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

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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/cm^2), large frequency response ($f_{-3\text{ dB}}$=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 $\lambda \sim 1.55$ 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 characteristically have high I_{th}, small T_0 (40–50 K), small T_1, and large values of chirp ($\geqslant$2 Å) and α factor.[1,2] 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.[3,4] In addition, the presence of miscibility gaps in the alloy system is a distinct shortcoming.[5] 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}, $T_0=\infty$, $\alpha \rightarrow 0$, chirp <1 Å, and $f_{-3\text{ dB}}$=12 GHz, has been demonstrated in 1.3 μm *pseudomorphic* InAs QD lasers.[6–8] 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 $\geqslant$70 meV, and the devices have very high threshold current ($J_{th} \sim 1000$ A/cm^2).[9] 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.[10–17] 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.[18] 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.[7,19] 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.[20] 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 J_{th} (63 A/cm^2—a reduction by a factor of more than 10, compared to previous reports),[9] large modulation frequency response ($f_{-3\text{ dB}}$ =8 GHz), and near-zero α parameter and chirp, and present a practical alternative to InGaAsP/InP and other heterostructure technologies.

The $In_{0.15}Ga_{0.85}As/In_{0.15}Al_{0.35}Ga_{0.50}As$ 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 $In_{0.15}Al_{0.35}Ga_{0.50}As$ 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.[10,14] 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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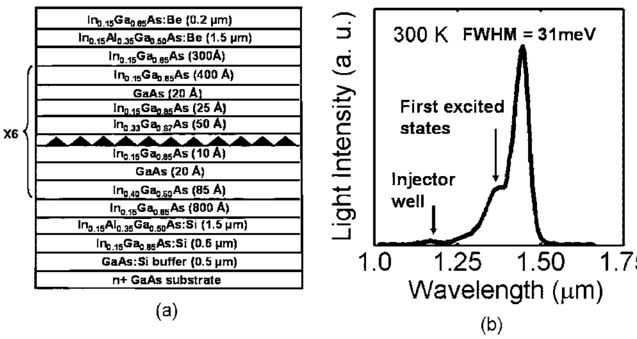

FIG. 1. (a) Metamorphic InAs tunnel injection quantum dot laser heterostructures grown on GaAs by molecular beam epitaxy and (b) photoluminescence spectra from the active region measured at 300 K.

tal quality of damaged materials or materials grown on highly mismatched substrates.[16,17] The presence of point defects can be largely eliminated during the annealing. After the growth of every 0.3 μm of the $In_{0.15}Ga_{0.85}As$ 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 0.3 μm of the $In_{0.15}Al_{0.35}Ga_{0.50}As$:Si cladding layer to eliminate any residual dislocations.

The growth conditions of the InAs QD layers and their surrounding InGaAs barrier layers are also optimized. Each InAs QD layer consists of 2.9 ML of InAs capped by an additional 50 Å $In_{0.33}Ga_{0.67}As$ layer, which are grown at an optimum temperature of 530 °C. To smoothen the growth front and avoid phase separation, thin (~20 Å) GaAs layers were grown before and after each InAs QD layer. Following the growth of each QD layer, an *in situ* anneal at 600 °C is performed, which helps in reducing any surface undulations, and therefore allows the growth of multiple layers of defect-free QDs.[21] The device active regions consist of six stacks of coupled well and dot tunnel heterostructures, separated by ~450 Å $In_{0.15}Ga_{0.85}As$ barrier layers. In each period, an 85 Å $In_{0.4}Ga_{0.6}As$ injector well is first grown, which is separated from the InAs QD layer by a 20 Å GaAs tunnel barrier. The PL emission of the injector well is carefully tuned to ~1.17 μm so that the electron ground state in the well is approximately one phonon energy above the first excited states in the dots. The measured room temperature PL spectra of the metamorphic InAs tunnel injection QD laser heterostructures are shown in Fig. 1(b), where 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.[7,8]

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 $In_{0.15}Ga_{0.85}As$/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.

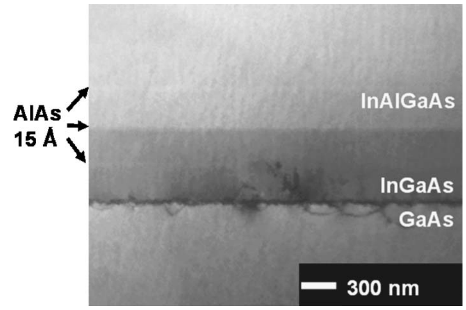

FIG. 2. Cross-sectional transmission electron microscopy image of the InGaAs metamorphic buffer layer and InAlGaAs lower cladding layer of the laser heterostructure grown on GaAs.

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 MgF_2/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/cm^2 is measured from a 1000×80 μm^2 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_i of 72% and cavity loss γ of 2.8 cm^{-1}.

Measurement of the dynamic characteristics was made on 600×3 μm^2 ridge waveguide devices under pulsed mode operation (1% duty cycle). The devices are coated with ~95% and 80% high reflectivity MgF_2/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 $GHz/mA^{1/2}$. 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-

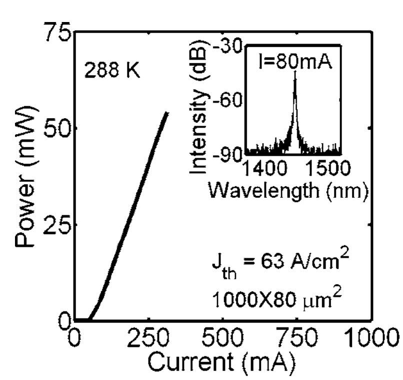

FIG. 3. Light-current characteristics and output spectrum (inset) of a broad area metamorphic InAs tunnel injection quantum dot laser under pulsed mode (1% duty cycle) operation.

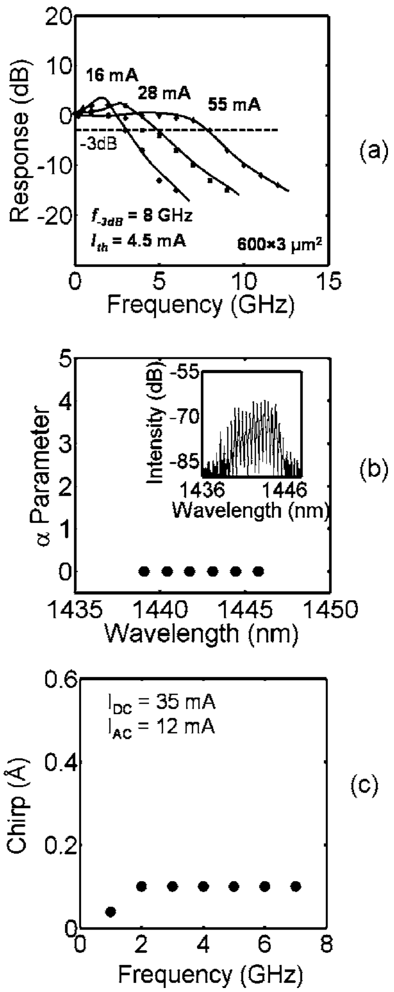

FIG. 4. Dynamic characteristics of metamorphic tunnel injection quantum dot lasers under pulsed mode (1% duty cycle) operation: (a) small-signal modulation response, (b) linewidth enhancement factor with subthreshold spectrum (inset), and (c) wavelength chirp as a function of frequency.

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.[22] In tunnel injection QD lasers, however, the α 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 α 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 α 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.

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