

Densely integrated membrane-based nano-beam lasers for optical interconnects.

Aura Higuera-Rodriguez¹, V. Pogoretskiy¹, P. J. van Veldhoven², A. Fiore², D. Heiss¹, M. Smit¹

Eindhoven University of Technology, Den Dolech 2, 5612AZ, Eindhoven, The Netherlands

¹ Photonic Integration, Department of Electrical Engineering

² Photonics and Semiconductor Nanophysics, Department of Applied Physics

Dense laser integration is an increasing necessity for communication systems. However, while dense small lasers bring advantages as smaller footprint and threshold current, it raises challenges due to the shortening of the gain section, which in turn increases the series resistance; require very efficient mirrors and tight fabrication control. Therefore, high density deployment in an on-chip scheme is not only limited by the device footprint but also by the high series resistance of micro-nano-scale-lasers.

Introduction

Today, more than ever before, communication data centers are entitled to fulfill the needs of increasing speed and bandwidth derived from Moore's law. Soon, the current electronics scheme will not be able to fulfil such requirements since it suffers from speed limitation and excess heating, factors that prevent further chip density deployment and speed rising because of the RC constant limitation. Therefore, moving towards photonic integrated devices is a natural choice [1]. A solution based on a III-V membrane platform named InP-Membranes on Silicon (IMOS) was recently proposed [2], where a high refractive index contrast between the membrane and the substrate enables extreme miniaturization of the photonic devices. These small devices are suitable for low threshold operation.

Many passive photonic devices have been made directly on silicon or using membrane platforms as Silicon-On-Insulator SOI and IMOS [3]. However, realization of lasers electrically pumped remain as the holy grail of any photonics platform, since the indirect bandgap of silicon prevents lasing; and, the immaturity of III-V processes still represents an expensive option in terms of integration in comparison with the very well established, standardized and cheap CMOS process.

In this contribution we present our efforts in fabricating electrically pumped nano-micron-scale-lasers. In the first part of this paper, we discuss the requirements for an efficient electrically pumped micrometer laser in terms of optical and electrical properties. In the second part, we describe the design of a 1D photonic crystal (PhC) nano-beam laser. We consider the fabrication complexity for the concept, and assess the potential challenges in terms of fabrication. Further, we describe how we dealt with the critical fabrication steps of the process and formulate concept-based conclusions.

Design of micro- and nano-scale lasers

As mentioned, miniaturization of lasers imposes strict requirements on the reflectivity of the cavity mirrors. This can be illustrated by considering a Fabry Perot cavity with mirror reflectivity R_{mirror} , length l and a modal gain g_{modal} . For a better understanding,

we plot $1-R_{\text{mirror}}$ on a logarithmic scale of such a cavity as a function of length for a range of modal gains between 10/cm and 500/cm. As the length of a laser is reduced, more perfect mirrors are required, for example $R_{\text{mirror}}=0.98$ is needed for lasers shorter than a micron (at $g_{\text{modal}}=500/\text{cm}$) which is very challenging to achieve. In the following, we consider a five micrometer length laser and a modal gain of 500/cm. As shown in Figure 1a) facet reflection of 90% is needed in this case. Similarly, in Figure 1b), the number of periods needed for 0.9 facet reflectivity is displayed for different geometries of holes. As can be seen from the figure, elliptical holes represent a good compromise between number of holes and facet reflectivity. Furthermore, in Figure 1c) at 1550 nm facet reflectivity of 90% is achieved with just 8 periods of holes which means that we can have small lasers for optical interconnects in C band.

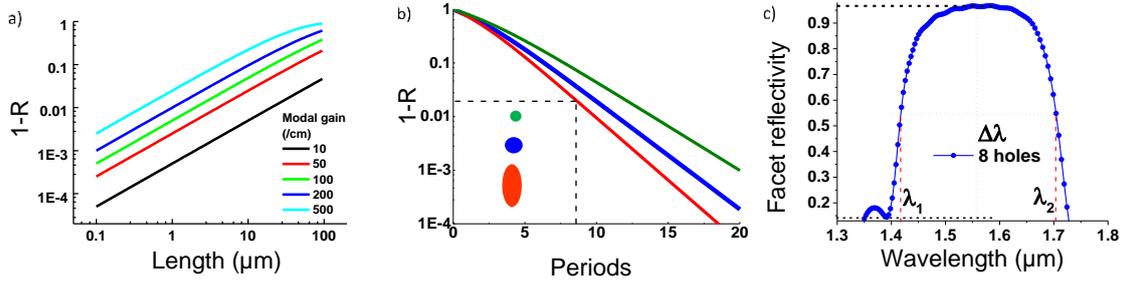


Figure 1: a) facet reflectivity versus device length in μm , b) facet reflectivity versus number of periods for different types of holes and c) wavelength versus facet reflectivity for 8 periods of elliptical holes.

In terms of performance, the wall plug efficiency is an important figure of merit, since it measures the ratio of the optical output power over the total electrical power used by the device. A high WPE is achieved by low power consumption, which in turn reduces the heat generated by the device leading to higher integration densities. In a simple model the WPE depends on the series resistance R_{ser} , differential efficiency η_d , threshold current I_{th} , current-independent series voltage V_s , and the ideal diode voltage V_d [4].

$$WPE = \frac{P_0}{P_{in}} = \frac{\eta_d \frac{h\nu}{q} (I - I_{th}) \cdot (I > I_{th})}{I^2 R_{ser} + IV_d + IV_s}$$

Figure 2 illustrates the dependence of the WPE on these parameters. In Figure 2a) the parameters are set to typical values for nano-lasers ($\eta=0.5$, $I_{\text{th}}=100 \mu\text{A}$ and $R_{\text{ser}}=1\text{K}\Omega$), and the WPE is plotted as a function of the output power (continuous line). The WPE is maximal with a value of 0.2 at an output power of 100 μW . For lower powers the WPE is limited by the threshold current as illustrated by the dotted line, where the series resistance is set to 0. For higher output power the threshold current is negligible compared to the current feeding the stimulated emission, and the WPE is limited by the series resistance of the device (dashed line). The maximum WPE is limited by the differential efficiency, as illustrated by the dashed-dotted line in fig 2a), where both I_{th} and R_{ser} are equal to zero. The maximum efficiency shifts when changing these parameters, making the ideal optimization dependent on the desired power output range.

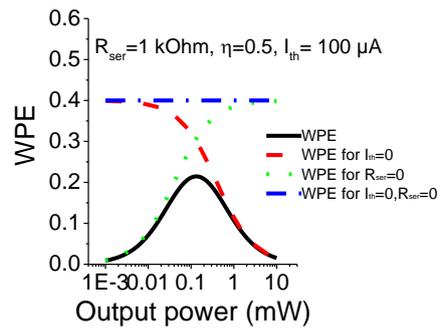


Figure 2: WPE versus output power in mW for $R_{ser}=1\text{K}\Omega$, $\eta=0.5$ and $I_{th}=100\ \mu\text{A}$.

Laser concept and fabrication process overview

The laser design has been performed with 3D FDTD and mode simulations. The design; depicted in Figure 3, is based on two main concepts. First, the use of elliptical 1D PhC holes as mirrors, which give high reflectivity with a small number of periods while having tight control of the wavelength and effective photon confinement by using the band gap effect [5]. The second concept is active-passive regrowth, which makes possible to design small in-line lasers with the advantage of high coupling efficiency to a passive waveguide. As for the contacts, we use Ge/Ag n-contact on the top of the cavity to reduce series resistance and optical losses [6], while Au/Pt/Ti is used for the p-contact, which is placed on the bottom and connected laterally to the structure.

The cavity length can be as short as $5\ \mu\text{m}$ with bulk InGaAs as active medium and reach Q factors of 690 at 1550 nm. As depicted, 8 periods of holes on the left side gives 90% of reflection, while five periods (85% reflection) on the right side are a good compromise between cavity feedback and waveguide coupling (Figure 3-center). Once established the design the main challenges of the concept are fabrication related.

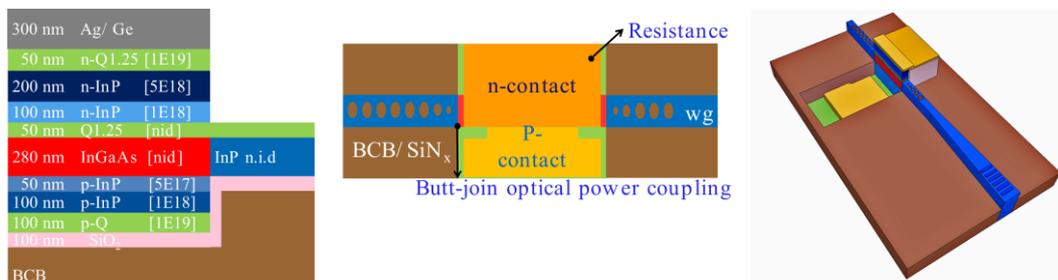


Figure 3: from left to right: layer stack, top view and 3D model of the nano-beam.

In the following we describe the main 3 fabrication challenges.

First issue arises due to the large surface to volume ratio of the device, which makes critical to reduce surface recombination and avoid erosion of the conducting layers. We solved this issue by an extensive passivation process that includes 4 cycles of oxygen plasma, followed by diluted phosphoric acid rinsing and deposition of a 100 nm layer of SiO_x by plasma enhanced chemical vapor deposition. This process has to be done in one single block to avoid oxidation of the sidewalls before SiO_x deposition.

The second critical issue is the lag effect, inherent of small features deeply etched. Severe degradation of the optical performance due to surface recombination and surface roughness is derived from a non-accurate definition of the holes. To solve this, several chemistries have been tried during etching on the inductively coupled plasma (ICP) for

the active part of our layer stack (780 nm). We tested oxygen chlorine, chlorine nitrogen and methane hydrogen. Figure 4a) shows the scanning electron microscopes of the aforementioned chemistries and the shape of the etched holes. Clearly, methane hydrogen is the best option to achieve uniform holes. However, because of the aspect ratio of the holes, the desired depth is challenging to reach, leading to long over-etch processes whose consequence is an increase of the lag effect. Therefore, we decided to pattern the ellipses on top of the waveguide area of the laser, reducing the etch depth from 780 nm on the active part to 280 nm on the passive part. In this way, a smoother, uniform etching with very small lag effect can be achieved.

The last and quite important challenge would be the quality of the active passive regrowth. We addressed this issue by developing a regrowth process capable to achieve a smooth transition with a dovetail shape on the light guiding axis, as shown in Figure 4b) right-SEM. Note how in the direction of the light the transition from active to passive is smooth and continuous while in the orthogonal cut (left-SEM in Figure 4b), the growth is interrupted by a V-groove gap formed because of the wet etching process on the $01\bar{1}$ crystal axis [7]. However, as the light is not traveling in that direction is does not harm the performance of the device.

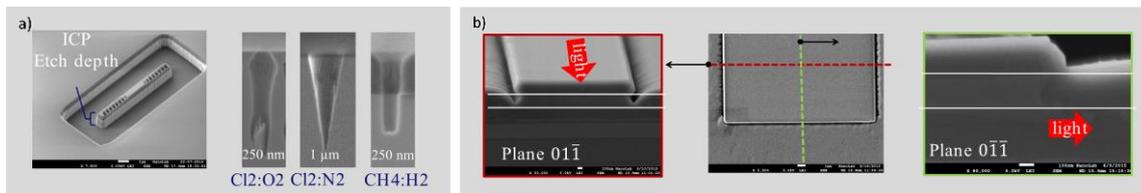


Figure 4: a) ICP tested etching chemistries for holes, b) active-passive regrowth planes.

Conclusions

A 1D photonic crystal butt-coupled nano-beam is the most suitable type of cavity for a micron size laser with output power around $100\mu\text{W}$. Although its fabrication is challenging, this type of cavity has advantages as very high reflection with small number of periods, high differential efficiency, short length and feasible Q factor. We showed initial fabrication results in terms of active-passive regrowth and PhC deep etching.

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