Electrically Programmable Non-Volatile Silicon Photonic Content Addressable Memory (CAM) cell

Chuanyu Lian,[1,2] Hongyi Sun,[1,2] Yi-Siou Huang,[1,2] Steven A. Vitale,[3] Juejun Hu,[4] Ichiro Takeuchi,[1,5] Nathan Youngblood,[6] Christos Vagionas,[7,†] Carlos A. Ríos Ocampo[1,2,*]

[1]*Department of Materials Science & Engineering, University of Maryland, College Park, MD, 20742, USA*
[2]*Institute for Research in Electronics and Applied Physics, University of Maryland, College Park, MD, 20742, USA*
[3]*Advanced Materials and Microsystems Group, MIT Lincoln Laboratory, Lexington, MA, 02139, USA*
[4]*Department of Materials Science & Engineering, MIT, Cambridge, MA, 02139, USA*
[5]*Quantum Materials Center, Department of Physics, University of Maryland, College Park, MD, 20742, USA*
[6]*Electrical & Computer Engineering Department, The University of Pittsburgh, Pittsburgh, PA 15213, USA*
[7]*Department of Informatics, Center for Interdisciplinary Research and Innovation, Aristotle University of Thessaloniki, Thessaloniki, Greece*
[†]*chvagion@csd.auth.gr *riosc@umd.edu*

Abstract: We experimentally demonstrate the first electrically programmable, non-volatile silicon photonic content addressable memory cell using Sb_2Se_3 phase change material on microring resonators, opening the path for light-based search operations in zero-power look-up tables.

1. Introduction

The demand for fast network-equipment along with the rise of neuromorphic computing and AI have triggered rapid advances of fast memory centric computing hardware [1]. Hardware based on memristive and memory-centric devices have been proposed to circumvent the well-known electronic memory throughput and energy waste bottlenecks by undertaking data-intensive operations, such as address look-ups and packet inspection in routing and similarity checks. To this end, data-intensive look-up and search operations are typically executed in specialized Content Addressable Memory (CAM) tables, utilizing 2D-table configurations that facilitate a rapid parallel comparison of the *Packet Address* or *Search Bits w*ith each CAM-Matchline (ML) entry in a single clock cycle [2]. However, these operations are still performed in the electronic domain at low rates ~400 MHz - 1 GHz, falling short in comparison with the frantic scaling of optical *linerates* [3]. Recently, ultra-fast photonic CAM alternatives have demonstrated 10 Gb/s binary and ternary operations [4] on an InP platform. This has lately been extended to a complete 4×2-bit optical CAM look-up table [5], or a 2-bit silicon photonic microring resonator (MRR) CAM operated at 4Gb/s [6]. Despite offering an order of magnitude speed enhancement, these are still limited by the high-power consumption of InP SOAs or volatile MRRs. To overcome this issue, phase change materials (PCMs) have been proposed as a robust, energy efficient non-volatile memory solution in integrated photonic waveguide platforms [1]. Here, we demonstrate a novel non-volatile silicon photonic CAM cell based on electrically programmable Sb_2Se_3-loaded MRR, comprising the first optical CAM memory with zero-power consumption.

2. Photonic CAM architedcture, Device and Experimental setup

Fig. 1(a) shows a conceptual architecture and operation of a 4×N CAM look-up table search operations, where the CAMs are configured to store all combinations of the two last bits, i.e. 00, 01, 10, and 11. The search bits are broadcasted to all CAM columns for a bitwise comparison with the stored content bits, using wavelength encoding scheme [4]. After setting the MRR at one of its two possible stored conditions, its optical response and resonance will effectively work similar to multiplying the incoming streams by the transmission-coefficient of the MRR, individually for each wavelength. When one of the two signals is high (e.g. λ1 at level of 1) and matches the MRR resonant wavelength, as configured and stored by the PCM, its transmission is attenuated or even blocked by the resonance, enforcing a low optical power output at this wavelength. Conversely, the complementary operation is the power level at the "Search Bit BAR" wavelength. We fabricated a photonic CAM table prototype featuring various Sb_2Se_3 MRRs towards multi-bit search operations, starting from individual cells up to a 4×2 (8-bit) CAM table, as shown in Fig. 1(b) and (c) respectively. However, this work encloses only the detailed results and evaluation of all

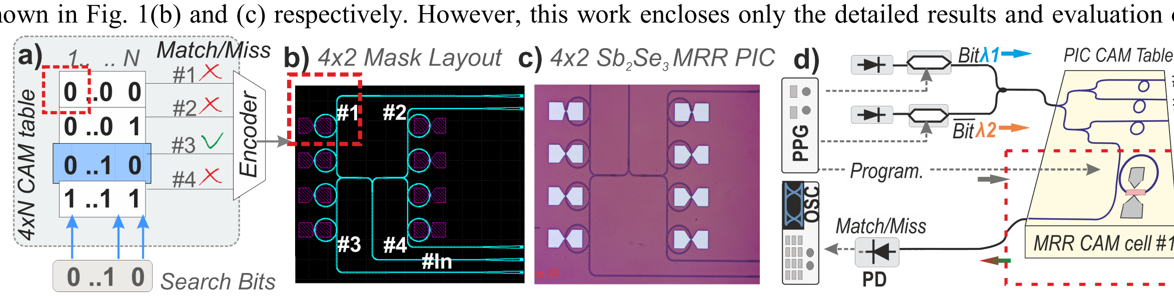

Fig. 1. a) Conceptual architecture and operation of a 4xN CAM table, b) Mask layout and c) microscope image of a developed 2D PCM memory array based on Sb_2Se_3 PCM MRRs as CAM table, d) experimental setup and first evaluation-demonstration of a non-volatile photonic CAM cell.

functionalities of a single CAM cell: programming/reversible electrical switching, search operation, and eye diagram evaluation in long data traffic patterns. The Sb_2Se_3-loaded MRR are fabricated following the same process in [7].

3. PIC characterization and Experimental results

The PCM-based MRR was initially prepared in the crystalline state, and subsequently amorphized in a stepwise manner using 2.45V pulses with varying pulse widths of 500-700ns (220nJ-308nJ), resulting in a 0.528π phase shift in resonance. To return the device to its initial state, a recrystallization pulse of 4.8V for 150μs (11μJ) is applied, as shown in Fig.1(a)-(d). After defining the pulses and configuring the PCM at either of the states, content addressing was performed by feeding the two complementary signals in Fig. 2(e) and (f), while recording the optical outputs of the CAM cell, shown in Fig.2(g) and (h). A low output power level, as marked with a green marker, is obtained only when the PCM ring is programmed to state ‘1’, i.e. having a resonant at the wavelength represented with the blue trace, equivalent to a Search Bit ‘1’. The performance of the CAM cell was evaluated also with 255-bit long random data traffic, capturing its eye diagram as shown in Fig. 2(i), validating the negligible distortion of the incoming signal. Finally, the device underwent four switching cycles, using the exact same amorphization and crystallization pulses. Each time the resonances were indeed tuned back to their expected wavelength, as shown in Fig. 2(j), validating the repeatable phase shift by the PCM, yet there was some noticeable reduction in ER, which is attributed to gradual degradation and deformation of the PCM patch after four complete switching cycles, as can be seen by the SEM images before and after switching in Fig. 2(k). This issue can be suppressed by further tailoring the electrical pulse, since larger number of repeatable cycles for the PCM memory can be achieved [7].

4. Conclussions

The first non-volatile silicon photonic Sb_2Se_3 CAM cell is described for fast, zero-power address look-ups. While we present a single cell, this approach is readably scalable and will be tested in the full 4×2 (8-bit) CAM table.

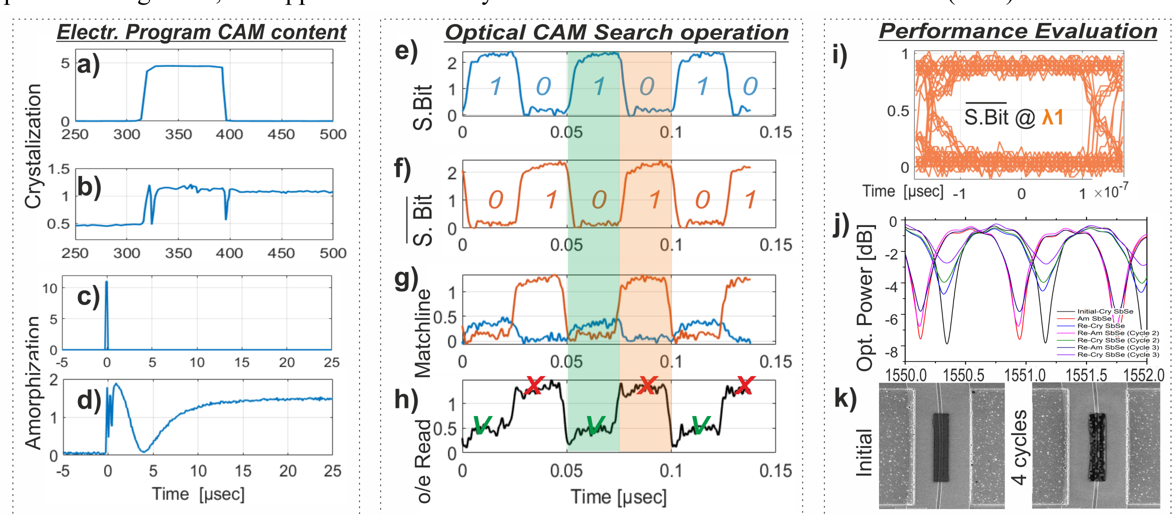

Fig. 2. Synchronized time traces tracking the electrical switching to program/store the CAM content: a) 150μsec external crystallization pulse of 4.8V, b) MRR output reaching stable crystalline state, c) 100ns electrical amorphization pulse of 10.5V peak, and d) MRR output reaching steady amorphous state after a 10μsec thermo-optic response. Synchronized traces of optical CAM search operation, including complementary external e) Search Bit and f) Search BitBAR, g) the combined optical Matchline output of the MRR after the drop operation on λ1/Bit by the PCM ring, and h) Electrical Matchline read output after the o/e operation at the PD, indicating when the low level power for a match (green highlight) or high level for a mismatch (red highlight) between the input Search Bit and the final o/e CAM Matlchline signal. Performance evaluation of the CAM using i) eye diagram of 2^8-1 random bit sequence, revealing open eye diagram, j) transmission spectrum of the MRR CAM after 3 cycles of reversible electrical switching. (k) SEM images of the device after the fabrication vs. after 4 switching cycles, revealing PCM degradation.

Acknowledgements

The work was supported by the Horizon Europe Project OCTAPUS (101070009) and the National Science Foundation through grants ECCS-2210168 and DMR-2329087. C. Vagionas acknowledges the support of Fulbright Visiting Scholar Program 2023- 2024 through the VESPUCCI-IC research project.

References

[1] N. Youngblood, et. al. "Integrated optical memristors," Nature Photonics, 17, 5461-572, 202
[2] K. Pagiamtzis, et. al., "Content-addressable memory (CAM) circuits and architectures: a tutorial and survey," IEEE JoSS, March 2006.
[3] C. Lian, et al., "Photonic (computational) memories: tunable nanophotonics for data storage and computing", Nanophotonics, 11, 17, 2022
[4] G. Mourgias-Alexandris, et al., "All-optical 10Gb/s ternary-CAM cell for routing look-up table applications", Optics Express, 26, 6, 2018.
[5] T. Moschos, et. al., "An all-optical address look-up table using optical CAM and optical RAM banks," IEEE JLT., 40, 24, 2022
[6] Y. London, “Multiplexing in Photonics as a Resource for Optical Ternary Content-addressable Memory Functionality”, Nanophotonics, 2023
[7] C. Ríos, et, al “Ultra-compact nonvolatile phase shifter based on electrically reprogrammable transparent PCMs,” PhotoniX **3**, 2023.