Electro-Optic Modulator on Silicon-on-Insulator Substrates Using Ring Resonators

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Abstract: We study a compact electro-optic modulator using high-index contrast silicon ring resonators on Silicon-on-Insulator substrate. Optical modulation is achieved using the plasma dispersion effect due to current injection under forward bias of a p-i-n junction.

OCIS codes: (230.4110) Modulators; (230.5750) Resonators.

Silicon-on-insulator (SOI) based optoelectronic and photonic devices and circuits are attractive due to their fabrication compatibility with the CMOS process and possibility of monolithic integration on CMOS chips. Most of the proposed Si electro-optic (E-O) modulators, however, are long and require high drive powers for obtaining a significant modulation depth. Such requirements impose difficulties in integrating these devices on a chip.

The main methods to alter the refractive index in Si are the thermo-optic effect and the electro-optic effect. The thermal change of the real optical refractive index in Si is large. However, the thermo-optic effect is rather slow and can be used only up to 1 MHz modulation frequencies [1, 2]. For higher modulation frequencies, up to few hundreds of MHz, electro-optic devices are required. Linear electrooptic (Pockel's) effect is absent in bulk, unstrained silicon due to the Si crystal being centrosymmetric [3]. The quadratic electrooptic or the Kerr effect can be used in silicon only under the application of large electric fields [4]. Therefore, the free carrier dispersion effect [5, 6] is used to change both the real refractive index and optical absorption coefficient.

Since the free carrier dispersion effect is relatively weak in Si, using it for modulating normally requires long devices to achieve significant modulation [7]. The transmittance near resonance of a ring resonator cavity is very sensitive to small refractive index changes, making it very appropriate for low-power modulation. Passive silicon based ring resonators have been demonstrated that can act as ultra-compact add-drop switching devices [8]. In this work, we demonstrate a compact SOI based tunable electrically injected modulator using ring resonators.

Refractive index change in silicon due to free carrier injection can be summarized with the help of the following equations based on the Drude model [4].

$$\lambda n = \lambda n_e + \lambda n_h = -[8.8 \times 10^{-22} \cdot \lambda N_e + 8.5 \times 10^{-18} \cdot (\lambda N_h)^{0.8}] \qquad (1)$$

The resonance condition of the ring resonator is given by equation (2). By changing the refractive index under carrier injection, the resonant frequency of a ring resonator can be changed.

$$f_0 = K(c/n_{eff})(1/2\mu R) \qquad (2)$$

where c = speed of light in free space, n_{eff} = effective refractive index of the ring, R = radius of the ring, K = integer corresponding to the multiple resonant wavelengths.

The transmission through the waveguide [9] is given by equation (3) and the quality factor of the cavity formed by the ring resonator is given by equation (4).

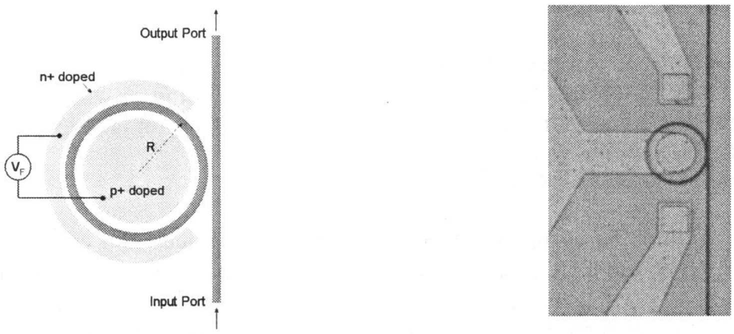
$$T = 1 - \frac{4/{-}_{p}^{2}}{(- - -_{0})^{2} + \left[\frac{2}{-_{p}} + \frac{1}{\neg}\right]^{2}} \qquad (3)$$

$$Q = \frac{2\pi^2 R n_{eff}}{\pi\pi^2} \qquad (4)$$

where λ_p = photon lifetime associated with coupling between cavity and waveguide, λ_l = photon lifetime associated with cavity losses, λ = coupling coefficient, and $\lambda_{0,}$ f_0 = resonant frequency.

The resonant frequency of the cavity and the corresponding transmission through the waveguide, described by equations (2) and (3), can be changed due to a refractive index change under free carrier injection.

The layout of the ring modulator is shown in Fig. 1(a). Fig. 1(b) shows a microscope image of a fabricated device. The devices are fabricated using standard CMOS compatible process technology. A high-index contrast 450 nm x 250 nm Si-SiO$_2$ waveguide structure is defined on a SOI substrate using e-beam lithography followed by reactive ion plasma etching (RIE). The doping regions are defined around the rings using ion-implantation. The waveguides are passivated and planarized by a combination of growth and deposition of oxide. Finally, ohmic metal contacts (Ti) and probe pads (Ti/Au) are deposited. The complex refractive index of the ring is changed by applying voltage across the anode and cathode probe pads [6].



(a) (b)

Fig. 1. (a) Layout of the ring modulator. The effective index of the ring is changed using carrier injection under applied forward bias.
(b) Microscope image of a ring resonator fabricated on SOI substrate, showing the metal contacts and vias. The waveguide width is 450 nm and the gap between the ring and the waveguide is 200 nm.

The measured spectrum of the ring resonators is shown in Fig. 2. The cavity Q of the ring cavity, estimated from the linewidth of the resonance peak/dip in the spectrum, is approximately 3300. The photon lifetimes in the cavity associated with coupling between the cavity and the waveguide is approximately 10 ps, much shorter than the carrier lifetime. Therefore, the photon confinement does not limit the speed of the device.

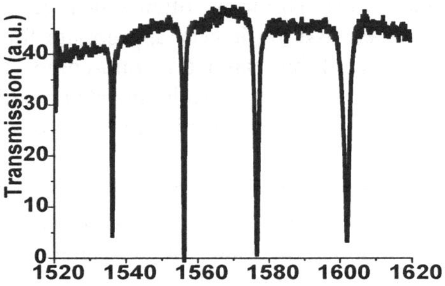


Fig. 2. Measured transmission spectrum of ring resonator fabricated on SOI substrate.

The carrier injection and corresponding change in index of the waveguide are plotted in Fig. 3. The carrier injection within the above described waveguide structure was studied by performing electrical simulations using Silvaco Atlas®. This program simulates internal physics and device characteristics of semiconductor devices by solving Poisson's equation and the charge continuity equations for electrons and holes numerically. The software allows a complete statistical approach (Fermi-Dirac statistics) when, for example, heavily doped regions are considered. Carrier recombination models include Shockley-Read-Hall (SRH) recombination, Auger recombination and surface recombination. A concentration and temperature dependent model has been used to model the carrier mobility. Electron and hole concentrations up to 5×10^{18} cm^{-3} can be obtained within the waveguide under forward bias voltage up to 0.9 V. The drive current for a bias voltage of 0.87 V was calculated to be 1.76 μA/μm, which corresponds to a dc power consumption of 1.53 μW/μm. This low dissipated power leads to a negligible increase of the device temperature, less than 10^{-2} K. This indicates that the modulator is capable of low-power operation. From eq. (1), using the above values of electron and hole concentrations, the refractive index can be changed up to 0.0122. The refractive index change corresponding electron-hole injection is shown on the secondary axis in Fig. 3.

The shift in resonance was simulated based on the measured photon lifetimes in the cavity with electron and hole injection densities of 5×10^{18} cm^{-3} each. We estimate a modulation depth larger than 90% can be achieved close to the resonant wavelength for a cavity with a Q factor of ~3000. Transient analysis of the structure reveals that the on-off switching times for such a device can be as small as 1.29 ns [6] and modulation speeds up to 775 MHz can be obtained. For smaller modulation depths (~20%), speeds in the GHz range can be obtained. By manipulating the degree of surface passivation or by using ion implantation [10], the free-carrier lifetime could be further decreased to be less than 100 ps.

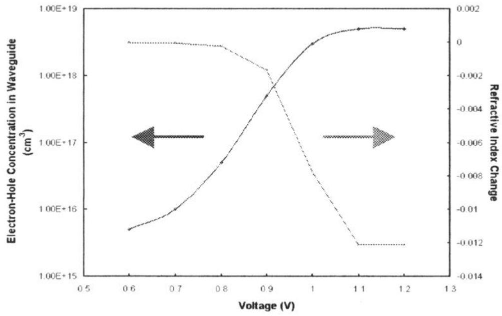


Fig. 3. Electron-hole concentration in the bulk of the waveguide and the corresponding index change under different forward bias conditions.

It is evident that the large measured Q of the cavity enables a small change in refractive index of the ring to produce a significant shift in the resonances of the transmission spectrum. As shown in Fig. 4, at the probe wavelength of 1549.21 nm a modulation depth of 50% was observed under a forward bias of 10 V. It must be mentioned that the device operating voltages are not representative of the device scheme. Figures 2 and 3 obtained from the device analysis presented earlier indicate that such a large modulation depth is possible with bias voltage as low as 1.1 V. Lower operating voltages can be obtained by minimizing the resistances of the ohmic contacts.

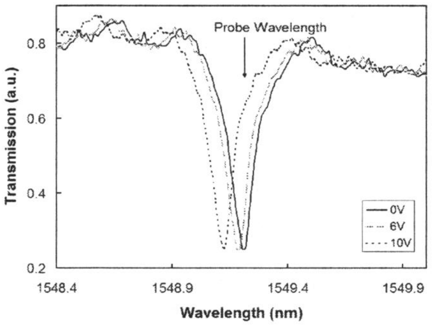


Fig. 4. Measured transmission spectrum of ring resonator with radius 18 μm under carrier injection.
The device shows a modulation depth up to 50%.

References

1. R. L. Espinola, M-C. Tsai, J. T. Yardley and R. M. Osgood, "Fast and low-power thermooptic switch on silicon-on-insulator", *IEEE Photon. Technol. Lett.*, **15**, 1366-8 (2003).
2. G. Cocorullo, M. Iodice, I. Rendina and P. M. Sarro, "Silicon thermooptical micromodulator with 700-kHz -3-dB bandwidth", *IEEE Photon. Technol. Lett.*, 7, 363-5 (1995).
3. R. A. Soref and J. P. Lorenzo, "All-silicon active and passive guided-wave components for λ =1.3 and 1.6μm", *IEEE J. Quantum Electron.*, **22**, 6, 873-9 (1986).
4. R. A. Soref and B. R. Bennett, "Electrooptical effects in silicon", *IEEE J. Quantum Electron.*, **23**, 123-9 (1987).
5. C. A. Barrios, V. R. Almeida and M. Lipson, "Low-power-consumption short-length and high-modulation-depth silicon electrooptic modulator", *IEEE J. of Lightwave Technol.*, **21**, 1089-98 (2003).
6. C. A. Barrios, V. R. Almeida, R. Panepucci and M. L. Lipson, "Electrooptic modulation of silicon-on-insulator submicrometer-size waveguide devices" *IEEE J. of Lightwave Technol.*, **21**, 2332-9 (2003).
7. A. Liu, R. Jones, L. Liao, D. Samara-Rubio, D. Rubin, O. Cohen, R. Nicolaescu, M. Paniccia, "A high-speed silicon optical modulator based on a metal-oxide-semiconductor capacitor" *Nature*, **407**, 615-9 (2004).
8. B. E. Little, J. S. Foresi et. al., "Ultra-compact Si-SiO$_2$ microring resonator optical channel dropping filters", *IEEE Photon. Technol. Lett.*, **10**, 549-51 (1998).
9. B. E. Little, S. T. Chu, H. A. Haus, J. S. Foresi and J-P. Laine, "Microring resonator channel dropping filters", *IEEE J. Lightwave Technol.*, **15**, 998-1005 (1997).
10. T. Sadagopan, S. J. Choi, S. J. Choi, P. D. Dapkus, and A. E. Bond, "High-speed, low-voltage modulation in circular microresonators", *IEEE/LEOS Summer Topical Meetings 2004*, MC2-3, San Diego (CA)(2004).