On device concepts for CMOS-compatible edge-emitters based on strained germanium

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***Abstract*—We consider a device concept for edge-emitting lasers based on strained germanium (Ge) microstrips. The special SiN stressor design induces an inhomogeneous (tensile) strain distribution and requires lateral current injection. Microscopic calculations of the material gain for strained Ge enter our two-dimensional simulation of the carrier transport and of the optical field within a cross section of the device orthogonal to the optical cavity. We study the optoelectronic properties of the device concept for two different carrier injection schemes.**

I. INTRODUCTION

Monolithically integrated light sources on CMOS-qualified materials are a challenge in silicon (Si) photonics. Pioneering work in this direction is the successful demonstration of both optically [1] and electrically [2] pumped lasers based on a slightly tensile strained germanium (Ge) layer by MIT researchers, but their approach suffers from extremely high lasing threshold current density of $300\,\mathrm{kAcm}^{-2}$. One promising way to reduce the threshold is the enhancement of the optical gain by increasing the tensile strain. By the deposition of a compressively stressed SiN layer on top of a Ge/Si heterostructure a tensile strain can be induced using a CMOS-qualified technology [3], see Fig. 1. Edge-emitting lasers following such a design concept have an inhomogenous strain distribution and require lateral current injection. Therefore, existing techniques to estimate the device performance for Ge emitters such as rate equation models or 1D simulations for carrier transport only are not sufficient. In this paper we present results from [4] obtained by fully coupled 2D optoelectronic simulations using WIAS-TeSCA for two different device designs.

II. OPTOELECTRONIC SIMULATION APPROACH

The optoelectronic simulations rely on 2D models for the carrier transport and the optical field within a cross section of the Ge emitter orthogonal to the optical cavity, see Fig. 1 and 2. As described in detail in [5] this modeling approach assumes stable wave guiding and a homogenous power distribution in longitudinal direction and contains the van Roosbroeck system, Helmholtz equations for the transverse optical field and balance equations for the corresponding photon numbers.

For consistent embedding of gain computations into the simulation we follow an upscaling approach using an effective band model that accounts for the direct radiative recombination in the Γ-band, but assumes that charge transport of electrons is predominant in the L-band. This is done using an empirical gain model fitted to the microscopically computed gain, where it is crucial to fine-tune the band-gaps and the effective DOS masses in the simulations to the effective band structure from tight binding calculations, see [4]. The full band structure of the tensile strained Ge layer enters the microscopic calculation of the optical gain. The model was validated against experimental data obtained by PL measurements [3]. For details of the gain calculation we refer to [6], [7]. Free carrier absorption (FCA) is an import loss mechanism when high carrier densities are present in the active region of the device. For the discussion of our particular choice of the FCA parameters in Ge see [4].

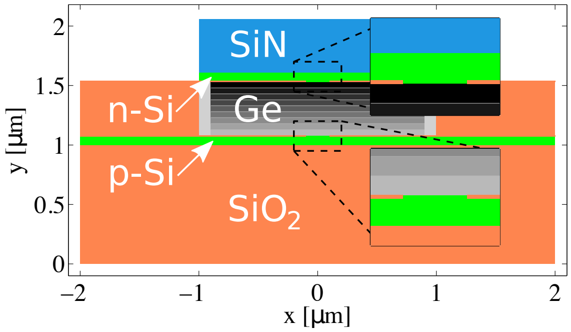

Fig. 1. Simulation geometry for the aperture device design. The device is made of SiN (blue), SiO$_2$ (orange), poly-Si (green) and Ge (gray). The nine shades of gray represent the values of the biaxial tensile strain increasing from bottom (0.35%) to top (0.7%). The insets magnify the oxide apertures used to inject the carriers into the central region.

III. DEVICE CONCEPTS AND SIMULATION RESULTS

A SiN layer as a stressor material on top of the optically active Ge region can be used to achieve higher tensile strain and material gain [3]. However, this stressor design requires a lateral current injection in contrast to the vertical MIT design based on thermal stress. We compare two different designs for Ge-on-Si edge-emitting lasers with tensile strained Ge microstrips (cavity length $400\mu\mathrm{m}$). Fig. 1 depicts a design with an oxide *aperture* for improving the current injection into the optical mode. This is in contrast to the *standard* design, for which the aperture is absent and the highly doped Si layers

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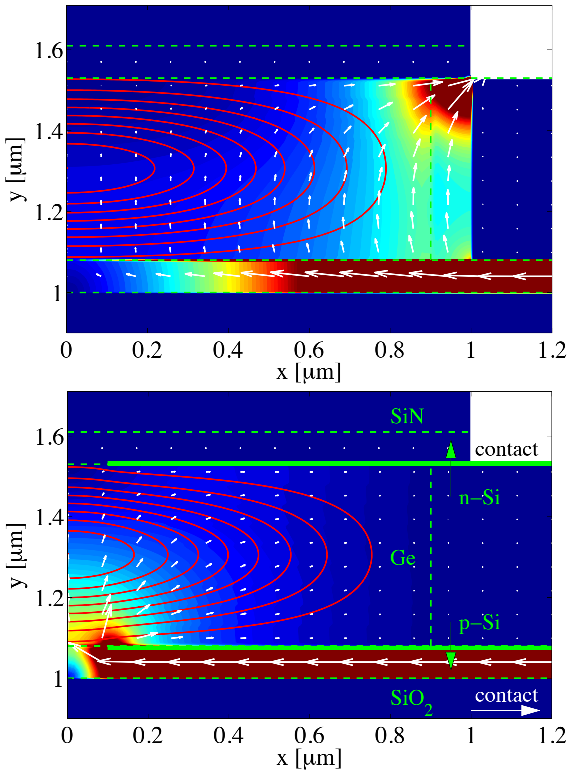

Fig. 2. Hole currents (white arrows) for the standard design (top) and the aperture design (bottom) above threshold for an optical output power of 0.05 mW, see [4]. The isolines of the mode intensity of the fundamental TM mode are indicated in red. The colored background indicates the distribution of Joule heating effects by showing the magnitude of the current density vector.

form a contact along the whole Ge active region, cf. Fig. 2.

We study the optoelectronic performance of the two device designs by 2D simulations with the device simulation package WIAS-TeSCA using a calibrated gain model. Both designs favor emission in TM polarization in comparison to TE polarization, mainly caused by higher material gain and optical confinement for TM. The typical hole current distributions above lasing threshold are depicted in Fig. 2. For the standard design one observes a high 'leakage' current along the lateral boundary not contributing to stimulated recombination. This 'leakage' effect limits the benefit of the increased material gain to reduce the threshold in comparison to vertical device concepts [2] with lower strain. In contrast, the aperture design improves the current injection into the optical mode resulting in a 4× lower threshold current than the one for the standard design. This demonstrates the high potential of the stressor concept.

An analysis of the modal gain shows that the inhomogeneous strain distribution, assumed to increase from 0.35% (bottom) to 0.7% (top) in our case, leads to a strong variation of the available material gain favoring higher values of the strain at the top of the Ge region, see Fig. 3. Since the modal intensity is concentrated in the center of the Ge layer, only a fraction of the available material gain contributes to the modal gain due to the reduced overlap. Therefore, overlap engineering for material gain and modal intensity is important for device concepts with inhomogeneous strain distribution.

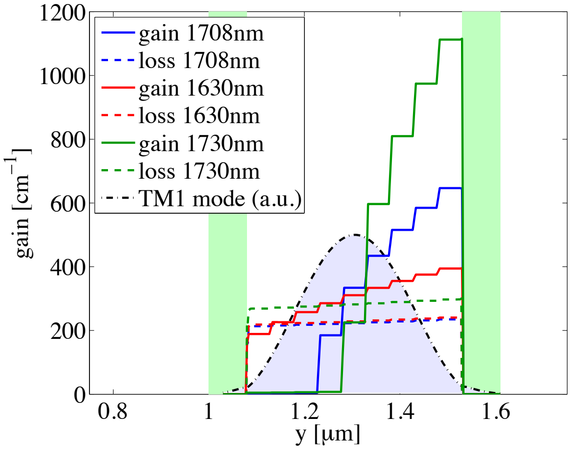

Fig. 3. Profiles for material gain and free carrier absorption for different wave lengths above threshold as a function of the y position shown at the center (x=0) of the device, see [4]. The intensity of the fundamental TM mode is indicated as the shaded area.

IV. CONCLUSION

We discussed the influence of current injection and modal gain on the performance of device concepts for Ge emitters with SiN stressors by 2D optoelectronics simulations. In particular a better overlap between material gain and modal intensity opens the opportunity for further performance enhancement.

ACKNOWLEDGMENT

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