2022-05-15

In-situ photonic circuit field characterization in electronics-photonics CMOS platform via backside flip-chip near-field scanning optical microscopy

K. Alqubaisi, M. Schiller, B. Zhang, D. Onural, A. Khilo, M. Naughton, M. Popovic. 2022. "In-situ photonic circuit field characterization in electronics-photonics CMOS platform via backside flip-chip near-field scanning optical microscopy." OSA Technical Digest (Optical Society of America, 2022). CLEO. San Jose, CA, 2022-05-15 - 2022-05-20.

https://hdl.handle.net/2144/45174

In-situ photonic circuit field characterization in electronics-photonics CMOS platform via backside flip-chip near-field scanning optical microscopy

Kenaish Al Qubaisi[1,*], Mark Schiller[2], Bohan Zhang[1], Deniz Onural[1], Anatol Khilo[3], Michael J. Naughton[2], and Miloš A. Popović[1,†]

[1] *Department of Electrical and Computer Engineering, Boston University, Boston, MA 02215, USA*
[2] *Department of Physics, Boston College, Chestnut Hill, Massachusetts 02467, USA*
[3] *Ayar Labs, Emeryville, CA 94608, USA*

[*] *kalqubai@bu.edu,* [†] *mpopovic@bu.edu*

Abstract: We demonstrate device field characterization using NSOM *collection* and *interaction* measurement modes via the backside buried-oxide of large scale photonic circuits fabricated in monolithic electronics-photonics CMOS platforms (here a microdisk resonator) post-processed using flip-chip substrate-removal.

Silicon photonic systems-on-a-chip are becoming ever more sophisticated, enabling groundbreaking new applications in high-bandwidth, low-energy data links [1], quantum optics, lidar, neuromorphic computing, and more. These capabilities are realized in large part due to the miniaturization of key devices such as modulators and the monolithic co-integration of photonics with electronics made possible by CMOS-photonics foundry platforms. As the complexity of silicon photonic circuits grows, so does the importance of characterizing their individual components *in-situ*. Near-field scanning optical microscopy (NSOM) is a valuable tool that has been used for field mapping of resonant [2] and non-resonant [3] devices. However, the photonic devices in active (e.g. CMOS) photonic chips are not readily accessible for NSOM probing due to the thick back-end-of-line (BEOL) layer stack of dielectrics and metal interconnects. On the other hand, testing uncladded devices has many drawbacks. For example, the presence of an NSOM probe on the surface of a photonic device can cause a significant local disturbance [4], such as shifting a resonator out of resonance at a given wavelength and drastically increasing loss. A method to enable in-situ field mapping within CMOS-photonic circuits, without interfering with the performance and packaging of the photonics and electronics, would be a highly valuable tool for future development of high performance photonic circuits.

In this paper, we demonstrate a method to non-invasively perform NSOM scans of a photonic device within a large-scale CMOS-photonic circuit via a flip-chip post-processing technique. The presented post-processing technique leaves a thin, planarized layer of buried oxide (BOX) that minimizes the disturbance caused by the NSOM probe on the photonic devices during the measurement process. This is achieved by flipping the chip, which allows electrical connections to be made to the pads at the bottom of the chip (commonly used in CMOS chip packaging), as seen in Fig. 1(b). The silicon substrate (now at the top of the chip) is etched away using xenon difluoride (XeF_2), with no effect on circuit operation [1]. Next, the BOX (now the top insulating layer) is thinned from multiple microns down to 55 ± 5 nm, as measured by profilometry, using a buffered oxide etch. This ensures that the NSOM probe has access to the near field of the photonic devices, while maintaining some cladding to minimize field distortion. The chip used in this work, shown in Fig. 1(a), contains thousands of photonic devices and was fabricated using the GlobalFoundries 45CLO platform, which is a 45 nm-node monolithic electronics-photonics process optimized for silicon photonics [5].

To demonstrate our proposed approach, a microdisk resonator shown in Fig. 1(c) was characterized as a representative device of more complex photonic circuits. This specific microdisk resonator geometry is a passive version of the

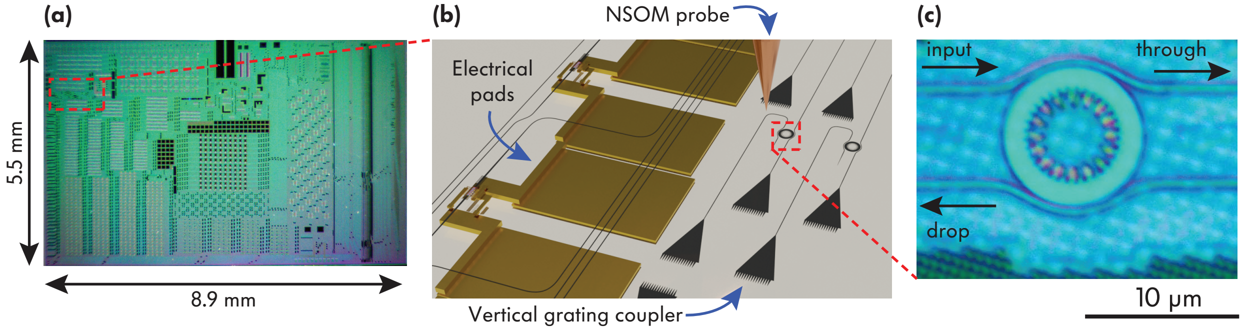

Fig. 1: (a) Optical micrograph of the post-processed chip. (b) 3D schematic illustrating the NSOM probe above the photonic circuit, electrical pads at the bottom of the chip for electrical I/O, and vertical grating couplers at the top of the chip for optical I/O. (c) Optical micrograph of the microdisk resonator.

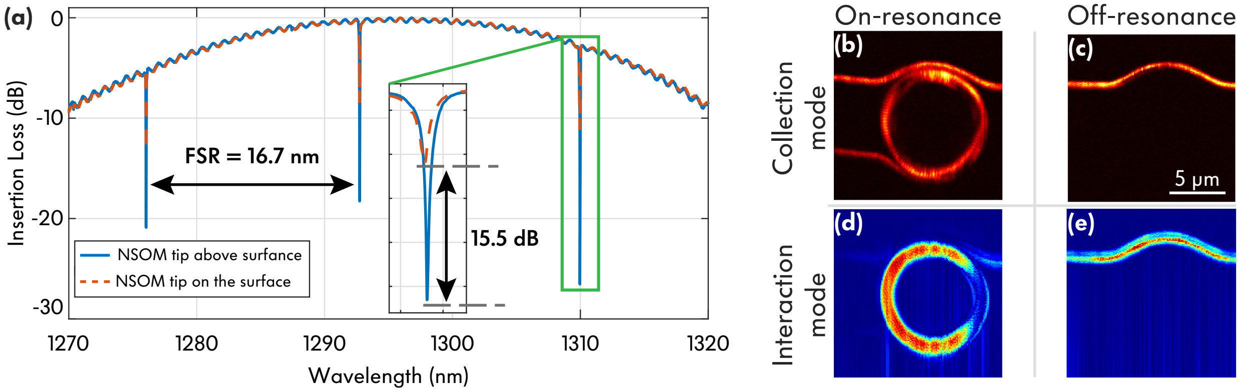

Fig. 2: (a) Through-port response of the microdisk resonator. (b) Collection mode images when the device in the on-resonance and (c) off-resonance states. (d) Interaction mode results when the device is in the on-resonance and (e) off-resonance states.

"spoked ring" modulator [6]. Two different and complementary NSOM measurement modes were performed simultaneously on the device during the same measurement session using a 400 nm aperture probe (Nanonics Multiview 4000). The first is the *collection* mode where near field optical intensity is directly collected through the NSOM probe. The second mode is the *interaction* mode where changes in optical transmission at the through-port of the device are measured as a function of the NSOM probe position in space and associated interaction with the field of the device [2].

Fig. 2(a) shows a wide spectrum of the through-port response of the microdisk resonator. The effect of the NSOM probe on the device can be seen in the inset of Fig. 2(a) by comparing the response when the probe is far above the chip (solid blue line) to when the probe tip is contacting the oxide surface above the resonator's waveguide (dashed orange line). The presence of the NSOM probe causes little to no resonance shift (~ 7 pm). However, the probe effectively acts as a weak additional drop-port and loss mechanism which increases the round-trip loss of the resonator. In this geometry, the BOX thickness controls the amount of power coupled to and scattered from the probe, increasing the collected signal by the probe as the thickness decreases. However, thinning comes at the expense of larger perturbations to the device [4]. In this case, with an oxide thickness of 55 ± 5 nm, the coupling condition of the device changes from near critical coupling to under-coupled, thus reducing the resonance's extinction ratio from -26.54 dB to -11.04 dB without significantly altering the resonance state of the resonator.

In the on-resonance state, light coupled into the drop-port can be clearly seen in the collection mode image in Fig. 2(b). Compared to the off-resonance case shown in Fig. 2(c) with near uniform light intensity along the bent waveguide, the on-resonance case has clear variations of the light intensity along the circumference of the microdisk resonator. This could be attributed to the dependency of the NSOM probe on the polarization of light within the device, in addition to the spatial dependency of the probe's perturbation of the microdisk resonator as it moves across the device (and associated changes in loss Q). These variations are less noticeable in the interaction mode as seen in Fig. 2(e), since this mode measures variations in the through-port intensity as a function of overlap between near-field in the device and the probe, irrespective of whether the near-field was collected or scattered by the probe. The nonuniformity of the intensity along the circumference in this case is in part due to the spatial drift of the output fiber over the 30 minute scanning duration.

In conclusion, we demonstrated the ability to characterize photonic devices, resonant or non-resonant, using collection and interaction NSOM applied to the device layer backside. Combined with a flip-chip packaging approach, this technique allows in-situ access of the NSOM probe to any photonic device realized in an advanced monolithic CMOS platform without long term affects to either access or performance of electronic and photonic systems.

Acknowledgments: We thank the GlobalFoundries 45CLO process team and Ayar Labs, Inc. for extensive support and interaction. Fabricated on the Haystack test vehicle. Funding: National Science Foundation Award #2023751 (ASCENT), ODNI/IARPA via U.S. ARO grant W911NF-19-2-0114 (SuperCables), and a fellowship from the Abu Dhabi National Oil Company.

References

1. C. Sun, M. T. Wade, *et al.*, "Single-chip microprocessor that communicates directly using light." *Nature* **528**, 534–538 (2015).
2. L. Lalouat, *et al.*, "Subwavelength imaging of light confinement in high-Q/small-V ..." Appl. Phys. Lett. **92.11**, (2008): 11111.
3. K. Foubert, *et al.*, "Near-field modal microscopy of subwavelength light confinement ..." Appl. Phys. Lett. **93.25**, (2008): 25113.
4. M.Abashin, *et al.*, "Effects produced by metal-coated near-field probes on the performance of ..." *Opt. Lett.* **32.17**, (2007): 2602-2604
5. M. Rakowski, *et al.*, "45nm CMOS - Silicon Photonics Monolithic Technology (45CLO) ..." OFC, OSA, paper T3H.3 (2020).
6. J.M. Shainline, *et al.*, "Depletion-mode carrier-plasma optical modulator in zero-change..." *Opt. Lett.* **38.15**, (2013): 2657-2659.