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Resonator-based silicon electro-optic modulator with ultra-low power consumption

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Abstract—This paper demonstrates, via simulation, an electro-optic modulator based on a subwavelength Fabry-Perot resonator cavity with ultra-low power consumption. The device is modulated at a doped *p-i-n* junction overlapping the cavity in a silicon waveguide perforated with etched holes, with the doping area optimized for minimum power consumption. The surface area of the entire device is only 2.1 μm^2. Our optical and electrical simulations demonstrate a resonance peak shift of 12 nm with 0.5 mW power consumption. Transient results indicate that the modulation depth exceeds 10 dB at a modulation speed of 100MHz with the power consumption comparing favorably to a previous report [1]. The etched holes forming the cavity have also been tapered [2] to optimize insertion. The device does not rely on ultra-high Q, and could serve as a sensor, modulator, or passive filter with built-in calibration.

1. Introduction

Recent research in silicon photonics is driven by its relatively low cost nature and the potential ease of integrating micro-optical components into microelectronic technology. However, because of the absence of a second-order nonlinearity, the only efficient way of achieving silicon- based optoelectronic devices such as modulators and switches is to utilize the free carrier plasma dispersion effect [3], and established approaches to free carrier perturbation involve either carrier injection [4] or carrier depletion [5]. Furthermore, recent application of photonic bandgaps and microcavities makes it possible to reduce device lengths to tens of microns thanks to the fact that low group velocities in both cases significantly enhance the plasma dispersion effect, reducing the interaction length.

2. Device Structure and Modulation Scheme

The optical model of the device is based on a subwavelength Fabry-Perot (FP) resonator achieved by introducing a central defect to a 1-D photonic crystal waveguide, which is defined by etched air holes on both sides of the structure, shown in Fig. 1. The central defect, as firstly shown in [6], will introduce a localized optical mode within the bandgap of the original photonic crystal structure, thereby forming a resonance peak due to Bragg reflection. In our design, the central defect is 580 nm long, only about 1/3 of the resonant wavelength, helping reduce the doping area and therefore power consumption. The radius of the air holes is 100 nm with a 420-nm lattice constant. To make it electrically active, an ultra-thin silicon slab (23 nm) below the waveguide is introduced and p+ and n+ regions are defined by lateral boron and phosphorous doping on each side of the waveguide, each with a doping concentration of $1x10^{20}cm^{-3}$. The ultra-thin silicon slab along with the relatively small waveguide height (200 nm) further reduces doping volume and more significantly, reduces the total number of injected free carriers, whilst maintaining significant modal overlap and the injected free carriers. This means a reduced carrier injection time and thus higher modulation speed without sacrificing modulation depth. The width of the waveguide is 470 nm. This device differs from that reported in [1] in that our cavity size is smaller, doping region is variably optimized and of smaller thickness, and hole radii are not constant. Our goal is to optimize for modulation depth and low power consumption.

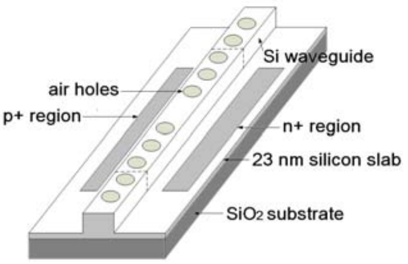

Fig. 1 Schematic of the resonator-based electro-optic modulator

The modulation scheme of the device is based on free carrier injection, and ON/OFF contrast is achieved by resonance peak shift due to the resulting index perturbation.

3. Simulation Results and Discussion

The ATLAS device simulation package from SILVACO has been used to predict both DC and transient characteristic of the device. The electrical simulator includes Shockley Read Hall (SRH), Auger, and Direct recombination models. The DC voltage applied between anode and cathode of the device varies from 1.1 to 1.2 V, where according to Fig. 2, driving current density is the smallest and sufficiently large index changes are detected.

Dynamically, the 10%-90% rise time and fall time are about 6.2 ns and 3.8 ns respectively according to Fig. 3 and almost unchanged under different bias voltages. Therefore, it is reasonable to expect hundreds of MHz modulation speed from the device. Of course, greater speed is possible in tradeoff with power consumption.

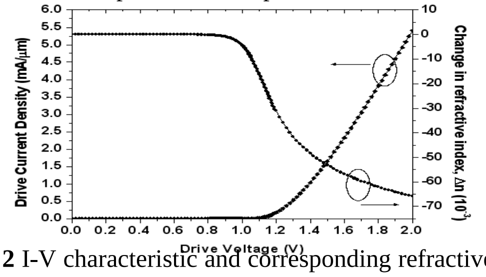

Fig. 2 I-V characteristic and corresponding refractive index change of the doped area.

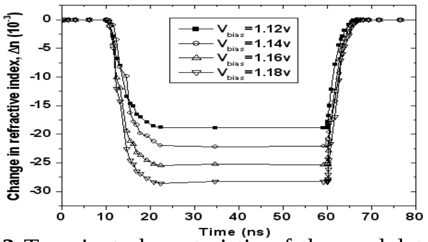

Fig. 3 Transient characteristic of the modulator under different bias voltages.

The doping area was optimized to reduce power consumption by extending the doping area from the central defect to a given hole, numbered starting from 1 from the cavity outwards and denoted as the variable N_{dop}, on each side of the cavity. The resonance peak shift corresponding to different N_{dop} at the same voltage bias of 1.14 V is measured using a 3-D FDTD simulator and the result is given in Fig. 4.

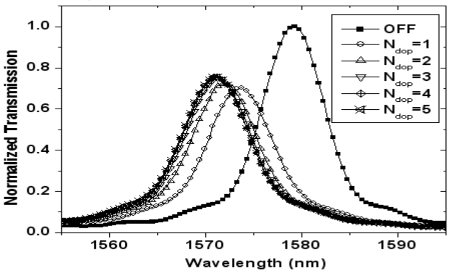

Fig. 4 Resonance peak shift of different doping areas at the same voltage bias of 1.14 V.

The peak shift is measured in reference to OFF state of the modulator, which corresponds to zero voltage bias and thus zero index change. According to Fig. 4, peak shift is insignificant when doping area extends to greater than 3 holes. Hence our design as shown in Fig. 1.

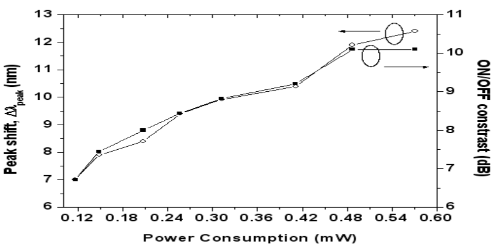

Fig. 5 Relationship between resonance peak shift, ON/OFF contrast and power consumption.

Further investigations have been conducted to explore the relationship between resonance peak shift, ON/OFF contrast and DC power consumption, shown in Fig.5. By combining information from Fig. 3 and 5, we expect a 10 dB modulation depth at speed of 100 MHz with power consumption of 0.5 mV. There is an order-of-magnitude greater resonance peak shift compared to a previous device [1], but this comes partially at the expense of achievable modulation speed. The large peak shift and ON/OFF contrast in our design are due to a small cross sectional device area and a very short active length.

Finally, the radius of 3 outmost holes on both sides is tapered at different steps to enhance overall transmission of the device. Our 3-D FDTD results indicate a maximum transmission improvement of 7 dB. Although larger tapering step guarantees higher transmission, Q value of the microcavity is reduced from 178 to 102, and peak shift may be reduced as a result.

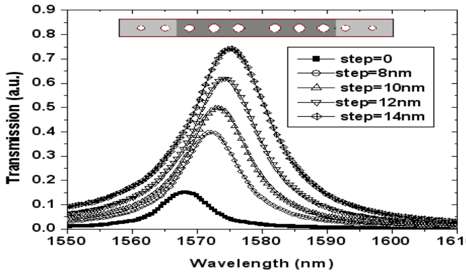

Fig. 6 Higher insertion is achieved by tapering the radii of air holes on each side.

4. Conclusions

To conclude, we have demonstrated a resonator-based electro-optic modulator with ultra-low power consumption. A larger resonance peak shift is detected due to the refinement in both electrical and optical designs. The large peak shift of the device can also be applied to biosensors or optical filters that are based on the same design in order to compensate for fabrication imperfections.

References

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