Characterization and Modeling of InGaAs Quantum Dot Lasers

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Highly strained InGaAs grown by molecular beam epitaxy (MBE) on GaAs has been shown to grow in a two-dimensional, layer-by-layer fashion for only a few monolayers before the transition to three-dimensional growth (Stranski-Krastanow). The islands that form in this manner are quantum-sized and coherently strained. They exhibit bright room temperature photoluminescence (PL) and can be used as the active region for an electrically-injected laser. In this presentation, we will discuss the growth and characterization of InGaAs quantum dot (QD) lasers grown on (100) GaAs substrates, as well as modeling of the unusual laser length dependence on the lasing wavelength.

The InGaAs quantum dots are grown using alternating MBE, whereby the In and Ga are deposited with the As shutter closed. This allows the Group III adatoms to migrate on the surface for very large distances and thus incorporate at a step edge. The nominal composition of the deposited layer is $In_{0.3}Ga_{0.7}As$. However, severe In segregation occurs at the growth temperature of 515°C due to the alternating MBE shutter sequence. The 2D-3D transition occurs between 7.1 and 8.0 monolayers of deposition, as indicated by the change of the reflection high energy electron diffraction (RHEED) pattern from streaks to chevrons. Deposition is continued beyond the 2D-3D transition, until 13.3 monolayers have been deposited. During this time, the RHEED pattern changes from a mixture of chevrons and streaks to a completely chevroned pattern. Atomic force microscopy shows that the island density increases from about 1×10^8 cm^{-2} to about 5×10^{10} cm^{-2}.

The laser samples are grown on n^+-(100) GaAs substrates. The structure is as follows: 1.1 µm n- $Al_{0.7}Ga_{0.3}As$, 100 nm GaAs, InGaAs quantum dots, 100 nm GaAs, 1.1 µm p-$Al_{0.7}Ga_{0.3}As$, and 50 nm p^+-GaAs. As a comparison, an InGaAs quantum well (QW) laser is also grown with a similar structure, except the layer of InGaAs quantum dots is replaced by an InGaAs quantum well. The quantum well consists of the 7.1 monolayer Stranski-Krastanow wetting layer, grown using the same alternating MBE sequence that is used to form the quantum dots.

Temperature-dependent L-I curves are measured from 80 K to 304 K (Figure 1). The characteristic temperature, T_0, is extracted from this plot. At temperatures less than about 150 K, the QD laser has a T_0 of 185 K compared to 173 K for the QW laser. At temperatures greater than about 150 K, the QD laser has a T_0 of 111 K compared to 95 K for the QW laser. The QD laser lases from an excited state at all temperatures. The improvement in the characteristic temperature is small because the linewidth of the transitions are broad due to the inhomogeneity in dot size. Thus, the energy separation between excited states is not large enough to prevent population of the higher lying states in the QDs.

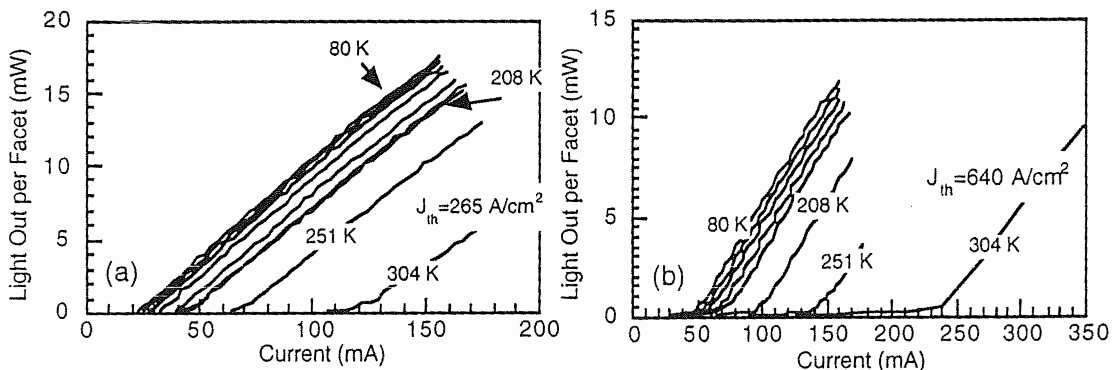

Figure 1 (a) L-I curves from an 800 µm long QW laser at various temperatures, and (b) L-I curves from an 800 µm long QD laser at various temperatures.

At room temperature, the lasing wavelength is about 940 nm for the QW laser and about 1029 nm for the QD laser. The QD laser is lasing from excited states. Figure 2 shows the subthreshold electroluminescence from the QD laser at 293 K. PL shows that the ground state emission is peaked at 1150 nm, approximately 120 nm away from the lasing state.

The lasing wavelength is plotted versus temperature in Figure 3. The QW laser lases at about 940 nm at 293 K and at about 890 nm at 80 K. This shift corresponds to the increase in bandgap of the InGaAs QW as the temperature decreases.

The QD laser behaves quite differently; at 293 K, it lases at about 1020 nm and at 80 K it lases at about 1010 nm. The small change in lasing wavelength in the QD laser comes about due to a decrease in state-filling as the temperature decreases. As seen in Figure 2, the position of peak gain blue shifts as the current is increased, until lasing finally occurs. Figure 3 shows that the threshold current density decreases as the temperature is decreased, thus leading to a decrease in the state filling at lower temperatures. Thus, the red shift due to the decreased state filling is compensated by the blue shift due to the change in bandgap, leading to a lasing wavelength that is only weakly dependent on temperature.

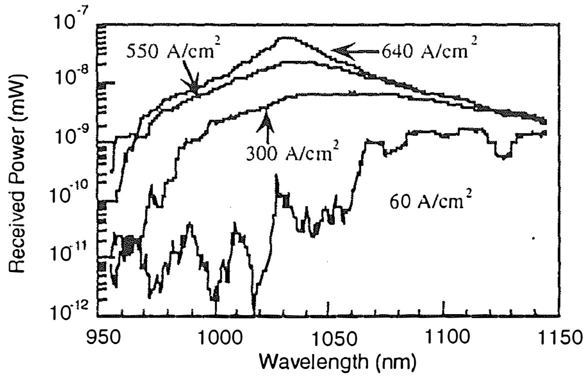

Figure 2 Subthreshold EL from the QDL at various current densities. The ground state emission is at 1150 nm.

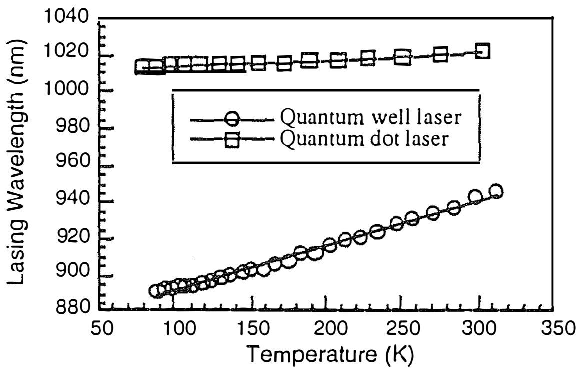

Figure 3 Lasing wavelength versus temperature for QD and QW lasers. The solid lines are linear curve fits to the data.

Further evidence to support the state-filling hypothesis is presented in Figure 4. The lasing wavelength is plotted versus laser length at 293 K. The lasing wavelength for the QD lasers decreases sharply as the length of the laser decreases, compared to the QW lasers that lase at about the same wavelength for all lengths. Since the mirror loss increases as the length decreases, the shorter QD lasers must operate higher on the gain curve. Thus, shorter lasers have more state filling and lase at shorter wavelengths compared to longer lasers.

In order to better understand these results, we have performed simulations of gain in the QDs. The key term in the expression for gain is the density of states (DOS). We have modeled the DOS as a superposition of Gaussian distributions centered around the various transition energies. The widths of the transitions are assigned from the measured experimental data. The integrated area under a given Gaussian is equal to the number of dots times the degeneracy of the given state. The gain versus energy at a specified carrier concentration is shown in Figure 5. The most important thing to observe is that the energetic position of the gain peak shifts to higher energies as the carrier concentration increases. This corresponds to the measured behavior of the QD lasers as shown in Figure 4.

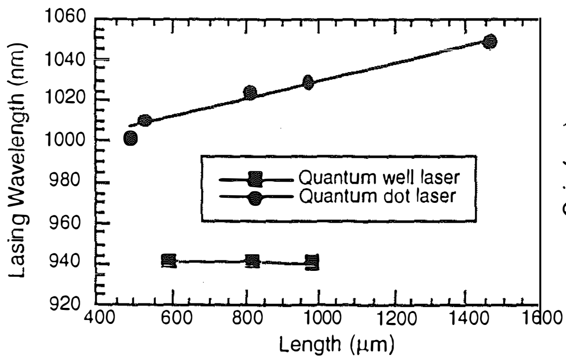

Figure 4 The quantum dot lasing wavelength changes dramatically as the laser length changes. The quantum well lasing wavelength barely changes.

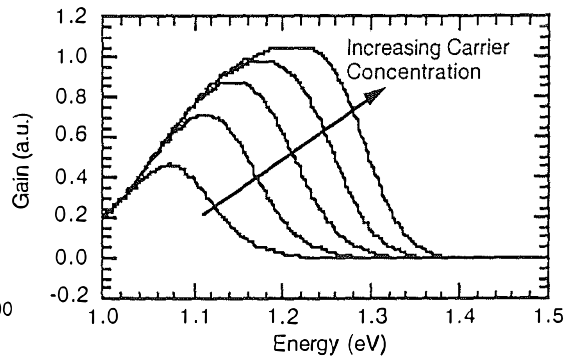

Figure 5 Gain versus energy for a quantum dot DOS that includes the energetic distribution of the discrete states due to size fluctuations in the quantum dots.

In conclusion, we have demonstrated QD lasers that lase from excited states at temperatures from 80 K to 300 K. The temperature dependence and length dependence of the lasing wavelength show that state filling is an important effect in QD lasers that have only a single layer of QDs. Simulations that account for the size distribution of the QDs can explain the length dependence of the lasing wavelength. Further modeling results will be presented at the conference.