Nano Scale Disruptive Silicon-Plasmonic Platform for Chip-to-Chip Interconnection

Decision on an optimized structure for metallic/plasmonic nano-laser and its coupling to Si waveguides

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Executive Summary

The design and optimization of a plasmonic laser structure coupled to a dielectric waveguide is described in this report. Modal characteristics, such as propagation loss and confinement factor were obtained for a wavelength of $1.55\ \mu m$. In addition, FDTD (Finite-Difference Time-Domain) simulations were used to calculate the reflectivity from the end facets of the laser structure and also to calculate the coupling between the laser and a dielectric waveguide. Simulations show that room temperature operation is possible for long lasers, although with a low internal efficiency.

Change Records

Version	Date	Changes	Author
1 (submission)	06/11/2012		Victor Calzadilla

Introduction

It is the aim of WP3 to develop a plasmonic laser coupled to a silicon waveguide. This report describes the design of an optimized plasmonic laser. For technological feasibility reasons, the laser is coupled as a first step to an InP waveguide on a silicon substrate. The coupling to a Si-waveguide will be done in a second stage, by tapering the InP-based waveguide to push the optical mode down to an underlying Si waveguide.

The laser structure proposed is shown in Fig. 1, which is based on previously reported plasmonic lasers [1]. The laser consists fundamentally of a MISIM (metal-insulator-semiconductor-insulator-metal) waveguide forming a Fabry Perot resonator, on an InP-membrane, coupled to a dielectric waveguide. The top n-contact and the lateral p-type contact should provide the electrical pumping for the InGaAs active medium, which has a bandgap at $1.65\ \mu m$.

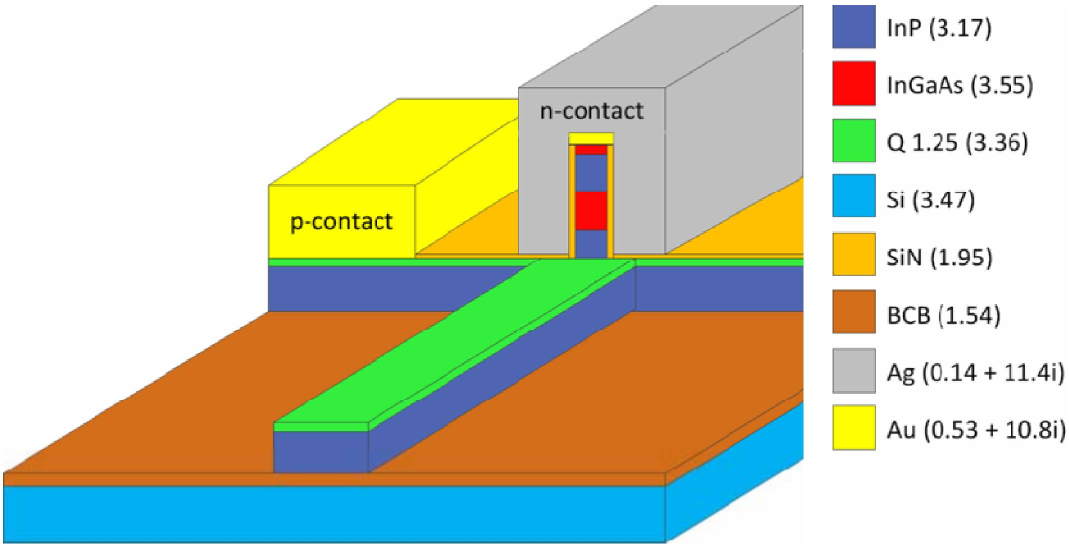

Figure 1. Plasmonic laser coupled to a dielectric waveguide. The refractive index of each material at $1.55\ \mu m$ is shown in parenthesis. Optical absorption in InGaAs has been neglected for the simulations.

As it can be seen in Fig. 1, there is a thin insulating layer of SiN between the semiconductor layer stack and the metal cladding, which serves to insulate the structure horizontally and therefore allow a top-down current flow. The quaternary ($Q\ 1.25$) layer acts as the ohmic contact layer for the p-contact. The back side of the Fabry Perot cavity is completely terminated by metal in order to achieve a strong reflection, whereas it has an open facet at the frontal end to achieve the outcoupling. For the design of this structure, it is important to calculate the propagation loss α , the confinement factor Γ , and the facet reflectivities R_1 and R_2 in order to be able to estimate the threshold material gain g_{th} to achieve lasing in a cavity with length L according to

$$g_{th}\Gamma = \alpha + \frac{1}{2L} ln\left(\frac{1}{R_1 R_2}\right), \qquad (1)$$

Modal properties

The intensity distribution of the hybrid surface plasmon polariton mode with lowest loss in the cavity is shown in Fig. 2b. Due to its plasmonic nature, it has a dominant E_x component and is mainly confined within the insulation layer, which leads to a very poor overlap with the active region. The post height h is important because it will determine the reflectivity and outcoupling coefficient.

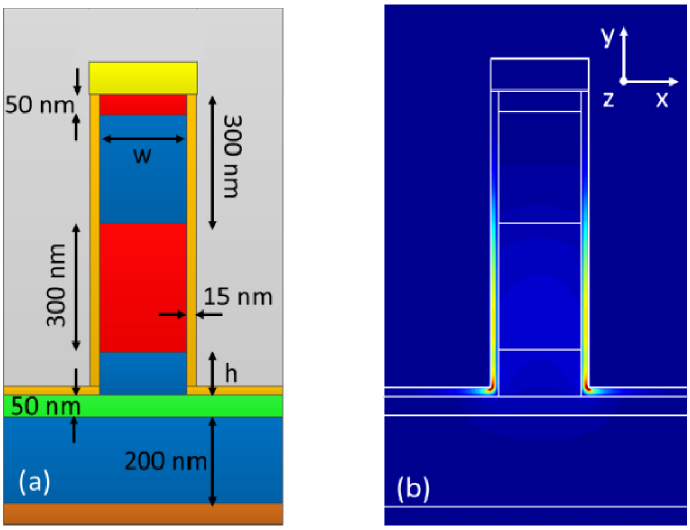

Figure 2. (a) Cross section of the plasmonic laser cavity with the dimensions used for the simulations. (b) Optical intensity of the plasmonic mode at $1.55\ \mu m$. Blue: low intensity. Red: high intensity.

The propagation loss and confinement factor as a function of the width w, can be observed in Fig. 3 for different values of the post height. This loss is due to the absorption by the metal and it decreases when the core is wider because the mode is increasingly confined in the core. An increase in the width of the MISIM structure also leads to a higher confinement factor. The confinement factor is defined as the ratio of the electric field square amplitude within the active medium with respect to the square of the total electric field amplitude and therefore determines the modal gain.

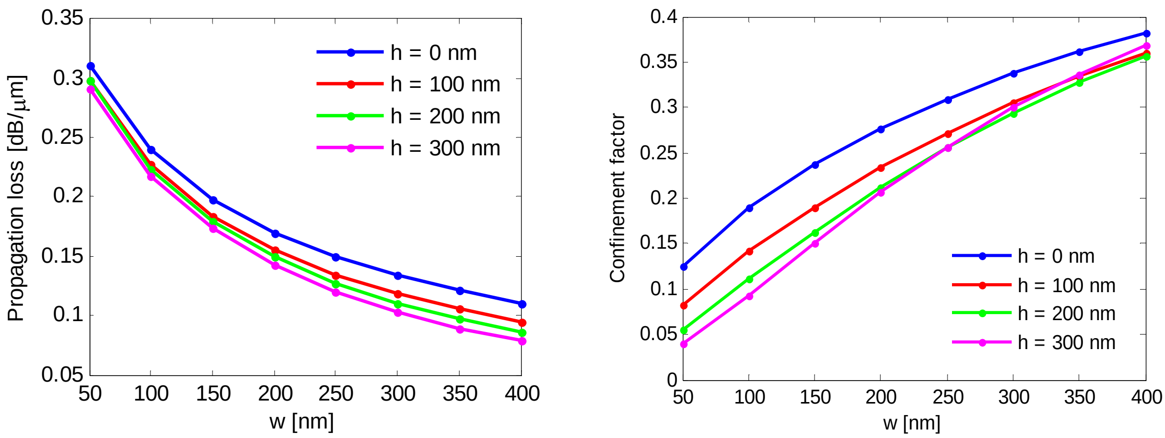

Figure 3. Left : Propagation loss due to the optical absorption of the metal cladding. Right: Confinement factor in the active region. The calculations were performed for a wavelength of $1.55\ \mu m$.

As it can be seen in Fig. 3, a wider MISIM structure leads to a lower propagation loss and a higher confinement factor, however dielectric modes with better characteristics could exist for such wide structures and then the lasing mode will not be plasmonic anymore. Therefore, we have fixed the width to $200\ nm$, which is believed to be near the minimum width for a structure to be able to operate at room temperature, although using long cavities as it is dicussed below.

Facet reflectivity and outcoupling

Figure 4 shows the facet reflectivity and outcoupling coefficient as a function of wavelength for an open facet and different post heights (colored curves). The first remarkable characteristic is the high reflectivity of around 0.6 at $1.55\ \mu m$, which is twice the Fresnel reflectivity for an interface given by InGaAs and air, considering perpendicular incidence. This strong reflection is due to the large effective mode index mismatch between surface plasmon modes and free propagating modes in air. In addition, the reflectivity at the backside of the laser, which is assumed to have a metal coating, is shown in black in Fig. 4a. As expected, it is high and hardly varies for different values of h .

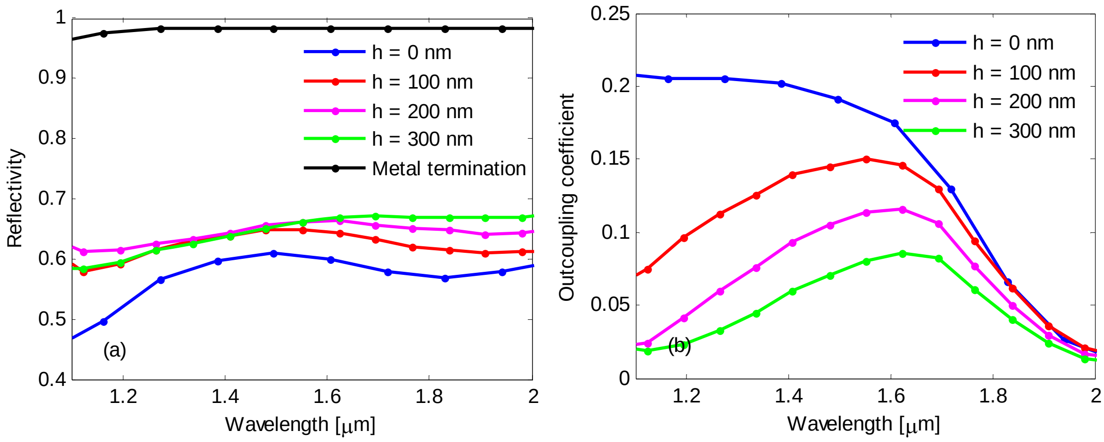

Figure 4. (a) Reflectivity of a laser structure with $w = 200\ nm$, for an open facet with post height h and a metal termination with $h = 0\ nm$. (b) Outcoupling coefficient of a laser structure with $w = 200\ nm$.

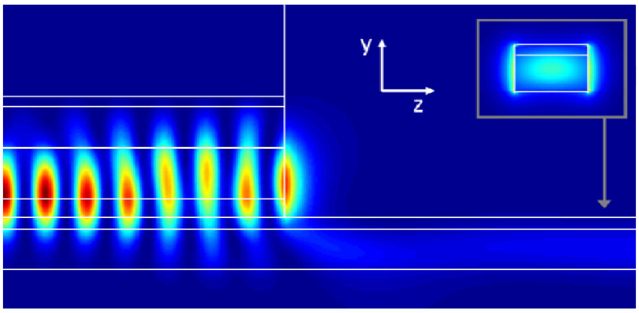

Figure 5. Longitudinal cross section showing the coupling between the laser and the dielectric waveguide. The inset shows a transversal cross section of the waveguide. Blue: low intensity. Red: high intensity.

The reflectivity presents only a small increase on increasing the post height because it is limited to the reflection between the laser structure and air. On the other hand, the outcoupling continuously decreases and becomes zero for a very high post. Since the primary interest is to design an efficient laser, a post height of $100\ nm$ would be suitable for an operating wavelength of $1.55\ \mu m$, since it maximizes the reflectivity without compromising the outcoupling. Using a higher post will lead to a decrease in the laser efficiency. Figure 5 shows the intensity distribution of the coupling between the laser and the dielectric waveguide.

Results

As commented above, it is possible to estimate the threshold material gain required to achieve lasing in the structure using Eq. (1). For example, assuming a laser length of $50\ \mu m$ and considering a cavity with $w = 200\ nm$ and $h = 100\ nm$, it gives $\alpha = 0.16\ {dB}/{\mu m}$, $\Gamma = 0.23$, $R_1 = 0.65$ and $R_2 = 0.98$, resulting in a threshold gain of $g_{th} = 1796\ cm^{-1}$ with only 11% of internal efficiency, which is possible at room temperature under a high injected carrier density above $6 \cdot 10^{18}\ cm^{-3}$ [2]. Shorter structures could be also realizable at room temperature, however they would require to be wider in order to have a higher confinement factor and lower propagation loss.

Despite the relatively large propagation loss and low confinement factor, this structure is interesting in view of the high reflectivity at its open facet and coupling to a dielectric waveguide mode. The threshold gain can be compatible with room temperature operation, albeit with a poor efficiency and at high carrier densities.

At the moment, we are investigating a metallic laser structure that relies on a dielectric mode to achieve high confinement factor and low metal loss. Such structure might offer a better performance compared to a plasmonic laser.

References

[1] M. T. Hill: Status and prospects for metallic and plasmonic nano-laser, J. Opt. Soc. Am. B, vol. 27, no. 11, pp. 36-44, 2010.
[2] C. Y. Lu, S. L. Chuang: A surface-emitting 3D metal-nanocavity laser: proposal and theory, Optics express, vol. 19, no. 14, pp. 13225-44, 2011.