Foundry-scalable phase change optical memristors for versatile photonic computing architectures

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1. Optical Neural Networks (ONNs)

• Hardware implementation of Deep Neural Networks (DNNs) requires parallelism and many interconnects.

• Photonic integrated circuits (PICs) provide a unique advantage in terms of low latency, high bandwidth and multiplexing.

• To realise ONNs:
  1. low-cost
  2. compact
  3. energy efficient

  modulators are required.

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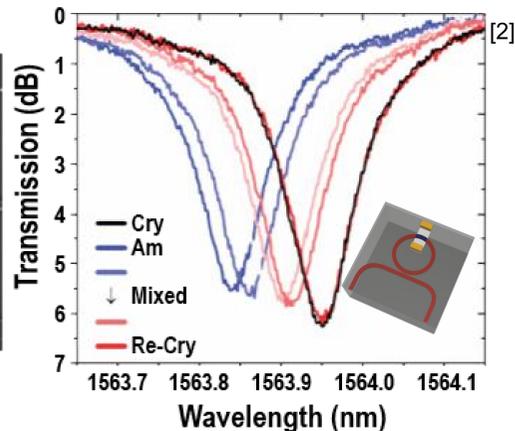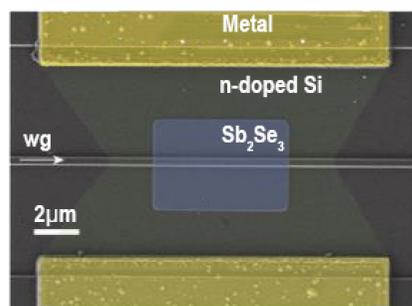[1] Moralis-Pegios et al. *2022 OFC*. IEEE, 2022.
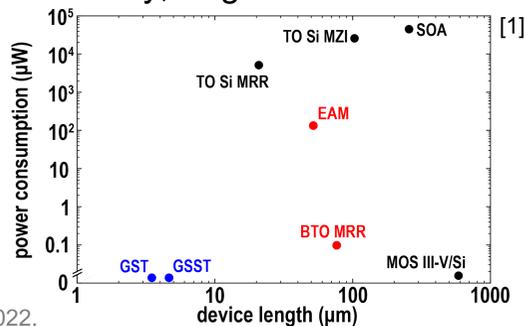
2. Phase change modulators

• Phase change materials (PCMs) exhibit a reversible phase transition between crystalline and amorphous phase.
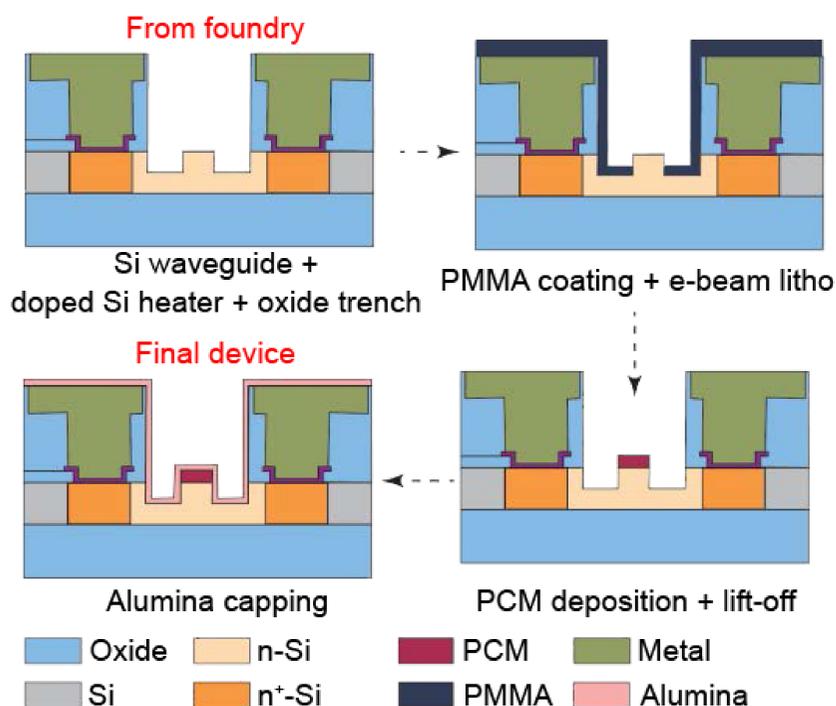
Amorphous   Quench ←   → Anneal   Crystalline
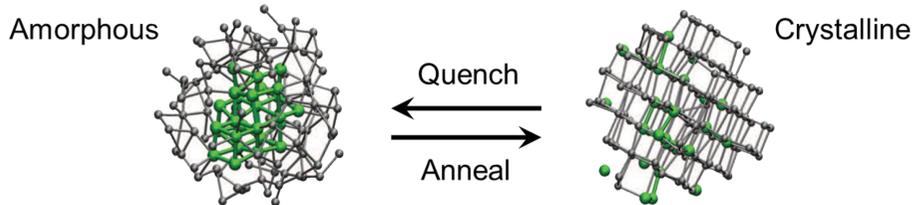
• This phase transition is accompanied by a change in (complex) refractive index.

• PCMs are a promising platform for compact modulators:
  1. large modulation of optical properties
  2. substrate blindness
  3. previously demonstrated commercial success (GST)
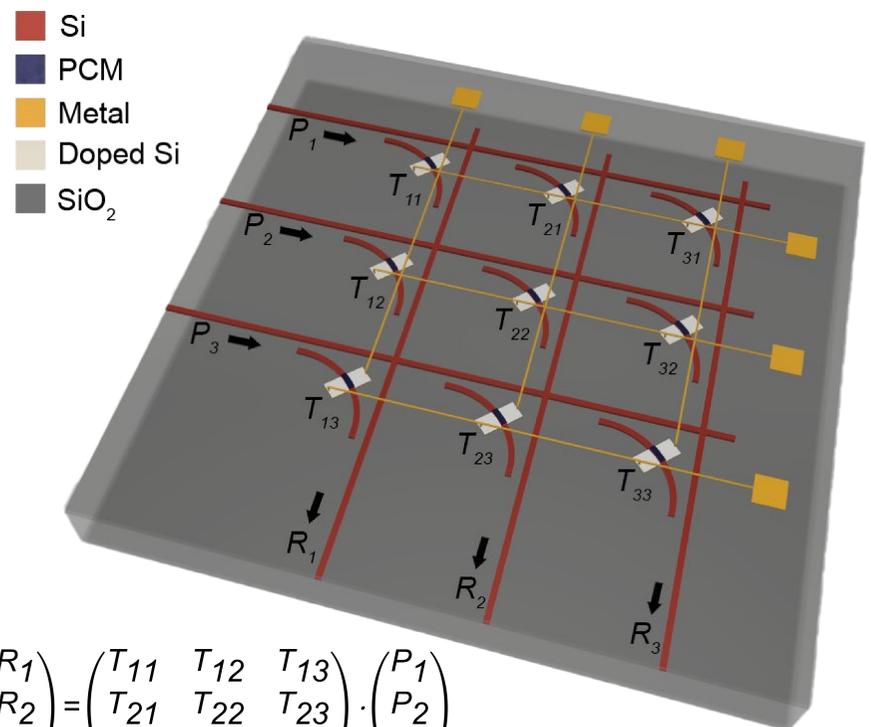 4. low cost
  5. true non-volatility

[2] Ríos et al. *PhotoniX* 3.1 (2022): 26.

3. Foundry Scalable BEOL Integration

From foundry

Si waveguide + doped Si heater + oxide trench

PMMA coating + e-beam litho

Final device

Alumina capping

PCM deposition + lift-off

Oxide | n-Si | PCM | Metal
Si | n⁺-Si | PMMA | Alumina

4. Photonic Matrix-Vector Multiplication (MVM)

Photonic Crossbar Array

Si | PCM | Metal | Doped Si | SiO$_2$
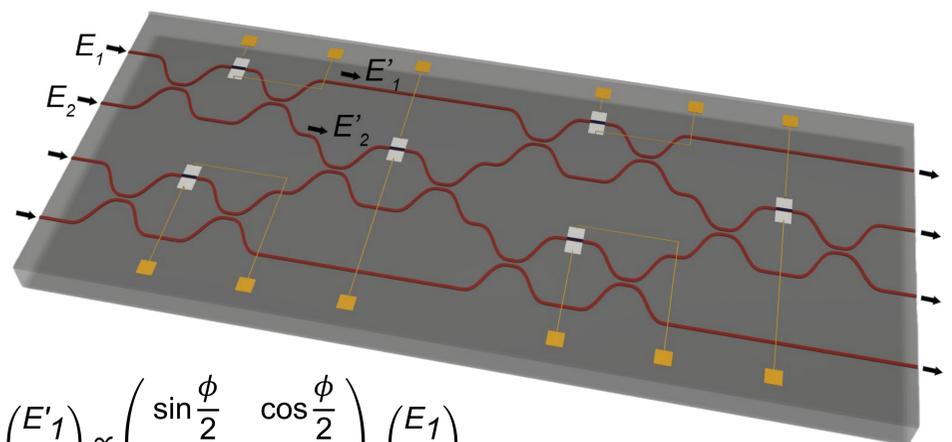
$$\begin{pmatrix} R_1 \\ R_2 \\ R_3 \end{pmatrix} = \begin{pmatrix} T_{11} & T_{12} & T_{13} \\ T_{21} & T_{22} & T_{23} \\ T_{31} & T_{32} & T_{33} \end{pmatrix} \cdot \begin{pmatrix} P_1 \\ P_2 \\ P_3 \end{pmatrix}$$

• Change in transmission (complex refractive index) between amorphous and crystalline phase.

• Compatible with the traditional Ge$_2$Sb$_2$Te$_5$(GST) and optical-PCM pioneered by our group Ge$_2$Sb$_2$Se$_4$Te$_1$ (GSST).

• Allows for in-memory computing.

Mach Zehnder Mesh

$$\begin{pmatrix} E'_1 \\ E'_2 \end{pmatrix} \propto \begin{pmatrix} \sin\frac{\phi}{2} & \cos\frac{\phi}{2} \\ \cos\frac{\phi}{2} & -\sin\frac{\phi}{2} \end{pmatrix} \cdot \begin{pmatrix} E_1 \\ E_2 \end{pmatrix}$$

• Phase shift induced by change of PCM state.

• MVM without loss of optical power (<0.1 dBm per modulator).

• Enabled by emergent, transparent PCMs, such as Sb$_2$Se$_3$ and Sb$_2$S$_3$.

• Allows for unitary matrix multiplication [3] and implementation of an arbitrary matrix through singular value decomposition (SVD) [4].

• Compatible with optical as well as optical/electrical/optical (O/E/O) non-linearities.

[3] Reck et al. *Physical review letters* 73.1 (1994): 58
[4] Shen et al. *Nature photonics* 11.7 (2017): 441-446.

5. Outlook

• Multi project wafer run with foundry (AMF, AIM).

• Proposed BEOL integration scalable to large networks with many interconnects.

• Photonic crossbar array has potential for implementation of on-chip differential equation solver using Kirchhoff's Photonic Nodes [5].

[5] Sun, et al. Nanophotonics 10.6 (2021): 1711-1721.