Bandgap-Engineered Broadband Stimulated Emission in Semiconductor Quantum Dash Interband Laser

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***Abstract*- Authors demonstrate the generation of broadband stimulated emission in the postgrowth wavelength tuned InAs/InAlGaAs quantum-dash (Qdash) laser grown on InP substrate. The laser exhibits room temperature lasing wavelength coverage of up to 50 nm at center wavelength of ~1.57 µm. Despite the bandgap blue-shift of ~70 nm after Qdash intermixing process, the laser exhibits a broadband signature of lasing linewidth, which is comparable to the as-grown laser. The integrity of the material is retained after intermixing, suggesting its potential application in the fabrication of monolitically-integrated ultra-broadband semiconductor Qdash laser.**

I. Introduction

The technology of self-assembled quantum confined nanostructures in the form of quantum dots (Qdots) or quantum dash (Qdash) has generated tremendous interest due to its near singular density of states, low threshold current densities, temperature insensitive characteristics, high modulation bandwidth, small linewidth enhancement factor and to name a few [1]. In addition, many interesting laser characteristics have been observed and reported from this class of quantum confined nanostructures with highly inhomogeneous gain media such as two-state switching and dynamics [2], broadband lasing emission [3], semiconductor swept laser source [4], etc. The realization of broad interband lasers can find wide applications in optical telecommunication, sensing of various chemical agents, atmospheric and planetary gases, high-precision optical metrology and spectroscopy, and biomedical imaging [5]. The approach of producing broadband lasers relies on engineering of dots/dashes inhomogeneity and energy separation of adjacent quantized states, such that the multiple state lasing can be obtained collectively from the spatially isolated dots/dashes within the lasing ensembles [6].

Spatially selective bandgap engineering of quantum confined nanostructures, such as quantum-well, wire, dash and dots [6], has been a subject of intense research due to the potential of this approach in the fabrication of advanced photonics devices, especially photonic integrated circuits (PICs), in a simple and cost-effective manner. This technology enables various benefits such as excellent alignment, negligible reflection losses, and intrinsic mode matching. In our recent work [7], we found that high annealing temperature will induce a significant interdiffusion effect in Qdot/Qdash, since the interface area volume ratio between Qdot/Qdash and the surrounding barriers is large, making this process is attractive for tuning the bandgap of low dimensional nanostructures.

In this paper, we report the utilization of intermixing technique via impurity-free vacancy disordering (IFVD) to spatially tune the wavelength emission in broadband Qdash laser device. With moderate degree of intermixing, whereby the Qdashes with varying size and composition are subjected to the interdiffusion at different rate, the preservation of broad lasing linewidth can still be achieved.

II. Experiments

The Qdash laser structure was grown by molecular beam epitaxy on (100) oriented InP substrate. The active region consists of four sheets of 5 monolayer InAs dashes, each embedded within a 7.6 nm thick compressively strained $In_{0.64}Ga_{0.16}Al_{0.2}As$ quantum well and a 30 nm thick tensile strained $In_{0.50}Ga_{0.32}Al_{0.18}As$ barrier [8]. The samples were coated with 475 nm of SiO_2 using plasma enhanced chemical vapor deposition prior to rapid thermal annealing at 750ºC in nitrogen ambient for one minute. During thermal annealing, the Ga atoms outdiffuse from semiconductor to the film, leaving behind the vacancy that further enhances the atomic intermixing in the Qdash structure. The refractive index of the as-deposited SiO_2 films, measured using a spectroscopic ellipsometer at a wavelength of 632.8 nm, is 1.47. Two fresh pieces of GaAs proximity caps were used to provide As over-pressure environment during the annealing process. Photoluminescence (PL) spectroscopy was performed at 77 K using a 980 nm diode laser as an excitation source.

Broad area lasers with 50 µm wide oxide stripes were fabricated from the intermixed Qdash samples. A fresh 200 nm thick SiO_2 layer was deposited and a 50 µm contact window was defined using a 10% buffer HF-based chemical etching. In order to maximize the gain, the optical cavity is aligned along the [011] orientation and is perpendicular to the dash direction. A p-metal contact consisting of Ti-Au layers was defined using electron beam evaporation and lift-off process. The samples were thinned down to ~150 µm and n-metal contact of Au-Ge-Au-Ni-Au layers was evaporated on the back side of the samples. After cleaving the sample into bars with different cavity lengths, the non-coated facet

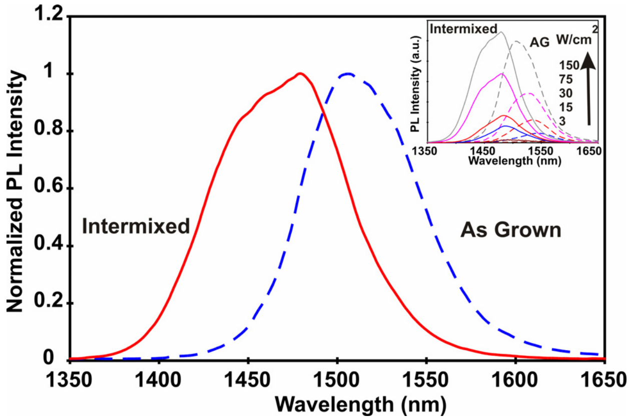

Fig. 1. Normalized PL spectra of as-grown (AG, dotted line) and intermixed (smooth line) wafers at 77 K under excitation density of 150 W/cm^2. The inset shows the PL spectra of both AG and intermixed samples with varying optical pumping levels taken from InAs Qdashes within InAlGaAs matrix.

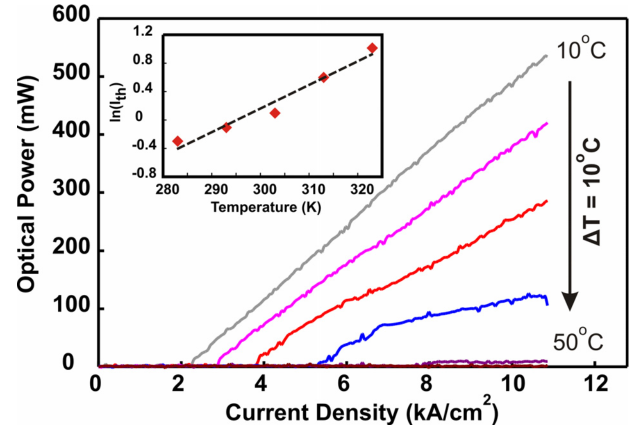

Fig. 2. *L-I* characteristics of the 50 x 700 μm^2 broad area Qdash laser at different temperatures. Up to 420 mW total output power has been measured at $J = 4 \times J_{th}$.

lasers were tested on a temperature controlled heat sink at 20ºC with the epitaxial p-side-up mounting configuration. Current injection was performed under pulsed operation at 0.2% duty cycle with 2 μs pulse width.

III. Results & Discussion

Self-assembled Qdash nanostructures can be viewed as elongated quantum dot structures and its properties are studied before and after intermixing, which is shown in the inset of Fig. 1. The graph depicts the evolution of state-filling spectroscopy results for both as-grown (AG) and intermixed Qdash-in-well, respectively at different excitation power densities. At low excitation below 3 W/cm^2, the ground state emission of 1.56 μm and 1.50 μm was dominant in both samples, respectively. The PL spectra are broadened with increasing optical excitation densities for both samples as a result of significant emission from the excited states, which also indicates the presence of the quasi-zero-dimensional carrier confinement at the lateral direction, even after annealing. Fig. 1 shows the normalized PL linewidth from both AG and intermixed samples at 77 K under the power excitation density of 150 W/cm^2. The PL linewidth of intermixed samples increases up to 88 nm (50 meV), which is significantly larger than that of AG (75 nm or 41 meV) samples. The broadening of the spectra is due to the contribution of multiple transition states indicates the significant effects of IFVD of improving the homogeneity of Qdash, especially for smaller sizes of Qdash that contribute to the emission in the shorter wavelength regime. This increase of PL linewidth and integral intensity in the intermixed samples implies radiative recombination of more Qdashes with different geometries, leading to broad interband bandgap tuned lasers.

The continuous blue-shift of the PL peak wavelength up to 88 nm in the as-grown sample and 61 nm in the intermixed sample at the optical excitation density of 1500 W/cm^2, relative to those obtained at the excitation of 3 W/cm^2, are shown in the inset of Fig. 1. The effect of band-filling is not sufficient to explain a significant blue-shift. Hence, it is reasonably ascribed this to the postulation of continuum states [9] in the Qdash nanostructures, although spectral widening at a shorter wavelength is expected in an inhomogeneous QDash structure [10]. Continuum states serve as an effective medium for exciton scattering and thus change the dephasing rate at each energy level within the highly inhomogeneous ensembles and the radiative recombination profile will be different from that of conventional quantum-well structures. The wide distribution of energy levels due to the nature of Qdash inhomogeneous (FWHM of 76 nm from PL measurement of as-grown sample at low excitation of 3 W/cm^2) will further serve as the radiative recombination states or "sink" for the scattered excitons from the dense continuum states.

Up to 420 mW of total output power has been measured at $J = 4 \times J_{th}$ at 20 ºC, which is significantly higher than the SLED fabricated from the same wafer [8]. The light-current (*L-I*) characteristics of the Qdash laser (L=700 μm) is shown in Fig. 2 with the corresponding J_{th} and slope efficiency, 2.6 kA/cm^2 and 0.146 W/A, respectively. From the dependence of J_{th} on temperature, the temperature characteristic, T_o, of 30 K in the range of 10-50 ºC has been obtained. This low value of characteristic temperature as compared to 50-70 K range in equivalent quantum well structure is due to Auger recombination, carrier leakage, intervalence band absorption effects and local heating due to the photon reabsorption in multiple transition energy states of Qdash with different sizes and compositions.

The progressive change of broadband signature of lasing spectra is shown in Fig. 3 with increasing current injection. Only ground state lasing with the wavelength coverage of ~10 nm is observed below a current injection of $1.5 \times J_{th}$. This broad lasing spectrum suggests the collective lasing from Qdashes with different geometries. At $J > 1.5 \times J_{th}$, bistate lasing is evident. The simultaneous lasing from both transition states is attributed to the relatively slow carrier relaxation rate and population saturation in the ground state

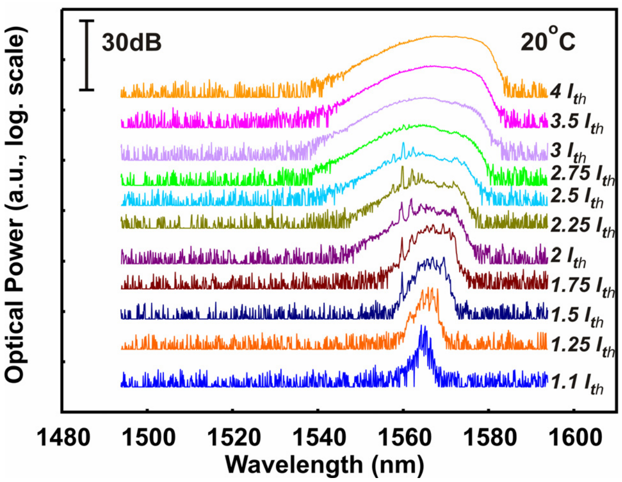

Fig. 3. The lasing spectra at the current injection above threshold condition at room temperature 20ºC. The spectra are acquired using an optical spectrum analyzer with resolution of 0.05 nm.

in low-dimensional quantum heterostructures. The bistate lasing spectrum is progressively broadened with increasing carrier injection up to a wavelength coverage of 50 nm at $J = 4 \times J_{th}$. The corresponding side-mode suppression ratio is over 25 dB.

From the linear fit of J_{th} versus inverse cavity length, a current density at infinite length (J_{int}) of 1.42 kA/cm^2 has been extracted from the intermixed, whilst the corresponding J_{int} for the as-grown laser is 1.32 kA/cm^2. The internal quantum efficiency, η_{int}, and the internal optical loss, α_i, are 96.8% and 35.3 cm^{-1}, respectively assuming reflectivity of the cleaved facets is 0.33. The high internal loss (as compared to AG of 10.5 cm^{-1}) implies the scattering loss of photons due to local undulation of refractive index at the dash/well interface and the uneven interdiffusion profile in Qdash with different geometries, as observed in PL spectra of Fig. 2.

IV. Conclusion

In summary, bandgap tuned broad interband lasers has been fabricated utilizing the process of IFVD to promote group-III intermixing in InAs/InAlGaAs dash-in-well structure. The intermixed lasers exhibit higher internal quantum efficiency, higher threshold current densities and comparable broad lasing spectra. Bandgap shift of 70 nm has been measured from the intermixed lasers with center wavelength of ~1.57 µm as compared to AG lasers with center wavelength of ~1.64 µm. Our results indicate a highly attractive wavelength trimming and selective bandgap tuning method, well suited for planar, monolithic Qdash integration of optoelectronics components. This technique can also be used for the fabrication of ultra-broadband semiconductor laser by monolithically integrating multiple-gain sections, with each section bandgap tuned to different degrees using the intermixing technique, along a single cavity.

Acknowledgment

This work is supported by National Science Foundation (Grant No. 0725647), US Army Research Laboratory, Commonwealth of Pennsylvania, Department of Community and Economic Development. Authors also acknowledge IQE Inc. for growing the Qdash material.

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