Wafer-Scale-Compatible Substrate Undercut for Ultra-Efficient SOI Thermal Phase Shifters

Matthew van Niekerk[1], Venkatesh Deenadalayan[1], Anthony Rizzo[2], Gerald Leake[3], Daniel Coleman[3], Christopher C. Tison[4], Michael L. Fanto[4], Keren Bergman[2], Stefan Preble[1,*]

[1] *Rochester Institute of Technology, Department of Microsystems Engineering, Rochester, NY 14623 USA*
[2] *Columbia University, Department of Electrical Engineering, New York, NY 10027 USA*
[3] *State University of New York Polytechnic Institute, Albany, NY 12203, USA*
[4] *Air Force Research Laboratory, Information Directorate, Rome, NY 13441 USA*

**sfpeen@rit.edu*

Abstract: We present a thermally isolated phase shifter through undercutting the silicon waveguide and resistive heaters, yielding a low-power ($P_\pi = 1.2$ mW) and low-crosstalk tunable Mach-Zehnder interferometer.

1. Introduction

Thermo-optic devices are necessary for many switching, filtering and programming tasks in silicon photonics. Unfortunately, thermal components typically consume on the order of tens of milliwatts per element and are susceptible to large intra-chip parastic crosstalk. For these reasons, thermal devices do not meet the performance requirements inherent in large scale circuits, such as microring arrays or programmable circuits [1]. However, the efficiency of thermal devices can be dramatically increased by selectively removing the silicon substrate under the heater, effectively eliminating the path of lowest thermal resistance and thus isolating the device. Drawbacks of previous demonstrations of efficient undercut thermal phase shifters in the silicon-on-insulator (SOI) platform include the use of a backside etch for substrate removal [2] and fabrication in a low-volume e-beam platform [3]. Here, we present and validate a thermally isolated phase shifting cell fabricated in a commercial 300 mm CMOS foundry, which exhibits low-crosstalk and low-power operation. While minimal post-processing steps were used for the final substrate removal, this approach can fundamentally be extended to entirely wafer-scale processing, enabling future high-throughput fabrication of circuits containing thousands of phase shifters with minimal crosstalk and energy consumption.

2. Results

The resistive heater is designed by placing doped silicon wires nearby the optical waveguide, which dissipate heat and impart a phase shift by changing the waveguide's effective refractive index via the thermo-optic effect [5]. We simulate the thermal behavior of the device with Ansys-Lumerical's HEAT solver [4]. As a baseline, we simulate the standard device cross section—a silicon-on-insulator (SOI) wafer with cladding oxide as shown in Fig. 1 a). This device suffers from low heat generation from the resistive elements, since the substrate acts as an escape path for the heat due to the high thermal conductivity of silicon as shown in Fig. 1 d). Alternatively, we explore a thermally isolated design which removes oxide and the silicon substrate around the heating and waveguiding elements, shown in Fig. 1 b). Fig. 1 e) displays the corresponding simulation for the undercut device, demonstrating a dramatic increase in heat ($> 300^\circ$ C) for the same 5 mW of power. Our MZI devices with thermal phase shifters were fabricated by AIM Photonics with a trench on either side of the waveguides [Fig. 1 c)], terminating at the buried oxide layer. We post-processed by performing an Inductively Coupled Plasma (ICP) Reactive Ion Etching (RIE) etch of the remaining buried oxide to expose the silicon substrate. The silicon substrate was partially removed using a vapor phase xenon diflouride (XeF_2) etch (resulting in 20μm undercut [Fig. 1 c)]).

We used standard SMF28 to couple light on to the chip to optically address the MZI. The thermal phase shifters are routed to metal pads which were individually addressed with a DC probe. The resistors are designed with resistance of 2.3 kΩ. We apply a voltage bias and track the optical transmission through the fully air clad, thermal isolated, MZI at 1550 nm. As the voltage bias increases, the transmission changes with a sine-squared relationship with respect to power as shown in Fig. 1 f). We extract P_π, the power required for a phase shift of π, of 1.2 mW, which has a corresponding voltage of $V_\pi = 1.65$ V. Fig. 1 h) reports the results of a modulation frequency sweep of the MZI. The standard cladding shows a roll-off frequency of $f_{3dB} = 4.5$ KHz, whereas the air clad MZI is an order of magnitude lower with a rolloff frequency of $f_{3dB} = 445$ Hz. The modulation result demonstrates the difference in thermal conductivity of the two designs.

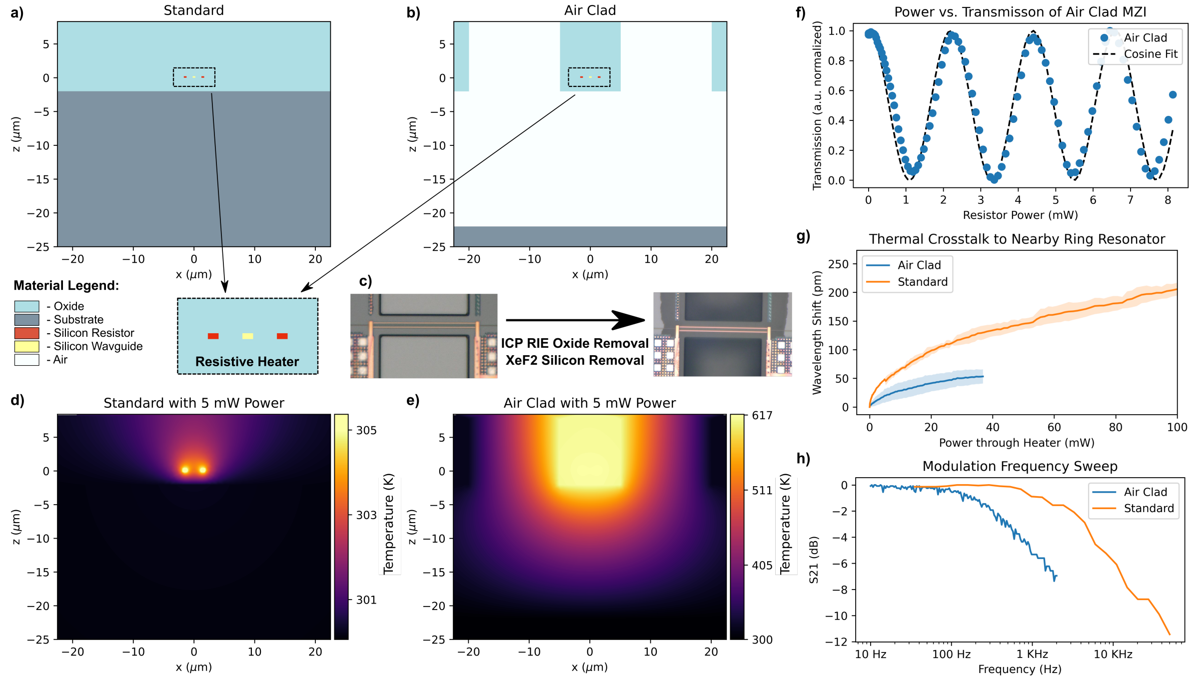

Fig. 1: (a-b) Cross sections of the standard and air clad devices, respectively. c) Optical microscope images of the as fabricated devices (with trench to BOX) and thermal isolated devices. (d-e) Corresponding simulations heat maps of the standard and air clad devices, respectively, at 5 mW power in the resistive heater [4]. f) Optical transmission of the MZI as a function of power dissipated by the resistive heater. g) Demonstration of thermal crosstalk of the standard and air clad devices, as measured by tracking the resonance shift of a nearby ring resonator. h) Modulation frequency sweep, which demonstrates a lower response speed for the air clad devices.

We determine the isolation of the thermal phase shifter by tracking the resonance peak wavelength of a nearby ($\sim 500\,\mu$m) ring resonator – a highly temperature sensitive device. We applied an increasing range of voltages to the thermal phase shifter, while optically probing the ring resonator. We investigate the resonance shift as a function of heat in the resistor, shown in Fig. 1 g). The standard device shifts the resonance more than the air clad for the same power, demonstrating the thermal isolation of the heaters. In addition, due to the dramatic performance increase of the air clad device we also note the difference in resonance shift at the operating power. The standard device has a characterized $P_\pi = 60\,mW$ and induces a 170 pm resonance shift, where as the air clad device has $P_\pi = 1.2$ mW, inducing a resonance shift of only 20 pm.

In summary, we demonstrate a wafer-scale-compatible thermally isolated phase shifter fabricated in a 300 mm commercial foundry which exhibits low-power consumption ($P_\pi = 1.2$ mW) and low thermal crosstalk. This will be key to the realization of low crosstalk, densely integrated, photonic chips.

References

1. W. Bogaerts, D. Pérez, J. Capmany, D. A. Miller, J. Poon, D. Englund, F. Morichetti, and A. Melloni, "Programmable photonic circuits," Nature **586**, 207–216 (2020).
2. J. E. Cunningham, I. Shubin, X. Zheng, T. Pinguet, A. Mekis, Y. Luo, H. Thacker, G. Li, J. Yao, K. Raj, and A. V. Krishnamoorthy, "Highly-efficient thermally-tuned resonant optical filters," Opt. Express **18**, 19055–19063 (2010).
3. P. Sun and R. M. Reano, "Submilliwatt thermo-optic switches using free-standing silicon-on-insulator strip waveguides," Opt. Express **18**, 8406–8411 (2010).
4. "Ansys-Lumerical. **HEAT**: 3D Heat Transport Simulator," http://lumerical.com.
5. Y. Xie, Y. Shi, L. Liu, J. Wang, R. Priti, G. Zhang, O. Liboiron-Ladouceur, and D. Dai, "Thermally-reconfigurable silicon photonic devices and circuits," IEEE J. Sel. Top. Quantum Electron. **26**, 1–20 (2020).

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