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COMMUNICATIONS

Temperature dependence of the lasing wavelength of InGaAs quantum dot lasers

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We observe that the emission wavelength of edge-emitting InGaAs quantum dot lasers has a much weaker temperature dependence (0.6 Å K^{-1}) than equivalent quantum well devices (3 Å K^{-1}). Measured gain and absorption spectra show that the gain peak wavelength due to dot states is almost independent of temperature for a given value of peak gain whereas the absorption edge shifts at a rate of about 2 Å K^{-1}. Above 100 K the occupancy of dot states can be described by Fermi functions and on this basis we find that the measured gain and absorption spectra are in excellent quantitative agreement. Although the band edge energy reduces with increasing temperature, this analysis shows that the energy distribution of dot states matches the evolution of the Fermi functions such as to leave the quasi Fermi level separation and the wavelength of the gain peak unchanged as a function of temperature for a given value of peak gain. This energy distribution is a consequence of the dot size distribution so the match to the Fermi functions is probably fortuitous. *© 2001 American Institute of Physics.* [DOI: 10.1063/1.1402666]

There is considerable interest in the use of quantum dots as the gain medium in vertical cavity surface emitting lasers (VCSELs). There have been reports of VCSELs operating at 1.0 μm using quantum dot active regions.[1–3] InGaAs quantum dots also offer the prospect of making lasers at telecommunications wavelengths on GaAs substrates and edge-emitting lasers[4,5] and VCSELs[6] working at 1.3 μm have been demonstrated. In a VCSEL, the emission wavelength is insensitive to temperature because it is controlled by the wavelength of the cavity mode. However, the penalty in quantum well VCSELs is that the threshold current has a ''U-shaped'' temperature dependence due to the shift of the gain peak relative to the cavity mode caused chiefly by the temperature coefficient of the band gap. At first sight it may be supposed that this behavior will be exacerbated in dot lasers because in an ideal system the energy states form a series of delta functions rather than a continuum. In practice, the distribution of energy states is inhomogeneously broadened by size variations and, as shown in Fig. 1, we have observed that in edge-emitting quantum dot lasers the temperature dependence of the lasing wavelength is substantially weaker (0.6 Å K^{-1}) than in an equivalent quantum well device (3 Å K^{-1}). This weak temperature dependence has also been reported by others[7,8] who have noted that the laser wavelength does not move with temperature at the same rate as the photoluminescence (PL) peak. The laser wavelength in an edge-emitting device is usually controlled by the position of the gain peak so this result is surprising because, even in a quantum dot, the recombination energy should follow the temperature dependence of the band gap as indicated by the PL peak. However from the viewpoint of VCSEL devices the behavior of the wavelength of quantum dots in Fig. 1 is very encouraging because it suggests that it may be possible to match the temperature dependence of the gain peak to that of the cavity mode to achieve a weaker temperature dependence of threshold current than in quantum well devices.

In this communication we describe experiments which have enabled us to identify the fundamental reasons for the temperature insensitivity of the emission wavelength of dot lasers. Using a multisection device[9] we have made single-pass measurements of both the modal gain spectrum and the unpumped absorption spectrum of InGaAs quantum dot lasers over the range 100–300 K. The devices comprise a single layer of InGaAs dots set in a 100 Å wide GaAs quantum well located in waveguide comprising a core of $\mathrm{Al}_{0.15}\mathrm{Ga}_{0.85}\mathrm{As}$ and a cladding layer of $\mathrm{Al}_{0.60}\mathrm{Ga}_{0.40}\mathrm{As}$. Measurements were made under low duty cycle pulsed conditions and all results refer to light polarized with the electric field vector in the plane of the dot layer (TE mode) which is the polarization of the laser emission.

Net modal gain spectra are shown in Fig. 2 measured for three different values of current at 100 and 300 K. The currents were chosen to give similar values of modal gain at

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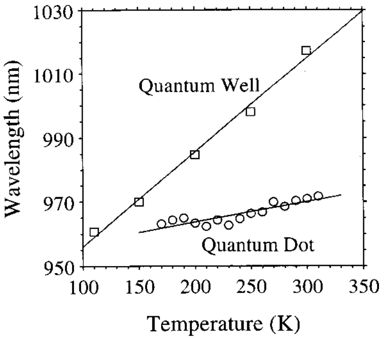

FIG. 1. Temperature dependence of the emission wavelength of an edge-emitting InGaAs quantum dot laser with a cavity length of 1500 μm (circles) and an InGaAs single quantum well laser with a cavity length of 450 μm (squares).

each temperature corresponding to the gain required for lasers of length 1300, 430, and 270 μm. In these structures there is considerable inhomogeneous broadening making it difficult to distinguish transitions due to the dot states and to identify the onset of gain from the wetting layer. From previous work we have shown that up to a value of about 20 cm^{-1} the gain is due to ground state and excited state transitions of the dots themselves.[10] At low values of gain, where lasing occurs only on dot states, the gain peak broadens to longer wavelength with increasing temperature with no shift in the wavelength of the peak. The long wavelength edge of the gain spectrum shifts at a rate of about 2 $\mathrm{Å\,K}^{-1}$. At the larger value of gain where there is a contribution from the wetting layer, the gain peak shifts to longer wavelength with increasing temperature. Figure 3 shows the rate of change of the wavelength of the gain peak with temperature between 100 and 300 K as a function of net modal gain, showing that when the gain is provided by the dots alone (gain below 20 cm^{-1}) the gain peak is insensitive to temperature. These results show that the weak temperature dependence of the laser wavelength is due to the temperature insensitivity of the gain peak itself. In the remainder of this communication we concentrate on gain spectra in this temperature-insensitive region associated with the dot states.

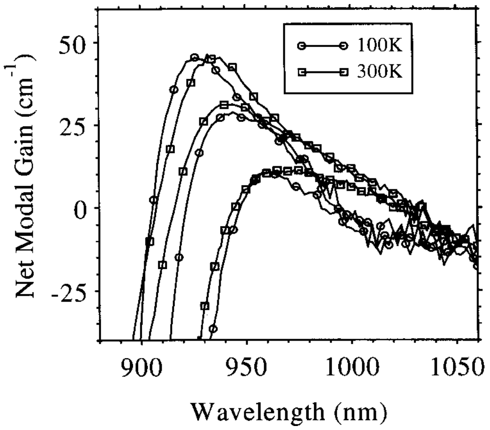

FIG. 2. Net modal gain spectra for an InGaAs quantum dot laser structure measured at 100 K (circles) and 300 K (squares) for different currents chosen to give similar values of peak gain at each temperature.

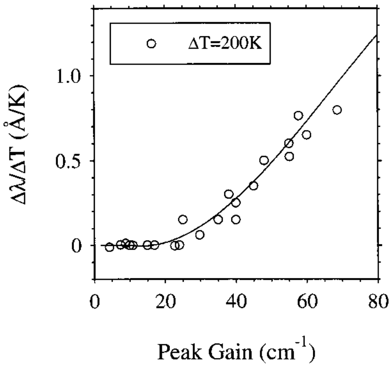

FIG. 3. Rate of change of the gain peak position with temperature for a temperature interval of 200 K (100–300 K) as a function of modal gain obtained from the spectra in Fig. 2.

Using the segmented structure, we have measured the absorption coefficient of the guided mode due to optical transitions between unpumped dot states in a passive section of the device. The absorption edge moves at a rate of about to 2 $\mathrm{Å\,K}^{-1}$ which is consistent with the observed movement of the long wavelength edge of the gain spectra in Fig. 2 but contrasts with the behavior of the gain peak. The gain spectra are intimately related to the unpumped modal absorption spectra through the occupancy factors of the electron and hole states when the structure is pumped. We have shown that down to 100 K, in these quantum dot structures the occupancy of the dot states is determined by Fermi factors with global quasi-Fermi levels for the electron and hole distributions.[11] If effects dependent upon carrier density, such as band gap narrowing, are negligibly small, under these quasiequilibrium conditions the modal gain spectrum $G(h\nu)$ and the modal absorption spectrum $\alpha(h\nu)$ are related by

$$G(h\nu)=\alpha(h\nu)[f_c(E_1,E_{fe})-f_v(E_2,E_{fv})] \tag{1}$$

with the transition energy given by

$$h\nu=E_1-E_2. \tag{2}$$

The gain and absorption coefficients are taken as positive quantities and f_c and f_v are the Fermi factors controlling the occupancy of the conduction and valence band states respectively.

Modal gain spectra were obtained from the measured net gain spectra by adding the experimentally determined value of waveguide loss of 10 cm^{-1}. Values of the loss obtained from the gain spectra and from passive absorption spectra at long wavelength were in good agreement. In quasiequilibrium the *separation* of the quasi-Fermi levels $\Delta E_f=(E_{fc}-E_{fv})$ can be determined experimentally at each temperature as the transparency photon energy of the gain spectra. We assumed that for any transition energy the difference between the photon energy [Eq. (2)] and the quasi-Fermi level separation is divided equally between the conduction and valence band dot states, i.e., $(E_1-E_{fc})=(E_2-E_{fv})=1/2(h\nu-\Delta E_f)$. The Fermi factors in Eq. (1) could then be evaluated as functions of photon energy using experimentally determined quantities. (We repeated the calculations

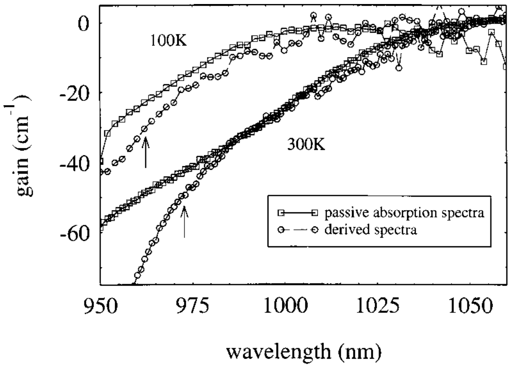

FIG. 4. Modal absorption spectra derived from the gain spectra in Fig. 2 at 100 and 300 K (circles) using Eq. (1) and values of modal absorption spectra measured directly through passive sections of the quantum dot laser structure (squares).

with this separation divided 3/4:1/4 between conduction and valence bands with no effect on the conclusions below.) Using these Fermi factors we derived absorption spectra from the measured gain spectra at 100 and 300 K in Fig. 2 having peak net gain values of 9 cm^{-1}. The modal absorption spectra derived in this way are in excellent quantitative agreement with the modal absorption spectra measured directly at these temperatures as shown in Fig. 4. Both sets of spectra have been measured in absolute units and the waveguide loss has been subtracted from the measured absorption spectra to give the modal absorption due to the dots alone. There are therefore no adjustable parameters in this comparison, so Fig. 4 shows that the measured gain and absorption spectra are indeed consistent with each other.

The experimental data in Fig. 2 show that there is very little change in the quasi-Fermi level separation between 100 and 300 K for the same value of peak gain (20 cm^{-1}) as indicated by the transparency energies. This means that as the energies of the dot states move with increasing temperature, the energy distribution of these states is such that the same peak gain is achieved with a nearly fixed quasi-Fermi level separation, ΔE_f. This implies that the form of the energy distribution of these states matches the increased thermal spread of the Fermi functions with temperature. Although ΔE_f does not change, the total carrier population on dot states for this peak gain value increases because of the reduction of the effective gap relative to the quasi-Fermi level separation with increasing temperature. The calculations show that the combination of the particular energy distribution of dot states and the thermal spread of the Fermi functions is such as to leave the wavelength of the gain peak unchanged for the fixed quasi-Fermi level separation. Since the energy distribution of the dot states is determined by inhomogeneous broadening due to dot size variations, the match between this distribution and the thermal evolution of the Fermi functions must be regarded as fortuitous. However, the fact that temperature insensitive laser emission wavelengths have been reported by several groups suggests that the size distribution which arises as a result of the Stranski–Krastanov growth mode is such as to produce this desirable energy distribution of dot states.

Using Fermi functions to describe the population of quantum dot states, as demonstrated in previously published work, we have shown that the evolution of the quantum dot gain spectra with temperature is determined by the rigid shift of the dot states due to the temperature coefficient of the band gap, and the thermal spread of carriers among these states. We conclude that the form of the energy distribution of dot states matches the thermal spread of the Fermi functions such that the quasi-Fermi level separation and peak gain wavelength hardly change with temperature for a fixed value of peak gain.

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