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Broadband emission in InAs/InGaAlAs quantum-dash-in-well laser

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Abstract. We report on the development of wide gain InAs/InGaAlAs/InP quantum-dash structure for broadband diode laser and amplifier. Characterizations of this material system have been performed using spectroscopy and microscopy techniques. Gain-guided broad area laser fabricated using this material system exhibits lasing wavelength coverage of up to 76 nm at ~1.64 µm center wavelength from simultaneous multiple confined states lasing at room temperature.

Introduction

Ultra-broad and continuous spectrum generation is an interesting physical phenomenon and an attractive technology for many applications. The development of a viable technology to generate continuous lasing spectrum crossing multiple communication bands in near-infrared will bring significant advances and impact to optical fiber communications, imaging, metrology, spectroscopy and sensing. To date most ultra-broadband sources are generated using nonlinear-optical transformations of ultra-short laser pulses and photonic crystal fiber based approaches. Although Gmachl *et al* demonstrated broadband stimulated emission at mid-IR using the quantum cascade approach, this method of generating broadband semiconductor laser is complex and the laser exhibits extremely low quantum efficiency at room temperature (RT) [1].

In this paper, we report on the development of a new class of diode laser that produces ultra-broad stimulated emission that inherits from the interband transition operation of quasi-zero-dimensional quantum confined heterostructure at near-IR region. Our novel device fabricated in InAs/InGaAlAs quantum-dash-in-well structure exhibits RT lasing wavelength coverage of up to 76 nm at ~1.64 µm from simultaneous multiple confined states lasing. This compact, cost effective and high efficiency broadband diode laser will unfold many new ideas across inter-disciplinary fields in photonics.

Experiments

The self-organized InAs/InAlGaAs QDash device structure was grown by molecular beam epitaxy (MBE) on (100) oriented S-doped InP substrate. The laser structure is a *p-i-n* configuration with the active region consists of four sheets of InAs dashes, each embedded within a 7.6 nm thick compressively-strained $In_{0.64}Ga_{0.16}Al_{0.2}As$ QW and a 30 nm thick tensile-strained $In_{0.50}Ga_{0.32}Al_{0.18}As$ barrier [1]. The surface morphology and device cross-section of InAs QDashes were investigated using an atomic force microscopy (AFM) and the cross sectional transmission electron microscopy (TEM) prepared along [110] and $[1\bar{1}0]$ orientations, respectively. TEM images were taken under the (002) dark field projection that is much more sensitive to chemical composition than to strain, the contrast observed should be dominated by group-III atomic composition contrast. State-filling photoluminescence measurement was performed at cryogenic temperature using a 532 nm diode pumped solid state laser as an excitation source. The optical pumping density is varied by adjusting the circular neutral density filter. Broad area lasers with 50 μm wide oxide stripes were fabricated using the standard semiconductor laser fabrication process. The laser optical cavity is aligned along [110] orientation and is perpendicular to the dash direction to maximize the optical gain. The QDash laser was tested under pulsed operation of 10 μs pulse width and 1 % duty cycle. The optical spectra were acquired using optical spectrum analyzer with wavelength resolution of 0.05 nm.

Results and discussion

Fig. 1(a)-(b) show the plane-view AFM from the uncapped QDash grown on sample surface, and the [110] and $[1\bar{1}0]$ cross-sectional TEM images from the laser structure taken under the (002) dark field projection. The QDash nanostructure consists of three-dimensional finite wire preferentially aligned along the $[1\bar{1}0]$ direction composed of dot-like and dash-like islands, that are formed from the coalescence of two or more dot-like islands. QDash assembly has an average height of 3.2 nm, an average width of 18 nm, and the base or length varied from 20 to 75 nm. The island density is high with area coverage of greater than 70%. Considering the large dispersion in shape, size and composition, the inhomogeneous dash ensemble causes the energy spreading in the confining potentials and a broadening in the optical gain, which is useful for the wideband optical devices such as superluminescent diodes (SLED) [2] and semiconductor optical amplifier (SOA) [3].

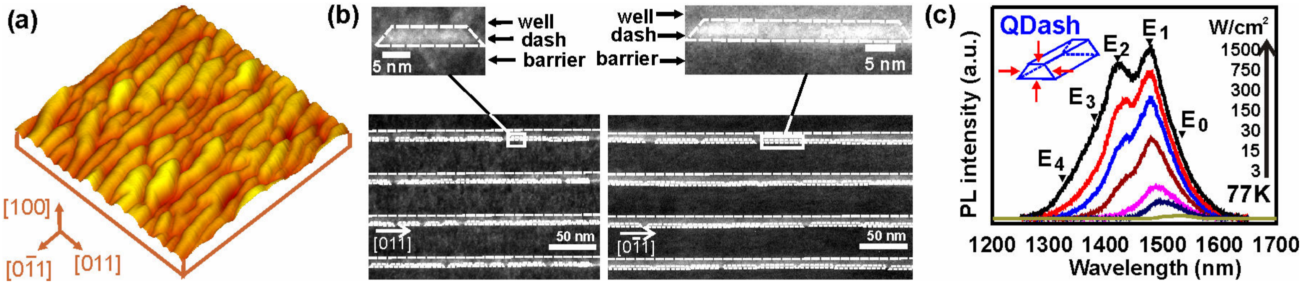

Fig.1. (a) The plane-view AFM image of surface QDash structures (area of 0.5x0.5 μm^2; height contrast of 8 nm); (b) The cross-sectional TEM images of buried QDash laser structures under (002) dark-field taken from different crystal orientations. (c) Optical power dependent PL spectra at 77 K taken from InAs QDashes within InAlGaAs matrix revealing the systematic filling of quantized states. The confined energy subbands are indicated with the arrow.

State-filling PL spectroscopy was performed by varying optical pumping density of laser excitation. As noted from Fig. 1(c), the QDash material exhibits quantized states (E_0 to E_4) with small energy separation, i.e. energy spacing between E_0 and E_1, ΔE, of 30 meV. At highest excitation density (1500 W/cm^2), a large number of minima in QDash spectra are populated, resulting a broad emission line. These properties corroborate the quasi-continuous interband transition characteristics in QDash assembly over a wide wavelength range.

As-cleaved broad area lasers with 50 μm wide oxide stripes were fabricated from the QDash laser using the standard laser fabrication process. Fig. 2(a) depicts the electroluminescence (EL) spectrum of QDash showing fine structures from different confined energy subbands that are well correlated to different lasing peaks with varying cavity length. Up to three distinct laser emissions

(1.65, 1.62, and 1.59 µm) from E_0, E_1 and E_2 energy transitions were obtained at 1.1×J_{th} from lasers with cavities L of 1000, 300, and 150 µm, respectively. The distinct lasing wavelength peak is attributed to the finite modal gain for each quantized state in QDash assembly. Fig. 2(b) shows the light-current (L-I) characteristics of the QDash laser (L = 600 µm). The corresponding threshold current density and slope efficiency are 2.6 kA/cm^2 and 0.165 W/A. Up to 400 mW total output power has been measured at $J = 4.5\times J_{th}$ at 20°C from the device. From the dependence of J_{th} on temperature, the temperature characteristic T_0 of 43.6 K in the range of 10 to 70°C has been obtained. At injection below 1.5 ×J_{th}, there is only ground state lasing E_0 with the wavelength coverage of up to 10 nm [Fig. 2(c)]. The broad E_0 lasing spectrum suggests the collective lasing from QDashes with different geometries. Above 1.5 ×J_{th}, the dual-state lasing occurs. The simultaneous lasing from both E_0 and $E_1$is attributed to the relatively slow carrier relaxation rate and population saturation in the ground state in low-dimensional quantum heterostructures [4]. The transition from mono-state to bi-state lasing is marked with a slight kink in the L-I characteristics. The bi-state lasing spectrum is progressively broadened with increasing carrier injection up to a wavelength coverage of 54 nm at $J = 4.5\times J_{th}$. The corresponding side-mode suppression ratio of lasing spectra is over 25 dB and a ripple measured from the wavelength peak fluctuation within 10 nm span is less than 3 dB.

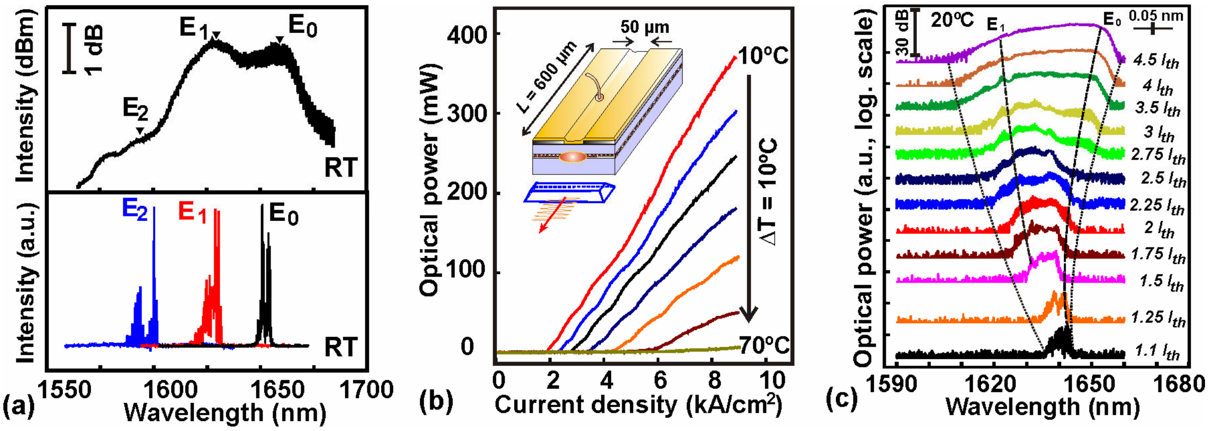

Fig. 2. (a) The spontaneous emission spectrum of QDash laser (L = 300 µm) at 0.8×J_{th} (top) and the lasing spectra at 1.1×J_{th} from QDash laser with varying cavity length. (b) The L-I characteristics of ultrabroadband QDash laser (L = 600 µm) with the cavity orientated perpendicular to the dash direction (inset). (c) The lasing spectra from QDash laser with varying injection current. The lines are as the guide to the eyes indicating the confined state lasing lines, E_0 and E_1 (dashed lines) and the wavelength coverage of laser emission (dotted lines).

Summary

The unprecedented broadband laser emission at RT up to 76 nm wavelength coverage has been demonstrated in the inhomogeneous InAs/InAlGaAs QDash structure. The results suggest that the quasi-one-dimensional QDash material can be utilized as a gain media for the generation of novel broadband semiconductor laser source and amplifier.

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