Growth and characteristics of ultralow threshold 1.45 μm metamorphic InAs tunnel injection quantum dot lasers on GaAs

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(Received 12 June 2006; accepted 22 August 2006; published online 10 October 2006)

The molecular beam epitaxial growth and characteristics of 1.45 μm metamorphic InAs quantum dot tunnel injection lasers on GaAs have been studied. Under optimized growth conditions, the quantum dots exhibit photoluminescence linewidths ~30 meV and high intensity at room temperature. The lasers are characterized by ultralow threshold current (63 A/cm²), large frequency response (f_{−3 dB}=8 GHz), and near-zero α parameter and chirp. © 2006 American Institute of Physics. [DOI: 10.1063/1.2358847]

Low threshold current (I_{th}), high speed, and zero chirp semiconductor lasers with operation wavelength λ ~ 1.55 μm are in demand for long-haul optical communication systems. The conventional workhorse has been InGaAsP/InP double heterostructure or multi-quantum-well lasers, but these devices characterized have high I_{th}, small T_{λo} (40–50 K), small T_{λ}, and large values of chirp (≥2 Å) and α factor. Some of these attributes result from the low gain and differential gain in the quaternary active region. Alternate material systems, including GaInNAs(Sb) quantum well and InAs/GaAs quantum dots (QDs), have been investigated for long wavelength lasers. GaInNAs(Sb) quantum well lasers, however, do not offer significant advantages in performance, compared to conventional InGaAsP based lasers, other than the use of GaAs substrates. In addition, the presence of miscibility gaps in the alloy system is a distinct shortcoming. The other alternative is the use of In(Ga)As/GaAs QDs as the gain material. Owing to three-dimensional quantum confinement, extraordinary performance, including low I_{th}, T_{λo}≈, α→0, chirp <1 Å, and f_{−3 dB}=12 GHz, has been demonstrated in 1.3 μm pseudo-morphic InAs QD lasers. The development of 1.55 μm InAs QD lasers on GaAs, wherein metamorphic QD heterostructures have to be used due to the large strain, however, has not been so optimistic. The laser heterostructures exhibit poor luminescence of the QDs, with linewidth ≥70 meV, and the devices have very high threshold current (I_{th} ~1000 A/cm²). Furthermore, no data on chirp and α parameter are available.

The performance of current 1.5 μm QD lasers is limited by the quality of the metamorphic QD heterostructure. Over the years, various techniques, including low temperature growth, high temperature annealing, and different composition grading schemes in InGa(Al)As and AlGaAsSb buffer layers, have been explored to reduce dislocation densities in metamorphic epitaxial layers. However, the achievement of truly dislocation-free metamorphic heterostructures has remained elusive. This has been largely limited by the complexity that arises in optimizing the growth conditions during a number of critical growth/annealing steps. The growth of high quality QDs buried in a metamorphic heterostructure has also proven to be difficult, due to the complicated surface diffusion kinetics at a metamorphic InGa(Al)As growth front. In addition, QD lasers suffer from hot-carrier related problems. At room temperature, injected electrons predominantly reside in the wetting layer and barrier states due to the much larger number of available states therein, and the system cannot be described by quasi-Fermi statistics. As a result, severe gain saturation occurs at the QD ground-state lasing energy.

With the objective of realizing high performance 1.5 μm QD lasers on GaAs, we have investigated the growth kinetics and characteristics of metamorphic InAs quantum dots on GaAs. We have also incorporated the tunnel injection scheme in the laser active region. This carrier injection scheme has proven to be highly effective, and essential, in the design of high performance QD lasers emitting at 1.1 and 1.3 μm. In the scheme of tunnel injection, “cold” electrons are directly injected to the ground state of the quantum dots from the InGaAs injector well, and so they do not heat other carriers and phonons as much. As a result, we have realized high quality InAs QDs on GaAs that are comparable, in both photoluminescence (PL) intensity and linewidth (~30 meV), to state-of-the-art 1.1 and 1.3 μm InAs pseudomorphic QDs. 1.45 μm tunnel injection lasers made with these heterostructures exhibit ultralow I_{th} (63 A/cm²—a reduction by a factor of more than 10, compared to previous reports), large modulation frequency response (f_{−3 dB}=8 GHz), and near-zero α parameter and chirp, and present a practical alternative to InGaAsP/InP and other heterostructure technologies.

The In_{0.15}Ga_{0.85}As/In_{0.15}Al_{0.35}Ga_{0.5}As separate confinement heterostructure InAs tunnel injection QD lasers, as illustrated in Fig. 1(a), were grown on n^+-GaAs (001) substrates in a Veeco Gen II molecular beam epitaxy system. The n- and p-cladding layers consist of 1.5 μm In_{0.15}Al_{0.35}Ga_{0.5}As layers doped with Si and Be, respectively. After oxide desorption from the substrate surface, a 0.5 μm GaAs buffer layer is first grown at 600 °C. The substrate temperature is then reduced to ~390 °C, and a 0.6 μm Si-doped In_{0.15}Ga_{0.85}As buffer layer is grown. The low growth temperature can greatly suppress the propagation of misfit dislocations. In addition, multiple steps of thermal annealing were utilized to further reduce defect densities. Thermal annealing has been widely used to restore the crys-

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tional quality of damaged materials or materials grown on highly mismatched substrates. The presence of point defects can be largely eliminated during the annealing. After the growth of every 0.3 µm of the In0.15Ga0.85As layer, a thermal annealing step is performed. Before the annealing, a thin (∼15 Å) AlAs layer was grown at 390 °C as a protective layer to avoid any potential indium desorption. The substrate temperature is then raised to ∼700 °C and annealed under an arsenic flux for 10 min. An in situ thermal annealing is also performed after the growth of each QD layer, an additional 50 Å In0.33Ga0.67As layer, which are grown at an estimated from the InAs QD layer by a 20 Å GaAs tunnel barrier.

The PL emission of the injector well is carefully tuned to approximately one phonon energy above the first excited states in the dots. The measured room temperature PL spectrum of the metamorphic InAs tunnel injection QD laser heterostructure was shown in Fig. 1. The PL emission peaks from the injector well and quantum dot layers are identified. The metamorphic InAs QDs exhibit intense PL emission with narrow linewidth (∼30 meV), which is comparable to state-of-the-art 1.3 µm pseudomorphic InAs QDs.

The surface of the laser heterostructures grown under optimized conditions is specular and exhibits a faint cross hatch pattern, free of any microstructural roughness or stacking faults. The metamorphic QD laser heterostructure was characterized by cross-sectional transmission electron microscopy. Misfit dislocations are largely confined at the In0.15Ga0.85As/GaAs interface, as shown in Fig. 2. Pinning of dislocations at the thin AlAs layer, where an in situ anneal was performed, is also evident in Fig. 2.

Both broad area (500–2000 µm long and 40–100 µm wide) and ridge waveguide lasers (500–2000 µm long and 3–8 µm wide) were fabricated using standard photolithography, wet and dry etchings, and contact metallization techniques. The facets of the processed laser bars are also coated with high reflectivity MgF2/ZnSe Bragg reflectors to minimize mirror loss. Light-current (L-I) measurements were performed under pulsed mode operation (1% duty cycle) at various temperatures. An ultralow threshold current of 63 A/cm² is measured from a 1000 × 80 µm² device with 95% and 80% high reflectivity coatings on both facets, as shown in Fig. 3. The laser output peak occurs at ∼1.45 µm at room temperature. From the L-I characteristics of various cavity lengths, we also derive an internal quantum efficiency η of 72% and cavity loss γ of 2.8 cm⁻¹.

Measurement of the dynamic characteristics was made on 600 × 3 µm² ridge waveguide devices under pulsed mode operation (1% duty cycle). The devices are coated with 95% and 80% high reflectivity MgF2/ZnSe Bragg reflectors on both facets. The small-signal modulation characteristics were measured at various injection currents, as shown in Fig. 4(a). These devices exhibit a maximum 3 dB bandwidth of 8 GHz at an injection current of 55 mA, suggesting that metamorphic QD lasers are suitable for 10 Gbits/s operation. The modulation efficiency is ∼1.06 GHz/mA¹⁄². The linewidth enhancement factor (α parameter) was measured by the Hakki-Paoli method under subthreshold bias conditions. The subthreshold spectra were measured with an HP 70952B optical spectrum analyzer at 300 K. The voltage increment was kept below 0.1 V. The measured linewidth enhancement factors are near zero, as shown in Fig. 4(b). It is important to note that the measured α parameter under sub-
threshold bias conditions can be very different from that at high bias conditions for a QD laser, due to carrier occupation of wetting layer and barrier states. In tunnel injection QD lasers, however, the $\alpha$ parameter is expected to be weakly dependent on injection currents, due to the injection of cold electrons directly into the lasing quantum dots. Therefore, the $\alpha$ parameter above threshold current in tunnel injection QD lasers is expected to be close to that measured under subthreshold bias conditions. The chirp in the metamorphic QD lasers was determined by measuring the broadening of a single longitudinal mode using an optical spectrum analyzer. The sinusoidal modulation current was superimposed on the pulsed dc bias current above threshold. The envelope of the dynamic shift in the wavelength was recorded and the difference between the half-width of the observed envelope with and without modulation was used to evaluate the chirp. The measurements were done as a function of the frequency of the modulating current. The measured chirp is $\sim$0.1 Å and is plotted as a function of frequency in Fig. 4(c). The near-zero chirp and $\alpha$ parameters in these devices are attributed to the reduction in hot-carrier effects due to tunnel injection.

In summary, we have demonstrated that long wavelength metamorphic InAs QD lasers on GaAs substrates, with optimization of the growth conditions and the incorporation of tunnel injection, can offer distinct performance advantages over other long wavelength lasers, such as pseudomorphic InGaAsP and GaInNAs(Sb) QW lasers.

This work is being supported by the Army Research Office under Grant No. W911NF-04-1-0229 and by the Center for Optoelectronic Nanostructures Semiconductor Technologies, a DARPA UPR award, under Contract No. HR0011-04-1-0040.