Gain and Loss in Active Waveguides Based on Lithographically Defined Quantum Dots

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***Abstract*— We report on the optical gain and loss of waveguides containing lithographically defined quantum dots. Lasing action has previously been demonstrated in a nominally identical structure. Measurements are made by monitoring the transmission of a resonant pulse while varying the injection current. We measure a maximum modal gain of 1.8 cm^{-1} at the peak of the ground state emission for a two-layer structure. The peak gain is insufficient for ground state lasing to be achieved in a structure with as-cleaved facets, but the gain per dot is comparable with that demonstrated in self-assembled quantum dots.**

***Index Terms*— Nanolithography, quantum dots, semiconductor lasers, semiconductor optical amplifiers.**

I. Introduction

THE introduction of quantum dots to optoelectronic devices has led to exciting new advances on many different fronts [1]–[3]. Leading this charge has been QDs fabricated using the self-assembly method due to the high quality interfaces possible with in situ nucleation, growth, and capping. As successful as self-assembled dots have been, there are still fundamental problems in controlling their position and size distribution. Lithographically defined QDs (LDQDs) are a potential solution to these problems. In particular, exquisite control of placement is possible [4]. Unfortunately, LDQDs have so far suffered from poor radiative efficiency most likely attributable to defects associated with the etched interface between the QD and barrier material [5], [6]. Advances in understanding and eliminating at least some of these defects have been ongoing, culminating with the recent achievement of low temperature lasing operation [7]. Still, the performance of LDQD devices is far inferior to devices based on self-assembled QDs. More detailed investigation of the optical and electrical properties is essential to making further progress in future devices. In this letter, we report low temperature transmission measurements on an active waveguide containing two layers of LDQDs with a structure identical to the device that achieved lasing action. From this we extract modal gain and loss as a function of device bias and make an estimate of the transition strength of the confined LDQD states. By comparing their respective properties to that of self-assembled QDs, we show that the performance of LDQDs can be comparable in some cases, and suggest pathways to make additional improvements.

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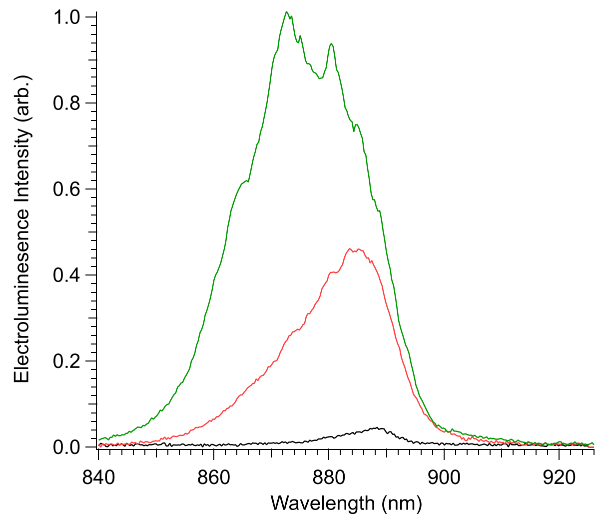

Fig. 1. A 40 K Electroluminescence spectrum from the quantum dot device at injection currents of 1, 3, and 6 mA.

II. Device Description and Experimental Details

The device investigated has a typical diode laser structure with the two layers of LDQDs embedded in the core of the waveguide. Details of the growth and fabrication are given elsewhere [7]. Briefly, the QD layers are 6 nm thick with 6 nm of GaAs between them. They are imbedded in a GaAs waveguide with an $Al_{0.75}Ga_{0.25}As$ cladding. The QDs are defined by electron beam lithography to be circular with 55nm diameter, wet-etched using a titanium mask, and the barrier material is regrown after reintroduction to the MOCVD reactor. A 3 micrometer wide ridge provides lateral confinement. The QDs are vertically stacked, so electronic coupling is possible across the barrier region. Band structure calculations reveal a manifold of closely spaced low energy states [7], which are responsible for the broad emission peak in the electroluminescence measurement at low injection currents. This peak is evident, centered at 885 nm, in the data presented in figure 1 under 3mA injection current.

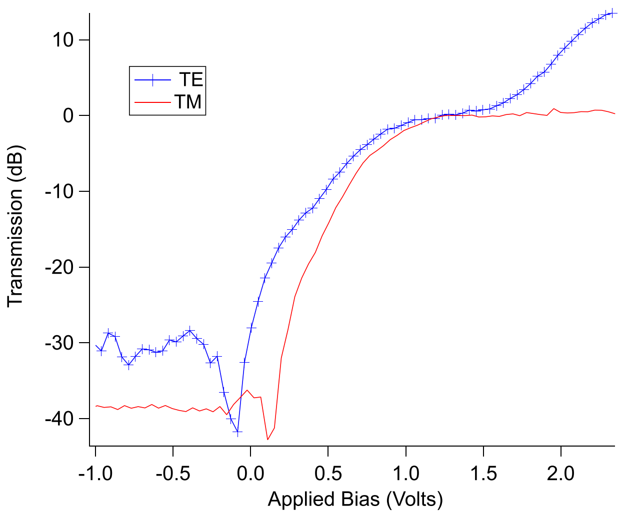

Fig. 2. Plot of the transmission of 870nm laser light through the active waveguide containing lithographically defined quantum dots as a function of applied voltage. The TE (TM) mode is perpendicular (parallel) to the growth direction.

As the injection level is increased, clear emission from excited states occur centered at 865 nm, and it is from these states that lasing action is initiated. To date, lasing in the ground state has not been achieved, because the gain is not sufficient to overcome cavity loses.

For all measurements shown here, the waveguide is mounted in a continuous flow L:He optical cryostat and held at a temperature of 40 Kelvin. For the transmission and photocurrent measurements, we use microscope objectives to couple light to and from the high numerical aperture waveguide. A modelocked Ti:Sapphire laser is used to excite the QDs, which is tunable across the QD transition region and has a constant bandwidth of 7 nm. Light collected from the output of the waveguide is then heterodyned with a frequency-shifted portion of the laser beam that did not interact with the sample. This detection scheme offers numerous advantages such as increased signal to noise at low light levels and insensitivity to electroluminescence from the device or stray reflections. Although it was difficult to estimate the optical power coupled into our waveguide structure due to large coupling losses, we ensured all measurements were taken it the linear propagation regime. This was explicitly verified by performing power dependent measurements and choosing the experimental power levels to be well below saturation. We believe that coupling instabilities to the waveguide are the main source of noise in these measurements and limits us to approximately +/− 0.2 cm^{-1}. Repeatability from scan to scan is excellent.

III. Results and Discussion

The transmission of 870-nanometer light as a function of the voltage applied to the device for TE and TM polarizations is displayed in figure 2. Above the diode turn on voltage (∼ 1.3 V), current is injected into the active region and gain is observed for light with TE polarization. Within our experimental uncertainty, we observe no gain in the TM polarization. The absence of TM gain is expected for high-aspect ratio structures like LDQDs [8], but is also an indication that the electronic coupling in our two-layer structures is not enough to induce a significant vertical component of the ground state dipole moment. It is also proof that the gain is originating from the confined QD states and not from the bulk GaAs waveguide core. With the diode biased to the flat-band condition, the QDs are emptied of carriers and are fully absorbing. The absence of carriers under these conditions is confirmed by the similar profiles for TE and TM transmission upon reverse bias.

The increasing loss as the device is pushed further into reverse bias is somewhat unexpected. The loss is significant and has a nonlinear dependence on bias voltage, rendering the device almost completely opaque at moderate negative voltage. Because the QDs are expected to be already empty, we would expect no further change in the QD carrier population, and therefore no change in QD absorption as the reverse voltage is increased. This additional loss is also present in both TE and TM polarizations, therefore we can safely rule out the QDs being responsible for this effect. We believe that this loss is a consequence of the relatively small energy difference between the QD transition energy and the bandgap of the GaAs in the waveguide core. With increasing reverse bias, the effect of absorption in the GaAs becomes stronger as the band-edge is red-shifted by the Franz-Keldysh effect [8]. This mechanism is further supported by the fact that the effect is stronger for excited state transmission, which is energetically closer to the GaAs band edge. Note that some parasitic absorption is still present with the device biased to the flat-band condition, representing a significant source of background absorption, especially for excited states. These results have significant implications for future device designs based on LDQDs.

To further investigate the amplifying properties of the devices, we also took measurements with a current bias applied to the device. The preferred method for determining the modal gain is based on resolving multiple passes of a resonant pulse injected into the waveguide [9]. Unfortunately, this technique proved nearly impossible due to the large background waveguide losses in this structure. Instead, we employed the method used in ref [10], and used the knowledge of the transparency current density to anchor the scale for the relative transmission measurements shown above. The transparency current densities for the different wavelengths investigated here were determined by ultrafast differential transmission experiments and reported elsewhere [11]. This method is only sensitive to the gain or loss associated with the QDs, and does not reflect background waveguide losses. Then, from the transmission data, we determined the modal gain using Equation 1, where T_{tr} is the transmitted intensity

$$\frac{T_{tr}}{T(I)} = e^{(g_{tr}-g(I))L} \quad (1)$$

at the transparency current, I is the injected current, g_{tr} is the gain at transparency, by definition zero, and L is the length of the device.

The data for three different excitation wavelengths is displayed in figure 3. As expected, the peak gain is larger

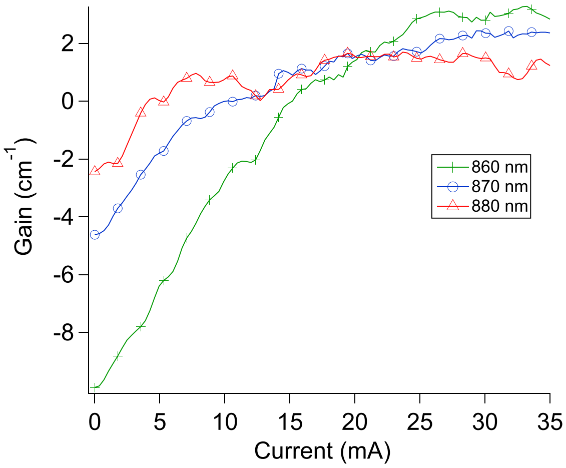

Fig. 3. Plot of the TE modal gain for the QD device as a function of injection current for three different wavelengths.

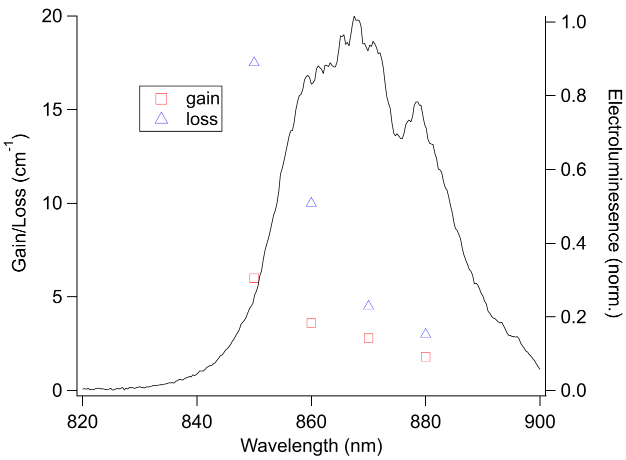

Fig. 4. Peak loss and gain for four different wavelengths along with an electroluminescence spectrum at injection current of 25mA.

at shorter wavelengths due to the influence of higher lying excited states with greater degeneracy. At low currents, the excited states are empty and gain is predominantly provided by the ground states. As the current is increased, the gain saturates for the lower lying states of the QDs, and increases for the higher lying states as state filling occurs. The ground state transition gain reaches a maximum of 1.8 cm^{-1} at an injection current of approximately 7 mA (58 A/cm^2), with a transparency current around 5 mA (41 A/cm^2). To summarize the absorption data, we have plotted the maximum modal gain and loss for the four wavelengths measured, along with the electroluminescence spectrum of the device at high current bias, in figure 4. As expected, the peak gain and loss both increase as we move to the higher excited states. Unexpectedly, there is a very large difference between the magnitude of the peak loss and gain at each wavelength measured. This additional loss is even more apparent as the transition energy is increased. Ideally, the peak gain and loss would be identical, and determined by the oscillator strength of the QD transition. This discrepancy has also been observed, albeit to a lesser degree, in self-assembled QDs at room and low temperature [10], [12]. Some of this effect can be attributed to incomplete filling of the QD states even at the highest current, but there is certainly an additional process at work as well. We believe that some of this can also be accounted for by the presence of below band gap tail states in the GaAs waveguide core material. These states will absorb strongly at zero bias, but will be very slow to fill as current is increased due to their 3-D density of states.

It is interesting to compare the properties of our LDQDs to that of InGaAs self-assembled QDs, as they are the 'gold standard' for epitaxial dots. Our peak ground state of 1.8 cm^{-1} is quite a bit lower than that reported in ref [10] and [12] of 20 cm^{-1} or 5 - 7 cm^{-1} reported in [9]. On the other hand, when accounting for the extra layer and higher QD density, they are very similar on a per dot basis. Much of this favorable comparison can be attributed to the narrow inhomogeneous spectrum of LDQDs (approximately 10 nm). A narrow distribution results in a greater percentage of QDs with resonances that can contribute gain to the laser emission and fewer carriers wasted to spontaneous emission. When comparing the transition strength of the different types of QDs, things are not so favorable for the LDQDs. From the transmission data, measurements of the low current emission linewidth, and knowledge of the QD density we are able to make an estimate the dipole moment [9]. Assuming the broadening mechanism is predominately inhomogeneous, we obtain 20 Debye for the dipole moment. This is compared to 30 Debye from measurements made in self-assembled structures [8]. It is not clear why the dipole moment for LDQDs should be less than that of SAQDs, especially considering that the large area of the LDQDs is expected to lead to an increase in the oscillator strength in the ideal case [13]. Further investigation is required to resolve this apparent discrepancy.

The maximum differential gain is extremely high in this device and is very competitive with some of the best amplifiers with conventional active regions [14]. Around transparency, the differential gain dg/dJ is approximately 0.1 cm/A at the ground state energy and 0.05 cm/A for the excited state manifold responsible for lasing action. Still, these values are about 50% lower than that measured in SAQDs, which have some of the highest differential gains reported for any semiconductor device. At least for the ground state, this number is expected to improve at higher temperatures because thermalization will occur more quickly, leading to a higher carrier density in the lower energy states for a given injection current [15].

In conclusion, we have, for the first time, measured the modal gain of an active device based on lithographically defined epitaxial quantum dots. The peak gain per dot and differential gain are similar to that of self-assembled QDs at low temperature. We have also shown that the close proximity of the QD transition energy to the GaAs band edge is the source of significant background losses.

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