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

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Abstract – A semi-empirical model is compared with experimental 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 designs for lasers and associated components.

I. Introduction

Quantum dot (QD) discussions have proliferated over the past two decades, owing to increased resistance to threading dislocations (TDs)[1] when grown on Silicon, resulting from the difference in lattice parameters. Though QDs offer resilience, degradation persists reducing modal gain and device lifetimes[3]. Further overall improvement is necessary to negate this and continuing furthering integration of Silicon and compound semiconductors.

InAs has imbalanced carrier occupation due to differences in electron and hole effective masses. In quantum wells (QWs) compressively strained layers can offset this[1],[4], though QDs require precise strain conditions for growth. A solution is p-modulation doping grown in waveguide core regions providing a reservoir of holes to the valence band states. This has detriments including carrier induced index changes and increased nonradiative recombination[1],[2],[4], which may limit associated benefits, reduced threshold current density, increased differential gain and radiative recombination[4]–[6].

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

Though p-doped lasers have been successfully demonstrated, in actuality often performance is worse than undoped structures as fine optimization is required to utilize the benefits without incurring negative effects. Here, we investigate the use of a simple gain calculation with Nextano[11] to capture the critical aspects of carrier transport and bandstructure 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 modeling procedure combines a Schrödinger-Poisson-current continuity solver[11], 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.

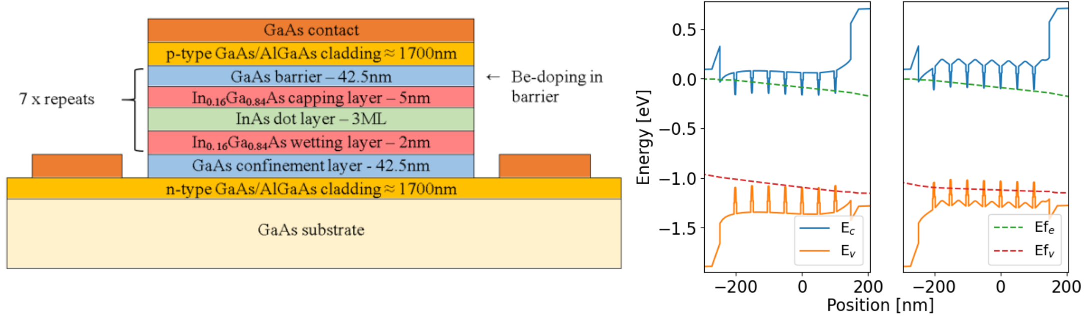

Fig. 1. (Left) epistructure of grown and simulated samples with 7 DWELL layers. Beryllium dopant for modulation doping layer situated within GaAs barrier in p-doped samples, with ≈ $5x10^{10} cm^{-3}$ dot density. (Right) calculated bandstructures for undoped and p-doped samples.

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 center 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 to 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 into the in-house routine using equation similar to [6] calculating gain and absorption at each layer.

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

Gain and absorption are calculated for individual layers, l, and summed across structure. The first three transitions between valence and conduction states, 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 dot density, n_r the real refractive index, L_z the primary dot height, E_{cv} the energy per transition and s_i is the degeneracy. $|M_b|^2$ is the bulk matrix element, with homogeneous and inhomogeneous broadening modeled as hyperbolic secant, $S(E_{cv})$ and Gaussian, $G(E_{cv})$ functions respectively. $S(E_{cv})$ and $G(E_{cv})$. The carrier occupation at each layer is considered with $(f_c - f_v)$, found using Fermi-Dirac statistics.

Samples were fabricated into multi-section devices with absorption, modal gain and loss measured using the segmented contact method. Full details of the approach can be found in [10]. In the figures below we consider data from an undoped, sample 1, and p-doped, sample 2 (10nm thick doping layer 15nm above nearest dot layer), and sample 3 (10nm thick, 8nm above nearest dot layer), showing typical absorption data and calculated gain. Our results on these and further samples indicate subtle differences due to dopant level and position and in the number of dot layers utilised.

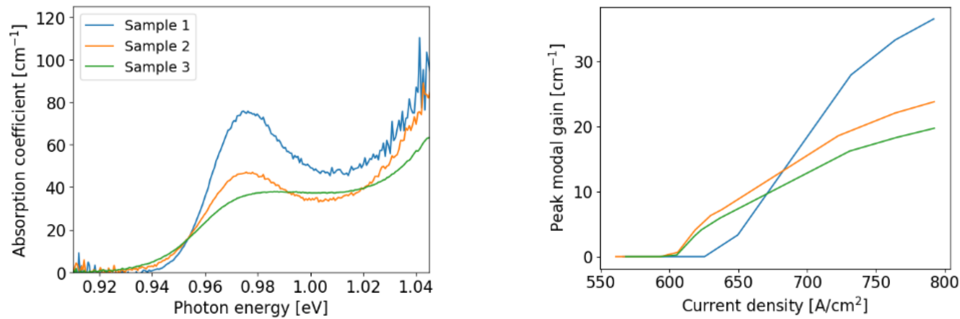

Fig. 2. (Left) measured absorption of grown samples with homogeneous and inhomogenous broadening linewidths extracted. (Right) modeled peak modal gain calculated with linear increase on extracted homogeneous broadening linewidth with carrier injection.

We compare the calculated performance with that 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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