Adaptive Design of Tensile Strained Ge-on-InGaAs QW Laser for MIR Applications

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Abstract

Here, we explore the benefits of an adaptive design (AD) methodology to improve the lasing performance of a ε-Ge-on-InGaAs SCH QW laser. This ε-Ge/InGaAs QW laser structure was analyzed by numerical solvers with aided in-house epitaxial growth and characterization results. The ε-Ge/InGaAs QW exhibited (i) 30% decrease in material loss, (ii) additional net modal gain of 10 cm^{-1}, and (iii) greater than 1 order of magnitude decrease in threshold current density (J_{TH}) at indium composition of 24 % by AD methodology. Due to the widespread spectral tunability of the ε-Ge QW laser in the MIR region, the AD approach is essential to ensure efficient performance improvement over standard design methodology with low J_{TH} and improved gain for integrated photonics.

Introduction

Due to the pseudo-direct band gap nature of germanium (Ge), the relative position of the indirect valley (L) and the direct valley (Γ) in the conduction band can be tuned using tensile strain [1] *via* a buffer template underneath the Ge layer and tin (Sn) alloying to make Ge a direct band gap material suitable for mid-infra-red (MIR) optoelectronics [2]. However, Ge [3] as well as epitaxially strained Ge (ε-Ge) [4, 5] has a growing interest in beyond Si CMOS and photonic technologies. Epitaxial growth of Ge has been extensively investigated on Si substrates, but the large lattice mismatch induced defects in Ge result in a poor minority carrier lifetime, consequently resulting in poor threshold current densities (J_{TH}) and internal quantum efficiencies (IQE) in lasers [6, 7]. To enable pseudomorphic growth without strain relaxation, InGaAs is a viable candidate for the strain template, as it is in lattice proximity to Ge as well as GaAs, and the lattice mismatch is tunable using the indium (In) composition in $In_xGa_{1-x}As$. GaAs can be used as a starting substrate and with the InGaAs of desired In composition, the material quality can be grown using a graded InGaAs defect mitigating buffer. Furthermore, such a technology on GaAs can be designed to be transferrable to a Si wafer [1]. Using this material system, one can easily envision different compositional $In_xGa_{1-x}As$ layers and thus different tensile strains in Ge, hence, enabling a Ge-on-$In_xGa_{1-x}As$ separate confinement heterostructure (SCH) based quantum well (QW) laser structure, as shown in **Fig. 1**. InGaAs layers on either side of the Ge active layer act (i) as the waveguide for optical confinement, and (ii) to provide the tensile strain in Ge. The large bandgap quaternary InAlGaAs layer provides the SCH layer for optical field confinement. In this paper, an adaptative design (AD) methodology is adopted and its merits are evaluated to optimize the performance of a ε-Ge -on-InGaAs SCH QW laser.

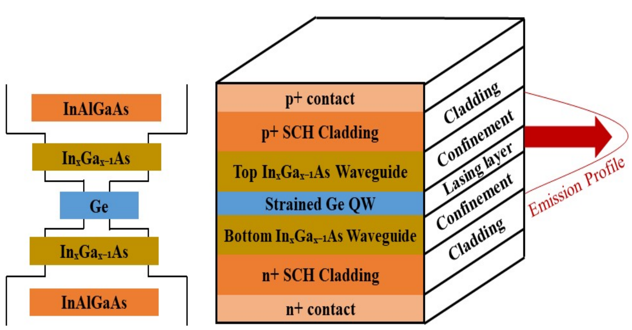

Fig. 1. Schematic of Tensile strained Ge-on-InGaAs SCH QW laser structure used to evaluate the merits of the adaptive design (AR) methodology.

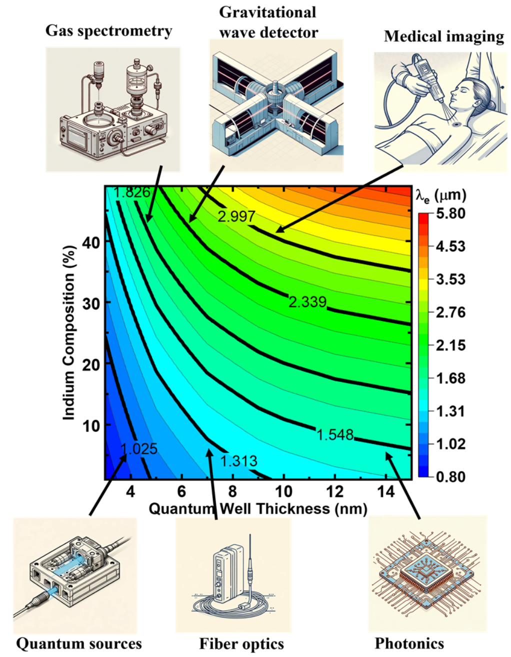

Fig. 2. Extensive tunability of the Ge QW laser in the MIR region and the corresponding application spaces [7, 9-14].

Ge-on-InGaAs QW laser: Band structure and emission

The various performance metrics of the ε-Ge QW laser such as wavelength of operation (λ_e), optical confinement factor (Γ_m), net gain, and IQE are dependent on the QW thickness, In composition in $In_xGa_{1-x}As$, and the tensile strain in Ge. Increasing the tensile strain in Ge results in a shifting of the Γ-valley lower than the L-valley, while also breaking LH and HH valence band degeneracy [1]. As Ge becomes more direct bandgap, the LH band begins to dominate, and the radiation becomes mostly quasi-TM mode [7]. The lowering of the bands also results in lowering Ge bandgap, resulting in emission at longer wavelengths [7]. Thus, the operating region of the proposed ε-Ge SCH QW laser is widely tunable by $In_xGa_{1-x}As$ layer, allowing for a wide range of applications, as summarized in **Fig. 2**.

A. Minority carrier lifetime and band offsets

The minority carrier lifetime measured through photoconductive decay (PCD) technique is a key metric to quantify non-radiative recombination which occurs in the (epitaxially grown) ε-Ge active region. Using molecular beam epitaxy (MBE) growth and material characterization reported elsewhere [1], a high PCD lifetime [7] was observed in ε-Ge indicating a good material quality for pseudomorphic growth and ascertaining that the strain has not relaxed, and defects are low [8]. Through growth of multiple samples of varying In compositions in $In_xGa_{1-x}As$, the band offsets for the ε-Ge/$In_xGa_{1-x}As$ QW structures were determined using x-ray photoelectron spectroscopy analysis. This ε-Ge/$In_xGa_{1-x}As$ QW system showed high valence and conduction band offset to support room temperature operation and Type-I band alignment [7]. These experimentally determined band offset values as well as the PCD lifetime were inputs to the numerical TCAD solvers along with 30x30 **k.p** determined band energies [1] and calibrated electrical and quantum-corrected ε-Ge TCAD models [3, 5].

B. Gain, J_{TH}, IQE and optical confinement

To evaluate lasing performance, metrics such as material loss, net material gain, and J_{TH} are considered. J_{TH} quantifies the injection of carriers required to overcome mirror losses (α_m) and free carrier absorption loss (α_{FCA}), where the modal gain (g) is equal to total modal loss (α_{tot}). Here, the material loss is $\alpha_{net} = \frac{\alpha_{tot}}{\Gamma_m}$, where $\alpha_{tot} = \alpha_{FCA}\Gamma_m + \alpha_m$. IQE is the ratio of radiative combinations in relation to other non-radiative combinations such as Auger, Shockley-Read-Hall, *etc*.

Adaptive Design Methodology for Ge QW design

The In composition alters the electrical and optical properties of $In_xGa_{1-x}As$, while also changing the band structure of Ge through tensile strain. Furthermore, the QW thickness determines the eigen energies and emission wavelength of the Ge QW laser [7]. Thus, the design of the QW laser needs to proceed using an AD methodology to attain optimum performance metrics by solving a 3 slab symmetric waveguide [7]. It has been shown that AD can optimize the optical confinement of emission (**Fig. 3**), even with the increasing λ_e resulting in significantly improved J_{TH} and net gains. The AD methodology provides the optimum $In_xGa_{1-x}As$ cavity thickness (d_0) as a function of the In composition and the QW thickness (**Fig. 4**). The d_0 for a given In composition was obtained by finding the maximum confinement factor over a range of practical cavity

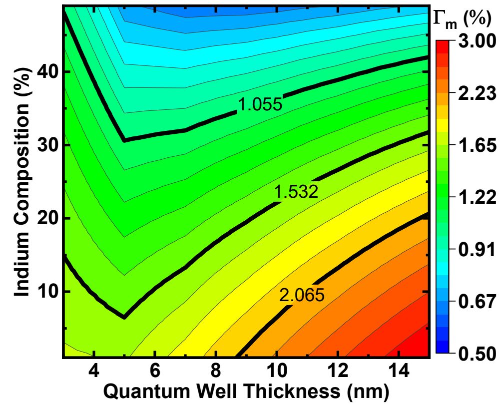

Fig. 3. The optimal confinement factor and In composition as a function of QW thickness in the ε-Ge QW laser structure, designed by AD methodology.

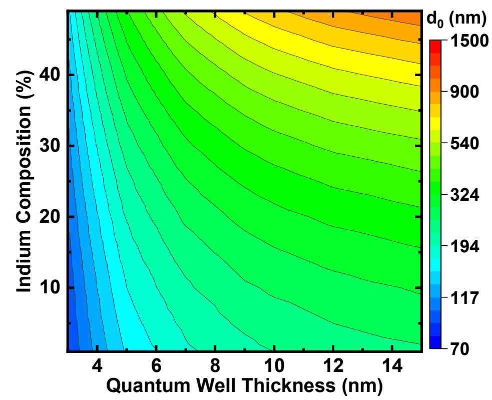

Fig. 4. The optimum choice of the cavity thickness as a function of In composition in InGaAs and QW thickness of the ε-Ge active layer.

thicknesses. Larger cavity results in a poor overlap of the optical field with the QW and thus a poor Γ_m. Whereas, for a smaller cavity, most of the optical field leaks into the cladding layer due to a large wavelength. A thin ε-Ge QW will result in a large effective band edge due to the large eigen energies (small λ_e) and a better Γ_m. Moreover, a thin QW will also have a smaller overlap with the optical field and thus will tend to lower the Γ_m. Due to these opposing effects, there exists an optimum value of cavity thickness at the inflection point, where the Γ_m is maximum. Thus, using AD, one can design an optimum ε-Ge/$In_xGa_{1-x}As$ QW laser with the desirable In composition in $In_xGa_{1-x}As$ layer and λ_e.

Results and Discussions

We identified that utilizing an optimal cavity thickness significantly enhances net gain while reducing J_{TH}. Our study

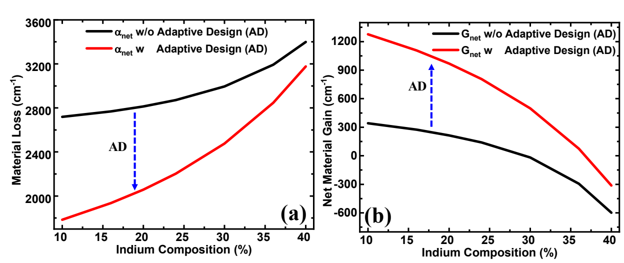

Fig. 5. Improvement in the lasing performance due to the AD as seen through (a) reduced net material loss and consequently (b) increased net material gain.

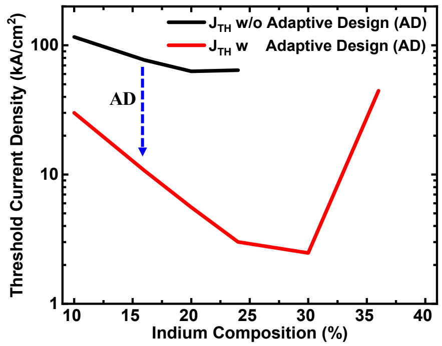

Fig. 6. Drastic improvement in J_{TH} indicating the importance of the AD methodology for the Ge QW laser.

reveals that neglecting AD results in not only a less optimized structure but degraded performance past In composition > 24%. Using AD methodology, as shown in **Fig. 5**, a 30% decrease in material loss and corresponding additional net material gain of approximately 700 cm^{-1} is calculated at In = 24%. As shown in **Fig 6,** when In > 24%, an unoptimized ε-Ge/$In_xGa_{1-x}As$ QW laser structure leads to a transition from Type-I to Type-II band alignment and gain does not overcome losses, where the J_{TH} is not quantifiable. As demonstrated in both **Figs. 5** and **6**, AD is not only crucial for enhancing lasing performance but is also imperative for maintaining optimal performance at higher In composition in $In_xGa_{1-x}As$. A decrease of ~1 order of magnitude in J_{TH} at In = 24% was observed using AD methodology (**Fig. 6**). Furthermore, **Fig. 7** shows a corresponding additional net modal gain of ~ 10 cm^{-1} at In = 24%, due to the compounding nature of increased modal gain and decreased loss. Our findings underscore the

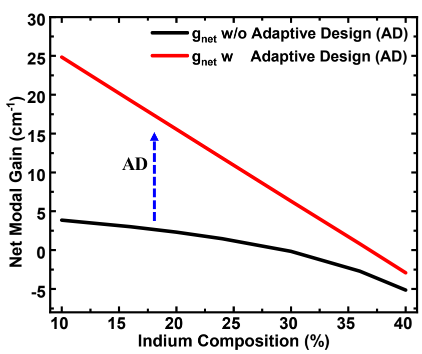

Fig. 7. Net modal gain for single Ge QW as a function of In composition in InGaAs layer, showing the improvement due to the AD methodology.

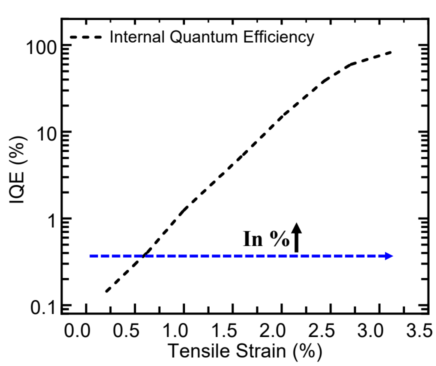

Fig. 8. An exponential rise in IQE with increasing tensile strain.

importance of IQE in tandem with optimal cavity thickness for improved lasing performance. Enhanced IQE correlates with increased radiative recombination rates and is directly influenced by the strain applied to the Ge layer, as shown in **Fig. 8**. Thus, one must need to implement an AD approach to improve the performance of ε-Ge/$In_xGa_{1-x}As$ QW laser for MIR applications with improved computation time.

Conclusion

The merits of an AD approach to improve lasing performance of a ε-Ge/InGaAs SCH QW laser were analyzed. Improvements in material loss (~30 % decrease), net modal gain (~10 cm^{-1} increase), and J_{TH} (> 1 order of magnitude decrease) at 24% In composition were observed using an AD approach. Moreover, an AD approach is imperative to realize a ε-Ge SCH QW laser, which is tunable for a wider range of In compositions. Taken together, this adaptative design reveals an efficient approach for implementation of a tunable tensile strained Ge laser for Si photonics.

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