Integrated PN Microheaters for Fast and Efficient Control of Phase-Change Photonic Memory

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Abstract: We present a multifunctional photonic memory cell integrating PN junctions with phase change materials. This enables nonvolatile coarse tuning and high-speed volatile fine tuning for faster modulation and higher efficiency than prior thermal or carrier-based approaches.

1. Introduction

Recent advances in photonic technologies have shown significant promise for artificial intelligence (AI) and neuromorphic computing applications [1,2]. A key advantage of photonic computing lies in its ability to leverage wavelength division multiplexing for parallel data processing with ultra-low latencies, offering a viable alternative to traditional digital processors. To maximize this potential, photonic processing units typically employ reconfigurable arrays of memory cells, programmed to implement trained weight matrices [3-7], where matrix-vector multiplication is achieved through parallel multiply-accumulate operations as optical inputs pass through the memory array [8].

While optical inputs can be modulated at high speeds using established electro-optic effects, memory cells—which often require greater tunability and precision—face limitations in speed, power efficiency, and scalability [9]. Phase-change materials (PCMs) have emerged as a promising solution for nonvolatile optical memory, offering advantages like large refractive index changes, compact footprint, long-term retention, and multilevel storage capabilities [10-12]. However, PCMs face challenges such as slow programming speeds, high power consumption and limited endurance [13]. While previous works have explored using volatile responses in PCMs [14] or underlying microheaters [15] for additional tunability, these approaches are constrained by slow response times and high static power dissipation. In this work we demonstrate the use of PN junctions for nonvolatile switching of PCMs under forward bias while maintaining high-speed volatile tuning under reverse bias. This enables two complementary operating conditions which can lead to greater efficiency and speed than alternative forms of volatile tuning while maintaining the ability to encode nonvolatile optical weights on-chip. An overview of the device is shown in **Fig. 1**.

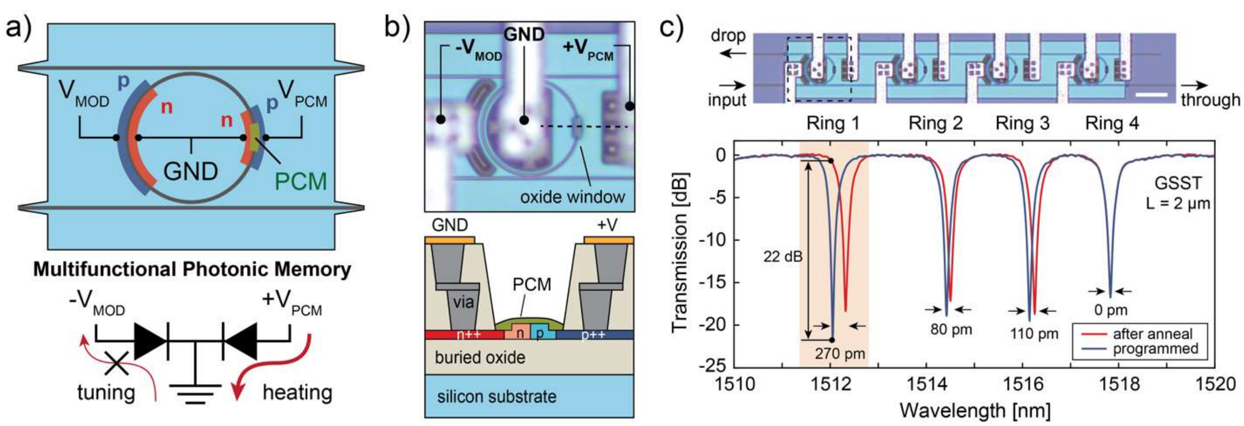

Fig. 1. Overview of multifunctional photonic memory. a) Illustration and working mechanism of multifunctional photonic memory leveraging a PN junction microheater (forward biased) and modulator (reverse biased). **b)** Optical microscope image of a single micro-ring with integrated multifunctional memory cell and cross-sectional view of PN microheater with PCM deposited in oxide window. **c**) Nonvolatile programming of arbitrary optical weights using memory cell arrays with four MRRs (25 μm scale bar).

2. Results

We demonstrate both nonvolatile and volatile tuning capabilities in our multifunctional photonic memory cell. For nonvolatile programming, we applied forward biased pulses (3.6–4.4V for 5 µs for amorphization and 2.8V for 5 ms for crystallization) and achieved 14 distinct levels (3.8 bits) with a 270 pm spectral shift using phase-change materials (PCM), resulting in -1.3 dB insertion loss and 22 dB extinction ratio between the fully crystalline and amorphous states (**Fig. 2a**). The device successfully combines both static and dynamic functionality, allowing coarse PCM programming and precise volatile tuning in the same memory cell (**Fig. 2b**). The integrated PN junction enables volatile fine-tuning through reverse biasing and shows excellent power efficiency (>10,000× better than forward biasing) and high-speed operation as shown in **Fig. 2c** (3dB bandwidth of 7.1 GHz is limited by measurement setup). While cycling tests show some degradation in the PCM's crystalline state over time, the PN junction maintains reliable performance even after 10,000 switching cycles, suggesting that using volatile tuning could help extend device lifetime by reducing the number of PCM rewrites needed.

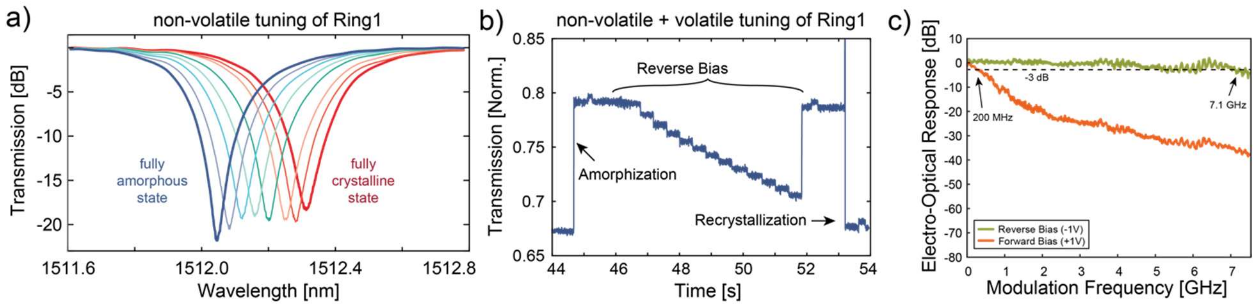

Fig. 2. Multifunctional operation of proposed memory cell. a) Non-volatile tuning by incremental amorphization of the PCM using a forward biased PN microheater. **b**) Volatile and non-volatile tunability of the multifunctional memory cell with volatile tuning occurring during the reverse bias sweep. **c)** Normalized frequency-dependent electro-optic response of the PN junction in both forward and reverse bias conditions.

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