Design and simulation of a high bandwidth optical modulator for IMOS technology based on slot-waveguide with electro-optical polymer

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Electro-optical modulators are considered to be a key devices for optical interconnects. In order to implement this device in the new InP membrane On Silicon platform (IMOS), a slot-waveguide configuration with a high nonlinear polymer is studied. Simulations and electrical calculations show good performance and fabrication tolerance using n-doped InP as the slot-waveguide material. The small dimensions of the structure and the high electro-optical coefficient of the polymer allow devices with a small footprint (hundreds of μ^2), high bandwidth ($> 100GHz$) and low $V_\pi \times L$ value ($\sim 0.7V mm$). This solution is suitable for integration with passive devices already developed for this platform, and with active devices that are under development.

Introduction

It has become clear in the last years that optical interconnects are replacing more and more electrical wires in shorter distance links. Some of the reasons for this technological migration are the demand for faster speed communications and lower energy consumption inside computer chips [1]. These requirements cannot be supported by electronics interconnects alone, therefore, a new technology has to emerge. One of the proposed solution is the use of a thin optical layer bonded with BCB on top of the electronic chips (InP Membranes On Silicon (IMOS)) [2]. This configuration allows the total integration of electronics chips with photonic counterparts. The signal processing is done in the electric layer (Si), while most of the communications is done optically in the InP layer.

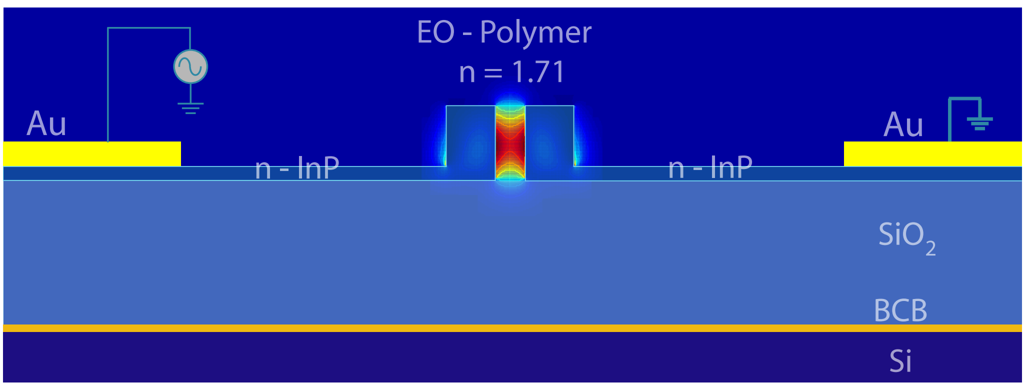

Figure 1: Cross section of the InP slot waveguide with the field strength of the TE mode indicated in the slot.

In order to create a working platform, several devices are needed. From the optical elements that need to be developed, an optical modulator has a key importance for communications applications. The configuration we select has to deal with two main problems: it has to be small to be attractive for on-chip/on-board interconnects, and it needs to able to integrate with other devices (e.g. laser and detectors). Considering the aspects presented above, a Mach-Zehnder (MZ) interferometer structure as a phase modulator based on a slot waveguide and an electro-optical polymer could fullfill the two main requirements. Moreover, this configuration is able to show high performance in terms of bandwidth, extinction ratio, half wave voltage and energy consumption.
The slot waveguide enhance and confine the TE mode in the low index refractive material due to the boundary conditions for a large discontinuity of the electric field at high index-contrast interfaces. This conditions force the mode to be confined in the slot obtaining a high overlap with the electro-optical polymer. Figure 1 shows a cross section of the slot waveguide with the field of the TE mode in a structure based on n doped InP material. The waveguide is placed on an insulator layer of SiO_2 and the two layers are bonded on a Silicon wafer. The insulator layer, due to its high refractive index contrast interface with InP, and lower refractive index than the electro-optical polymer ($n = 1.71$), will maintain the optical mode inside the slot in the vertical direction. The n-doped InP-layer next to the slot waveguide is necessary to apply a voltage to the slot. Due to this electrical connection, the applied electric field inside the slot is strong, besides it is highly coupled to the optical mode, allowing an efficient phase modulation effect on the optical mode.

Optimization of the Slot Waveguide

In order to optimize the structure, we set the thickness of the membrane to be $H = 300nm$. One reason for this decision is that previous passive IMOS devices were already optimized for this thickness [3]. In terms of slot waveguide properties, the confinement factor of the optical mode in the slot increase if the thickness of the membrane increase, however, if the thickness is too large, higher order modes can propagate as well. Taking these elements in account, $H = 300nm$ presents a good trade-off. Another consideration is to use a thickness of $t = 50nm$ for the connection layer next to the slot waveguide. This value is a trade-off between the resistance of this layer (which increase when we shrink its thickness) and the confinement factor of the TE mode in the slot (which is maximum when the thickness is zero). Furthermore, this layer works as a protector layer of the insulator layer (SiO_2) during processing.
To determine the width of the ridges (W) and the size of the slot (W_g), a study was carried out with an eigenmode solver (Lumerical ^{TM}MODE solver). Figure 2 (a) display how the the confinement factor (Γ) changes for these two parameters. The maximum of the confinement (30%) is found of ridge width of $W = 240nm$. One issue consist that in the lower left part of the plot, the paramenters are close to the cut-off condition of the TE mode. In order to have fabrication tolerance, we consider that a gap from $W_g = 120nm$ to $W_g = 150nm$ provides a stable optical mode with a good confinement factor and fabrication tolerances.
In the fabrication process, the waveguides are made with not perfectly vertical sidewalls. In the slot-waveguide, the optical field is strong confined at the interface of the InP material and the EO polymer. This condition lets small angles have a huge effect on the optical mode. In figure 2 (b) we analyze the behavior of the confinement factor with variation in

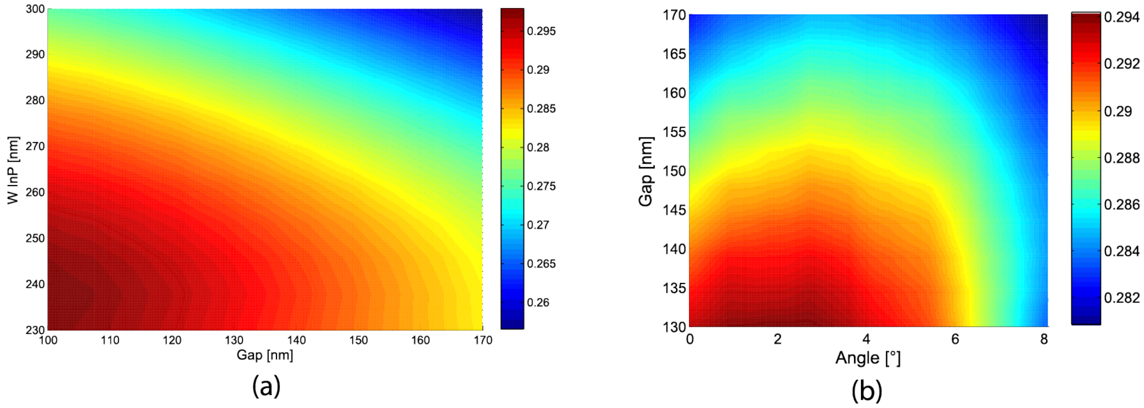

Figure 2: (a) Confinement factor Γ versus the width of the ridges (W) and the gap of the slot (W_g), with $H = 300nm$ and $t = 50nm$; (a) Γ versus the gap of the slot (W_g) and the sidewalls angle, with with $H = 300nm$ and $t = 50nm$ and $W = 240nm$.

the sidewall angle and the gap width (W_g) of the slot. According to previous experience, a sidewall angle between 2 and 5 [°] can be obtained. In the plot 2 (b), considering the range $120nm < W_g < 150nm$, the slot gap of $W_g = 130nm$ presents the maximum confinement factor, nevertheless, we select a gap of $W_g = 140nm$ to gain some tolerance for fabrication process moving far from the cut-off conditions.

Performance analysis

For the slot waveguide modulator we contemplate to use an electro-optical (EO) polymer material from Soluxra ™. The electro-optical coefficient is up to $110pm/V$ if a good poling technique is developed. We can determine the half wave voltage by the equation 1.

$$V = \frac{\lambda d}{2{n_0}^3 r_{33} L \Gamma} \tag{1}$$

with wavelength $\lambda = 1.55\mu m$, refractive index of the EO polymer $n_0 = 1.71$, and desire length of $L = 300\mu m$. Due to the high EO coefficient and a strong electric effect originated by the slot waveguide, we obtain a half wave voltage $V_\pi = 2.34V$. The $V \times L$ product is around $\sim 0.7Vmm$, much lower than typical values in $LiNbO_3$ modulators ($\approx 10Vmm$) [4]. The MZ modulator we consider is a push-pull configuration. This scheme allows to halve the length of the MZ since the same voltage is applied to both MZ arms with opposite polarity.

For bandwidth analysis, with the help of a semiconductor device simulator (Silvaco ™), the resistance of the structure as a function of the doping level is found (figure 3). At low levels of doping, the resistance increases dramatically, so high doped material has to be use. In order to limit the losses, a value of $1e18cm^{-1}$ was selected which correspond to losses in the InP material of $L \approx 13db/cm$ [5]. This value allows some tolerance for the doping levels without sacrificing so much the resistance properties of the material. A resistance $< 10\Omega$ is predicted for our device with a connection layer of $2\mu m$ length.

In the case of capacitance, we calculate it to be $C = 15fF$. The theoretical bandwidth based on the RC time constant is around $1.3THz$. The limitation in the bandwidth will be

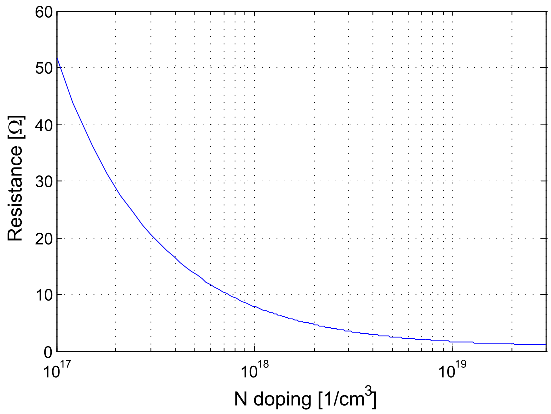

Figure 3: Resistance of the slot waveguide versus the doping concentration.

mostly due to the walk-off effect between the microwave signal in the electrodes and the optical mode. If we consider the effective refractive index of the slot waveguide ≈ 2 and a typical effective microwave refractive index of ≈ 4.6 [6]. The bandwidth for a $300\mu m$ long modulator is $f_0 = 170GHz$.

Conclusions

The design of using a slot waveguide phase modulator based on electro-optical polymer has been presented. Optimization of the slot waveguide structure leads to for a high optical confinement (30%) and good fabrication tolerances. A Mach-Zehnder modulator using this configuration can be achieved with $0.7Vmm$, and a theoretical bandwidth limit around $170GHz$. These parameters will allow the use of simplified electrode configurations for our devices.

Acknowledgments

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