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Systematic Study of the Effects of δ-p-doping on 1.3 μm Quantum Dot Lasers

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1. Introduction

The temperature sensitivity of quantum dot (QD) lasers has been significantly reduced by the introduction δ-p-doping [1]. In this paper we report a systematic study of the effect of δ-p-doping on the gain spectrum, saturated gain, internal loss and linewidth enhancement factor (LEF), via the Hakki-Paoli technique and length dependence of the operating characteristics. We show an increase in the gain and loss, and an almost zero LEF.

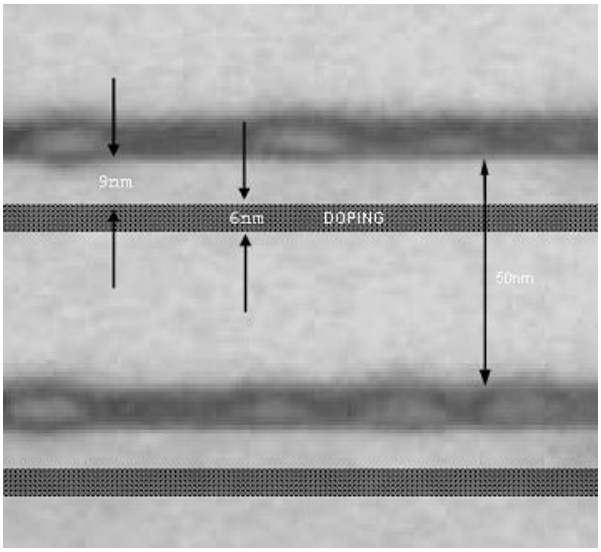


Fig. 1. Schematic showing TEM micrograph of DWELL structure and position of δ-p-doping

A series of 7 layer QD dot-in-well (DWELL) lasers were grown by solid source molecular beam epitaxy, each with different levels of δ-p-doping using Be as the dopant. Figure 1 shows a schematic of the δ-p-doping scheme. A 6nm thick region of GaAs, 9nm below each DWELL layer, was doped to give 0, 6, 12 & 18 acceptors per QD. 15um wide shallow etched lasers were fabricated for characterization.

We carried out a series of Hakki-Paoli gain measurements as a function of injected current up to the lasing threshold on 2mm long cavities of each device. Figure 2 shows sub-threshold gain spectra for all four devices. A comparison of the gain spectra shows a more asymmetrical gain profile with increased doping. A "mixed Auger" model has recently predicted a narrowing of the gain spectra for δ-p-doped QD

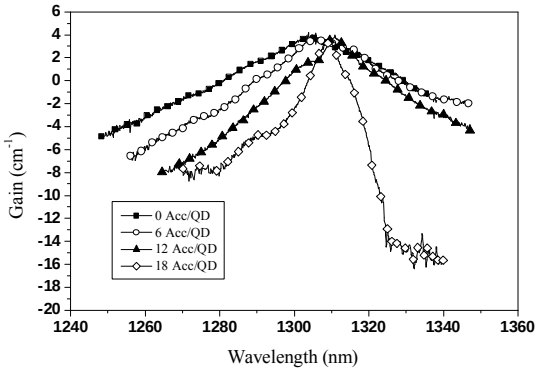


Fig. 2. Comparison of gain spectra close to threshold for doping levels of 0,6,12&18 acc/dot

lasers [2], however, the strong loss of the symmetry of the gain spectrum is suggestive of a change from a non-thermal carrier population to a "more-thermal" population. Figure 3 shows the internal loss as a function of δ-p-doping obtained from the characterization of devices as a function of cavity length, and Hakki-Paoli measurements. An increase in internal loss with δ-p-doping is observed for both measurement techniques. Length characterisation also indicates the saturated ground state gain for 12 acc/dot sample to be double that of the undoped sample. This increase is attributed to the increased hole concentration ensuring rapid electron decay to the ground state; and increased probability of a ground state electron recombining with a ground state hole [3].

Knowing the gain at different currents allows dg/di to be calculated, which is plotted in Figure 4 for current densities ranging from ~50-75% of threshold. A clear increase in dg/di is observed for increased δ-p-doping. Our calculations of the spontaneous decay times show a monotonic increase in dg/dn from ~4×10^{-16} cm^{-3} for the undoped sample to ~4×10^{-15} cm^{-3} for 18acc/qd sample.

The Linewidth Enhancement Factor was calculated using equation 1,

$$a \approx \frac{-2p}{dl} \cdot L \cdot \frac{dl/di}{dg/di} \qquad (1)$$

where L is the cavity length and δλ the F-P mode spacing [4].

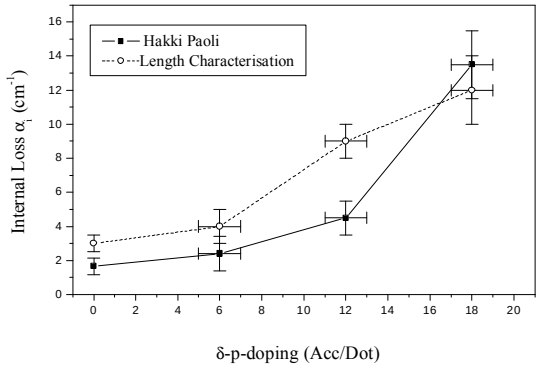


Fig. 3. Internal loss as a function of doping level

The shift of the lasing wavelength (dλ/di) is plotted as a function of pulsed duty cycle [5] to determine the free carrier effect (i.e. excluding heating effects) for 0 and 18 Acc/QD samples in Figure 5. For the 0 and 6 Acc/QD devices a blue shift of the lasing wavelength with increasing current, while for the 12 and 18 Acc/QD devices a red shift of the lasing wavelength is observed. These values yield values for the LEF for 0 Acc/QD of +~0.01 and for 18 Acc/QD -~0.01. In addition to the fact that these values are almost zero, the change in sign is of particular interest. The change in sign of LEF would be expected if the differential gain peak were at longer wavelength than the gain peak. This may be brought about by a change in the quasi-Fermi level with δ-p-doping [6].

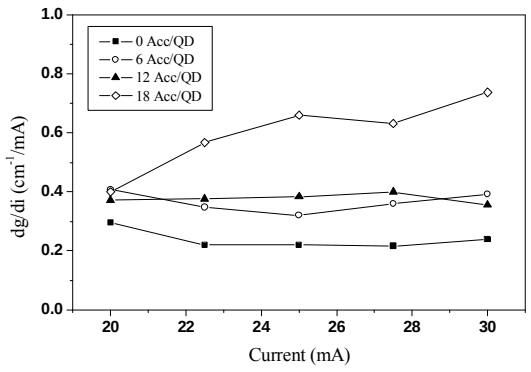


Fig. 4. Differential peak gain as a function of current for 0,6,12&18 Acc/QD

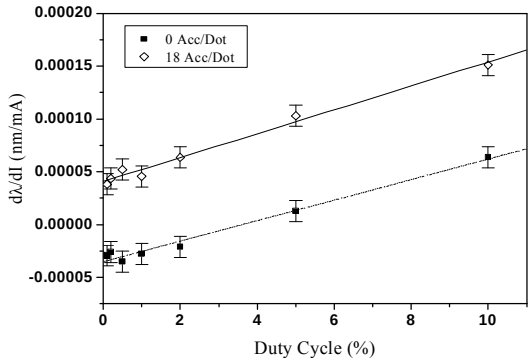


Fig. 5. Lasing wavelength change with current as a function of duty cycle for 0 and 18 Acc/QD

2. Conclusions

In conclusion, the effect of δ-p-doping on the gain spectrum, saturated gain, differential gain, and internal loss, for δ-p-doped 1.3 μm QD lasers has been discussed. The LEF is measured to be almost zero, with negative values for doping >12 Acc/QD.

Acknowledgements

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