Small-signal modulation and differential gain of single-mode self-organized $In_{0.4}Ga_{0.6}As/GaAs$ quantum dot lasers

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We report small-signal modulation bandwidth and differential gain measurements of a single-layer self-organized $In_{0.4}Ga_{0.6}As/GaAs$ quantum dot laser grown by molecular beam epitaxy. The 3 dB bandwidth of single-mode ridge waveguide lasers was measured to be 7.5 GHz at 100 mA under pulsed measurements, demonstrating the possibility of high speed operation of these devices. The differential gain was measured to be 1.7×10^{-14} cm^2. © *1997 American Institute of Physics.* [S0003-6951(97)03222-1]

The use of quantum dots as the gain medium of semiconductor lasers has received much attention due to the singular density of states in the lower dimensional quantum confined structure. This in turn, promises large differential gain, low threshold current, and a very weak temperature dependence of the threshold current (large T_0).[1–3] Self-organized growth[4–6] has proven to be very successful in realizing a highly ordered array of InGaAs/GaAs quantum dots.[7,8] With this technique it is possible to produce defect free, highly uniform pyramidal quantum dots through strained layer epitaxy. Room-temperature operation of InGaAs/GaAs (Refs. 9 and 10) and InAs/GaAs (Refs. 11 and 12) single and multilayer quantum dot lasers has recently been demonstrated by us and other authors. All of the characteristics of these devices, investigated until now, relate to their dc operation. For future applications it is of immense interest to understand their dynamic properties and characterize their small and large signal modulation response.

From time resolved photoluminescence measurements we have recently confirmed that the spontaneous recombination times of excited carriers in the ground and higher order confined states of $In_{0.4}Ga_{0.6}As/GaAs$ quantum dots are 2.5 ns and 250 ps, respectively.[9,13] The former time is in good agreement with previously reported data.[11] The relatively fast relaxation from the excited state, through which lasing occurs in single layer pyramidal dots, promises reasonable small signal modulation bandwidths. We have therefore measured the small signal modulation response of single-mode ridge waveguide quantum dot (single layer) lasers. Analysis of the small signal modulation response of a laser provides a convenient and direct technique to obtain the differential gain dg/dn. We have, therefore, measured this parameter as well.

Separate confinement heterostructure (SCH) lasers, shown in the inset of Fig. 1, were grown by molecular beam epitaxy (MBE). Details of the growth parameters have been previously reported by us.[9,13] The structure consists of an $Al_{0.3}Ga_{0.7}As$ outer clad, GaAs inner clad, and a single layer of $In_{0.4}Ga_{0.6}As$ self-organized quantum dots as the active region. The nominal thickness of the $In_{0.4}Ga_{0.6}As$ layer was 10 ML. Observation of the reflection high energy electron diffraction (RHEED) spectra *in situ* indicate that the wetting layer is 8 ML. Single-mode ridge waveguide lasers with dimensions of 3 μm$\times$600 μm were made by photolithography, contact metallization, and a combination of wet and dry etching. The contact geometry was arranged in a ground signal–ground configuration to facilitate probing with high frequency probes. Cross-sectional transmission electron microscopy (XTEM) of the heterostructures show that the quantum dots are pyramidal in shape with a base length of ~20 nm and a height ~6 nm. Lasing in these devices occurs at $\lambda \cong 1.0$ μm through transitions involving excited electron and hole states.[9,13] It may also be noted that the wetting layer transition is at ~0.92 μm. Light–current characteristics of the single-mode lasers are shown in Fig. 1.

The small signal modulation response of the single-mode lasers was measured using a Hewlett-Packard 8350B sweep oscillator, low noise amplifier, New Focus high speed detector, and a Hewlett-Packard 8562A spectrum analyzer. The frequency response for varying current injection is shown in Fig. 2(a). A bandwidth of $f_{3\,\mathrm{dB}}=7.5$ GHz is measured for an injection current of 100 mA under pulsed bias conditions (5 μs pulses, 5% duty cycle). It may be noted that the modal gain is small. Furthermore, the photon density, or

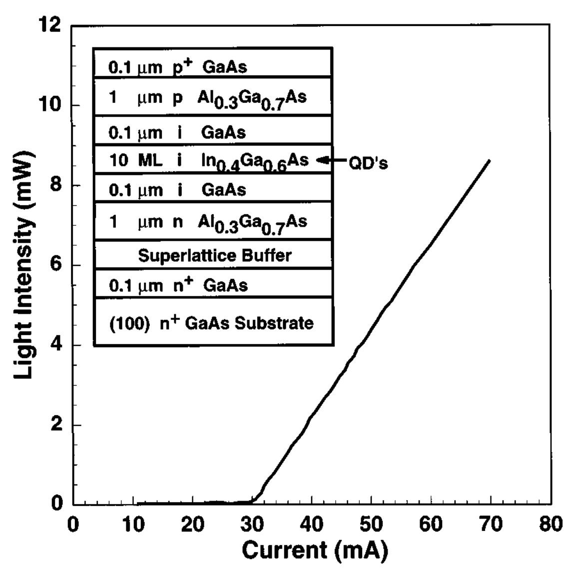

FIG. 1. Room-temperature light-current characteristics for single mode lasers. The inset shows the SCH laser structure grown by MBE with a single layer of quantum dots in the active region.

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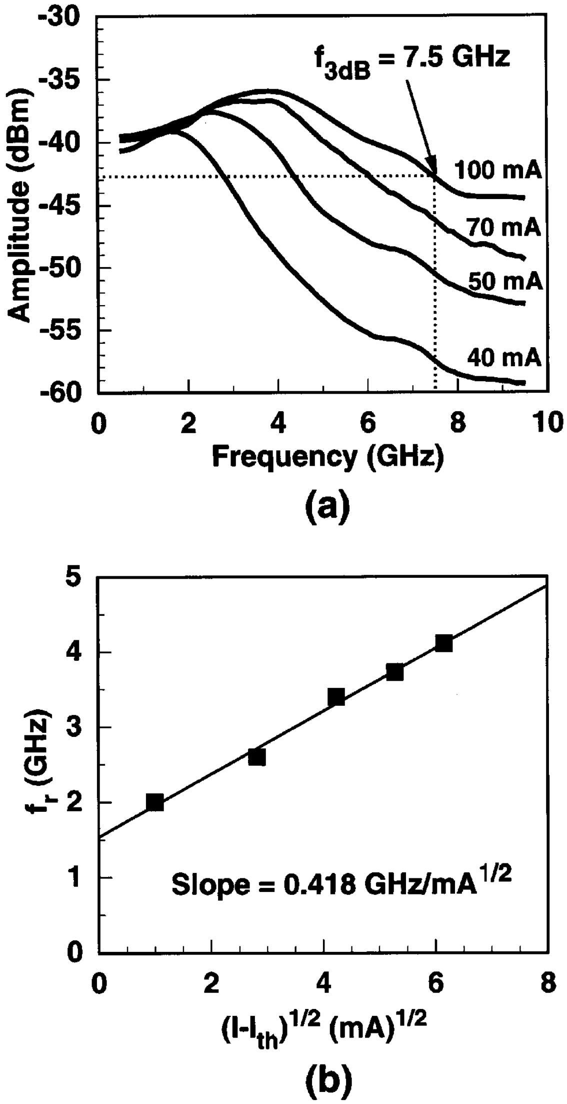

FIG. 2. (a) Pulsed small signal modulation response under varying current injection and (b) best-fit resonance frequency vs $(I-I_{\mathrm{th}})^{1/2}$ for differential gain determination.

the value of I/I_{th} is also small. Enhancement in the value of both of these parameters, which can be done by dense or multilayer dots, should increase the value of $f_{3\,\mathrm{dB}}$. Nonetheless, the data of Fig. 2(a) represent the first measured modulation response of quantum dot lasers. Figure 2(b) shows a plot of the resonance frequency f_r of the modulation response versus the square root of the injection current, from which the slope of 0.42 GHz/mA$^{1/2}$ is obtained which will be used in calculating the differential gain.

The confinement factor, which is needed to calculate the differential gain, is estimated as follows. The volume of the pyramids with 20 nm base width and 6 nm height is equivalent to a flattened cube of a base width of 20 nm and height of 2 nm. Comparing the volume of an array of these dots to the volume given by the nominal thickness of the quantum dots (2 ML), given by change in RHEED spectra from 2D to 3D growth, results in a fill factor of 28%. Taking the fill factor into account, and a 2 nm active region, the confinement factor is $\Gamma=2.7\times10^{-3}$ for the laser heterostructure. The differential gain, obtained from the slope of Fig. 2(b) is $dg/dn=1.7\times10^{-14}$ cm^2. This value is somewhat conservative with the calculation of the confinement factor and assuming the internal quantum efficiency $\eta_i=1$. Our measured value for the differential gain is lower than the value of 2×10^{-12} cm^2 reported by Kirstaedter *et al.*[14] We believe that the difference may be arising partly from the techniques and approximations. However, theoretical calculations of differential gain for similar sized quantum dots by Willatzen *et al.*[15] yield a value of 2×10^{-15} cm^2 for a broadened linewidth of 3 meV. If we consider a linewidth of 0.2 meV, which has been observed by us and other authors,[11,13] similar calculations would yield a differential gain in the range of 10^{-14} cm^2, similar to our measured results.

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