A novel approach to an efficient LED on SOI

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A novel design geometry for an optically pumped LED by integrating thin III-V membranes on SOI is proposed. The depicted device consists of a silicon waveguide feeding a high refractive index contrast III-V membrane waveguide. Several simulation tools were used to optimize the design of the coupler, the absorption properties of the pump, the collection efficiency of the generated spontaneous emission and the heat properties of the membrane. Combined these simulation results predict a high power efficiency of the device, while keeping the fabrication tolerances high. Following the simulation, we present a first proof-of-concept demonstration of the LED.

Introduction

Despite being initially aimed at data and telecom application, silicon photonics is rapidly branching out to a broader range of applications, such as sensing and microscopy. These new applications, e.g. spectroscopic sensing, often need a broadband optical light source. Generally speaking, one can choose between three options for the optical source: tunable lasers, laser arrays and (superluminescent) LEDs. [1] To overcome the bottleneck of silicon photonics, the lack of efficient light sources due to the indirect band gap, heterogeneous integration of III-V materials such as InP with the SOI platform has been developed. However, designs such as in [2] and [3] still require many processing steps after bonding. Keeping in mind that we primarily want to leverage from fabrication technologies in silicon rather than InP, the post-bond complexity is a significant disadvantage. Of the three options above, only LEDs are simple enough to achieve decent total yield, but they will typically suffer from poor efficiency.
Therefore we propose a novel LED device geometry. By integrating thin InP-based membranes, we can create an efficient, optically pumped LED. The III-V processing after bonding is straightforward. In order to have a fully integrated device, a pump light source such as a VCSEL can be envisaged to be flip-chip bonded on top of an SOI grating coupler [4, 5].

Device design

The overall device design is depicted in figure 1. The LED consists of a SOI photonic wire, a III-V ridge waveguide and a tapering section connecting the two. The SOI photonic wire is a fully etched 220nm thick silicon-on-insulator wire. Because of the adhesive bonding process used, the upper cladding is DVS-BCB. The III-V ridge waveguide is

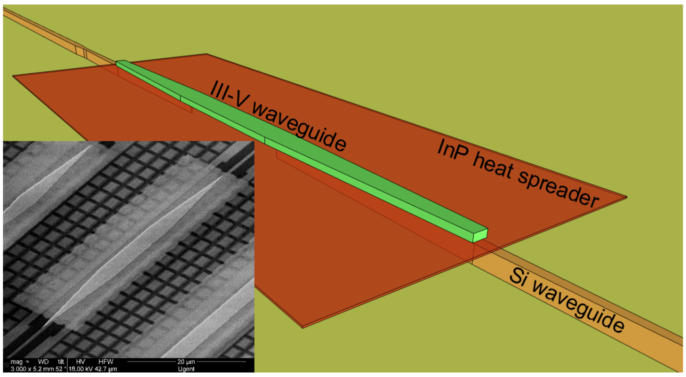

Figure 1: Illustration of the proposed LED structure.

composed of a InP-based 120nm thin membrane, consisting of multiple InGaAsP quantum wells and barriers and two InP SCH layers. The ridge etch goes through the upper SCH and active region. The dimensions and shape of this membrane were chosen such that the optical pump (injected through the silicon waveguide) will be efficiently absorbed and the spontaneous emission will be efficiently collected. A ridge waveguide is preferred over a stripe because of thermal reasons as the lower SCH acts as a heat spreader. Because of the high index contrast in the III-V membrane waveguide, the tapering section can be short (18μm) and fabrication tolerant. We elaborate on the choice of these parameters in the sections below.

The pump and signal in the proposed membrane-LED can be either co-propagating or counter-propagating (so-called transmissive and reflective mode). Since the pump is absorbed very strongly, the carrier concentration will be much higher at the incoming taper than at the end of the III-V waveguide. There will be an optimal length for transmissive mode, as the end of a too long device will be absorbing the signal. Reflective mode Given the strong pump absorption, the carrier concentration will be highest at the incoming taper and lower towards the end of the III-V waveguide due to pump depletion. For the signal in transmission, there will be an optimum length as a very long device may not be pumped completely to transparency and hence absorb the signal. A signal in reflection does not suffer from this drawback, but adds more complexity to the SOI design as one needs a circuit to (de)multiplex the pump and signal.

- *Efficient pump absorption* -

In optically pumped device it is of paramount importance the pump is well absorbed. Therefore, figure 2 shows the confinement in each quantum well as a function of the membrane height (the quantum barrier thickness was varied). Simulated by FIMMWAVE, we assumed a pump at 1310nm, a membrane width of 1.5μm. The black vertical line depicts 120nm, which we used in further simulations.

One can see that there is a clear optimum as a function of membrane thickness, at 115nm. The confinement per well is virtually independent of the number of quantum wells, hence we best put as many quantum wells in the 115nm as possible. We choose 4 quantum wells, which give us a total confinement of 18.4%.

- *Efficient collection of spontaneous emission* -

The high refractive index contrast waveguide also boosts the collection of spontaneous

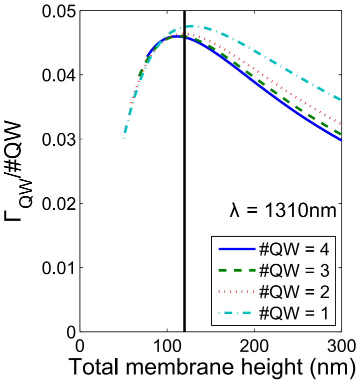

Figure 2: Confinement as a function of III-V membrane height.

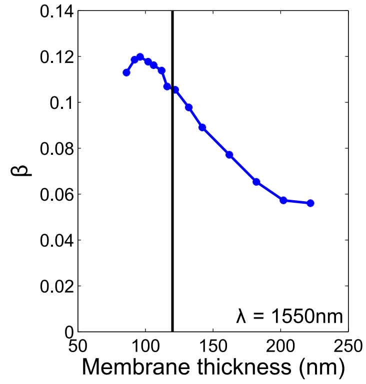

Figure 3: Spontaneous emission collection efficiency as a function of III-V membrane height.

emission, which is where the traditional LED loses a lot in efficiency.Figure 3 shows the coupling of a dipole source (1550mn, TE polarization) to the fundamental TE mode, as simulated by Lumerical FDTD Solution. To emulate the multiple uncorrelated recombinations, the result was averaged for different dipole positions.
Again, there is a clear optimum, this time at about 96nm, where 12% of the radiated light is collected in one direction (there is another 12% collected in the reverse propagating mode). At our chosen membrane thickness the collection is slightly lower, at 10%.

- Thermal heatsink -
To simulate the effect of heat on this small device, we used COMSOL's heat transfer module. We assume the active region to be a source of heat, BCB cladding around the membrane (320nm below and 2μm on top), the buried oxide is 2μm thick and the silicon substrate at room temperature. A stripe waveguide of 1.5μm wide and 120nm high has a length specific heat resistance of 76KcmW^{-1}. For the same rib waveguide, where the 20nm bottom InP SCH is 40μm wide, the length specific heat resistance has reduced to 45KcmW^{-1}. Hence, although the 20nm thick InP heat spreader has virtually no influence on the optical mode, the thermal resistance has been decreased by 40%.

- Efficient and simple tapering section -
The thin III-V membrane renders a small effective refractive index of only 2.3 (for a 1.5μm wide device). This means that even with a 220nm thick silicon device layer, we can make an efficient, fabrication tolerant taper design, as confirmed in figure 4 with the FIMMPROP module of FIMMWAVE. The III-V tip was chosen 800nm, which is a lot broader than what can be tolerated in other designs in heterogeneous integration. First of all, at longer taper lengths, we can see that the transmission is quasi constant, indicating that the abrupt interfaces such as the taper tips don't induce a lot of loss or higher order modes. Thicker bonding layers offer slightly better transmission, showing still slight influence of the interfaces. The difference is within 0.5dB though. The shorter tapers are of course not adiabatic, which can clearly be seen. Once the taper is longer then $\pm 10\mu$m, we come into the adiabatic regime. This means that we can make very short tapers, even as short as 18μm is a safe choice.

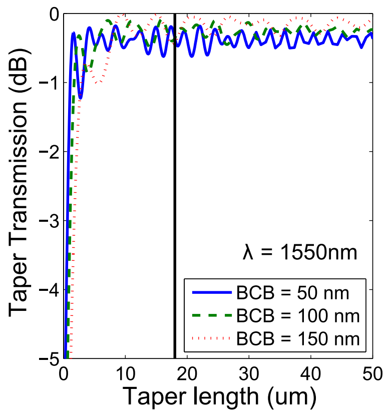

Figure 4: Taper transmission as a function of taper length.

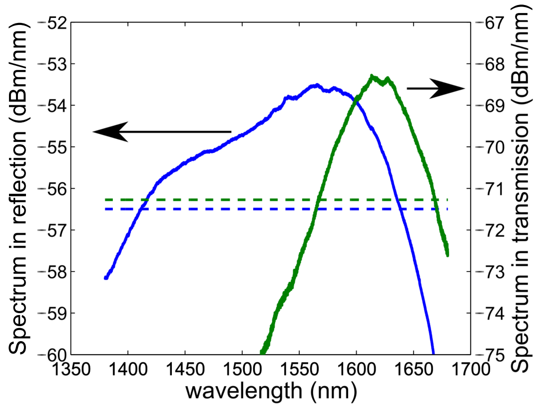

Figure 5: Measured spectrum from the LED light coupled to the silicon waveguide.

Experimental result

The depicted device was fabricated using wet etching and photoresist masks. Figure 5 shows the spontaneous emission spectrum in the silicon waveguide. The 50μm long LED was pumped using a 1310nm laser diode through the waveguide (0.5mW in the Si waveguide) and the generated light was measured both in reflection and transmission. We can see that the signal power spectrum in transmission is $\pm$15dB lower than the one in reflection. Also the peak wavelength and the 3dB bandwidth are different: for the signal in reflection, these are 1565nm and 227nm respectively, in transmission 1613nm and 100nm. Note that these bandwidths are huge, the reason is currently under investigation. The fact that the signal in transmission is blue shifted with respect to the one in reflection could indicate the LED is not pumped completely. A similar spectrum is generated at the beginning of the LED, but towards the end the shorter wavelengths are absorbed again.

Summary

To combine easy fabrication and efficiency, an optically pumped membrane LED was proposed and supported by simulations. A first experimental demonstration of the optically pumped LED in both reflective and transmissive mode was also shown.

References

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