Manufacture-compliant InP-based metal cavity nanolaser design

Student Paper

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ABSTRACT

Nanolaser cavity structures are very sensitive to fabrication non-idealities. One of the important aspects is the cavity sidewalls non-verticality, produced with reactive ion etching, which have an impact on total optical losses. In this work the influence of etching slopes on the lasing performance is studied, and novel nanolaser cavity design on InP Membrane on Silicon platform with increased etching slopes tolerance is proposed. For cavity with width 800 nm and length 1000 nm threshold gain remains less than 1000 cm^{-1} for etching slopes up to 2 degrees.

Keywords: photonic integrated circuits, photonic nanolasers, nanophotonics.

1. INTRODUCTION

Nanoscale light sources (e.g.nanolasers and nanoLEDs) with high emission efficiency are an active area of study, as they can operate efficiently at low powers [1], GHz speeds [2], and be densely integrated [3]. This made nanolasers ideal candidate for short-distance communication devices in integrated neuromorphic photonics [4]. Since the first demonstration of electrically pumped metallic nanolaser [5], significant improvements in this area were achieved by different groups, e.g. lasing on higher temperatures [6] and waveguide coupling [3]. However, currently continuous wave operation was achieved for metal-dielectric cavity nanolaser on room temperature without exact output power reporting [7]. The fabrication technology remains a challenge to achieve high-quality factor cavities that can lase, especially when waveguide coupling needs to be considered for future spike-based neuromorphic circuit architectures [4]. One of the main reasons for quality factor degradation is the nanopillar facets inclination, caused by etching process. In this work, we analyze numerically optical properties of metal-dielectric cavities with introduced etching slopes non-idealities, and propose novel cavity design on InP Membranes On Silicon (IMOS) integrated platform, which allow double-side processing technique, increasing fabrication flexibility, and compatibility with nanophotonic waveguides [3].

2. NANOLASER DESIGN

Nanolasers are particularly prone to mask erosion during fabrication and the subsequent off-vertical facets and sidewalls. There are three main sources of optical performance degradation caused by non-vertacality. The first source is caused by effective increase of nanolaser width in active medium layer, changing propagation loss and confinement factor. The second change corresponds to the front and end facets reflectivity reduction, the associated increase in the scattering loss and coupling to higher order modes. Finally, due to the nanopillar shape change, optical mode will be coupled more efficiently to highly doped bottom InGaAs contact layer. Since coupling to the bottom layer will increase propagation losses, in order to minimize bottom layer coupling contribution we propose a novel pillar/ridge based metal cavity design, which can be fabricated on the IMOS platform (Fig. 1, right). In this design cavity is flipped, which can be achieved by means adhesive bonding to a silicon substrate using Benzo-Cyclo-Butene (BCB) [8]. Partially removed contact layer would allow for reduced propagation losses and also for direct optical characterization of the cavities from the top.

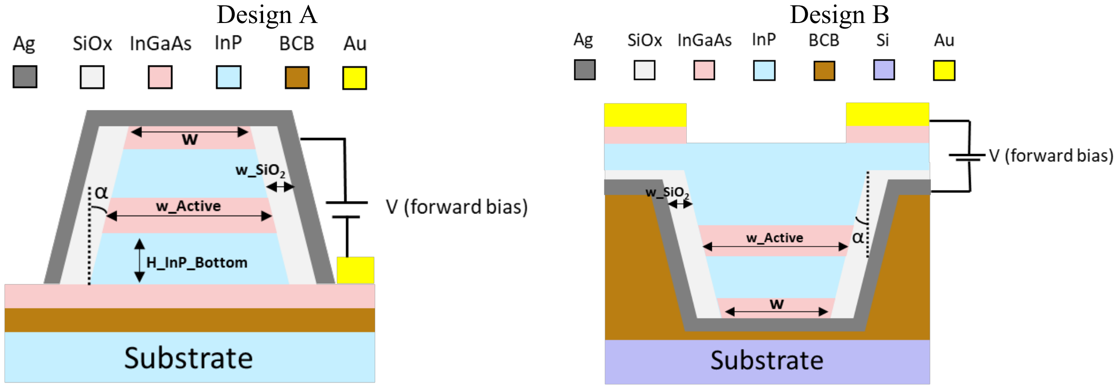

Figure 1. Metal-dielectric cavity InP-based nanolaser structure. Left: classical metal cavity nanolaser design [3,5,6]. Right: flipped metal cavity InP-membrane nanolaser design.

3. MODE PROPAGATION PROPERTIES

The fabrication process of metal-dielectric cavity nanostructures requires the etching of semiconductor nanopillar structures with a height larger than 1 µm [3]. Such etch depth is usually done via inductive coupled plasma (ICP) reactive-ion etching (RIE) which introduces a slope during the etching which results typically in increasing nanopillar's cross-section area from top to bottom. This effect causes the active medium volume increase, in comparison with an ideal cavity. To investigate how this affects the cavity's optical properties, mode analysis was done using Lumerical software [9]. Active medium was assumed to be transparent at 1.55 µm wavelength. To investigate the effects of the etching slopes on the laser cavity for different designs, mode analysis was done for different inclination angles α and cavity widths *w* (Fig. 2).

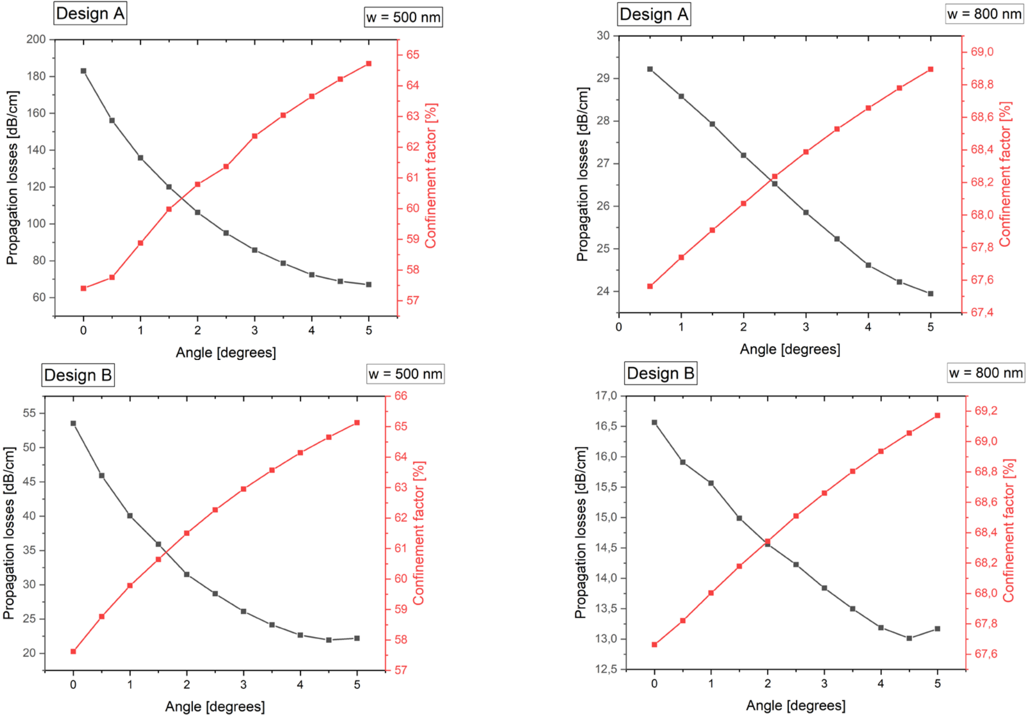

Figure 2. Propagation losses and confinement factor change as a function of facets inclination angle. Left: semiconductor nanopillar width w = 500 nm, Right: w = 800 nm, Up: Design A, Down: Design B.

Due to the optical mode coupling to bottom p-InGaAs layer, for the Design A, optical losses will be significantly higher, in comparison with the flipped cavity (design B). Here the main influence for the change in propagation losses and confinement factor with angle is the active medium volume, as compared with an ideal cavity. This effect is less significant for wider cavities, due to the smaller active medium area change.

4. FACET REFLECTIVITY

Another crucial effect due to tilted facets is the change in effective facet reflectivity. Due to the tilted reflective surface, the mode is less efficiently coupled back to the fundamental mode upon reflection, and scattering losses are increasing. To investigate this effect numerically, 2D finite-difference time-domain (FDTD) simulations were performed in Lumerical. We calculated the effective reflectivity as a ratio of the optical power which is coupled back to the fundamental TE mode after the reflection to incident fundamental mode. Thus, calculated reflectivity is taking into account metal absorption, high order modes coupling and scattering losses (Fig. 3).

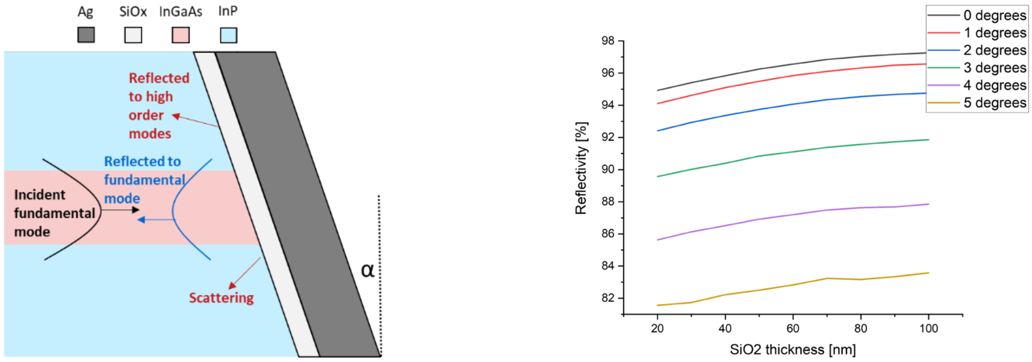

Figure 3. Left: facet reflection scheme in metal-dielectric cavity; Right: nanocavity facet's reflectivity as a function of SiO$_2$ insulation thickness for different facets inclination angle α.

For all the simulated angles, the reflectivity change in the same range for a given dielectric thickness range, so absorption losses in the metal are assumed to be constant with facet tilt. Thus, the mode coupling efficiency and scattering losses are giving the highest impact on reflectivity drop. Finally, summing up all the losses contributions, we can calculate the required gain to overcome the introduced losses as following [10]:

$$g_{th}\Gamma = a + \frac{1}{2L}\ln(\frac{1}{R_1 R_2})$$

, where g_{th} is the threshold gain, Γ – confinement factor, a - propagation loss, L is a cavity length, R_1 and R_2 are the facets reflectivity. The calculated threshold gain for different cavity widths is presented on on Fig. 4.

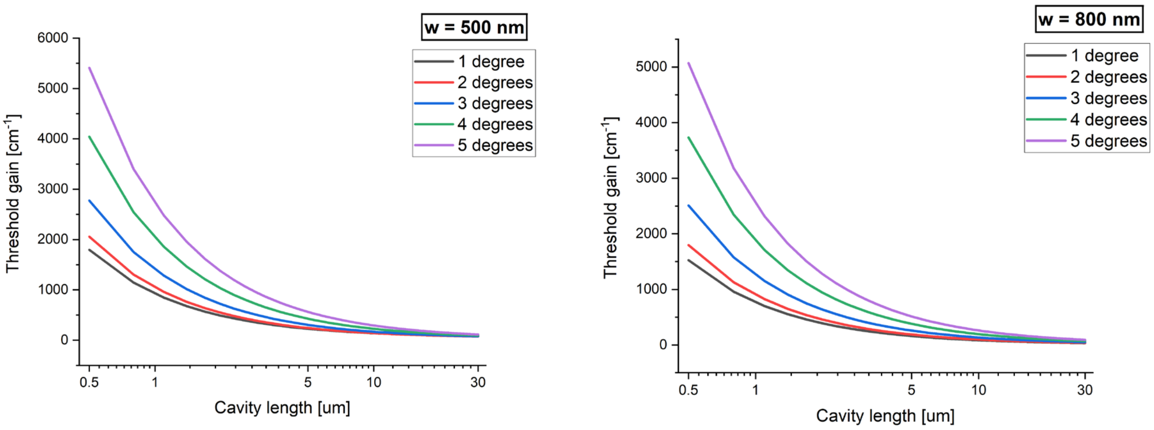

Figure 4. Nanolaser's calculated threshold gain as a function of cavity length (logarithmic scale) for different inclination angles. Left: semiconductor nanopillar width w = 500 nm, Right: w = 800 nm.

Considering a cavity width w = 500 nm and cavity length L = 1 µm, the threshold gain increases from 722 cm^{-1} for an ideal cavity to 2482 cm^{-1} for 5 degrees sidewall slopes. As it is shown on Fig. 4, the impact of etching slopes non-verticality becomes negligible for longer cavities, as reflection losses contribution become smaller over against propagation losses. For a wider cavity (w = 800 nm), the threshold gain initially is lower due to the smaller propagation loss, however for cavity length L > 10 µm this effect is insignificant.

5. CONCLUSIONS

The effect of etching slopes in the laser cavity was numerically investigated, both in the transversal and longitudinal directions which affect the propagation loss and reflectivity, respectively. Despite the increase in mirror reflection loss, the reduction in propagation loss and improvement in confinement almost compensate it for small angles and large cavity lengths. The proposed flipped cavity design showed smaller propagation losses, and due to the fabrication on IMOS platform can be potentially compatible with nanophotonic waveguide.

ACKNOWLEDGEMENTS

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REFERENCES

[1] K. Ding, *et al.:* Modulation bandwidth and energy efficiency of metallic cavity semiconductor nanolasers with inclusion of noise effects, *Laser & Photonics Reviews*, 9, pp. 488-497, 2015.
[2] A. N. Chi-Yu, *et al:* Theory of high-speed nanolasers and nanoLEDs, *Opt. Express 20*, pp. 450-470, 2012.
[3] V. Dolores-Calzadilla, *et al.:* Waveguide-coupled nanopillar metal-cavity light-emitting diodes on silicon, *Nature communications* vol. 8 p. 14323, 2017.
[4] P.R. Prucnal, *et al.:* Recent progress in semiconductor excitable lasers for photonic spike processing, *Advances in Optics and Photonics* 8, 228, 2016.
[5] M. T. Hill, *et al.:* Lasing in metallic-coated nanocavities, *Nature Photonics*, vol. 1, pp. 589-594, 2007.
[6] C.-Y Fang., *et al.:* Lasing action in low-resistance nanolasers based on tunnel junctions, *Optics Letters*, 44(15), 3669, 2019.
[7] K. Ding, *et al.:* Record performance of electrical injection sub-wavelength metallic-cavity semiconductor lasers at room temperature. *Opt. Express* 21, 4728–4733, 2013.
[8] L. Shen *et al.:* Double-sided processing for membrane-based photonic integration, presented at the 18th Eur. Conf. Integrated Opt., Warsaw, Poland, 2016.
[9] Lumerical Inc. http://www.lumerical.com/
[10] Larry A. Coldren, *et al.:* Diode Lasers and Photonic Integrated Circuits, *2nd ed. Hoboken,* Wiley, 2012.