Gain-current relationships in quantum-dot and quantum-well lasers: theory and experiment

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Abstract: The gain-current relationships for quantum-dot and quantum-well lasers are compared experimentally and theoretically. Rigorous treatment of collision effects using quantum-kinetic equations improves precision in determination of extrinsic parameters and prediction of performance.

There are indications that present quantum-well (QW) laser technology is approaching a stage where fundamental constrains are limiting performance. If indeed true, changes at the underlying-physics level may have to be introduced. A strong candidate is a quantum-dot (QD) system.

A good starting point for an evaluation of QW versus QD lasers is a comparison of gain-current relationships. Figure 1 shows modal gain versus current data obtained from room temperature, pulsed, light versus current measurements. A total of 108 QD and 126 QW lasers of various cleaved cavity lengths were measured. The QD active region has five 8nm $In_{0.15}Ga_{0.85}As$ QWs, each embedding a density of $5x10^{10}/cm^2$ InAs QDs. The QW active region has three 8nm $In_{0.2}Ga_{0.8}As$ QWs. Comparison of QD and QW data shows a potential for lower threshold currents with QD lasers. However, there is greater concern for gain saturation.

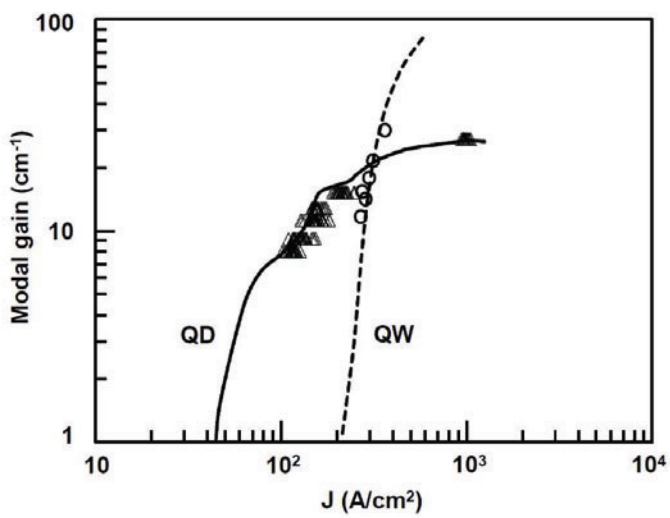

Figure 1. Modal gain versus current density from light-current measurements of QD (triangles) and QW (circles) lasers. The fitting of experimental points using a first-principles gain model (solid and dashed curves) allow characterization of experimental samples and anchoring of model for further simulations (see e.g. Fig. 2).

To characterize the present samples and predict future QD laser performance, we anchor a QD laser-gain model to experimental results, in order to extract the extrinsic contributions due to inhomogeneous broadening and defect loss. Central to the model is the treatment of line-broadening effects from carrier-carrier and carrier-phonon scattering at the level of quantum kinetic equations. [1] The more rigorous treatment distinguishes the present model from the more widely-used free-carrier descriptions, where scattering effects are described phenomenologically by introducing a free parameter, the dephasing rate. From the fit to experimental data (see curves in Fig. 1), we determined the defect related Shockley-Read-Hall coefficient to be $A = 9 \times 10^8 s^{-1}$ and $6.5 \times 10^8 s^{-1}$ for the QD and QW lasers, respectively. The fitting also found the QD inhomogeneous broadening to equal 20meV.

Next, we examine the possible improvement in QD laser performance. The following predictions are obtained using the same first-principles gain model. Comparison of solid and dotted curves in Fig. 2 shows reduced gain saturation and a doubling of maximum achievable gain when inhomogeneous broadening can be cut in half, from 20meV to 10meV. The maximum achievable gain may also be increased with higher QD density. However, this increase comes at the price of higher transparency current (see dot-dashed and solid curves for $N_{dot} = 10^{11}cm^{-2}$ and $5x10^{10}cm^{-2}$, respectively). Finally, the dashed curve indicates the change in gain-current performance if defect loss in the present QD samples can be reduced to that of the InGaAs QW lasers measured in Fig. 1. Roughly 1.5 times reduction in transparency current is predicted. However, there is no corresponding increase in maximum achievable gain.

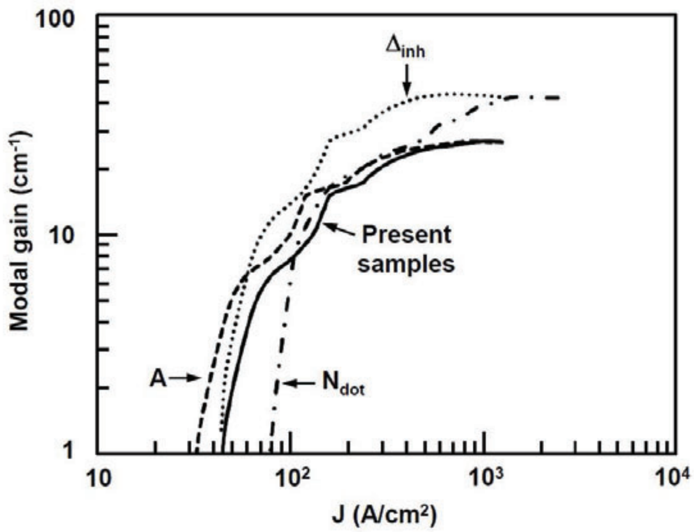

Figure 2. QD modeling results showing improvements in gain-current performance. Fitted curve for present devices (solid curve) is baseline: inhomogeneous broadening Δ_{inh} = 20meV, QD density $N_{dot} = 5x10^{10}cm^{-2}$, defect loss $A = 9x10^8s^{-1}$. The dotted curve is for decreasing inhomogeneous broadening to Δ_{inh} =10meV, dot-dashed curve for increasing QD density to $N_{dot} = 10^{11}cm^{-2}$ and dashed curve for decreasing defect loss to $A = 6.5x10^8s^{-1}$.

In summary, we showed the extraction of inhomogeneous broadening and defect loss by fitting experimental gain-current data with a first-principles gain model. The information is useful for evaluating samples, and in guiding material and device design optimizations for QD optoelectronic devices.

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References

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