Applied Physics Letters

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Citation: Appl. Phys. Lett. **98**, 011103 (2011); doi: 10.1063/1.3535607
View online: http://dx.doi.org/10.1063/1.3535607
View Table of Contents: http://apl.aip.org/resource/1/APPLAB/v98/i1
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# Characteristics of a high speed 1.22 $\mu$m tunnel injection p-doped quantum dot excited state laser

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(Received 8 November 2010; accepted 15 December 2010; published online 4 January 2011)

The measured characteristics of excited state lasing in tunnel injection p-doped InAs quantum dot lasers are reported. Excited state lasing at 1.22 $\mu$m is ensured by a high-reflectivity facet coating which is designed to suppress ground state lasing in the devices. The saturation modal gain in the excited states is 56 $cm^{-1}$, which is a factor of ~2.5 higher than that of the ground state. The small-signal modulation bandwidth for $I=4.5I_{th}$ is 13.5 GHz and the differential gain is $1.1 \times 10^{-15}$ $cm^2$. © *2011 American Institute of Physics*. [doi:10.1063/1.3535607]

A general problem with long wavelength lasers is that the gain and differential gain tend to be lower than those in shorter wavelength (e.g., 0.8–1.0 $\mu$m) lasers.[1,2] One of the consequences of this is a lower small-signal modulation bandwidth.[3] Self-organized quantum dots (QDs) which emit at 1.3 $\mu$m have larger size and smaller aerial density than those which emit at 1.0 $\mu$m. As a result, their gain is smaller.[1,2] Furthermore, the optical matrix element of InAs QDs, typically used in 1.3 $\mu$m lasers, is ~30% smaller than the matrix element of $In_{0.4}Ga_{0.6}As$ QDs incorporated in 1.0 $\mu$m lasers.[2] Consequently, a small-signal modulation bandwidth of ~25 GHz has been measured indirectly modulated in 1.0 $\mu$m QD lasers,[1] while the measured bandwidth of 1.3 $\mu$m QD lasers is considerably smaller (3–12 GHz).[1–6]

Nearly all quantum dot lasers that have been experimentally demonstrated, and are in use, emit light resulting from ground state transitions in the quantum dots. Because of the symmetry of the quantum dot geometry, the excited state (ES) level in each dot has a twofold degeneracy.[7] It has been shown theoretically that a 1.3 $\mu$m QD laser with emission resulting from ES transitions can have a larger modulation bandwidth, compared to that from ground state (GS) lasing.[6,8,9] Some reports on excited state lasing from QDs have been made.[6] In the present study, we have investigated the design, fabrication, and characterization of high-performance lasers in which lasing occurs as a result of excited state $e_1$-$hh_1$ transitions and electrons are transported to the excited state by LO phonon-assisted tunnel injection.[5] The peak wavelength of ES lasing is 1.22 $\mu$m. A high differential gain of $1.1 \times 10^{-15}$ $cm^2$ and a small-signal modulation bandwidth of 13.5 GHz have been measured.

The QD laser heterostructure grown by molecular beam epitaxy on (001)-Si-doped GaAs substrate is shown in Fig. 1(a). One period of the QD tunnel heterostructure is shown in the inset. The thickness of these layers is first estimated from a calculation of the QD bound states using an eight-band $\boldsymbol{k}\cdot\boldsymbol{p}$ model (with the strain described by the valence force field model),[10–12] and then the heterostructure design is fine tuned using photoluminescence measurements as a feedback. The quantum dots are modulation doped p-type at a level of $5 \times 10^{17}$ $cm^{-3}$, which corresponds to ~12 acceptors per QD, to maximize the differential gain.[2,13] The active region consists of seven QD layers with tunnel barriers and 50 nm GaAs spacer layers between them. The thin $In_{0.15}Ga_{0.85}As$ layers, which form the matrix in which the dots are immersed, also serve as strain engineering layers to tune the output emission peak wavelength.

Fabrication of ridge waveguide lasers was accomplished by standard photolithography, dry etching, and Ohmic contact metallization techniques. The ridge width is 3 $\mu$m and the length, obtained by cleaving, varies from 480 to 2600 $\mu$m. One facet of the laser, with 480 $\mu$m cavity length, was coated with a high-reflectivity distributed Bragg reflector (DBR) mirror consisting of six pairs of $ZnSe/MgF_2$ layers. The simulated reflectivity spectrum is shown in Fig. 1(b). The center of the pass band of the DBR is tuned to 991 nm, such that 1.224 $\mu$m (ES) and 1.3 $\mu$m (GS) reflectivities are 91% and 45%, respectively. These emission wavelengths correspond to the peaks of the ES and GS emission in the measured room temperature photoluminescence spectrum, also shown in Fig. 1(b). It should be noted that the linewidth of the GS emission wavelength is only 27 meV due to the filtering action in the presence of the tunnel heterostructure, which injects electrons in QDs with a more homogeneous size distribution.[14] Typically, the full width at half maximum (FWHM) of In(Ga)As/GaAs QD is in the range of 40–60 meV, in structures which do not incorporate tunnel injection.

The steady state characteristics of the lasers were measured under pulsed bias condition (4 $\mu$s pulse width, 500 Hz repetition rate). The lasing emission spectrum for $I = 38$ mA is shown in the inset of Fig. 2. The peak is observed at $\lambda \cong 1.22$ $\mu$m. The light-current characteristics for the laser with cavity length of 480 $\mu$m and with facet coating are shown in Fig. 2. The threshold current density and external quantum efficiency for emission from one facet are 2.6 $K A/cm^2$ and 46%, respectively. The relatively high value of the threshold current is attributed to two factors: p-doping of the dots which enhances the rate of nonradiative Auger recombination,[15] and the required occupation of the ground states before the excited states can be filled. A plot of the inverse external quantum efficiency $\eta_d$ versus cavity length, obtained from the measurements, is shown in Fig. 3(a). Lasing is observed from the ground state for devices with larger values of cavity length and the data of Fig. 3(a)

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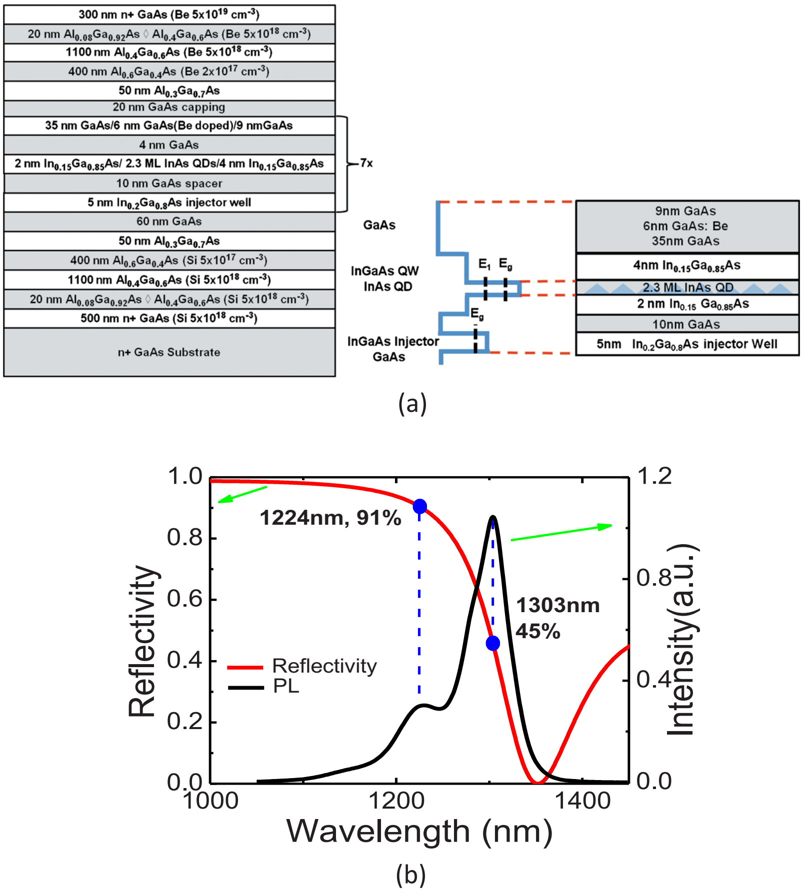


FIG. 1. (Color online) (a) Heterostructure of quantum dot laser grown by MBE. The inset shows the detailed description of one dot layer period in the active region; (b) measured photoluminescence of the laser heterostructure and calculated reflectivity of the $MgF_2/ZnSe$ high-reflectivity coating showing the reflectivity at the excited state (91%) and at the ground state (45%).

can be analyzed with the equation $1/\eta_d = (1/\eta_i)[1 + \alpha_i L_c/\ln(1/R)]$, where $\eta_i$ is the internal quantum efficiency, $\alpha_i$ is the cavity loss, and $\alpha_m$ is the mirror loss. Values of $\eta_i$ and $\alpha_i$ equal to 80% and 1.9 $cm^{-1}$, respectively, are obtained for ground state lasing from the fit to the data. For shorter cavity lengths, lasing takes place at $\lambda = 1.22$ $\mu m$ from the excited states. The measured values of $\eta_d$ decrease sharply, and the values of $1/\eta_d$ versus L do not follow the trend dictated by this equation. In short-cavity lasers the mirror loss increases, more carriers are required to provide optical gain, and $\alpha_i$ also increases due to increases in free carrier absorption. Consequently, the threshold gain also increases and $\alpha_i$ will be a function of cavity length.[16] The inset of Fig. 3(a) depicts plots of threshold modal gain $(\alpha_i + \alpha_m)$ versus threshold current density for GS and ES lasing, obtained from measurements on lasers with different cavity lengths.

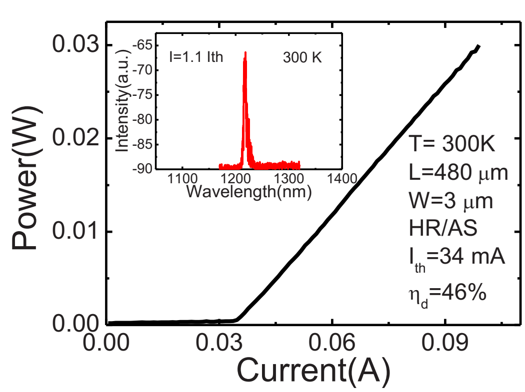


FIG. 2. (Color online) Light-current (L-I) characteristics for excited state lasing of QD laser. The inset shows the lasing spectrum at 300 K.

As mentioned earlier, $\alpha_i$ is constant for ground state lasing. For excited state lasing $\alpha_i$ is calculated for each cavity length, using the above equation, where $\eta_i$ is replaced with $\eta_i^*$, which is calculated following the method outlined in Zhukov *et al.*[17] and is found to be 78%. The data are fitted to the empirical relation $g_{mod} = g_{sat}\{1 - \exp[-\gamma(J_{th} - J_{tr})/J_{tr}]\}$,[18] plotted as the solid curves in the inset of Fig. 3(a) where $g_{mod}$ is the modal gain, $g_{sat}$ is the saturation modal gain, $J_{tr}$ is the transparency current density, and $\gamma$ is a nonideality factor. The values of $g_{sat}$ for GS and ES lasing are 22 and 56 $cm^{-1}$, respectively. The ratio of the two values is ~2.5, which is well within the range of 2–3.[7,18] The gain per dot layer is 8 $cm^{-1}$. Similarly, the value of $J_{tr}$ for the excited state is nearly a factor of 2 larger than that of the ground state. The differential gain is calculated for lasers of different cavity lengths and an average value of $1.1 \times 10^{-15}$ $cm^2$ is obtained, assuming $\tau = 0.5$ ns in the excited state for quantum dots with p-doping.[19] This is larger than that in comparable quantum well lasers ($\sim 4.5 \times 10^{-18}$ $cm^2$) (Ref. 20) and in quantum dot lasers ($4.3 \times 10^{-16}$ $cm^2$) emitting from the ground state.[21]

Small-signal modulation measurements were made with the laser with high-reflectivity facet coating and cavity length of 480 $\mu m$ under pulsed biasing condition.[1] The modulation-response characteristics for different levels of injection are shown in Fig. 3(b). Excited state lasing at ~1.22 $\mu m$ is confirmed for all the injection currents. A modulation bandwidth $f_{-3\ dB} = 13.5$ GHz is measured for $I = 4.5\ I_{th}$. This suggests that a similar device could be used for 20 Gbps data transmission with a bit error rate of $< 10^{-11}$. The measured bandwidth is larger than those previously reported for 1.3 $\mu m$ QD lasers with emission from the ground

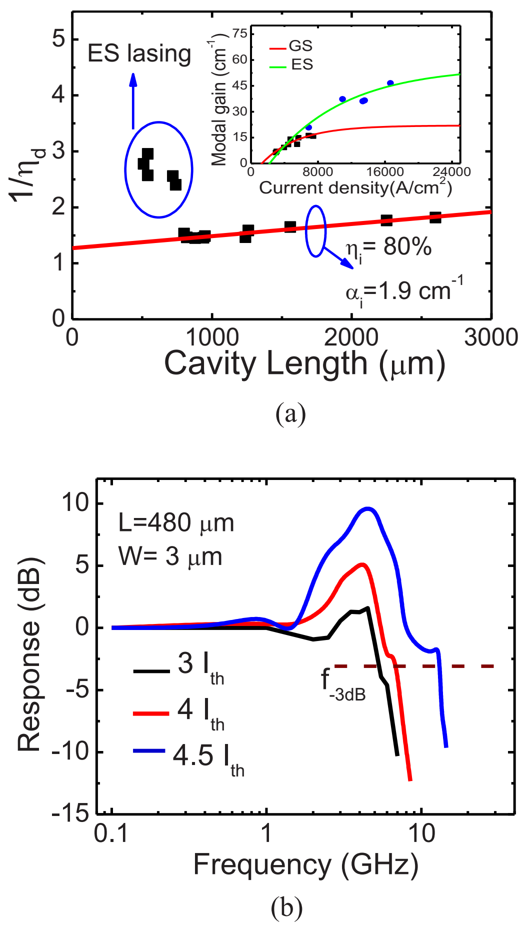


FIG. 3. (Color online) (a) Cavity length dependence of inverse external quantum efficiency. The inset shows modal gain vs current density from which a ground state modal gain of 22 cm$^{-1}$ and an excited state modal gain of 56 cm$^{-1}$ are derived; (b) measured small-signal modulation response for excited state lasing. A maximum modulation bandwidth ($f_{-3\ dB}$) of 13.5 GHz is measured.

state.[1–6] The larger modulation bandwidth in the present devices results from the enhanced saturation modal gain in the excited states and due to the incorporation of tunnel injection.[5] The modulation bandwidth for ES lasing has been calculated as a function of $\tau_{21}$, the ES-GS carrier relaxation time, and QD size fluctuation.[8] We have measured $\tau_{21}$ $\sim$1 ps by differential transmission spectroscopy in $In_{0.6}Ga_{0.4}As/GaAs$ QDs.[14] The size fluctuation of the 1.3 $\mu$m QDs in our laboratory is estimated to be $\sim$15%. For these values of the two parameters, our measured bandwidths are in excellent agreement with the calculated data. The reported modulation bandwidth in an ES 1.3 $\mu$m laser without tunnel injection is $\sim$7 GHz.[6] We believe the improvement in the present case results from tunnel injection. Finally, a comment is made regarding the peak of the modulation response. It is observed that with increase of injection current, the peak moves to higher frequencies, as expected, but the peak value is enhanced and so is the width. The characteristics are similar to those observed by Stevens *et al.*[6] Interdot coupling in the same dot layer, which will cause level splitting in the same dot layer, is more efficient among the QD excited states.[22] Together, with the inhomogeneous broadening due to size fluctuation and the twofold degeneracy, there will be an efficient dynamic redistribution of carriers among dots with increasing injection. This can effectively broaden the width of the resonance and can also reduce gain compression effects.

This work is supported by a grant from Intel Corporation, Hillsboro, OR.

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