

Optical Modulation in Silicon and the ORPEL Device

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Abstract—Optical modulation is discussed and ORPEL, an optical modulation device in silicon, is presented. A paradigm for signal modulation is theorized and reflectance spectra are presented showing a “resonance” condition. In addition, an analysis of failures during device processing is given.

Index Terms—Optical Modulation, Photonics, ORPEL

I. INTRODUCTION

For many years silicon has been the material of choice for electronic applications but its use in optical applications has been hindered by significant challenges. Optical components are currently in use but are primarily fabricated from III – V compounds and electro-optical materials such as lithium niobate (LiNbO₃). A silicon-based optical modulator presents clear cost and integration advantages over these more exotic materials and this is the primary research motivation behind ORPEL, an optically resonant periodic electrode structure in silicon. In recent years silicon-on-insulator (SOI) technology has become a great enabler in the electronics industry and also presents technological opportunities for optics in the formation of a low-loss waveguide for radiation below the bandgap of silicon. A reliable silicon-based optical modulator would find widespread application in the telecommunications and IC industries and enjoy all of the processing capabilities of today’s silicon-based fabrication facilities.

II. THEORY

An optical modulator, a key component in photonic circuitry and optical interconnect technologies, is any device that modulates an optical signal. This modulation is analogous to a transistor modulating a current signal and would allow for optical data transfer.



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Fig. 1. Proposed application of an optical modulator (left grey box) and optical detector (right grey box) to transmit data optically

The ORPEL device uses diffractive optics to couple radiation into a waveguide formed on an SOI wafer. Only wavelengths that are specifically matched to the spacing of the electrodes will be coupled and as such the device creates a resonant dip in the reflection spectrum. Waveguide coupling follows (1), where λ is the incident wavelength, θ is the angle of incidence away from the normal, Λ is the electrode spacing and n_{eff} is the effective refractive index of the waveguide [1].

$$\frac{2\pi}{\lambda} n_{eff} = \frac{2\pi}{\lambda} \sin \theta + m \frac{2\pi}{\Lambda} \quad (1)$$

Once the wave is coupled it undergoes a phase change and is coupled back out of the waveguide, destructively interfering with the normal spectral reflection. While in the waveguide the coupling of the radiation is described by the Bragg equation (2), where a δ of zero is needed to keep the wave internally reflected and confined to the ORPEL structure.

$$\delta = \pi \left[\frac{2n_{eff}}{\lambda} - \frac{1}{\Lambda} \right] \quad (2)$$

Previous research at RIT has shown that the ORPEL structure shows high spectral reflectance across a wide range of wavelengths, showing a sharp decrease in reflectance when resonance is obtained [2]. The point of resonance can be tuned to a given wavelength by fabricating devices with certain electrode spacings. A very narrow resonance spike is desirable for switching as only a small perturbation in refractive index will be needed to give high contrast in reflection.

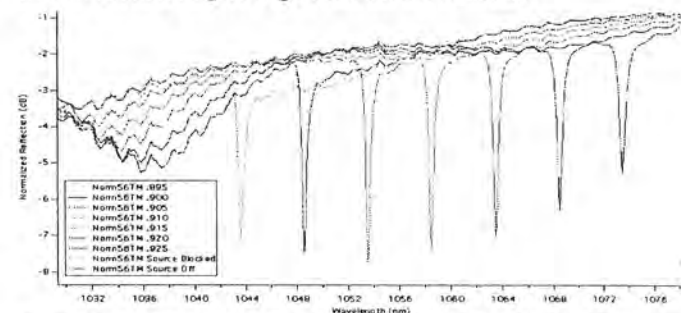


Fig. 2. Normalized spectral reflection versus wavelength for ORPEL devices

of varying electrode spacing. A reduced spectral reflectance due to thin-film interference (wide dip at left) alongside multiple resonance dips is shown.

Optical modulation can be achieved by modulating the effective refractive index of the waveguide structure. Changing the refractive index will change both coupling and resonance and can be accomplished by injection of free carriers which changes both the real portion of the index (n) and the imaginary portion of the index (α). Free carrier generation by optical pulsing is preferred to injection as it generates no current and implies low power consumption. Modulation of the resonance spike can create an optical switching mechanism. The relationship given in (3) describes the electro-optical effect in silicon [3], where ΔN_e and ΔN_h represent the changes in electron and hole concentration, respectively, while other constants have their usual meaning.

$$\Delta n = - \left[\frac{e^2 \lambda^2}{8\pi^2 c^2 \epsilon_0 n} \right] \times \left[\frac{\Delta N_e}{m_{ce}^*} + \frac{\Delta N_h}{m_{ch}^*} \right] \quad (3)$$

To target these optically generated carriers to the center of the waveguide structure, where the intensity of the coupled radiation is the strongest, a $p^+/i/n^+$ vertical doping scheme was incorporated into the waveguide. Carriers are generated by laser pumping at an absorbable wavelength and the resulting excess carriers are swept out of the waveguide by biasing the $p^+/i/n^+$ photodiode. After out-coupling the radiation must destructively interfere with the otherwise present spectral reflection from the distributed electrodes. For this reason the intensity of the radiation in the waveguide must be maintained and as such an effort was made to keep the heavily doped regions as thin as possible to create a low-loss crystalline silicon waveguide. An effort to minimize thermal budget during processing was made to accomplish this goal.

III. PROCESS

As the starting substrate, silicon-on-insulator (SOI) wafers, fabricated by the SmartcutTM process, were obtained. A shallow P_{31} implant was done to obtain a blanket n^+ layer of $2E19cm^{-3}$. The SOI was repeatedly thinned using dry and wet oxidation steps to a thickness of $\sim 1000\text{\AA}$. Almost all the phosphorous dose was maintained during thinning due to the segregation coefficient at the Si/SiO₂ interface. The substrates were then outsourced to Fairchild Semiconductor for epitaxial silicon growth of varying thicknesses. Upon return, a TEOS isolation technology was used as an implant mask to minimize the thermal processing. A shallow BF_2 implant was done to create a $2E19cm^{-3}$ p^+ layer at the top of the waveguide, unique to each device. Dopant activation was done by furnace and was the only thermal processing to occur. The above processes were modeled using ATLAS/SUPREM modeling software.

The silicon in the kerf region of the device was etched and implanted with a high phosphorous dose to obtain a contact to the n^+ ground plane. Electrodes of varying sub-micrometer pitch were created by a negative resist lithography step and subsequent evaporation and lift-off of a chrome/gold film

stack. The evaporation was done under the same vacuum in a thermal evaporator.

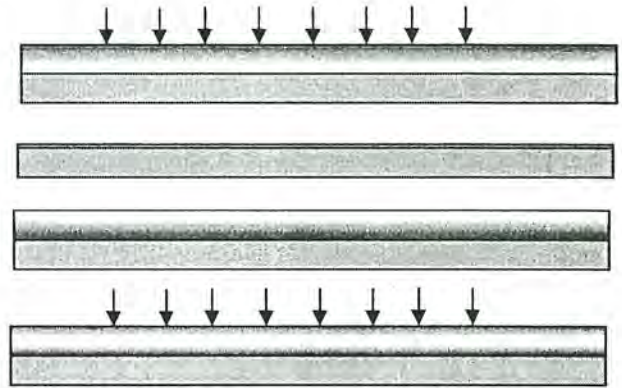


Fig. 3. Formation of $p^+/i/n^+$ doping in waveguide. From top to bottom: Implantation of P_{31} , thinning of SOI, epi-growth and implantation of BF_2 .

The final device was tested at the University of Rochester's Institute of Optics.

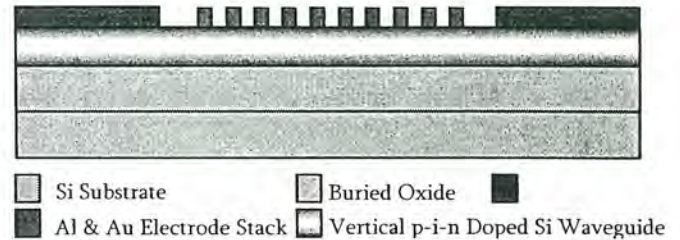


Fig. 4. Cross-section of the completed ORPEL device

IV. RESULTS

A. Process

The n^+ buried layer implant and subsequent thinning of the SOI led to an ultimate surface that was not desirable for epitaxial silicon growth. This is seen through the resulting epitaxial film appearance and high-degree of non-uniformity as measured by variable angle spectroscopic ellipsometry (VASE). The surface of the epitaxial silicon was also very pock-marked, indicating a polycrystalline layer.

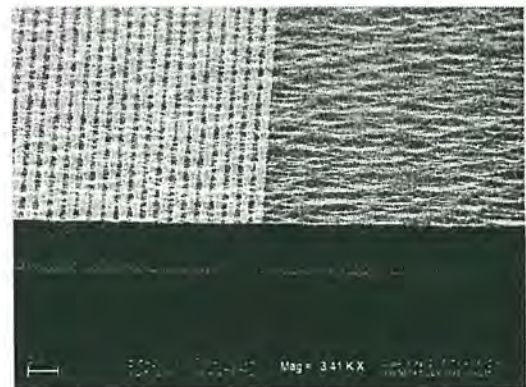


Fig. 5. SEM micrograph showing periodic metallized electrodes on a pock-marked epitaxial silicon layer. This wafer did not yield testable devices.

The resolution required to image the sub-micrometer pitch electrodes pushed the limits of the Canon i-line exposure tool chosen for this process. As such, the lines were difficult to form and had a large degree of line edge roughness and non-uniformity. This is attributed to the non-planarity of the epitaxial silicon film being imaged onto. Greater care must be taken in future processing to develop a smooth, planar epitaxial silicon film. Ultimate cause for the roughness must be determined.

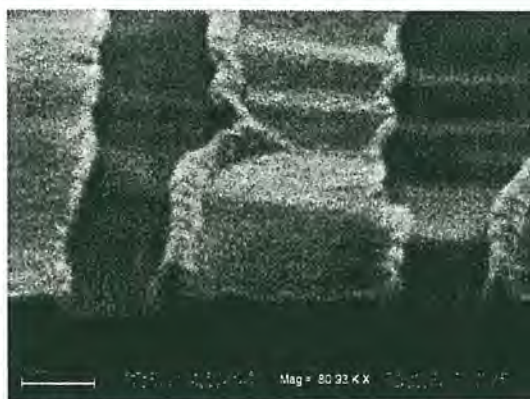


Fig. 6. SEM micrograph showing electrode with high degree of line-edge roughness and non-uniformity. Edge damage due to liftoff is seen.

B. Testing

Devices with pitch spacings of 0.695, 0.700, 0.725 and 0.730 μm yielded resonance responses when tested, shown in figures 7a – 7d. Due to imperfections in processing, the resonances of all four devices appear on or near a region of thin film interference, analogous to the interference seen in spectrometer measurements of thin films. In figure 7a the resonance falls in the middle of this valley and, as there is no background spectral reflection to destructively interfere with, the out-coupled wave manifests itself as a spike.



Fig. 7a. Resonance for a device of pitch 0.695 μm .

In figure 7b – 7d this region of thin film interference is generally static as it depends on the film stack composing the device and as such will only vary with device to device non-uniformity around the wafer. In figure 7b the resonance appears to the right of the valley.

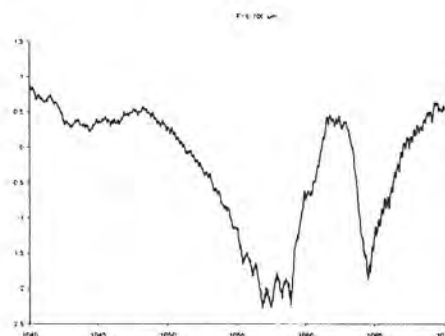


Fig. 7b. Resonance for a device of pitch 0.700 μm .

In figures 7c and 7d the resonance appears increasing further to the left of the valley. While it would be desirable to have the resonance peaks appear in an area of high spectral reflectance, unconfounded with thin film interference effects, these figures clearly show a dependence of resonance on electrode pitch.



Fig. 7c. Resonance for a device of pitch 0.725 μm .



Fig. 7d. Resonance for a device of pitch 0.730 μm .

Since these resonances are shallower and wider than those shown in figure 2, modulation by carrier injection is still being investigated and testing is currently underway at the Institute of Optics.

V. CONCLUSION

ORPEL devices have been fabricated which exhibit pitch dependent resonance effects. These resonance conditions are, however, confounded with an area of thin-film interference dependent on the film stack comprising the device. A paradigm for modulation has been discussed but testing is still underway with the most recent iteration of the device to see if

modulation is realizable. More accurate processing, including minimizing losses in the waveguide structure due to doping, will yield deeper and narrower resonance dips which will be more conducive to modulation. In future processing it will be important to fabricate a more uniform and planar epitaxial silicon surface to serve as the substrate for electrode formation. In addition, thin film thicknesses must be more carefully controlled to target resonances away from areas of thin-film interference effects.

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