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Substrate Removal for Ultra Efficient Silicon Heater-Modulators

Nicholas J.D. Martinez, Christopher T. DeRose, Robert Jarecki, Andrew L. Starbuck, Andrew T. Pomerene, Douglas C. Trotter, Paul S. Davids and Anthony L. Lentine
Sandia National Laboratories
Albuquerque, New Mexico, USA

***Abstract*—We present our experimental results of ultra efficient (up to 2.16 nm/mW) thermally tunable modulators with n-type heaters and the Si substrate removed. To our knowledge, this is the most efficient thermally tunable modulator demonstrated to date. We include results of externally heated modulators with commensurate performance enhancements through substrate removal.**

I. Introduction

Silicon microring modulators have proven to be the pinnacle for modulation of optical signals such as in wavelength division multiplexing (WDM) [1]. Their easy integration with standard CMOS processing and possibility for small diameters offers circuit densification. Fast switching can be achieved by electro-optic means with speeds exceeding 30GHz [2]. However, using this method of free carrier absorption to reach high data rates requires robust fabrication and temperature stability. A solution for stabilizing the modulators susceptibility to these tolerances is through thermal tunability.

Previous Si modulators have shown impressive efficient thermal tunability [3,4] for an internally heated design using doped heaters without removal of the Si substrate. The most efficient heater-filter and heater-modulator prior to this work are 1.78 nm/mW [3] and 1.48 nm/mW [4] respectively. In contrast, less efficient thermally tunable modulators have seen ~20x improvement through substrate removal [5] directly below the modulator. Here we present measured and calculated efficiencies with and without substrate removal for two 2 µm radius modulator designs utilizing heavily n-type doped heaters. In one design [4], the heater is in the interior of the disk, and in the other design [6], the heater is external to the ring. These two cases will be referred to as 'internal' and 'external' heaters in the disucssion that follows. Power coupled from the external heater is transferred to the modulator through Aluminum conduits in order to increase efficiency. Experimental data is bolstered through finite element simulations (COMSOL) of identical input power. Agreement between simulated and experimental data is greater than 82%, allowing us to simulate optimized structures with confidence.

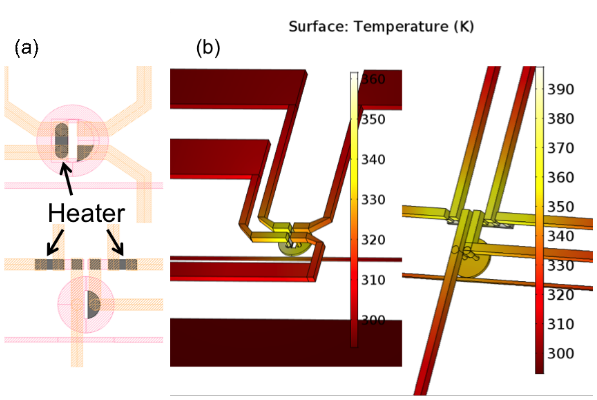

Fig. 1. (a) Design layout showing the heater placement relative to the microring and waveguide. (b) Simulated temperature distribution of integrated heater (left) and external heater (right) modulator.

II. Experimental Results

The devices were fabricated as part of Sandia's CMOS process explained in [7]. The heaters are a heavily doped (n-type) Phosphorous stripe, $10^{18}/cm^3$, with ohmic contacts from Tunsten (W) vias to Aluminum (Al) probe pads. The Si substrate was removed through Reactive Ion Etching (RIE) for a hole nominally 60 µm in diameter down to the oxide layer. The small diameter of the micro-ring modulator provides a wide free spectral range (FSR). The FSR was measured for several of both types of heated modulators to be 58.59±0.02 nm, covering the entire C-Band. Coupling to the modulator is done through a Si ridge waveguide with 320nm width. Figure 1(a) , inset, shows the external and integrated heater-modulator design. The left simulated image of Fig. 1(b) is the integrated heater design showing the temperature distribution. The right simulated image of Fig. 1(b) is an externally heated modulator with the bar heaters placed opposite to the waveguide.

A tunable laser (Agilent HP-8164) was used to sweep through wavelength for resonances. Shifting resonances was accomplished by applying up to 2.3 V through GSG-RF probes. Voltage and Current levels were recorded in order to calculate the power dissipated through the heaters. Where as the integrated heater, pictured in Fig. 1(b) to the left, is only on one side of the modulator, the external heaters are two symmetrically displaced N+ Si stripes opposing the waveguide. The efficiency is better for the integrated heater design, however, the external design allows for better optimization of the micro-disk modulation [6].

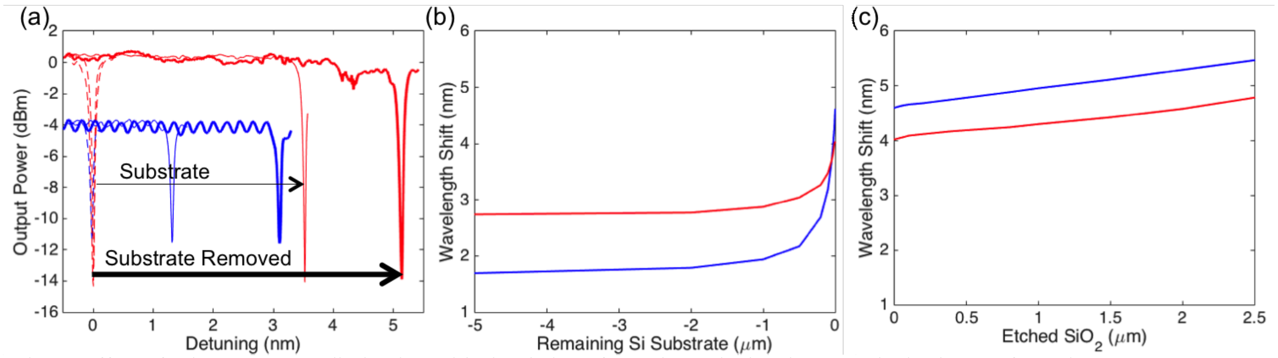

Fig. 2 Effect of substrate power dissipation with simulations for under-etched and over-etched substrate for a given constant power. (a) Experimental comparison of resonance shift for external (BLUE) and integrated (RED) heater design with and without substrate both biased at 0.5 V. (b) Simulated wavelength shift dependent on remaining Si substrate thickness after etching. (c) Simulated wavelength shift dependent on continued etching of the oxide layer after substrate removal. Power dissipation is 4.84 mW (2.32 mW) for the external (integrated) heater design.

	Units (nm/mW)	Integrated Heater	External Heater	Previous Work
With Substrate	*Measured*	1.48	0.27	0.38 [3]
	Simulated	1.29	0.26	
Substrate Removed	*Measured*	2.16	0.68	1.14 [4]
	Simulated	1.8	0.66	

Table 1. Summary of measured and simulated efficiencies and comparison to earlier work.

Simulations of the integrated heater-modulator with varying levels of substrate removal were done in order to understand the efficiency capabilities of our design. Figure 2(a) is experimental data highlighting the increased efficiency of an external (BLUE) and integrated (RED) heater-modulator with and without the Si substrate below the modulator. Figure 2(b) shows the simulated effect remaining Si substrate has on wavelength shift. It can be seen that completely removing the Si substrate underneath the device maximally reduces the amount of power dissipated. Figure 2(c) shows the simulated effect if etching continued through the oxide layer. Etching through the SiO_2 cladding is limited since the Si substrate is 2.5 µm from the Si active components in our design.

III. Conclusions

We demonstrate ultra-efficient heater-modulators with and without substrate removal of internally and externally located n-type heaters, with the former being the most efficient heater-modulator to date at 2.16 nm/mW. Interestingly, the improvement by removing the substrate for our devices is less for the most efficient case of an internal heater (1.4X) compared to an external heater (2.5X), and the overall improvement is less than devices reported in the literature that see up to 20X improvement. We believe previous integrated heater modulators [4] with high efficiency already have low heat flow to the substrate relative to heat flow to the wiring and through the coupled waveguide, hence removing the substrate doesn't provide a huge improvement in overall efficiency. While the externally heated device shows some efficiency improvement, from 0.27 nm/mW to 0.68 nm/mW, heater location, substrate hole dimensions, and metallic pad locations can be further optimized for greater improvements by removing the substrate and heater efficiencies more comparable to that of an internally heated modulator.

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