determined from the Shubnikov–de Haas effect. The obtained carrier concentration n and mobility μ are listed in Table 1. The maximum value of electron mobility 9400 cm^2/Vs is observed in a sample with a InAs thickness 0.33 monolayers. When InAs thickness increases the mobility decreases down to approximately 4000 cm^2/Vs at temperature 4.2 K (Fig. 4). The relatively high mobility in sample with minimum submonolayer thickness $Q = 0.33$ ML of InAs may be explained by a small fluctuation of elastic strains and most

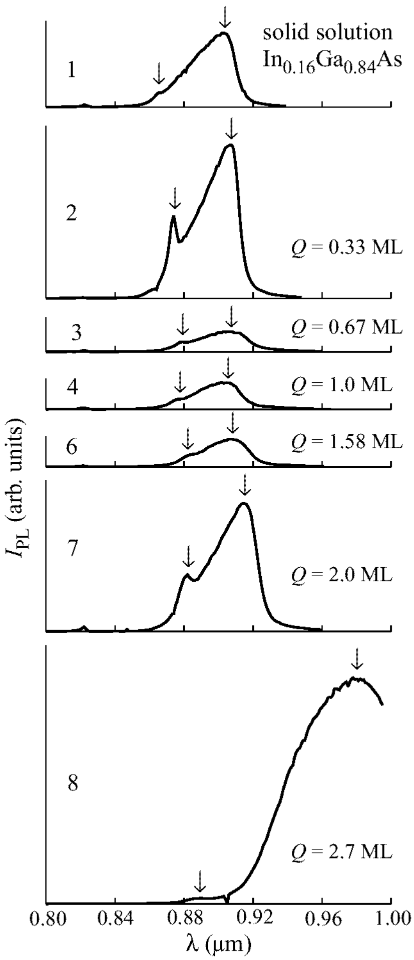

Fig. 1. Photoluminescence spectra of modulation doped InAs/GaAs superlattices with InAs layer thickness Q from 0.33 up to 2.7 monolayer and the mean composition $In_{0.16}Ga_{0.84}As$ sample.

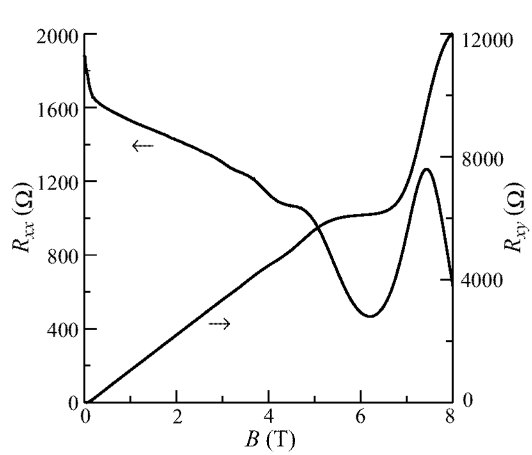

Fig. 2. Transverse magnetoresistance R_{xx} and Hall resistance R_{xy} for sample with InAs layer thickness $Q = 1.58$ ML at $T = 0.4$ K.

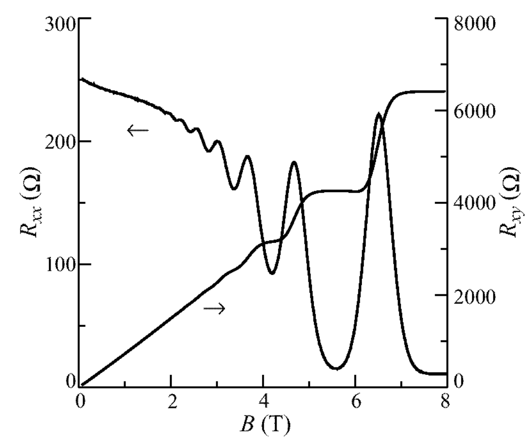

Fig. 3. Transverse magnetoresistance R_{xx} and Hall resistance R_{xy} for sample with solid solution $In_{0.16}Ga_{0.84}As$ at $T = 0.4$ K.

perfect crystal lattice as compared with solid solution $In_{0.16}Ga_{0.84}As$. In sample 8 quantum dots are formed and electron concentration is much lower than in other samples. Due to low electron concentration the electron mobility in this sample is very low.

4. Anisotropy of conductivity

In all samples except solid solution $In_{0.16}Ga_{0.84}As$ the anisotropy of conductivity is observed. The dependence of ratio of resistance R_{pe} in the $[\bar{1}10]$ direction to resistance R_{pa} in the [110] direction on thickness of InAs layers is shown in Fig. 5.

The anisotropic electron mobility correlates to the asymmetric dislocation distribution [5]. The anisotropy of resistance in 2D electron system is typical for structures with

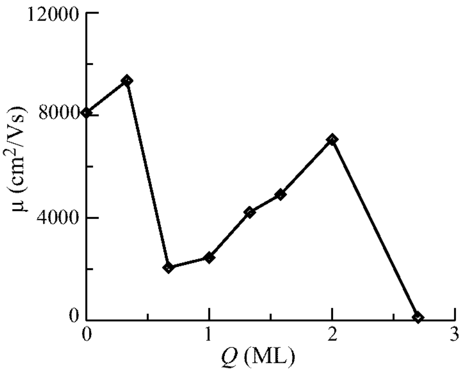

Fig. 4. Dependence of Hall mobility μ on InAs layer thickness Q for different superlattices at $T = 4.2$ K.

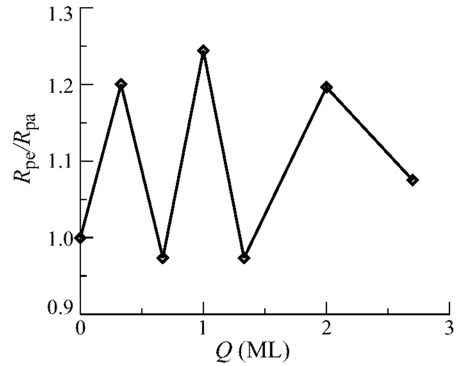

Fig. 5. Dependence of ratio of resistance R_{pe} in the $[\bar{1}10]$ direction to resistance R_{pa} in the [110] direction on thickness Q (in ML) of InAs layers.

preferential growth of deposited material in one direction (see [6, 7], for example). The dependence of anisotropy on thickness of InAs layers shows that at definite ML deposition Q there are an island growth which leads to the anisotropy of resistance (see Fig. 5).

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