On and Beyond CMOS

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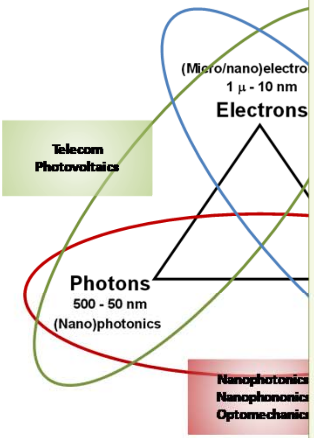
VTT Technical Research Centre of Finland Ltd

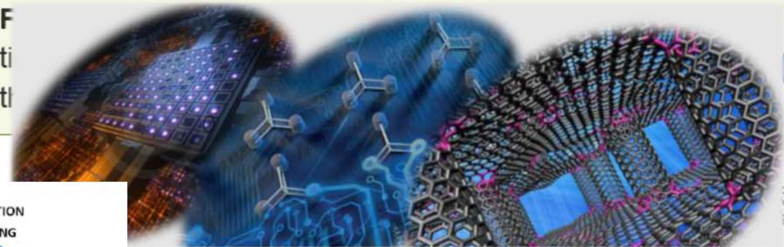
ICOS
International Cooperation On Semiconductors

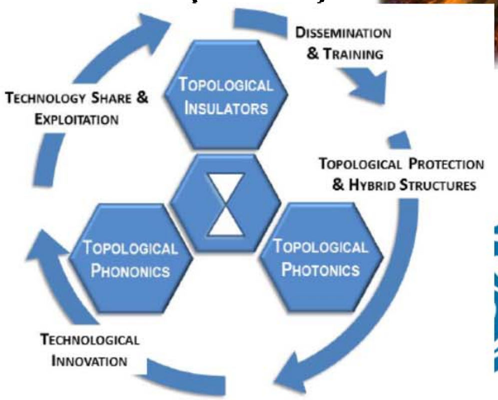
Roadmapping and Position Papers for

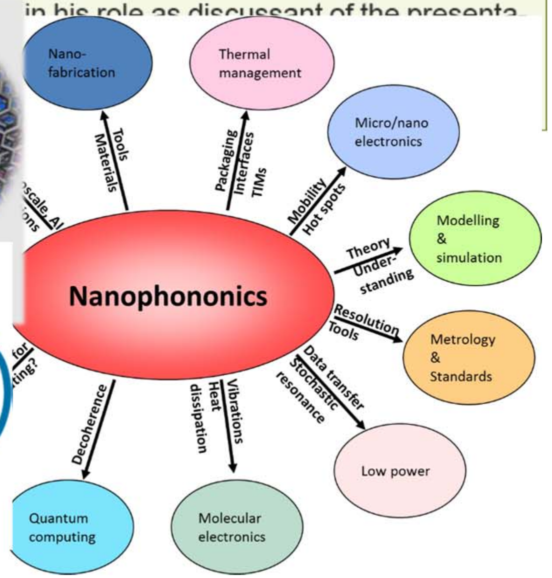
Projects:

- NanoICT (2012)
- NANO-TEC (2013)
- EUPHONON (2014)
- NANOARCHITECTRONICS (2018)
- NEREID (2019)
- TOCHA (2023)









NEREID

“Quantum leap” in computing

VTT’s quantum computer **HELMI** (“Pearl”) has been connected with the pan-European supercomputer **LUMI** (“Snow”), hosted by CSC - IT Center for Science. The connection to Europe’s most powerful classical supercomputer enables the best possible use of the quantum computer’s computing power. This is the first time in Europe that this kind of hybrid service connecting a supercomputer and a general-purpose quantum computer is opened for researchers.

Supercomputer LUMI

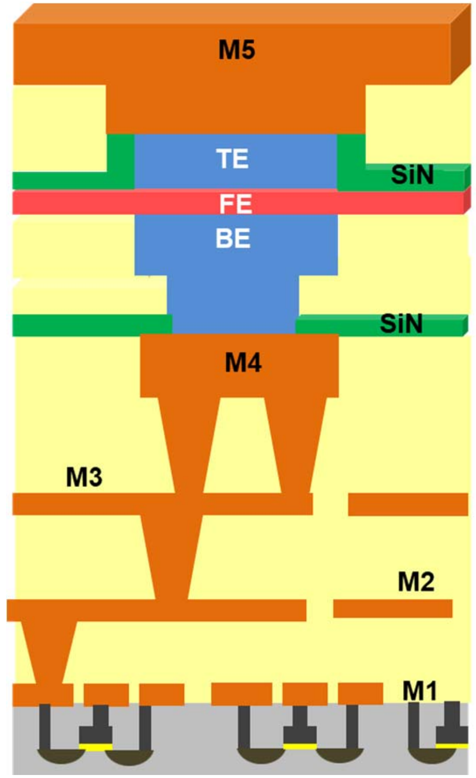
- Connected to HELMI
- For testing quantum algorithms and programming
- Open to academics

Quantum computer HELMI

- 5 qubits 2021
- 20 qubits 2023
- 50 qubits 2024

On CMOS

- Integration with CMOS requires **material and process compatibility and suitable back-end processing.**
- Downscaling of CMOS transistors is pushing **the driving voltage limit to <1.5V**. Matching with low voltage requires development of materials and device structures.
- **Maintaining distinguishable programmable states** is a challenge.

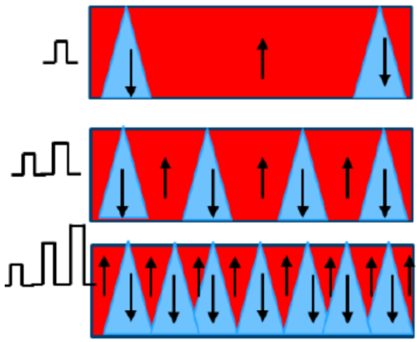


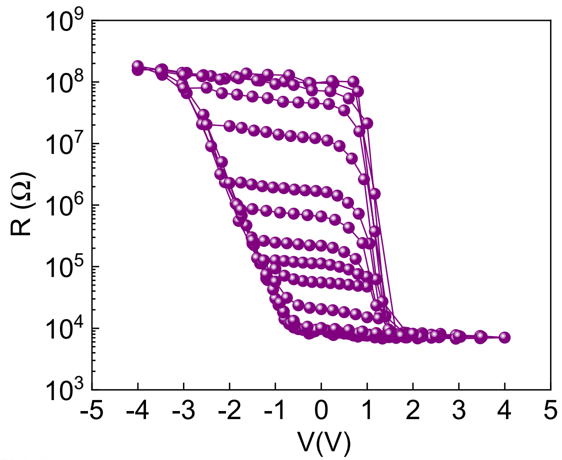
On CMOS

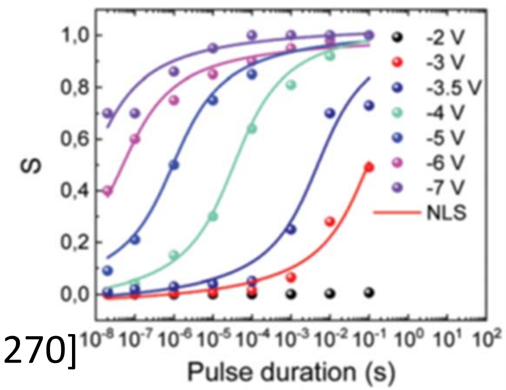
Ferroelectric Devices as Analog Memories

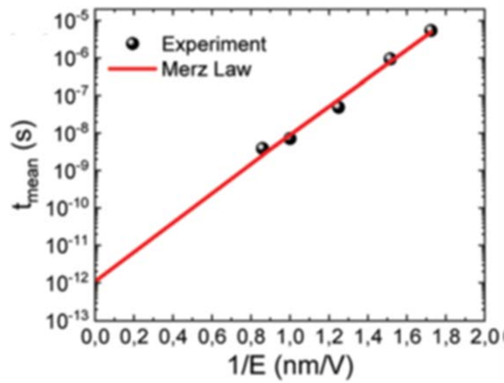
Possibilities
- Multiple Analog States
- Fast Switching (<20 ns)
- Low power consumption

Challenges
- Operating voltage – switch speed trade-off
- Scale down without sacrificing intermediate states reliability
- Leakage currents









[S. Majumdar, Nanoscale 13 (2021) 11270]

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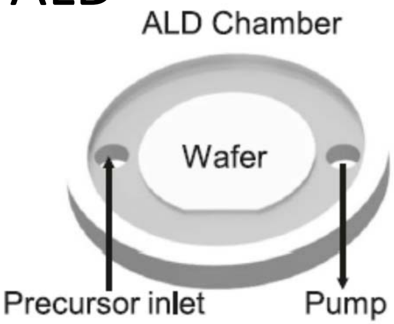
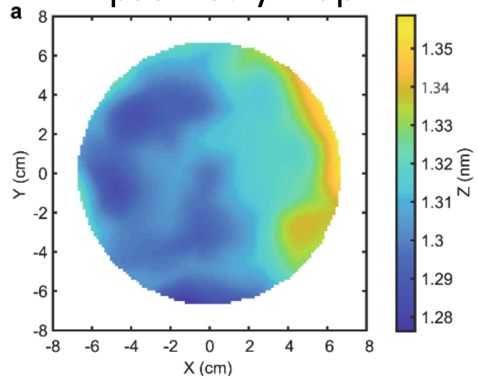
On CMOS

Wafer-scale 2D semiconductor based FeFET devices

MoO_3 by ALD

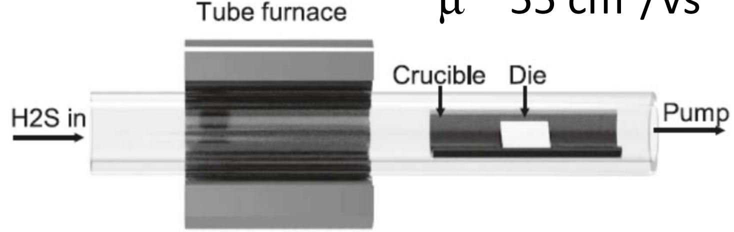


Ellipsometry map

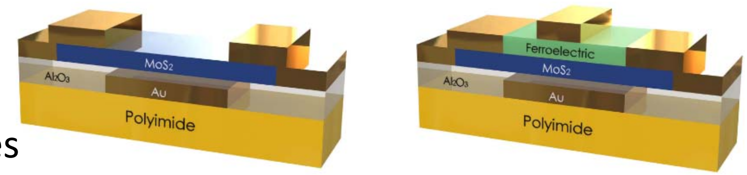


MoS_2

$\mu \sim 55\ cm^2/Vs$

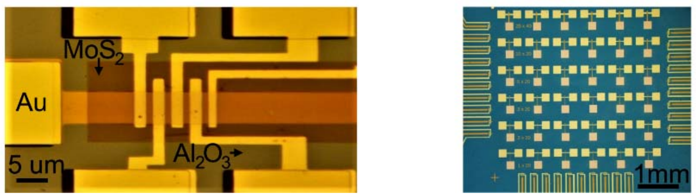


P(VDF-TrFe)

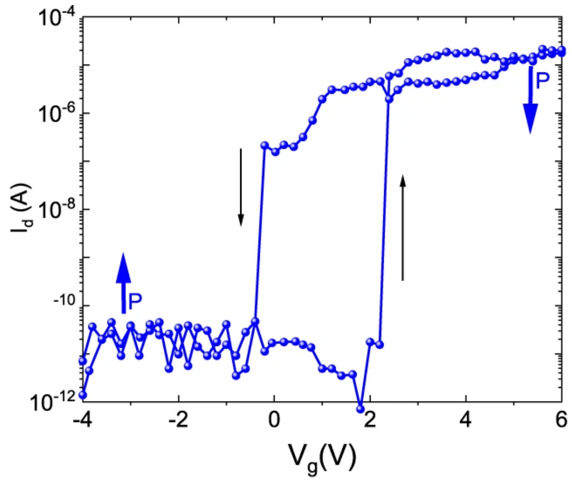


•Transfer to other substrates

•Flexible or CMOS back end



I_d/V_g characteristics

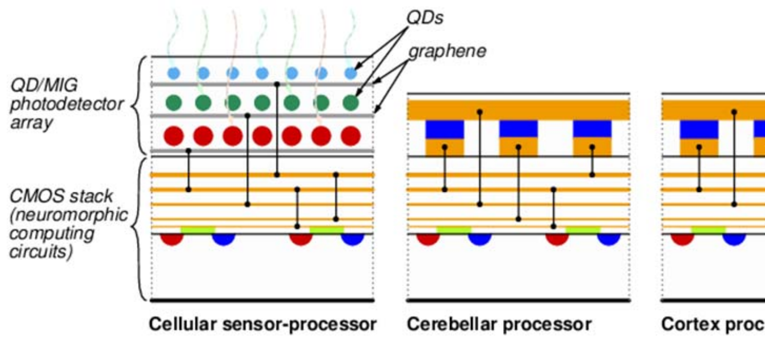


[N. Aspiotis et al., npj 2D Mater. Appl. **18** (2023)]

Examples of Ongoing Projects

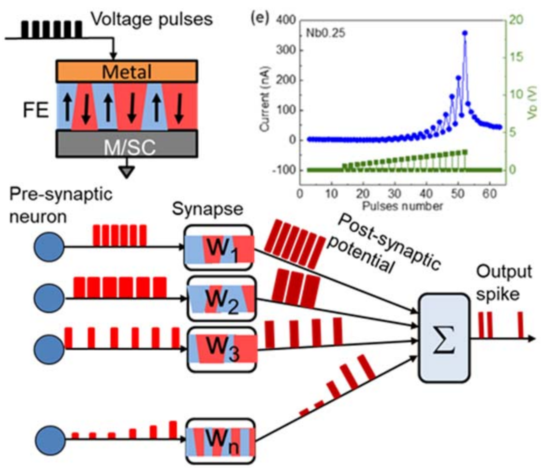
MISEL

Multispectral Intelligent vision System with Embedded Low-power neural computing



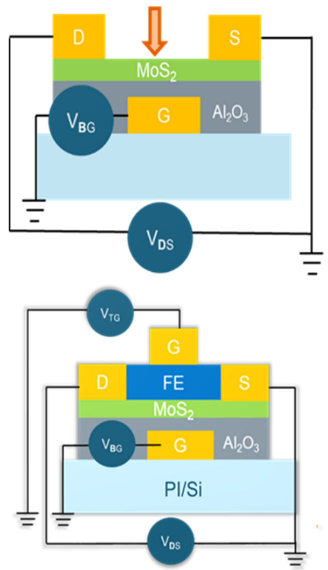
FeMTo

Nanoscale ferroelectric analog memory for neuromorphic computing



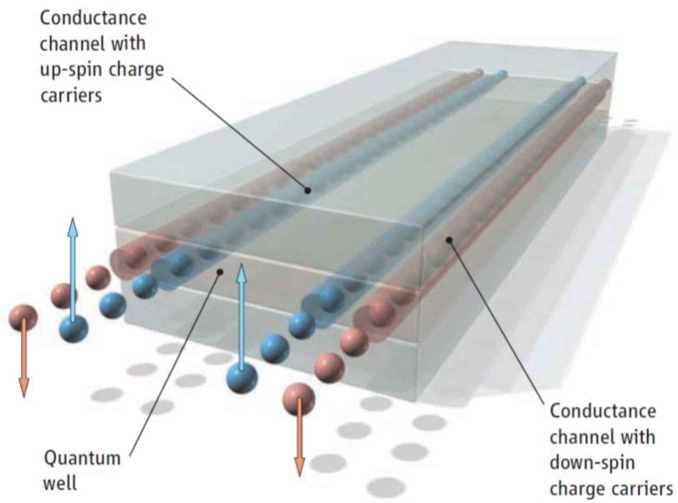
Intelisense

Ubiquitous in-sensor computing for adaptive intelligent systems



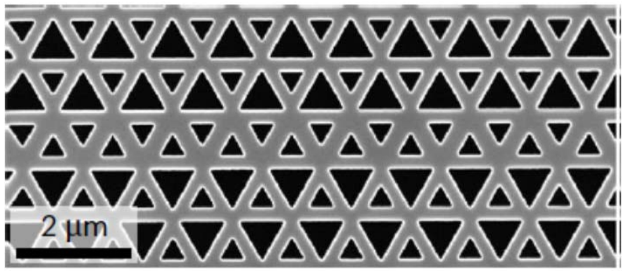
Topologically protected structures

Electrons



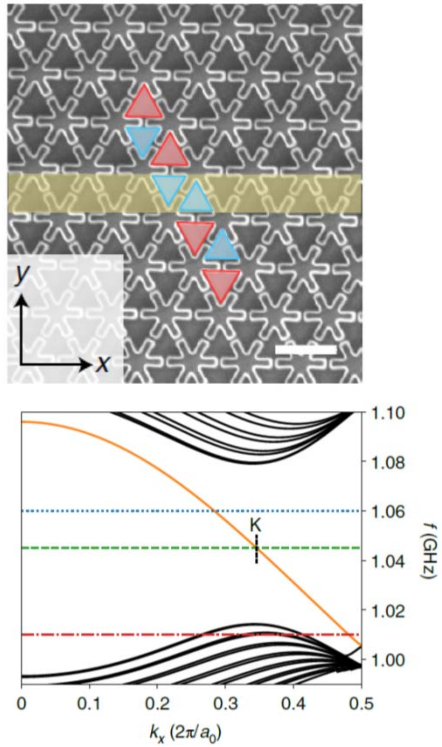
Quantum spin Hall effect in HgTe QW
[M. König et al., Science 318 (2007)]

Photons



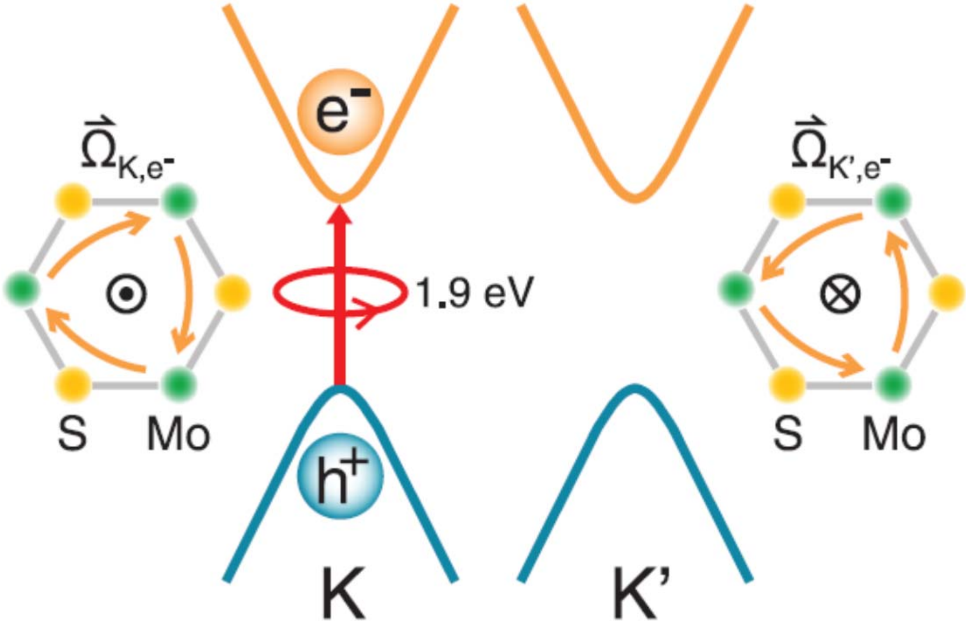
Valley Hall topological interface
[C. A. Rosiek et al., Nature Photonics (2023)]

Phonons



GHz topological vHe in AlN
[Q. Zhang et al., Nature Electronics 5 (2022)]

Valley Hall Effect in MoS_2 transistors



Valley-dependent optical selection rules and the electrons
at the K and K' valleys.

Potential for topological insulator structures (77 K).

[K. F. Mak et al., Science 344 (2014)]

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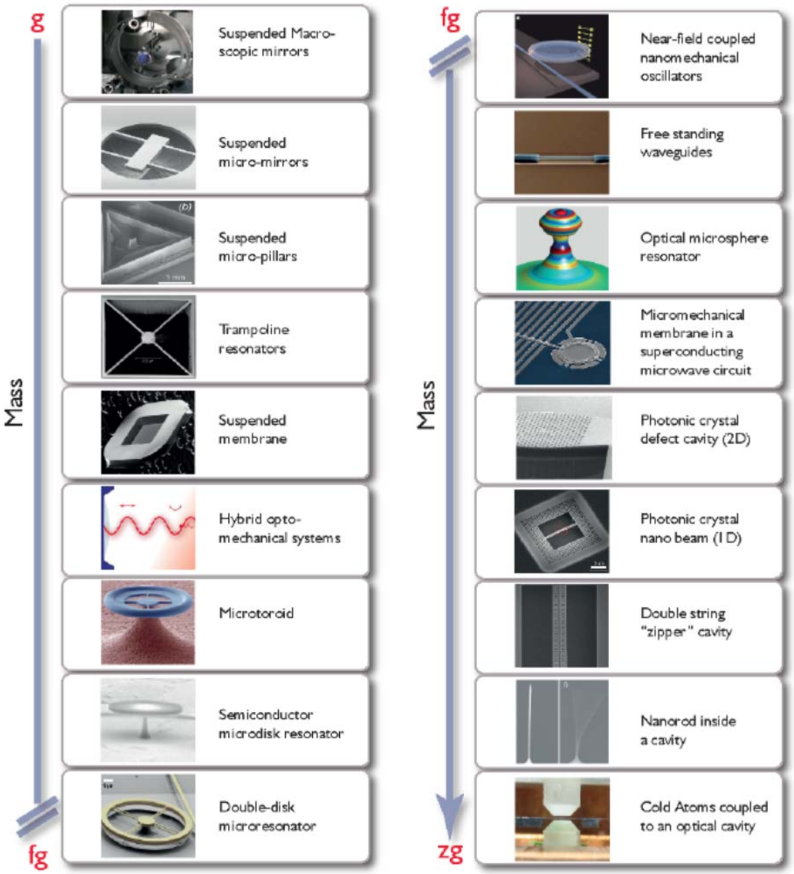
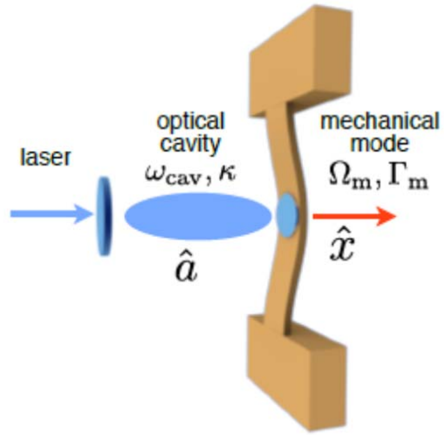
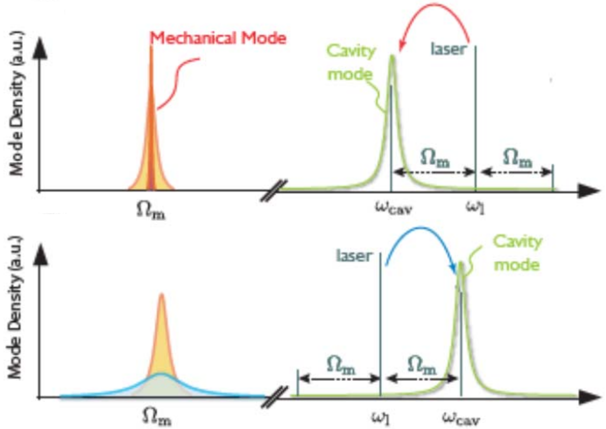
Optomechanics

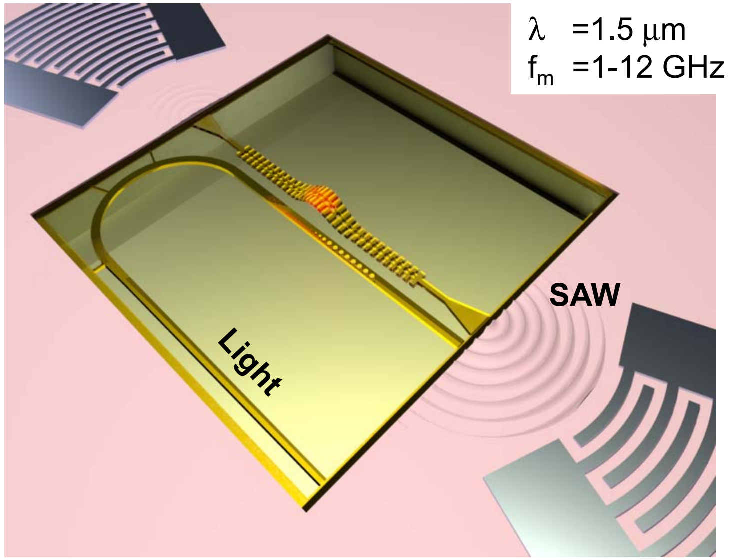




Blue and red detuning

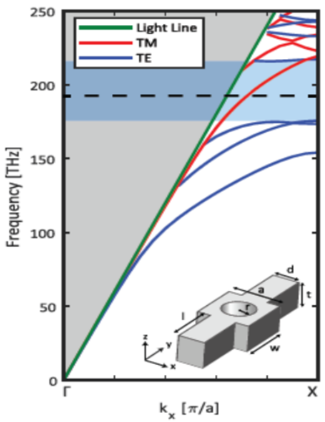


Nano-optoelectromechanics based on nanobeams

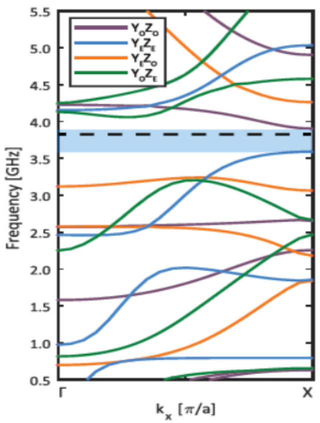


[M. Aspelmayer, T. Kippenberg and F. Maguardt, Rev. Mod. Phys., 2014]

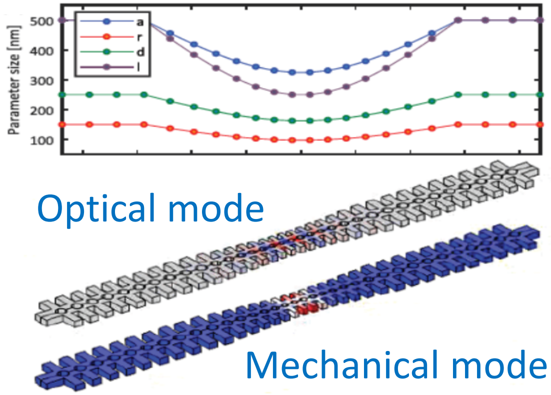
Nanobeam optomechanics



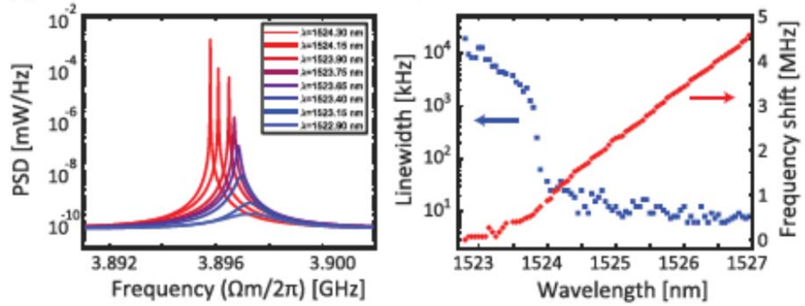
Photonic bands

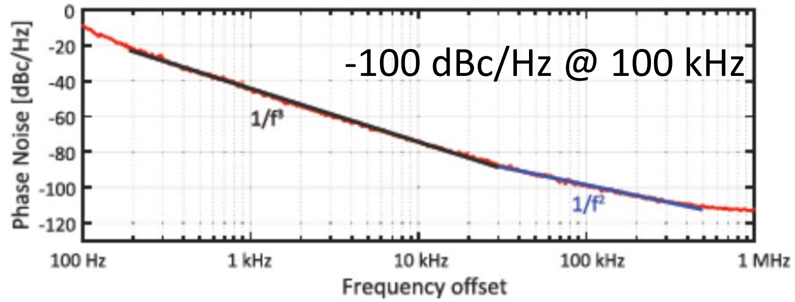


Phononic bands

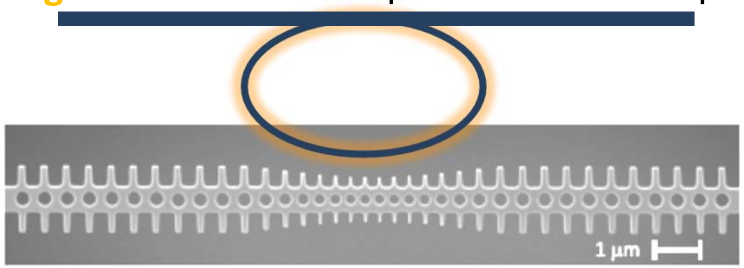


Phonon lasing and phase noise

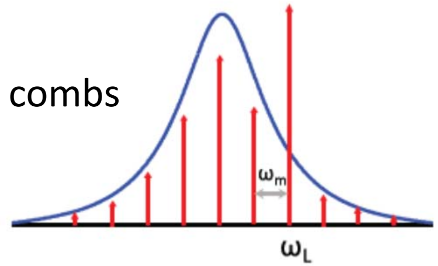




Coupling light to the nanobeam



Generation of frequency combs



[L. Mercadé et al., Nanophotonics 2020]

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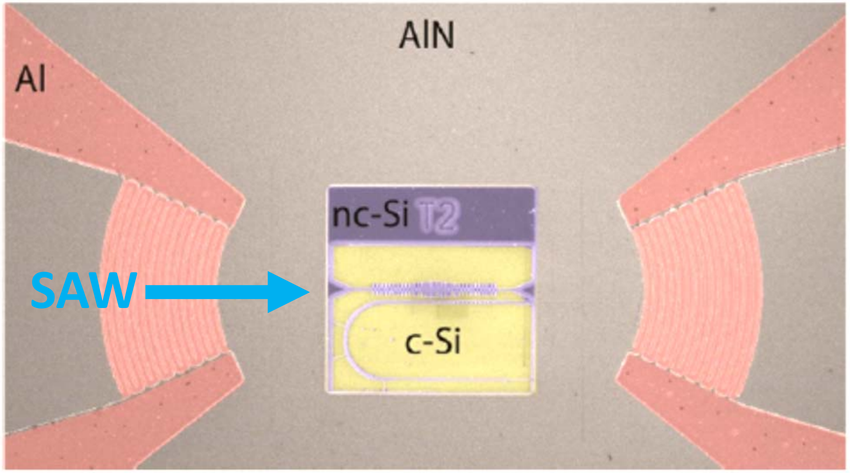
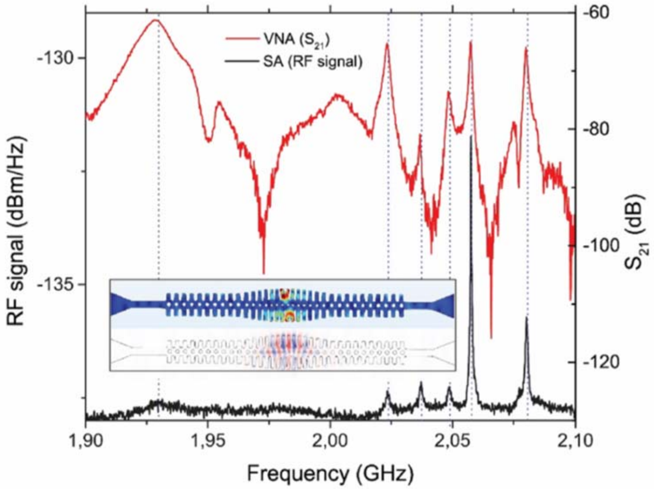
Nano-optoelectromechanics

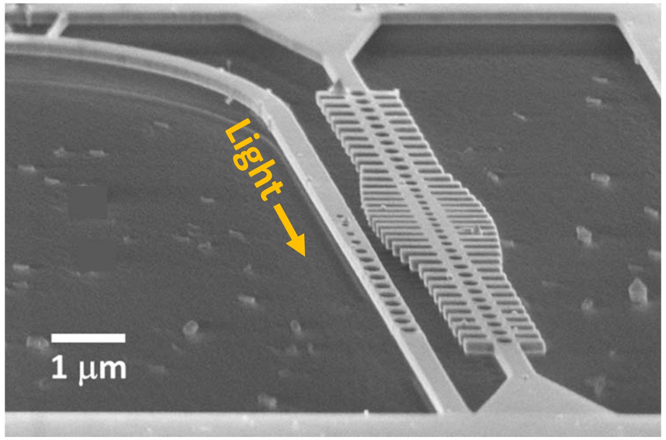
Opto-and electromechanical excitation





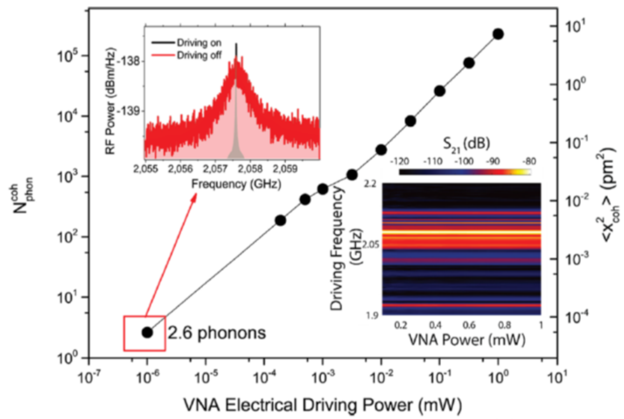
Electromechanical excitation using SAW

SEM image of the nanobeam and optical waveguide



[D. Navarro-Urrios et al., ACS Photonics 2022]

Coupling to the coherent phonon mode



NOEMS

Nano-optoelectromechanical systems

- **Rf signal ↔ optical signal conversion (1-12 GHz ↔ telecom wavelength 1.5 μm)**
- **Up and down conversion**
- **Local oscillators**
- **Frequency combs**
- **Low power**
- **CMOS compatible**
- **Application in, e.g., 5G and SATCOM**
- **Currently low TRL 2-3**

- **Related to IRDS CEQIP (qubit→phonon→photon) and OSC**

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Summary

- High number of new ideas and device concepts
- Potential for high efficiency and low power operation
- Most of the concepts are at low TRL
- Stand-alone beyond CMOS circuits or CMOS compatible / on CMOS devices?
- CMOS compatible: Voltage, current, speed levels and signal format have to be compatible with CMOS
- Material and fabrication process development needed
- Plenty of room for interesting theoretical and experimental science

Funded by the European Union

ICOS International Cooperation On Semiconductors

Funded by the European Union

SiNANO Institute

IRDS International Roadmap for Devices and Systems

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WORKSHOP - Sustainable Electronics & International Cooperation On Semiconductors

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