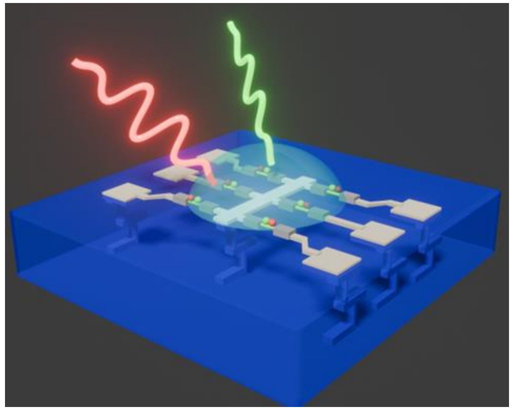
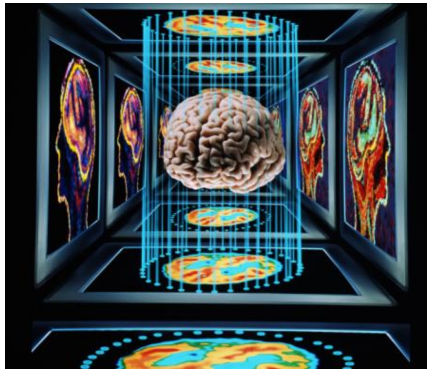
Photonic Sensing, Processing, and Computing





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Project organization chart (from the proposal)

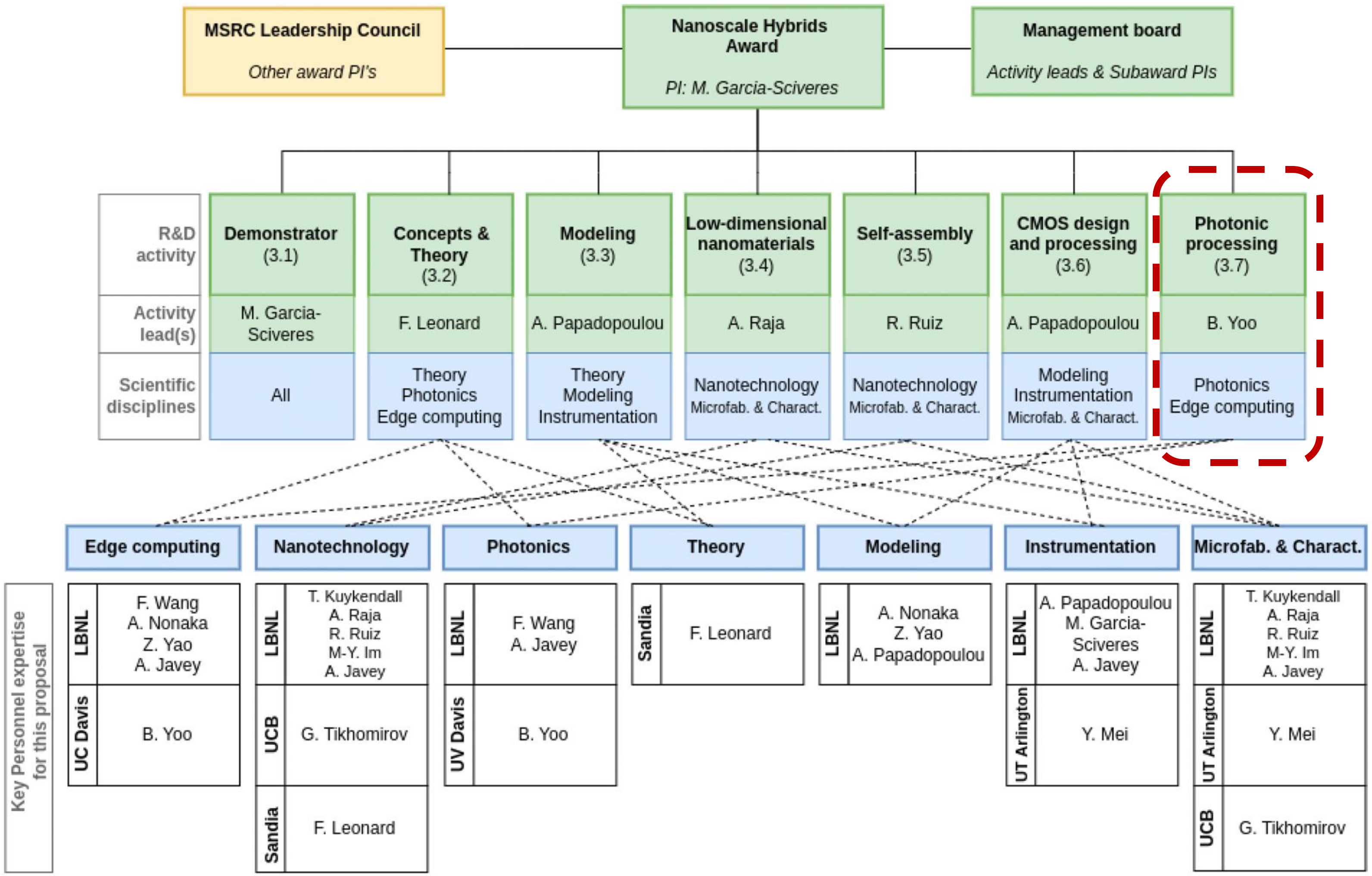
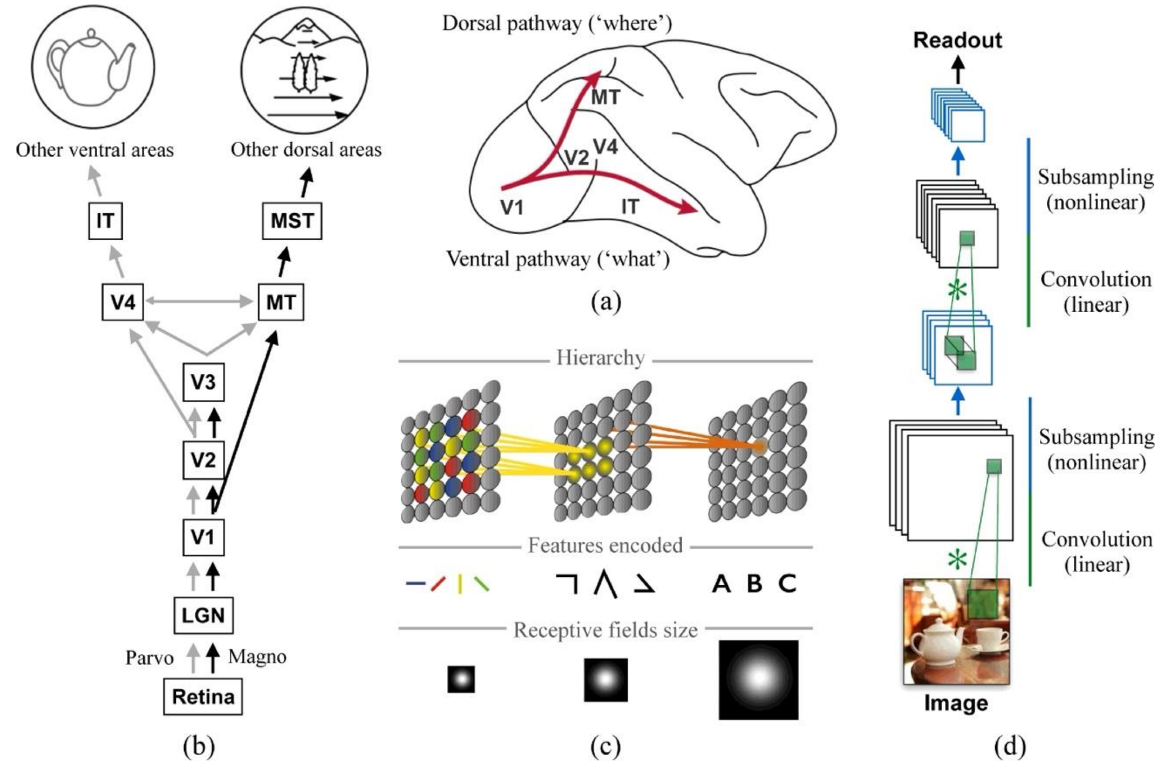
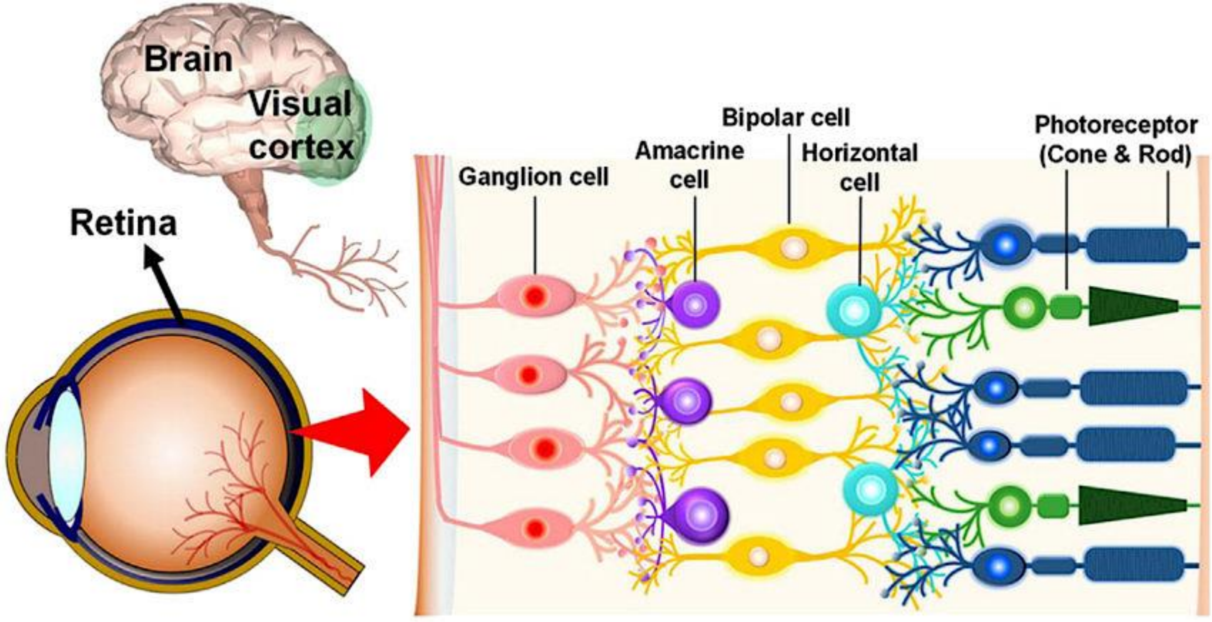


Figure 16: Project organization chart. The management structure is shown in green while the interconnection between activities through scientific disciplines is shown in blue.

Example of Photonic Sensing, Processing, and Computing at Nanoscale



Medathati, et al,. *Computer Vision and Image Understanding*, 2016



From W. Chen, et al, *iScience*, 2022

Photonic Sensing, Processing, and Computing with 10^5 : 1 Feature Extraction

Imaging with Intelligence
Sensor Fusion integrated with Neuromorphic Computing

DARPA Hi-MEMS [Hybrid Insect Micro-Electro-Mechanical Systems]

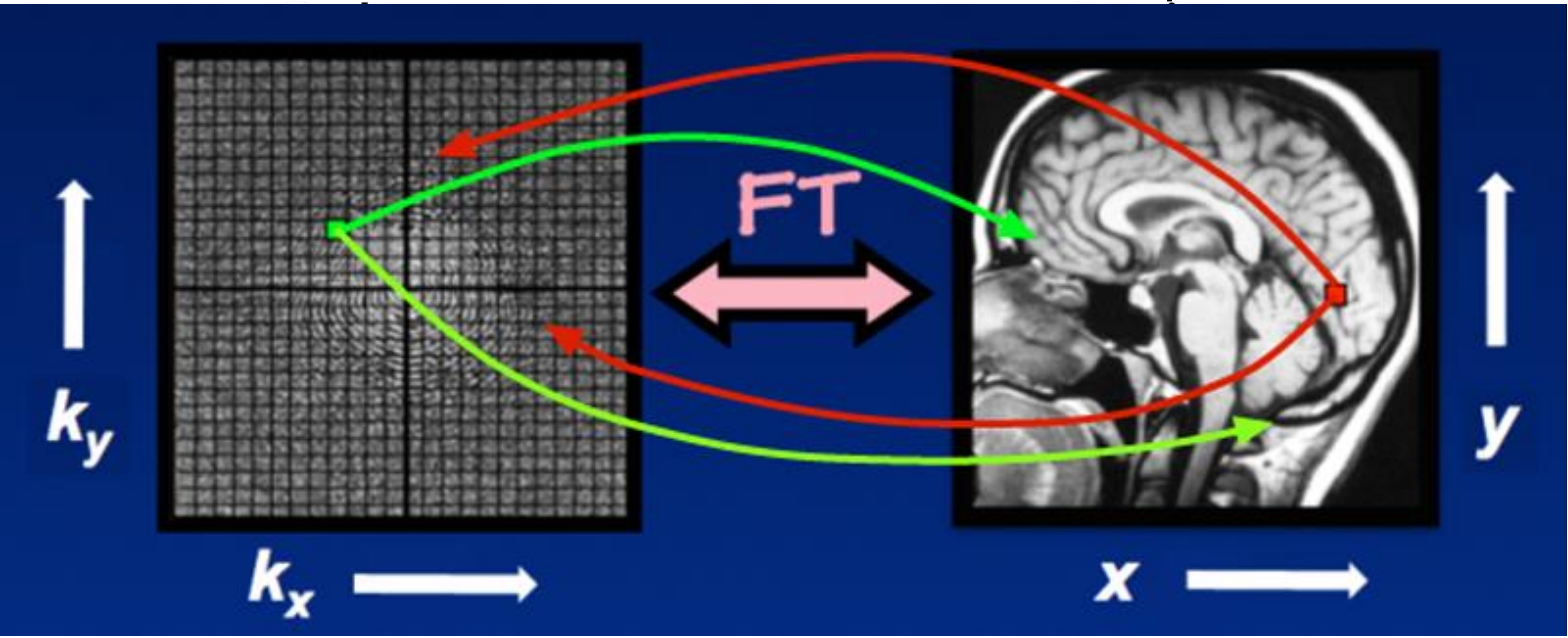
OODA loop (observe, orient, decide, act)

DARPA Micro-Brain

[Image courtesy of BuiltIn]

Real Space & Fourier Space Computational Imaging

Fourier Space　　　　Real Space



Project activities and milestones (from the proposal)

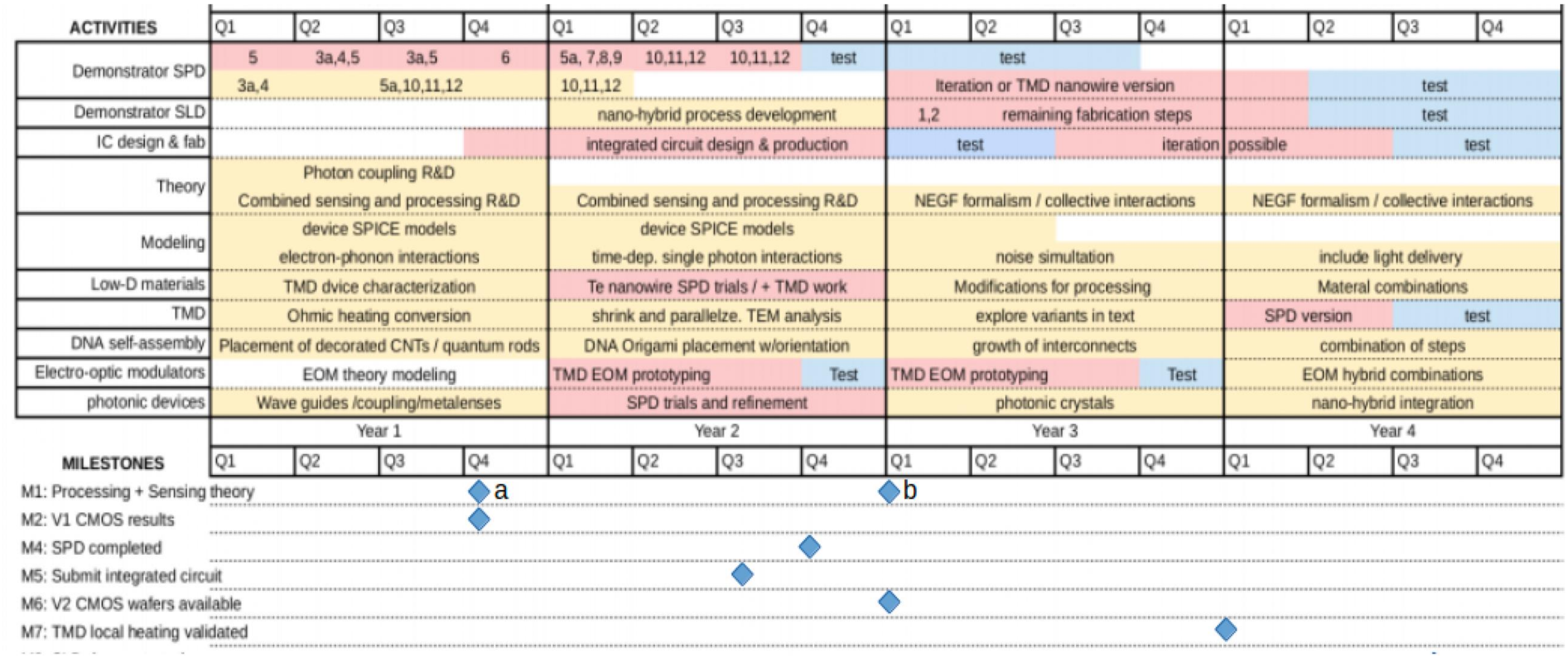
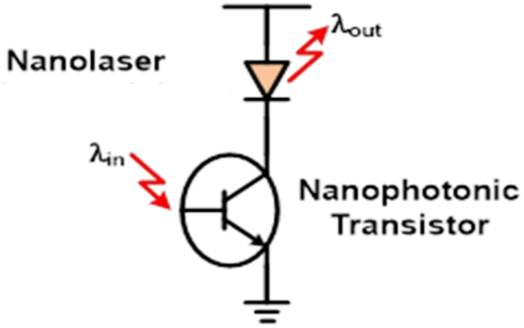


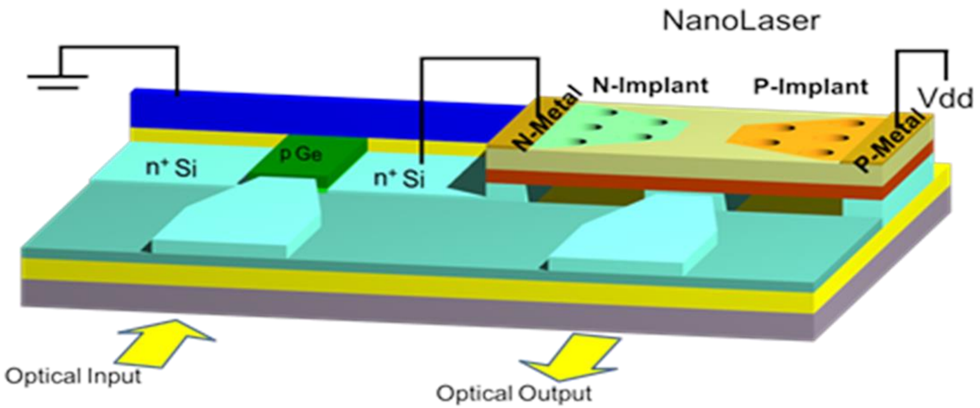
Figure 15: Timetable of activities and milestones. Yellow indicates R&D, orange fabrication, blue testing.

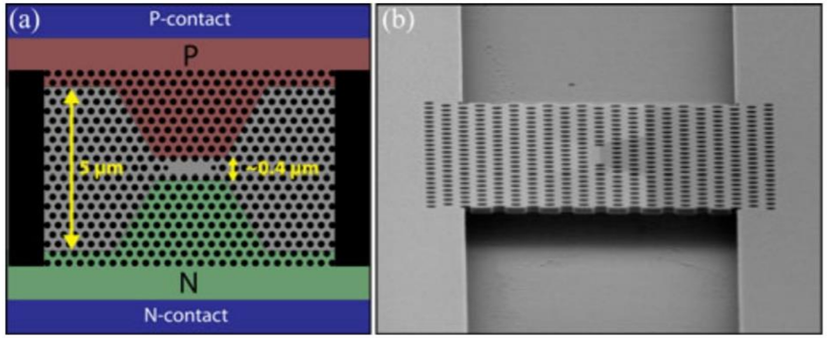
Possible Activities for Photonic Sensing, Processing, and Computing ?

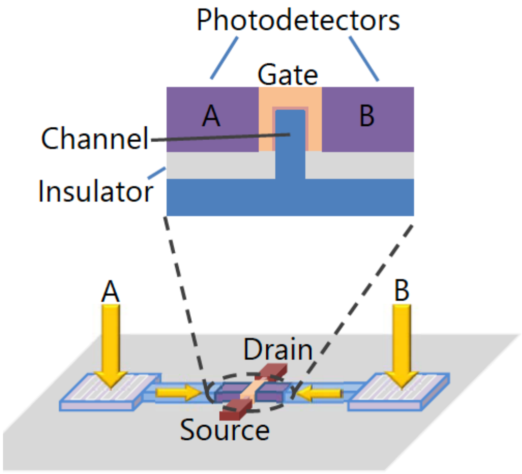
- Nanoscale Materials
- Hyperspectral Sensing
- Nonlinear Photonics
- Nanoscale Photonic-Electronic Devices
- 3D Heterogeneous Integration
- New paradigms on sensing, processing, and edge computing with photonics
- Modeling, Theory, …

Imagine Attojoule Nanophotonics-Nanoelectronics









DM, JLT **35**, 343 (2017)

- ~ 1 fJ/b interconnect exploiting quantum impedance conversion by close integration with electronics with < 1 fF capacitance.
- At 10 fJ/b energy efficiency ~19 dB (80x) link loss budget and ~30% wall plug efficiency of the light source.
- ~80x fanout on low-loss waveguides at 10 fJ/b, nearly independent of the communication distance.
- ~8000x fanout possible

S. J. Ben Yoo, *2017 IEEE Photonics Society Summer Topical*
M. Nazirzadeh, M. Shamsabardeh, and S. J. Ben Yoo, CLEO 2018 paper ATh3Q.2.

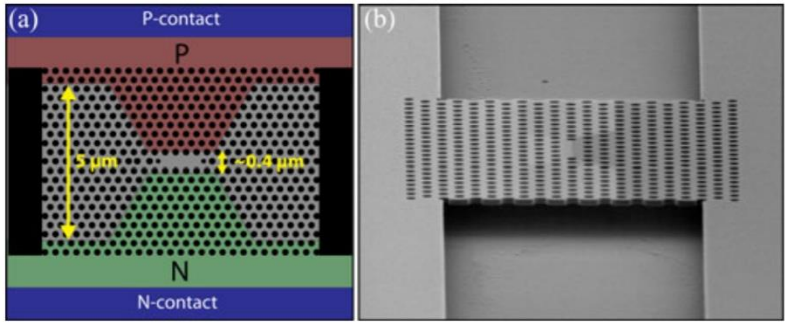
- Nanophotonic Lasers

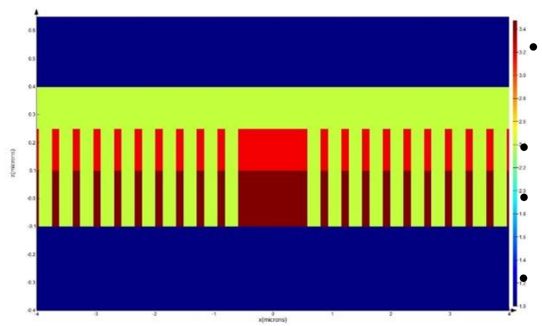
e.g.: B. Ellis, et al, "Ultralow-threshold electrically pumped quantum-dot photonic-crystal nanocavity laser," ***Nature Photonics*****, vol. 5, p. 297, 04/24/online 2011.**

David A. B. Miller, "Attojoule Optoelectronics for Low-Energy Information Processing and Communications," J. Lightwave Technol. 35, 346-396 (2017).

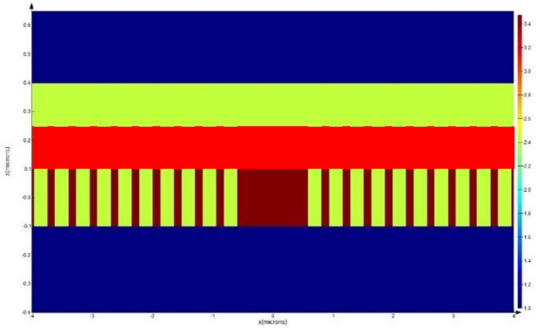
Nanolasers--- photonic crystal version

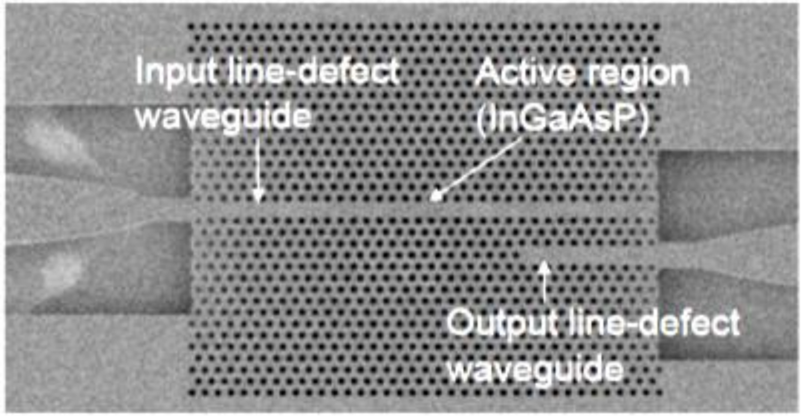
- Prior Art and Our New QD-PC Laser Design

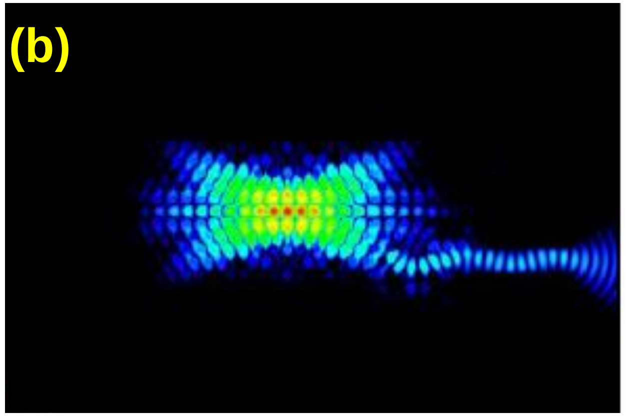


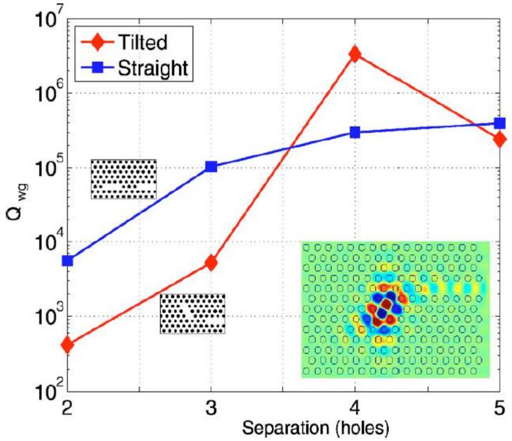


- SiO2
- III-V
- Silicon
- BOX









Bio-Inspired Optoelectronic Neuron Design (modified Izhikevich-model)

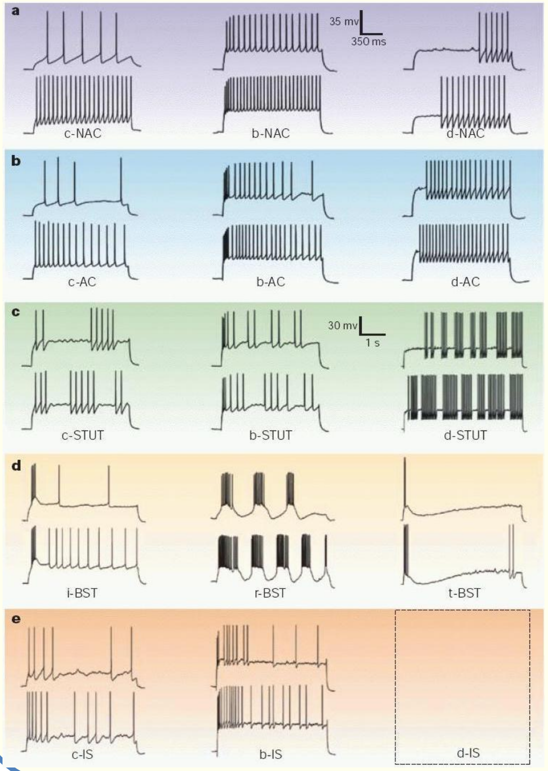
Izhikevich-model and biological Neurons

$$\frac{dv}{dt} = 0.04v^2 + 5v + 140 - u + I$$

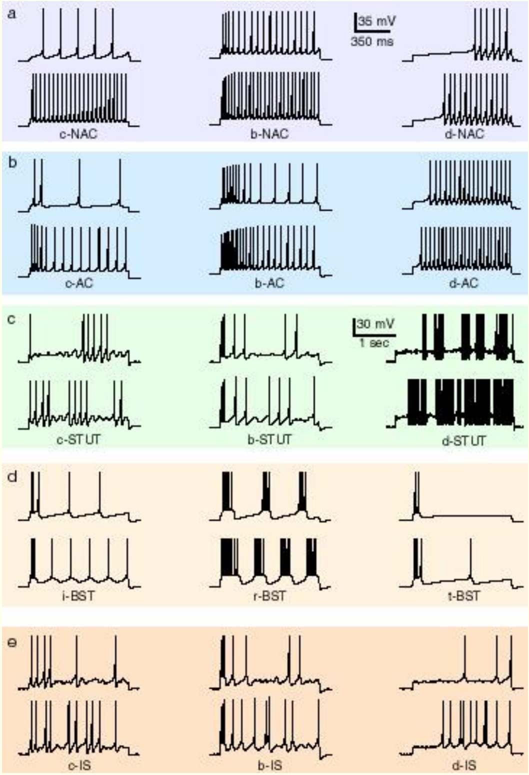
$$\frac{du}{dt} = a(bv - u)$$

$$when\ v \geq V_{threshold} \begin{cases} v \leftarrow c \\ u \leftarrow u + d \end{cases}$$

simulated neurons



real neurons

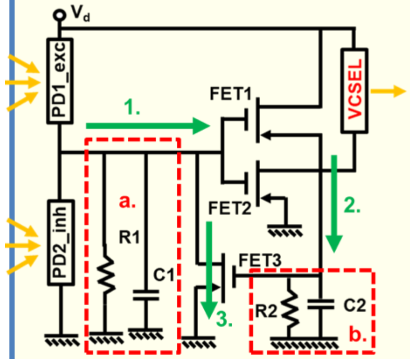


Izhikevich, "Simple Model of Spiking Neurons," *IEEE Trans. Neural Networks*, vol. 14, 2003

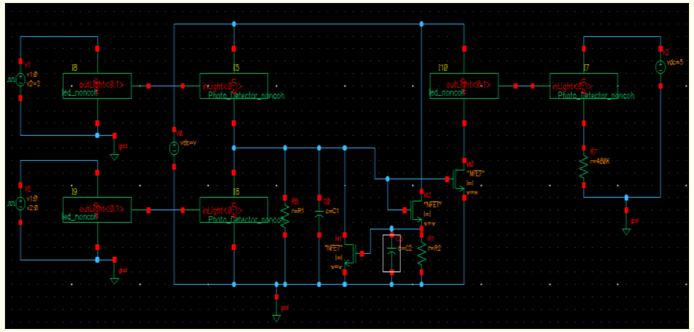
Izhikevich-model based bio-inspired optoelectronic neurons with Excitatory and Inhibitory Inputs

$$R_1C_1\frac{dv}{dt} = R_1(I_{exc} - I_{inh}) - R_1K_1\max\{0, u - V_{th1}\}^2 - v$$

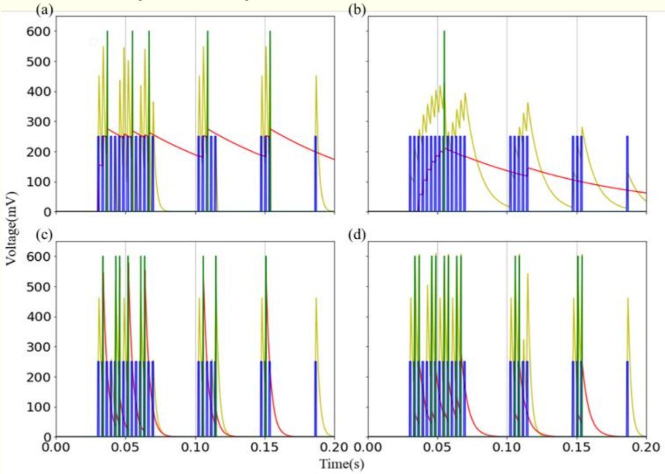
$$R_2C_2\frac{du}{dt} = R_2K_3max\{v - V_{th3} - u\}^2 - u$$



Bio-Inspired Optoelectronic Neuron Circuit



Bio-Inspired Optoelectronic Neuron Circuit

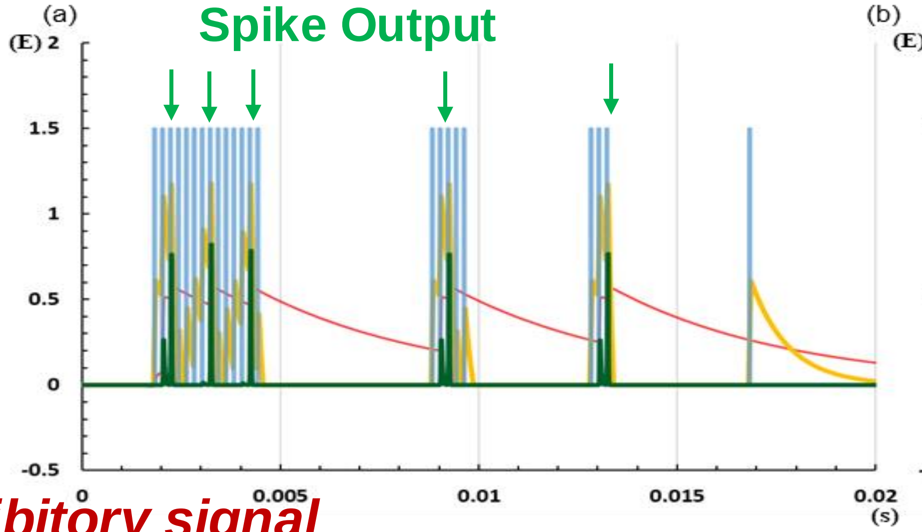


Y. Lee, M. B. On, X. Xiao, and S. J. Ben Yoo, "Demonstration of an Optoelectronic Excitatory & Inhibitory Neuron for Photonic Spiking Neural Networks," in *Conference on Lasers and Electro-Optics*, OSA Technical Digest (Optical Society of America, 2020), paper SM1E.6

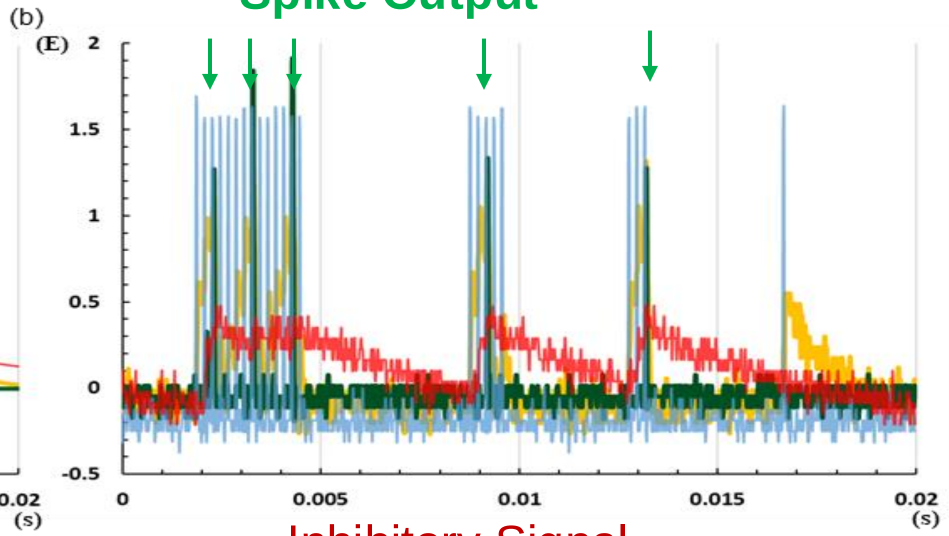
Prototype Optoelectronic Neuron Demonstration with Excitatory-Inhibitory Inputs

- ***Excitatory signal input only:***
  - Excitatory Light Input
  - Membrane Potential(v)
  - Refractory variable(u)
  - Spike Light Output

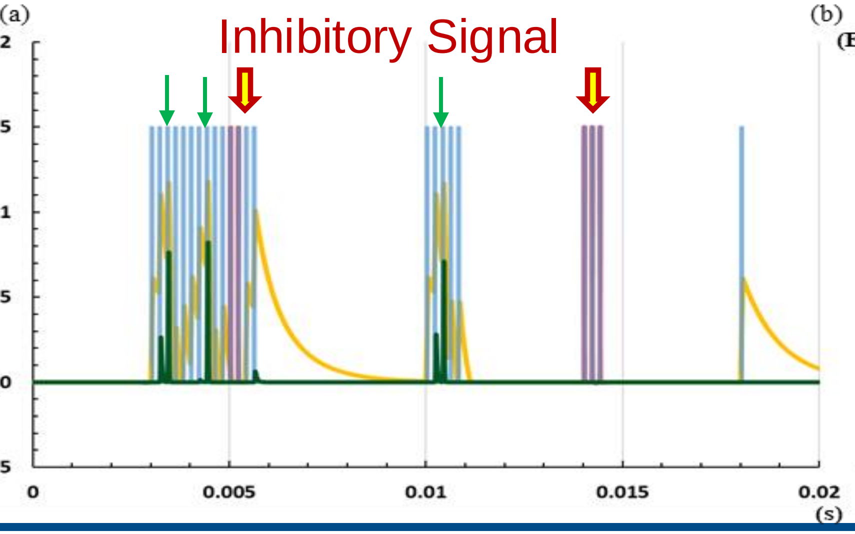
SPICE Simulations

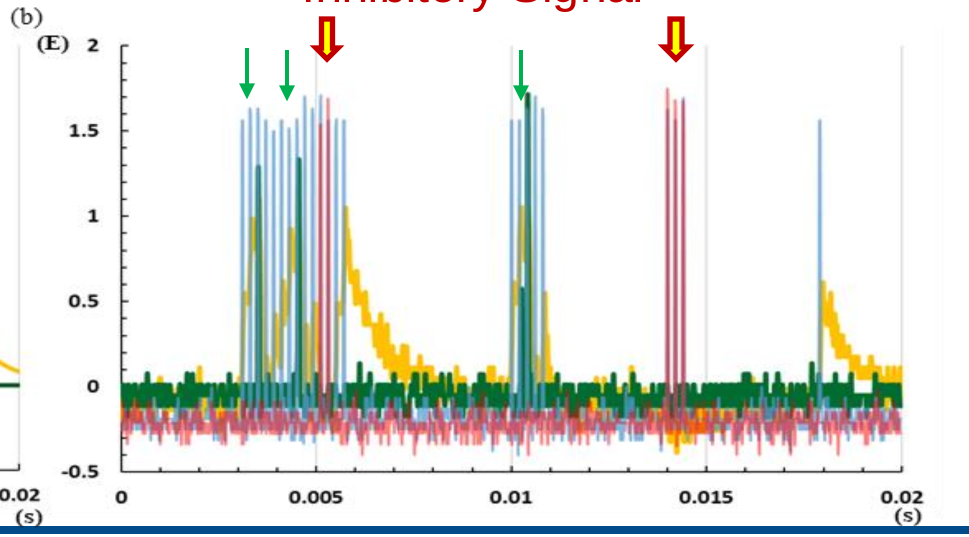


Experimental Results



- ***Both excitatory and inhibitory signal inputs:***
  - Excitatory Light Input
  - Inhibitory Light Input(u)
  - Membrane Potential(v)
  - Spike Light Output

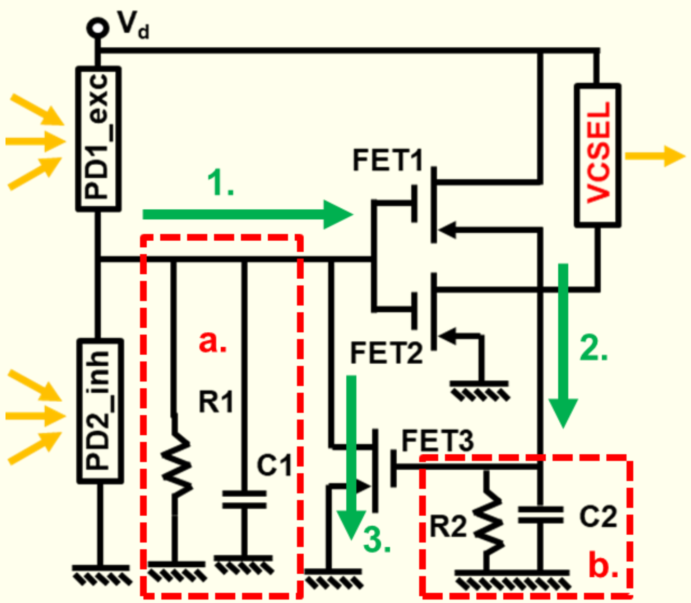




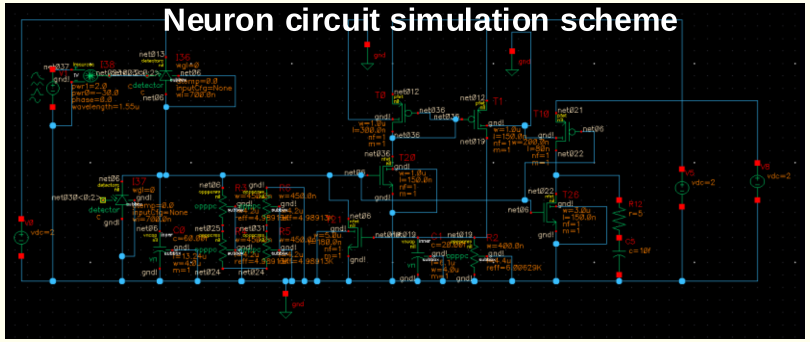
Yun-Jhu Lee, Mehmet Berkay On, Xian Xiao, Roberto Proietti, and S. J. Ben Yoo, "Photonic spiking neural networks with event-driven femtojoule optoelectronic neurons based on Izhikevich-inspired model," Optics Express, Vol. 30, Issue 11, 2022.
Luis El Srouji, Yun-Jhu Lee, Mehmet Berkay On, Li Zhang, S.J. Ben Yoo, "Scalable Nanophotonic-Electronic Spiking Neural Networks," under submission, available online: https://arxiv.org/abs/2208.13144

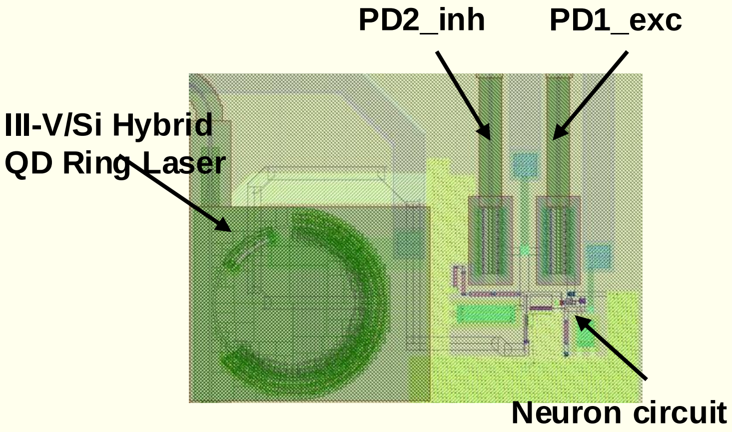
Optoelectronic Neurons: towards Nano-Scale Attojoule Optoelectronic Neurons

Testbed Implementation optoelectronic neurons

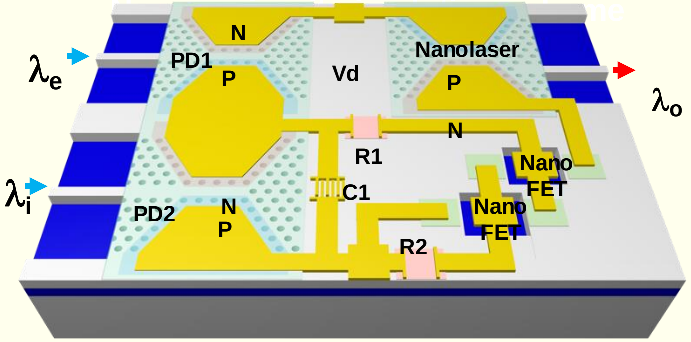


Foundry Implementation micron-scale optoelectronic neurons

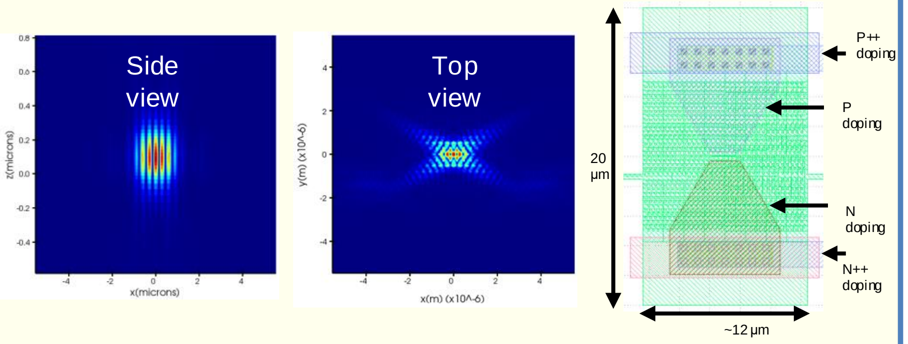




Future Nano-scale attojoule optoelectronic neurons



III-V/Si Hybrid QD Photonic Crystal Lasers

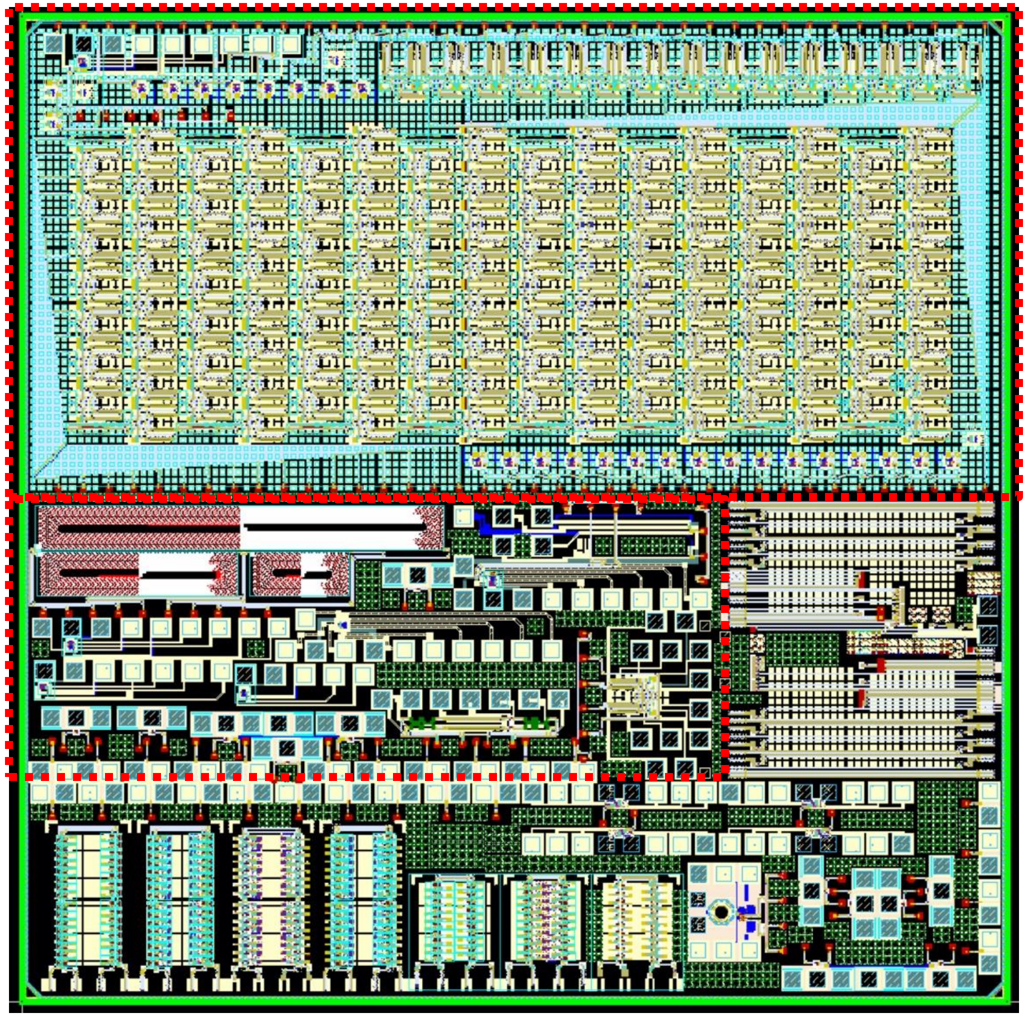


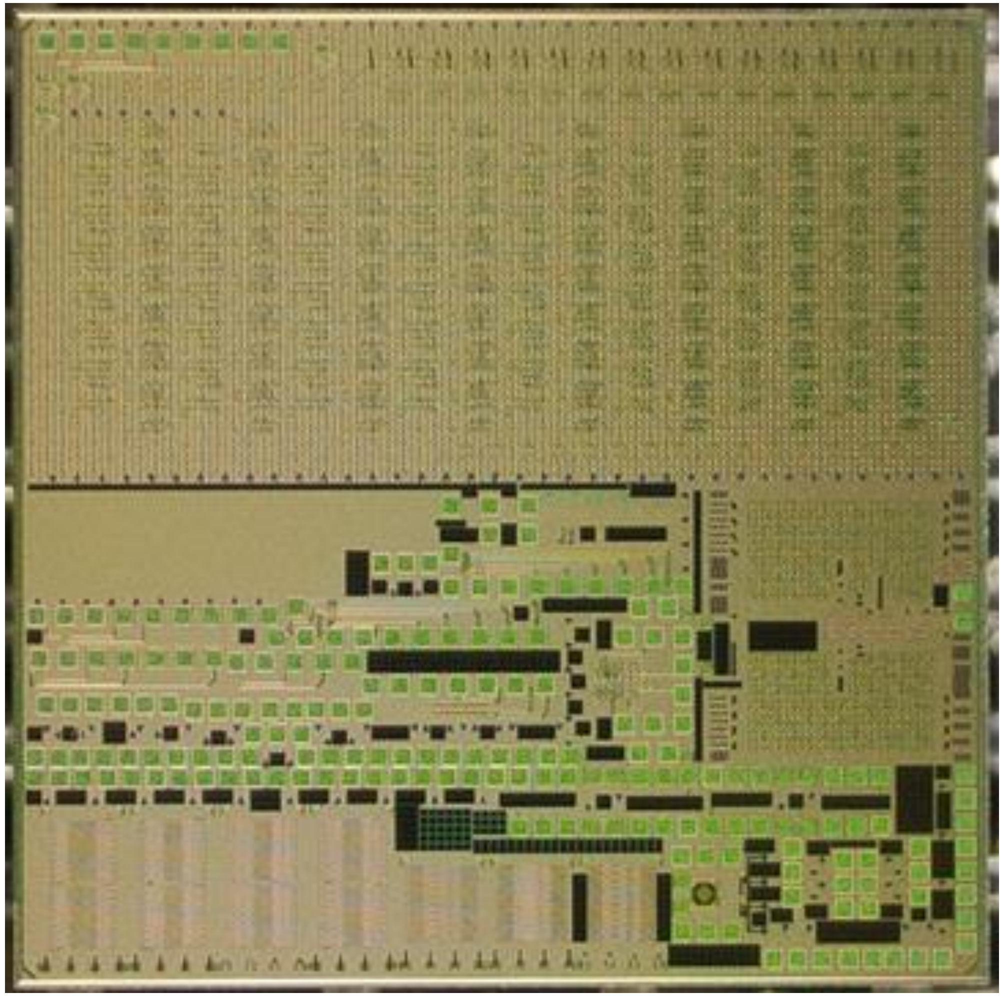
Similar structures for Photonic Crystal Photo Detectors

Work supported by FA9550-18-1-0186

- Y. Lee, M. B. On, X. Xiao, and S. J. Ben Yoo, "Demonstration of an Optoelectronic Excitatory & Inhibitory Neuron for Photonic Spiking Neural Networks," in *CLEO 2020*, paper SM1E.6
- M. Nazirzadeh, M. Shamsabardeh, and S. J. Ben Yoo, "Energy-Efficient and High-Throughput Nanophotonic Neuromorphic Computing," in *CLEO 2018*, paper Th3Q.2.
- Yun-Jhu Lee, Mehmet Berkay On, Xian Xiao, Roberto Proietti, and S. J. Ben Yoo, "Photonic spiking neural networks with event-driven femtojoule optoelectronic neurons based on Izhikevich-inspired model," Opt. Express 30, 19360-19389 (2022)

Neuromorphic Computing GF45SPCLO Dies for 3D EPIC

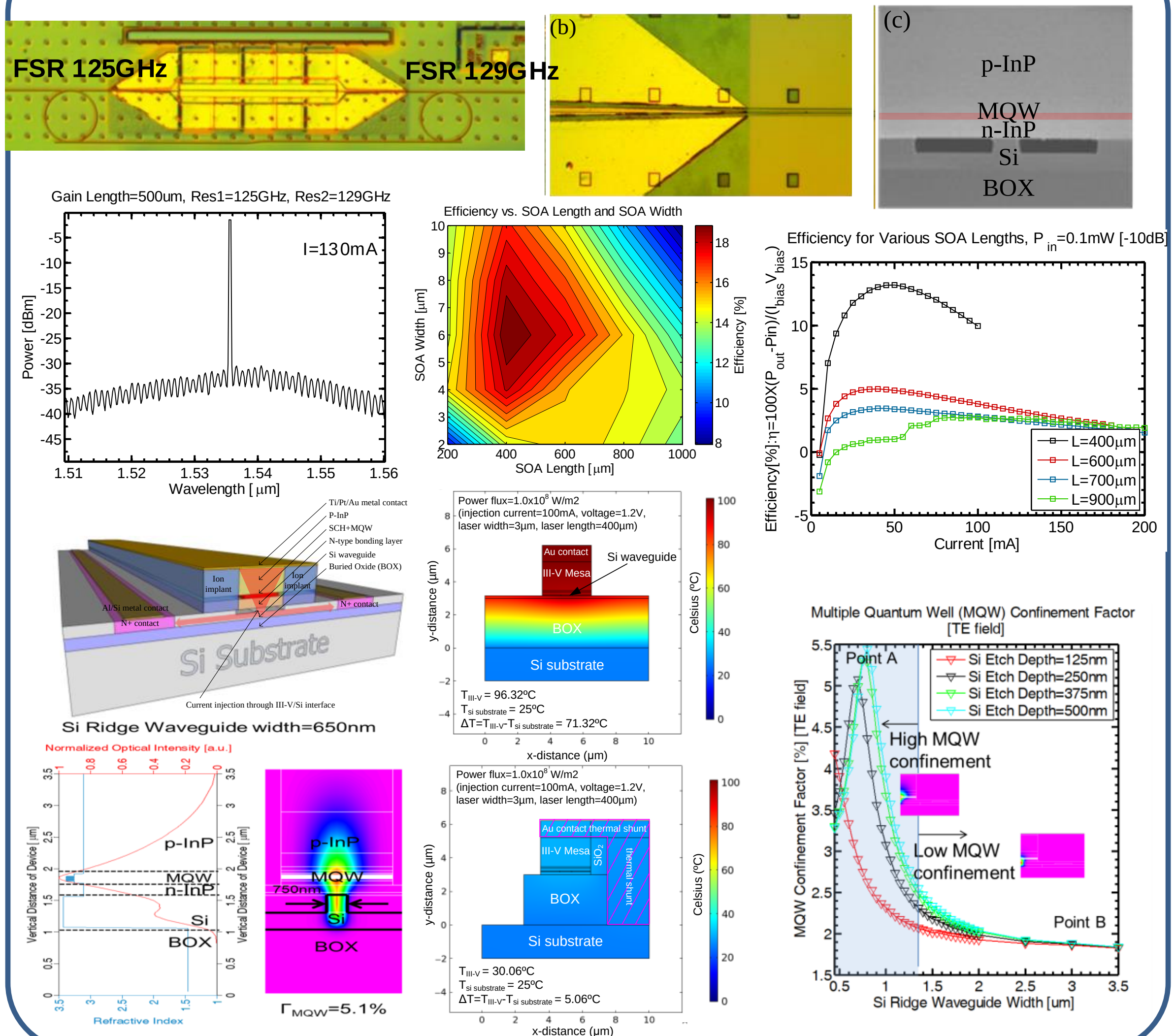




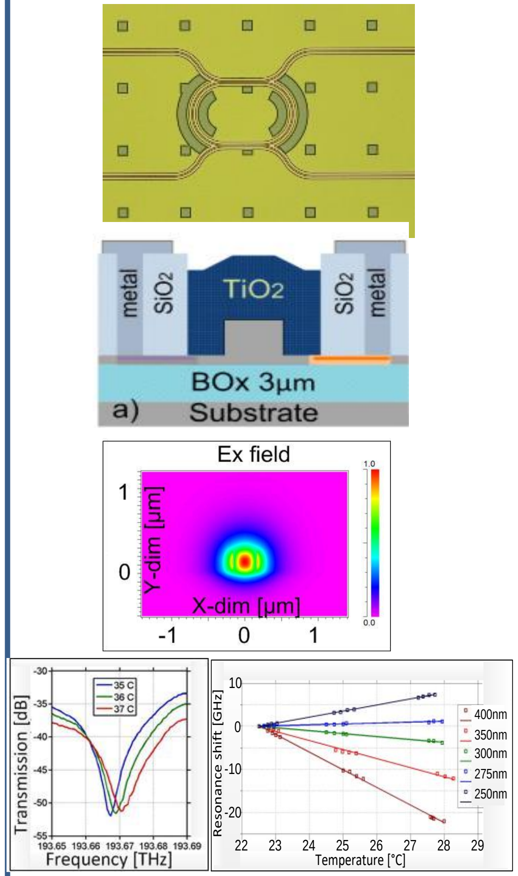
Heterogeneous Integration on Silicon Examples at UC Davis

S. J. Ben Yoo, University of California, Davis; sbyoo@ucdavis.edu

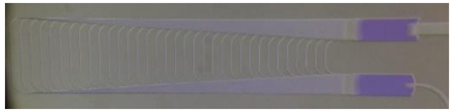
Hybrid III-V/Si hybrid lasers and SOAs



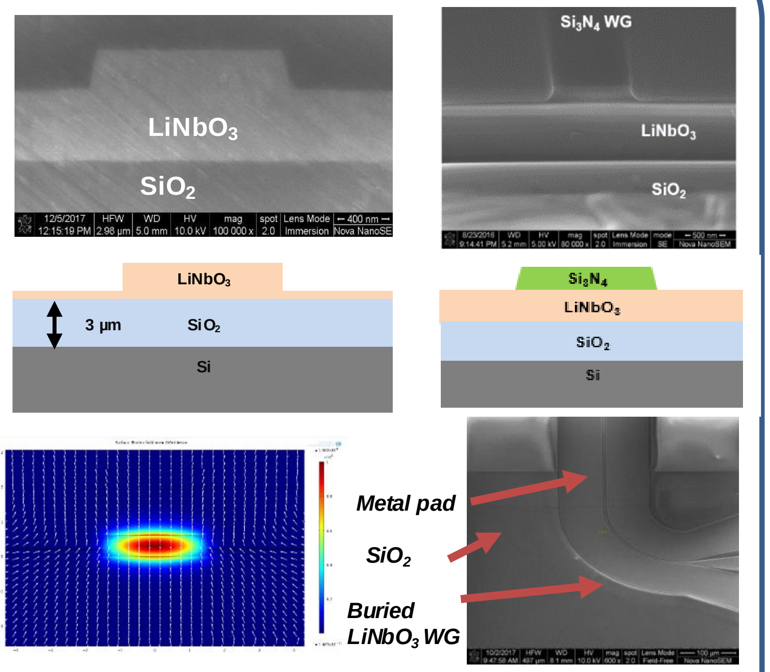
Athermal Silicon Photonics



Application: Athermal AWGs

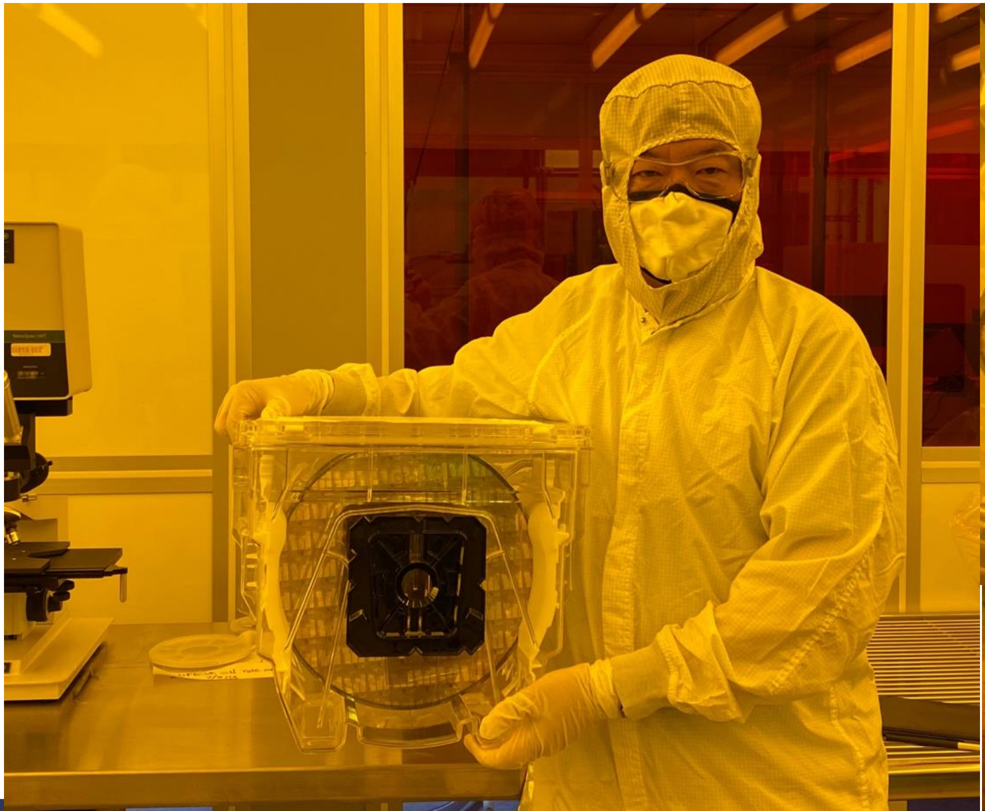


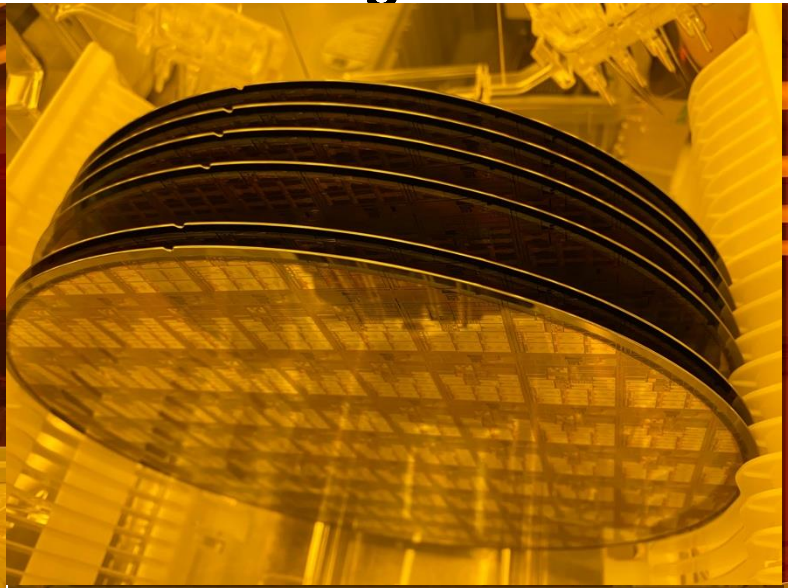
Thin-Film LiNbO3 on Insulator on Si

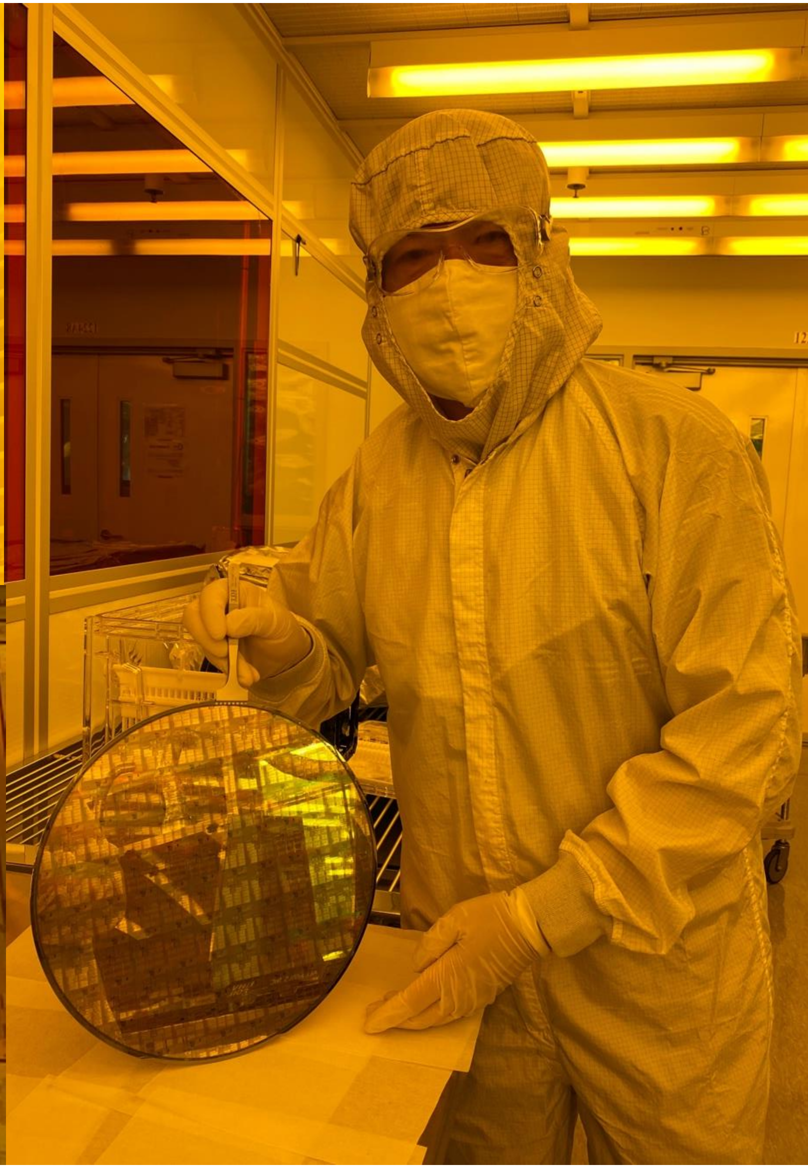


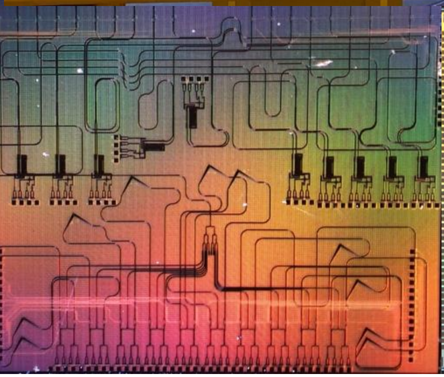
Thin-Film $LiNbO_3$ AWG

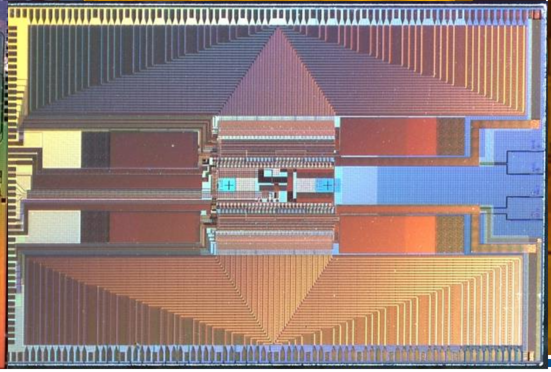
300 mm Custom Wafer Run with Custom Device Layers & Post Fabrication & Integration at UC Davis

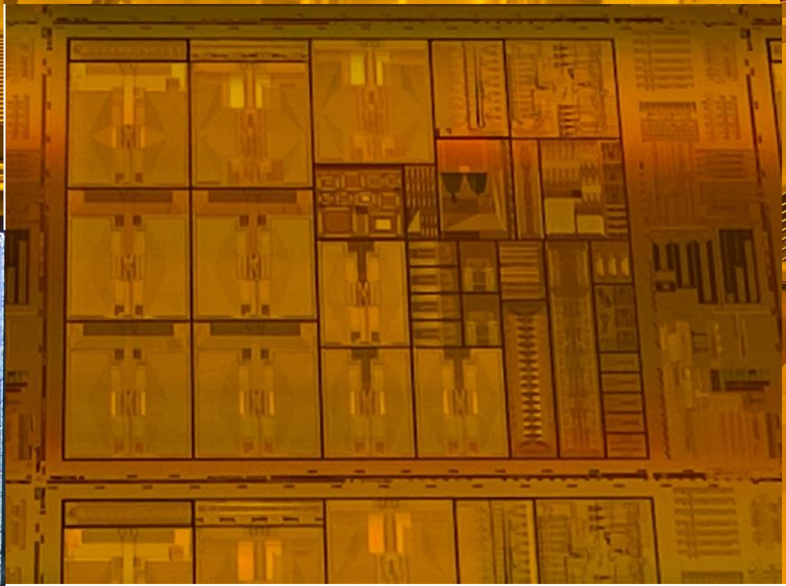




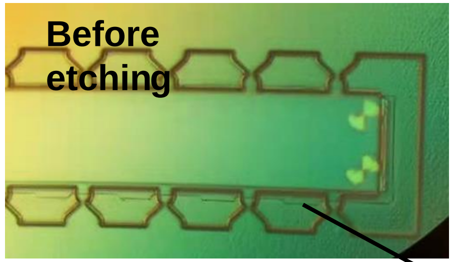


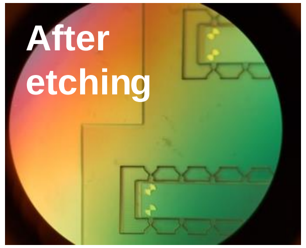




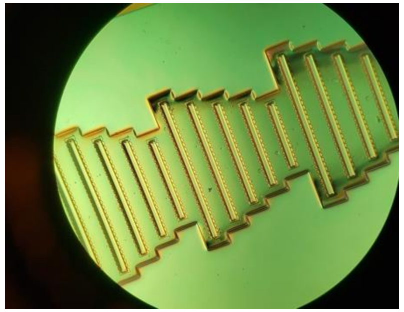


μTransfer Printing at UC Davis

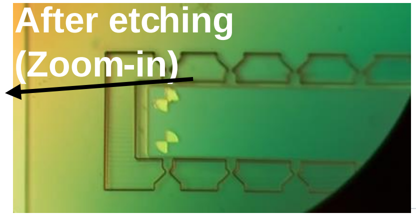


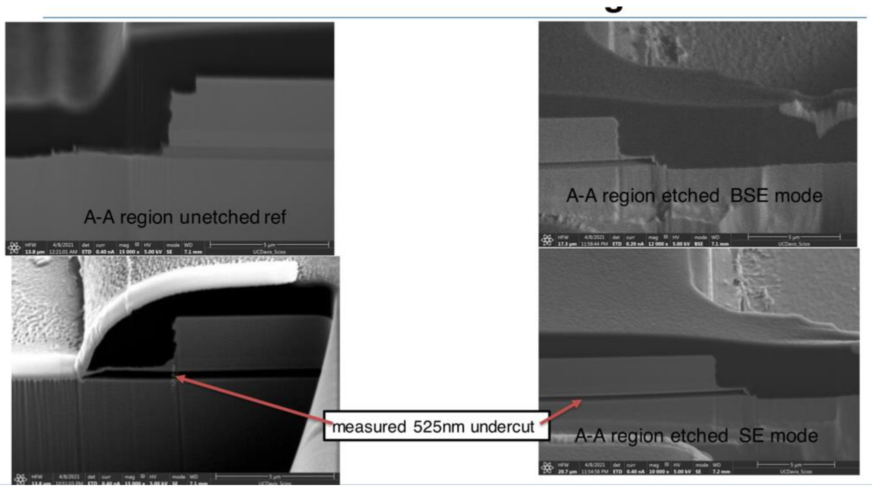


PED

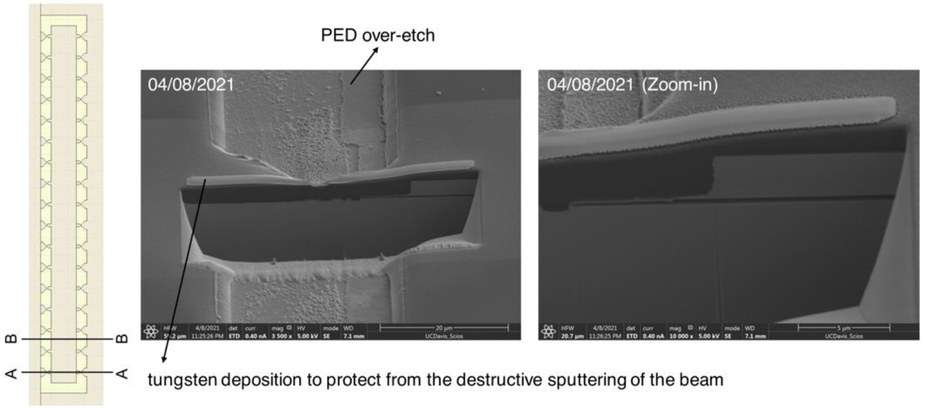


No
PED

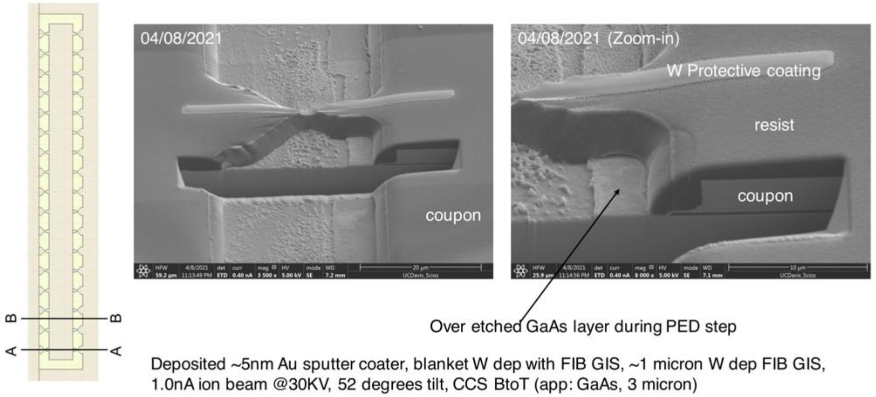




Post Wet Etching FIB (AA)

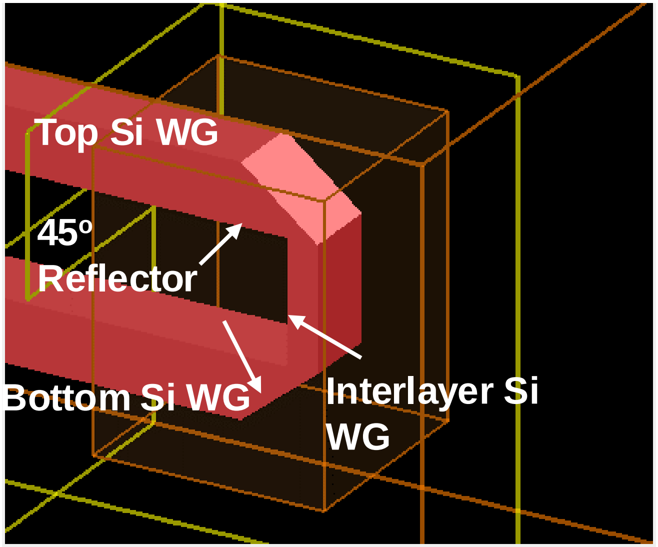


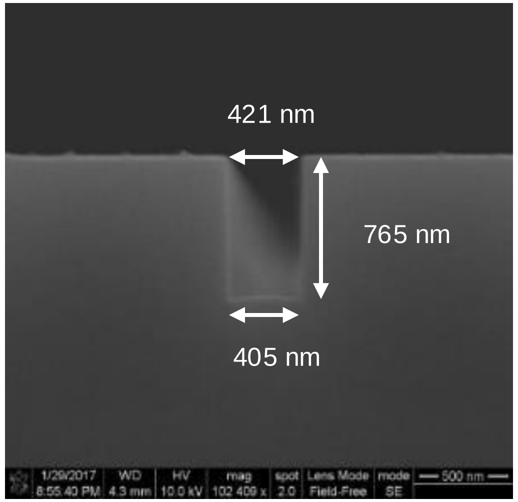
Post Wet Etching FIB (BB)

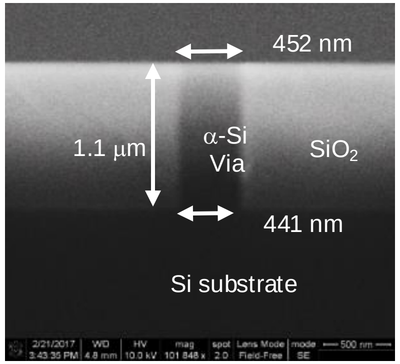


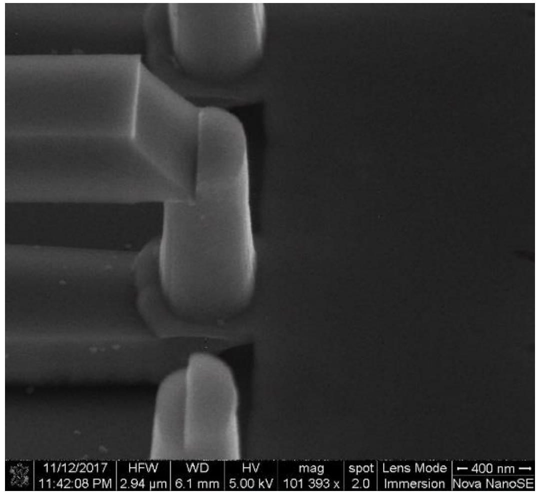
Deposited ~5nm Au sputter coater, blanket W dep with FIB GIS, ~1 micron W dep FIB GIS, 1.0nA ion beam @30KV, 52 degrees tilt, CCS BtoT (app: GaAs, 3 micron)

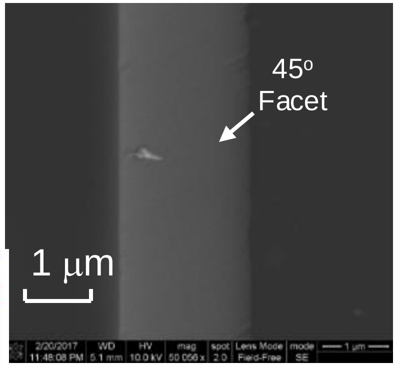
UC Davis' Through Silicon Photonic Vias (Optical TSVs)

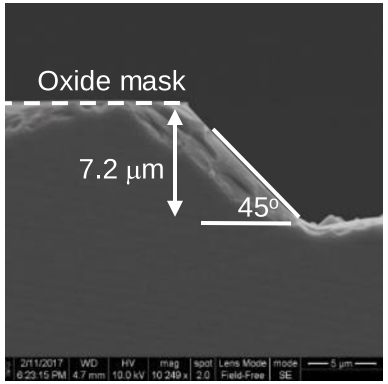


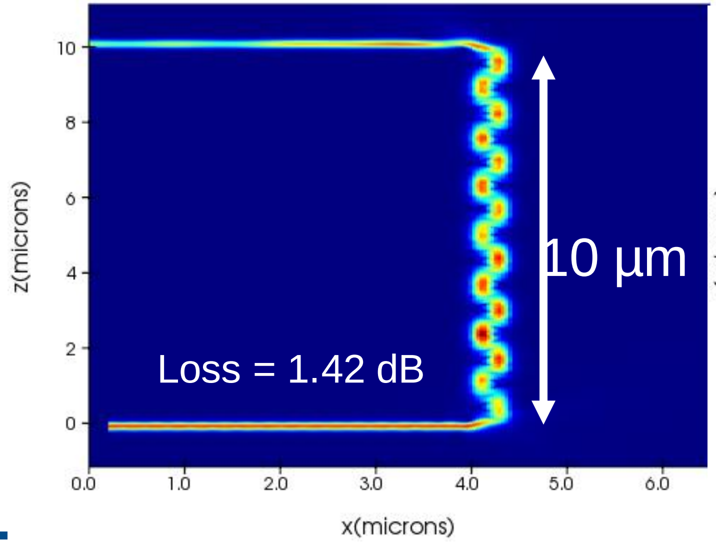


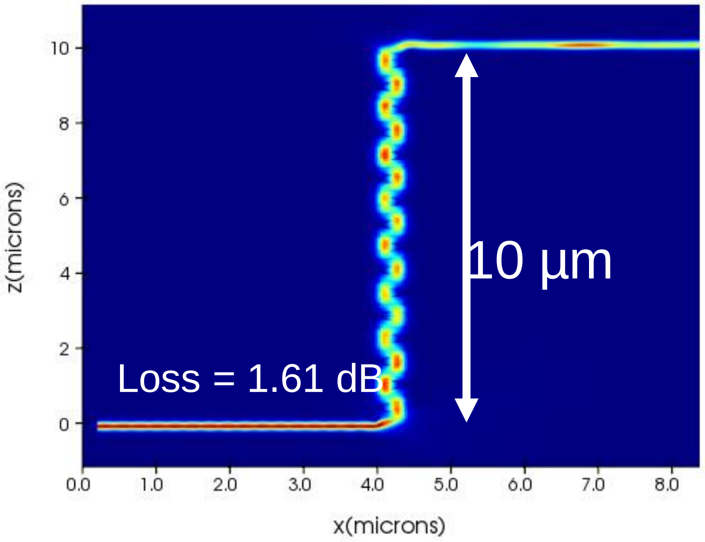












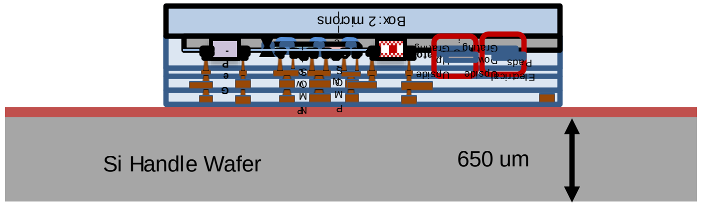
Yu Zhang, Kuanping Shang, S. J. B. Yoo. Opex 2017

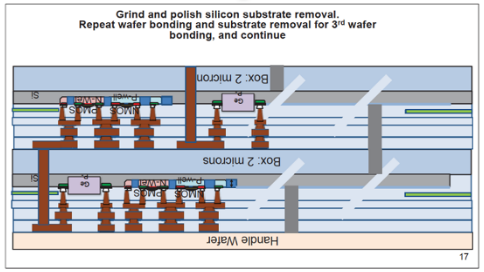
Y. Zhang, Y. Ling, Y. Zhang, K. Shang and S. J. B. Yoo, JSTQE, vol. 24, no. 6, pp. 1-10, Nov.-Dec. 2018,

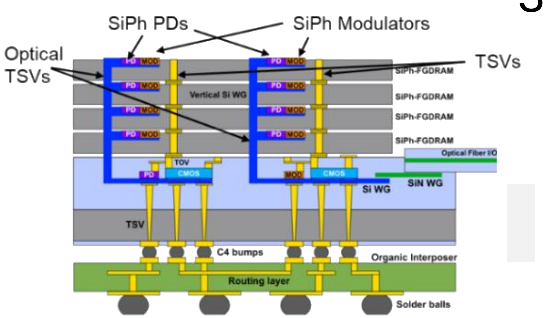
Y. Zhang, A. Samanta, K. Shang and S. J. B. Yoo, JSTQE, vol. 26, no. 2, pp. 1-10, March-April 2020, Art no. 8201510 *(Invited)*.

3D Electronic-Photonic Integrated Circuits (3D EPICs)

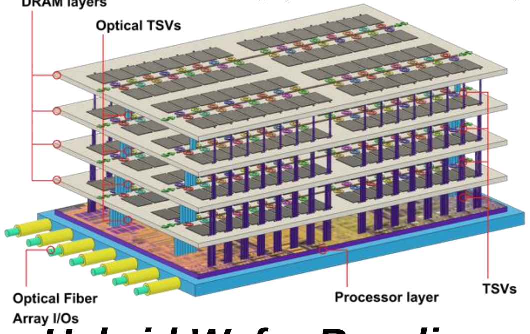
Wafer Reconstitution of GF45CLO on Full Wafers







3D EPIC Prototype on Interposer

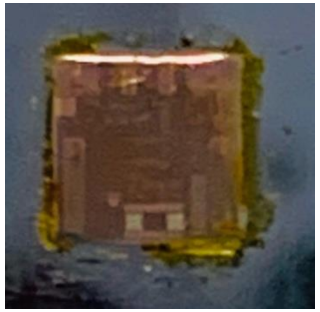


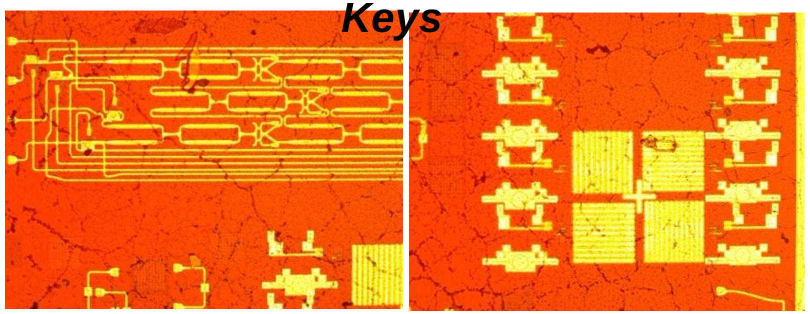
Substrate Removal

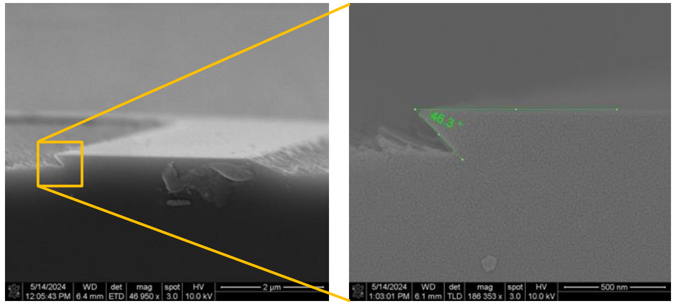
Registering Alignment Keys

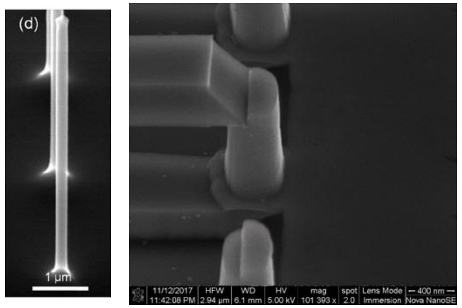
Angled Dry Etching

Hybrid Wafer Bonding



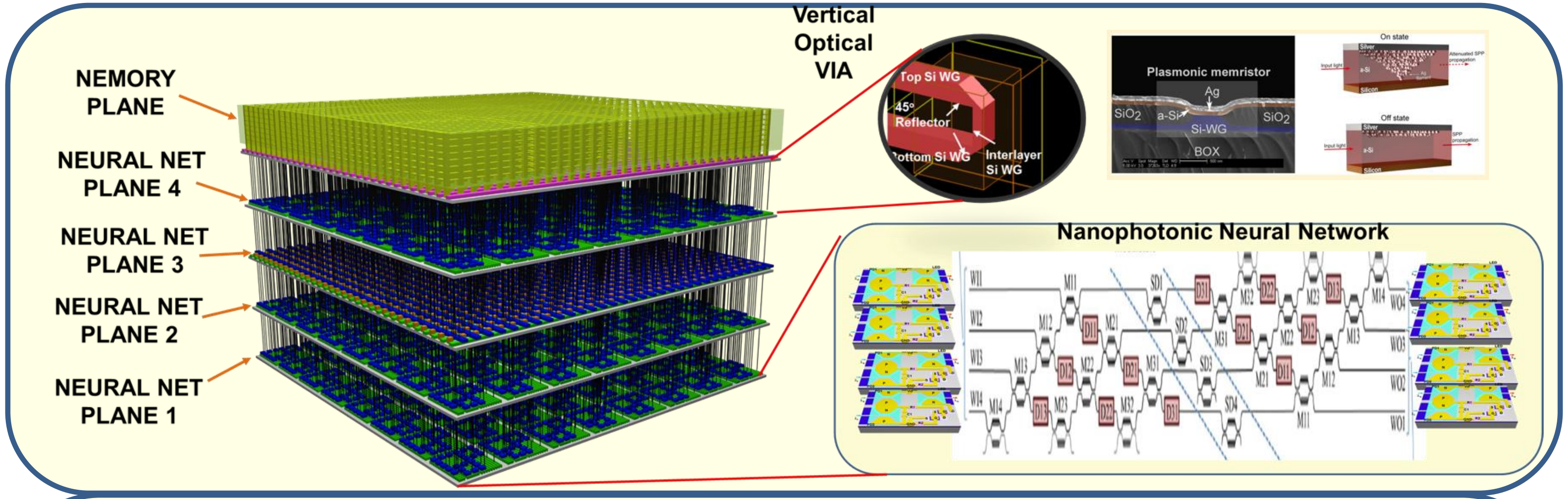


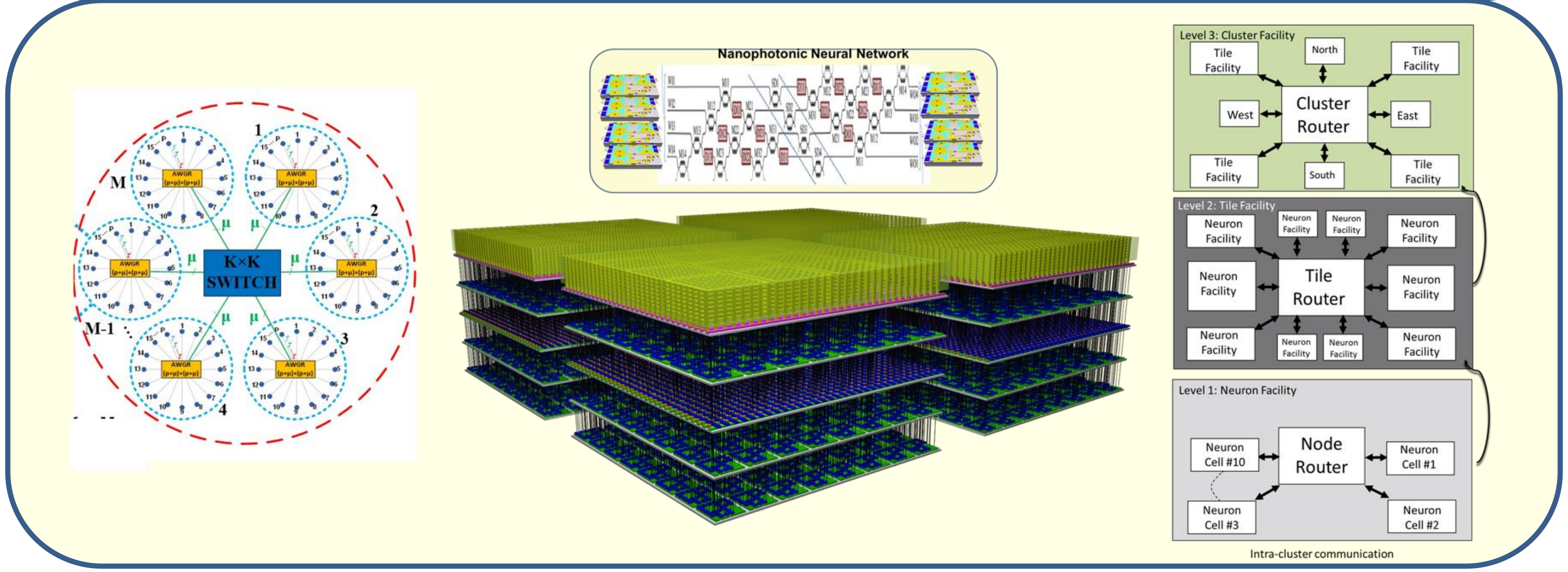




- ❑ Optical TSVs on Monolithic CMOS Photonic Dies (GF45SPCLO).
- ❑ Wafer Reconstitution (including substrate removal, alignment keys, planarization) and Optical TSV fab & integration preserving CMOS (to be shown in Annual Review)
- ❑ Hybrid Wafer Bonding in 3D and Integration with E-O Interposer completes 3D EPICs
- ❑ New gen. memories with photonic-electronic interconnects in pursuit with S. Yu of GTech

3D Scaling of Nanoscale Photonic-Electronic-Integrated-Circuits





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