

# Silicon Microring Modulator with Integrated Heater and Temperature Sensor for Thermal Control

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**Abstract:** The first demonstration of a silicon microring modulator with both an integrated resistive heater and diode-based temperature sensor is shown. The temperature-sensor exhibits a linear response for more than an 85 °C external temperature range.

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## 1. Introduction

In recent years silicon microring-resonator based filters and modulators have received increased attention as potential devices for reducing interconnect power consumption in high performance computers. Recently energy consumption in silicon microring modulators was demonstrated to be as low as 85 fJ/bit [1]. Such low power devices are enabled by narrow bandwidth, high Q resonances. Due to the high thermo-optic coefficient of silicon and the wide variation in temperatures at the core of micro-processors thermal control may be required to maintain the desired resonance frequency of the microring to within less than 10 GHz in data communications applications.

Previously the use of negative thermo-optic materials as an overlay on microring-resonators have been used in an attempt to athermalize the ring resonance frequency [2]. However, the use of such polymer overlays does not fit within standard CMOS process flows and may not be able to correct for fabrication errors in the position of the resonance frequency making their practical implementation challenging. We have previously demonstrated a thermo-optic device consisting of an integrated resistive heater in an adiabatic resonant microring which showed a fast response time of 1  $\mu$ s and a low tuning power of 4.4  $\mu$ W/GHz [3]. Here we demonstrate a microring modulator with an integrated resistive heater and a temperature sensing diode to enable thermal control.

## 2. Device Layout and Theory

The resonators were fabricated on a silicon-on-insulator (SOI) wafer with 3  $\mu$ m of buried oxide and an initial 250 nm thick silicon layer. The devices were defined using an ASML deep ultra-violet (DUV) laser scanner and silicon etch. An As implant was used to achieve an *n*-type doping level of  $\sim 2 \times 10^{18}/\text{cm}^3$  in the heater region. Electrical contact from the device to aluminum bus lines was made through tungsten vias. A schematic of the device can be seen in Fig. 1.

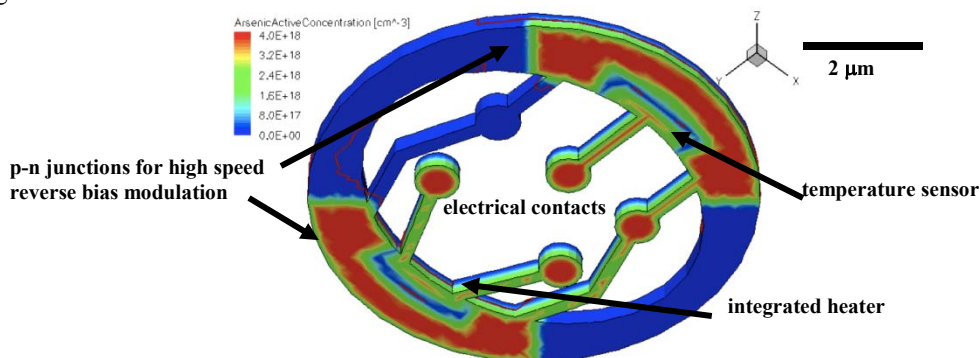


Fig. 1 A schematic of the fabricated microring modulator with integrated heater and temperature sensor.

The Shockley ideal diode equation is given by:

$$I = I_S \left( e^{V_D q / nkT} - 1 \right) \quad (1)$$

where  $I$  is the diode current,  $I_S$  is the reverse bias saturation current,  $V_D$  is the voltage across the diode,  $n$  is the ideality factor,  $q$  is the elementary charge,  $k$  is Boltzmann's constant and  $T$  is the absolute temperature of the *p-n* junction. Equation 1 implies that for a constant current source applied to the diode a linear shift in the voltage dropped across the diode as a function of temperature occurs making a diode an ideal candidate as an integrated temperature sensor for microring modulators.

### 3. Experimental Results

Experimental testing of the devices was done in the following manner: Chips were mounted onto a temperature controlled stage using K275 thermally conductive two-sided tape from CS Hyde. A 6 pin DCQ-06 probe from Cascade was used to electrically contact the heater, temperature sensor and optical modulation diode and Keithley 2400 source meters were used to drive both the heater and temperature sensor. An Agilent 8164B tunable laser was used as the optical source. The voltage dropped across the temperature sensing diode with a 1nA current source applied was measured as a function of both the stage temperature and the power dissipated by the resistor. The results of these measurements can be seen in Fig. 2.

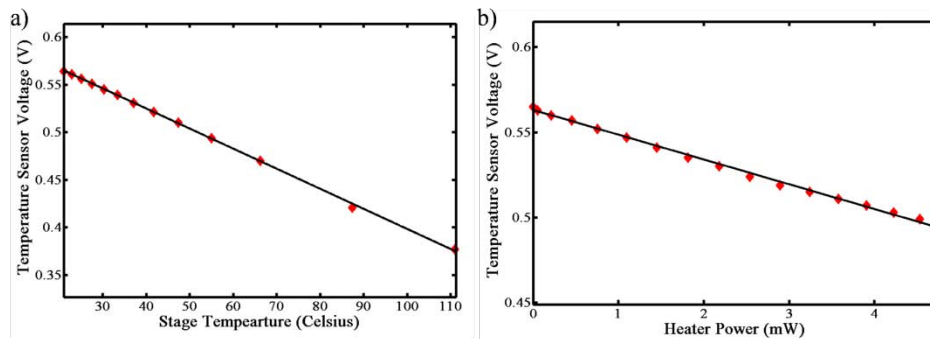


Fig. 2 Temperature sensor with a 1 nA current source applied as a) a function of the stage temperature and b) a function of the power applied to the integrated resistive heater. The solid line is a linear fit and the red points are measured data.

From Fig. 2 it can be seen that the temperature sensor has a linear response to both external and internal temperature modulations in agreement with the diode equation and that the range is at least 85 °C. The differences in slopes of the two curves are due to thermal gradients in the microring caused by the integrated heater, a problem that can be alleviated with greater thermal isolation of the microring. Furthermore the position of the ring resonance due to thermal drift is also related to the sensor voltage in a linear fashion (Fig. 3). From Fig. 3 it can be seen that the temperature sensor voltage can be used as a measure of the ring resonance position to a precision of ~ 8 GHz which is acceptable for control of thermal drift and may still be improved with greater thermal isolation of the microring.

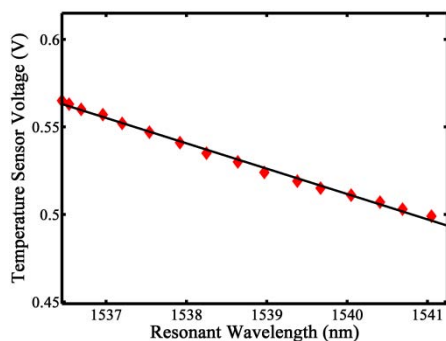


Fig. 3 Temperature sensor with a 1 nA current source applied as a function of the ring resonance wavelength when the temperature is changed using the integrated heater. The solid line is a linear fit and the red points are measured data.

### 4. Conclusions

A microring modulator with an integrated heater and temperature sensor has been demonstrated. The temperature sensor has a linear response for both external heating from a temperature controlled stage and internal heating from an integrated resistive heater and can be used to measure the position of the ring resonance. In the future the integrated sensor and heater should enable a fast response ( $\sim 1\mu\text{s}$ ) temperature control loop with a range of at least 100 °C.

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### 5. References

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