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Optimization of quantum dot molecular beam epitaxy diode for broadband applications

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1. Introduction

Optical coherence tomography (OCT) is a well establsihed low coherence interferrometric tecnhique to image the near surface of biological specimens specially in dermatology [1] and and [2] opthalmology.Broadband light sources are the crucial component of the OCT system [3].The bandwith of the source dictates the spatial resolution along the optical axis (lateral resolution depends on numerical aperture of focussing optics) and the source power decides the signal to noise ration (SNR), and upto a point depth of penetration of infrared light depending on how scattering the specimen is [4]. There are myriad of choices for selecting broadband light sources such as super continumm sources [3], swept source lasers[5], thermal sources [6] and superluminescent diodes [SLDs][7,8]. The SLD is an ideal light source of choice for lower cost and robust clinical applications, in addition SLD may outperform more complex sources in terms of power output and relative intensity noise. Recently, self assembled quantum dots (QDs) have attracted interest as the active element in SLDs [8].

For QDs, the emission is inhomogeneously broadened, and state saturation occurs at low current densities, introducing emission from higher order states. Both factors are advantageous in realizing broad emission and gain bandwidths. The majority of the history of active QD device development has been in QD lasers. For QD lasers, those QDs outside the homogeneous line-width of the lasing energy do not merely fail to contribute to lasing, but are parasitic. As a result, optimization of QD laser epitaxy is fundamentally different to that of a broadband QD device where all QDs contribute to gain and in the case of SLEDs, to the generation of spontaneous emission. In QD laser optimization the realization of high gain and narrow inhomogeneous linewidths, and for optical communications applications simultaneously attaining 1310 nm emission is key.Forbroadband applications in optical coherence tomography of skin tissue the wavelength (~1200-1300nm) specifications are relaxed with a wide spectral region being of interest. Furthermore, narrow line-width is a distinct disadvantage. As a result, the majority of existing epitaxial processes for active QD devices are unsuited to broadband applications.

In this paper we describe a systematic study of the key MBE parameters affecting 1200~1300nm quantum dot-in-well (DWELL) structures with a view to optimization for broadband applications. The key parameters we have addressed for realizing broadband QDs are the deposition temperature (including InGaAs and GaAs capping, see Fig. 1), QD InAs deposition thickness and deposition rate. The effect of reducing temperature is to increase the QD areal density (Fig.2) and size inhomogeneity. However, as the QD density increases, coalescence (inset Fig. 2) of the QDs results in additional non-radiative defects, evidenced by a strong reduction in photoluminescence (PL) efficiency (Fig. 3). In order to benefit from the broad size distribution and high density of low temperature growth the amount of InAs deposited to form the QDs may be reduced. Photoluminescence (PL) studies were carried on to maximize the spontaneous emission (SE) effciency and line-width. The PL intensity of test structures is shown to correlate to SE efficiency in electroluminescence results of fabricated devices (Fig. 3). Further atomic force microscopy (AFM) allowed the maximization of dot density and size non-uniformity which in turn lead us to broadband gain in the system. A maximum 3dB bandwidth of 160nm (Fig. 4) is obtained for SLDs fabricated from a sample grown under *optimized conditions*. This corresponds to a coherence length and theoretical axial resolution in OCT system of 4µm.

2. Experimental

All the samples studied in this work were grown by molecular beam epitaxy on on Si-doped GaAs (100) substrates. Fig.1 shows the epitaxial structure of the DWELL. The active region consists of six-repeat of DWELL structure and 45 nm of undoped GaAs spacer layer. The QDs are formed by depositing 2.6 monolayers (MLs) of InAs deposited at a growth rate of X ML/s grown on 1nm of $In_{0.15}Ga_{0.85}As$ strained buffer layer and capped by 6 nm of $In_{0.15}Ga_{0.85}As$ strain reducing layer (complete DWELL structure) and 5 nm (low-temperature (LT) GaAs) of the GaAs before increasing the temperature to 580°C for the remaining 40 nm of GaAs. The temperature was then reduced again for the growth of the next DWELL. The high-growth–temperature GaAs spacer layer (HGTSL) is found to reduce the defect density and improves the laser performance [9]. After the active region, an upper cladding layer grown at 600°C and a 300 nm highly doped GaAs contact layer have been grown at 580°C. For AFM, PL, electrical characterization the samples are grown with identical conditions. Broad area SLDs were fabricated for electrical characterization. All the devices are mounted on ceramic tiles and probed directly using multi-probe. All measurements are done at a tile temperature of 300 K. Characteristics are measured in the pulsed regime (5 µs pulsed duration, 1% duty cycle) to minimize the thermal effects.

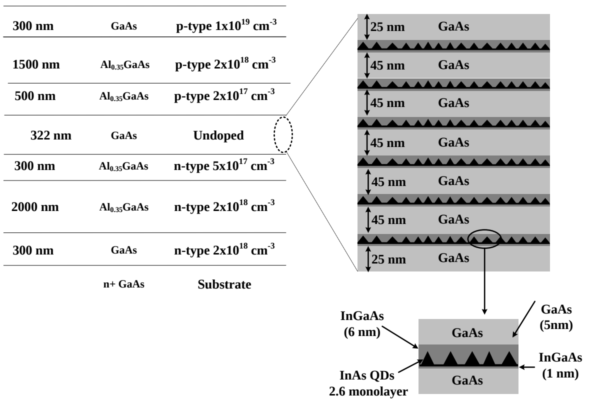

Figure. 1. Schematic of epitaxial structure indicating key features.

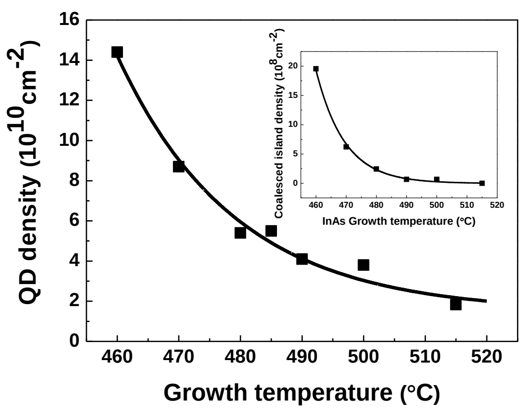

Figure. 2. QD areal density (coalesced island-inset)plotted as a function of QD InAs/GaAs DWELL growth temperature.

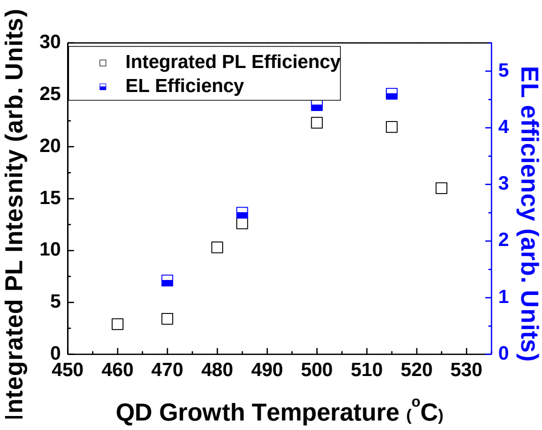

Figure. 3. Integrated PL intensity and EL efficiency plotted as a function of QD growth temperature.

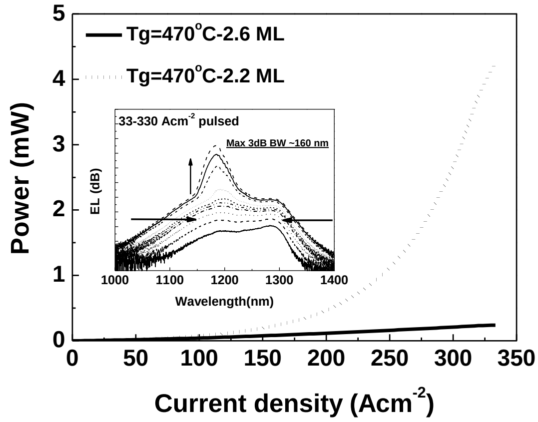

Figure. 4. Power-current characteristics of optimized (growth temperature 470°C and InAs deposition 2.2 ML and growth rate 0.1 ML/s) and unoptimized QD SLED. Inset shows the 3dB bandwidth of 160 nm for optimized stcuture.

3. Conclusions

In this paper we addressed the key parameters for realizing broadband QDs, for high power and high bandwidth superluminescent diodes. The effect of decreasing temperature is to increase the QD and coalesced island density, but a concomitant reduction in PL and EL efficiency. A careful balance of QD parameters and PL and AFM studies allows us to maximize the spontaneous emission and quantum dot density which in turn leads to broadband gain in the system. A maximum 3dB bandwidth of 160nm is obtained, which corresponds to a coherence length and theoretical axial resolution in OCT system of 4µm.

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