Co-doped 1.3µm InAs Quantum Dot Lasers with high gain and low threshold current

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Abstract – The mechanism by which co-doping reduces threshold current in O-band Quantum dot lasers is examined with n-type direct doping of the dots reducing threshold current and p-modulation doping improving the temperature dependence of threshold current density relative to undoped samples.

I. Introduction

P-type modulation doping is extensively used to reduce the sensitivity of threshold current density to temperature in 1.3 µm emitting QD lasers, even though the performance can be poorer at lower temperatures compared to structures with an undoped active region. Direct n-doping into QDs during growth is also known to reduce threshold current density in QD lasers at lower temperatures [1]. Here we present calculations of the confining potential and confined states in quantum dots with differing quantities of n-dopant in addition to p-modulation doping. We demonstrate improvements in the band structure and allowed transitions and, based on these simulations, grow, fabricate and characterise QD lasers with both p-modulation doping and direct n-doped QDs. We report experimental results on molecular beam epitaxy (MBE) grown lasers and demonstrate reduced threshold current density and sensitivity of threshold current to temperature.

II. Modelling

One dimensional band structures were calculated using a self-consistent Schrödinger-Poisson-current continuity solver with a single-band effective mass approximation and finite difference method from Nextnano. The band alignment in this software was calculated using average valence band energies derived from Van De Walle and Martin's model solid theory (MST). Other material parameters were from Vurgaftman and Meyer [2]. The charge distribution used in the Poisson equation to solve for the potential was defined by donor and acceptor concentrations, in addition to conduction and valence band occupation probabilities given by quasi-Fermi levels, calculated using Fermi-Dirac statistics. A parabolic confining potential was assumed for the dots to match the equidistant allowed transitions observed by absorption spectroscopy and the density of states in the growth plane was modified artificially to reflect the observed dot density. Bound energy states and wavefunctions were then calculated for this band potential using the Schrödinger equation. This approach has previously been used to model p-modulation doped quantum doped lasers and to produce results consistent with experimental observation [3].

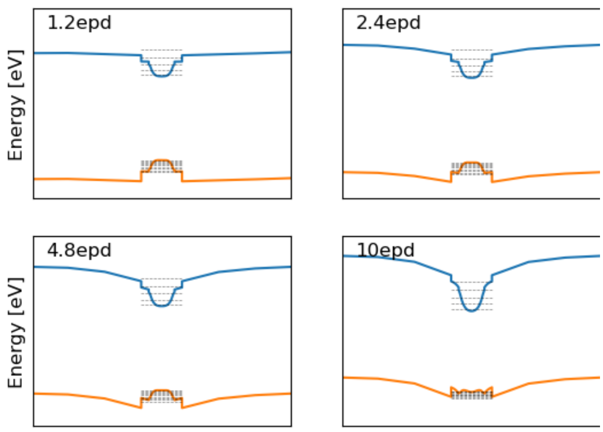

Fig. 1: Calculated dot potential as a function of ionized n-dopant atoms per dot (epd) with p-type modulation doping in the barrier. Electron and hole energy levels shown by dashed lines.

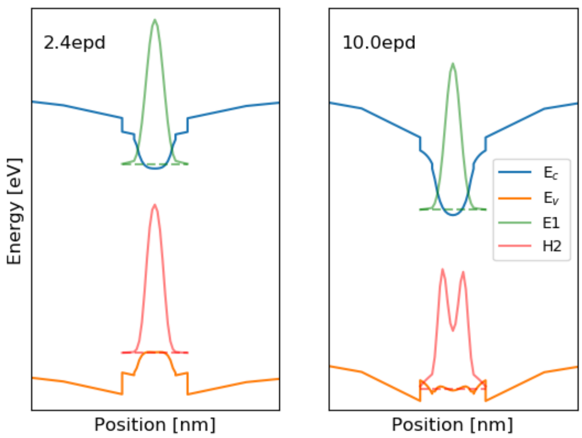

Fig. 2: Calculated potential with ground state energy levels and wavefunctions for electrons and holes respectively at 2.4 and 10 epd with p-type modulation doping

III. Experimental Results

Experimental results were taken on wafers grown by MBE, with the structures as indicated in the schema of Figure 5 and compared to samples without either the n-doping, p-modulation doping or any doping in the active region. Seven layers of QDs were grown in each sample under nominally identical conditions to give emission at 1.3-µm. A range of n-doped concentrations were investigated, which resulted in 1.2, 2.4 and 4.8 electrons per dot. The sample with 4.8 electrons per dot had the lowest threshold current density, and is plotted as the n-doped sample in Figure 6. For the co-doped sample, a density resulting in 1.2 electrons per dot is used. Wafers were fabricated into broad area, mesa stripe lasers of 50-µm wide mesa width lasers of different length with uncoated laser facets. The mesa depth was chosen as 3.3-µm, a depth greater than the device's active region layers. The threshold current density was measure under pulsed operation as a function of heat sink temperature and is plotted as a function of temperature in Figure 6.

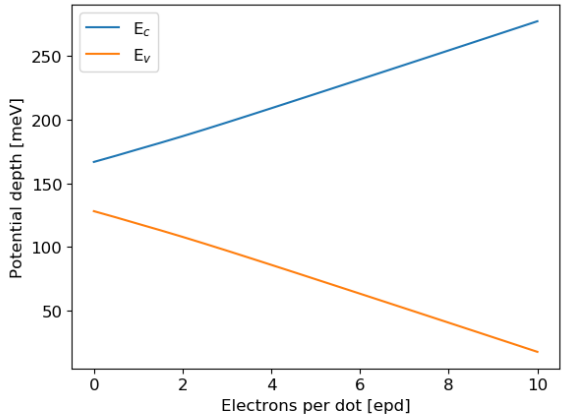

Fig. 3: Calculated conduction and valence band dot potential depth as a function of n-type direct dopant with p-type modulation doping

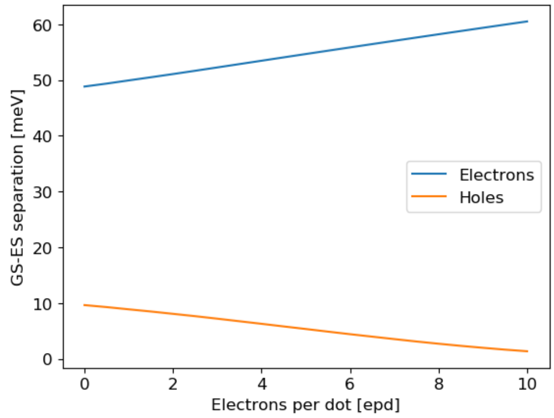

Fig. 4: Calculated energy separation between ground and excited states for electrons and holes respectively as a function of epd

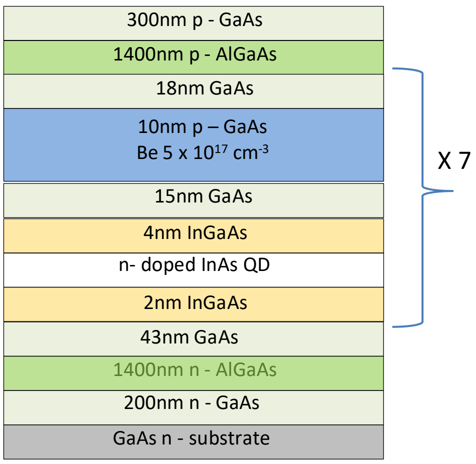

Fig. 5. General layer structure used for all four designs and detail of doping. Left p-modulation doped, centre undoped and right co-doped. The n-doped samples are the same as the right hand structure but with the GaAs layers nominally undoped.

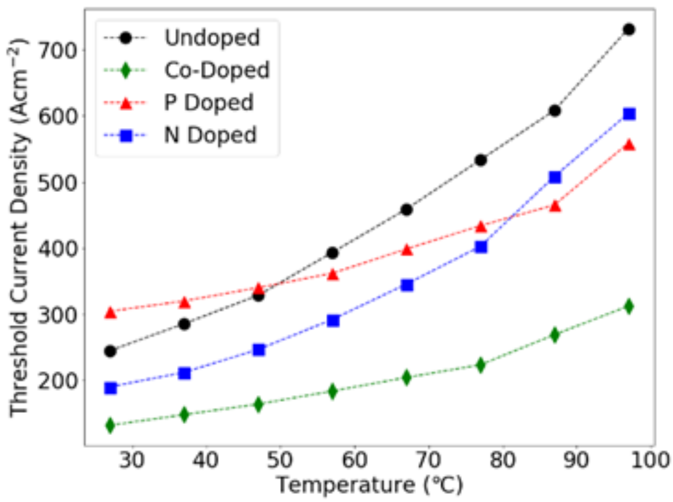

Fig. 6. Threshold current density for 1mm long lasers with uncoated facets as a function of temperature over the range 27 °C – 97

The undoped and n-doped samples have a similar temperature dependence as do the p-doped and co-doped with the co-doped and n-doped both having a lower threshold current density suggesting p-doping improves the temperature dependence and n-doping improves the threshold current.

IV. Summary

We have demonstrated improved performance in terms of threshold current density and the temperature dependence of threshold current density by both direct n-doping the QDs and modulation p-doping.

V. References

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