Extended Abstracts of the 2007 International Conference on Solid State Devices and Materials, Tsukuba, 2007, pp. 100-101

E-1-1 (Invited)

High-Speed Quantum Dot Lasers

P. Bhattacharya and Z. Mi
Solid-State Electronics Laboratory, Department of Electrical Engineering and Computer Science
University of Michigan, Ann Arbor, MI 48109-2122, USA
pkb@eecs.umich.edu

The desirable characteristics of a semiconductor laser required for optical communications and related applications include large modulation bandwidth, uncooled operation, and small chirp and α-parameter. One of the materials of choice is self-organized InAs quantum dots (QDs) grown on GaAs or InP substrates. Conventional QD lasers, however, suffer from hot carrier problems due to the presence of a two-dimensional wetting layer and closely spaced hole energy levels, leading to large temperature dependence of the threshold current and small modulation bandwidth. Special techniques, such as p-doping and tunnel injection, have been demonstrated to be very effective in alleviating these problems to a large extent [1-3]. In the scheme of tunnel injection, cold carriers are directly injected into the lasing ground states of QDs by phonon assisted tunneling from the injector well, leading to minimized hot carrier effects and greatly increased differential gain and modulation bandwidth. P-doping, on the hand, provides excess holes in the dots. Deleterious effects, such as carrier spreading and gain compression due to thermally broadened hole distributions, can be largely eliminated. The effectiveness of these special techniques, as well as the performance of InAs QD lasers are, ultimately, strongly influenced by the quality and spectral broadening of the dots. In this context, we present a thorough study of the growth and characteristics of p-doped and tunnel injection QD lasers with operation wavelength λ ranging from 1.0 to 1.7 μm on GaAs, InP, and Si. The lasers exhibit nearly ideal characteristics, such as ultralow threshold current (~ 60 A/cm^2), temperature invariant operation ($T_0 \approx \infty$), large modulation bandwidth (f_{-3dB} = 24.5 GHz), and near-zero α-parameter and very low chirp (~ 0.1 Å).

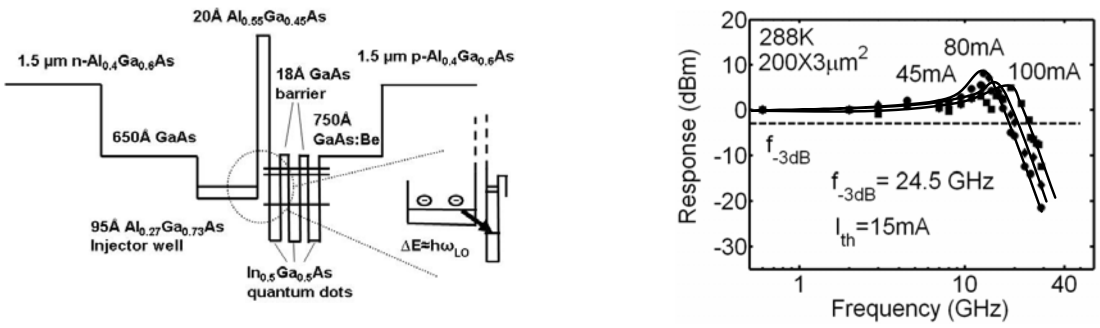
The active region of the 1.1 μm $In_{0.5}Ga_{0.5}As$ tunnel injection QD lasers consists of a 95 Å $In_{0.27}Ga_{0.73}As$ injector well, a 20 Å $Al_{0.55}Ga_{0.45}As$ tunnel barrier, and three coupled $In_{0.50}Ga_{0.50}As$ QD layers, as illustrated in Fig. 1(a). The growth conditions and parameters of both the injector well and QD layers are carefully controlled so that the ground state of the injector well is approximately one phonon energy (~ 36 meV) above the lasing ground state of the QDs, allowing efficient LO phonon-assisted tunneling to take place from the injector layer to the dots. We measure a maximum 3-dB bandwidth of ~ 25GHz (Fig. 1(b)) in the 1.1 tunnel injection lasers. These devices exhibit low threshold current and large T_0 (upto ∞). The variation of of threshold current with temperature of the 1.3 μm lasers are shown in Fig. 2(a). Near-zero α-parameter and negligible chirp (~ 0.1 Å) are also measured in both 1.1 and 1.3 μm tunnel injection QD lasers, as shown in Fig. 2(b) and (c). The derived *dg/dn* are 2.7×10^{-14} and 9.8×10^{-15} cm^2 for the 1.1 and 1.3 μm lasers, respectively.

To extend the emission wavelength of InAs QD lasers on GaAs to 1.55 μm, metamorphic QD heterostructures have to be used, due to the large strain. By detailed investigation of the growth kinetics, we have achieved nearly dislocation-free $In_{0.15}Ga_{0.85}As/In_{0.15}Al_{0.35}Ga_{0.50}As$ metamorphic QD laser heterostructures (Fig. 2(a)) that exhibit intense and narrow (linewidth ~ 30 meV) photoluminescence emission at 300 K, comparable to state-of-the-art pseudomorphic 1.3 μm InAs QDs. We have demonstragted 1.45 μm p-doped and tunnel injection QD lasers that exhibit, for the first time, ultra-low threshold current (J_{th} = 63 A/cm^2, *a reduction by a factor of more than 10*, compared to previous reports) (Fig. 2(b)), nearly temperature invariant operation (T_0 = 620 K), large modulation frequency response (f_{-3dB} = 8 GHz), and near-zero chirp and α-parameter. Utilizing step-graded InGaAs meatmorphic buffer layers, we have also achieved 1.52 μm InAs meatmorphic QD lasers that exibit relatively low threshold current (J_{th}=460A/cm^2) (Fig. 2(c)).

Additionally, we have studied the growth and characteristics high performance 1.65 μm InAs quantum dash lasers grown on InP (001). Significantly improved photoluminescence intensity and narrow linewidth (~ 50 meV) are measured from stacked InAs quantum dash layers with optimized growth conditions. The p-doped tunnel injection quantum dash lasers exhibit very large T_0 (204 K), large modulation bandwidth (f_{-3dB} = 12 GHz), near-zero α-parameter, and very low chirp (~ 0.3 Å).

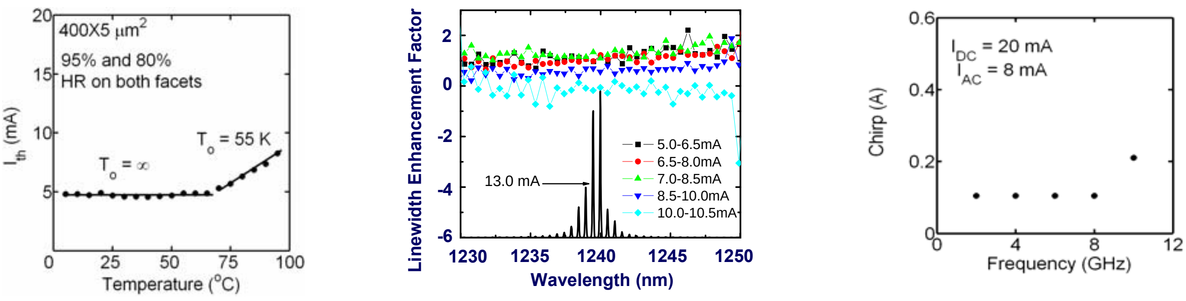
We have also performed detailed analysis of the DC and dynamic characteristics of p-doped and tunnel injection quantum dot/dash lasers. The role of p-doping and tunnel injection in enhancing the performance of QD lasers is examined. These results, together with our recent work on high performance QD lasers monolithically grown on Si, will also be presented.

[1] P. Bhattacharya, S. Ghosh, S. Pradhan, J. Singh, Z.-K. Wu, et al., *IEEE J. Quantum Electron*. **39,** 952 (2003).
[2] O. B. Shchekin and D. G. Deppe, *IEEE Photon. Tech. Lett*., **14**, 1231 (2002).
[3] S. Fathpour, Z. Mi, and P. Bhattacharya, *J. Physics D*: *Applied Physics*, **38**, 2103 (2005).



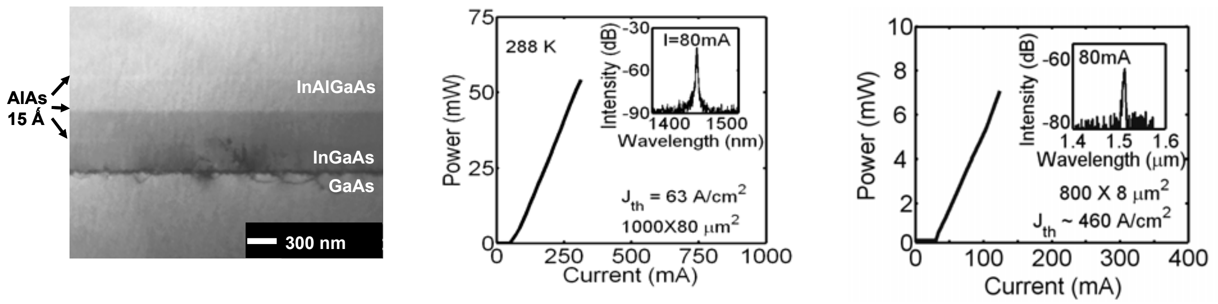
(a) (b)

Fig. 1. (a) Conduction band diagram of 1.1 µm p-doped quantum dot tunnel injection laser and (b) measured small-signal modulation response of 1.1 µm tunnel injection quantum dot laser.



(a) (b) (c)

Fig. 2. Characteristics of 1.3 µm tunnel injection quantum dot lasers: (a) variation of threshold current with temperature, (b) measured α-factor under subthreshold bias conditions, and (c) measured chirp as a function of frequency.



(a) (b) (c)

Fig. 3. (a) Cross-sectional transmission electron microscopy image of the InGaAs metamorphic buffer layer and InAlGaAs lower cladding layer of the laser heterostructure grown on GaAs, (b) light-current characteristics of 1.45 µm InAs metamorphic quantum dot lasers, and (c) light-current characteristics of step-graded 1.52 µm InAs meatmorphic quantum dot lasers.