Investigation of optical properties of In(Ga)As/GaAs mesa structures with active region based on quantum wells, quantum dots, and quantum well-dots

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Abstract. In this work photoluminescence (PL) of mesa-structures that contain three different types of active regions based on InGaAs/GaAs quantum wells (QWs), InAs/InGaAs/GaAs quantum dots (QDs) and InGaAs/GaAs quantum well-dots (QWD) is studied. Comparative analysis of the PL intensity obtained at different temperatures and optical excitation powers on mesa diameter is done.

1. Introduction
In recent few years, the development of new semiconductor optoelectronic devices based on microcavities, such as single photon sources, miniature radiation sources, detectors, compact sensors, etc., has attracted increasing interest. During the processing of microcavities, etching of epitaxial layers is usually required through the active light-emitting region. This can lead to a significant effect of surface nonradiative recombination on the etched side walls on the optical characteristics. The effect of the nonradiative recombination of carriers in mesa-structures with InAs/InGaAs/GaAs QDs was considered in detail in [1]. It was shown that, due to the strong localization of carriers in InAs/InGaAs/GaAs quantum dots, the effect of nonradiative recombination on the mesa surface is insignificant. The use of QDs arrays as the active region of microlasers helps to achieve very small diameters [2] and high operation temperatures [3]. Despite the fact that lasers based on InAs/InGaAs/GaAs quantum dots showed record characteristics (high operating temperature, low threshold current, etc.), gain saturation in quantum dots stimulates studies of microlasers based on two-dimensional quantum wells or InGaAs quantum well-dots (QWD)[4].

2. Experimental details
All the structures studied were grown on GaAs substrates. Samples containing QDs was synthesized by molecular beam epitaxy (MBE). Three sheets of QDs were inserted into the middle of 0.2-μm thick GaAs cavity confined from the bottom and top sides with Al0.35Ga0.65As barriers. Each QD plane was formed by InAs seeding islands covered with InGaAs capping layer. The structures with QWD and QWs were grown by metalorganic chemical vapour deposition (MOCVD). The active region was
placed into a 0.6-μm thick GaAs optical cavity. The cavity was confined with Al$_{0.39}$Ga$_{0.61}$As barriers. The QW structure contains two InGaAs QWs. Each QW has a thickness of about 8 nm, indium mole fraction is about 15%. The QWD structure comprises a single plane of QWD formed by deposition of InGaAs thin layer on slightly misoriented GaAs surface. The 50-nm thick AlGaAs barriers were used to prevent the diffusion of the optically excited non-equilibrium carriers into the surface or the substrate were they could recombined non-radiatively.

The epitaxial structures were then processed into arrays of deep mesas. Electron-beam lithography and dry etching were used. The mesa diameter varied from ~ 0.3 to ~ 10 μm. Etching was performed through the whole thickness of the cavity. The mesa height was about 1 μm. Photoluminescence (PL) was excited with a neodymium-doped yttrium lithium fluoride (YLF:Nd$^{3+}$) laser. Excitation power was about 1 mW. We investigated the dependences of the PL intensity on temperature and pump power for each array of mesa. The temperature interval was 77–290 K.

3. Results and discussion

Figure 1 shows a couple of representative scanning electron microscopy (SEM) images taken for the mesa arrays with the smallest diameters. Good reproducibility of etching and high verticality of the sidewalls are observed.

![SEM images of mesa-structures array with mesa diameters of 0.5 μm (a) or 0.3 μm (b)](image)

First, we studied PL of the mesa-structures of the largest diameter (10 μm), where the effect of sidewalls is minimal compared to mesas of smaller diameters. PL signal was measured at various temperatures with the excitation power of 1 mW. The results are presented in Figure 2(a-c) for the mesas containing QWs (a), QWDs (b), and QDs (c). All the samples demonstrate comparable intensity of PL signal at liquid nitrogen temperature. The room-temperature emission (dominant peak) is centred around 0.97, 1.04, and 1.26 μm in QW-, QWD-, and QD-structures, respectively. Wavelength of luminescence is directly related to the localization energy of charge carriers in the active region: longer wavelength corresponds to deeper potential well with respect to surrounding matrix material (GaAs). Among the structures studied, QDs provide the deepest and QWs provide the shallowest localization with QWDs having an intermediate characteristic. In the spectra of QD-structure, several less intense peaks are clearly seen as a result of carrier localization within excited electronic states.

Another important feature, which can be extracted from PL spectra, is the linewidth. The QW structure has the narrowest peak with full width at half maximum (FWHM) gradually changes from 8 to 25 nm as temperature rises from 77 to 290 K. This indicates that the linewidth in this case of two-dimensional QW is predominantly determined by temperature-induced broadening of the Fermi function. In contrast, in the case of QDs the spectral width is practically independent of the temperature: FWHM of the ground-state peak changes from 40 to 49 nm within the temperature
We conclude that the linewidth of the QD structure reflects non-uniformity of quantum dots (size, chemical composition, etc) within the array. Meanwhile the full spectral interval of QD emission is much broader as it covers the wavelengths from ~1.05 to 1.3 μm as the result of the overlay of several quantum sub-levels. The QWD structure again demonstrates an intermediate behavior with FWHM that varies from 35 to 72 nm from liquid-nitrogen temperature to room temperature.

Figure 2. PL spectra of QW (a), QWD (b), and QD (c) mesa-structures with diameter of 10 μm taken at different temperatures; (d) normalized PL intensity as function of temperature

Figure 2(d) reveals temperature-induced variation of the integrated PL intensity of mesa-structures with diameter of 10 μm and different type of the active region. The intensities for each type of the structures are normalized to their values at the lowest measured temperature, i.e. the 77-K data are taken as 1. As the temperature rises to 290 K, the integrated intensity of luminescence decreases by 7.6, 2.2, or 3.5 times in QW-, QWD-, and QD-structures, respectively. We would like to emphasize that the QW- and QWD-structures have identical layer design (excepting the active region itself), were grown by the same method and in the same MOVPE apparatus. Therefore, it is hardly possible that these two structures are characterized by different concentrations of the growth defects. Taking into account that QWs are grown far from the border of the pseudomorphic growth, a noticeable quenching of PL signal at room temperature in the QW-based mesa-structure compared to the QWD-based counterpart can only be explained by stronger effect of non-radiative recombination at mesa sidewalls in the case of the QW mesas.

In order to further investigate this effect, we compare the luminescence properties of the mesa-structures having smaller diameters, where the contribution of the sidewalls should be more significant. The results are shown in Figure 3 where the integrated PL intensity measured at 77 K (a) or 290 K (b) is shown as a function of the mesa diameter for all three sorts of the active region. Again,
the intensities for each type of structures are normalized to their 77-K values measured in the largest mesas.

![Graph](image)

**Figure 3.** Normalized luminescence intensity as function of mesa diameter as measured at 77 K (a) and 290 K (b).

We observed that in case of the QDs active region, the 77-K intensity is independent of the mesa diameter (up to the mesas as small as 0.3 μm). At room temperature, the intensity decreases with decreases the diameter by about 2 times. In the case of QWD active region, the PL intensity (both at 77 and 290 K) shows fast decrease with reducing the mesa diameter. The smallest mesas, where the PL signal was detected, was 1 μm (at room temperature) and 0.3 μm (at liquid nitrogen). In the case of QW active region, PL was observed only in 6-10 μm mesas, whereas in the smaller mesas the luminescence was practically absent.

### 4. Conclusions

According to the experimental results, the nonradiative recombination at the etched sidewalls can be crucial for characteristics of GaAs-based device with InGaAs QW active region. Free lateral diffusion of charge carriers along the QW plane gives them the possibility to reach the sidewalls. The negative effect of non-radiative recombination becomes more significant with increasing the temperature and decreasing the mesa size. Though InGaAs QWDs provide three-dimensional localization of the carriers, the shallow energy levels are thermalized at room temperature and nonradiative recombination starts play significant role. For these reasons the realization of the effective InGaAs QW or QWDs microdevices requires suppression of sidewall nonradiative recombination by surface passivation especially when the typical dimension become less than 10 μm. In case of InAs/InGaAs QDs, the etched sidewalls have negligible effect owing to the deep 3D localization potential. In its turn, this leads to a significant reduction of the diffusion length compared to quantum wells [5]. This makes QDs suitable for application in microdevices without passivation and/or in light-emitting devices grown on non-parent substrates, such as III-V on silicon.

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