Applied Physics Letters

Spectral analysis of InGaAs/GaAs quantum-dot lasers

P. M. Smowton, E. J. Johnston, S. V. Dewar, P. J. Hulyer, H. D. Summers, A. Patanè, A. Polimeni, and M. Henini

Citation: Applied Physics Letters **75**, 2169 (1999); doi: 10.1063/1.124954
View online: http://dx.doi.org/10.1063/1.124954
View Table of Contents: http://scitation.aip.org/content/aip/journal/apl/75/15?ver=pdfcov
Published by the AIP Publishing

APPLIED PHYSICS LETTERS VOLUME 75, NUMBER 15 11 OCTOBER 1999

Spectral analysis of InGaAs/GaAs quantum-dot lasers

P. M. Smowton,[a] E. J. Johnston, S. V. Dewar, P. J. Hulyer, and H. D. Summers
Department of Physics and Astronomy, University of Wales Cardiff, Cardiff CF2 3YB, United Kingdom

A. Patanè, A. Polimeni, and M. Henini
School of Physics and Astronomy, University of Nottingham, Nottingham NG7 2RD, United Kingdom

(Received 12 July 1999; accepted for publication 17 August 1999)

The cause of the unusual spectral distribution, often observed in InGaAs/GaAs quantum-dot lasers, is investigated by analyzing the spectra from devices fabricated with different substrate thickness (100–400 μm). Using a Fourier transform analysis to determine the optical path length, it is found that the measured modulation period correlates with the device 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. © *1999 American Institute of Physics.* [S0003-6951(99)02741-2]

Since the early eighties, predictions have indicated that quantum-dot lasers should have superior characteristics to other higher dimensional structures such as quantum well devices[1,2] and, with the advent of the self-organized growth technique, progress towards this goal has been made—at the present time, the best results being for lasers incorporating InGaAs or InAs dots.[3]

One unexpected feature of InGaAs/GaAs quantum-dot lasers is the nature of the longitudinal mode distribution. It has been observed[4–6] that the laser emission spectra are broad and consist of peaks at regularly spaced intervals (approximately 1–5 nm) superimposed on the normal longitudinal Fabry–Perot modes. Such behavior has been attributed to the discrete nature of the dots and the resulting inhomogeneous broadening (lack of a global Fermi function) leading to either spatial or spectral hole burning.

Further hypotheses have been advanced[4] to account for the periodic nature of the spectra (in the explanation above, where different subsets of dot sizes contribute to different groups of modes, the groups of longitudinal modes do not necessarily have a regular spacing (but see Ref. 7). The suggested mechanisms include intracavity photon scattering (observed in QW lasers[8]), a nonuniform distribution of dot electronic states (due perhaps to some preferred dot sizes), a gain that is dot size or shape dependent (due to size and shape dependence of either the oscillator strength or the efficiency with which dots capture carriers) and a modulation of the losses by constructive interference with the reflection of a transverse leaky mode propagating in the transparent substrate.[9] The effects due to the leaky mode have previously been reported in quantum well (QW) lasers operating at the same wavelength.[10,11] They lead to an optical mode loss (α_i)[11] and an optical confinement factor (Γ)[9] that vary as a function of wavelength with a period that is inversely proportional to the device thickness.

In this letter, we describe an experiment to determine whether a mechanism involving leaky modes in the substrate could account for the observed modulation of the emission spectra. We have fabricated InGaAs/GaAs quantum-dot lasers with three different substrate thicknesses from otherwise identical material. We find that the period of modulation of the emission spectra we observe is inversely proportional to the thickness and so conclude that in our devices the cause of the periodic modulation is related to a mode propagating in the transparent substrate.

The laser structure we have examined is represented in Fig. 1 and consists of three layers of InGaAs quantum dots each of which is grown in a matrix of GaAs (10 nm thick). These are themselves grown in $\mathrm{Al_{0.3}Ga_{0.7}As}$, and together comprise the waveguide core of the device. Atomic force microscopy (AFM) studies[12] indicate the dots are lens like in shape, are 2.2 nm high and 36 nm in diameter with a dot density of $4.5\times10^{10}\,\mathrm{cm}^{-2}$.

Typical spectra for 50 μm wide oxide isolated stripe devices fabricated from the above structure are presented in Fig. 2(a). The spectra were measured, using a spectrum analyzer (0.07 nm resolution), as a function of drive current (I $=1.1$, 1.2, 1.3, and $1.4\times I$th) at a temperature of 280 K. The devices being operated pulsed with a pulse length of 300 ns and a duty cycle of 0.03%. In addition to the normal longitudinal modes (spacing ~0.09 nm for the device that is 1500 μm long), which we can just resolve with the spectrum analyzer and just pick out in the spectrum shown magnified in the inset, there is a more widely spaced periodicity present in the data. The groups of longitudinal modes or supermodes

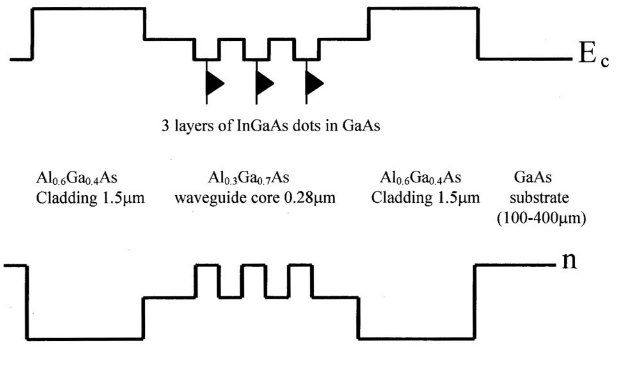
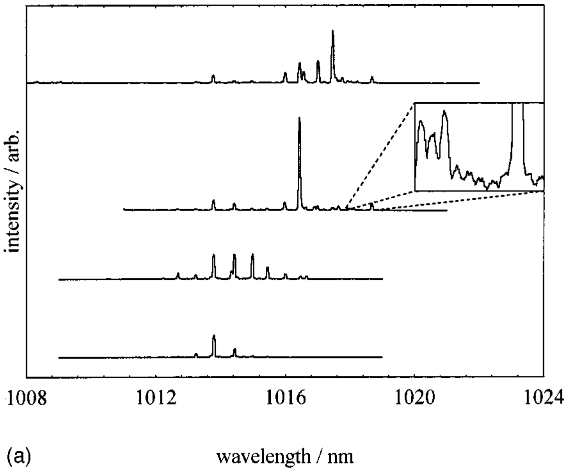


FIG. 1. Schematic of the conduction band profile of the quantum-dot laser structure and below, of the corresponding real part of the refractive index profile. The picture is not to scale.

---

[a] Electronic mail: smowtonpm@cf.ac.uk

0003-6951/99/75(15)/2169/3/$15.00



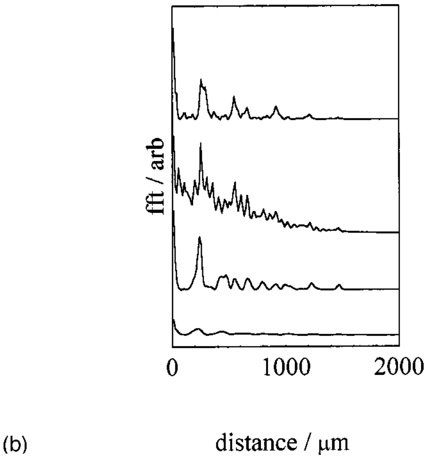


FIG. 2. (a) Quantum-dot laser spectra taken at drive currents of 1.1, 1.2, 1.3, and 1.4× *I*th and a temperature of 280 K for a 50 μm wide, 1500 μm long oxide isolated stripe device. The spectra have been offset on the vertical scale for ease of comparison (higher current have larger offsets). The spectra exhibit groups of longitudinal modes separated by approximately 1nm intervals in addition to the normal longitudinal modes shown in the magnified section of the 1.3× *I*th spectrum in the inset. (b) Fourier transforms of the data in (a) plotted in terms of wave number. The spectra are offset on the vertical scale for clarity (increasing offsets for higher currents).

are much more obvious than the longitudinal modes themselves and have a spacing of approximately 0.6 nm. The Fourier transform of each of the four spectra (plotted in terms of wave number so that the conjugate variable is length) are shown in Fig. 2(b) and demonstrate the presence of a periodicity in all four spectra even at the relatively low drive currents used here. At still higher currents, lasing spreads to a second group of higher lying energy states as shown in Fig. 3 for spectra recorded at currents of 1.4 and 1.5× *I*th. This second group of modes complicates the Fourier transform, introducing extra detail, but the Fourier transforms of each of the two groups taken individually indicate a similar periodicity within each group.

To examine the cause of the periodicity (of spacing ≈0.6 nm), we need to return to the device structure of Fig. 1. In addition to the waveguide core region of the device described above, the device was constructed with $Al_{0.6}Ga_{0.4}As$ cladding layers that are 1.5 μm wide and which are themselves surrounded on one side by an 0.5 μm wide GaAs contact layer and on the other by the GaAs substrate. These GaAs layers have a higher refractive index than the region which would normally be considered the waveguide core of the device (as pictured in Fig. 1) and are transparent to the laser light. The optical mode that interacts with the gain producing region of the device is therefore a leaky mode. It has been suggested that such leaky modes can cause a modulation of the intensity of the emission spectrum.[9–11] This occurs because for certain wavelengths, the mode is confined by the outer GaAs layer rather than the waveguide core region of the device alone, reducing the optical confinement factor dramatically and in a resonant (or periodic) manner. The optical mode loss can also be modulated periodically due to loss in either the GaAs substrate and/or the gold metallization surrounding the outer GaAs layers, which provides both strong absorption and reflection. We have confirmed that this description applies to our structure using a simple one-dimensional transfer matrix approach. We have enclosed the structure in what are considered to be infinitely thick layers of gold ($n = 0.2 - j6.0$),[13] and where the dots themselves are considered as 1.1 nm thick layers with the same refractive index as GaAs. These two approximations have little affect since the loss in the gold layers is extremely high and the dots are small on the scale of the wavelength of light. Refractive index values for GaAs and AlGaAs were taken from Ref. 14. This model also confirms, as has previously been observed,[9–11] that the period of the modulation is inversely related to the device thickness.

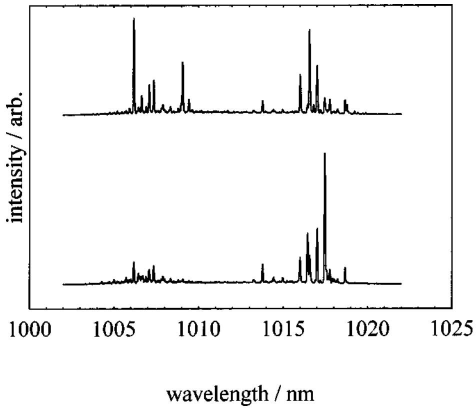


FIG. 3. Spectra of the device of Fig. 2 taken at 1.4 and 1.5× *I*th and at a temperature of 280 K. The larger wavelength range shows the presence of a second group of lasing modes at higher energies. The two spectra are offset on the vertical scale.

To experimentally test the hypothesis that the periodicity we have observed in our dot laser spectra is due to the device structure, we have chosen to thin the GaAs substrate by different amounts in the fabrication procedure. We prefer this approach to growing devices with different cladding layer thickness since using our approach we can make use of a single wafer and the devices are otherwise identical. We have produced 50 μm oxide isolated stripe devices with total thickness (measured by calibrated optical microscope to within ±10 μm) of 100, 260, and 410 μm.

The spectra of the three sets of quantum-dot lasers with different substrate thickness were measured as a function of drive current and temperature. Fourier transforms were used to simplify the analysis of the spectra. As recently shown[15] by plotting the spectra in terms of wave number, the Fourier transform gives information about the optical path length

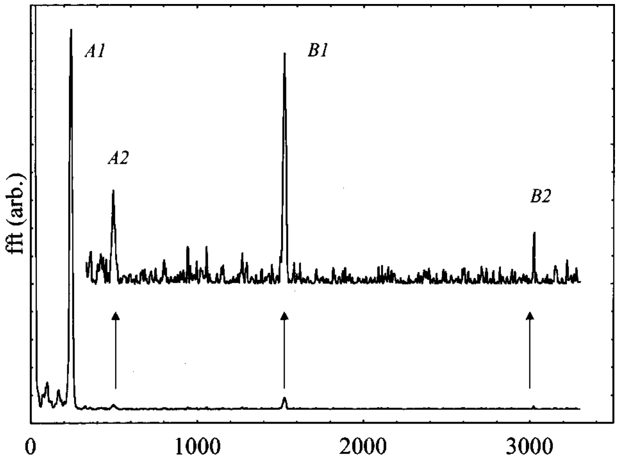


FIG. 4. Fourier transform of the wave-vector spectrum of a 1500 μm long, 260 μm thick laser taken at $2\times I$th and at a temperature of 150 K. The upper trace is a ×20 magnification of the raw data to reveal the presence of features at lengths of 1500 μm (B1), 3000 μm (B2), and 500 μm (A2) in addition to the feature (A1) at 250 μm apparent in the raw data.

within the laser cavity. Furthermore, by using the refractive index and refractive index energy dependence[14,16] this information can be converted into the device length. The length dependence of any other periodicity within the spectrum also then becomes apparent. In Fig. 4, we have plotted the Fourier transform of the wave-number spectrum of a 1500 μm long, 260 μm thick device operated at $2\times I$th and at a temperature of 150 K. The low temperature allows us to drive the device well above threshold without exciting the higher energy states observed in Fig. 3. In the upper trace, which is the lower trace amplified by a factor of 20, a feature exists at both the device length (B1) and twice the device length (B2). The largest feature (A1), which is readily apparent in the trace that has not been amplified, corresponds to a length of 250 μm, with another feature (A2), apparent in the amplified trace, at 500 μm. Similar measurements taken on the other devices of different thickness and cavity length are summarized in Table I. The features apparent in the Fourier transform spectra, which represent the periodicity present in the measured spectra, show a correlation with the thickness.

These results indicate that the dominant mechanism leading to the regular modulation of the emission spectra in these quantum-dot lasers is related to the device thickness, although there are some additional features present in some of the measured spectra that do not appear to be related to the cavity length or thickness. It may be that in quantum-dot devices where substrate effects are suppressed that other mechanisms cause regular or quasiregular mode distributions.

TABLE I. Thickness and device length information derived from Fourier transform analysis for devices fabricated to have three different values of thickness and compared to length and thickness information measured by calibrated optical microscope.

Measured length (μm)	Length from fft (μm)	Measured thickness (μm)	Thickness from fft (μm)
1500	1520	100	105
1500	1520	260	250
1700	1650	410	430

[1] Y. Arakawa and H. Sakaki, Appl. Phys. Lett. **40**, 939 (1982).

[2] M. Asada, Y. Miyamoto, and Y. Suematsu, IEEE J. Quantum Electron. **22**, 1915 (1986).

[3] D. Bimberg, N. Kirstaedter, N. N. Ledentsov, ZH. I. Alferov, P. S. Kop'ev, and V. M. Ustinov, IEEE J. Sel. Top. Quantum Electron. **3**, 196 (1997).

[4] L. Harris, D. J. Mowbray, M. S. Skolnick, M. Hopkinson, and G. Hill, Appl. Phys. Lett. **73**, 969 (1998).

[5] H. Shoji, Y. Nakata, M. Mukai, Y. Sugiyama, M. Sugawara, N. Yokoyama, and H. Ishikawa, IEEE J. Sel. Top. Quantum Electron. **3**, 188 (1997).

[6] A. Patanè, A. Polimeni, M. Henini, L. Eaves, P. C. Main, and G. Hill, J. Appl. Phys. **85**, 625 (1999).

[7] H. Jiang and J. Singh, J. Appl. Phys. **85**, 7438 (1999).

[8] F. H. Peters and D. T. Cassidy, Appl. Phys. Lett. **57**, 330 (1990).

[9] E. P. O'Reilly, A. I. Onischenko, E. A. Avrutin, D. Bhattaacharyya, and J. H. Marsh, Electron. Lett. **34**, 2035 (1998).

[10] I. A. Avrutsky, R. Gordon, R. Clayton, and J. M. Xu, IEEE J. Quantum Electron. **33**, 1801 (1997).

[11] E. V. Arzhanov, A. P. Bogatov, V. P. Konyaev, O. M. Nikitina, and V. I. Shveikin, Quantum Electron. **24**, 581 (1994).

[12] A. Polimeni, M. Henini, A. Patanè, L. Eaves, P. C. Main, and G. Hill, Appl. Phys. Lett. **73**, 1415 (1998).

[13] *American Institute of Physics Handbook*, 3rd ed. edited by D. E. Gray (McGraw–Hill, New York, 1972).

[14] M. A. Afromowitz, Solid State Commun. **15**, 59 (1974).

[15] D. Hofstetter and R. L. Thornton, IEEE J. Quantum Electron. **34**, 1914 (1998).

[16] J. S. Blakemore, J. Appl. Phys. **53**, R123 (1982).