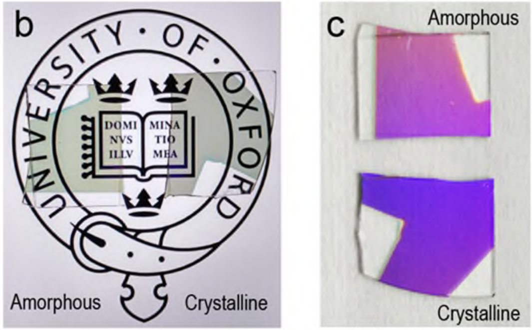
Functional materials for energy efficient devices

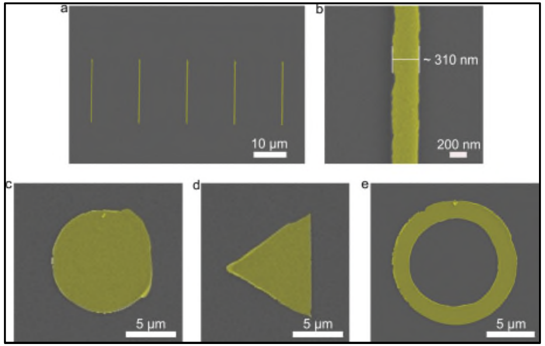
Harish Bhaskaran

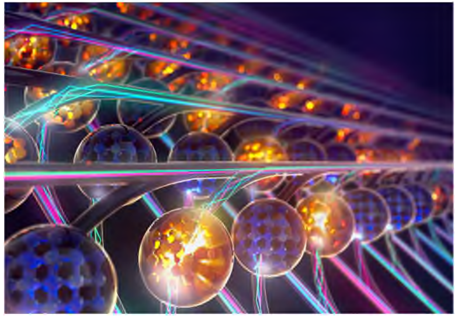
Talk Outline

"Smart" Windows

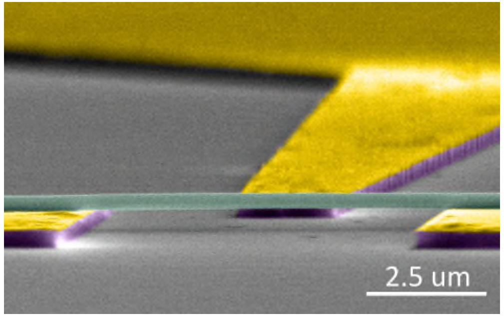


Sustainable Nano-manufacturing





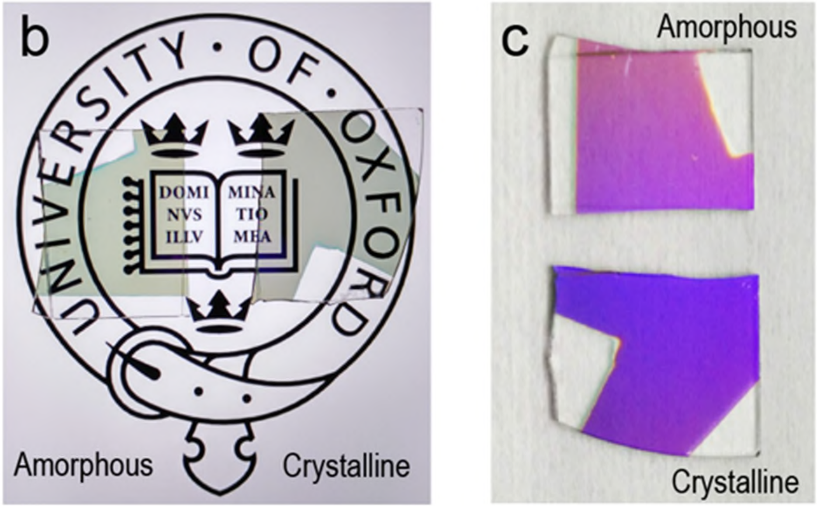
Photonic Computing for AI and ML



Energy efficient communications

...enabled by nanoscale engineering using functional materials

"Smart"
Windows



Motivation

(image credit: Sławomir Kowalewski, https://pixabay.com/photo-455239/)

- 20% to 40% of energy in developed countries is used to maintain indoor temperature[1]
- Up to 50% of heat is lost through windows in winter[2]

[1] L. Pérez-Lombard, et al., *Energy Build.*, vol. 40, no. 3, pp. 394–398, Jan. 2008.

[2] S. D. Rezaei, et al., *Sol. Energy Mater. Sol. Cells*, vol. 159, pp. 26–51, 2017

Current smart window technologies

Solar modulation via tunable scattering
(hydrogel, LC, nanoparticles, etc.)

X. Li et al., *Joule* 3, 290–302 (2019)

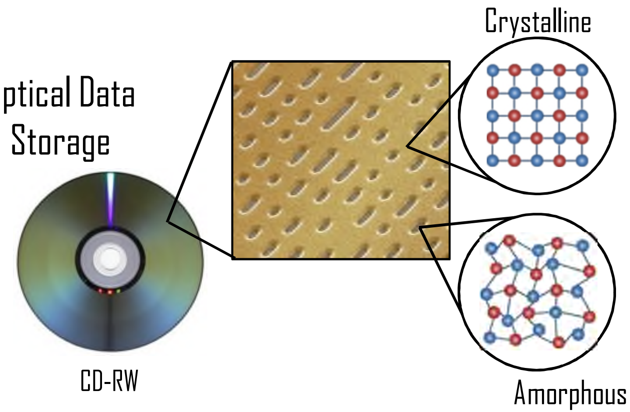
Solar modulation via tunable absorption
(Reversible reactions, VO_2, nanoparticles, etc.)

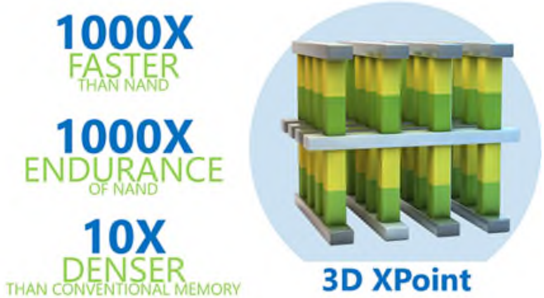
C. Barile et al., *Joule* 1, 133–145 (2017)

Majority of technologies strongly modulate visible transmission to achieve high solar modulation.

Phase-change materials as an optoelectronic platform

Optical Data Storage

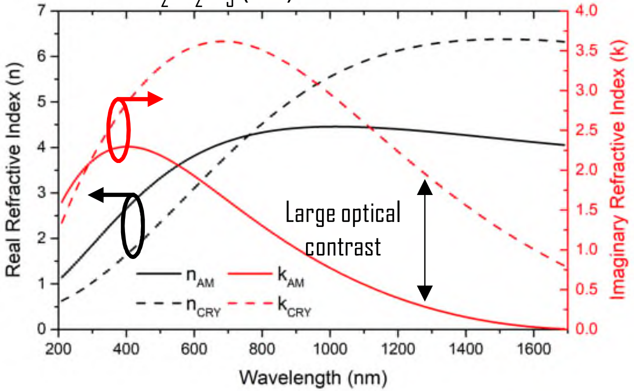




Electrical Data Storage

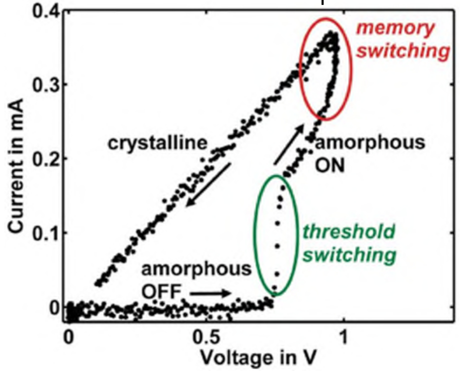
(Image source: Intel)

$Ge_2Sb_2Te_5$ (GST) – Refractive Index



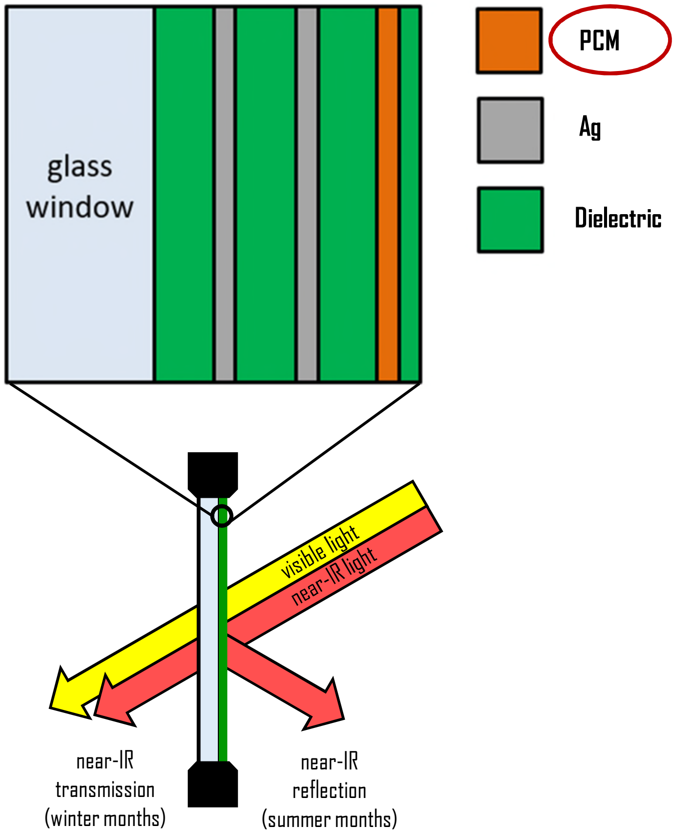
Pernice & Bhaskaran, *APL* (2012)

GST – IV Sweep

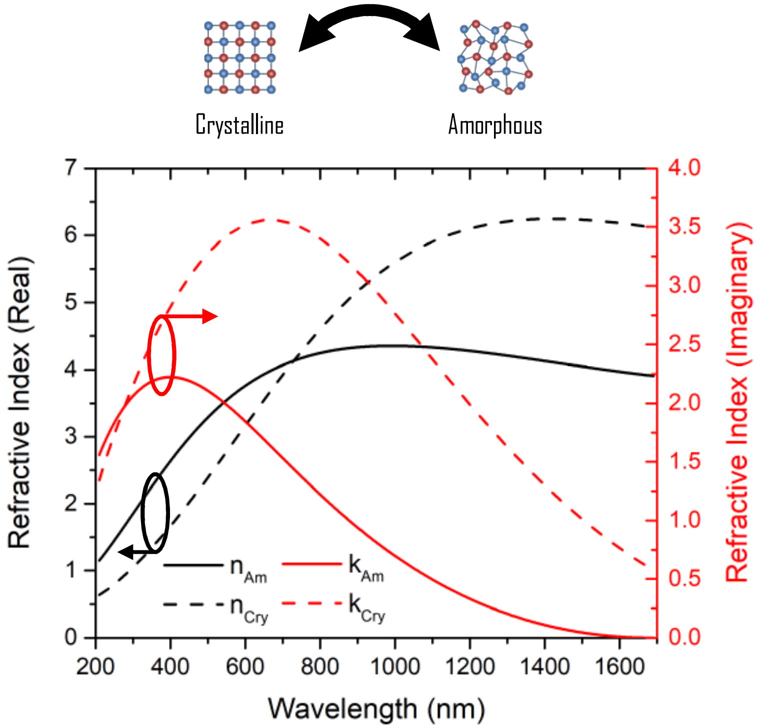


M. Wuttig et al., *Nature Mat.* 6, 824–832 (2007)

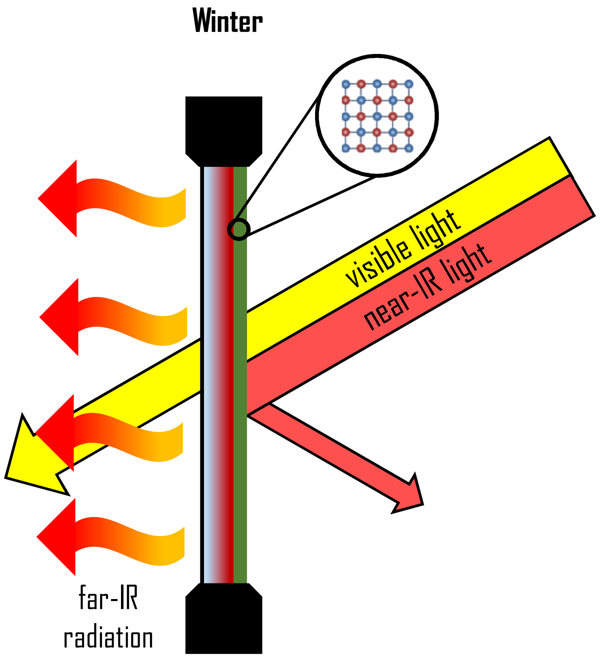
Smart window design

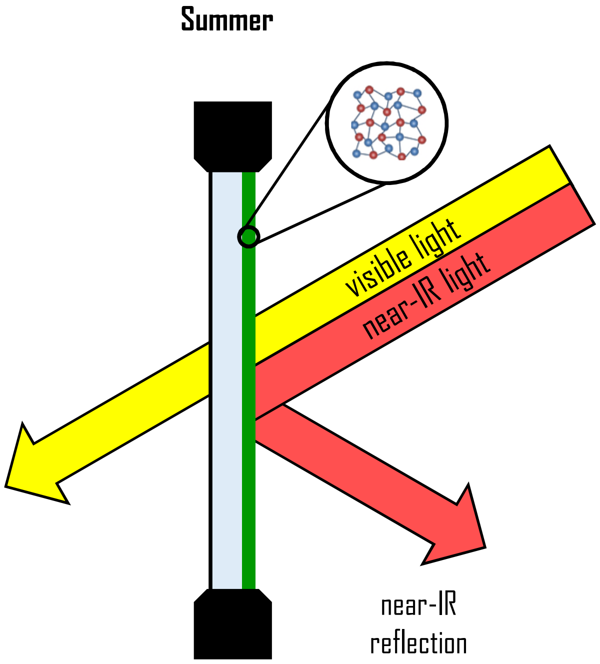


Reversible/non-volatile phase change via heat



Smart window design





Nathan Youngblood
Former Postdoc, now Assistant Prof
at University of Pittsburgh

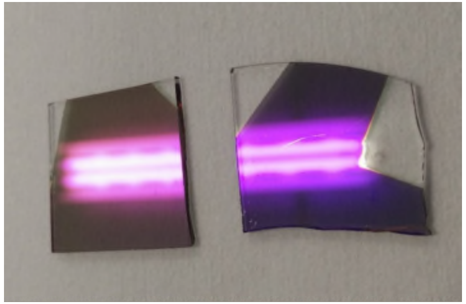
Peiman Hosseini
Former Postdoc, now Director of
Operations at Meta Materials

N. Youngblood et al., *ACS Photonics* 9(1), 90–100 (2022)
P. Hosseini et al., *Nature* 511, 206–211 (2014)

Visible properties

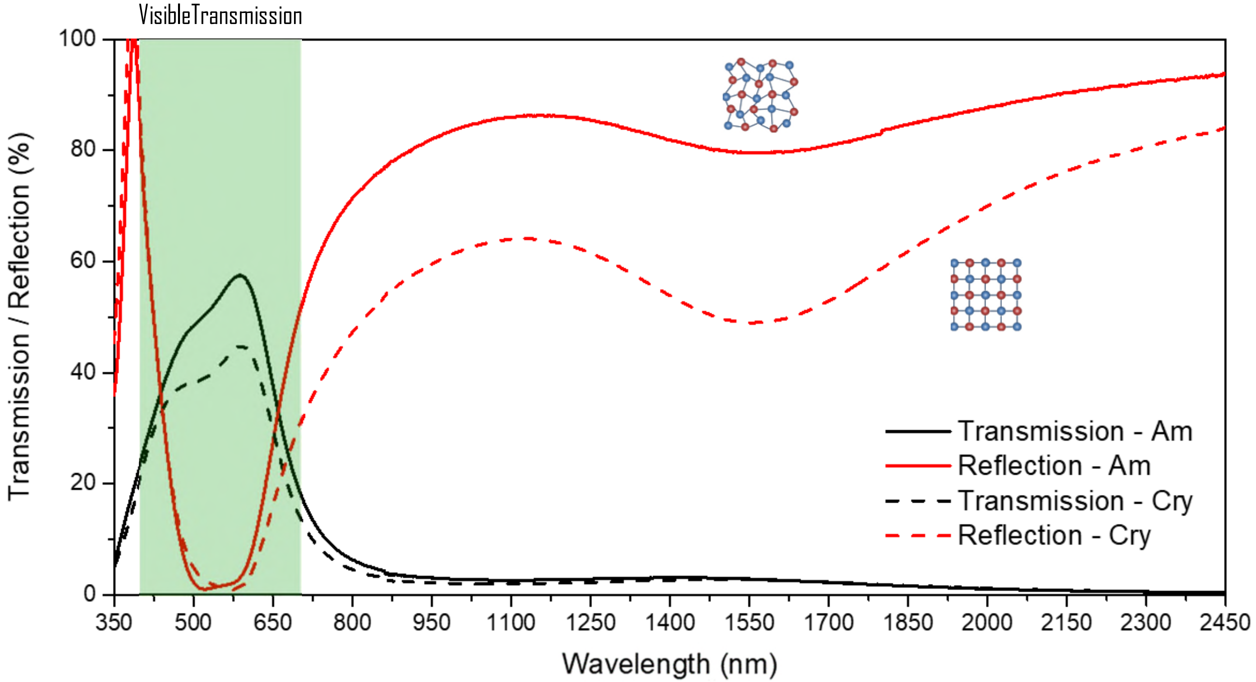
Amorphous Crystalline

Amorphous Crystalline



N. Youngblood et al., *ACS Photonics* 9(1), 90–100 (2022)

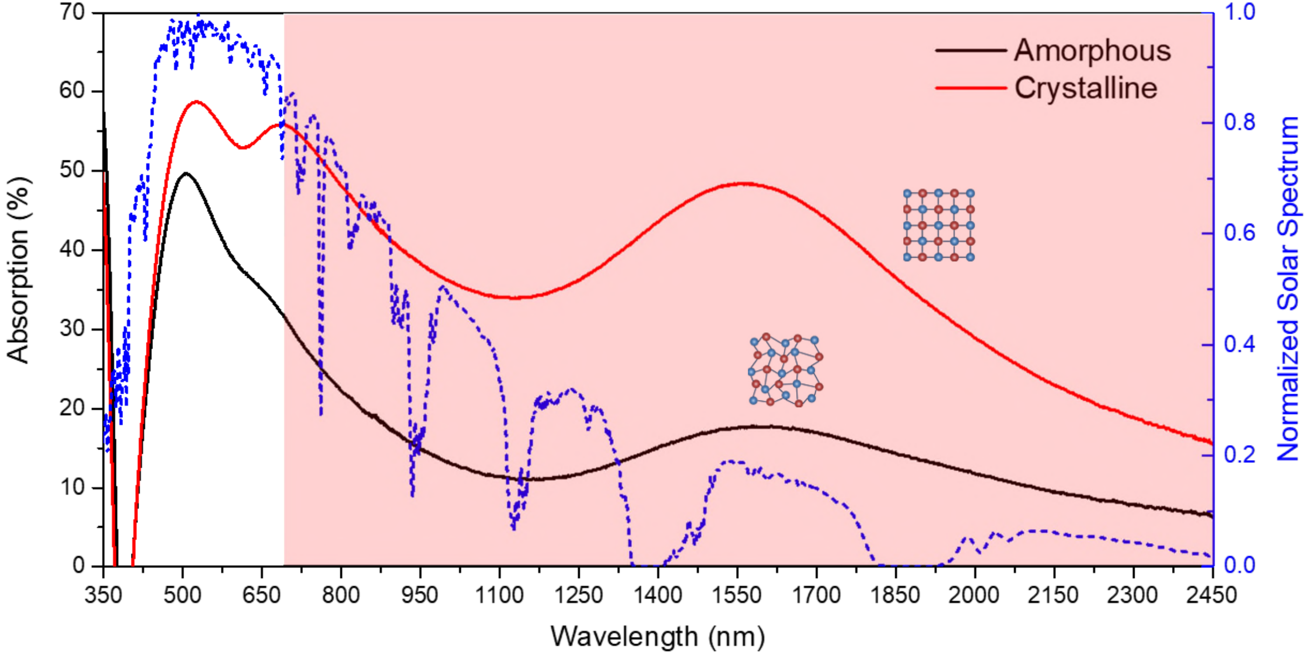
Spectral response



N. Youngblood et al., *ACS Photonics* 9(1), 90–100 (2022)

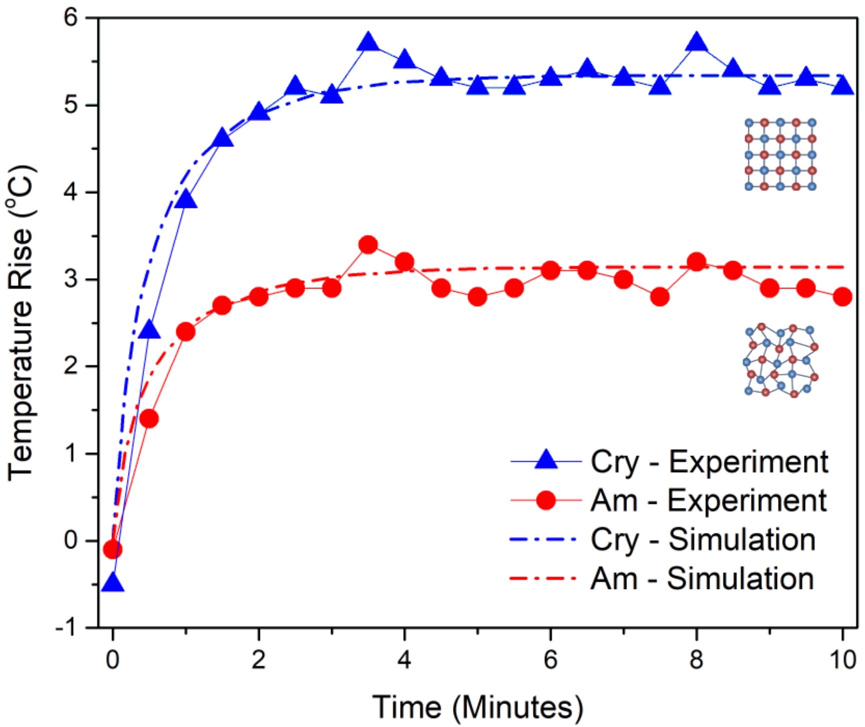
Spectral response

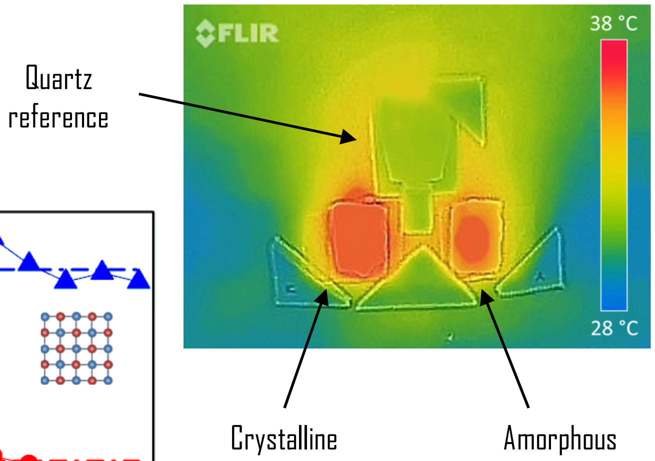
2x modulation of near-IR solar energy



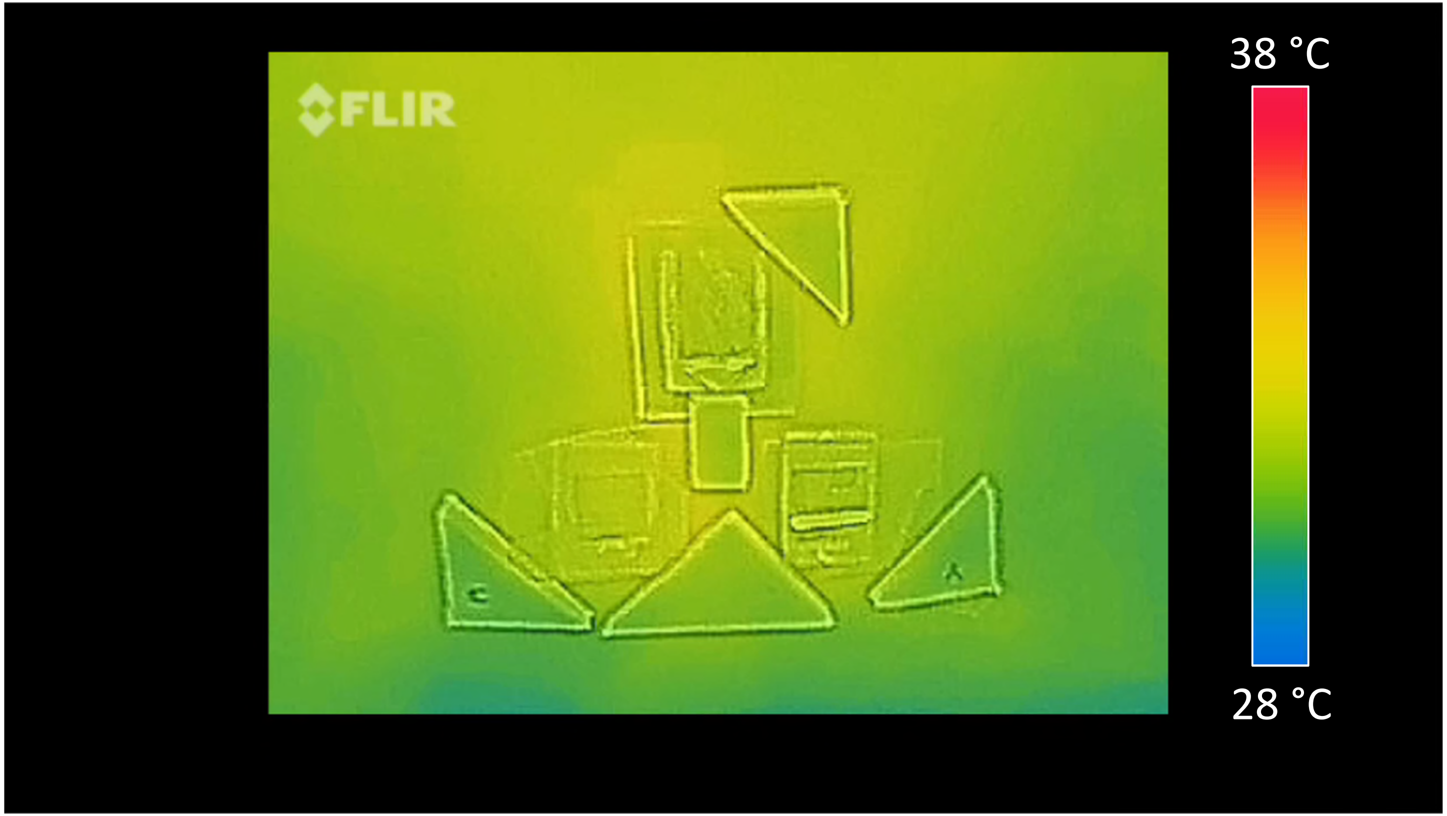
Reflects **78%** of near-IR energy in summer and absorbs **45%** in the winter.

Near-IR to far-IR conversion





Thermal response (12x speed)



On Smart Windows…

- Demonstrated a solid state smart window using only 15 nm of PCM as an active material.
- 78% of near-IR energy is reflected in the amorphous state and 45% is absorbed in the crystalline state.
- Absorbed energy is converted to far-infrared radiation and preferentially radiates into the room
- Glazing acts as low-emissivity coating, reflecting thermal radiation from environment.

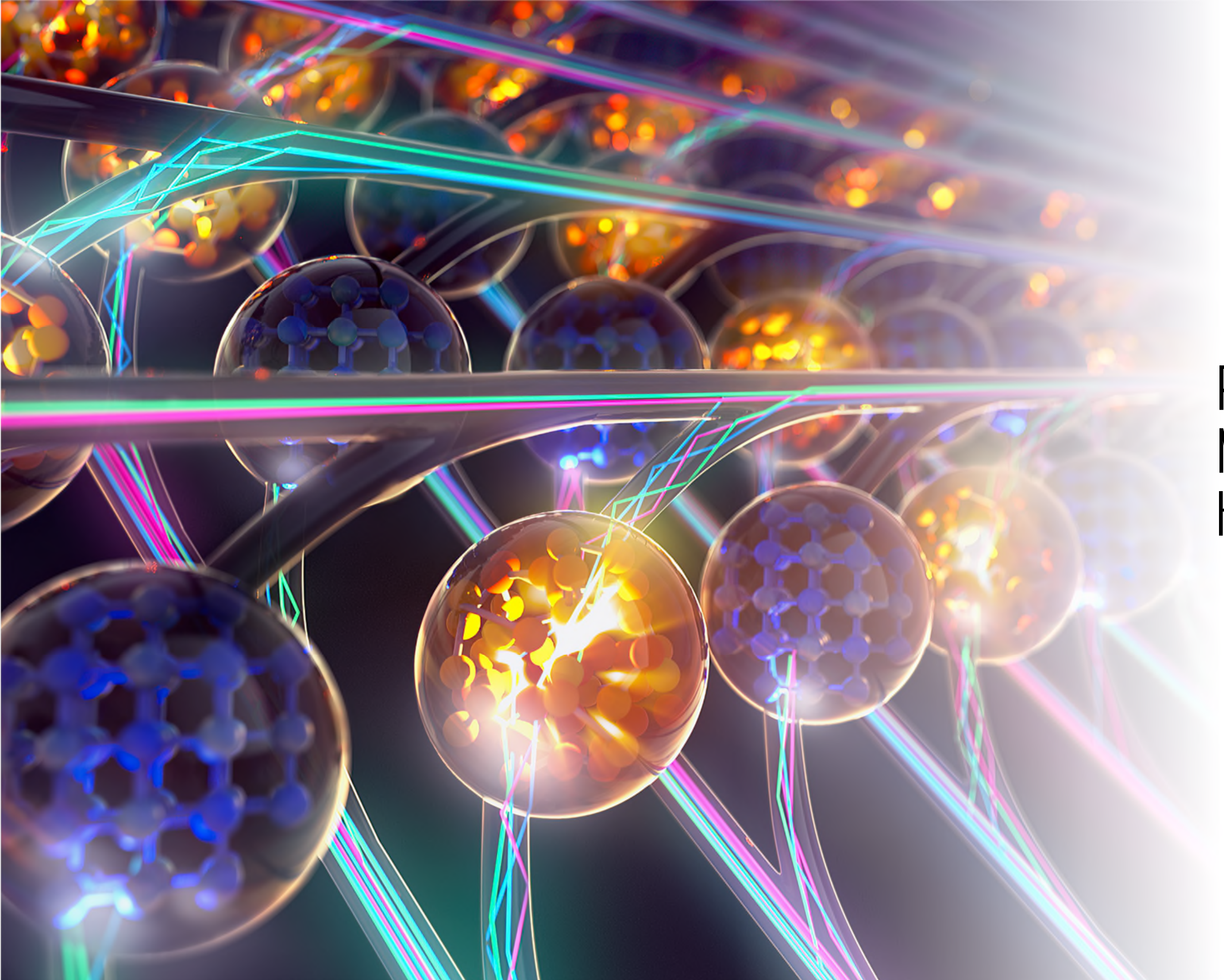
Eckersley O'Callaghan

PLASMA APP

META Go Beyond.

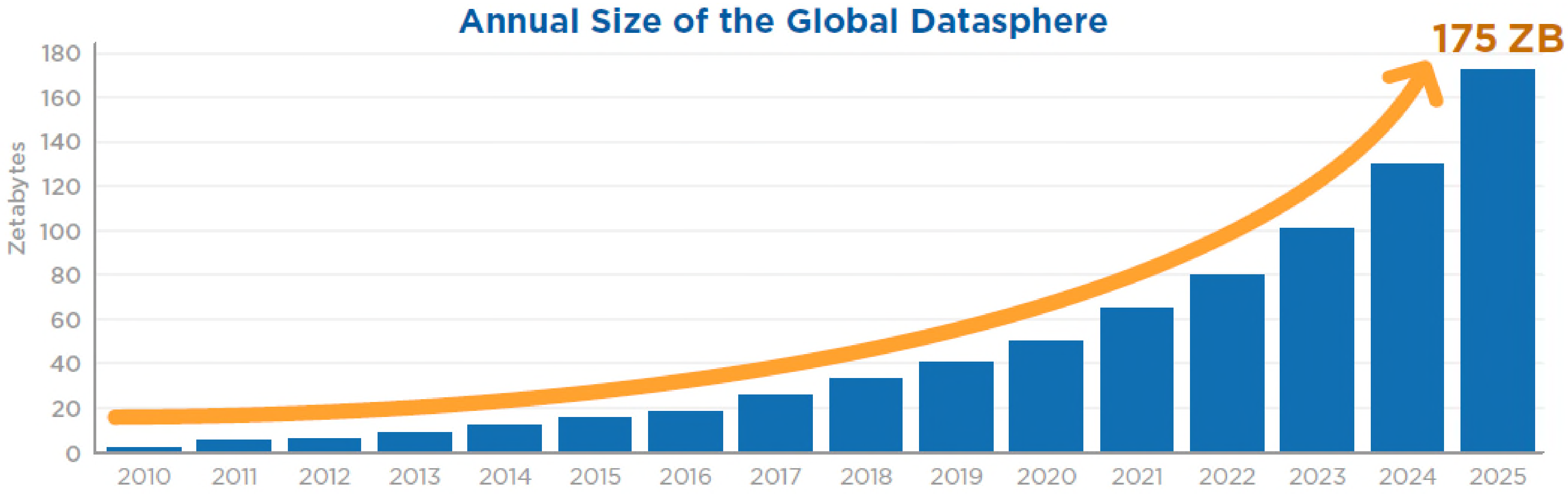
EPSRC Engineering and Physical Sciences Research Council

www.waftcollaboration.org



Photonic Computing for Machine Learning and AI hardware

Data volume has shot up

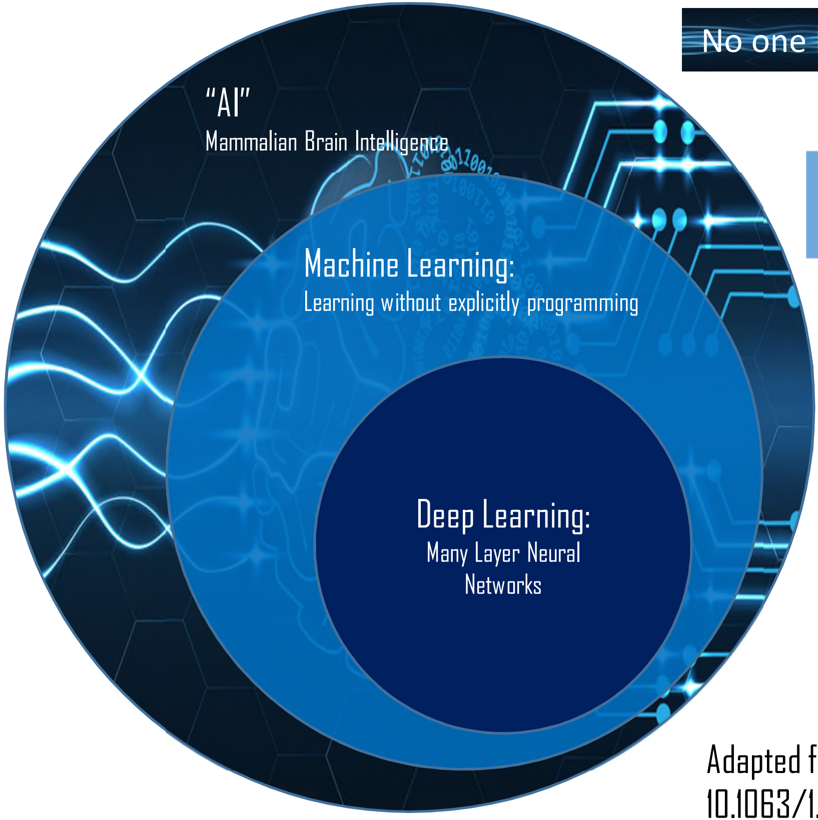


- AI applications currently generate 80 Exabyte/year and it is expected that it will be 845 Exabyte/year in 2025

https://www.datanami.com/2018/11/27/global-datasphere-to-hit-175-zettabytes-by-2025-idc-says
https://www.mckinsey.com/~/media/McKinsey/Industries/Semiconductors

But AI’s Computing Efficiency Sucks

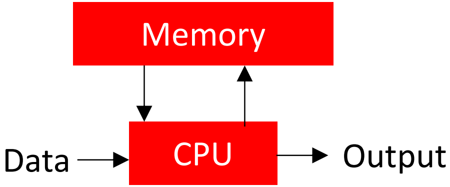
1 million W vs 20 W



No one knows yet!

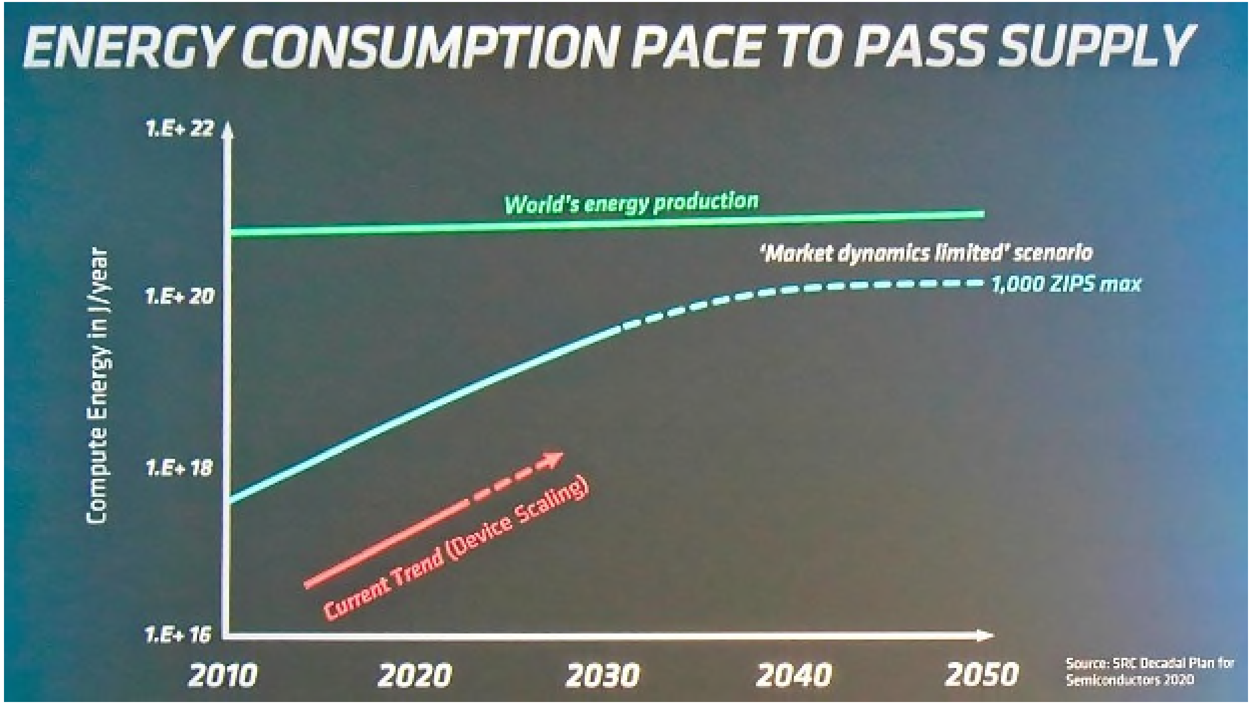
CPUs and GPUs; some specialized FPGAs

GPUs do the training; CPUs and sometimes FPGAs infer; race to “new” ASICs



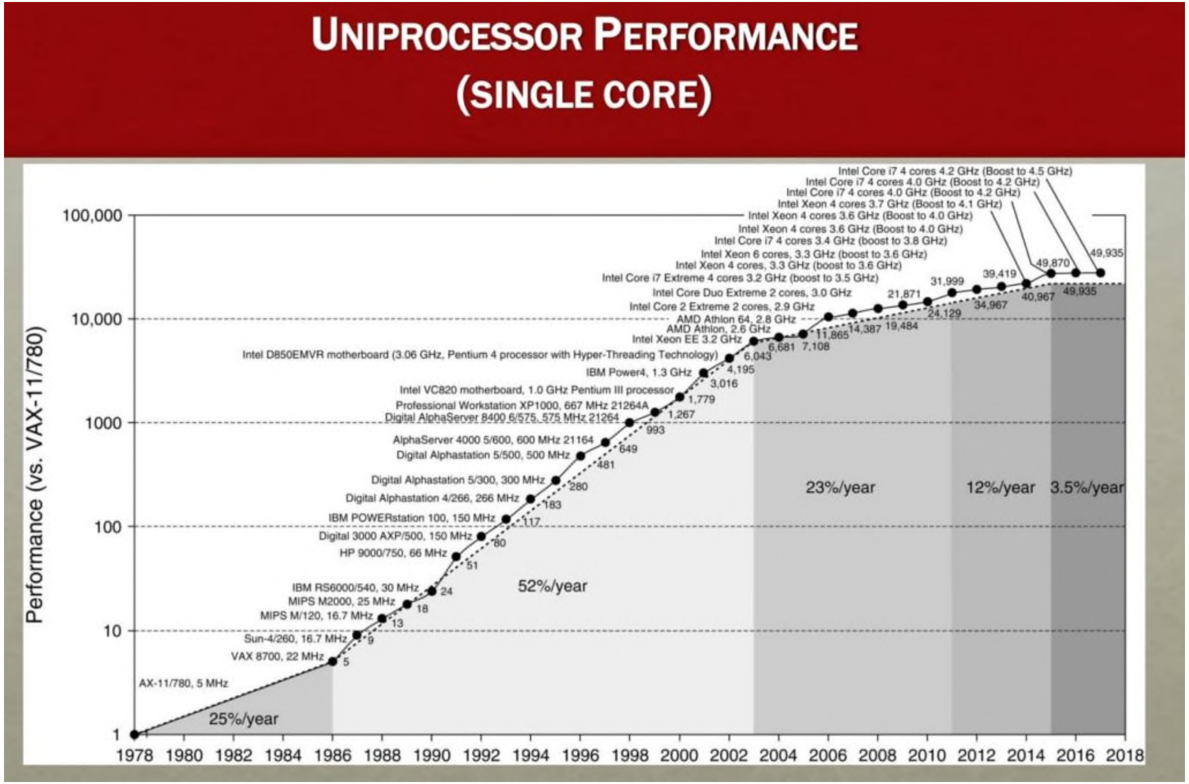
Adapted from Sebastian et al, JAP 124, doi: 10.1063/1.5042413 (2018).

But AI’s Computing Efficiency Sucks



Doing nothing is not an option

Scaling ≠ Better performance/area

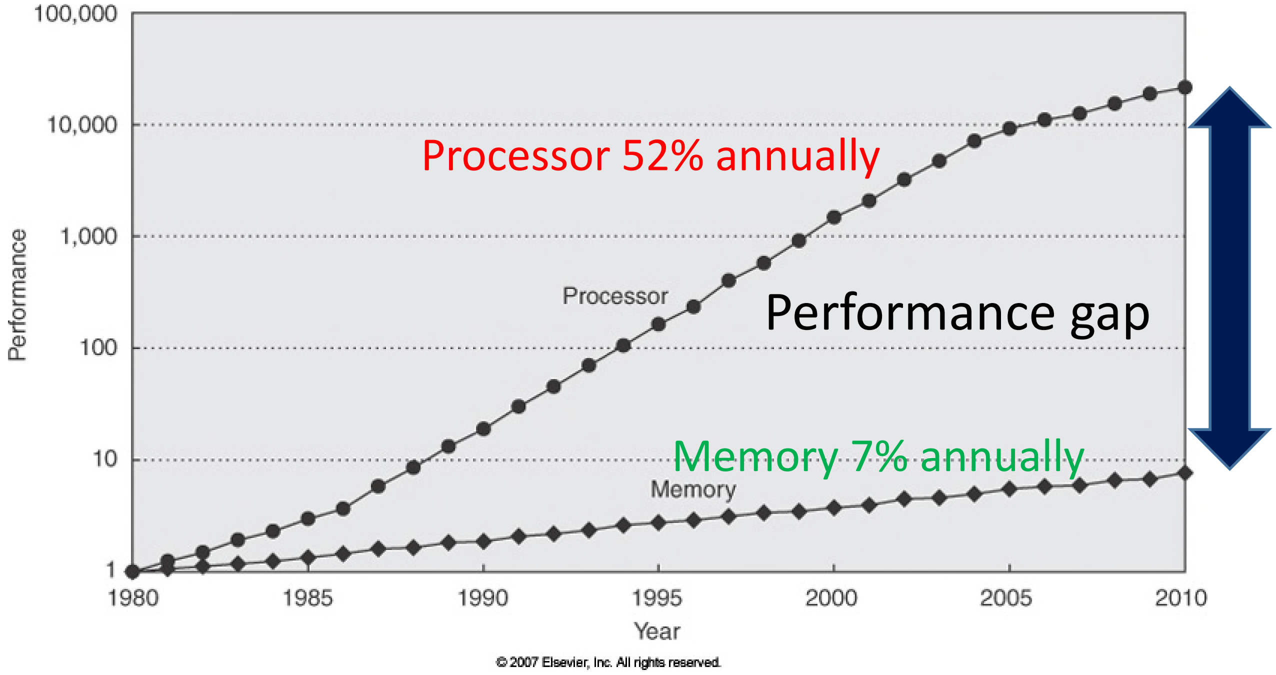


https://www.nextbigfuture.com/2019/02/the-end-of-moores-law-in-detail-and-starting-a-new-golden-age.html, 11/20/2020

Solution: co-locate memory and processor using accumulative memories

Performance gap

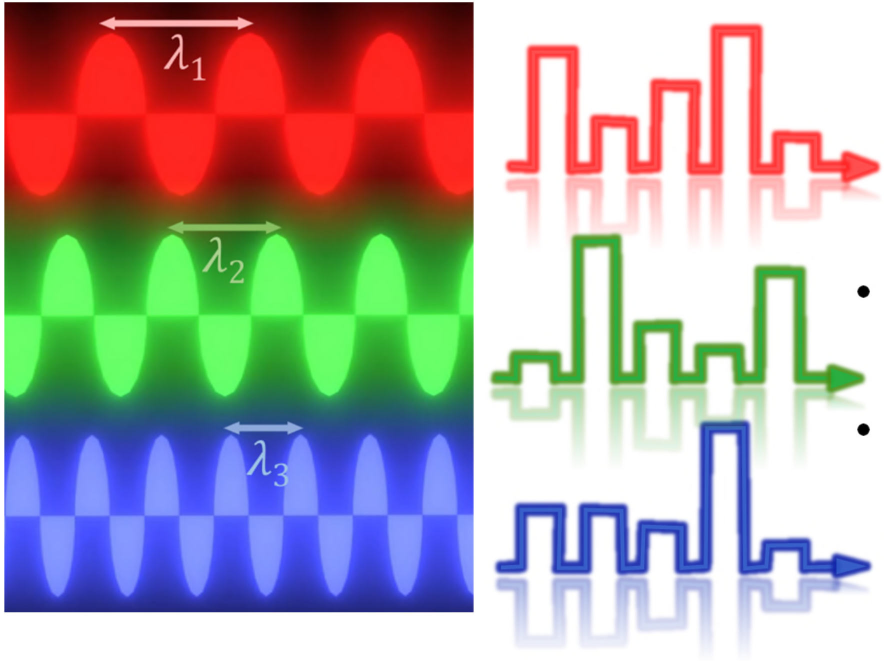
"Memory Wall"



https://www.extremetech.com/computing/261792

Photonics is better?

"The future is optical. Photonic processors promise blazing fast calculation speeds with much lower power demands" @IEEE Spectrum (2022)



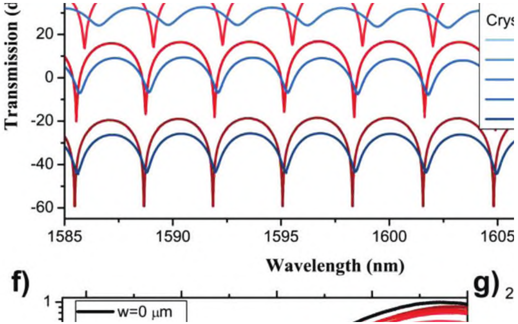
- Large bandwidths
  - Wavelength, phase, polarization, etc
- Faster communication speed

Good for communication, but for programming?

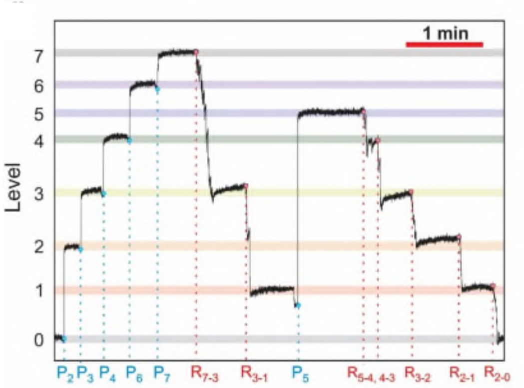
“Phase Change Optical Memory” Background

Simulations → On a hotplate → Experimental multilevel Demonstration

Pernice and Bhaskaran, Appl. Phys. Lett (2012)



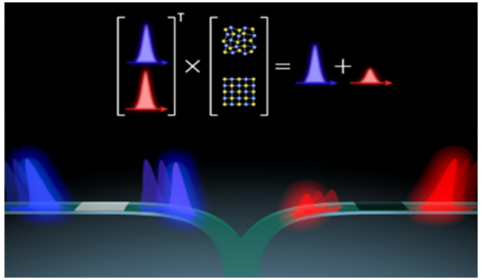
Rios et al, Adv. Mater. (2014)

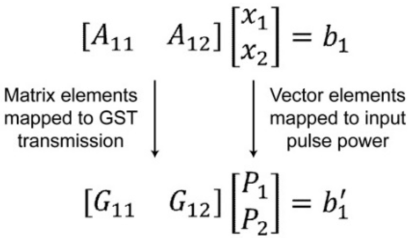


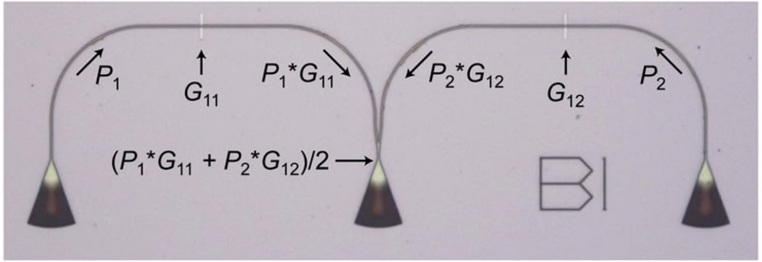
C. Rios et al., Nature Photonics 9, 725-732 (2015).

In-Memory Photonic Computing

- In-memory computing schemes are growing (IBM using electronics)
- Non-volatile, reprogrammable memory banks are efficient for inferencing applications





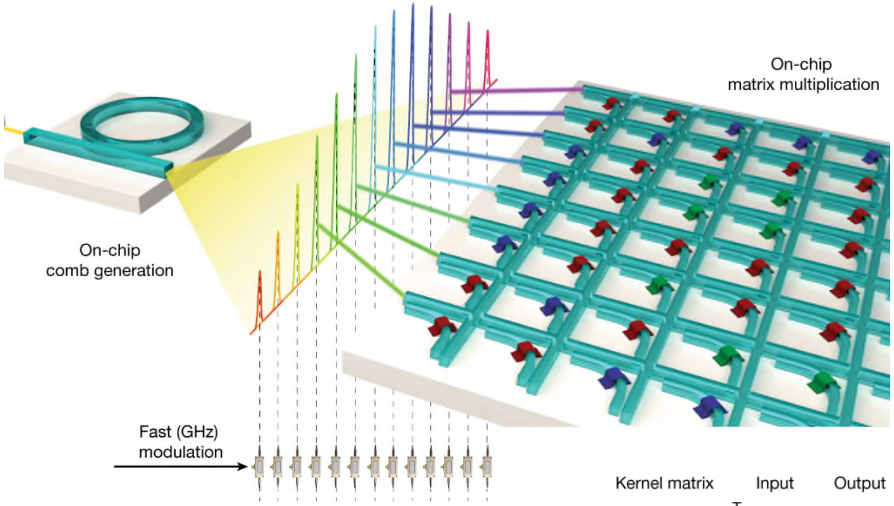


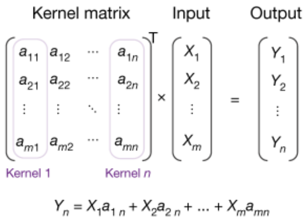
Rios, Youngblood et al., *Science Advances* (2019)

Carlos Rios
(Former Student,
now faculty @ UMD)

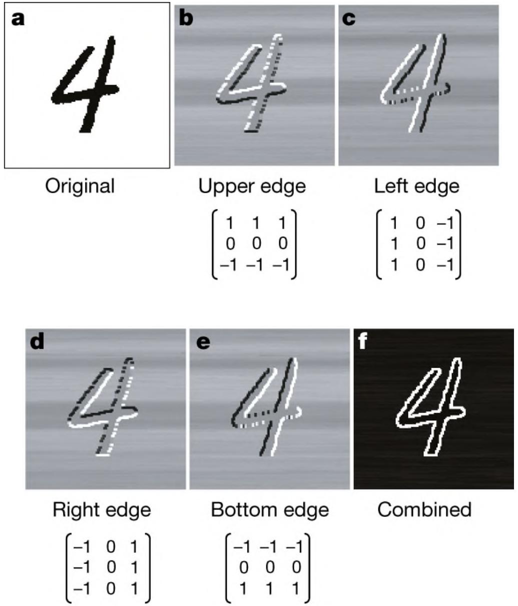
Nathan Youngblood
(Former Post-doc,
now faculty @ UPitt)

From Single Devices to Computing Systems





Feldmann, Youngblood, Karpov et al., *Nature* (2021)



Johannes Feldmann
Former Postdoc, now
CTO at Salience Labs

Nathan Youngblood
Former Postdoc, now Assistant Prof
at University of Pittsburgh

Highest compute density for inferencing – potential for 162 TOPS/mm^2 on SOI (in the lab, demonstrated 1.2 – compared to Google TPU ~ 0.28 TOPS/mm^2)

Energy consumption per MAC in a N×N array

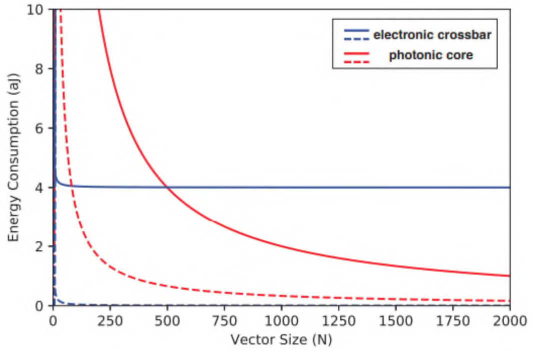
This term is missing in photonics

$$E_{total}(electronics) = E_{charging} + E_{mod} + E_{rec} + E_{noise} = N \times CV^2 + \frac{1}{N}(E_{mod} + E_{rec}) + 2k_B T \times 2^{2N_b+1}$$

$$E_{total}(photonics) = E_{mod} + E_{rec} + E_{noise} = \frac{1}{N}(E_{mod} + E_{rec}) + \frac{h\upsilon}{\eta} \times \max[2^{2N_b+1}, \frac{C_{rec}V_{rec}}{e}]$$

This can be further optimized.
We achieve single photon data processing if η=1.

At 4-bit precision, assuming η=0.2



Mitchell A. Nahmias et.al., Photonic Multiply-Accumulate Operations for Neural Networks, IEEE JSTQE, 8844098 (2020).

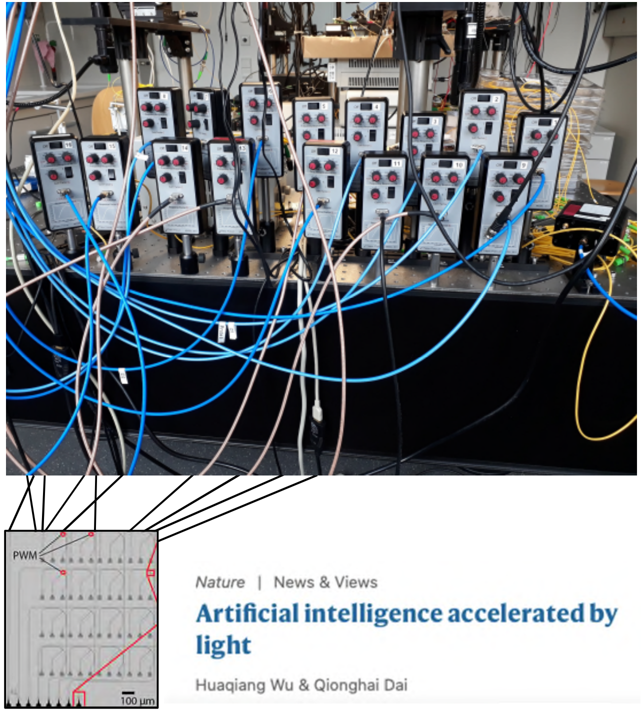
$$\eta = \eta_{laser} \times \eta_{waveguide} \times \eta_{memory} \times \eta_{detector}$$

- We are working on reducing the losses in memory.
- There is collaborative effort on reducing the other three terms
- Low-precision neural network (to reduce N_b) is also a direction.

Photonics are still bulky!

Free-space optics

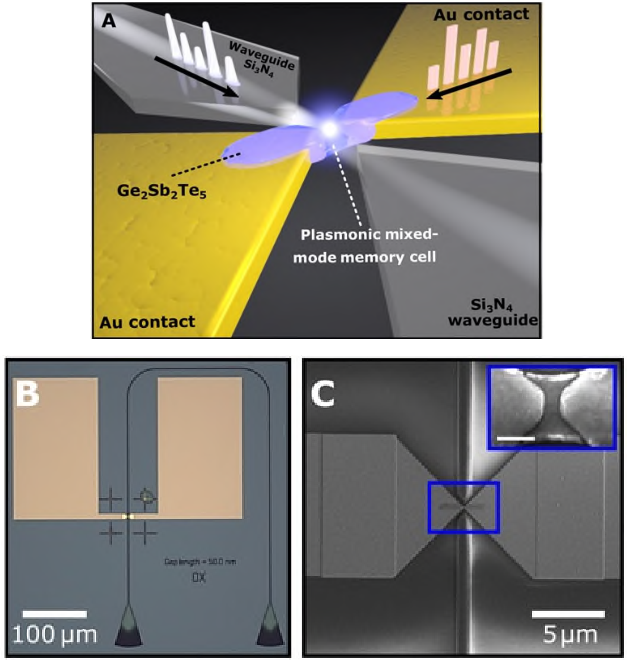
Integrated photonics

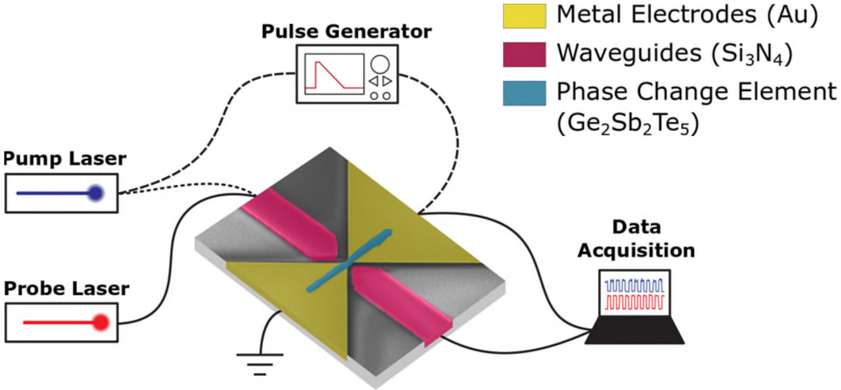


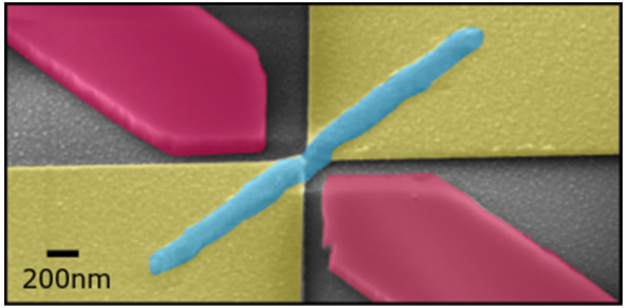
More volume of switching
= Higher energy

Plasmonic nanogap: Dual electronic and optical functionalities

Fully addressable nanoscale memory in both optical and electrical domains!

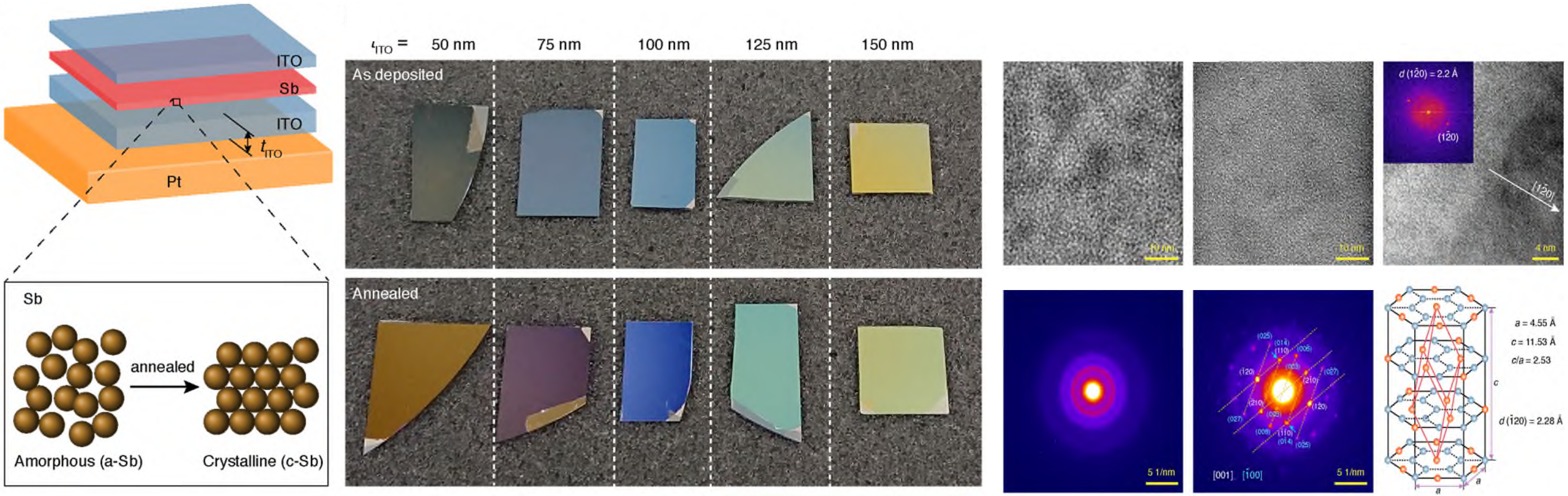






N. Farmakidis, N. Youngblood et al., *Science Advances* (2019)

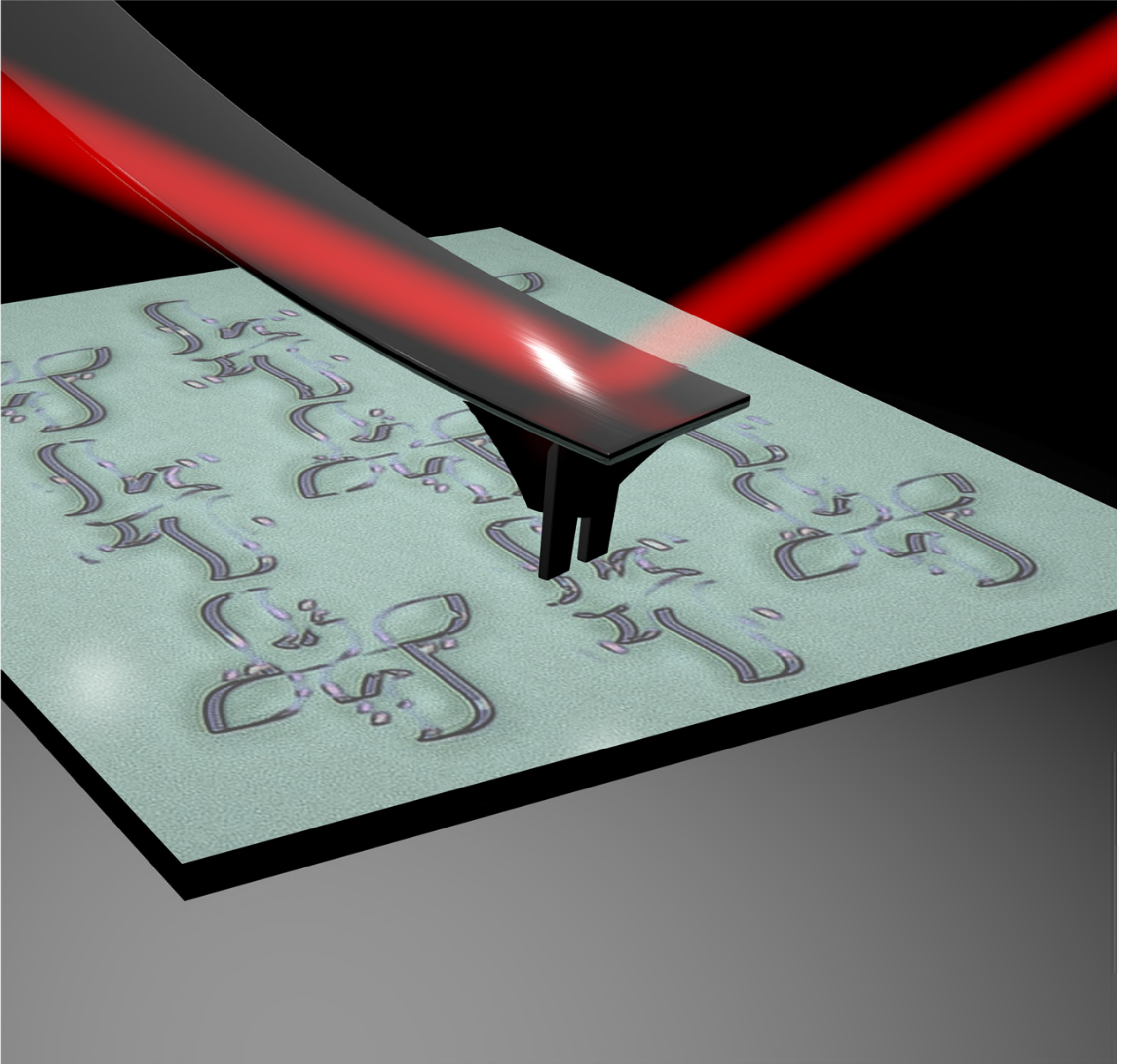
New Materials – What and How?



Cheng, Milne et al, Science Advances (2021)
DOI:10.1126/sciadv.abd7097

Tara Milne
DPhil Student

Zengguang Cheng
Former Postdoc now Assoc. Prof at Fudan



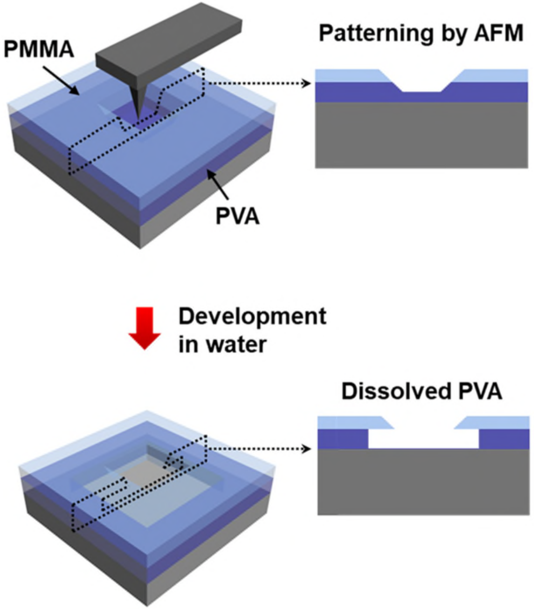
Nanomanufacturing

Nanomanufacturing is not sustainable

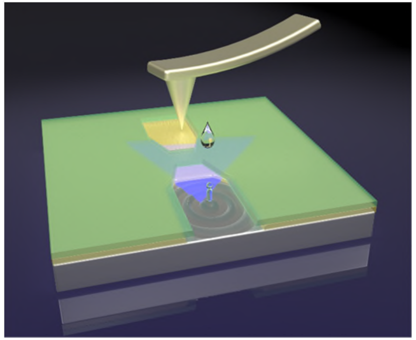
- The manufacturing of a typical 2g chip takes 1.6 kg of fossil fuel, 72 g of chemicals and 32 kg of water.
- Over 200 high-purity organic and inorganic chemicals are used for the manufacture of semiconductor devices.
- According to author Harvey Black of the *Environmental Health Perspectives Journal,* in San Jose, California "it costs $28 per ton to landfill waste compared with $147 a ton to recycle".

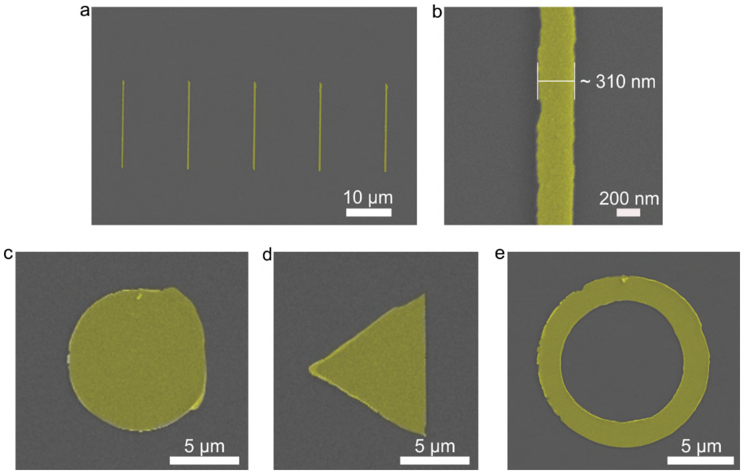
Sustainability in nanomanufacturing

Yu Shu (DPhil)



Yu Shu *et al. Nano Letters* 21, *(2021)*

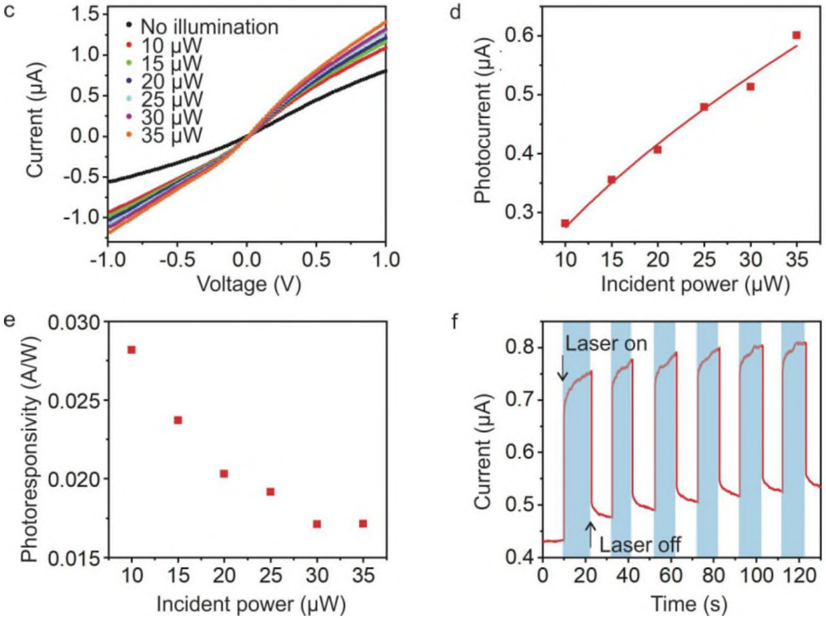


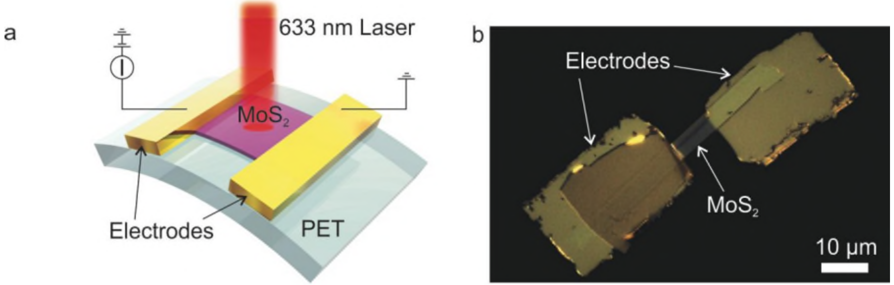


Flexible MoS_2 photodetector

Yu Shu (DPhil)

Photoresponse time improves to 42 ms owing to the water-based fabrication process.



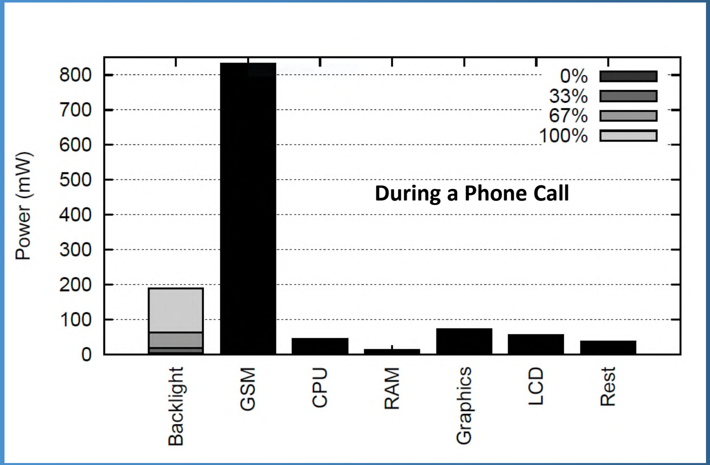


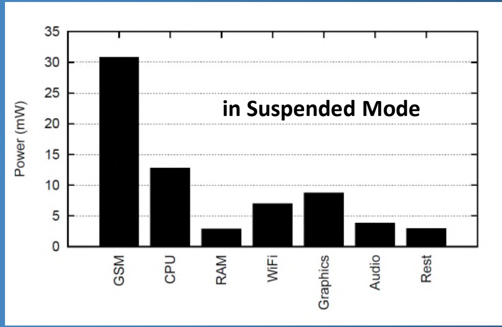
Yu Shu *et al. Nanoletters 21, (2021)*

Communication receivers

Battery is running low!

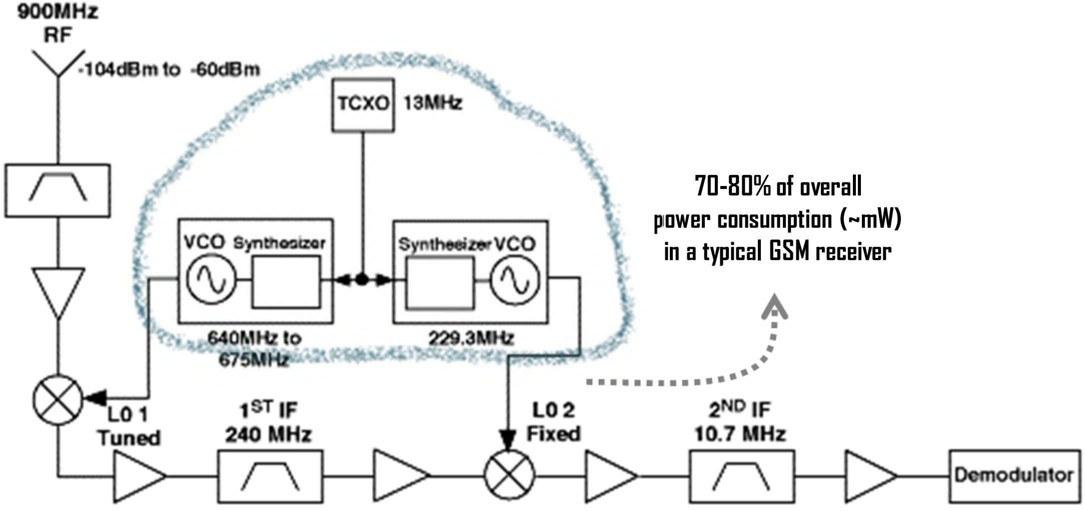
Average Power Consumption of a Smart Phone





Images: A. Carrol and G. Heiser, An Analysis of Power Consumption in a Smartphone, University of New South Wales, 2010.

Frequency synthesis



Ref: Analog Devices, https://www.analog.com/en/analog-dialogue/articles/pll-for-high-frequency-receivers-and-transmitters-1.html

PLL based:

- **PLL synthesizers** usually require > 100 mA (d.c.) from the voltage supply. → ~0.5 W

Traditional NEMS based:

- **Capacitive** tuning requires fast-settling & high-precision D/A converters.
  - e.g. AD7524 (8-bit, 0.3 μs settling, 30 mW) or LTC8043 (12-bit, 1 μs settling, 10 mW)
- **Electrothermal** tuning consumes ~3 mW just to tune the resonator (plus DACs).

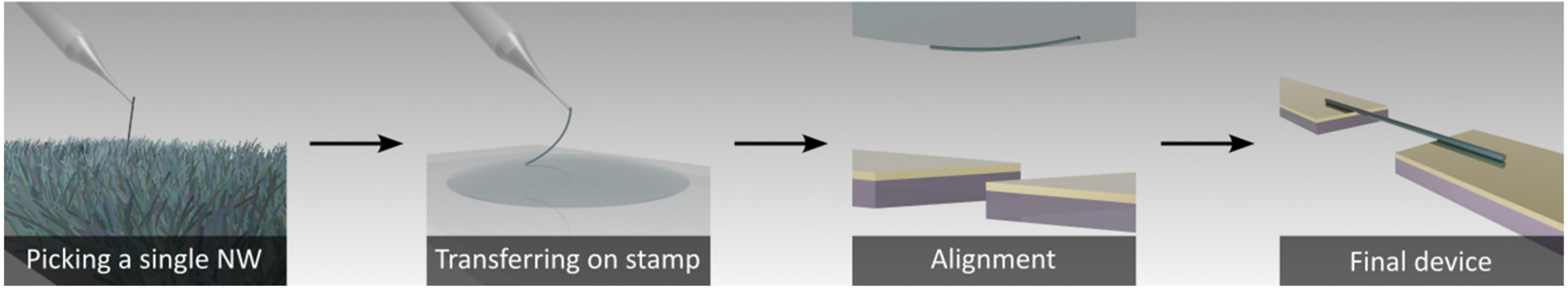
Phase-change NEMS based:

- **Phase-change** tuning does not require tuning power.
  - Even in a frequency-hopping system, with the fastest tuning speeds required (10 μs), the dynamic tuning power is < 6 μW.

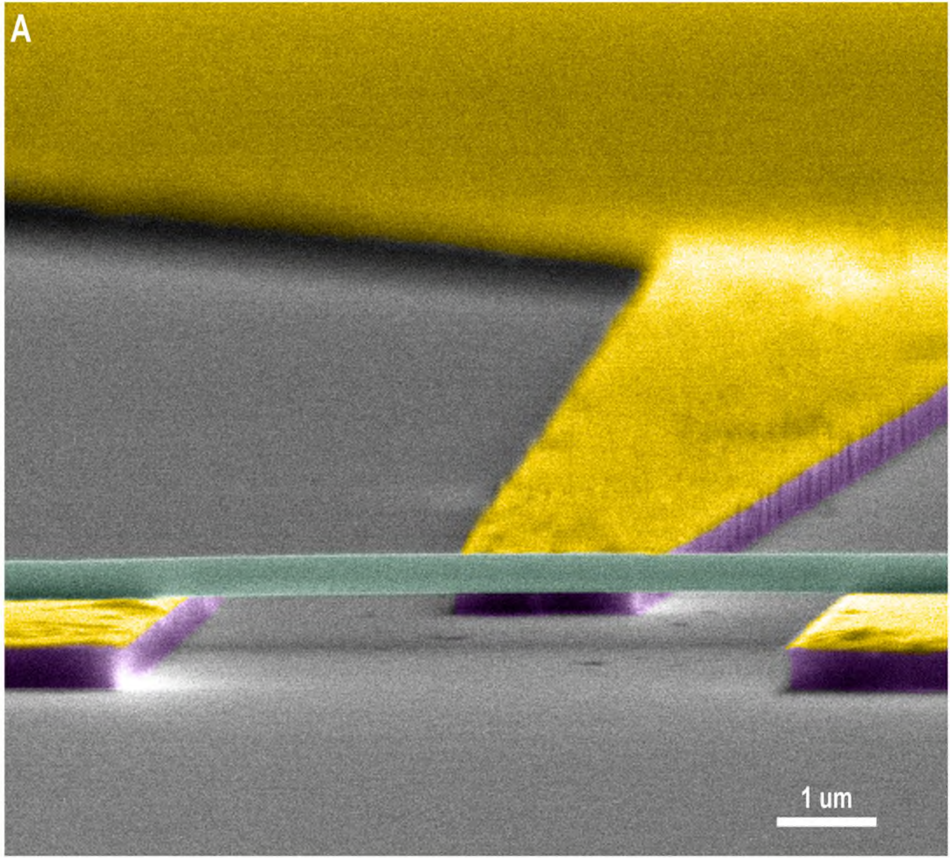
Thus, phase-change NEMS would be **100x more efficient** than traditional NEMS and **20,000x more efficient than commercial** PLL based synthesizers.

Pick-and-Place of Nanomaterials

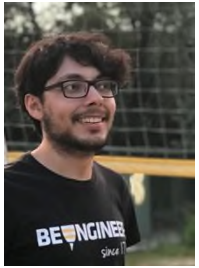
- Allows integration of exotic nanomaterials in real devices

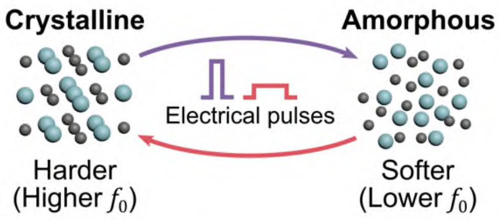


Phase-change nanowires



Utku Emre Ali
(DPhil student)

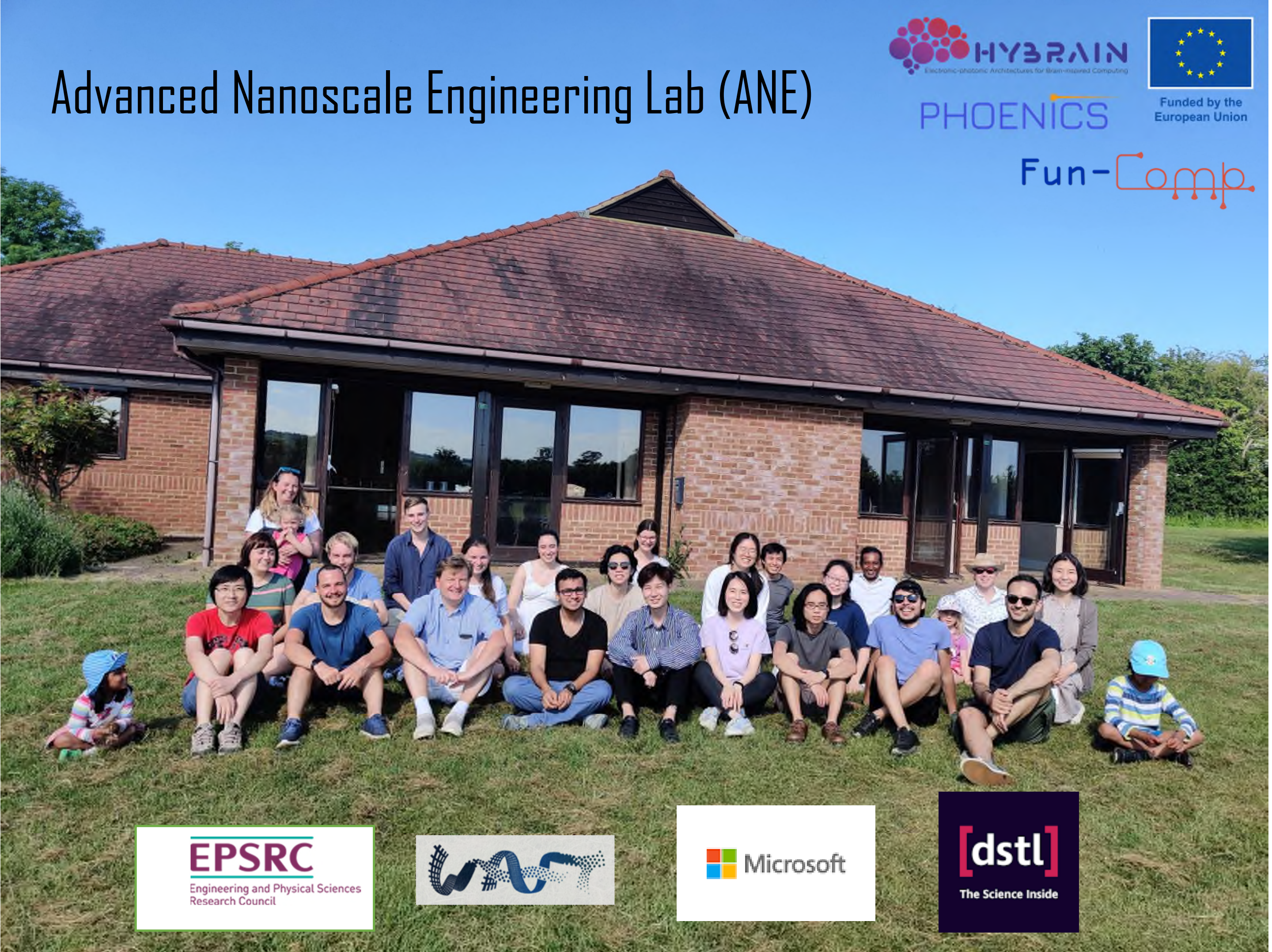




U. E. Ali et al., *Nature Communications* (2022)

Guglielmo Marconi’s telegram on 14 December 1930

Advanced Nanoscale Engineering Lab (ANE)



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