Modelling phase-change integrated photonic devices

Emanuele Gemo[1,†], Nathan Youngblood[2], Zengguang Cheng[2], Carlos Ríos[2,3], Matthias Stegmaier[4], Anna Baldycheva[1], Wolfram H.P. Pernice[4], Harish Bhaskaran[2], C. David Wright[1]

1. Department of Engineering, University of Exeter, Exeter EX4 4QF, UK
2. Department of Materials, University of Oxford, Parks Road, Oxford OX1 3PH, UK
3. Dept. of Materials Science & Engineering, Massachusetts Institute of Technology, Cambridge, MA 02139, USA
4. Institute of Physics, University of Muenster, Heisenbergstr, 11, 48149 Muenster, Germany

†. eg402@exeter.ac.uk

ABSTRACT

We report the progress made on the development of a self-consistent 3-dimensional simulation framework, yielding the time and spatially resolved electric field, temperature and material phase, for integrated phase-change photonic devices. We illustrate the analysis made for a prototypical integrated phase-change photonic memory, and report the results of SET and RESET operations.

Key words: GST225, modelling, photonics, integrated phase-change device, integrated phase-change memory

1. INTRODUCTION

Integrated phase-change photonic devices are a high interest research topic, due to their experimentally demonstrated capability to perform sub-nanosecond, low power, light driven non-volatile memory storage[1]. Novel implementations have also expanded the application scope of such devices to signal processing, with both arithmetic[2] and neuromorphic[3] operations having recently been successfully demonstrated experimentally. Current proof-of-concept devices implement a $Ge_2Sb_2Te_5$ optical cell as a thin layer deposited over a SiN or Si waveguide, whose transmission is modulated by the optical cell crystal fraction, owing to the phase-dependent attenuation constant. Despite the enthralling experimental results, the underpinning physical mechanisms that lie behind device operation are not completely understood. Whilst readout behaviour can generally be modelled with good experimental agreement, SET and RESET optical memory operations (as well as the more complex arithmetic and neuromorphic behaviours) are more difficult to predict. To understand the importance and role of the variables and physical processes involved, we developed a numerical emulation tool capable of calculating the time-resolved wave-propagation, heat diffusion and phase-change transition, via FEM analysis and matrix calculation software, using a self-consistent approach.

2. SIMULATION METHODOLOGY

The simulation framework calculates iteratively wave propagation, heat diffusion and phase-transition, with a sub-nanosecond time-stepping to prevent computational artefacts. To set the basis of a realistic wave-propagation and heat-diffusion simulation (calculated through FEM analysis), phase and temperature dependencies of optical and thermal properties are included. With respect to the optical cell material, we consider temperature dependencies for both refractive index[4] and thermal conductivity. A thermal boundary resistance between the waveguide and GST cell of 1e-9 m^2K/W is assumed. We also assume that both waveguide and cladding material thermal conductivities depend on temperature. Through electromagnetic field calculation we obtain the optical losses, which drive the temperature increase within the optical cell. The phase-transition model currently used is a nucleation and growth cellular automata, evaluating the transition from amorphous to crystalline for every lattice unit (*monomer*, 0.82 nm lattice parameter), as a function of temperature, time-step and monomer neighborhood phase. We include an arbitrary step function to determine the formation of the molten phase above melting temperature.

3. RESULTS & DISCUSSION

In figure 1a we represent the device configuration, based on a 1300x330 nm SiN waveguide, and a 2 µm optical cell. In figure 1b and 1c we report the FEM results for, respectively, e.m. field and temperature distribution, at the end of a RESET pulse of 1550 nm /1.5 nJ / 100 ns . In figure 2 we report the phase-state of the optical cell for the consecutive RESET and SET pulses. The simulation yields a change-in-readout (C.I.R) of 28.6% after RESET, and 8% after SET. Experimental measurements performed on the same device, with a 375 pJ / 20 ns RESET pulse, reports good agreement with our calculation.

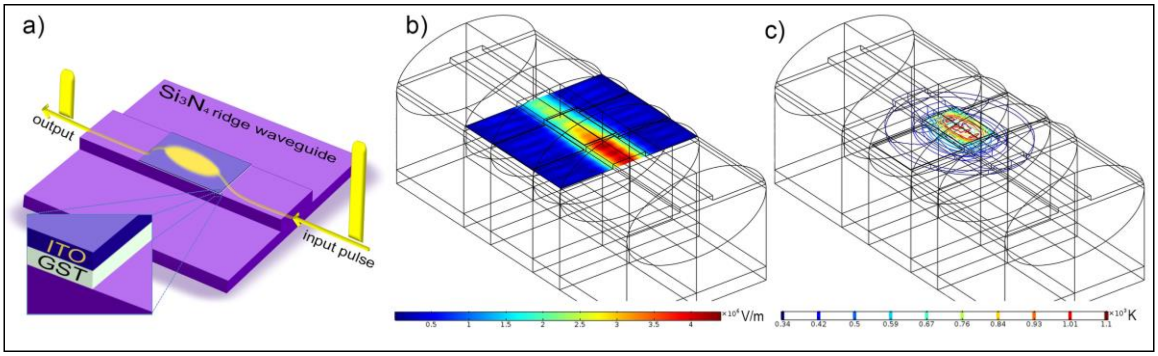

Figure 1. a) Device configuration, with a 2 µm / 10 nm GST optical cell, capped with ITO, fabricated on a 1300x330 nm SiN waveguide. Telecom-C band light propagates without loss through the waveguide, interacting via evanescent field with the top layer. b,c) Simulation results during the RESET pulse (100 ns, 15 mW) calculation, at t = 100 ns, starting from a crystalline cell; b) electric field distribution [V/m] c) temperature distribution [K] due to optical losses.

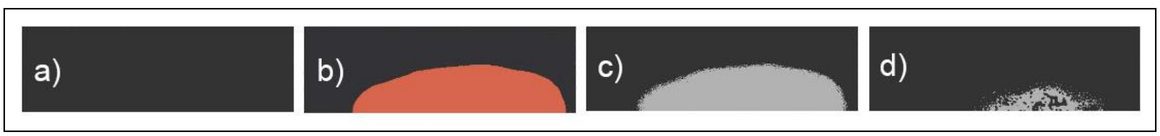

Figure 2. Top view of half-cell phase distribution before and after RESET/SET operations. a) t = 0; b) t = 100 ns, after RESET pulse; c) t = 1 s, after RESET cooldown; d) after SET pulses and cooldown. SET consists of 7 x (100 ns pulse time + 100 ns cooldown time), with energies of 1|0.9|0.8|0.7|0.6|0.6|0.6 x RESET pulse power. Darker color represents crystalline phase, light grey represents solid amorphous phase, and red represents the molten phase.

4. CONCLUSION

We have developed a simulation framework to solve the self-consistent calculation required to emulate SET and RESET operations in novel phase-change integrated photonic devices. We have presented exemplar calculations performed via a ns-scale high power pulse, on an integrated photonic phase-change memory. Future work will investigate multi-level memory operation and arithmetic and neuromrophic operations, while also carrying our further modelling developments to allow for the investigation with enhanced flexibility of different photonic integrated architectures.

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