Comparison of thermo-optic phase shifters in imec's silicon photonics platform

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Abstract. Taking advantage of the high thermo-optic coefficient of silicon is an effective way to realize optical phase shifting in silicon photonic circuits. Based on the imec iSiPP200 silicon photonics platform, different types of integrated silicon photonic phase shifters are compared, including doped-silicon side heaters, diode-loaded heaters, doped waveguides, and metal top heaters. The effect of thermal insulation on phase shifter efficiency and bandwidth is discussed for different architectures with and without substrate undercut. By locally removing the silicon substrate underneath the heater, the efficiency of doped-silicon side heaters is improved by a factor of 2.7 for a π phase shift.

Keywords: Silicon Platforms, Thermo-optic Phase Shifter, Undercut, Efficiency, Bandwidth.

1 Introduction

Silicon platform is becoming a key technology for photonic integrated circuits, due to its CMOS compatibility and small footprint. In many applications, such as optical switching, optical communication, and programmable photonic integrated circuits [1], thermo-optic phase shifters form a key building block. Taking advantage of the high thermo-optic coefficient of silicon [2], local heaters are an effective way to realize optical phase shifting in silicon platforms.

Using on the imec iSiPP200 silicon photonics platform [3], we implemented various phase shifters to illustrate the impact of thermal insulation on both efficiency and bandwidth, including doped-silicon side heaters, diode-loaded heaters, doped waveguides, metal top heaters, and folded metal heaters. Due to the local removal of the silicon substrate underneath the heater, the efficiency of doped-silicon side heaters could be improved by a factor of 2.7 for a π phase shift. We compare doped waveguides with lateral and longitudinal current injection, the -3 dB bandwidths of the lateral-injected is 3.4 times larger than that of longitudinal-injected doped waveguides. Furthermore, the asymmetric electrical response of diode-loaded heaters provides opportunities for utilizing pulse-width modulation (PWM) or multiplexed driving techniques, which offers valuable guidance in selecting appropriate phase shifters for large-scale programmable circuits. The most efficient heater we tested is a folded tungsten heater, with an efficiency of 1.97 mW for a π phase shift.

2 Design and Measurement method

2.1 Different Designs of Phase Shifters

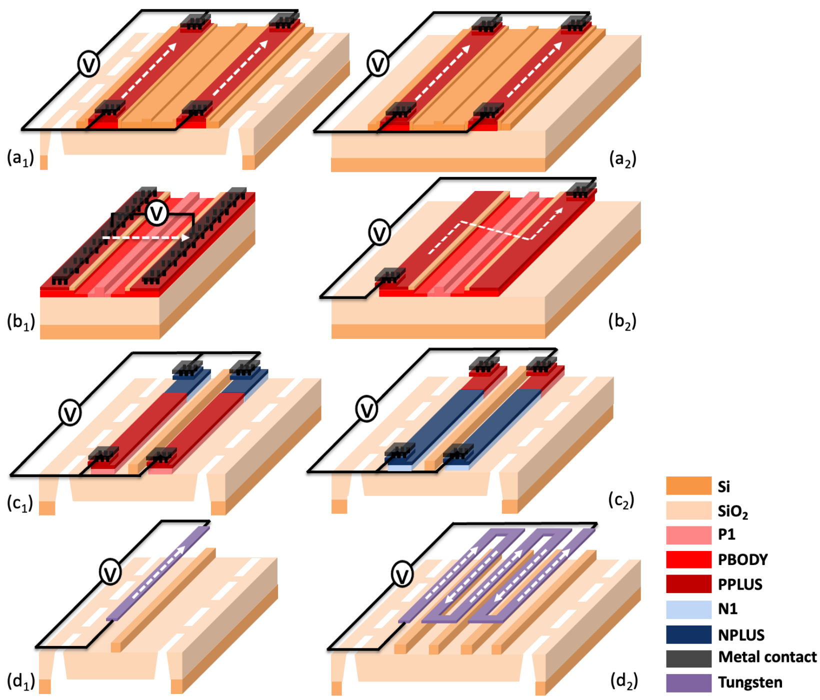

Fig. 1. Schematic diagram of doped-silicon side heaters (a_1) with and (a_2) without undercut, (b_1) lateral and (b_2) longitudinal-injected doped waveguides, (c_1) P and (c_2) N diode-loaded undercut heaters, (d_1) single and (d_2) 4 folded tungsten heaters.

Figure 1 depicts three types of heaters in imec's platform. Doped-silicon side heaters with and without undercut are shown in Fig. 1(a_1) and (a_2), respectively. Based on typical shallow-etched rib waveguides, P-doped silicon is positioned as a resistor next to the waveguides. The dopants increase the conductivity of side heaters, allowing current to flow through them via electrical contacts. Using deep-etched rib waveguides, we propose two doped waveguides in Fig. 1(b_1) and (b_2), using waveguide itself as a resistor. The current flows through the waveguides directly in Fig. 1(b_1). Therefore, this type of heater is more efficient. As shown in Fig. 1(b_2), only one electrical contact is placed on each side, two side heaters and a central waveguide form a circuit. We utilize full-etched strip waveguides to demonstrate the diode-loaded heaters. As shown in Fig. 1(c_1), we use P-type dopants to dope the main body of the heaters, and use N-type dopant to dope the area near one of the electrical contacts, creating a PN junction inside the heater. This is defined as P diode-loaded heater. Likewise, Fig. 1(c_2) shows a N diode-loaded heater. Another alternative is to use a metal resistor on top of the waveguide. Fig. 1(d_1) shows the standard single-line heater. To improve the efficiency, we use folded tungsten lines above the waveguides, as shown in Fig. 1(d_2).

2.2 Measurement Methods

We use asymmetric Mach-Zehnder interferometers (MZIs) to demonstrate the phase shifters. Each type of heater is placed in such an MZI with standard 2×2 multimode interferometers (MMI). We could characterize electrical and optical response of the heaters using the method shown in Fig. 2 (a). Light is coupled into the MZI by grating couplers, and we drive the heaters by sweeping the direct current (DC) voltage, then monitor the current and the optical output power simultaneously. We could further measure the frequency response of the heaters, as depicted in Fig. 2(b). Using a function generator, we inject a radio frequency (RF) signal at a single frequency to the heaters. Light couples out of the fiber and enters the photodetector.

After adjusting the DC bias, we set the heaters to the quadrature point to get the maximum modulation amplitude on the oscilloscope. By sweeping different frequencies, a Bode plot could be constructed.

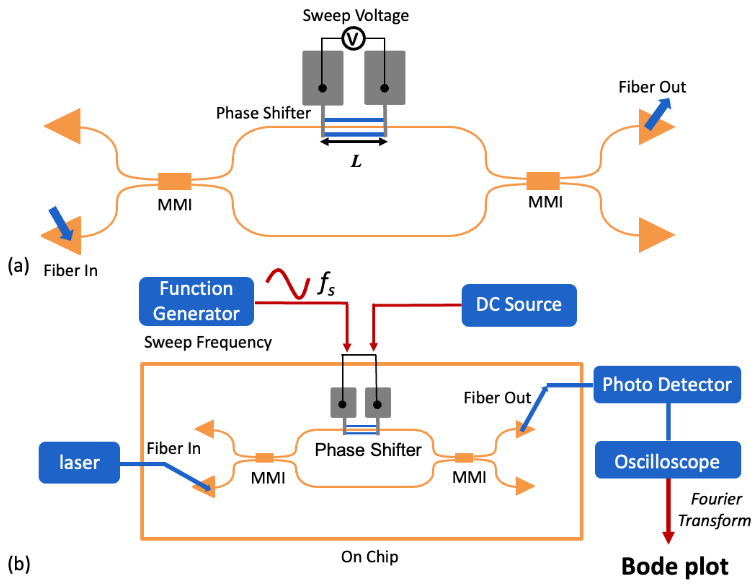

Fig. 2. Schematic diagram for (a) efficiency and (b) bandwidth measurement.

3 Experimental Results

3.1 Doped-silicon Side Heaters

As shown in Figure 3, the normalized optical transmission follows a sinusoidal curve, from which the thermal efficiency can be extracted. We first demonstrate the influence of the thermal insulation undercut. We take the P-doped silicon side heater as an example, with a length of 28 µm. For a π phase shift, the efficiency of side heaters with and without undercut is measured as a P_π (power to induce a π phase shift) of 13.20 mW and 35.16 mW, respectively (lower P_π is better). The doped-silicon side heater with undercut is approximately 2.7× more efficient than without undercut. As the length of the undercut heater increases from 28 to 53 µm, the P_π decreases from 13.2 mW to 8.92 mW, and the efficiency improves by a factor of 1.48×. As the heater length increases, the relative area of substrate removal increases, helping to trap the heat in the region around the waveguide. Therefore, the efficiency of the 53-µm heater is higher.

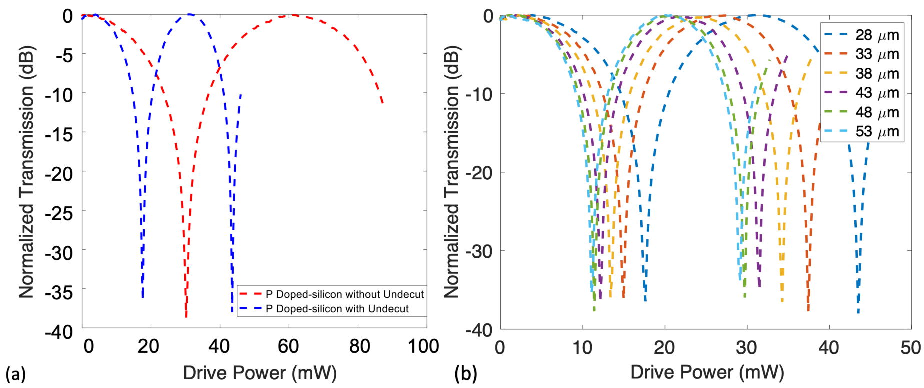

Fig. 3. Transmission as a function of electrical power for (a) 28-µm P-doped silicon side heaters with and without undercut, (b) P-doped silicon side undercut heaters with different length.

3.2 Diode-loaded Heaters

From Fig. 4(a), one can see a clear diode I-V curve in 28-µm diode-loaded heaters. For P or N diode-loaded heater, the reverse current is negligible below the breakdown voltage (-3 V). All diodes show a similar threshold around 0.8 V. As shown in Fig. 4(b), if we operate the heaters in the range of ±3 V, it will only drive one heater in a matrix addressing topology.

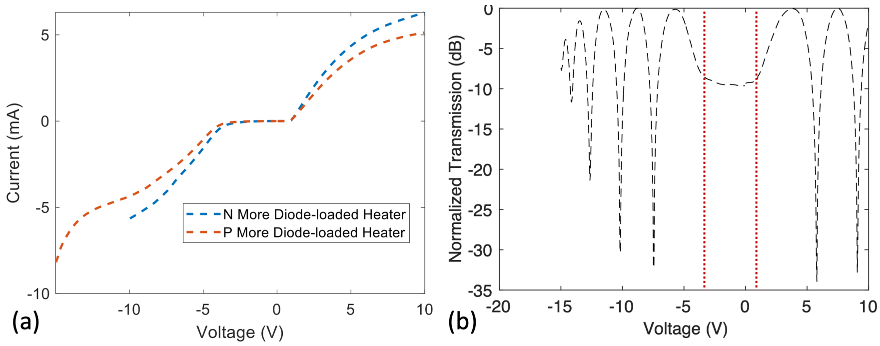

Fig. 4. (a) I-V curve of a 28-µm N and P diode-loaded heaters, (b) transmission as a function of voltage for a 28-µm P diode-loaded heater.

3.3 Doped Waveguides

Figure 1(b$_1$) shows the doped waveguides with lateral current injection (over the entire length) and without thermal insulation, with a P_π of 18.73 mW. The design in Fig. 1(b$_2$) is also a doped waveguide, but the current is injected only at the ends. Therefore, the driving power is distributed over three parts: two side heaters, and the waveguide itself. The result is a P_π of 32.43 mW, which is significantly larger than with the lateral injection, as a larger volume is heated. This difference is also reflected in the response time. The -3 dB bandwidths of the lateral-injected and longitudinal-injected doped waveguides are 139 and 41 kHz, respectively. We can use a simplified thermal resistor-capacitor (RC) model to explain it. Compared to longitudinal-injected doped waveguide, the lateral-injected doped waveguide has a smaller thermal resistance, which means the RC time constant is smaller, thus the bandwidth is larger. Also, as the heated volume is smaller, it has a lower thermal capacitance.

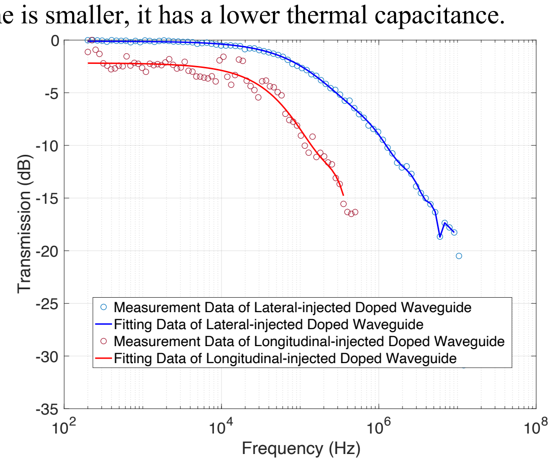

Fig. 5. Bandwidth of lateral-injected and longitudinal-injected P-type doped waveguides.

3.4 Metal Top Heaters

We propose two types of overhead tungsten heaters, including a single tungsten line and 4 folded lines above the 5× folded waveguides. For a π phase shift, the power consumption is 6.6 and 1.97 mW, respectively, showing the increased efficiency thanks to the folding, which passes the same waveguide multiple times through the same heated volume.

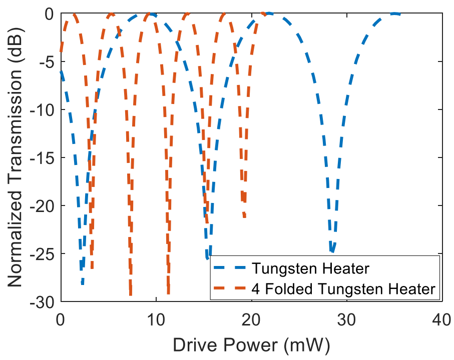

Fig. 6. Transmission as a function of electrical power for tungsten and 4 folded tungsten heaters.

4 Conclusion

In conclusion, substrate undercut makes the heater about 3× more efficient than before. Through using lateral current inject, the efficiency could be improved 1.73 times than longitudinal-injected doped waveguides, and the corresponding response time is faster. In addition, a 4 folded tungsten heater has the smallest P_{π}, which is below 2 mW.

Acknowledgement

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