Leveraging a Nonvolatile MEMS Switch for Sub-Lithography Silicon Photonics

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Abstract: Silicon photonics is accelerating high-performance computing, and integrated MEMS devices offer low-power reconfiguration. However, MEMS device performance is limited by lithography resolution. Here, we unveil a post-fabrication technique to reduce a photonic foundry-defined 230 nm starting gap to 50 nm, using a nonvolatile MEMS switch.

1. Introduction

With the rapid rise of co-packaged optics [1], silicon photonics is delivering on its promise to accelerate high-performance computing. The continuation of this trend will bring ever tighter integration of photonics and electronics in the datacenter. However, such applications require a high density of reconfigurable integrated photonic devices with efficient tuning to provide the control over phase and amplitude necessary for coherent information processing. Currently, thermal tuners are used for such reconfiguration, but they consume around 1 mW of static power per device, leading to heating and thermal crosstalk in densely integrated circuits. In contrast, photonic MEMS phase shifters offer the low optical loss and minimal power consumption needed for circuit scaling, with recent estimates of fW level static power consumption [2,3]. However, their performance is limited by the minimum gaps that can be patterned by the lithography tools used in photonics foundries. An option for reducing gaps below the lithography limit is to use mechanical elements that can be reconfigured post-fabrication. For example, Tsoukalas et al. demonstrated self-assembled sub-10 nm gaps by leveraging Casimir forces, but the self-assembly required starting gaps only achievable by e-beam lithography [4].

Here, we use electrostatic actuation of a nonvolatile MEMS switch to lower the tuning gap of a foundry-produced photonic MEMS phase shifter down to 50 nm.

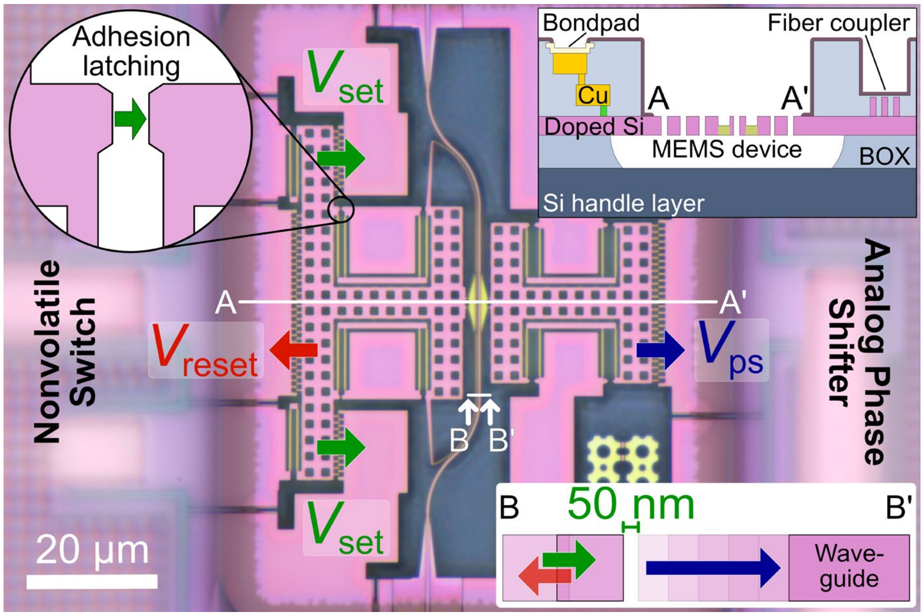

Fig. 1. An optical microscope top view of the device, including the nonvolatile gap-reducing MEMS switch (left) and the gap-increasing analog phase-shifter (right). The insets illustrate design details: the adhesion-based latch (top left), the full stack cross-section (top right), and the phase perturbing waveguide cross-section (bottom right).

2. Design

To demonstrate the potential of our method for sub-lithography silicon photonics, we implemented a photonic MEMS phase shifter relying on in-plane evanescent tuning of the guided mode. The device comprises a suspended waveguide with a phase tuning section in the center, the nonvolatile switch on the left, and the phase shifting actuator on the right, see Fig. 1. The phase shifting actuator is attached to the center of the 400 nm-wide waveguide to enable pulling it away from a suspended 220 nm-wide perturber. As the gap between the waveguide and the perturber is increased, the effective index of the guided mode is decreased due to a higher portion of the mode field in the low-index cladding material (air). This gap-increasing evanescent field tuning gives a linear phase shift [5], but the tuning range is limited by the minimum resolvable gap of the lithography. Gap-reducing analog photonic MEMS designs have been demonstrated before and also enable the formation of sub-lithography gaps [6]; however, their highly non-linear response inhibits their practical application in large circuits, due to the dramatic effect that device-to-device variation has on the tuning.

In the present work, we enhance the tuning range of the gap-increasing phase shifter by using the nonvolatile MEMS switch to reduce the starting air gap from 230 to 50 nm, below the capabilities of standard lithography tools available on current silicon photonics foundry platforms. Our nonvolatile MEMS switch uses push–pull comb-drive actuators for motion and relies on surface adhesion dominated by van der Waals forces to mechanical stoppers to maintain two stable in-plane positions [7]. The switch can be set to its lower-gap state by applying a bias V_{set} across a first comb-drive actuator, and reset by applying a bias V_{reset} across a second comb-drive actuator providing displacement in the opposite direction.

3. Results

We implemented the 50 nm-gap phase shifter on IMEC's iSiPP50G silicon photonics platform. The MEMS actuators were released using two main post-processing steps: (i) alumina deposition and patterning to protect the Back-End-Of-Line, and (ii) vapor HF etching (Orbis Alpha, MEMSSTAR) of the SiO2 BOX layer.

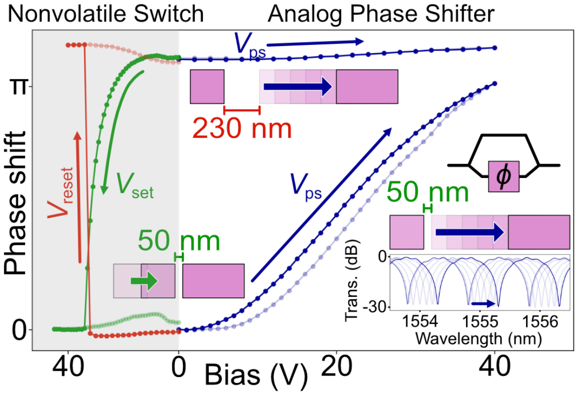

Fig. 3. Measured phase shift versus V_{ps} in the default 230 nm-gap state, during the $V_{\mathrm{set}}/V_{\mathrm{reset}}$ cycle, and V_{ps} phase shift in the 50 nm-gap state. Inset: Measured transmission spectra during the 50 nm-gap V_{ps} sweep, used to extract phase shift versus voltage.

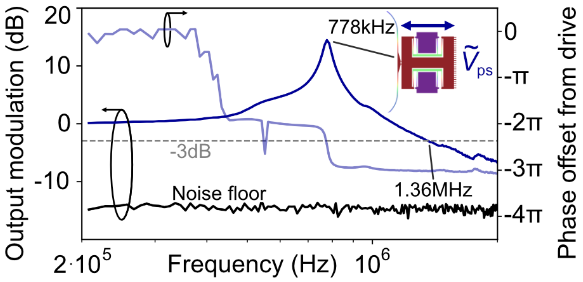

Fig. 2. Measured frequency response (demodulated amplitude and phase offset from drive) of our phase shifter in the 50 nm-gap state. The device was driven with an amplitude of 0.5V and an offset of 9V.

To test the phase shifter, we implemented a simple length-unbalanced Mach-Zehnder Interferometer (MZI) circuit using standard components from IMEC's library. We used a fiber array and an electrical probe array with a custom driver board to drive the multiple MEMS actuators in the required sequence. We measured the transmission through the MZI from 1540 to 1560 nm wavelength at multiple voltage values of the V_{ps}, V_{set}, and V_{reset} actuators to obtain the response curves of the device.

As illustrated in Fig. 2, in its as-fabricated 230 nm-gap state, the measured phase shift when running a V_{ps} sweep is only 0.05π. We then set the device to its 50 nm gap state by increasing the V_{set} bias past the contact point to the mechanical stoppers. Once set, the measured phase shift using V_{ps} increases to 1.01π. The device can also be reset to its original gap state using V_{reset}. To quantify the operating speed of the device, we also measured its frequency response, illustrated in Fig. 3. From the curve, we extracted the resonance frequency and -3 dB bandwidth in the 50 nm-gap state, yielding 778 kHz and 1.36 MHz, respectively. In comparison, traditional thermal tuners in silicon photonics are limited to an operation frequency of the order of 10 kHz [8]. Finally, we verified that

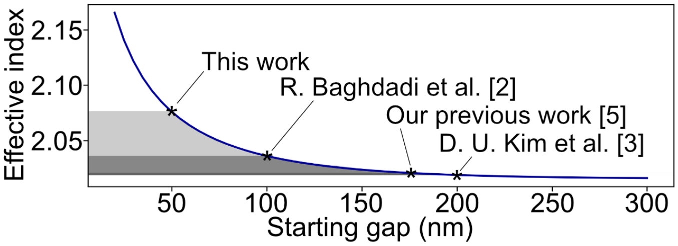

Fig. 4. Simulated effective index versus gap for the waveguide geometry used in this work. For comparison, we added the starting gaps of state-of-the-art silicon photonic MEMS phase shifters.

the device can retain its 50 nm gap state over time even after disconnecting the probes from the sample. Until now, we have observed retention of the latched nonvolatile state for over two weeks.

For the phase shifter itself, the enhancement in the tuning range is clearly observed, resulting in a π-phase shift at 1555 nm with good linearity from 5 to 30 V. The phase shift is lower than for our previously reported gap-increasing device with a 175 nm initial gap [5], but here we suppressed the actuation-dependent losses by increasing the waveguide width to 400 nm; increased the device resonance frequency from 503 to 778 kHz by increasing the springs' stiffness (total stiffness increased from 1.92 to 3.71 N/m); reduced the device footprint (shuttle size decreased from 40 × 25 μm^2 down to 25 × 25 μm^2); and reduced the length of the phase-shifting waveguide section from 50 to 30 μm.

The reduction in the initial gap enables all those improvements since a smaller displacement is needed to achieve a large effective index tuning, as illustrated in Fig. 4 showing the dependence of the waveguide effective index on gap in such a silicon waveguide-perturber configuration. We compare our 50 nm-gap phase shifter to the initial gaps used by similar devices on silicon photonic foundries. Our technique potentially also allows further reducing the gap below 50 nm by setting a smaller gap difference between the gap at the mechanical stoppers and the fabricated waveguide gap.

We also note that the device footprint can be significantly reduced if a single irreversible state switch is sufficient and the V_{reset} actuation is not needed. For instance, in programmable photonic circuits, many phase shifters could be set at once to the lower gap state by using a single V_{set} line directly after fabrication, and then left perpetually in that state.

4. Conclusions

We have demonstrated a technique for sub-lithography silicon photonic MEMS manufacturing using an adhesion-based nonvolatile MEMS switch. We applied it to the starting gap of a linear gap-increasing photonic MEMS phase shifter to greatly increase its tuning range. The access to sub-lithography gaps will facilitate the ever-tighter integration of photonics and electronics by better matching their footprints and lowering the power requirements, and thus accelerating the rise of silicon photonics in the data center.

5. Acknowledgement

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6. References

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