Evanescent Wave Coupling in Hybrid III-V/SOI Nanolaser

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ABSTRACT
Heterogeneous integration of III-V semiconductor compounds on SOI is one of the key technologies for next generation on chip optical interconnects. The use of photonic crystals nanolasers, within this context, represents a disruptive solution in terms of footprint, activation energy and ultrafast response. In this work, we study the evanescent wave coupling occurring between the nanolasers and a subjacent Si wire and demonstrate that more than 90% of the light is funneled into the Si circuitry.

1. INTRODUCTION
Heterogeneous integration of III-V semiconductor compounds on Silicon on insulator (SOI) is believed to be one of the key technologies for next generation on chip optical interconnects. Indeed, this hybrid platform combines the best of both material systems: on one hand, the CMOS compatibility and the predispositions of silicon to be used for fabricating an ultra compact low loss optical circuitry; on the other hand, the versatility of III-V semiconductors for making laser sources and active devices. This approach was recently used for demonstrating laser emission [1,2]. In this article, the concept of hybrid Si/III-V semiconductor photonics is scaled down to nanophotonics. III-V Photonic crystal nanolasers are integrated with and coupled to SOI waveguides circuitry. This disruptive approach allows us to obtain low threshold hybrid lasers in the telecom window within a footprint as small as 5um². We experimentally study the evanescent wave coupling in the device as a function of the structure parameters and show that more than 90% of the emitted light is funneled into the SOI wires.

2. DESIGN AND FABRICATION OF THE HYBRID STRUCTURE
The hybrid structure under study is schematically represented on Fig. 1a. It is a 2 optical level structure where one level is constituted by a single mode SOI wire waveguide and the other, by an InP-based photonic crystal nanocavity with 4 InGaAs/InGaAs quantum wells embedded which emit at 1.55 μm. The 2 levels are separated by a low index layer which preserves the vertical optical confinement within the SOI waveguide and the PhC cavity. Coupling is ensured by the penetration the evanescent tail of the optical modes into the other level [3].

The chosen nanocavity is a “wire” cavity, which is a Fabry-Perot type cavity formed in a single mode wire waveguide (550 nm width and 255 nm height). High reflectivity mirrors are constituted by a single row of holes drilled into the material. The holes diameter and the pitch of the 1D lattice are fixed to be respectively at 177.5 nm and 370 nm to obtain a large high reflectivity bandwidth around 1.55 μm. The sizes of the 3 holes on each side of the cavity are tapered down in order to increase the quality factor by adapting the propagating guided mode to the evanescent mirror mode [4].

![Figure 1. Hybrid III-V Semiconductor Photonic Crystal on SOI waveguide circuitry. a) Schematic view of the structure. b) SEM images of the fabricated sample. Inset: SEM image close-up of a wire cavity.](image_url)

The fabrication of the hybrid structures is based on die-to-die adhesive wafer bonding and mix-and-match deep UV/electron beam lithography. The low index layer is a bilayer composed of a thin layer of BCB (80 nm) and a layer of SiO₂. 3 samples are fabricated with different SiO₂ thicknesses (200 nm, 300 nm and 400 nm).

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A scanning electron microscope picture of one of the fabricated structures is given on Fig. 1b where a wire cavity can be seen positioned on top of a SOI waveguide. The lithographic positioning has a demonstrated precision better than 30nm, which allows us to neglect the impact of the lateral offset between the two levels on the evanescent wave coupling [5].

3. LASER OPERATION
Laser emission is explored at room temperature by optically surface pumping the wire cavities using a modulated 800 nm laser diode. The emitted light is collected via the gratings at the extremities of the 8 mm long SOI waveguides with SMF-28 optical fibres tilted at an angle of $10^\circ$ to the surface normal and is analysed using a spectrometer equipped with a cooled InGaAs detector array. We plot in Fig. 2a, in log-log scale, the output peak power of the emitted light as a function of the absorbed pump peak power for a 450 nm-long cavity coupled to a 500 nm wide SOI waveguide (SiO$_2$ thickness is 400 nm). As expected for laser emission, the curve is S-shaped, with a threshold of $17 \mu W$ (external peak power 2 mW). The emission wavelength can be easily tuned by adjusting, for example, the cavity length as shown in Fig. 2b [6].

![Graph showing laser output power vs absorbed pump power and emission wavelength vs cavity length](image)

**Figure 2:** a) Intensity of the emitted light outputting the SOI waveguide as a function the absorbed pump power. The black line is a fit of the experimental data using the rate equations. b) Emission wavelength as a function of the cavity length, i.e. centre to centre distance between the first 2 tapered holes.

4. COUPLING EFFICIENCY
In order to determine the coupling efficiency of the laser emission into the SOI wire, we perform pump and probe measurements to obtain transmission spectra around the cavity resonant wavelength as a function of the pump power, i.e. as a function of the material gain or absorption.

![Graph showing transmission and coupling efficiency](image)

**Figure 3:** a) Transmission at resonance as a function of the pump power. b) Coupling efficiency of the emitted light into the SOI wire as a function of the structure parameters.

As can be seen on Fig. 3a, the transmission at resonance firstly decreases when the pump power is increased reaching a minimum at 12.4 $\mu W$. By analysing the system with coupled-mode theory [3], we can show that, at this minimum, gain compensates exactly the unloaded cavity losses $\Gamma_0$ (cavity without waveguide).
The coupling constant to the SOI waveguide $\Gamma_c$ can then be determined by measuring the full width at half maximum of the resonance in the transmission spectrum. Then, as the pump power is further increased, net gain is observed. In order to retrieve the coupling efficiency, which can be written
\[ \eta = \frac{\Gamma_c}{\Gamma_{so}/(\Gamma_{so}+1)}, \]
where $\Gamma_{so}$ is obtained by fitting the light-light curve with regular rate equations model for QWs laser.
We performed this study for different types of samples where the thickness of the low-index layer and the width of the Si waveguides are varied in order to vary the strength of the evanescent coupling. The coupling efficiency can be controlled by adjusting the parameters of the structure and can reach values as high as 90% as seen on Fig. 3b. A good balance between $\Gamma_c$ and $\Gamma_{so}$ has to be found in order to obtain large coupling as well as efficient laser emission.

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