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Analysis of the optical coupling between 2.3 μm GaSb diode lasers and passive waveguides for monolithic integration on Si platforms

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***Abstract*—Although discrete lasers grown on silicon have been demonstrated, light coupling into on-chip passive waveguides remains to be properly studied. We investigate theoretically the optical coupling between 2.3 µm GaSb-based diode lasers (DLs) epitaxially grown on a Silicon photonic chip and the passive waveguides.**

Keywords—III-V integration on Silicon, Silicon Photonics, Photonic Integrated Circuits.

I. INTRODUCTION

Silicon photonics has been widely used for telecom applications as well as for realization of optical interconnects, exploiting the miniaturization provided by Photonic Integrated Circuits (PICs). Nowadays, PICs can also be implemented for sensing purposes. Gases such as CH_4, NH_3 or CO show fingerprint absorption lines in the wavelength region of 2-2.5 μm, with CH_4 displaying its second most important absorption line at 2.3 μm [1]. The increased use of silicon for PICs applications is mainly based on availability of cheap Si wafers, strong optical confinement and low losses in the wavelength range between 1.1 and ~ 6.5 μm [2]. However, the main bottleneck of silicon photonics is related to its indirect bandgap making it an inefficient light emitter. The best technology to get coherent light emission is based on III-V semiconductor laser diodes (LDs). In this work, we consider a GaSb-diode laser (DL) grown on on-axis (001) Si substrate butt-coupled with a passive waveguide. The cavity mirror is based on the definition of etched-cavity ridge DLs [3]. Moreover, during epitaxy of the III-V laser on Si, poor quality III-V materials are deposited close to the passive waveguide interface and should be removed. Consequently, an unavoidable air gap (> 5 µm wide) separates the passive and active waveguides. 3D Finite Difference Time Domain (FDTD) simulations are performed to evaluate the transmitted power as function of this air gap between a GaSb- based DL and a passive waveguide made of SiN, Si, Germanium (Ge) and Chalcogenide (ChG). Efficient light coupling is achieved in the absence of a gap between the two waveguides. However, the introduction of an air gap drastically reduces the optical transmission. In order to improve the coupling performances, we propose alternative approaches such as filling the gap with high-index materials or using polymer-based optical waveguides.

II. RESULTS

A. Waveguide based on silicon technology

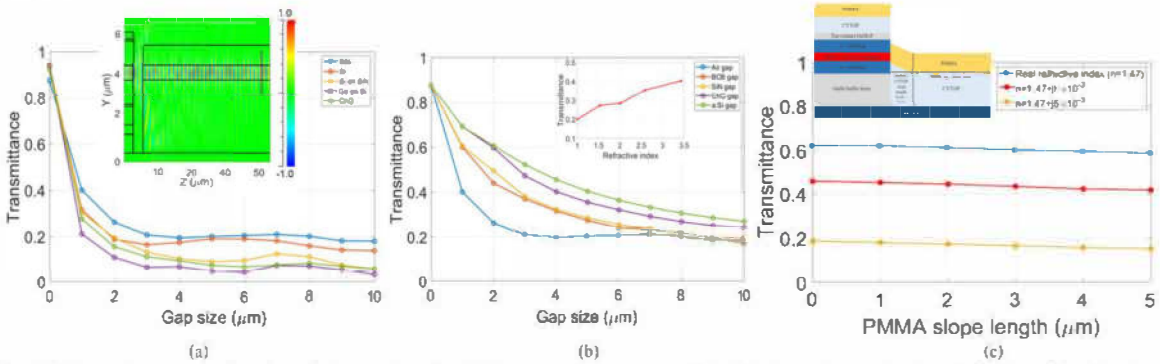
In this section, we focus on the light transmission analysis based on a butt-coupled geometry between a GaSb-DL and a passive waveguide based on Si technology. First, we analyze the impact of the air gap on the optical coupling for a waveguide made of SiN, Si, Ge or ChG core surrounded by a SiO_2 cladding. The DL ridge as well as the passive waveguide is chosen to be 10 µm wide, lossless media and emission wavelength fixed at $\lambda = 2.3$ µm. The simulation results point out an important coupling reduction when the air gap is introduced. Particularly, the transmittance decreases from ~80 % down to ~20 % for a 5 µm gap width and stays approximately constant for wider gaps (Fig.1 (a)). These results outline the influence of the air gap and the necessity to reduce the losses once the light propagates in the free-space region before to be coupled into a passive waveguide. We propose to use materials such as Benzocyclobutente (BCB), SiN, ChG and amorphous Silicon (a-Si) to fill the gap in order to reduce the beam divergence and improve the coupling (Fig. 1(b)). Considering a 5 µm wide gap, the results show a doubling of the optical coupling, from ~20 % (Air gap) to ~40 % (a-Si gap) (inset in Fig. 1(b)). However, a-Si would not be easy to implement during the fabrication process as it would require the deposition of a thick conformal a-Si layer, and could create shorts on the laser facets. Among all the other filling materials, a viable approach is to use BCB by spin coating, even if the coupling enhancement will be smaller.

B. Polymer based waveguide

Another option to improve light coupling is to use polymer-based waveguides that can be fabricated using spin-coating and photolithography or electron beam lithography. In this approach, the air gap is suppressed as the polymer will match the end facet of the DL thanks to a uniform distribution. However, the DL is an obstacle to the uniform polymer spreading. We thus assumed a slope configuration combined with a planar waveguide geometry (inset in Fig. 1 (c)). We studied the optical coupling for $\lambda = 2.3\ \mu m$ into a passive polymer waveguide made of cyclized transparent optical polymer (CYTOP®) as lower cladding, Polymethyl Methacrylate (PMMA) as core and an air top cladding and at the sidewalls. We analyzed the optical coupling as function of the PMMA slope length. Considering a lossless PMMA material, ~60% of the light is transmitted (Fig. 1(c)). This value is smaller than the ~ 80% in the case of SiN waveguide as previously discussed. However, the transmittance stays almost constant when varying the slope length. In order to account for a potential absorption contribution from the PMMA material, we introduced an extinction coefficient of 1×10^{-3} 5×10^{-3} [4]. The transmitted power reaches values close to 40% and 20% with 1×10^{-3} and 5×10^{-3} extinction coefficients, respectively, which shows that the coupling performances can rapidly deteriorate when the imaginary part of the polymer complex refractive index is taken into account.

III. CONCLUSION

We have modeled the optical coupling between 2.3 µm GaSb DL epitaxially grown on on-axis silicon (001) and on chip passive waveguides pointing out the effect of the unavoidable air gap on the light coupling and proposed different scenarios to improve the transmission.



(a) (b) (c)

Fig. 1. Transmittance as a function of air gap sizes for different passive core materials. The inset shows the electric field profile related to the fundamental TE optical mode coupled into the passive waveguide through an air gap 3 µm wide. (b) Coupling study for a SiN waveguide: transmittance as a function of gap sizes filled with different materials. The inset outlines a transmittance improvement as the refractive index value, in a gap 5 µm wide, is increased. (c) Transmittance as function of the PMMA slope length. The inset shows the cross-section of the hybrid device with a passive waveguide made of polymeric materials.

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