Diffusion Doped Plasma Dispersion Silicon Modulators

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ABSTRACT

We present a diffusion doping based plasma dispersion optical modulator in Silicon-On-Insulator platform. To the best of our knowledge this is the first demonstration of a diffusion-doped (Boron and Phosphorus) modulator in a compact Silicon waveguide. However, it results in a graded, isotropic doping profile where lateral diffusion length of the dopants is a critical parameter. We use a micro-ring resonator and proximity doping with varying offset besides the waveguide to experimentally measure the lateral diffusion length. The lateral diffusion is characterized from the change in the extinction of the ring resonator. Experimental measurement shows a lateral diffusion length of 1600 nm in a 220 nm thick Si device layer, which agrees well with the theoretical calculation. With the lateral dopant diffusion length, we have designed and fabricated a 1mm long pn MZI modulator. Fabrication was done using a combination of optical and e-beam lithography. The MZI waveguides were defined with 160 nm etch in a 220 nm device layer with a waveguide width of 450 nm. As an initial demonstration, we show plasma dispersion based spectral blue shift of 1.5 nm with a reverse-bias voltage of 5 V.

Keywords: Plasma dispersion,Diffusion doping, Mach-zehnder modulator, Lateral diffusion length

1. INTRODUCTION

Optical modulator is one of the key component in photonics integrated circuits which determines the operational speed of the device. It imprints the information contained in the electronic signals onto the optical signal. In recent years, there have been various demonstration of electro optic modulation in silicon platform. In Plasma dispersion based modulator, the effective index variation in the waveguide is either accomplished by carrier injection,[1] carrier depletion,[2] accumulation[3] or by capacitive effect.[4] Recently, electro optic modulator employing two dimensional material like Graphene[5] operating at telecommunication wavelength at 10 Gb/s is also demonstrated. These modulators require active regions to either vary the effective index or to tune fermi level of the two dimensional materials. These active region can be formed using ion implantation or diffusion doping technique.

In both the doping technique, after creating enough dopants on the surface subsequent annealing step is required. While in ion implantation, the annealing helps in removing the structural damage caused in first step of implanting ions with high energy, in diffusion doping annealing is required to activate all the dopants. In both the technique, annealing at higher temperature results in a isotropic doping profile. So it is necessary to have the knowledge about lateral diffusion of the dopants in order to precisely locate the junction in the waveguide which helps in evaluating the performance of the device and to minimize the absorption loss in the device due to dopants. We have used micro-ring resonator to measure the lateral diffusion of the dopants[6] and the lateral diffusion length is observed to be 1600 nm.

In ion implantation technique, the high energy bombardment of ions on silicon surface creates both structural and optical defect. These optical defects are not removed in the subsequent annealing step which can contribute to losses. Here in this work, we have fabricated plasma dispersion based electro optic modulator employing diffusion doping technique and we have observed a spectral blue shift of 1.5 nm with a reverse bias of 5 V.

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2. DIFFUSION DOPING AND LATERAL DIFFUSION LENGTH MEASUREMENT

2.1 Diffusion Doping Design

In this work, we have used diffusion doping technique to create active regions in the device silicon layer. So it is necessary to obtain the doping parameters for boron(p-type) and phosphorus(n-type) region. For this optimization, a blanket SOI wafer with 160 nm thick device silicon layer is used and the sheet resistance is measured using four probe technique. The temperature at which the predeposition is done is determined by the solid solubility limit of the dopants i.e., around 850 ^{0}C for both boron and phosphorus in silicon. Fig. 1 shows the sheet resistance obtained at different stages of diffusion doping. Generally, predeposition stage is followed by the drive-in annealing to activate the dopants. For Boron doping, predeposition is done at 900 ^{0}C for 15 min with the source of diborane gas and drive in at 950 ^{0}C for 15 min in oxygen atmosphere. For Phosphorus doping, predeposition is done at 850 ^{0}C for 25 min with P_2O_5 liquid source and drive-in is done at 1100 ^{0}C for 15 min in nitrogen atmosphere. Since the device layer of SOI is very thin, in order to minimize the lateral diffusion boro/phospho silicate which is formed after the predeposition stage is removed using dilute hydrofluoric acid(HF).

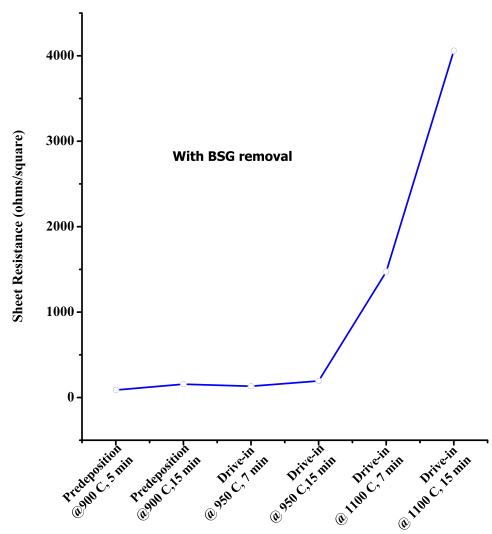

Figure 1. Sheet resistance of the device silicon layer of SOI after predeposition and drive in at different temperature and different duration

2.2 Micro-ring resonator to measure the lateral diffusion length of the dopants

The drive-in step in diffusion doping results in a graded, isotropic doping profile. It is necessary to understand the lateral diffusion of the dopants in prior to the modulator design. Here, we have used a micro-ring resonator and proximity doping with varying offset besides the waveguide to experimentally measure the lateral diffusion length. The lateral diffusion is evaluated by measuring the extinction ratio of the ring resonator.

A micro-ring resonator of 50 μm radius, coupled to the bus waveguide with the separation of 300 nm is chosen as the test device. The ring is radially doped along its outer edges. Fig. 3 shows the top view and the cross-section of the structure used. The width and etch depth of the waveguide is chosen to be 600 nm and 75 nm respectively, supporting transverse electric(TE) single mode operation at around 1.31 μm. The process flow is similar to that of electro-optic modulator till the phosphorus diffusion step discussed in Sec. 2.3.

Multiple devices are fabricated with varying offsets of the doping window from the waveguide edge. Fig. 3 shows the normalized transmission spectrum of the devices.

Figure 4 shows the extinction ratio of devices with varying offsets extracted from the transmission spectra. There is an expected change in the extinction ratio for different doping window offset. As the offset increases the the extinction ratio increases i.e., the device operation transits from under-coupled($a<t$) to the critically-coupled

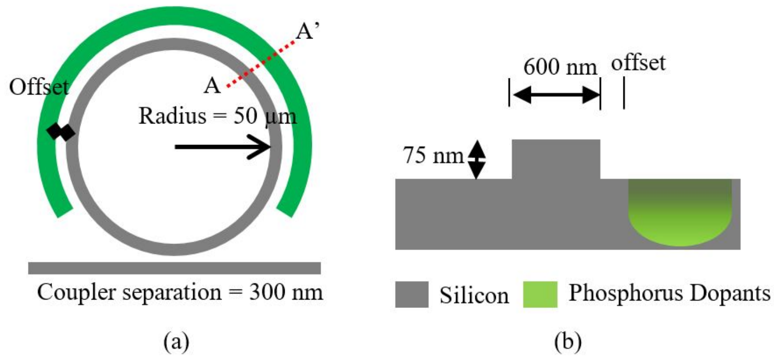

Figure 2. (a)Schematic of the micro-ring resonator used for measuring the lateral diffusion length of the dopants and (b) the cross section of the device

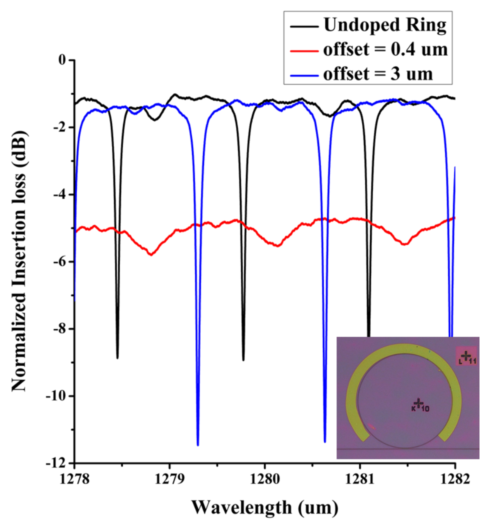

Figure 3. Normalized Transmission spectrum of the devices and the inset shows the microscope image of the fabricated device

regime The offset at which the extinction ratio of the doped device equals that of the undoped device gives the measure of the lateral diffusion of the dopants. From the graph, we can see that the extinction ratio of 10 dB (undoped ring resonator) corresponds to the offset of 1.6 μm that gives the lateral diffusion length of the dopants.

2.3 Electrooptic modulator - Fabrication Process Overview

The device is fabricated on a silicon-on-insulator (SOI) substrate with 220 nm thick device silicon layer and 2 μm buried oxide. The GDS design of passive device i.e., Machzehnder modulator(MZM) is done using IPKISS package and is fabricated utilizing the MPW run imec-ePIXfab SiPhotonics: passives.

Fig. 5 shows the process flow of the electrooptic modulator employing diffusion doping technique on the passive devices. Fig. 5(a) shows the schematic cross-section of the passive device obtained from imec-ePIXfab MPW run. Firstly, a hard mask for diffusion doping, i.e., silicon dioxide and silicon nitride of 50 nm and 100 nm thick respectively is deposited using plasma enhanced deposition technique. The sample is then spin coated with positive photoresist and it is patterned using Direct Laser Writer. The pattern is transferred into the silicon nitride using reactive ion etching process. Thereafter the sample is transferred to the diffusion furnace for Phosphorus doping where P_2O_5, a liquid source is used. The predeposition is performed at 850 ^{0}C for 25 min. The phospho silicate glass which is formed at the end of predeposition stage is removed using dilute HF and

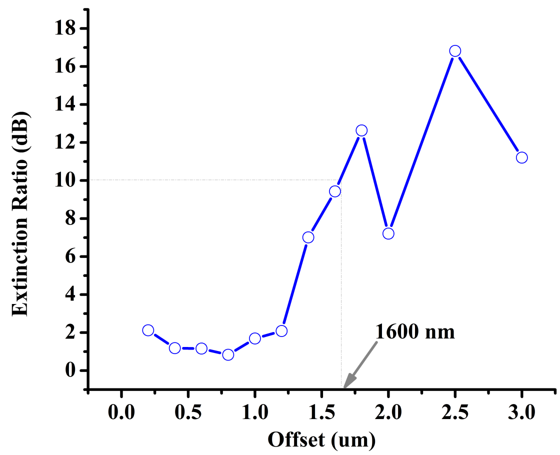

Figure 4. Extinction ratio of the devices with varying offsets

drive-in is performed at 1100 ^{0}C for 15 min in nitrogen atmosphere. After the diffusion process, silicon nitride and silicon dioxide which is used as the hard mask is removed using Hot Orthophosphoric acid (at 180 ^{0}C) and dilute HF (50 %) respectively. The above steps are repeated for Boron Diffusion except that the source used is diborane gas. In boron diffusion, predeposition is done at 900 ^{0}C for 15 min, similarly borosilicate glass is removed at the end of the predeposition stage and then the drive-in is done in oxygen atmosphere at 950 ^{0}C for 15 min.

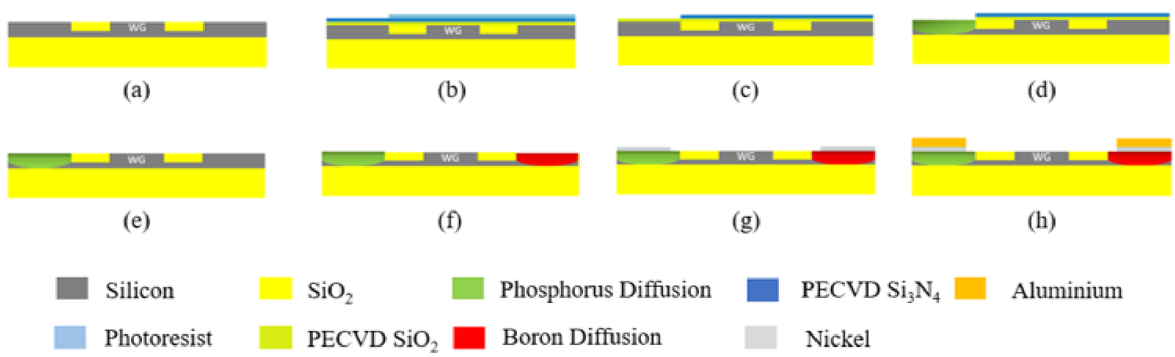

Figure 5. Process flow of the electrooptic modulator employing diffusion doping technique

Aluminum(Al) is chosen as a contact material for both p- and n- doped region. Since Al has a problem of spiking in silicon, Nickel (Ni) of 20 nm thick is deposited over the doped regions using electron beam evaporation technique and a rapid thermal anneal at 400 ^{0}C is done for 1 min to ensure the Nickel silicide formation. This step is followed by the Aluminum deposition of 100 nm thick using electron beam evaporation technique and then the sample is annealed at 450 ^{0}C for 15 min in forming gas. In the above two steps before the metal deposition, the sample is spin coated with positive photoresist and is patterned using Direct Laser Writer and the metal deposition is followed by a lift-off process. Fig. 6 shows the microscope image of the fabricated device with the pn junction in one arm of the MZM.

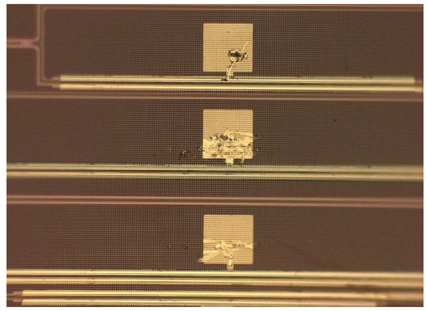

Figure 6. Microscope image of the MZM after Metal Deposition

3. RESULTS AND DISCUSSION

The boundary of the doping profile is very essential, since it plays an important role in locating the pn junction precisely in the waveguide.Here, boron and phosphorus diffusion is done 1 μm away from the waveguide edge and from Sec. 2.1 we know that the lateral diffusion length of the dopants is 1.6 μm.Therefore,pn junction is formed approximately in the middle of the waveguide.

The pn junction is included in one of the arms of the MZM. The length of the phase shifter is 1 mm. The path length difference between the two arms is chosen to be 40 μm . The free spectral range(FSR) and Extinction ratio(ER) of the MZM is approximately 14 nm and 14 dB respectively. We have used curved grating coupler to couple the light-in and out of the device.

Fig. 7 shows the DC response of the MZM when reverse bias is applied to one of the arms. When the pn junction is reverse biased, the carriers are swept away from the junction, resulting in the increase of effective index of the waveguide. The effective index change induces a phase shift in one arm and results in shift in the transmission spectrum. Fig. 8 shows the wavelength shift obtained when reverse biasing the device.The spectrum shows a blue shift of 1.5 nm for an reverse bias voltage of 5 V.

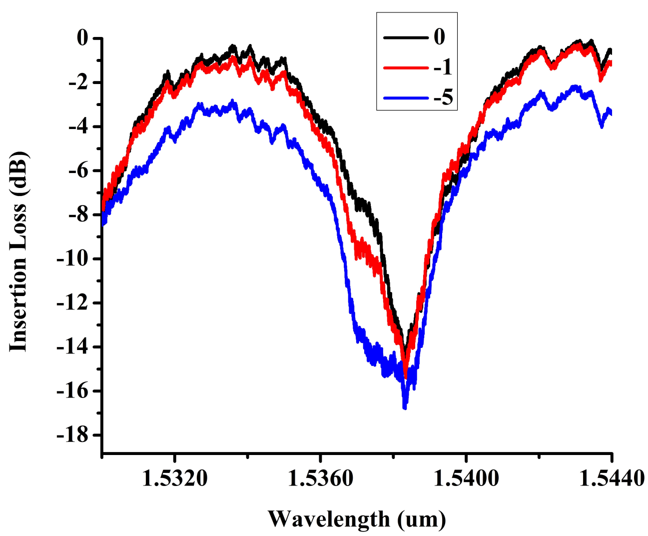

Figure 7. DC response of the MZM with the active length of 1 mm when reverse bias is applied to one of the arms

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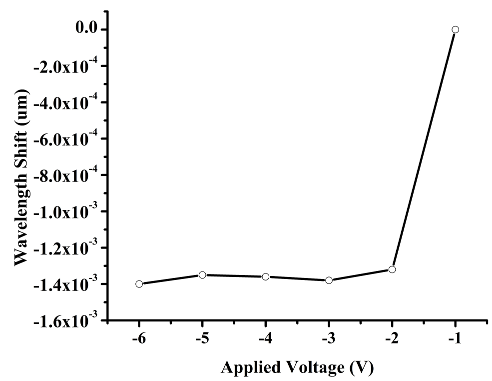

Figure 8. Wavelength shift extracted from the transmission spectrum of reverse biased MZM

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