CATHODOLUMINESCENCE STUDY OF SELECTIVELY GROWN SELF-ASSEMBLED InAs/GaAs QUANTUM DOTS

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We have examined the optical properties of self-assembled InAs quantum dots (QDs) grown on pre-patterned GaAs(001) substrates with time-resolved cathodoluminescence (CL) imaging and spectroscopy techniques. InAs QDs were selectivley formed on mesa stripes using a novel application in self-assembled molecular beam epitaxial growth which entailed the growth of InAs on pre-formed [1-10]-oriented stripe mesas. Differences in the luminescence energy, lineshape, and lifetime are examined between QDs formed on the mesa tops and in the valley regions between the mesas.

1 Introduction

The molecular beam epitaxial growth and formation of a high-density of strained pyramidal InAs islands on unpatterned GaAs(001) substrates has been demonstrated and systematically studied by a number of authors.[1-3] The InAs self-assembled quantum dots (SAQDs) form with a substantial variation in size, thereby yielding a unique spectrum of confined δ-like states for each QD. Various attempts have been made to control the size, shape, and spatial arrangement of InAs SAQDs.[4-8] Recently, a lateral spatial selectivity in the control of InAs SAQD formation has been demonstrated by the growth of InAs on patterned GaAs(001) substrates.[8] Owing to a stress-driven interfacet In adatom migration on GaAs mesa sidewalls, parallel chains of InAs SAQDs on GaAs stripe mesa tops have been fabricated.[8]

In this paper, we report on the optical properties of InAs QDs grown selectively on top of mesa stripes prepatterned into GaAs(001) substrates. The studies were carried out utilizing time-resolved cathodoluminescence (CL) imaging and spectroscopy techniques.

2 Results and Discussion

A GaAs(001) substrate patterned with stripes along the $[1\bar{1}0]$ direction was prepared by chemical etching. In order to achieve the desired GaAs substrate template for spatially selective growth of linear arrays of SAQDs, we employed a size reducing epitaxial growth to obtain, *in situ*, mesa top widths of less than ~200 nm.[8] Subsequently, In adatom interfacet migration occurred during the InAs growth on stripe side walls that possessed a pre-arranged facet orientation and enabled the selective formation of InAs QDs on stripe mesas.[8] After the GaAs mesa preparation, 1.45 ML of InAs was deposited at 500 °C. A separate AFM study of samples grown in this way for mesa top widths less than 0.2 μm showed that SAQDs form on the mesa top for an InAs delivery of 1.45 ML owing to In migration from the sidewalls to the mesa top. The total InAs deposition needed to induce the 2D to 3D morphology change on the stripes is less than the ~1.6 ML that is required to initiate QD formation on the unpatterned substrates, owing to the In migration on the mesa side walls.[8] The CL experiments were performed with a modified JEOL-840A scanning electron microscope (SEM) using a 15 keV electron beam with probe current ranging from 0.1 to 10 nA. The temperature (T) of the sample was varied from 87 to 200 K. Details of the time-resolved CL system have been previously reported.[9]

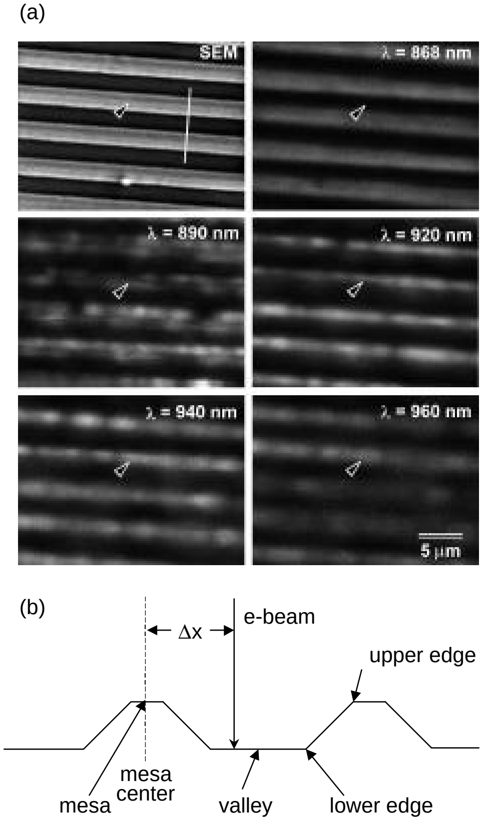

Figure 1. SEM and CL images of the InAs QD sample showing the valley and mesa regions (a) and a schematic diagram showing a cross-sectional view of the mesas (b).

SEM and corresponding CL plan view monochromatic images of the sample maintained at T=87 K are shown in Fig. 1(a). The arrows in the images point to the approximate center position (Δx=0) of a mesa stripe and are used as a marker to reference the same position on the sample for all images. The white vertical line in the SEM image delineates a line along which the e-beam was positioned. Figure 1(b) illustrates the positioning of the electron beam along a line with variable distance, Δx, relative to center of a mesa top so as to acquire CL spectra with a localized excitation. Such local CL spectra were obtained to assess the spatial variation in the SAQD emission, as shown in Fig. 2. A spatial variation in the spectra is expected, owing to a facet-dependent In cation migration that can occur on a length scale of ~1 μm during MBE growth leading to a spatially dependent SAQD density.[7] The CL spectra exhibit a broad (~50 nm) asymmetric hump centered at ~950 nm when the e-beam is positioned near the center of a stripe mesa (Δx=0). The spectra exhibit a sharper multi-component lineshape with the center of gravity blue-shifted by ~30 nm when the e-beam is positioned near the center of the region between the stripes (i.e., the valley region) at Δx = 1.91 μm. The distinct emission at 868 nm in the valley region is due to the excitonic recombination in the InAs wetting layer (WL).[1] This emission is noticeably absent for excitation on the mesa top (Δx=0), revealing marked differences in the carrier relaxation and collection in the QDs between the mesa top and valley regions.

The broad emission peaks with wavelengths greater than ~880 nm are due to excitonic recombination in QDs for the e-beam positioned in both the mesa top and valley regions. The presence of QD emission for an e-beam positioned in the mesa top regions is expected, given the AFM results on the existence of SAQDs on mesa tops.[8] The presence of such emission for excitation in the valley region, less than a μm from the mesa bottom edges, indicates that In migration along the facet sidewalls occurred towards the valley region as well, and some SAQDs formed near the valley edges. CL spectra of an unpatterned region of this sample, far from the stripe mesas, confirms the absence of a QD luminescence and presence of only the WL emission. Thus, these CL results show that the In migration yields an effective local coverage greater than ~1.57 ML on the mesa tops as well as the mesa bottom edges (i.e., the valley edges), thereby yielding QDs in both regions. The ~30 nm blue-shift of the center of gravity of the QD luminescence in the valley edge region relative to the mesa top indicates that the QDs in the valley possess a distribution of smaller or more strained QDs relative to the ensemble residing on the mesa tops. The reduced total SAQD emission when the beam is positioned in the valley region indicates a reduced average density of QDs in the valley relative to the mesa tops. We note that the center wavelength positions of the CL spectra for excitation of both the mesa top and valley regions are blue-shifted by 50-100 nm relative to that for samples with SAQDs grown on planar substrates with similar growth conditions.[3,4] Thus, the stress-driven cation migration is evidently responsible for creating an ensemble of smaller QDs or QDs possessing larger average compressive strains relative to SAQDs grown on planar substrates.

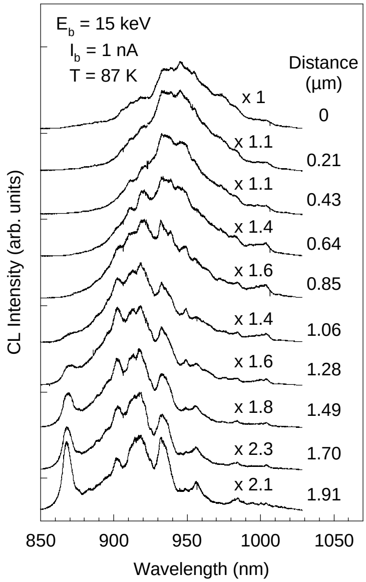

Figure 2. Local CL spectra acquired along a line orthogonal to the mesa stripes. Note distance=Δx=0 for an e-beam excitation on the mesa top.

The carrier relaxation kinetics have been studied with time-resolved CL measurements. The spectrally integrated CL intensity versus time is

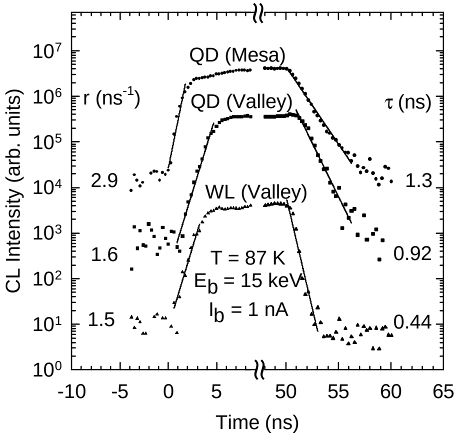

Figure 3. The integrated CL intensity versus time for emissions from the QDs on the mesa, QDs in the valley, and the wetting layer (WL) in the valley.

shown in Fig. 3 with a semi-logarithmic plot, from which onset rates and decay times can be extracted. The onset rate, *r*, is defined as $r = \Delta ln(I_{CL})/\Delta t$ and is given by the slope of the tangent to the onset curves in Fig. 3. Likewise, an exponential behavior is assumed during the decay, and decay times, τ, are obtained from the slopes of fitted lines, as shown in Fig. 3. Onset rates of 2.9, 1.6 and 1.5 ns^{-1} were obtained for QDs on the mesa, QDs in the valley, and the WL in the valley, respectively. Decay times of 1.3, 0.92 and 0.44 ns were also obtained, respectively, for these emissions. The larger onset rate for QDs on the mesa relative to that for QDs in the valley may be due to the ~100-fold increase in the average QD density on the mesa relative to the valley region. This leads to a shorter average diffusion time of carriers before capture into the QDs when excited in close proximity to the mesa top. The difference in decay time between QDs on the mesa and in the valley may be related to differences in the electron and hole wavefunction overlaps between QDs in the valley and mesa regions.

This work was supported by NSF, ARO, ONR, and AFOSR.

3 References

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