The limits to peak modal gain in p-modulation doped indium arsenide quantum dot laser diodes

Benjamin Maglio[1*], Lydia Jarvis[1], Craig P. Allford[1], Sara-Jayne Gillgrass[1], Samuel Shutts[1], Mingchu Tang[2], Huiyun Liu[2], Peter M. Smowton[1]

[1]*School of Physics and Astronomy, Cardiff University, The Parade, Cardiff, CF24 3AA, United Kingdom*
[2]*Department of Electronic and Electrical Engineering, University College London, Malet Place, London, WC1E 7JE, United Kingdom*

*Email: MaglioB2@Cardiff.ac.uk

Abstract – A semi-empirical model is compared with measurements to establish limiting factors in the performance of p-modulation doped InAs quantum dot (QD) lasers. Fitted absorption spectra allow identification of supposed factors and comparison of multiple samples isolates their origin, providing insights for future laser design.

I. Introduction

Quantum dot (QD) discussions have proliferated over the past two decades, owing to their tolerance to threading dislocations (TDs)[1], which arise when III-V material is grown directly on mismatched substrates, such as silicon. Though QDs offer resilience, degradation still persists, reducing modal gain and device lifetimes[2]. Further improvement is necessary to negate this and allow the continuing progress of photonic integration via heteroepitaxial growth methods.

InAs has an imbalanced carrier occupation due to the differences in electron and hole effective masses. In quantum wells (QWs), compressively strained layers can be engineered to compensate for this effect[1], [3], whereas this is not possible in systems utilising QDs due to the precise strain conditions required for QD growth. One solution is to use p-modulation doping, positioned in the waveguide core region to provide a reservoir of holes to the valence band states. However, this also has disadvantages including carrier induced index changes and increased nonradiative recombination[1],[2],[4], which may limit the associated benefits of reduced threshold current density, increased differential gain and radiative recombination[3], [5], [6].

P-modulation doped QD lasers have been researched thoroughly, both experimentally and theoretically[1],[2],[4]–[7], demonstrating good performance. Modelling these structures can be computationally intensive even before the inclusion of p-doping, and after experimental characterisation it can often be challenging to decouple the effects of doping parameters from variations in growth[2],[8],[9].

Though p-modulation doped lasers have been successfully demonstrated, in actuality their performance is often worse than undoped structures as fine optimisation is required to exploit the benefits without incurring negative effects. Here, we investigate the use of a simple gain calculation in conjunction with Nextano[10] to capture the critical aspects of carrier transport and band structure effects across multilayer structures, with values extracted from absorption spectra, thus providing insight into the limitations and benefits of p-modulation doping.

II. Results

Our modelling procedure combines a Schrödinger-Poisson-current continuity solver[10], and an in-house routine to calculate gain and absorption for each QD layer. Sample dependent parameters are found from absorption data. Only layer thicknesses are defined, reducing complexity, though additional approximations are included to retain validity. The epi-structure, grown by solid source molecular beam epitaxy, and subsequently calculated band structures are shown in figure 1.

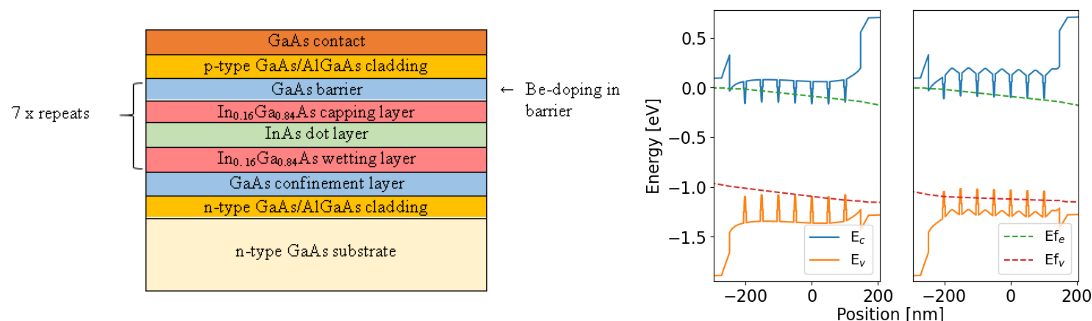

Fig. 1. (Left) epi-structure of grown and simulated samples with 7 DWELL layers. Beryllium dopant for modulation doping layer situated within GaAs barrier in p-doped samples, with ≈ 5×10^{10}cm^{-3} dot density. (Right) calculated band structures for undoped and p-doped samples near transparency.

Parabolic quantum wells are implemented for QD layers with an $In_{(x)}Ga_{(1-x)}As$ composition varying from 0.16-1.0 between dot edge and centre respectively. Additionally, a mass tensor ellipsoid is implemented to account for

the large variation between QW and QD density of states (DOS) functions. Transverse masses are reduced to match the effective DOS with the dot density. The optical confinement factor of each layer, Γ_l, is calculated followed by fitting absorption spectra for corresponding samples to estimate a ratio of bimodality as in [9], in addition to the homogeneous broadening, providing approximate carrier relaxation times.

Outputs are read through the in-house routine using an equation similar to [6] for calculating gain and absorption at each layer.

$$g = \sum_{l} \sum_{c,v} \frac{\Gamma_l \pi e^2 \hbar |M_b|^2 N_d s_i}{c m_0 \varepsilon_0 n_r L_z E_{cv}} S(E_{cv}) G(E_{cv}) (f_c - f_v) \quad (1)$$

Individual layers, l, are summed across the structure. Here, valence and conduction states are c and v. Elementary charge, e, Dirac constant, $\hbar$, speed of light in a vacuum, c, electron rest mass, m_0, and vacuum permittivity, ε_0, are used. N_d the QD density, n_r the real refractive index, L_z the primary QD height, E_{cv} the energy per transition and s_i is the degeneracy of the transition. $|M_b|^2$ is the bulk matrix element, with homogeneous and inhomogeneous broadening modelled as hyperbolic secant, $S(E_{cv})$ and Gaussian, $G(E_{cv})$ functions respectively. The carrier occupation at each layer is considered with $(f_c - f_v)$, found using Fermi-Dirac statistics.

Samples were fabricated into segmented contact devices with the modal gain and absorption measured using the segmented contact method[11]. . In figure 2 we consider typical measured modal absorption and calculated gain results from an undoped (sample 1), and p-modulation doped (samples 2 and 3), where samples 2 and 3 have a 10nm thick doping layer 15nm and 8nm above nearest QD layer respectively. We observed subtle differences due to the dopant level and position and in the number of dot layers utilised on these and further samples.

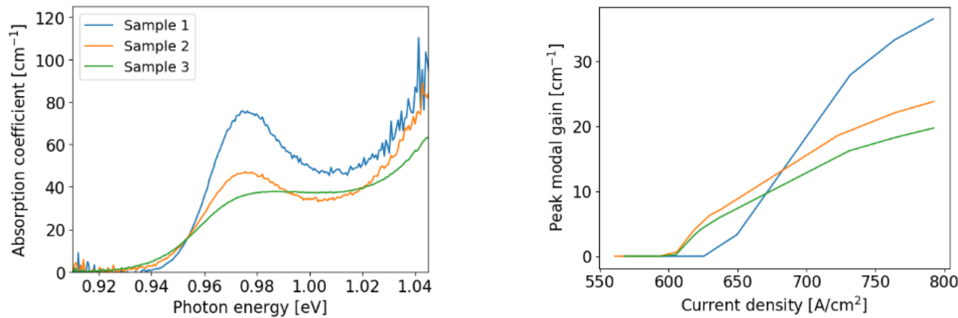

Fig. 2. (Left) measured modal absorption spectra of grown samples with homogeneous and inhomogenous broadening linewidths extracted. (Right) modelled peak modal gain calculated with linear increase on extracted homogeneous broadening linewidth with carrier injection.

In summary, we compare the calculated performance of the modelled structures with those measured for a variety of structures, identifying the critical factors and calculate the implications for application of such structures in lasers and modulators suitable for photonic integrated circuits.

III. References

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