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


Solid State Electronics Laboratory, Department of Electrical Engineering and Computer Science, The University of Michigan, Ann Arbor, Michigan 48109-2122

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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 $1.7 \times 10^{-14}$ cm$^2$. © 1997 American Institute of Physics.

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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. We have recently confirmed that the spontaneous recombination time of excited carriers in the ground and higher order states of In$_{0.4}$Ga$_{0.6}$As/GaAs quantum dots is 2.5 ns and 250 ps, respectively. The former time is in good agreement with previously reported data. 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. The structure consists of an Al$_{0.3}$Ga$_{0.7}$As outer clad, GaAs inner clad, and a single layer of In$_{0.3}$Ga$_{0.5}$As self-organized quantum dots as the active region. The nominal thickness of the In$_{0.3}$Ga$_{0.5}$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 $\mu$m$\times$600 $\mu$m 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 $\sim$20 nm and a height $\sim$6 nm. Lasing in these devices occurs at $\lambda \approx 1.0$ $\mu$m through transitions involving excited electron and hole states. It may also be noted that the wetting layer transition is at $\sim 0.92$ $\mu$m. 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 $f_{3\text{ dB}}=7.5$ GHz is measured for an injection current of 100 mA under pulsed bias conditions (5 $\mu$s 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.](image-url)
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 \( \Gamma = 2.7 \times 10^{-3} \) for the laser heterostructure. The differential gain, obtained from the slope of Fig. 2(b) is \( \frac{dg}{dn} = 1.7 \times 10^{-14} \text{ cm}^2 \). 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 \( 2 \times 10^{-12} \text{ cm}^2 \) reported by Kirstaedter et al.\(^\text{14}\) 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.\(^\text{15}\) yield a value of \( 2 \times 10^{-15} \text{ cm}^2 \) 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,\(^\text{11,13}\) similar calculations would yield a differential gain in the range of \( 10^{-14} \text{ cm}^2 \), similar to our measured results.

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