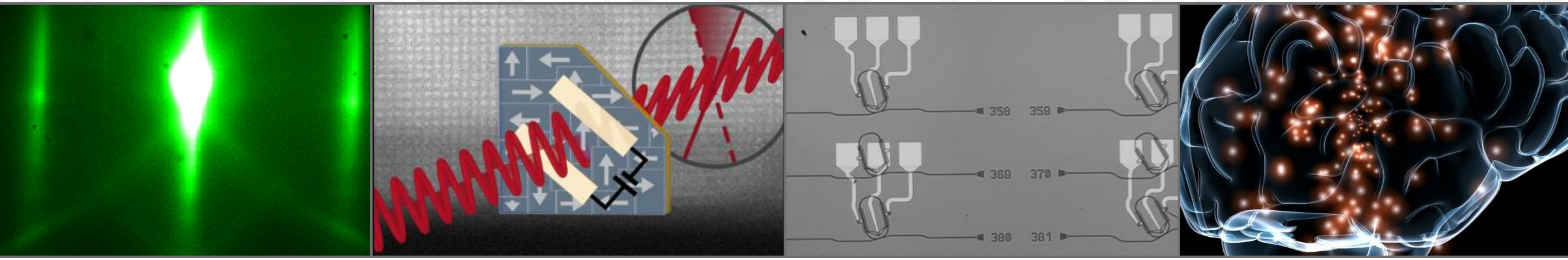
Novel 3D Technologies for the Transition to Cognitive Systems

Bert Jan Offrein



D43D'2017 WORKSHOP

Neuromorphic Devices and Systems Group

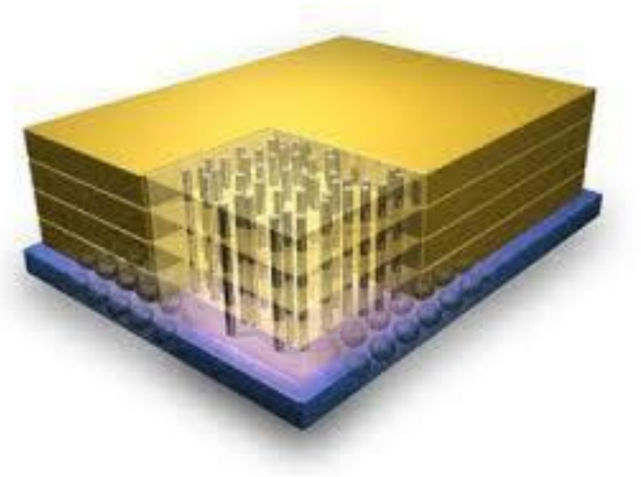
Outline

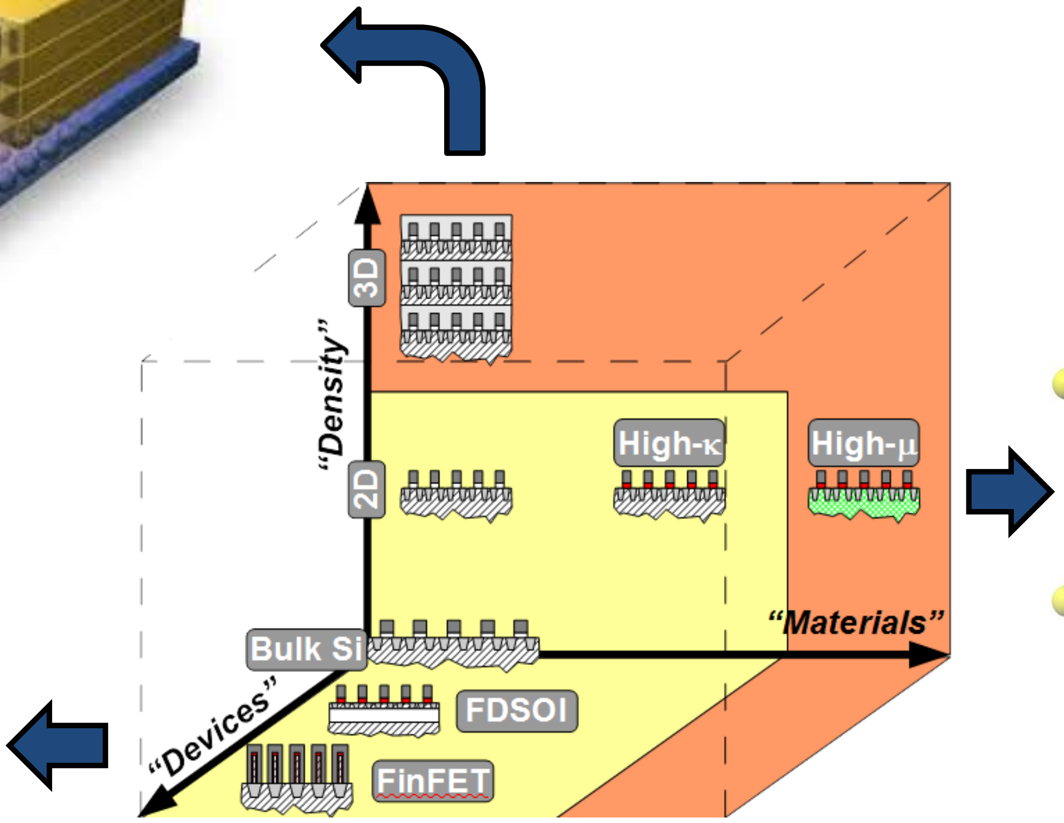
- Chip-level 3D Technologies
  - Introduction
  - 3DM for enhanced CMOS performance

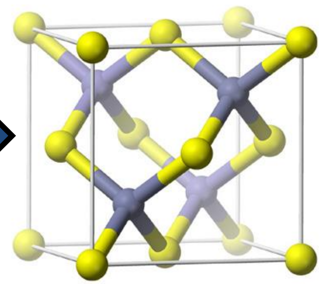
- Enhanced CMOS functionality
  - CMOS Silicon Photonics
    - Monolithic laser integration
  - Novel hardware for Neural Networks
    - Resistive Crossbar Arrays
    - Photonic Synaptic Processor

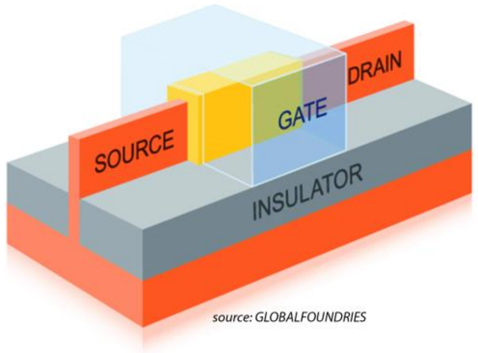
- Conclusions

What would be the ultimate CMOS Technology?



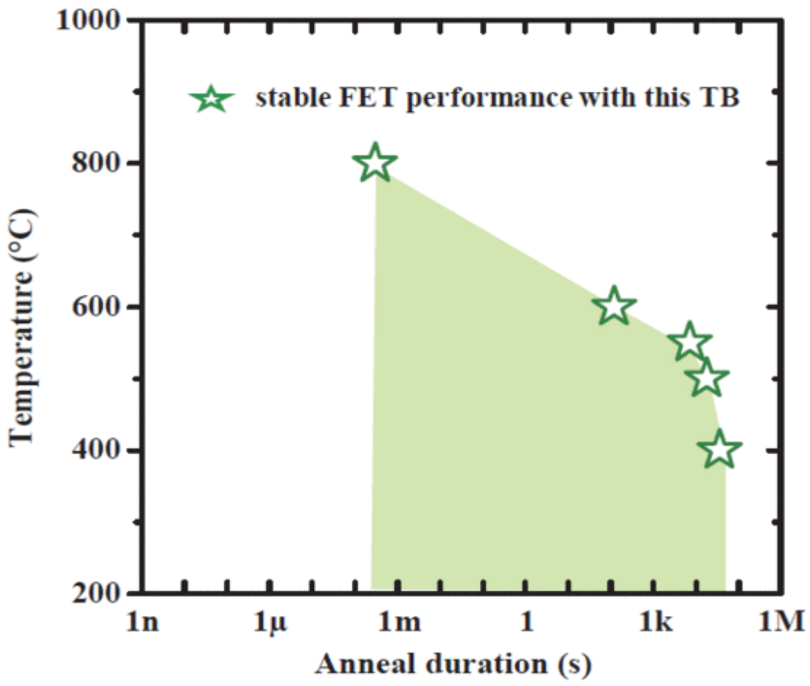






Challenge for 3D Monolithic (3DM)

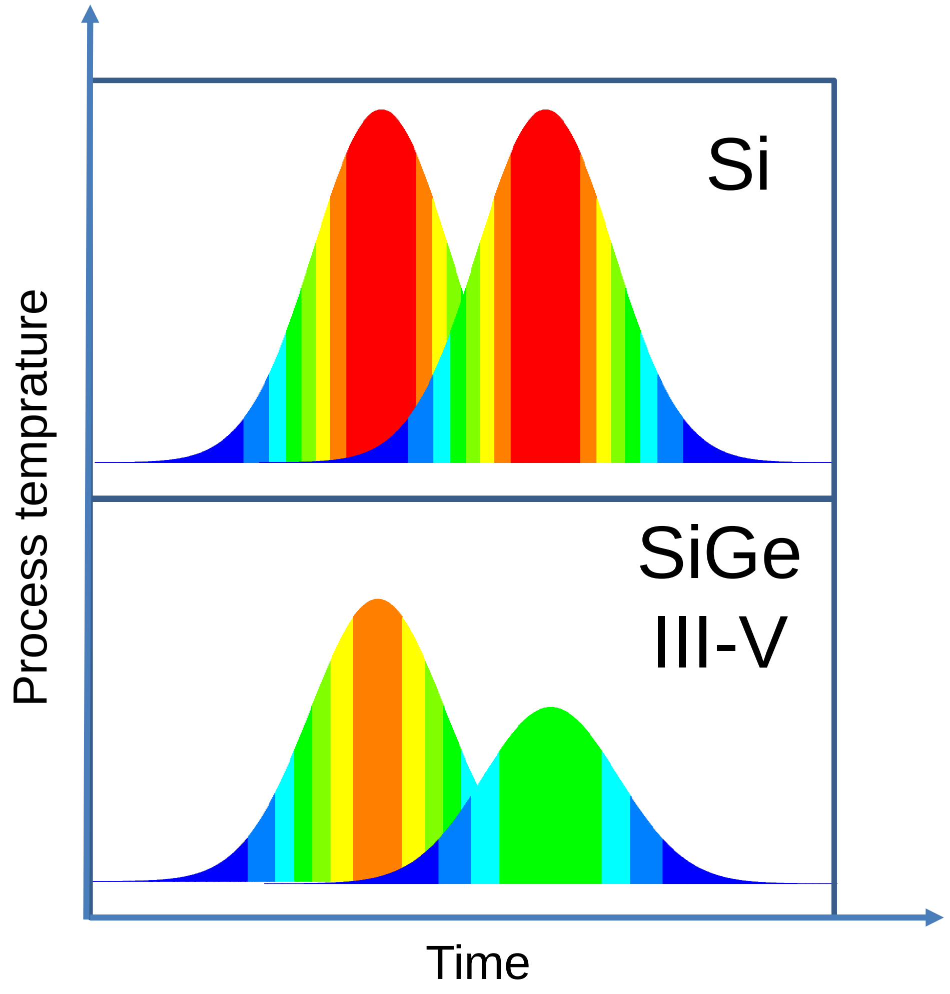
Thermal budget stability of bottom FETs

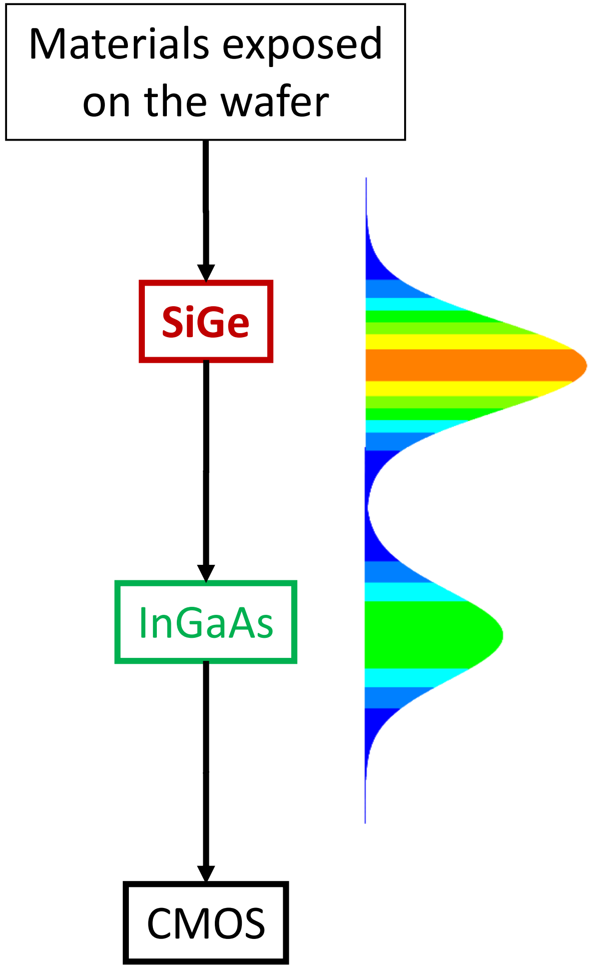


- 500°C for 5 hours
- 550°C for 2 hours
- 600°C for 2 minutes

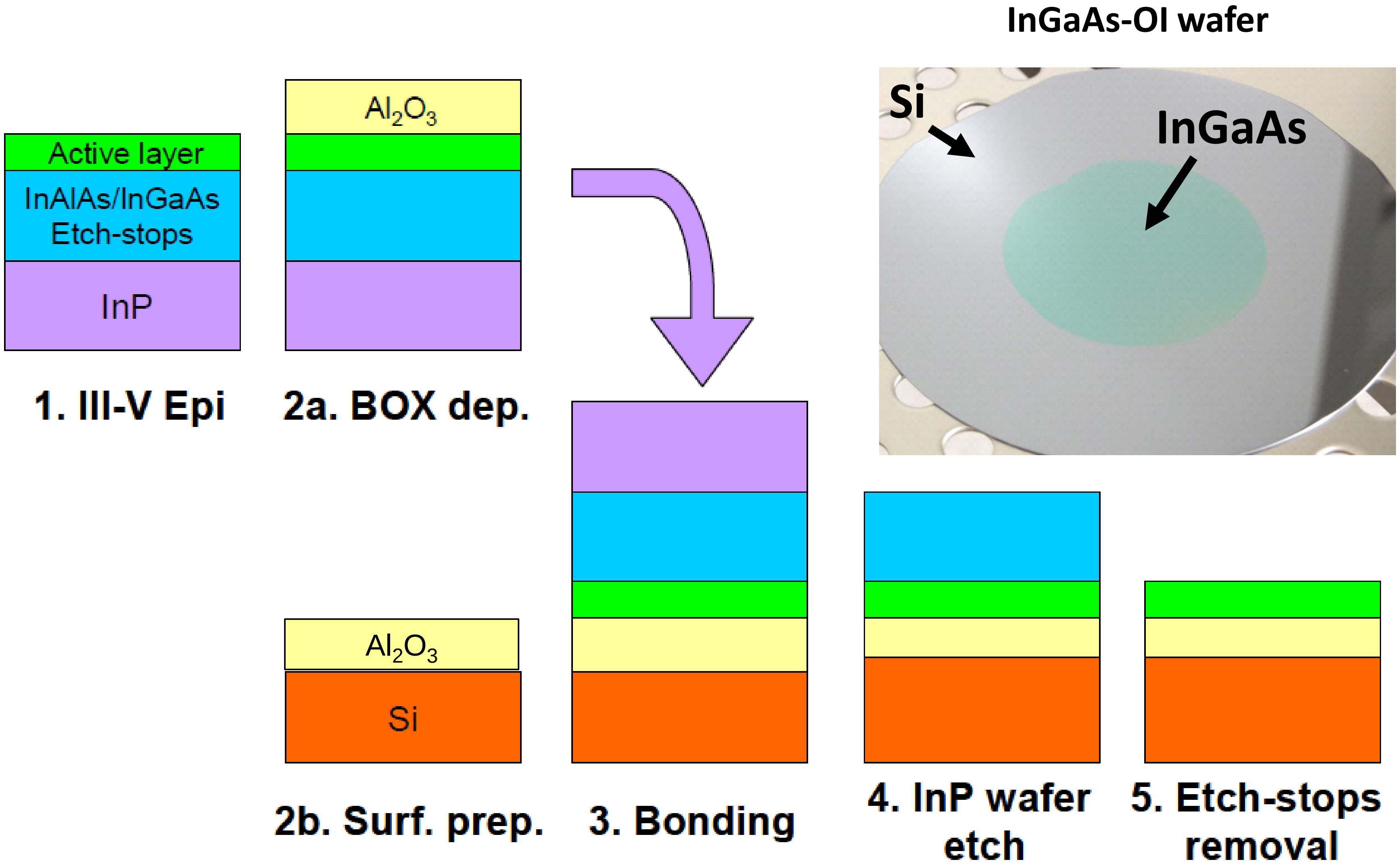
P. Batude, *et al.*, VLSI 2015

Temperature flow – bottom to top



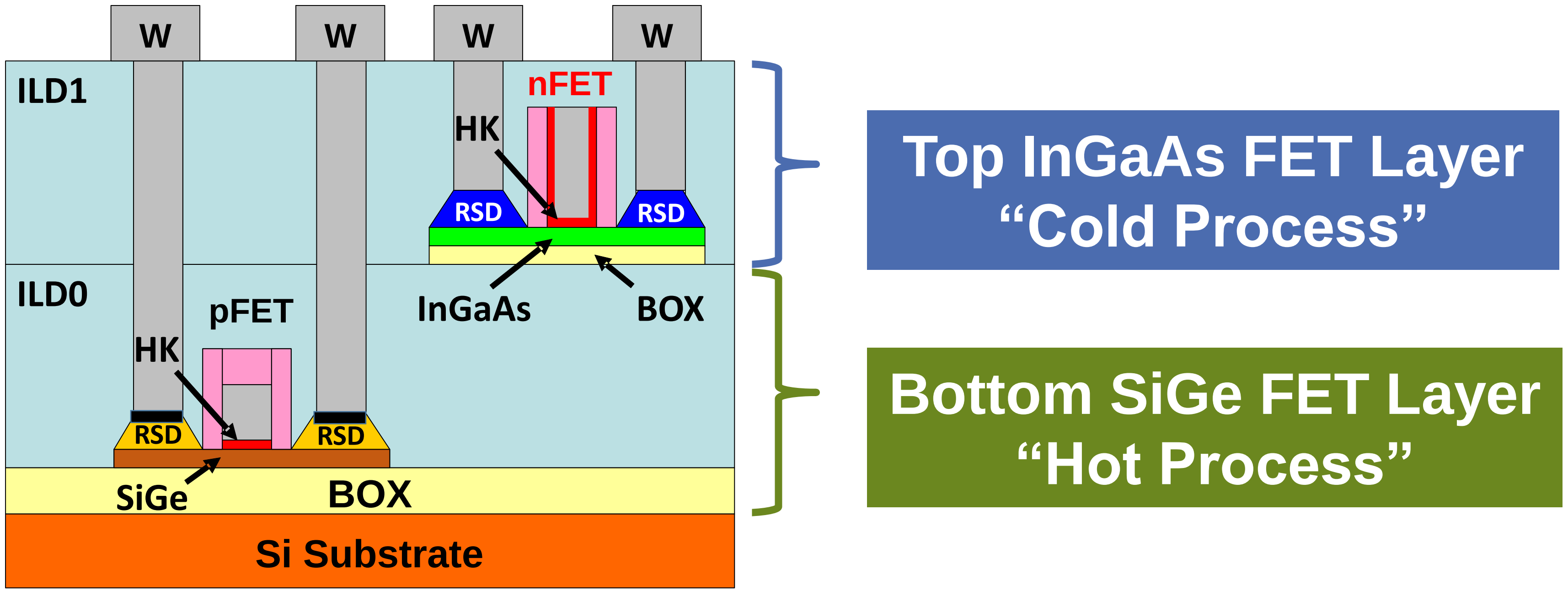


Direct Wafer Bonding



[1] M. Yokohama, et al., VLSI 2010, [2] L. Czornomaz, *et al.*, ESSDERC 2013

InGaAs-on-SiGe 3DM Integration



Combined benefits of:

- 3DM integration
- High-mobility channel materials in both layers

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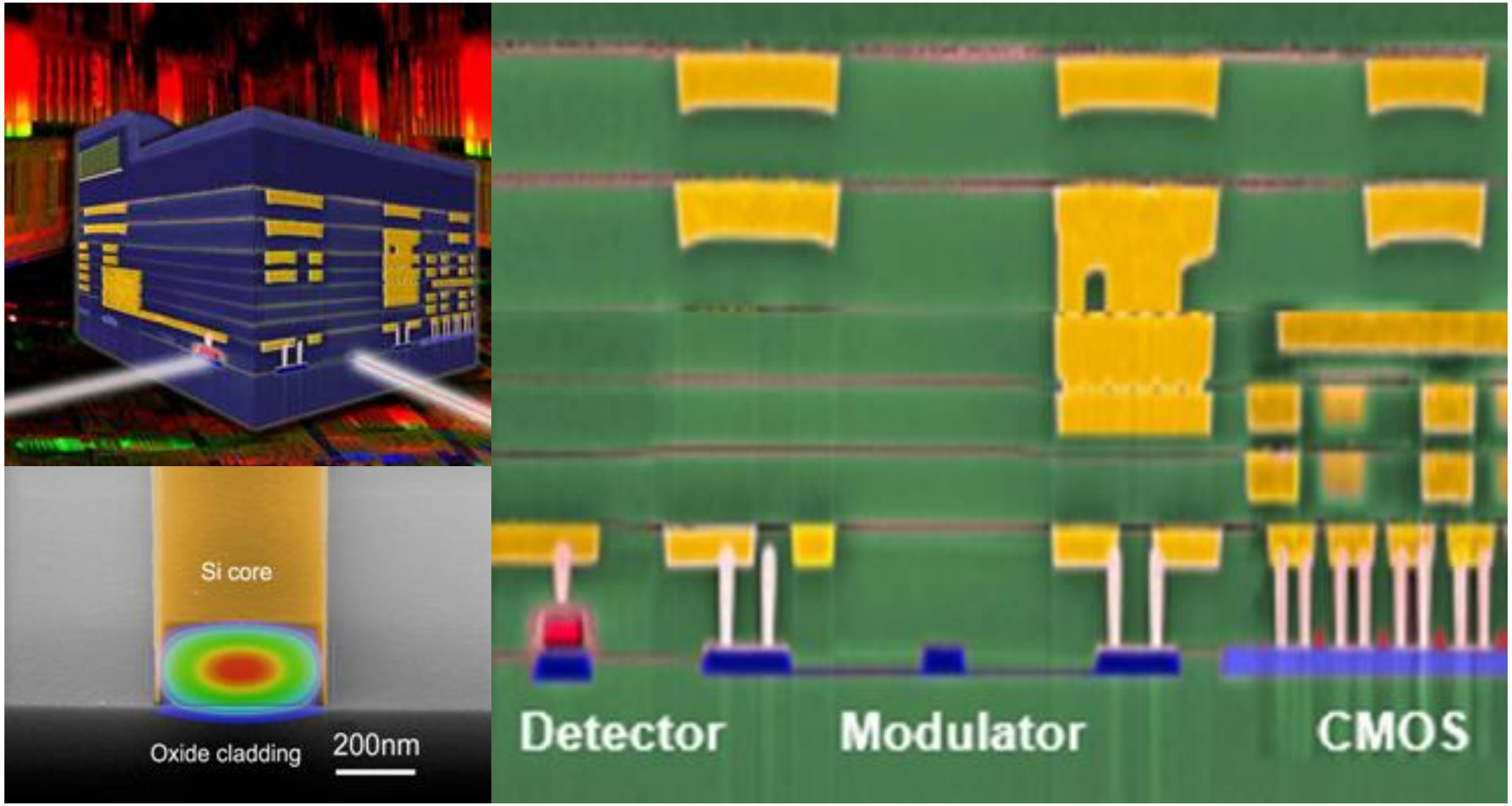
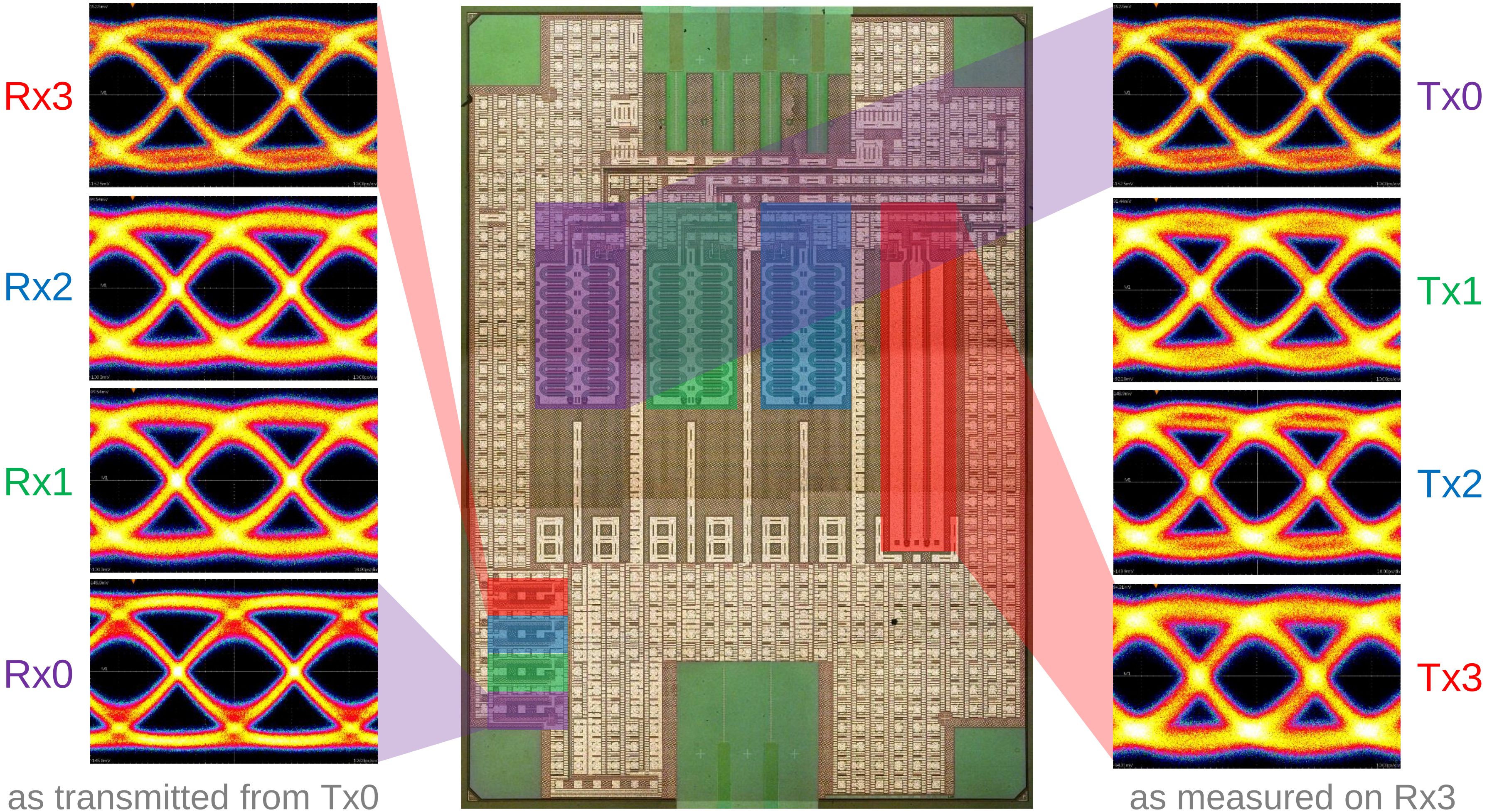
CMOS Silicon photonics



Integrate electrical **& optical** functions in silicon

4 λ x 25 Gb/s optical transceiver demonstration



as transmitted from Tx0

as measured on Rx3

Demonstration of a flip chip mounted 100G transceiver with four wavelength multiplexing at 25 G each.

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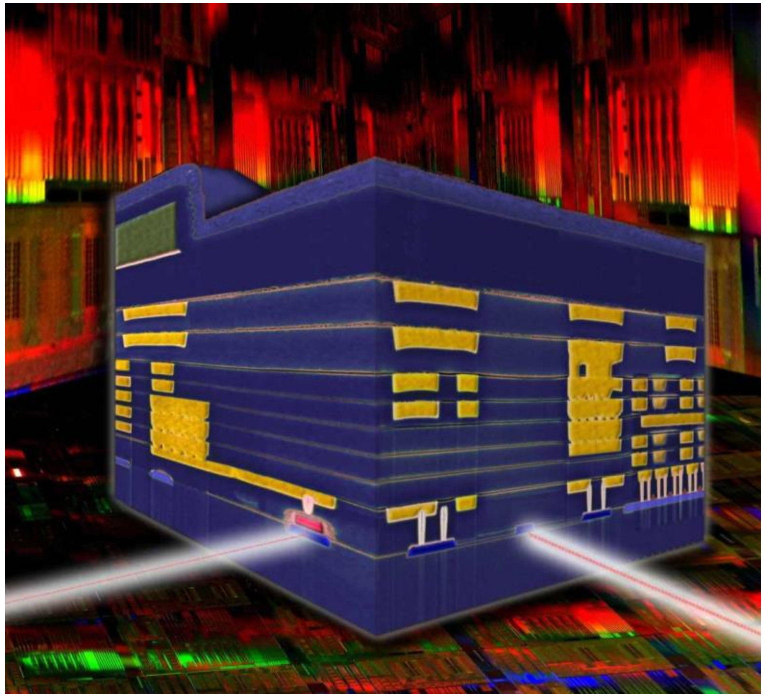
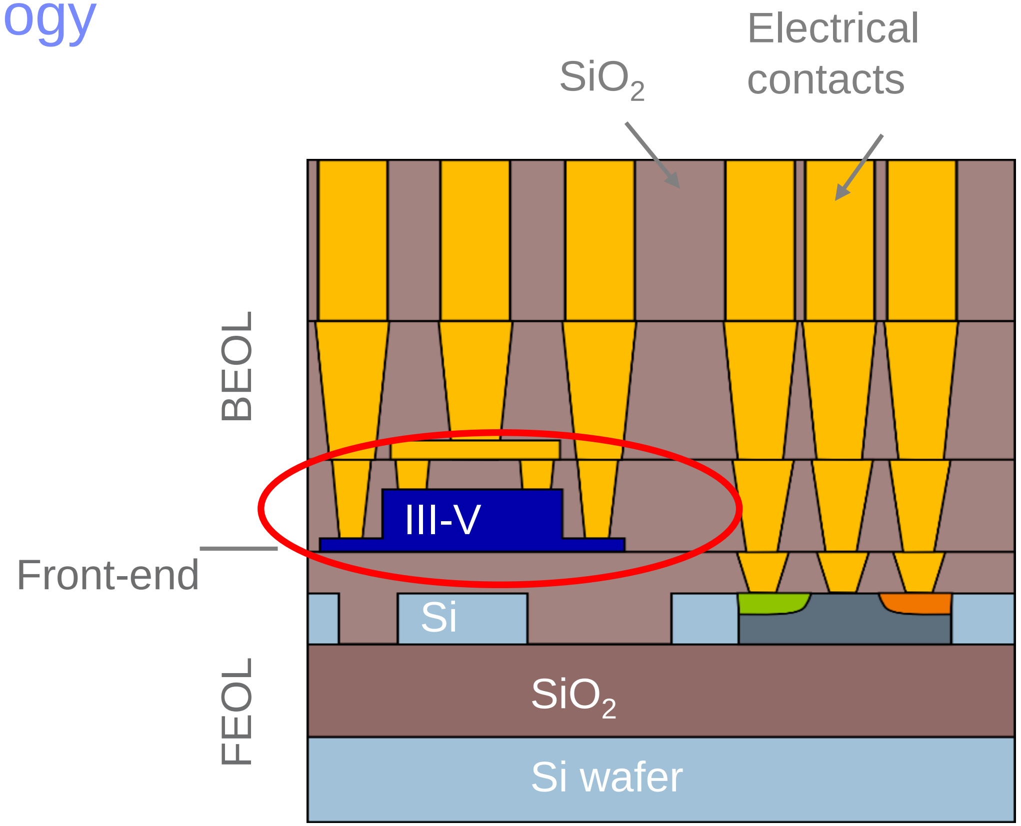
CMOS Embedded III-V on silicon technology



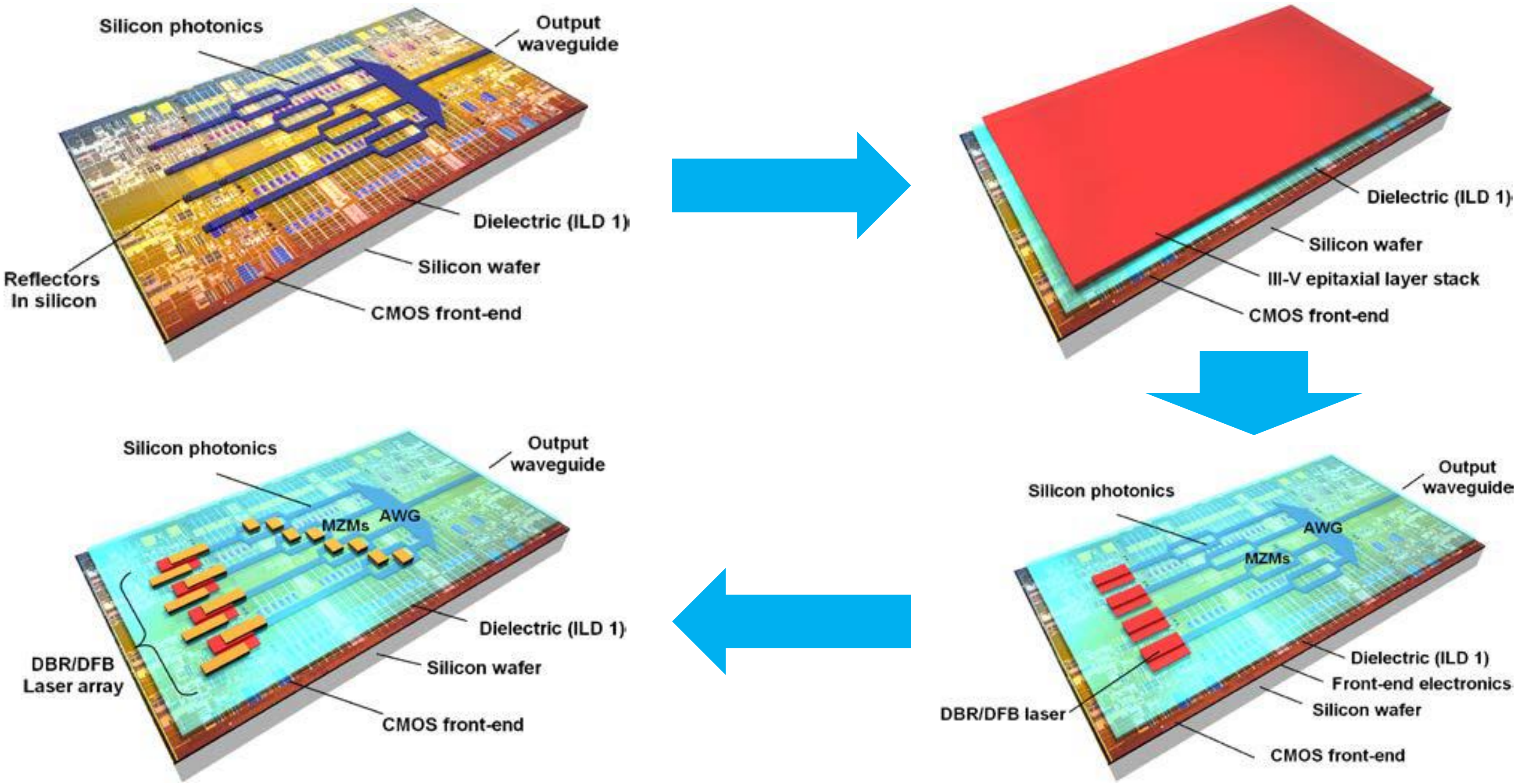
CMOS Si Photonics



… + III-V functionality

- Overcome discrete laser and assembly cost
- New functions, directly combining electronics, passive and active photonics

H2020 EU project DIMENSION



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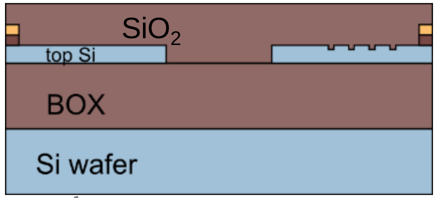
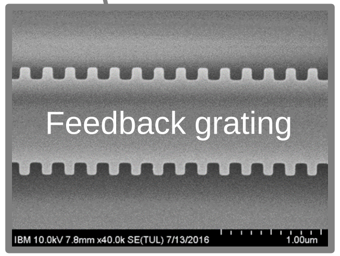
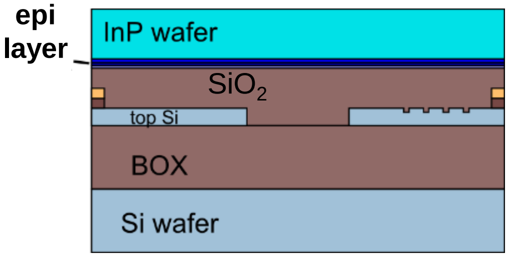
Processing scheme

- 5 InAlGaAs quantum wells (MOCVD)

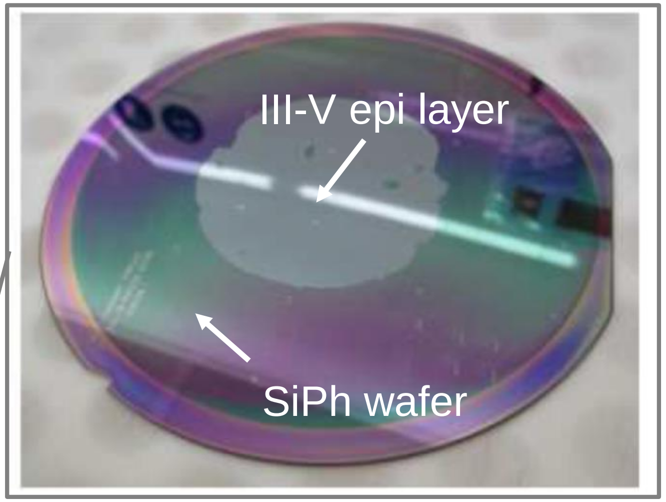


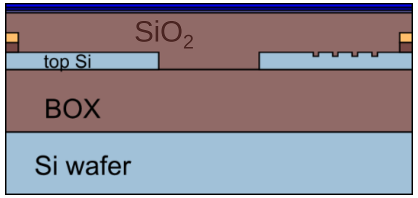
SiPh wafer



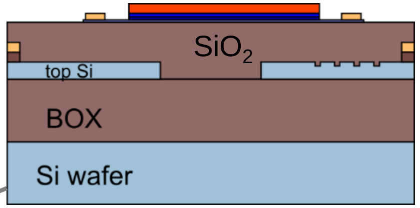


Wafer bonding

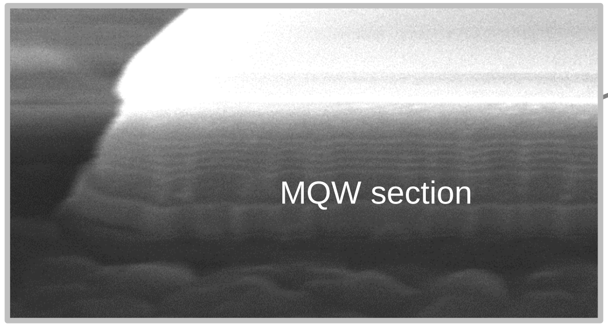


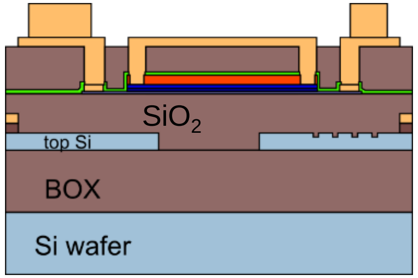


Substrate removal



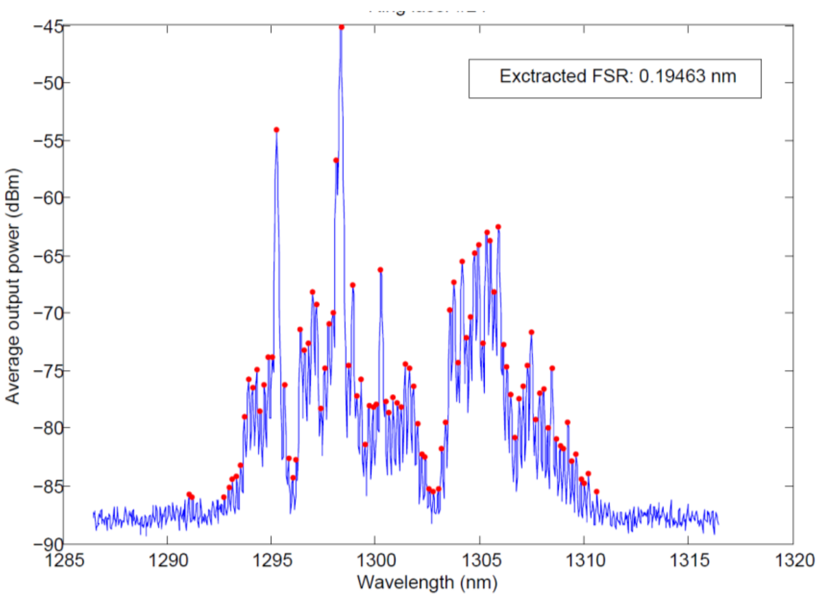
III-V structuring





Metallization

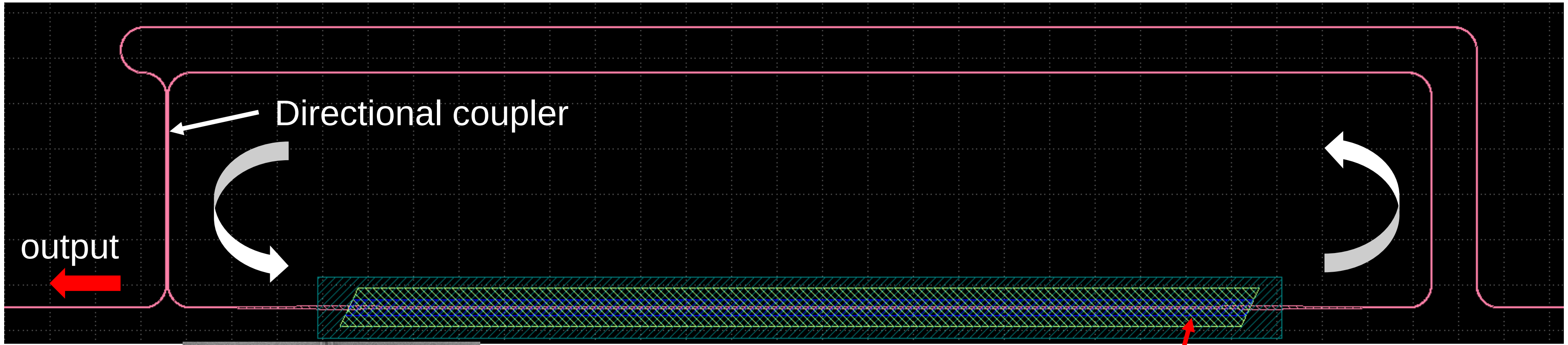
Optically pumped ring laser

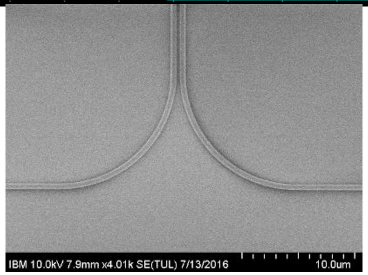


Measured FSR: 0.194 nm

Estimated FSR from ring: 0.203 nm
Estimated FSR from III-V: 0.266 nm

➢ <u>Lasing with feedback from silicon photonics</u>





Gain section

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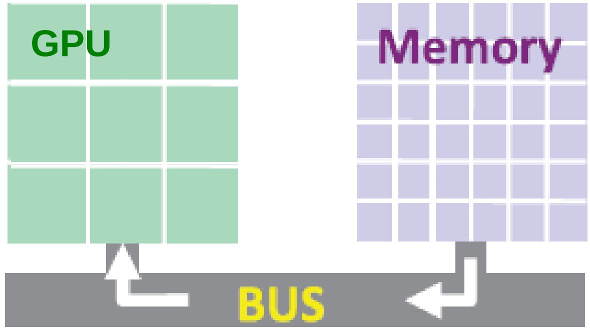
    - Photonic Synaptic Processor

- **Conclusions**

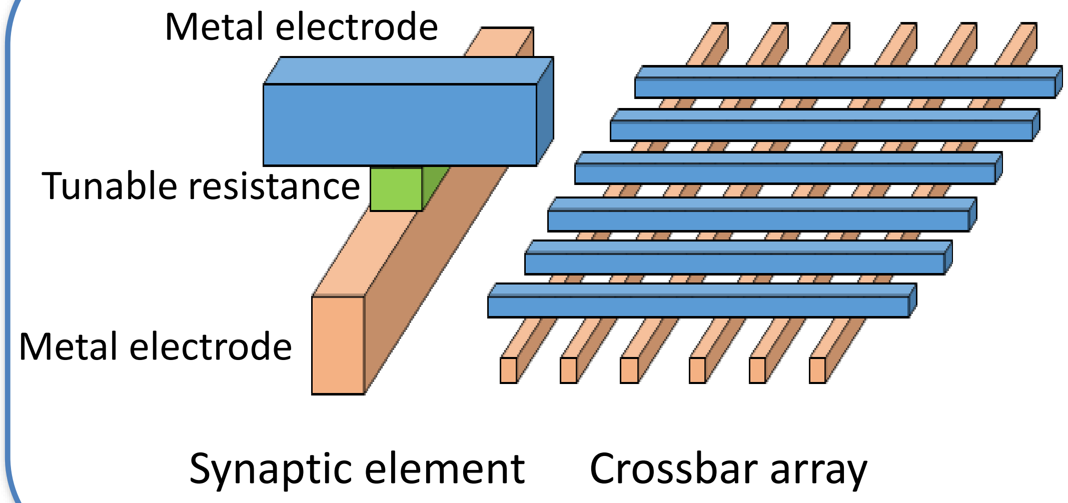
Neuromorphic hardware for big data analytics



- **Today’s status on deep neural networks**
  - Software based on Von Neumann systems
  - Training is the bottleneck – HPC required
  - GPU accelerators – processing memory bottleneck

- **Fast and efficient neural network data processing**

1. Analog approximate signal processing
2. Tight integration of processing and memory
   – 10’000x improvement using crossbar arrays



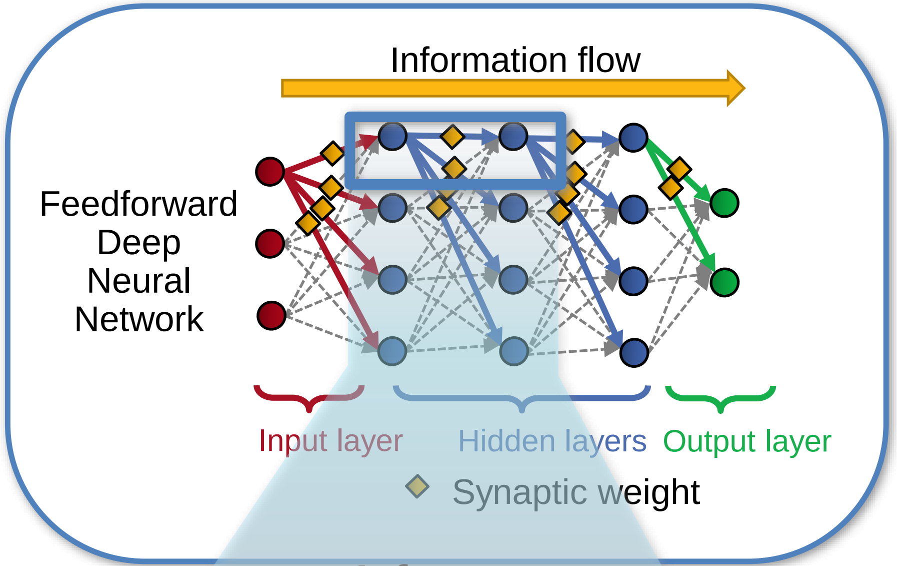
- **Hardware implementations**
  – *Electrical* crossbar arrays
  – *Photonic* crossbar arrays

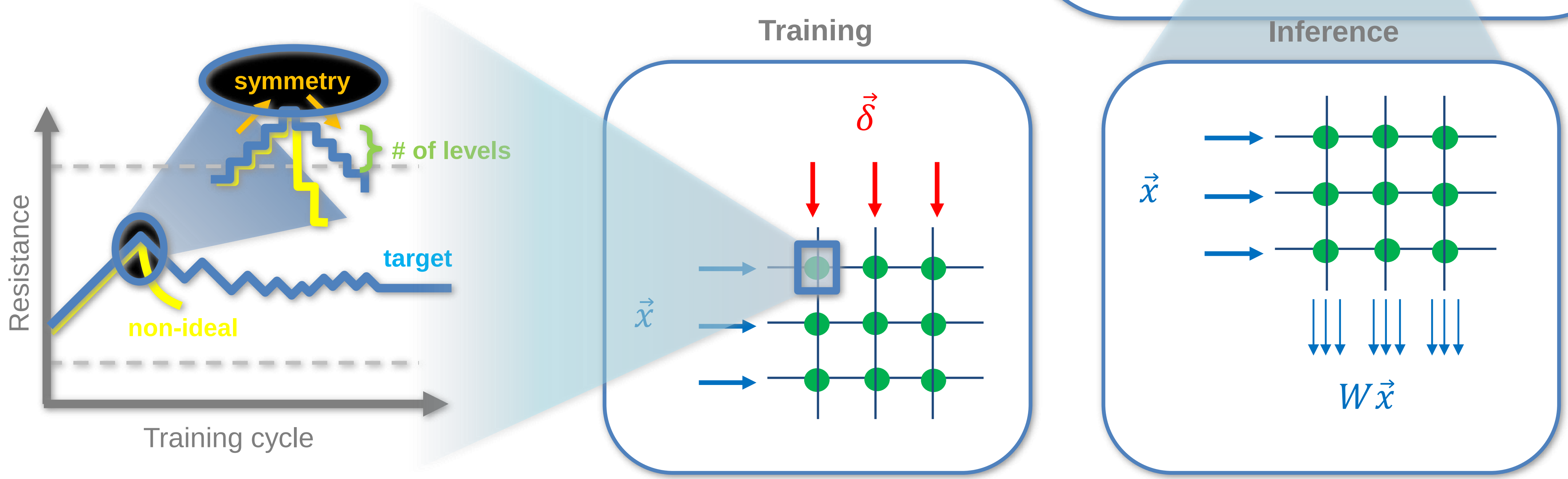
Accelerated learning: Analog crossbar arrays

Update weight proportional to signals on crossbar row and column

- Increase and decrease of weight
- Symmetric behavior for positive and negative updates
- High weight resolution (~1000 levels) required

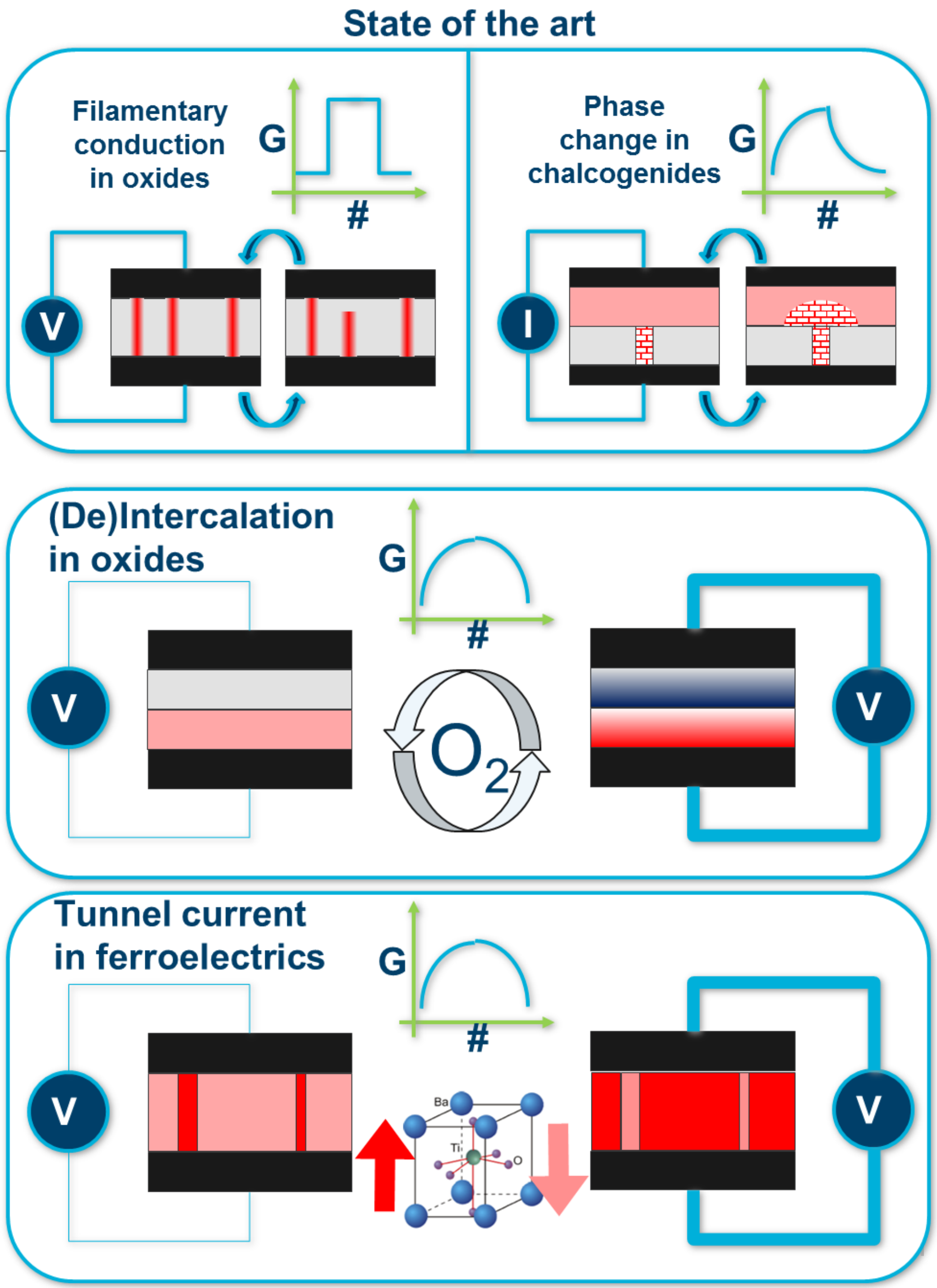
Physical challenge: Identify material systems fulfilling those requirements





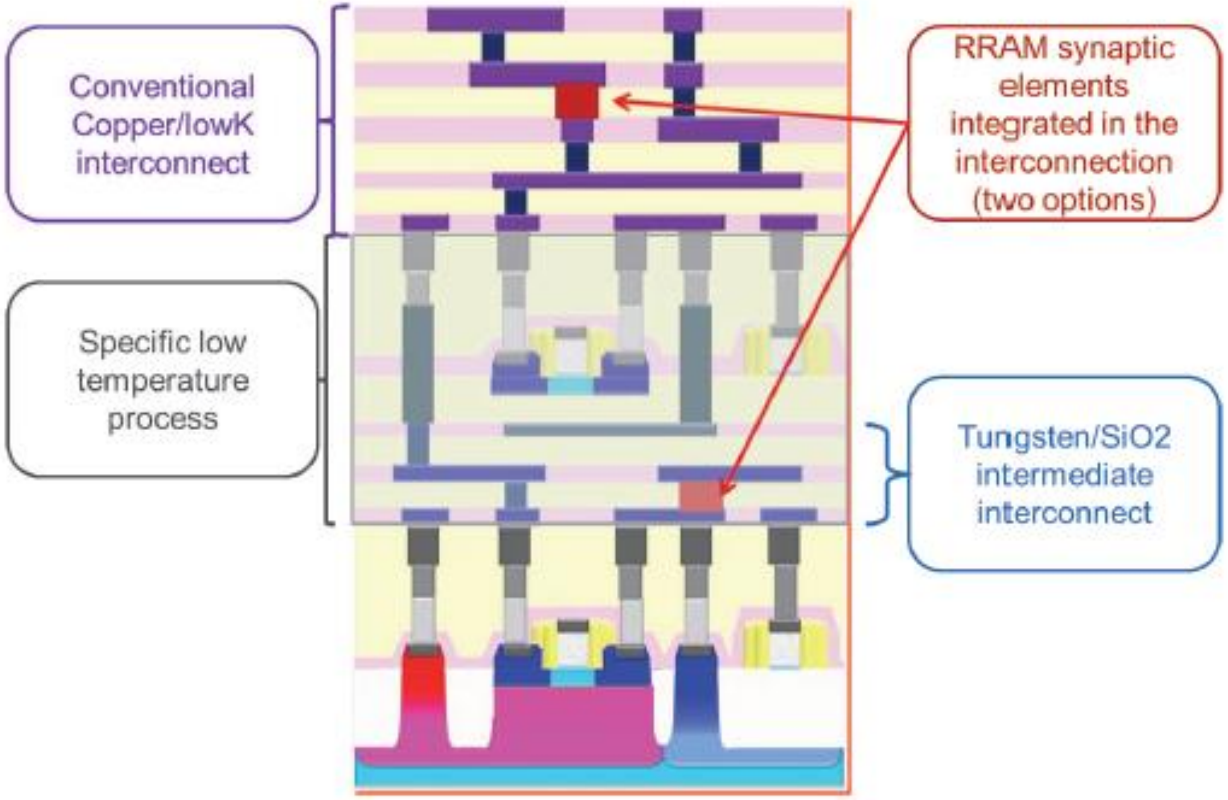
Materials for Resistive Crossbar Arrays

- **Synaptic functionality**
  - Multiply: Ohm's law; Accumulate: Kirchhoff's law
  - Weight update: *Tunable resistance*
- **Tunable resistance**
  - State of the art: filamentary oxides, PCM
    - Not analog enough or not symmetric enough
  - Search for *uniform* effects leading to ΔG with the appropriate resolution and symmetry
    - Electrochemical (de)intercalation
    - Control domain structure in ferroelectrics

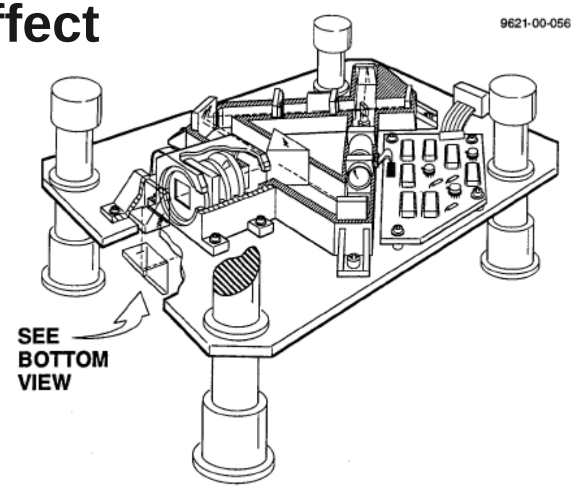


EU project NEURAM

- **Novel 3DM technology for neural networks**



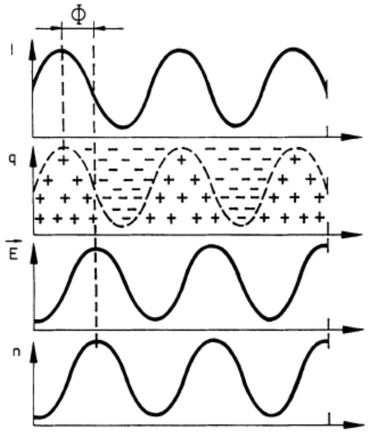
Photonic crossbar unit

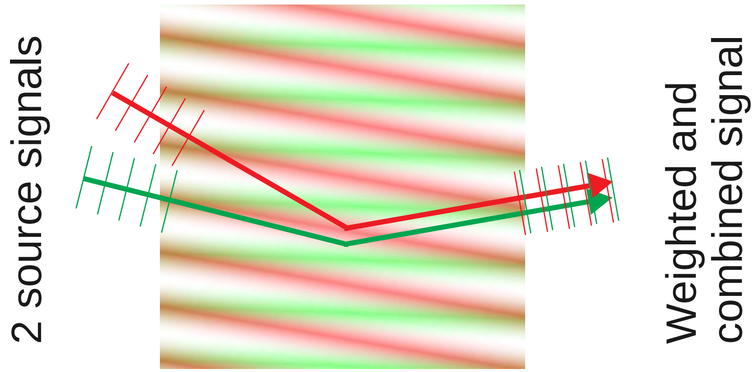


- **Alternative crossbar physical principle leveraging the photorefractive effect**
  - Demonstrated in 3D free space photonic neural networks in the 90s
    - i.e. Hughes Research Laboratories
  - New developments we can leverage
    - *Integrated* optic technology
    - Co-integration of new materials

- **Non-volatile weights applying the photorefractive effect**
    - Grating writing by interference of optical plane waves in an electro-optic material

      Strength proportional to product of the amplitudes of the writing beams
    - Written grating acts as the synaptic interface between plane optical waves



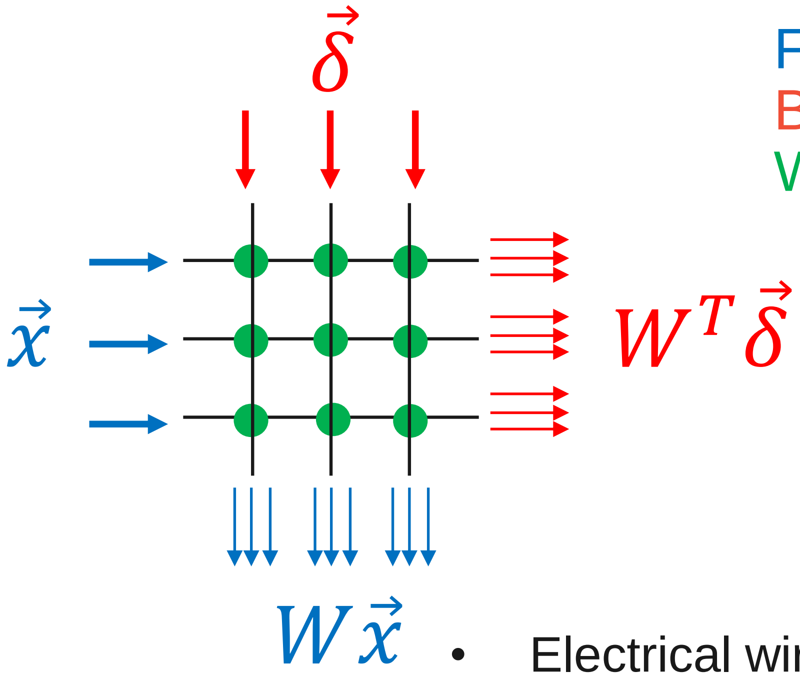


Photonic crossbar unit - operating principle

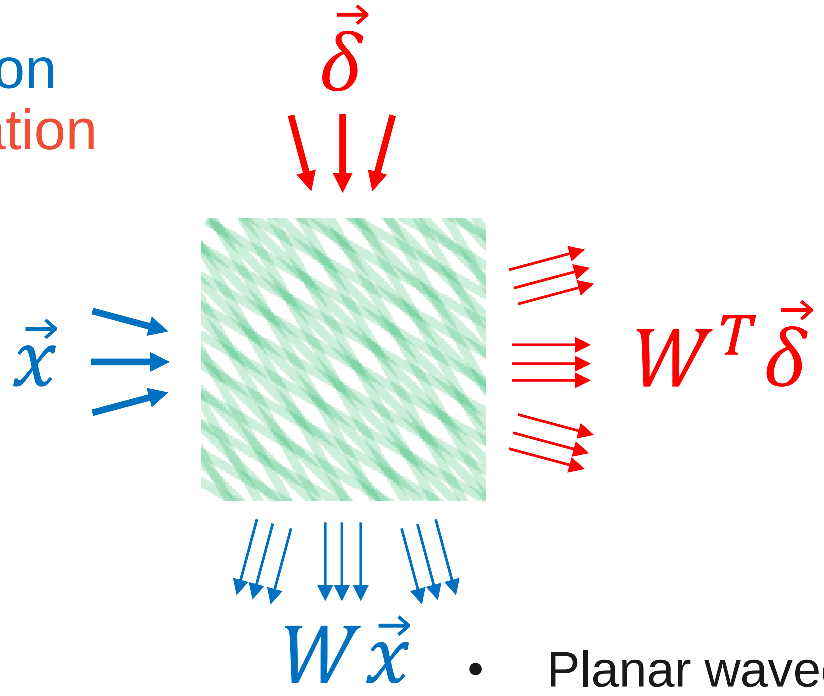
Electrical crossbar

Photonic crossbar

Forward propagation
Backward propagation
Weights



- Electrical wires
- Local weights
- Resistance tuning



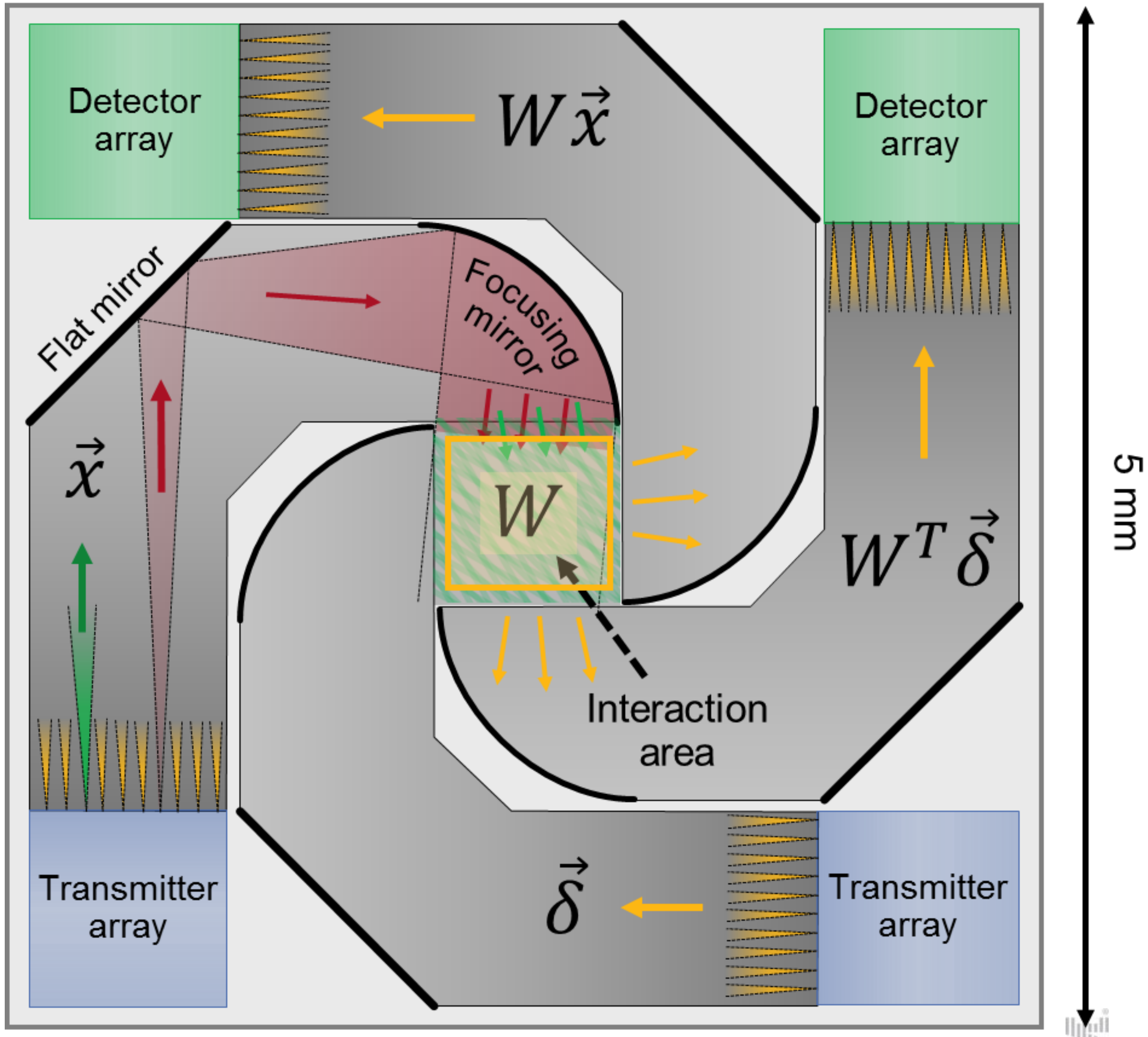
- Planar waveguiding
- Distributed weights
- Refractive index tuning

Writable photorefractive gratings provide the same functionality as the tunable resistive elements in a crossbar unit

Photonic crossbar unit - subsystem layout

Design study: 200 x 200 processing unit

- Weighting elements
  - Thin planar photorefractive slab on SOI, 1mm x 1mm
  - BTO or GaAs
- 200 Pre-synaptic electrical input signals
  - Optical power control through silicon photonic eo modulators
  - Plane optical waves under different angles in Si slab layer
- 200 Post-synaptic electrical output signals
  - Diffracted plane wave outputs are focused by Si mirror
  - Converted to electrical signals by a Si photonic detector array
- Weight adjustment
  - Photorefractive index modulation through interference pattern originating from the two transmitter arrays
- Scalability
  - A 200 x 200 processing unit fits in 5mm x 5mm
  - Theoretical capacity of interaction area is 2000 x 2000
  - Linear width and height scaling with # channels



Conclusions

- **CMOS technology performance enhancement**
- **3D Monolithic integration using III-V Materials**
  - Technology established

- **Enhanced silicon photonics**
  - Monolithically integrated lasers

- **Novel hardware for neural networks**
  - Co-integrated analog processing and memory
  - Electrical and Optical implementations of the synaptic processing unit

Acknowledgements

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