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Precision tuning of InAs quantum dot emission wavelength by iterative laser annealing

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ABSTRACT

Controlling the emission wavelength of quantum dots (QDs) over large surface area wafers is challenging to achieve directly through epitaxial growth methods. We have investigated an innovative post growth laser-based tuning procedure of the emission of self-assembled InAs QDs grown epitaxially on InP (001). A targeted blue shift of the emission is achieved with a series of iterative steps, with photoluminescence diagnostics employed between the steps to monitor the result of intermixing. We demonstrate tuning of the emission wavelength of ensembles of QDs to within approximately ±1 nm, while potentially better precision should be achievable for tuning the emission of individual QDs.

1. Introduction

Semiconductor quantum dots (QDs) have been investigated for their potential performance advantages in devices, such as telecommunication lasers [1,2], light emitting diodes [3,4] or single photon emitters [5–7]. The commercial use of such devices strongly depends on the technology that underlies fabrication of wafers with highly uniform arrays of QDs. For example, in linear optical quantum computing sources of indistinguishable single photons is a requirement which entails multiple dots emitting at identical energies [8]. However, the dispersion of photon energy emitted by as-grown self-assembled QDs prevents reliable production of such devices. To further enhance the performance of single dots as single photon sources they are typically coupled to optical microcavities. To facilitate the spectral matching of such dot-cavity systems, numerous post-growth processes have been investigated involving designing and tuning of dedicated optical microcavities [9–11] and a variety of photonic crystal microstructures [12,13]. The ability to tune the quantum dot energy in such systems would be highly advantageous.

It has been demonstrated that dimensions of colloidal QDs could be trimmed by wavelength dependent photoelectrochemical etching [14]. This approach has also been investigated for etching epitaxially grown InGaN QDs [15]. The drawback of this approach, however, relates to the difficulty in preserving the emission intensity of etched QDs due to the incompatibility of the photoelectrochemical etching environment with the epitaxial growth environment that is required for satisfactory passivation of QDs with protective caps. Rastelli et al. have demonstrated tuning of the emission wavelength of devices comprising GaAs microdisks with In(Ga)As QDs by application of a 532 nm laser for selective area annealing [16]. However, this method is based on low-temperature measurements of the microdisk photoluminescence (PL) emission, which again is a significant drawback of the proposed approach.

Wafer level bandgap engineering of III-V QD materials has been demonstrated with numerous post-growth intermixing techniques based on ion-implantation [17], proton implantation [18,19], impurity-free vacancy disordering [3,20–22], argon-plasma exposure [23] and the use of infrared (IR) lasers for intermixing [24]. A laser-based technique, similar to the laser technique for resistor trimming employed in the electronics industry [25], could be attractive for adjusting the QD emission wavelength from an industrial point of view, if applied for automated tuning of the emission wavelength of individual QDs located within a single wafer. Previously, we reported on the use of an IR laser for iterative annealing of multi-bandgap wafers [26,27] and the fabrication of InGaAs/InGaAsP quantum well (QW) wafers designed for

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fabrication of superluminescent diodes [28]. In pursuit of developing a technique for tuning the emission wavelength of arrays of single QDs, we report on the iterative laser annealing (ILA) technique employed for selective-area processing of InP (001) wafers with ensembles of InAs QDs.

2. Experimental details

The QD microstructure (sample 02-161A) used in this study was grown on an S-doped (1×10^{18} cm^{-3}) InP (0 0 1) wafer using chemical beam epitaxy [1]. A 3.3 monolayer (ML) thick InAs was grown on a 230 nm thick InP buffer to form the QDs. This was capped with a 150 nm InP layer and a further 3.3 ML of InAs to form QDs on the surface of the wafer. The surface dots were examined using scanning electron microscopy to provide an indication of buried dot density. All growth was performed at a temperature of 510 °C.

A 20 mm × 10 mm sample was cleaved from the 2-inch diameter wafer and its back and front surfaces were coated, respectively, with 500 and 50 nm thick SiO_2 films to prevent material decomposition during high-temperature annealing. A cross-section view of the investigated QD microstructure is shown in Fig. 1a. Before annealing, the sample was cleaned sequentially with OptiClear, acetone, isopropyl alcohol and rinsed with deionized water.

The laser annealing setup is shown schematically in Fig. 1b. It includes a 150 W 980 nm fiber-coupled laser diode (LD) designed for irradiation of the backside of the sample. The irradiation increases the temperature of a 10 mm diameter spot to a maximum of 500 °C, which is below the threshold for intermixing of the investigated microstructure. Note that direct heating of a semiconductor wafer with LD, as opposed to using a conventional hot plate, allows rapid cooling of the wafer between processing steps. This is advantageous for rapid employment of photoluminescence (PL) diagnostics and, although not applied in the current experiment, it would also allow processing without the need of relocating the wafer between the laser and diagnostics stations. A closed loop system consisting of an IR camera coupled with the LD power supply was employed to provide a stable background temperature. The sample background temperature was monitored with a custom IR camera capable of collecting temperature maps at 10 Hz. By irradiating the front surface of the sample with a focused beam of a CW 1064 nm Nd:YAG laser operating in a TM_{00} mode, a series of high-temperature spots were created, one after another. The temperature of each spot was set at 700 °C and measured with a Mikron M680 infrared (IR) pyrometer collecting data from a 400 μm diameter area. The use of two laser sources allowed to avoid excessive heating of the sample with just the Nd:YAG laser and thus reduced the potential for damage of the sample surface.

Room temperature PL measurements were carried out with a commercial mapper (Philips, PLM-150) at a step resolution of 10 μm. The emission from as-grown samples was observed in the range of 1495–1500 nm. With a 0.5 mm diameter Nd:YAG laser spot, the average diameter of the intermixing inducing spots was approximately 100 μm, which covered approximately 10^7 QDs.

A visible range camera operating at 15 Hz recorded images of the sample, which allowed relocation to its original position each time it was removed for collecting PL measurements. An image recognition procedure was employed to identify the position of individual spots. The computer-based procedure employed a LabVIEW interface, which allowed the precision of spatial and rotational positioning of samples to within ±5 μm and 0.05 deg, respectively [29].

3. Results and discussion

Fig. 2 shows a scanning electron microscope image of the surface of the sample before any processing was performed. A surface density of 320/μm^2 InAs dots was measured, typical for self-assembled dot structure on InP.

To investigate the effect of selective-area QD intermixing, we first fabricated two series of 3 spots annealed either for 30 or 15 sec. This produced spots emitting at 1483 nm (A1), 1478 nm (A2) and 1482 nm (A3) in the first series, and at 1485 nm (B1), 1492 nm (B2) and 1494 nm (B3) in the second series. The PL wavelength maps of a sample processed under these conditions are shown in

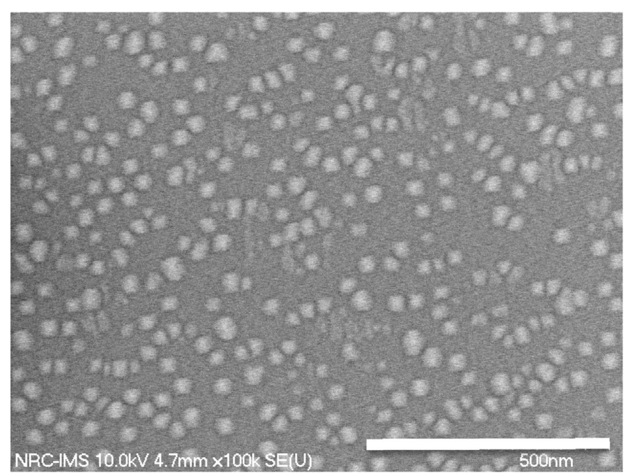

Fig. 2. Scanning electron micrograph of the InAs/InP QD sample surface before any processing.

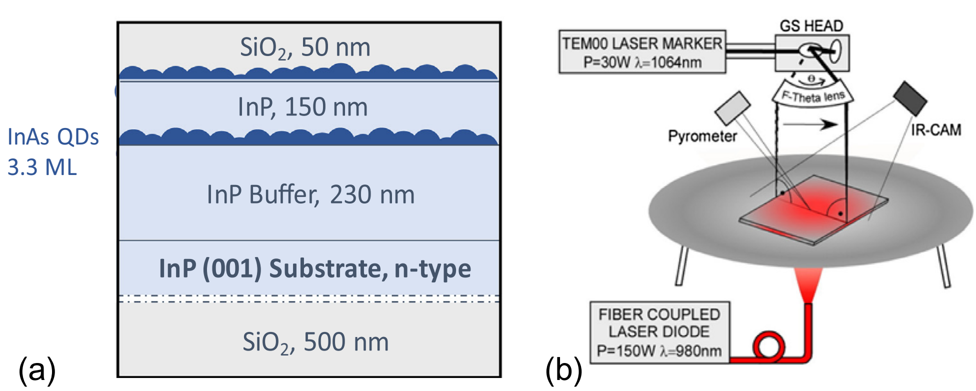

Fig. 1. Cross-section view of the QD microstructure (a) investigated with the ILA technique that makes use of a laser diode (980 nm) and a CW Nd:YAG laser (1064 nm) for selective area annealing of a sample installed on a graphite plate (b).