Evanescent Coupling of a Center-Cleaved Mid-Infrared Quantum Cascade Laser to a Suspended Silicon-on-Insulator Waveguide

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Abstract: Two-dimensional finite-element analysis of the evanescent coupling of a center-cleaved quantum cascade laser to a suspended silicon waveguide in Silicon-on-insulator shows peak efficiency at a separation of 1.0 μm for a wavelength of 4 μm.

OCIS codes: (130.0130) Integrated optics devices; (140.5965) Semiconductor lasers, quantum cascade; (130.3060) Infrared

1. Introduction

While the benefits of integrated silicon photonics are broadly accepted and have received significant interest in the near-infrared (near-IR), currently, there are only a few groups around the world investigating the role of group IV photonics in the mid-IR range. Among the attractions of silicon based technology for the mid-IR is the chip-level integration of passive and active components, as well as utilizing silicon's strong nonlinear optical effects. Also, given the already established role of silicon in the electronics industry, an integrated approach may drastically reduce the cost of manufacturing and miniaturization of such systems, enabling potentially disposable lab-on-chip CMOS compatible optoelectronic systems for use in spectroscopy, chemical and biological sensing, and free space communication [1]. Despite the many advantages, a major challenge for mid-IR group IV photonics is the absence of monolithic lasers, amplifiers and detectors, while a wide variety of active photonic components already exist in III-V based semiconductor devices.

Hybrid integration using direct and adhesive-assisted wafer bonding of GaAs and InP, the primary substrate materials of III-V photonics, with silicon require tackling the large lattice constant and thermal expansion coefficient mismatch between the substrates and have been extensively studied [2]. Here we present a hybrid non-contact approach, where Quantum Cascade (QC) lasers, which are a very promising source of mid-IR radiation currently covering the 3-25 μm and the THz regions [3], are evanescently side-coupled to suspended silicon waveguides in order to relax the stringent wafer surface requirements.

2. Waveguide design and modeling

Figure 1(a) shows the schematic of a center-cleaved QC laser ridge, where the red region signifies the active core. The waveguide, on the right, is fabricated in the silicon-on-insulator (SOI) material system. At telecom wavelengths the oxide layer provides the needed index contrast for optical confinement, however, silicon dioxide becomes optically lossy at $\lambda > 3.6$ μm [4] and hence is not suitable for the longer wavelengths. As a solution, the oxide layer underneath the guiding region is etched away, resulting in a suspended air-clad structure to minimize loss while increasing optical confinement.

The dynamics of the coupled system show a strong dependence on the size of the gap between the center-cleaved QC laser and the waveguide, the width of the waveguide, the waveguide's radius of curvature, the length of the coupling region, as well as the wavelength of the propagating mode. In this work we have used the commercial software COMSOL Multiphysics for a 2D finite element analysis of this system which offers a variety of advantages compared to empirical or analytical descriptions and allows for the possibility of a more accurate prediction and optimization of aforementioned parameters. Figure 1(b) and 1(c) show a finite element simulation of such a setup, where the air gap between a single transverse-mode QC laser and an SOI waveguide is varied between 0.05 μm and 0.95 μm. The widths of the laser and the waveguide are chosen such that the propagation constant in the two regions is matched and the bending radius of the waveguide is 100 μm. The simulations show that coupling efficiency peaks when the separation of the QC laser and the waveguide is about 1.0 μm at a wavelength of 4.0 μm and that the gap size corresponding to the peak efficiency is larger at longer wavelengths, making the structure easier to assemble for longer wavelengths.

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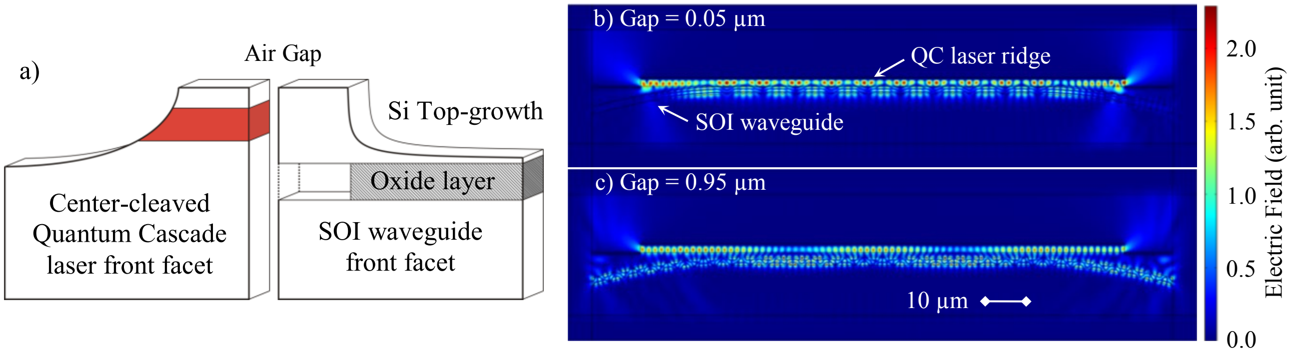

Fig. 1: a) Schematic of a center-cleaved Quantum Cascade laser ridge evanescently coupled to an SOI waveguide. The oxide layer is etched from underneath the SOI guiding region to reduce loss for the longer wavelengths and improve optical confinement. b) The top view of the electric field distribution in a quantum cascade laser, evanescently side-coupled to a suspended silicon waveguide where the gap is 0.05 µm and c) 0.95 µm respectively. The mode is excited at the leftmost part of the center-cleaved QC laser ridge and is TM polarized; λ = 4.0 µm.

3. Processing and fabrication

The waveguides are first patterned on SOI using conventional lithographic techniques and processed via Bosch dry etching. The thickness of the top device silicon and the oxide are 1.5 µm and 3.0 µm, respectively. Next trenches are etched parallel to the waveguides to allow for the buried oxide to be chemically etched away, leaving a suspended structure. The edges of the diced wafers are processed using chemical mechanical polishing (CMP) and in case of edge damage, the facet is restored using focused ion beam (FIB) milling (see figure 2).

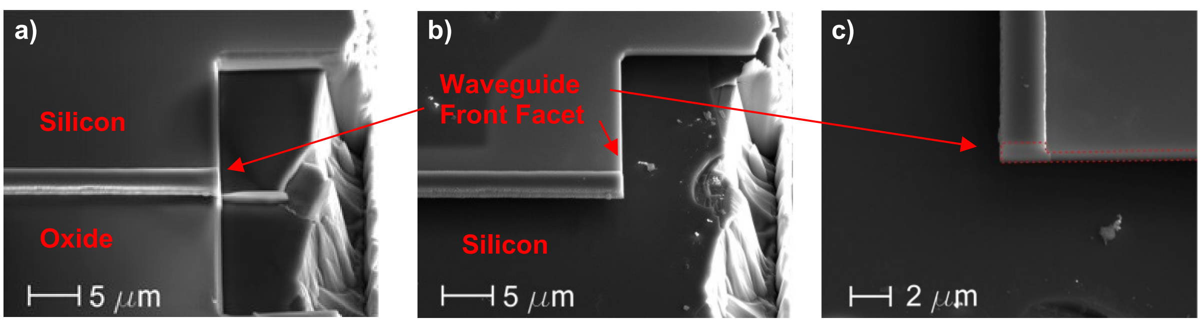

Fig. 2: Scanning electron microscope (SEM) image at 45 degree inclination of a silicon waveguide before and after the oxide removal. a) Waveguides are patterned via optical lithography and Bosch dry etching and the front facet is processed by chemical mechanical polishing (CMP) and focused ion beam milling. b) Trenches are etched parallel to the waveguide, exposing the buried oxide and the oxide is then removed by HF chemical etching forming the undercut. The cross-section of the suspended waveguide is shown in c).

4. Conclusion

We have numerically investigated the evanescent coupling of a center-cleaved QC laser to a suspended silicon waveguide fabricated on an SOI platform. The simulations show that the optimum value of separation between the laser ridge and the waveguide is about 1.0 µm corresponding to a wavelength of 4 µm. The feasibility of the method is further demonstrated by fabricating the suspended structures which proved resilient upon etching away the supporting buried oxide. This work is supported in part by MIRTHE (NSF-ERC).

5. References

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