Depletion-mode polysilicon optical modulators in a bulk CMOS process

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Abstract: We demonstrate the first depletion-mode modulators in polysilicon bulk CMOS. They use a new, wiggler-mode microcavity for process compatibility with fully-etched silicon and lateral pn junctions. We show 4.2dB extinction and 60fJ energy/bit at 5Gbps.

OCIS codes: (250.4110) Modulators; (250.5300) photonic integrated circuits; (130.3120) integrated optics devices.

Silicon photonics promises to provide energy efficient CPU-to-memory interconnects, critical to enabling exascale computing [1]. A key requirement for this is the integration of photonic links in advanced logic and DRAM CMOS processes used for state-of-the-art microelectronics. Recently, monolithic integration of photonics in advanced logic silicon-on-insulator (IBM 45nm SOI) CMOS was demonstrated [2], but the vast majority of microelectronics employs bulk CMOS rather than SOI, with no crystalline silicon device layer. Passive, monolithically integrated photonics has been demonstrated in bulk CMOS [3]. But, it is efficient, monolithically integrated *active* photonics that promise tremendous impact. While injection modulators have been demonstrated in polysilicon [4,5], these devices were in custom photonics processes, and are energy hungry in comparison to depletion-mode devices [6-7]. Bulk silicon CMOS poses several challenges: (1) a single polysilicon device layer, with substantial loss and strongly nonlinear dopant activation; (2) lack of a partial etch step, i.e. no ridge waveguides; and (3) lateral *p-n* junctions.

In this paper, we use a novel type of microcavity to demonstrate the first depletion-mode modulators in a single polysilicon device layer, and the first depletion-mode modulators in bulk CMOS. This work will enable photonic links in DRAM, and most of logic CMOS. The process used here is a DRAM-emulation flow fabricated by Micron Technology in a commercial memory wafer fab. It was subject to many of the constraints of the full-flow process, including the absence of a partial silicon etch [4,6,7], and the absence of vertical *p-n* junction implants [8].

We introduce a new type of "wiggler-mode" optical cavity [9] wherein multi-modal interference gives rise to field nulls at waveguide sidewalls where electrical contacts can be placed without introducing substantial optical loss. This circumvents the need for either a partial etch or a vertical *p-n* junction. A schematic of the device is shown in Fig. 1(a), and the field profile from a FDTD simulation of one arm is shown in Fig. 1(b). The straight electrically active multimode sections couple to single mode waveguides with virtually no loss via short

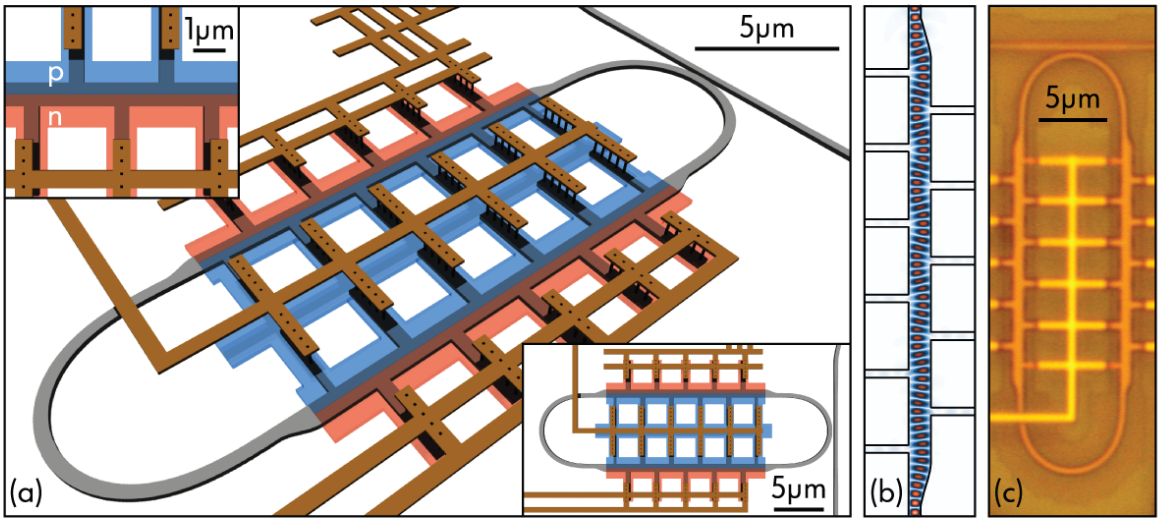

Fig. 1. (a) Schematic (from actual GDS layout) of the five-period device (left inset: close-up of the *p-n* junction; right inset: top view), including the dopant masks (red/blue); (b) multimode field profile from FDTD simulation; (c) microscope image of fabricated device.

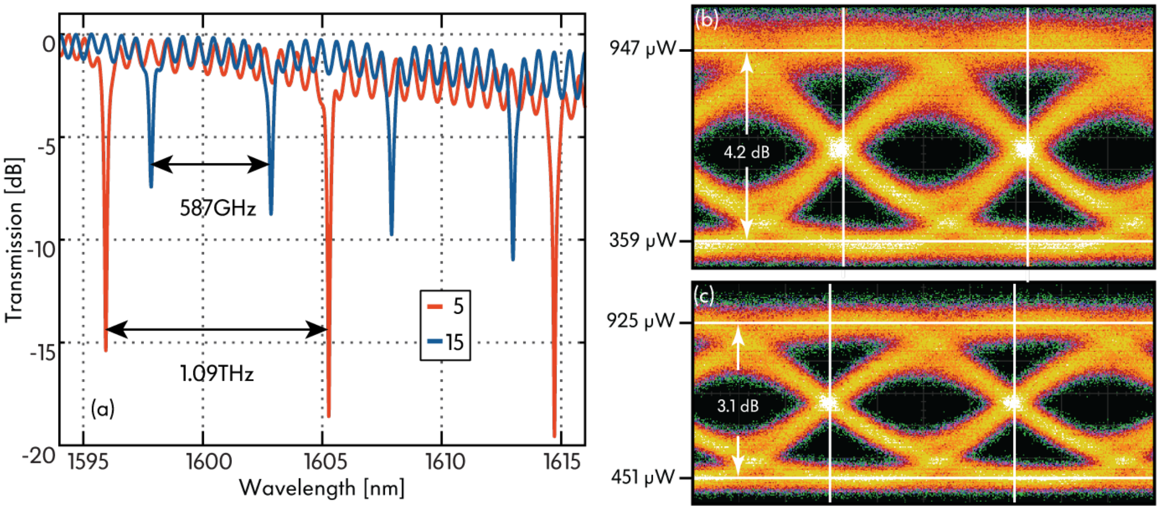

Fig. 2. Experimental data: (a) Spectra from polysilicon (process gate layer) microcavities with five and 15 periods of contacts (22 and 62 total contacts); (b) eye diagram at 5 Gbps from 5-period device (4.2dB extinction, 4dB insertion loss); (c) eye diagram at 5 Gbps from 15-period device (3.1dB extinction, 1.5dB insertion loss. Time between the two vertical lines is 200 ps in each eye.

(nonadiabatic), asymmetric tapers, and are connected via variable-radius 180° bends. A microscope image of the device is shown in Fig. 1(c). Waveguides are fabricated above a deep-trench isolation oxide that provides optical confinement in bulk CMOS. Modulator variants occupying 300 and $600\mu m^2$ in area were demonstrated at 5 Gbps.

For modulators based on this type of cavity, the number of periods of contacts affects several aspects of device performance including free-spectral range (FSR), resonant frequency shift, and on-resonance extinction for a given coupling gap. We present data from a device with five periods of contacts (22 total contacts) and one with 15 periods (62 total contacts). Fig. 2(a) shows passive spectral responses of the two cavities. The 5-period device has >15dB passive extinction and a larger FSR. The 15-period device was undercoupled due to a spacing rule, limiting passive extinction to ~7dB, something that can be remedied by a stronger (longer) coupler in a future design.

Figures 2(b) and 2(c) show eye diagrams from the 5- and 15-period devices respectively. The devices were driven with a 5 Gbps, 2^{31}-1 bit pseudo-random binary sequence via a 40-GHz GSG probe. The voltage swing seen by the modulator was -3.5V to +0.5V in each case, keeping them in depletion mode. Such a voltage swing is achievable by integrated driver circuits. Under these operating conditions, the 15-period device achieved 3.1 dB modulation depth with 1.5 dB insertion loss and an energy consumption of 160 fJ/bit calculated with the standard expression for the average switching energy ($1/4\ CV_{pp}^2$ for NRZ data) and the 0V capacitance. The 5-period device achieved 4.2 dB modulation depth with 4.0 dB insertion loss and a calculated 60 fJ/bit energy consumption. I-V curve measurements indicate that driving current contributes negligibly to the energy consumption.

We believe that this demonstration of a depletion-mode optical modulator in polysilicon on a bulk CMOS process, within a commercial memory wafer fab, is a major milestone towards enabling complete photonic links monolithically integrated with advanced electronics, including in bulk CMOS logic and DRAM processes.

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