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Experimental investigation of the effect of wetting-layer states on the gain–current characteristic of quantum-dot lasers

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Using experimental measurements of the gain–current characteristic as a function of temperature in InGaAs quantum-dot lasers, we demonstrate that it is the population of wetting-layer states that leads to a saturation of the population inversion in dot states and hence to the saturation of gain in a quantum-dot laser. At 300 K, the maximum modal gain for a three-layer structure is reduced from 53 to 14 cm^{-1}. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1532549]

The impetus to develop quantum-dot (QD) lasers has come from the numerous performance improvements predicted for a zero-dimensional system, for example, a threshold current independent of temperature, zero linewidth enhancement factor, and extremely high differential gain.[1–3] In practice, dot lasers have delivered significant benefits relative to quantum-well devices,[4–6] and their potential for applications such as femtosecond pulse generation over a wide wavelength range[7] is of increasing interest. However, in reality dots cannot be treated as isolated zero-dimensional systems. In the Stranski–Krastinov self-assembled material, used for semiconductor lasers, the dots are sited within a wetting layer, and this has a major influence on the laser performance. The localized QD states and the two-dimensional wetting-layer states must be considered as an electronically coupled system. Within this system, the carrier distribution in the dot states is mediated by the wetting-layer states. The number of accessible two-dimensional (2-D) states can be as much as two orders of magnitude greater than those in the dots, so that the influence of the wetting layer can be extremely marked.

Theoretical models of QD lasers have already shown how the presence of higher energy states, both within the dots themselves and in the wetting layer, influence dot laser performance, increasing the threshold current,[8] reducing the available gain[9] and damping the frequency response.[10] In this letter, we present detailed experimental measurements of the saturation of the QD laser gain–current relationship as a function of temperature, and show that the saturation results from occupancy of high lying energy states rather than complete population inversion of the available dot states. A theoretical treatment of the degree of carrier inversion within these lasers shows that the large wetting-layer density of states (DOS) acts as a source of inertia, slowing the movement of the Fermi levels as charge is injected. The damping of the differential gain that this produces is in agreement with the experimental results.

The laser structures contain three layers of InGaAs QDs formed by depositing 2.1 nm of InGaAs on 100 nm of $Al_{0.15}Ga_{0.85}As$. Barrier layers of $Al_{0.15}Ga_{0.85}As$, 7 nm wide, separate each layer of QDs. The wafer was processed into 8-μm-wide, ridge lasers and nonlasing test devices with segmented contacts of 300 μm length. The emission wavelength of the 1200-μm-length lasers was 1000 nm at 300 K. The modal gain of pumped material or, in a separate experiment, the absorption of unpumped laser material, is measured using a modified version of the variable stripe length method in which the gain length is altered by electrically injecting different sections of the device.[11] The amplified, single-pass spontaneous emission is collected via a 0.3 m spectrometer, thus allowing us to collect full gain or absorption spectra. Typical results are shown in Fig. 1. The high degree of inhomogeneous broadening in these dot samples produces a continuous gain spectrum over 200 nm in width, within which the ground and excited dot states cannot be resolved.

The large variation in dot size also effects the absorption spectra of the lasers, producing a shallow absorption edge. From the gain spectra, we can extract the modal gain as a function of injected current. Plots of the gain versus current, achieved at the lasing wavelength, are shown in Fig. 2 for a range of temperatures. At all temperatures there is strong

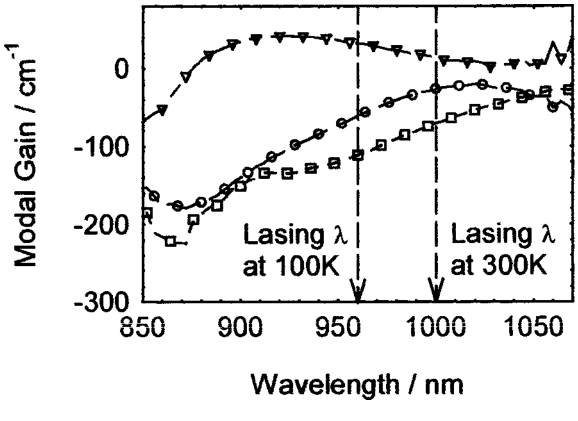

FIG. 1. Typical modal gain and absorption spectra at 300 K (triangular and square symbols, respectively). Also shown is an absorption spectrum at 100 K (circular symbols). At the 300 K lasing wavelength (1000 nm), the absorption is ~58 cm^{-1} compared to the modal gain of ~14 cm^{-1}. At the 100 K lasing wavelength (960 nm), the absorption takes a value of ~49 cm^{-1}, which is very close to the saturated modal gain value of 53 cm^{-1}.

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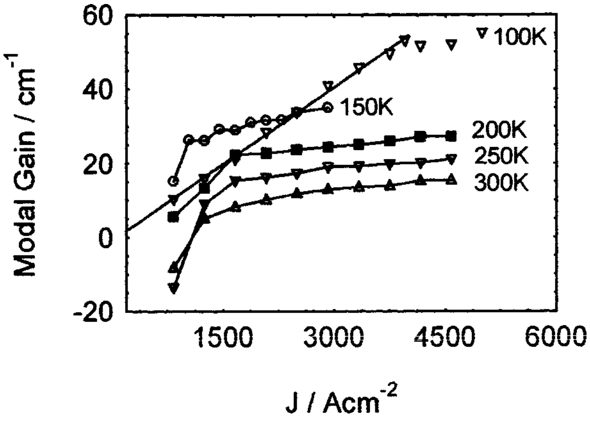

FIG. 2. Measured modal gain as a function of injection current and temperature. The measurement is taken at the lasing wavelength.

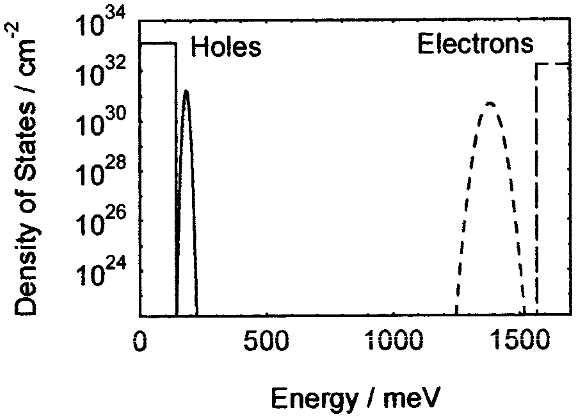

FIG. 3. Estimate of the DOS for the lasers. An equivalent DOS is plotted for the dots, where the integral area represents the total number of available energy states.

saturation of the gain at higher values of the injection current. Such saturation is expected in a QD system due to the finite number of electronic states. However, as the temperature is decreased, the maximum value of the gain increases, thus indicating that the saturation effect is not due to the complete occupancy of the dot states. We show later that such saturation, where the maximum gain increases with decreasing temperature, is consistent with the presence of a populated wetting layer with a larger number of states than the QDs. Additional current density at constant temperature increases the population of the wetting layer, but does not significantly change the Fermi-level position or the population of the dot states. At a temperature of 100 K, the gain–current curve shows distinctly different behavior. The gain increases linearly until it reaches a maximum value and then abruptly saturates. At this low temperature, the rate at which carriers thermally escape from the dots to the wetting layer is significantly decreased, and this effectively decouples the dots from both the wetting layer and each other. Thus, carriers are no longer thermally distributed among the QD states, and the system can no longer be described by Fermi–Dirac statistics. In this regime, the occupancy of the dots increases with increasing current density as carriers are randomly captured, and will saturate when the occupancy becomes complete. The gain–current characteristic at 100 K in Fig. 2 is consistent with this explanation and in agreement with theoretical models of dot lasers at low temperature.[12]

Further verification of this interpretation of the experiment is provided by the absorption data in Fig. 1. The absorption and gain of the system are given by the same expression related to the interaction matrix element, number of states, and occupancies of the conduction and valence band electron states. Thus, the magnitude of the absorption, corresponding to a valence band occupancy of 1 and conduction band occupancy of 0 is equal to the maximum gain achievable by completely inverting the carrier population within the dots. At 100 K, where the saturation of the gain occurs due to complete occupation of the available dot states, there is a saturated gain value of $53\pm5\ \mathrm{cm}^{-1}$ at high currents in Fig. 2. The absorption value at 100 K at the lasing and measurement wavelength of 960 nm is $49\pm3\ \mathrm{cm}^{-1}$. Thus, within the error bounds of the experiment, the absorption and maximum gain are of the same magnitude. However, at 300 K, where the saturation of the gain is due to a saturated Fermi level, the gain value of $14\pm5\ \mathrm{cm}^{-1}$ is significantly less than the absorption value of $58\pm3\ \mathrm{cm}^{-1}$ at the lasing wavelength of 1000 nm.

Figure 3 shows an estimate of the DOS for the dots and the wetting layer. The density of wetting-layer states is simply calculated assuming a 2-D electron gas in the wetting layer, and this is represented by the rectangular functions in Fig. 3. The relative energies of the dot and wetting-layer states are calculated assuming a conduction band/valence band offset ratio of 60/40 and solving the Schrödinger equation for lens-shaped dots.[13] Due to the zero-dimensional nature of the QDs, their energy states should be represented in terms of number rather than density. However, for the purpose of comparison, an equivalent DOS has been plotted in Fig. 3, assuming a dot coverage of $2\times10^{10}\ \mathrm{dots\,cm}^{-2}$ and a full width at half maximum of 50 meV for the dot inhomogeneous broadening. The heavier hole mass produces a Gaussian distribution of states that is much narrower than that of the electron states. The integral area under the Gaussian distributions, in Fig. 3, corresponds to the total available QD states. It should be noted that the graph is plotted on a logarithmic scale and that there is at least a two orders of magnitude difference in the number of available states in the wetting layer compared to the dots. By calculating the convolution of the DOS and Fermi-functions we can calculate the total carrier density for a given Fermi energy. We then obtain the occupancy of the QD states as a function of carrier density. It is the difference in the occupancy of the conduction and valence states, f_c-f_v, at the lasing energy, that determines the gain available in a laser device. Figure 4 shows a plot of f_c-f_v as a function of the total carrier density. This confirms that the large number of wetting-layer states damps the movement of the Fermi energy and so complete population inversion ($f_c-f_v=1$) cannot be achieved within the dots even at carrier densities ten times greater than the total number of available QD states. Figure 4 also shows the effect that decreasing temperature has on the population inversion. At room temperature the population inversion saturates at ~0.2 to 0.3 of the maximum value, so that the gain available is limited to ~20% to 30% of its maximum. As the temperature is decreased, the Fermi function becomes sharper and the influence of the wetting layer is reduced. The population inversion therefore approaches the maximum

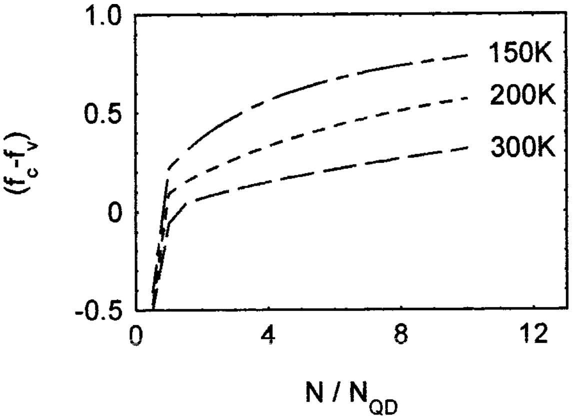

FIG. 4. Population inversion factor plotted as a function of total carrier density. Here, the carrier density is normalized to the total number of available dot states ($N_{QD}=4\times10^{10}$ cm^{-2}).

value. The analysis confirms that the gain saturation seen in the experimental data is consistent with the occupancy of wetting-layer states. Population of excited dot states would also lead to gain saturation,[9] however, for our samples the wetting layer is dominant due to its large relative degeneracy and the small confinement energies for carriers within the QDs.

In summary, we have presented experimental evidence of gain saturation in QD lasers. The results are consistent with a calculation of the current and temperature dependence of the inversion in the dot states when the population of wetting-layer states is included. Thus, the dot gain can saturate below its maximum value, with this saturated value increasing with decreasing temperature. At room temperature this reduces the available gain to ~30% of its maximum. The gain data also indicates that at 100 K the dots are effectively de-coupled from the wetting layer, and in this case total population inversion can be achieved.

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