Temperature dependence of photoluminescence of GaAs/AlGaAs quantum rings

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Abstract. Samples with arrays of GaAs/AlGaAs quantum rings (QRs) of different shapes were grown by molecular beam epitaxy in droplet epitaxy mode. Photoluminescence (PL) spectra of the samples were measured at 20 – 90 K and 300 K, intense peaks attributed to the QR layers were observed. The peaks were identified by comparison of as-grown and selectively etched samples and by the calculation of the ground state energy for charge carriers in GaAs QRs. FWHM narrowing with the temperature increase was observed below 70 K.

1. Introduction
Quantum rings (QRs) are novel nanostructures similar to quantum dots but with unique electronic and optical properties, especially in magnetic fields [1]. Photoluminescence spectra of GaAs/AlGaAs quantum rings were studied in several works [2-5], though the temperature dependence of the spectra has not been investigated in detail. In addition, there are some difficulties with identification of additional PL peaks at higher energy (some authors attribute them to AlGaAs barrier layer, while others – to the GaAs wetting layer). Also, QR layers are usually overgrown and annealed before the PL experiments, so the spectrum of as-grown surface layers of QRs has not been studied so far.

2. Experiment and results
Two samples were investigated in the present work, containing one layer of single QRs (A1) and two layers of double QRs (A2), formed by droplet epitaxy [6]. Both samples were grown on GaAs(001) substrate with GaAs buffer layer and Al_{0.28}Ga_{0.72}As barrier layer. For A2 sample one QR layer was overgrown by Al_{0.28}Ga_{0.72}As, and another (identical) QR layer was grown on the surface. For more information on the growth procedure see [7].

The mean diameter and height of the rings were measured using atomic force microscopy and scanning electron microscopy. The outer/inner diameter of the QRs were 53±12/22±6 nm for A1, 56±9/28±3 nm for A2 inner rings and 140±24/100±23 nm for A2 outer rings. The mean height of QRs was 4.5±0.5 and 4.3±0.3 nm for A1 and A2, respectively.

For PL measurements 488 nm Ar⁺ laser was used with intensity of 100 mW/cm². Spectra were measured at 20-90 K and at room temperature. PL peaks of QR layers were identified by comparing their energy with GaAs band gap (1.52 eV at 20 K) and Al_{0.28}Ga_{0.72}As band gap (1.87 eV at 20 K). The A2 low temperature PL spectrum has an additional peak at lower energy
Figure 1. Normalized PL spectra of the samples A1 (left) and A2 (right) at T=20 K. As-grown (solid line) and etched (dashed line) samples are compared.

Figure 2. Temperature dependence of the energy (left) and FWHM (right) of QR peaks for samples A1 and A2. GaAs bulk band gap (Varshni relation) is shown shifted to higher energy for comparison.

which is attributed to the buried QR layer. The reference spectra of the etched samples without QR layers were also measured (Fig. 1).

Room temperature (RT) spectra were measured in accumulation mode. There was no PL from the Al$_{0.28}$Ga$_{0.72}$As layer at RT, but there was a peak at 1.42 eV (which is GaAs bandgap at 300 K) from the substrate/buffer layer for both samples in addition to the peaks from GaAs quantum rings. For reference, we also measured the PL spectra of the substrates, where only bulk GaAs peak at 1.42 eV was found.

3. Discussion
The temperature dependences of QR peak energy and full width at half-maximum (FWHM) are presented in Fig. 2. The FWHM narrowing with the temperature increase was observed below 70 K. This phenomenon has been noticed before in disordered systems such as quantum dots [8,9] and rough quantum wells [10] and is usually explained by thermal assisted tunnelling and
relaxation of the carriers into global minima of the potential (larger QRs in this case) instead of local minima. The peak energy also decreases more rapidly with the temperature increase than GaAs bulk band gap (Fig. 2), which is in good agreement with the proposed model. At temperatures higher than 70 K electron-phonon scattering starts to play major role, leading to the peak broadening.

Figure 3. (a) Electron confinement energy dependence on the QR height for surface and buried layers, the considerable difference is shown for 4.3 nm (sample A2) (b) Peak shape approximation for the buried QR layer of A2 at T=20 K, (c) Peak shapes for surface and buried QR layers with the same height distribution.

Finally, the ground state energy of QRs was calculated. We use one-particle two-band model here for electrons and heavy holes. Because the height of QRs is much smaller than their diameter, simple 2D quantum well model is sufficient for estimating the quantum confinement energy. This model shows that the ground state energy is much higher for surface QR layer than for buried QR layer (Fig. 3a) which is confirmed by the spectrum of sample A2. We can also model the low temperature shape of the peaks, determined by the QRs size distribution (Fig 3b). We consider gaussian distribution for QR height and model the peak shape using energy dependence on the 2D quantum well width. The calculated FWHM is smaller for the buried layer than for the surface layer with identical height distribution (Fig. 3c).

For more accurate calculation of the confinement energy for 3D quantum rings numerical method described in [11] was implemented. We expand the envelope function into a complete orthonormal set of eigenfunctions of a rectangular potential well with infinite barrier. Then we transform the Schrodinger equation into matrix form which is solved numerically. The size of the well for any number of the basis functions can be chosen so as to minimize the ground state energy. The method was tested by comparing with the analytical results for exactly solvable
problems, such as quantum well and two-dimensional quantum ring. For final calculation we used the basis set of 11 functions in each dimension. The results for the peaks from the surface QR layers are shown in the Table 1. They are in good agreement with the experiment.

For the buried QR layer of the sample A2 the calculated energy is higher than the experimental value which can be explained by interdiffusion with the $\text{Al}_{0.28}\text{Ga}_{0.72}\text{As}$ barrier layer during overgrowth. In that case the height distribution would also be different compared to the surface layer, which can explain the large FWHM of the peak.

### Table 1. Experimental and calculated values of e1-hh1 transition energy for the samples.

| Sample | Experimental | Calculated |
|--------|--------------|------------|
| A1     | $\Delta E_{\text{exp}} = 0.217 \pm 0.028$ eV | $\Delta E_{\text{calc}} = 0.20 \pm 0.03$ eV |
| A2     | $\Delta E_{\text{exp}} = 0.220 \pm 0.018$ eV | $\Delta E_{\text{calc}} = 0.21 \pm 0.01$ eV – inner ring $\Delta E_{\text{calc}} = 0.20 \pm 0.01$ eV – outer ring |
| A2     | $\Delta E_{\text{exp}} = 0.102 \pm 0.041$ eV | $\Delta E_{\text{calc}} \approx 0.12$ eV |

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