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Experimental studies of the multimode spectral emission in quantum dot lasers

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We investigate the electroluminescence spectra of edge-emitting lasers having self-assembled quantum dots as the active medium. A broad laser emission is observed with a modulation of intensity corresponding to single or bunches (supermodes) of Fabry–Pérot modes. The variation of the laser spectra with magnetic field shows that the supermodes originate from laser cavity effects and are not related directly to the electronic properties of the quantum dots. Measurements taken on devices of different cavity height, length, and lateral width indicate that the important parameter controlling the laser multimode emission is the cavity height, effectively the substrate thickness. In particular, the period of the supermodes is inversely proportional to this thickness, indicating that the modulation of the laser emission intensity is due to the leakage of modes into the transparent substrate. © *2000 American Institute of Physics.* [S0021-8979(00)00204-8]

I. INTRODUCTION

Since the first report of lasers based on self-assembled quantum dots (SAQDs),[1] there has been a considerable effort to improve their performance. Despite the promising potential (low threshold current densities, J_{th}, and high characteristic temperatures, T_0) of reduced-dimensionality systems,[2] the best results obtained to date do not match the performance of commercial quantum well (QW) lasers. A severe drawback to the exploitation of the zero-dimensional properties of dots is the dispersion of the SAQD size and/or shape,[3] which produces a broadening of the laser spectrum. Nevertheless, threshold current densities as low as 45 A/cm^2 at room temperature[4] and characteristic temperatures as high as 385 K[5] have been obtained recently. Different SAQD systems have been used, such as (InGa)As/GaAs,[4–10] (InGa)P/InP,[11] (InAl)As/(AlGa)As,[12] and (InGa)N/GaN[13] based heterostructures. The wide choice of materials and the extensive studies of their growth properties have now extended the range of wavelength covered by SAQD lasers from near-infrared (~1 μm) to visible (~400 nm) wavelengths. Also they represent an alternative system for accessing the 1.3 μm window of signal transmission through silica fibers.[8]

Despite this large body of work dealing with the performance of SAQD lasers, relatively little attention has been devoted to a systematic study of the laser mode energy distribution. Broad laser spectra have been reported[7–10] consisting of groups of longitudinal Fabry–Pérot modes. They are commonly attributed to a population inversion, which takes place simultaneously in dots of different sizes. An alternative explanation[14,15] is that interference effects associated with waveguide leakage into the substrate can produce a periodic intensity modulation of the laser spectrum superimposed on the Fabry–Pérot modes. Further explanations have also been offered,[9] involving the modulation of the gain spectrum of the quantum dot material. Such a modulation could be associated with a size or shape dependence of the oscillator strength or of the efficiency of carrier capture. The plausibility of these mechanisms, which are based on the electronic properties of the dots, has been demonstrated[9] along with one more candidate, a process previously observed in QW lasers[16] involving intercavity photon scattering. In QW devices, the scattering is thought to arise because of strain-induced microcracks,[17] with the additional possibility in quantum dot lasers of scattering from the spatial distribution of the dots themselves. Although there are a number of possible mechanisms, a complete understanding of laser diode spectra is still lacking and no convincing experimental investigation of the laser spectra in SAQD based devices has been reported to date.

In this article we report an analysis of laser spectra of (InGa)As/GaAs/(AlGa)As ridge and stripe edge-emitting lasers incorporating (InGa)As SAQD as the active medium. Various laser structures and geometries are analyzed. We show that the laser spectrum of a given device can exhibit two kinds of intensity modulation, each characterized by a particular energy scale. In addition to the Fabry–Pérot modes, we observe distinct groups of Fabry–Pérot modes or supermodes. We provide experimental evidence that the supermodes are due to cavity effects and are not a property

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unique to SAQD devices. This is accomplished by the use of a magnetic field, which is a convenient means of controllably changing the electronic properties of the dots within an individual device, without modifying the optical properties of the cavity. As a consequence it allows us to distinguish cavity effects from those directly related to the dots. In addition, by analysis of the spectra of devices with different cavity sizes (length, width, and height), we find that the energy spacing of the supermodes correlates only with the cavity height, which is determined mainly by the substrate thickness. Such a result provides evidence for spectral modulation mediated by the device structure rather than the quantum dot material itself and is consistent with the idea that the modulation is due to a mode propagating in the transparent substrate.

II. EXPERIMENT

Our SAQD laser structures are grown by molecular beam epitaxy and consist of a cavity formed by three GaAs QWs each of width 10 nm, separated by 10 nm $Al_{0.3}Ga_{0.7}As$ barriers. The dots are formed in the center of each QW by depositing a 1.1-nm-thick $In_{0.5}Ga_{0.5}As$ layer. This design allows us to minimize carrier thermal escape from the dot states to barrier levels.[5,18] The laser cavity is clad by 1.5 μm of $Al_{0.6}Ga_{0.4}As$, which is n doped on the substrate side and p doped on the top side. The SAQDs and the cavity were grown at 450 °C and the (AlGa)As cladding layers at 600 °C.

Our devices are index-guided, in-plane lasers produced by standard etching and lithography. The cavity length, L, and lateral width, w, have been varied between 0.5 and 2 mm and between 5 and 50 μm, respectively. Also devices having different cavity heights were studied. We have produced 50 μm wide oxide-isolated stripe devices with height (measured by calibrated optical microscope to within ± 10 μm) of 100, 260, and 410 μm.

Electroluminescence (EL) measurements were performed at temperatures, T, ranging from 10 K to room temperature and in magnetic fields, B, up to 11 T. The magnetic field was applied in two different orientations with respect to the growth axis (defined as z) of the samples: $B \perp z$ and $B \| z$. The luminescence was dispersed by a 3/4 m monochromator and detected by a cooled Ge diode detector.

III. RESULTS

Figure 1(a) shows the laser EL spectra above threshold current, J_{th}, at $T = 10$ K for a laser having a cavity width of 20 μm and a cavity length of 0.5 mm. A broad laser emission appears at $J_{th} = 100$ A/cm^2 and involves carrier recombination from dots having different size and/or shape. The EL spectra are characterized by an intensity modulation on two different energy scales. The Fabry–Pérot modes have an energy separation of $\Delta\varepsilon_1 = 0.31$ meV close to the value $\Delta\varepsilon_1 = hc/2\mu L = 0.35$ meV calculated for a nominal cavity length $L = 0.5$ mm and a refractive index $\mu = 3.5$. The small discrepancy can be ascribed to both the deviation of L from its nominal value and the uncertainty in the exact value of μ. A weaker modulation of the EL spectrum is observed on a larger energy scale of $\Delta\varepsilon_2 \sim 1-2$ meV. In particular, the second modulation (or supermodes) becomes more pronounced with increasing the current density, J. The presence of two different modes (the Fabry–Pérot modes and the supermodes) is confirmed by performing a Fourier transform (FT) of the EL spectra. The amplitudes of the FT are shown in Fig. 1(b) as a function of the conjugate variable of energy, t. The FT amplitude has different harmonic components (n) with periods, t_1 and t_2, corresponding to a laser intensity modulation on energy scales of $\Delta\varepsilon_1 (= t_1^{-1}) = 0.31$ and $\Delta\varepsilon_2 (= t_2^{-1}) = 1.7$ meV, respectively.

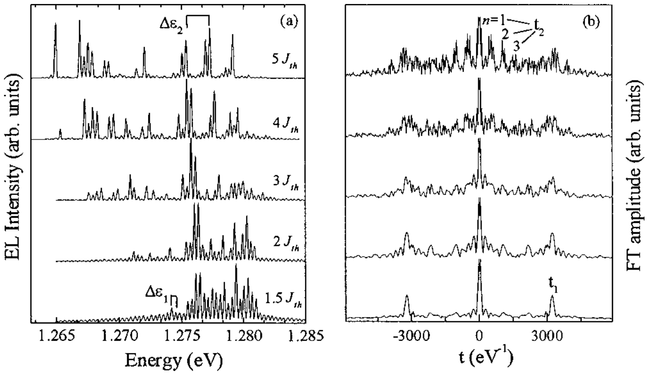

FIG. 1. (a) EL spectra at $T = 10$ K for different current densities J (threshold current density, $J_{th} = 100$ A/cm^2) of a SAQD laser having a cavity lateral width equal to 20 μm and a cavity length of 0.5 mm. (b) Amplitude of the FT of the EL spectra shown in part (a). t_1 and t_2 are the two different periods of the FT amplitude corresponding to the periodic modulations of the EL intensity, $\Delta\varepsilon_1$ and $\Delta\varepsilon_2$, respectively. n indicates different harmonic components of the FT amplitude.

The line shape of the laser spectra differs from device to device, but without showing any dependence of $\Delta\varepsilon_2$ on the laser cavity width, w, or cavity length, L. Figure 2 shows the laser spectra of two devices differing only for the cavity length ($L = 0.5$ and 1 mm), but otherwise identical for active medium, nominal cavity width, and cavity height. The energy spacing of the Fabry–Pérot modes scales accordingly to

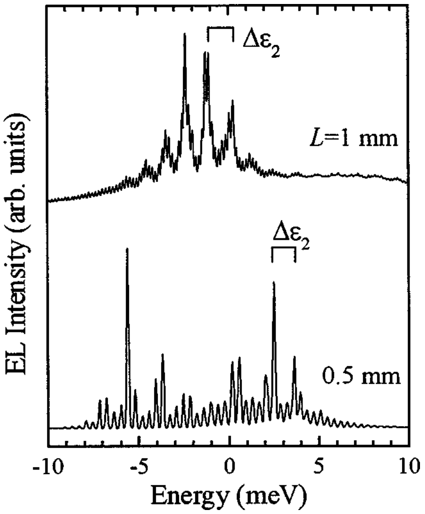

FIG. 2. Laser spectra at a current density $J \sim 4$ J_{th} (J_{th}=threshold current density) and $T = 10$ K, of two SAQD lasers having the same active medium and different cavity lengths, L. $\Delta\varepsilon_2$ indicates the energy spacing of the supermodes. For each spectrum the energy axis has been shifted for comparison purposes.

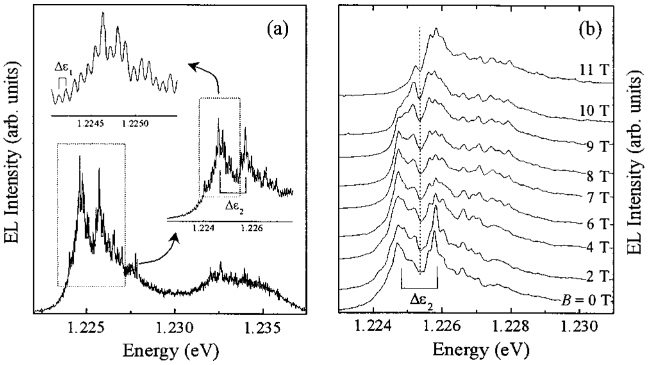

FIG. 3. (a) EL spectrum at a current density $J=1.7\,J_{\mathrm{th}}$ (threshold current density $J_{\mathrm{th}}=96$ A/cm^2) and $T=220$ K, of a SAQD laser having a cavity lateral width equal to 20 μm and a cavity length of 2 mm. The EL spectrum is characterized by an intensity modulation on different energy scales $\Delta\varepsilon_1$ and $\Delta\varepsilon_2$. (b) Magnetic field dependence of the EL spectra of the same device shown in part (a). The spectra are recorded at $T=220$ K and $J=1.7\,J_{\mathrm{th}}$ ($J_{\mathrm{th}}=96$ A/cm^2). The magnetic field is directed along the growth axis of the sample ($B\|$ configuration). The dotted line indicates a feature in the laser spectrum present at different B.

the cavity length ($\Delta\varepsilon_1=0.36$ and 0.18 meV for $L=0.5$ and 1 mm, respectively). In contrast, the supermodes show similar energy spacing in both devices ($\Delta\varepsilon_2\sim1.2$ meV).

In order to investigate further the origin of the complex structure which appears in the laser spectrum, we studied the effect of magnetic field B. Previously, it was shown that the magnetic field can induce an improvement of the laser performances, such as a larger value of the characteristic temperature T_0.[2] This results from the increased carrier localization under a magnetic field. This study was performed on semiconductor lasers having bulk (or 3D) material as active medium. In contrast to the 3D lasers, the magnetic field is not expected to affect strongly carrier localization inside the dots. As a matter of fact we do not observe important changes of J_{th} with B. We observe only a small increase of J_{th} with B (less than 10% at 11 T and for different T), which could arise from a diminishing mobility of carriers in the growth plane.

We studied the degree of localization and the symmetry of carrier wave function confined in the dots using the magnetic field (B) dependence of the SAQD EL peak position monitored for $J<J_{\mathrm{th}}$. Two different field orientations are considered: along the growth direction ($B\|$) and in the growth plane ($B\perp$). In the $B\|$ geometry, we measured a diamagnetic shift of the SAQD EL band of $\sim$2 meV at 11 T. In contrast, for the $B\perp$ geometry the diamagnetic shift is almost zero up to 11 T. These results are qualitatively consistent with atomic force measurements revealing a flat geometry for our dots (they have diameter $d=15$ nm and height $h=1.6$ nm) and, hence, a strong anisotropic confinement potential. Furthermore, the magnetic field does not affect the linewidth of the SAQD EL spectrum, evidence for a negligible influence of the magnetic field on carrier redistribution between the dots.

According to the variations with B of the EL spectra monitored for $J<J_{\mathrm{th}}$, we observe changes in the laser spectra. Figure 3(a) shows the laser EL spectrum above threshold current, J_{th}, at $T=220$ K and $B=0$ T for a laser having a width of 20 μm and a cavity length of 2 mm. The EL spectrum is characterized by an intensity modulation on different energy scales [see the expanded sections of the EL spectrum in Fig. 3(a)]. In addition to the Fabry–Pérot modes, with an energy separation of $\Delta\varepsilon_1=0.08$ meV, a modulation of the EL spectrum on an energy scale, $\Delta\varepsilon_2\sim1$ meV, is observed. Figure 3(b) shows laser spectra recorded at $T=220$ K in the $B\|$ configuration for the same device shown in Fig. 3(a). With increasing B the laser modes separated by $\Delta\varepsilon_2$ (supermodes) do not move in energy. However, their relative intensity is modified continuously and the weighted line center of the spectrum blueshifts by $\Delta E_{B\|}=2$ meV at 11 T. In the $B_{\perp z}$ configuration, we found a smaller shift $\Delta E_{B\perp}=0.2$ meV.

We attribute the blueshift of the weighted line center of the laser spectrum to the diamagnetic shift of the dot levels. It is consistent with the measured value for the spontaneous EL spectra and is similar to luminescence data reported for similar dot samples.[19] Although the diamagnetic shift measured at 11 T, $\Delta E_{B\|}$ ($\sim$2 meV), is larger than $\Delta\varepsilon_2$ ($\sim$1 meV), the energy position and each supermode is not affected by B. This proves that the supermodes are due to cavity effects and allows us to rule out that the supermodes arise from preferential lasing of different groups of dots. We believe that, with increasing B, the same dots provide the laser emission but, due to the diamagnetic shift of their energy levels, they couple to different cavity modes (the Fabry–Pérot and the supermodes). This results in a blueshift of the weighted line center of the laser spectrum, but in a unchanged laser intensity modulation.

Structured laser spectra similar to ours have been reported for several different systems, such as blue-light emitting lasers based on (InGa)As,[20] (InGa)N,[17,21,22] and (InGa)(AsP) lasers.[16] A common feature of these devices is that they are all characterized by a broad laser gain. As a consequence, a possible modulation of the laser EL intensity may be readily observed. We propose that for those cases the magnetic field may represent a useful means of investigating the nature of the complex laser spectra.

Various cavity mechanisms can be envisaged to account for structured laser spectra. It has been demonstrated that even a very small number of cavity defects can strongly affect the spectral output of diode lasers.[16] In particular, cleaving can produce microcracks inside the cavity;[17] these can act as cavity mirrors and generate groups of Fabry–Pérot modes with a constant energy separation. In order to assess the influence of the mirror cleaving on our devices, we studied two lasers processed from the same wafer, but having as cavity mirrors two different facet orientations. For this purpose, we used samples grown on (311)B GaAs substrates with cleaved mirrors corresponding to (011) and (011) planes. The two planes form angles of 90° and 65° with the growth plane, respectively. In both cases, the laser spectra exhibit similar properties, strong evidence against the hypothesis of a strong influence of mirror-cleaving angle on laser spectra.

As an alternative explanation we note that in (InGa)As/GaAs strained QWs, the leakage of the radiation field out of the waveguide and reflections from the device contacts act to

TABLE I. Summary of the results of the FT analysis on devices of different height and length (as measured by calibrated optical microscope).

Measured length (μm)	Length from FT (μm)	Measured height (μm)	Height from FT (μm)
1500	1520	100	105
1500	1520	260	250
1700	1650	410	430

modulate the gain spectrum with a period of 3–4 meV.[20] This model could explain the laser intensity modulation in our devices on the energy scale $\Delta\varepsilon_2$ of 1–2 meV, which we found to correspond to an equivalent optical length ($=hc/2\mu\Delta\varepsilon_2$) of about 100–200 μm. These are also typical values for the cavity height of these laser devices.

To test whether the periodicity we have observed in our dot laser spectra is due to the effects of this leaky mode, we prepared lasers with different cavity height, namely with different GaAs substrate thickness. The periodicity of the leaky mode behavior is known to be inversely proportional to the substrate thickness.[15,20] We have produced 50 μm wide, oxide-isolated, stripe devices with a cavity height of either 100, 260, or 410 μm and cavity length between 1500 and 1700 μm. The spectra of the three sets of quantum dot lasers with different cavity height were measured as a function of drive current and temperature. As shown in Table I, the measured cavity length and height are very close to the equivalent optical lengths responsible for the single and bunches of Fabry–Pérot modes. The equivalent lengths were derived by a Fourier analysis of laser spectra: the energy period of the laser intensity modulation $\Delta\varepsilon$ is converted into an effective optical length, l, by the relation $l=hc/2\mu\Delta\varepsilon$. These results indicate that the supermode periodicity present in the measured spectra is strongly correlated with the cavity height, thus supporting the idea that the observed laser intensity modulation (period ~1 meV) is due to the propagation of a leaky mode in the transparent substrate.

Finally, we point out that it is not possible to explain all the features present in our laser spectra in terms of the resonant leaky mode picture. In fact, the laser mode distribution depends strongly on temperature and current. A thermal narrowing of the laser spectra is observed, evidence for a strong electronic and/or optical thermal coupling between the dots.[14,23,24] Also an additional modulation of the laser intensity spectrum is sometimes observed at high currents (e.g., groups of modes separated of ~5–10 meV), which is the subject of further investigation.

In conclusion we have studied the laser spectra of devices incorporating SAQDs as the active medium. The broad laser spectra show an intensity modulation on two different energy scales. In addition to the Fabry–Pérot modes, we observe distinct groups of Fabry–Pérot modes or supermodes. We have provided experimental evidence that the supermodes are due to cavity effects and do not represent a property unique to SAQDs:

(1) We studied the magnetic field dependence of the laser spectra; since the magnetic field changes the electronic properties of the dots without modifying the properties of the optical cavity, it allows us to distinguish cavity effects from those directly related to the dots; since the supermodes are not affected by B, we conclude that they are due to cavity effects;

(2) We studied the dependence of the supermode spacing on the cavity sizes (length, width, and height). This study indicates that the dominant mechanism leading to the regular supermode spacing in these quantum dot lasers is related to the cavity height, which is determined mainly by the substrate thickness. This is in agreement with a description based on the resonant propagation of a leaky mode in the transparent substrate.

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