Design and Fabrication of a segmented Slot waveguide modulator for InP membranes on Silicon (IMOS) using a highly doped InGaAsP-layer

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Slot waveguide based modulators with highly nonlinear electro-optical polymers are attractive for use in optical interconnects. These devices typically use a bottom layer with a moderate doping level for electrical contacting. This thin layer is defined with highly controlled etching. Here we present a segmented slot waveguide where electrical contacts are obtained with a thin highly doped InGaAsP-layer on top, making the fabrication much simpler. These waveguides present a quasi-continuous electrical contact due to subwavelength segmentation. The high conductivity of the top layer allows high performance devices ($V_\pi L = 0.9 V mm$, energy consumption $63 fJ/bit$, RC bandwidth $> 35 GHz$).

Introduction

Electronic Integrated Circuits (ICs) have been the most successful technology in computing, storing and short interconnects. Nevertheless, we have arrived a crucial point where further performance improvements are limited by power consumption. This is known as the interconnect bottleneck. To solve this, optical interconnects are replacing more and more the 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]. One of the most promising solutions is the use of a thin optical layer of III-V material bonded on top of a silicon wafer using the polymer Benzo Cyclo Butene (BCB) as adhesive. This platform is called InP Membranes On Silicon (IMOS) [2]. This configuration allows the integration of electronics chips with photonic counterparts where the electronics is done in the Si layer and the communication in the InP layer.

In the development of the IMOS platform, several functions have to be demonstrated in order to offer a complete interconnect platform. An optical modulator is one of these. A Mach-Zehnder (MZ) interferometer structure with a phase modulator based on a segmented slot waveguide using highly nonlinear electro-optical (EO) polymers, can show high performance in terms of bandwidth, extinction ratio and energy consumption.

Segmented slot waveguide modulator

Slot waveguides are a special kind of waveguides which confine the TE mode in the low refractive index material, due to the boundary conditions for a large discontinuity of the electric field at high index-contrast interfaces. This property force the optical mode to be confined in the slot, obtaining a high overlap with an electro-optical polymer in that slot.

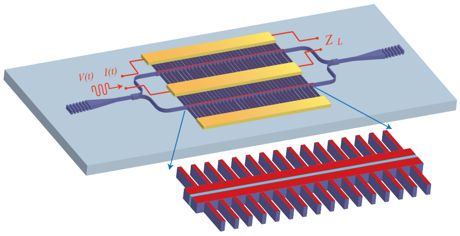

Figure 1: Segmented slot waveguide in a Mach Zehnder configuration.

The most common configuration for a slot waveguide modulator using EO polymers consists of a slot waveguide with two layers; one of a thin n-doped material layer covered by an intrinsic material layer. The n-doped layer works as a strip loaded layer which electrically connects the slot waveguide with the metal contacts. This design faces several difficulties, such as the need to provide a high-frequency electrical driving signal to the slot. To face this problem, a tradeoff has to be made between a low resistivity of the strip loaded layer, which can be obtained by increasing the doping of the material; and low optical losses, which require low doping levels. The second difficulty consists of the fabrication of such a small geometry and the high accuracy needed in the etching to reach the correct dimensions of the strip loaded layer. In this work we present a different configurations, consisting of a quasi-continuous electrical contact based on subwavelength segmentation lines [3] with the addition of a thin highly doped InGaAsP layer on top used as the conductive layer, whereas the bottom layer is made by intrinsic InP material. Hereby we solve the problem for high accuracy needed on the etching of strip loaded layer. However, the optical losses are problem still present in this case. To overcome this complication, the highly doped layer can be removed with selective wet etching in sections where it is not needed, reducing the total losses of the complete device.
Other elements needed to complete the device are grating couplers which couple light to and from the chip, 1x2 Multi Mode Interferometer to split and combine the light for the MZ and asymmetric convertors which couple the TE mode from a standard waveguide to a slot waveguide. Figure 1 illustrate a schematic of the proposed MZ modulator in a push pull configuration.

Performance

In the analysis of the performance, we consider the use of an commercial EO polymer material with an electro-optical coefficient of $90pm/V$ and the refractive index 1.57. An optimization of the slot waveguide was carried out with an eigenmode solver. The membrane thickness is $300nm$, the ridge width of $230nm$ and the gap of $120nm$. This geometry gives a confinement factor of 30% in the low refractive index area. The optical losses from the high doped material are limited due to the small thickness of this conductive layer and the high confinement of the optical field in the low refractive index material This leads to acceptable losses; around 11 dB/cm.
With this geometry and a working voltage of $1.2V$, the length of the modulator could be calculated by equation $L = \lambda d/2 * n_0^3 r_{33} \Gamma$
The calculated length is around $750\mu m$. The electric contact, as mentioned before, will be made with segmented lines of $60nm$ width. We select a segmented period of $350 \pm 30nm$, which would be safe from Bragg grating reflections, calculated to be at periods of $420nm$. In the electrical analysis, the higher doped layer reduces the resistivity to a level around $0.00049\Omega cm$. With a capacitance of around $44fF$, this results in a RC bandwidth of several hundreds of GHz if ours segmented lines have $3\mu m$ length ($f_{3dB} = 1/2\pi RC \approx 900GHz$). The main advantages of this segmented connection layers are: only one step height fabrication is required, and due to high doping levels, the contact resistance using

Ge/Ag/Au is predicted to be extremely low ($10e-6$) [4] which effectively removes the RC limitation of the modulator. In terms of energy consumption, this can be calculated as ($\Delta E = CV^2 = 63 fJ/bit$).

Finally, we need to optimize the RF structures. This tends to be difficult for these kind of devices, due to the extremely different wavelength scales between RF and optical waves. For a RF analysis, with the help of a finite element method solver, the RF effective index, the RF losses and the impedance of the Coplanar Waveguide (CPW) were calculated. For this analysis we started with some restrictions: due to fabrication limitations, the thickness can be up to $500nm$, the separation of the metal contacts (length of the segmented lines) cannot be less than $1.5\mu m$ to avoid extra losses by metal absorption, and the thickness of the buffer layer is fixed at $1.8\mu m$. The optimization is difficult because the RF signal is highly present in the slot area, which cannot be modified significantly, and modification in other regions have much less impact. In the proposed design, the signal electrode width is $70\mu m$, and the CPW gap size is $4.5\mu m$. The electrode thickness is $450nm$. Figure 2 plots the frequency dependent RF effective index and the optical effective refractive index value, as well as the frequency dependent propagation losses. It is important to mention that the effective index mismatch reduces the bandwidth (see equation 1), which gives a bandwidth $f_{3dBeo} = 150GHz$. The calculated impedance of the CPW is calculated to be $Z = 18\Omega$. This impedance is different from the 50Ω impedance of the feeding lines. This impedance mismatch would produce a deterioration of the speed of the devices by reflected propagation signal, which can be estimated eith equation 2. This gives $f_{3dBeo} = 35GHz$. With all this difficulties ahead, the bandwidth is estimated $> 35GHz$, which could provide for high speed communications. If higher bandwidth is needed, more complex transmission lines need to be designed.

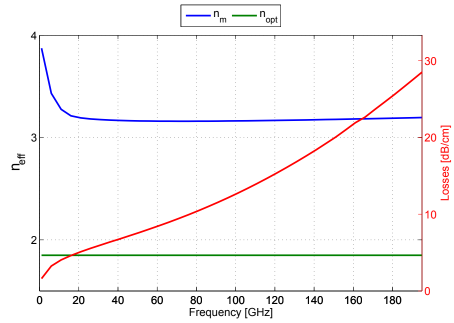

Figure 2: Left axis: RF index and optical index. Right axis: RF losses

$$f_{3dBeo} = \frac{1.39c}{\pi L(n_m - n_{opt})} \quad (1) \qquad f_{3dBeo} = \frac{1.39c}{\pi L(n_m + n_{opt})} \quad (2)$$

Fabrication

The fabrication process is based on several electron-beam lithography (EBL) steps. Three different lithographic masking schemes are used during these EBL steps. These are depicted in Figure 3. EBL is used due to the high resolution required.

The first lithographic step defines the marks and gratings. It uses ZEP resist in combination with a SiNx layer. ZEP is preferred for this purpose because it is a positive resist where only the exposed pattern will be open, leaving the rest of the sample protected by SiNx during the etching. The second lithographic step gives waveguide definition. For this Hydrogen SilsesQuioxane (HSQ) is used. This is a

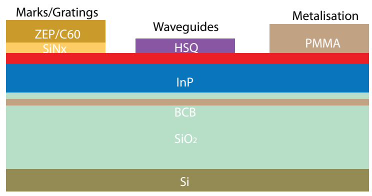

Figure 3: Lithography mask schemes used in the fabrication.

negative resist material and hard mask for the subsequent etching process.
This technique requires enhancing the resistance of HSQ to the semiconductor etching chemistry used in the Reactive-Ion Etching (RIE), which can be done either by curing [5] or by treating it with an oxygen plasma [6]. After HSQ was spun, e-beam exposed, developed, and treated with an O_2-plasma, it is used to etch the waveguide using a methane hydrogen chemistry ($CH_4 : H_2$) in a RIE process. Figure 4 shows the HSQ mask of the segmented slot waveguide.

Finally, the last lithographic step has been carried out with PMMA resist for a lift off process. After exposing and developing, we evaporate Ge/Ag/Au metals on the chip. The lift off process is done with dissolving the resist with the metal on top, leaving the metal only in exposed area. PMMA is also used in another lithography step to define areas where wet etch the quaternary layer. This etching is done with a $H_2O_2 : H_2SO_4 : H_2O$ solution in a 10 : 10 : 100 mixture.
Fabrication of the device has been tested. Nevertheless, optimization of some steps is needed in order to complete the fabrication of the devices.

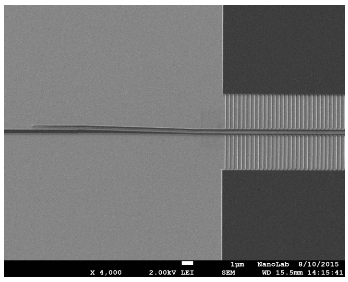

Figure 4: Example of HSQ pattern of a segmented slot waveguide.

Conclusions

The design of a segmented slot waveguide modulator in IMOS, based on electro optical polymer, has been described. The optical, electrical and RF analysis and optimization have been carried out. Devices can achieve a half wave voltage of $V_\pi L = 0.9Vmm$ and an energy consumption of $63fJ/bit$. It is demonstrated that in the worst case scenario a bandwidth of $35GHz$ can be achieved. There is room to improve the RF capabilities if more complex transmission lines are designed. The main fabrications step which are also presented. Some optimization on these steps are currently being done to be able to fabricate the complete device.

Acknowledgements

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