Maximally Confined Silicon Microphotonic Modulators and Switches

Michael R. Watts, Douglas C. Trotter, Ralph W. Young, and Anthony L. Lentine
Sandia National Labs, P.O. Box 5800, Albuquerque New Mexico 87185
mwatts@sandia.gov

Abstract: We demonstrate a 4µm silicon microdisk modulator with a reverse-biased, vertical *p-n* junction. The modulator demonstrates a power consumption of 85fJ/bit at a data rate of 10Gb/s, 3.5V drive, BER<10^{-12}, and without signal pre-emphasis. High-speed silicon bandpass switches are constructed from pairs of modulators.

1. Introduction

High performance computers currently use electrical or directly modulated laser optical communication links that are connected to microprocessors indirectly through electrical transmission lines, resulting in inefficient and relatively low bandwidth communications. However, silicon microphotonics, closely integrated with CMOS electronics [1], has the potential to enable ultralow power wavelength division multiplexed [2] systems with multi-terabit per second communication links. While many silicon modulator designs have been implemented [3-5], to date, all such devices, both resonant and non-resonant, have consumed a considerable amount of power, and, in the case of forward biased structures [3,5], required signal pre-emphasis in order to achieve data rates of 10Gb/s. Here, we demonstrate a new class of silicon microdisk modulators that utilize a vertical *p-n* junction. The vertical *p-n* junction in a 4µm diameter microdisk modulator enables sufficient modal overlap to achieve 10Gb/s reverse-biased operation with a low, 3.5V, drive voltage and without signal pre-emphasis. A bit-error-rate (BER) below 10^{-12} was demonstrated along with a measured power consumption of only 85fJ/bit (85µW/Gb/s), a new record for silicon modulators. Further, we demonstrate the first high-speed silicon bandpass switches by coupling a pair of these modulator structures [6].

2. Discussion and Experimental Results

A cross-sectional diagram and a scanning electron micrograph (SEM) of the fabricated silicon microdisk modulator are presented in Fig. 1a and 1b, respectively. The modulator consists of a 4µm diameter microdisk resonator with a vertically oriented *p-n* junction coupled to a pair of silicon bus waveguides. Contact to the p-n junction was made

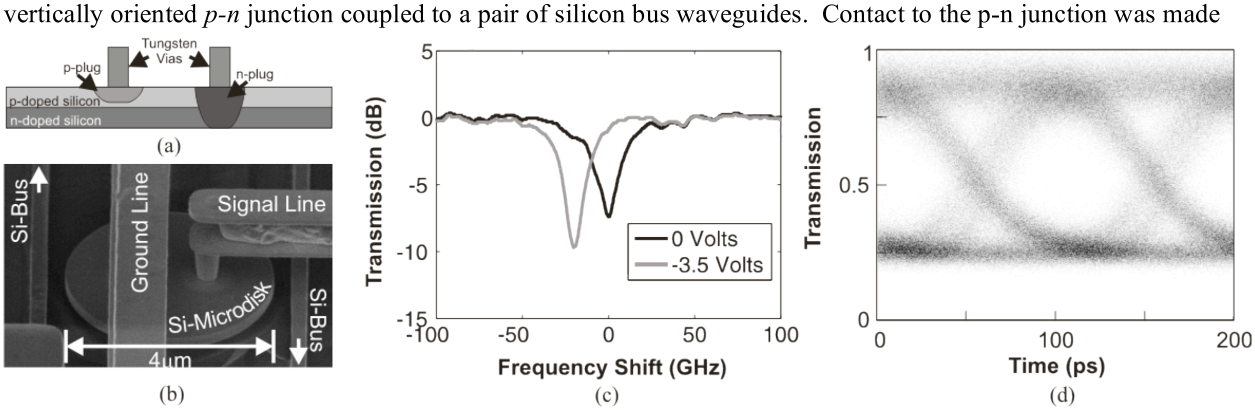

Figure 1. (a) Cross-sectional diagram of the microdisk modulator highlighting the vertical p-n junction and method of contact. (b) A scanning electron micrograph of the fabricated 4µm diameter microdisk modulator and (c) the optical spectra of the microdisk with no bias and a 3.5V reverse bias applied (λ_0=1578nm). Shown in (e) is an eye-diagram for the modulator with a 10Gb/s NRZ data format with a PRBS pattern length of 2^{31}-1. The bit-error-rate (BER) was measured to be less than 10^{-12} for a pattern length of 2^{15}-1.

with tungsten vias connected to highly doped p+ (B) and n+ (P) plugs. The modulator operates on the free-carrier-effect in silicon [7] and a reverse-biased voltage serves to modulate the depletion width of the vertical *p-n* junction and thereby modify the modal index, and resonant frequency of the microdisk. In contrast to all previous demonstrations contacts are kept within the interior of the microdisk enabling a hard outer silicon wall of the microdisk to be maintained that enables maximum confinement of the whispering gallery mode and the 2µm bend radius to be achieved without significant radiation loss. Further, the use of a vertical *p-n* junction maximizes the overlap of resonator mode with the depletion width, enabling large changes in resonant frequency to be achieved

978-1-4244-1932-6/08/$25.00 ©2008 IEEE

with low reverse-biased voltages. The optical responses of the modulator with no applied bias and with a 3.5V reverse-bias are presented in Figure 1c. With a 3.5V reverse bias, a frequency shift of -20GHz is achieved.

The modulator was driven directly with the 1.8V output of a 10Gb/s non-return-to zero (NRZ) pseudo-random bit-stream (PRBS) generator with no signal amplification or pre-emphasis. An eye-diagram for the modulator with a 10Gb/s NRZ data format and a PRBS pattern length of 2^{31}-1 is presented in Figure 1d. A bit-error-rate (BER) less than 10^{-12} was measured for a pattern length of 2^{15}-1. Although the drive voltage from the PRBS was only 1.8V, the voltage realized across the *p-n* junction was 3.5V due to the impedance mismatch. The power absorbed in the modulator was determined by a series of small-signal time domain reflectometry measurements with step voltage inputs in ½Volt increments up to 3.5V. The switching energy was measured to be 340fJ by integrating the absorbed power. It is important to note that the 0-to-0, 0-to-1, 1-to-0, and 1-1 transitions are all equally probable in an NRZ PRBS, and since the device has essentially no dark current (<100pA) and energy is only required to make the 0-to-1 transition, the energy/bit is ¼ of the 0-to-1 switching energy. Therefore, the average energy/bit is 85fJ (85μW/Gb/s). Further, high-speed, high-order bandpass switches can be constructed from multiple modulators coupled together. An SEM of a fabricated and previously demonstrated [6] structure is shown in Fig. 2a and the filter response depicted in Fig. 2b as a function of applied forward bias. The switch demonstrates 16dB extinction in the Thru port and 20 dB extinction in the Drop port with a ~2.4ns switching time (Fig. 2c).

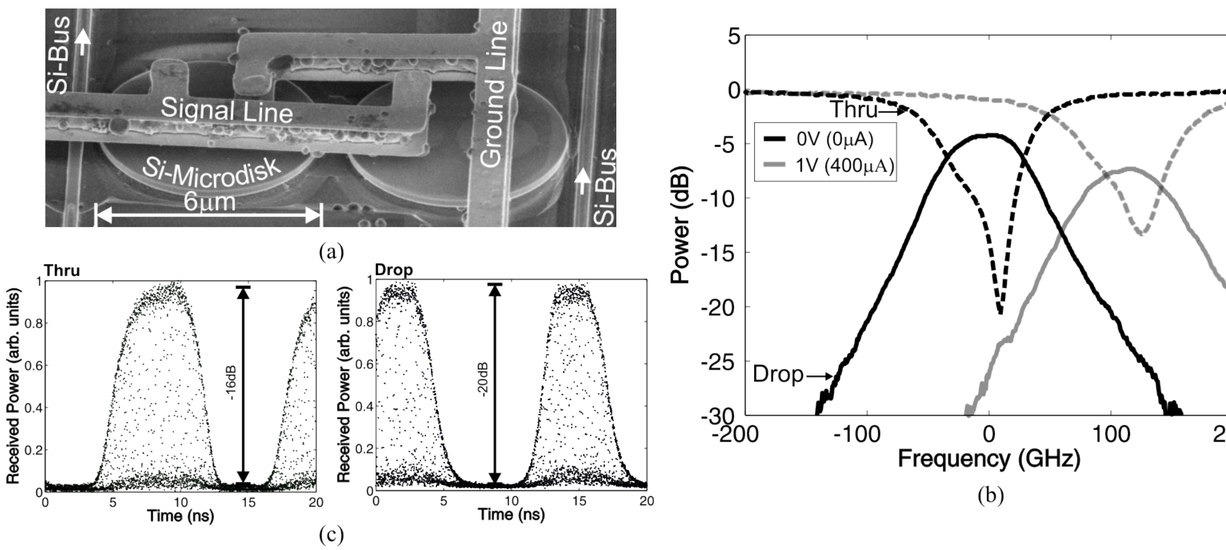

Figure 2. (a) Cross-sectional diagram of the microdisk bandpass switch. (b) The bandpass of the switch under 0V and 1V applied bias and (c) the dynamic response of the switch in the Thru and Drop ports switching 10Gb/s data. The center wavelength is 1533nm.

3. Conclusions

We demonstrate the first silicon microphotonic modulator to achieve less than 100fJ/bit. The modulator, utilizes a reverse-biased, vertical *p-n* junction to achieve 10Gb/s data transmission, with low drive voltage (3.5V), BER<10^{-12}, and without signal pre-emphasis. Together with high-speed, low-power, bandpass switches, microdisk modulators have the potential to form the building blocks for richly interconnected short-range optical networks. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

4. References

1. D. A. B. Miller, "Optics for low-energy communication inside digital processors, quantum detectors, sources, modulators as efficient impedance converters," Optics Letters, 14, 1460148 (1989)
2. T. Barwicz, M. R. Watts, M. A. Popovic, P. T. Rakich, L. Socci, F. X. Kärtner, E. P. Ippen and H. I. Smith, "Polarization-transparent microphotonic devices in the strong confinement limit," *Nature Photonics* **1**, 57 – 60 (2006)
3. William M. Green, Michael J. Rooks, Lidija Sekaric, and Yurii A. Vlasov, "Ultracompact, low RF power, 10 Gb/s silicon Mach-Zehnder modulator," Optics Express, **15**, p. 17106 (2007)
4. A. Liu, R. Jones, L. Liao, D. Samara-Rubio, D. Rubin, O. Cohen, R. Nicolaescu, and M. Paniccia, "A high-speed silicon optical modulator based on a metal-oxide-semiconductor capacitor," Nature **427**, 615-618 (2004)
5. Q. Xu, B. Schmidt, S. Pradhan and M. Lipson, "Micrometre-scale silicon electro-optic modulator," *Nature* **435**, 325-327 (2005)
6. M. R. Watts, D. C. Trotter, and R. W. Young, "Maximally Confined High-Speed Second-Order Silicon Microdisk Switches," *OFC 2008* PDP14
7. R. A. Soref, and B. R. Bennett, "Electrooptical Effects in Silicon," *IEEE J. Quantum Electronics*, **QE-23**, pp. 123-129 (1987)