

Point defects in semiconductors as quantum platform

Ongoing research at the Semiconductor Physics Section

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UNIVERSITETET
I OSLO



Semiconductor Physics Section

LENS – Light and Electricity from Novel Semiconductors

Application-motivated basic research...

focus on **defects**, doping and diffusion, synthesis of novel **semiconductors** and **ion beam physics**, towards applications within solar cells, QT, power electronics and sensors

Office: Kristen Nygårds hus (3.etg.)

Lab: MiNa-Lab

- Clean room(440 m²) and 9 Characterization labs

~45 people:

- 5 Profs.
- 4 admin/engineers
- 10 postdocs/researchers
- 12 PhD students.
- 15 Master students

Norwegian Micro- and Nanofabrication Facility

NORWEGIAN MICRO- AND NANOFABRICATION FACILITY

NorFab

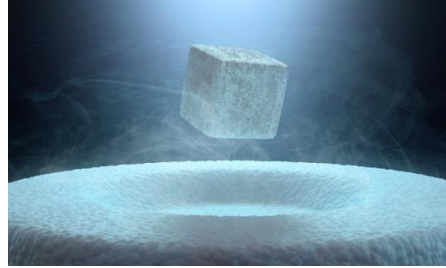


MiNa-Lab

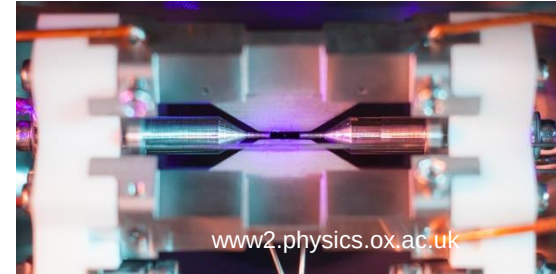


Choice of material platform for physical realizations of QT

- Superconductors
- Trapped ion
- Atomic vapor
- Optical gratings
- Quantum dots
- Defects in semiconductors
- ...



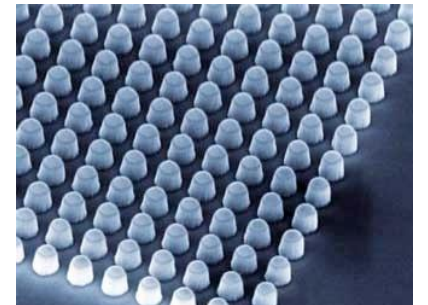
Superconductors



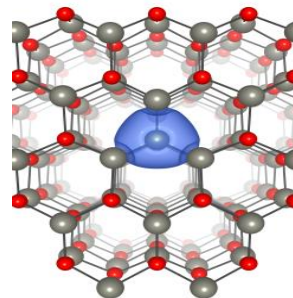
Trapped ions



Optical gratings



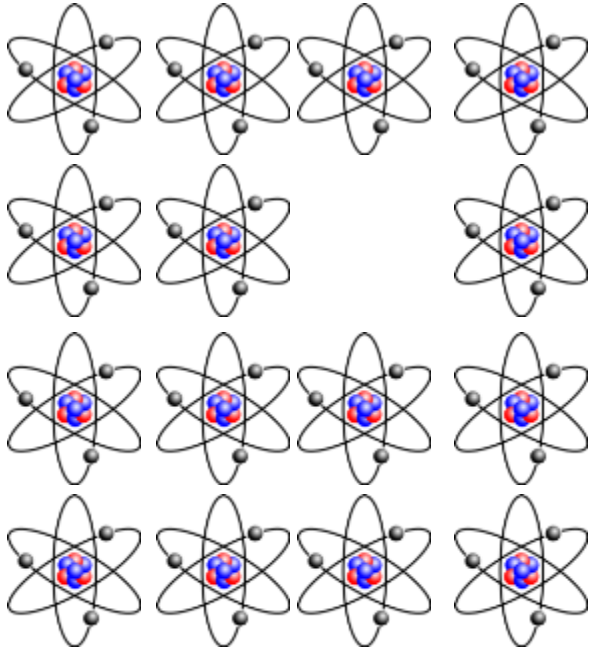
Quantum dots



Point defects

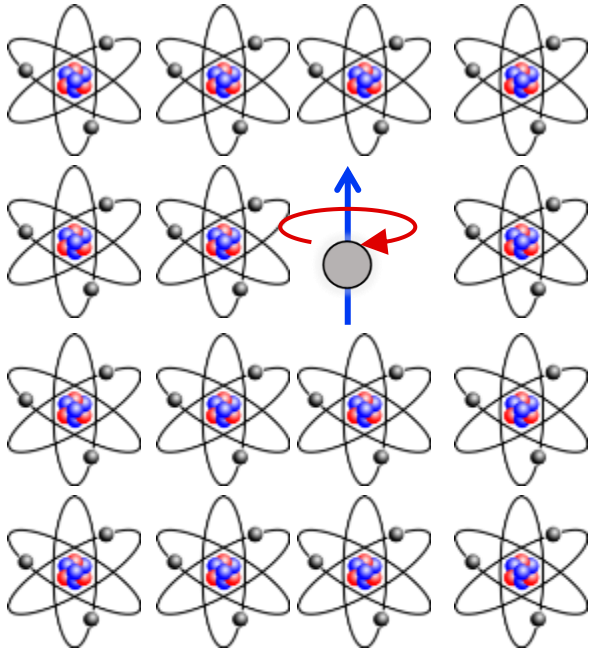
Point defects in semiconductors for QT

Certain point defects can act as isolated two level systems with possibility for spin manipulation and single photon emission properties satisfying the qubit requirements



Point defects in semiconductors for QT

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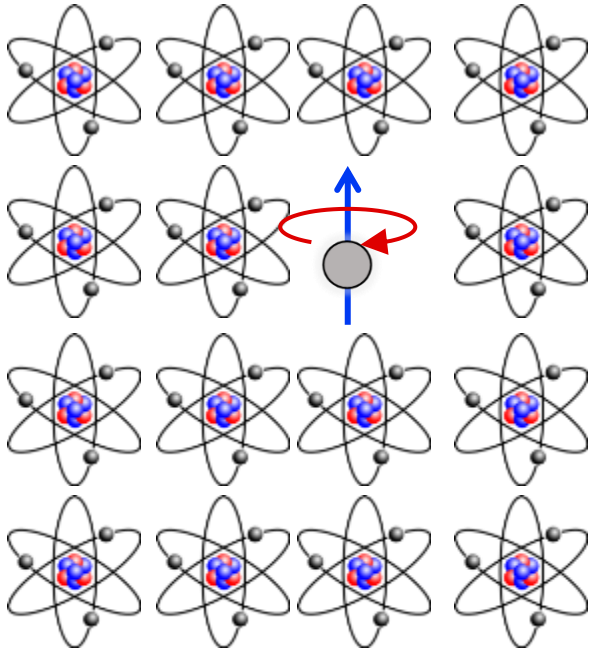


Example: The NV- center in diamond

- ✓ N atom next to C vacancy
- ✓ Spin state with $S = 1$
- ✓ Spin state is stable for milliseconds even at RT → what you need for QC
- ✓ Spin state can be optically initialized, entangled and read out
- ✓ Excite with laser → single-photon emission

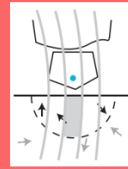
Point defects in semiconductors for QT

Sensing applications



Magnetic sensor

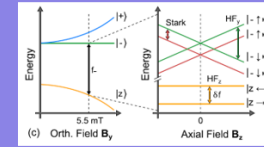
- utilize Zeeman effect
- predicted sensitivity: $250 \frac{aT}{\sqrt{\text{Hz}}} / \text{cm}^{-3}$



Nature Phys., 4, 813 (2008)

Electric field

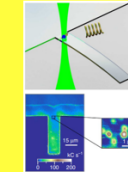
- Utilize Stark effect
- Detection of single charge was demonstrated



PRL 112, 097603 (2014)

Strain

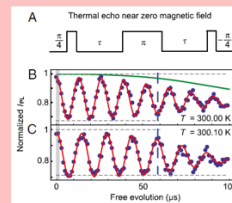
- Interaction with the resonant phonon modes of a macroscopic mechanical resonator through crystal strain



Nature Comm., 5, 4429 (2014)

Temperature

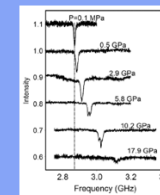
- Fluorescence thermometry with sensitivities $\sim 10 \text{ mK} \cdot \text{Hz}^{-1/2}$



PNAS 110, 8417 (2013)

Pressure

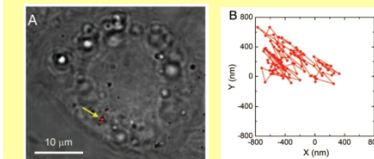
- Hydrostatic pressures up to 60 GPa have been measured



PRL 112, 047601 (2014)

Biomarkers

- Single fluorescent nanodiamonds as cellular biomarkers



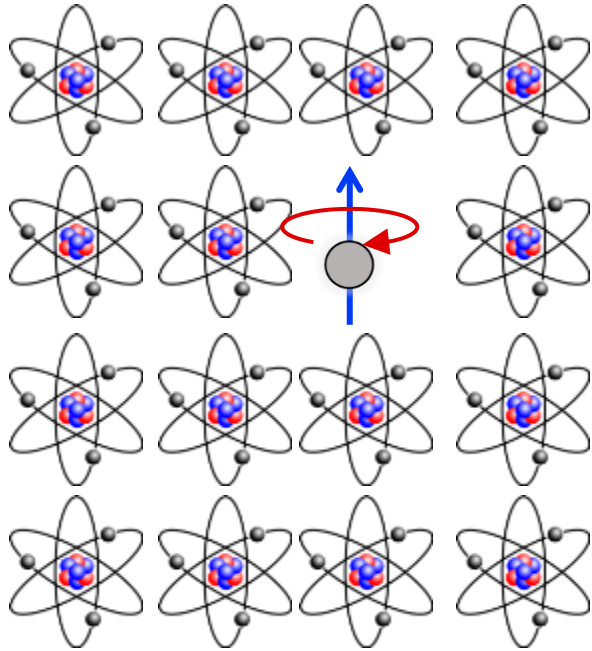
PNAS 104, 729 (2007)

Point defects in semiconductors for QT

SaxonQ

Mobile Quantum Computer

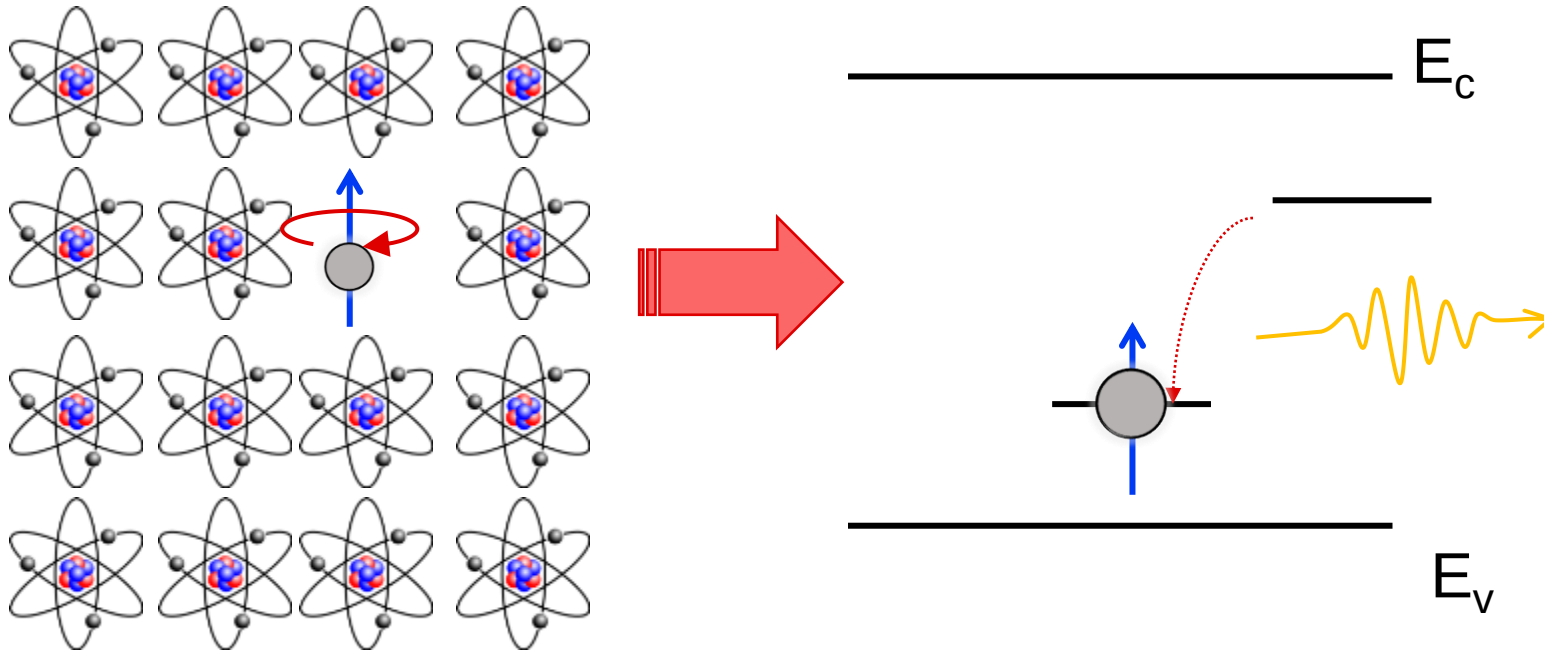
We offer a diamond-based, freely programmable qubit system, which makes it possible to perform various arithmetic operations. Here you have the possibility to manipulate the qubits directly to understand the functionality of quantum computers and to test optimised algorithms.



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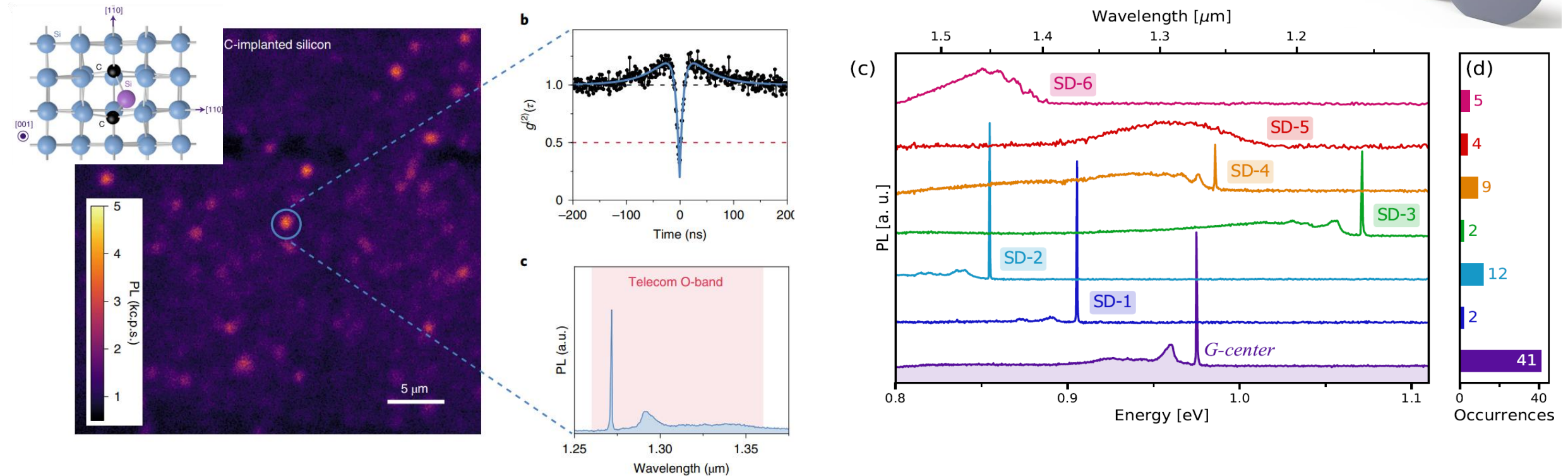
Single photon emission from point defects



Ideal single-photon source:

- Triggered (on-demand)
- $g^{(2)}(0) = 0$
- Indistinguishable photons
- High repetition rate
- Room temperature
- Chip integration

Identification and single photon emission (SPE) from point defects in **Silicon**

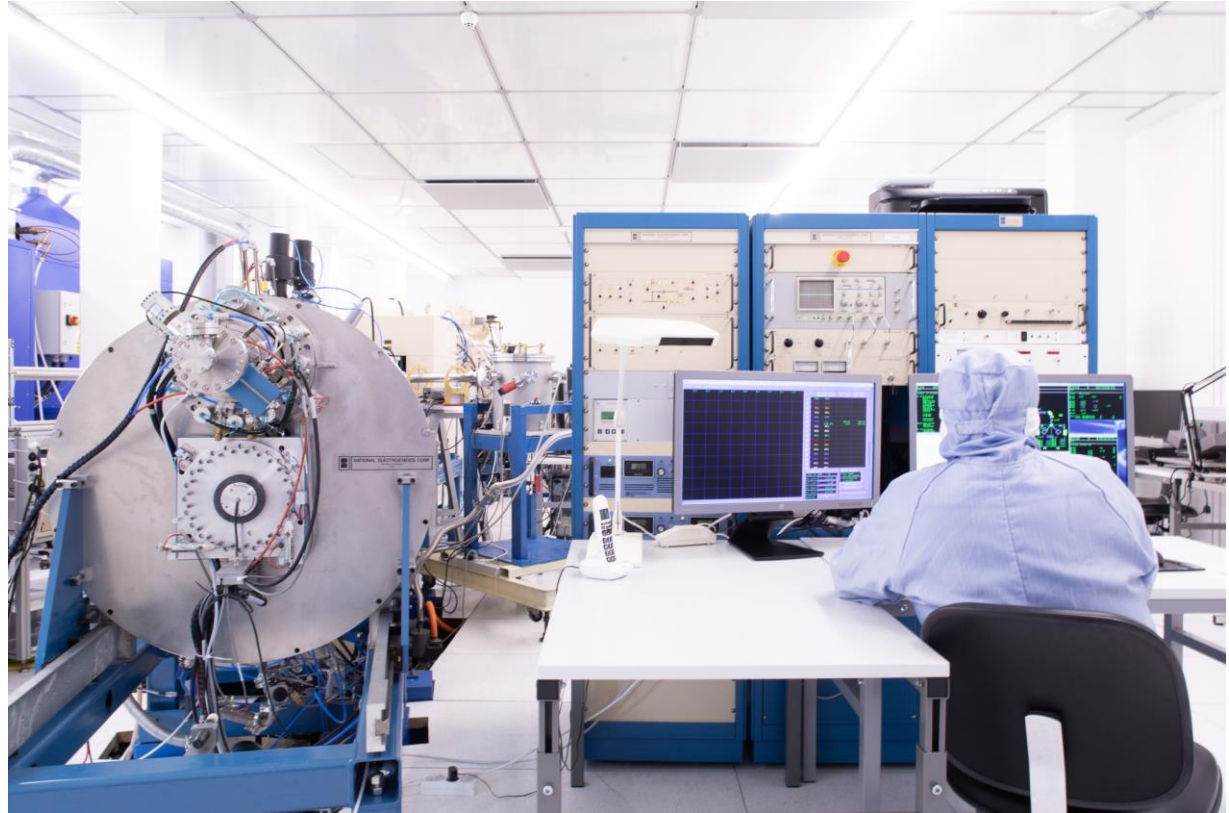
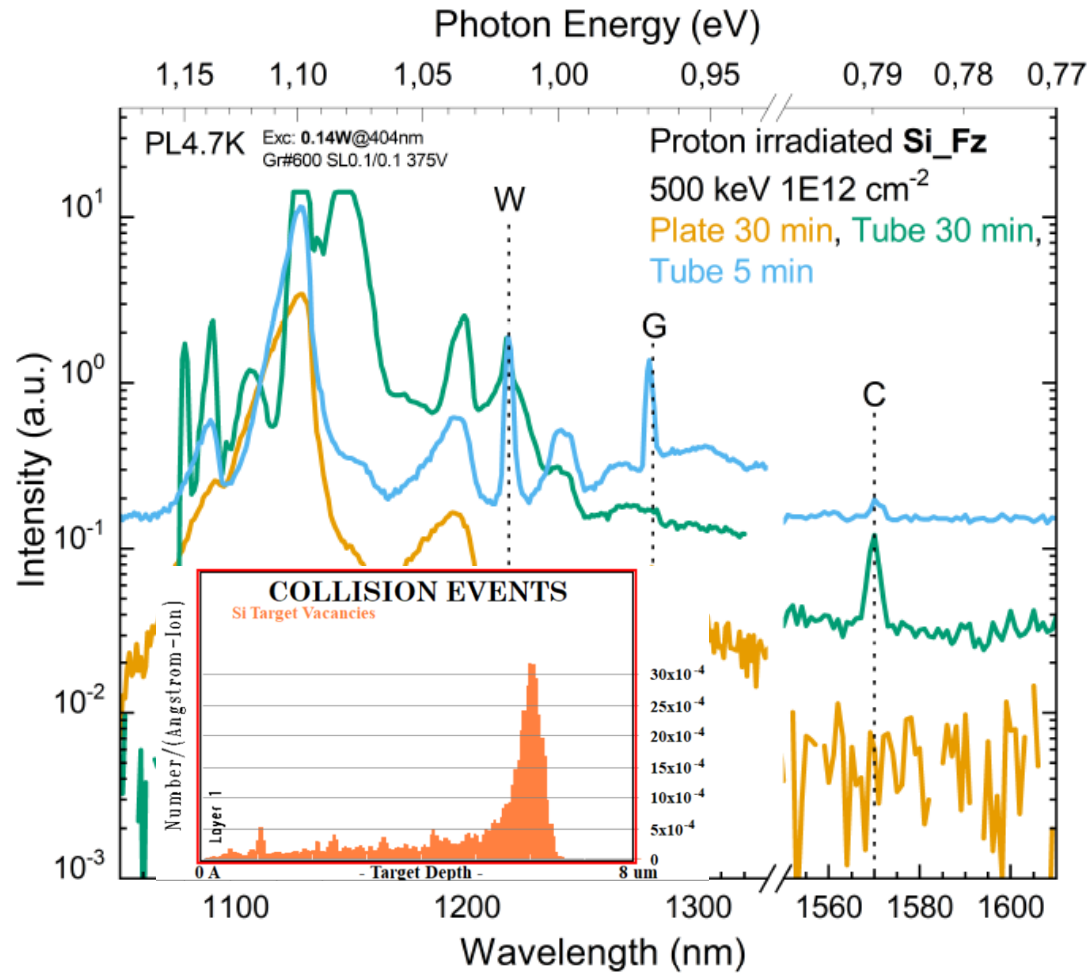


Point defects suitable as solid state qubits and single photon emitters (SPE)

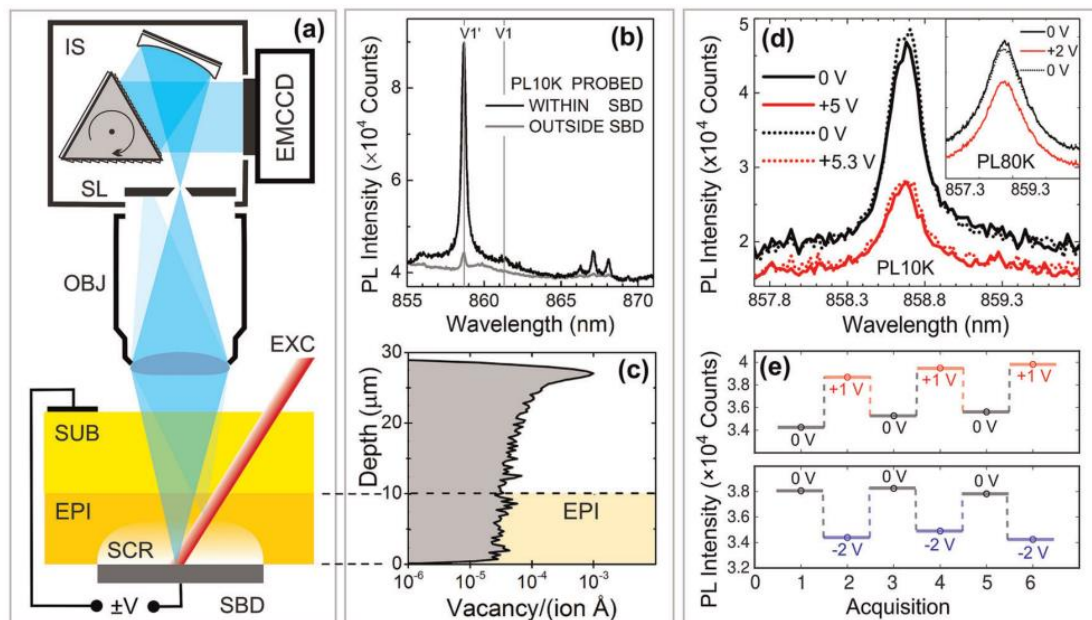
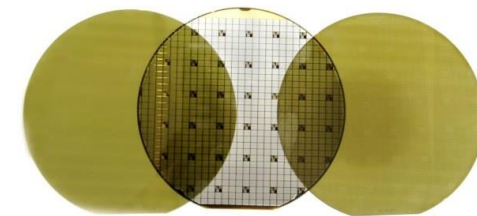
- First identification of SPE in Si, the G-center

Si reveal several other SPEs, e.g. W, T and C-center, but also several unknown defects suitable for telecom wavelengths

Formation of qubit candidates through ion implantation



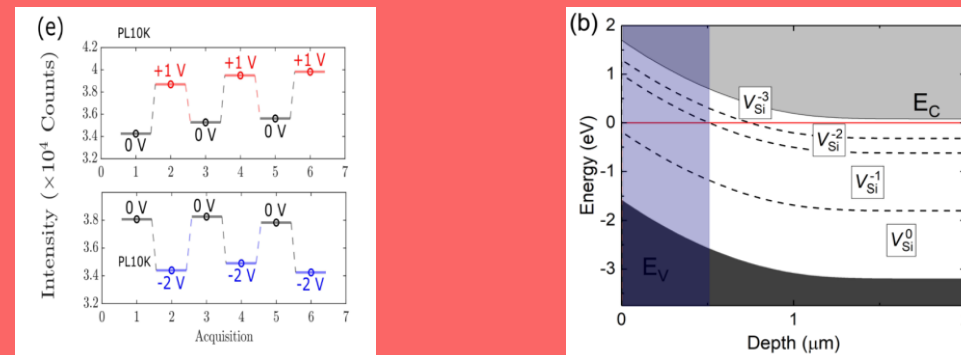
Charge state identification and control of quantum defects in **Silicon Carbide**



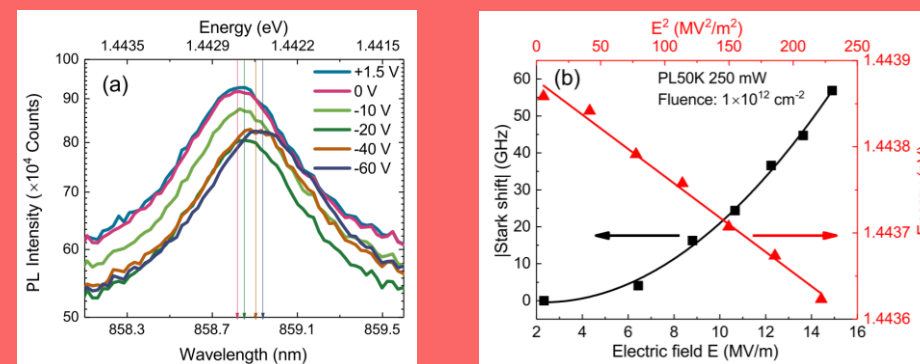
SiC hosts several well-known “quantum defects”

- Only one charge state is bright
- The charge state can be controlled by an electric field
- V_{Si} exhibit a quadratic Stark shift

Emission control



Stark effect (for tuning and sensing)



M. Bathen, ..., L. Vines, *npj Quantum Information*, vol. 5, 111 (2019)

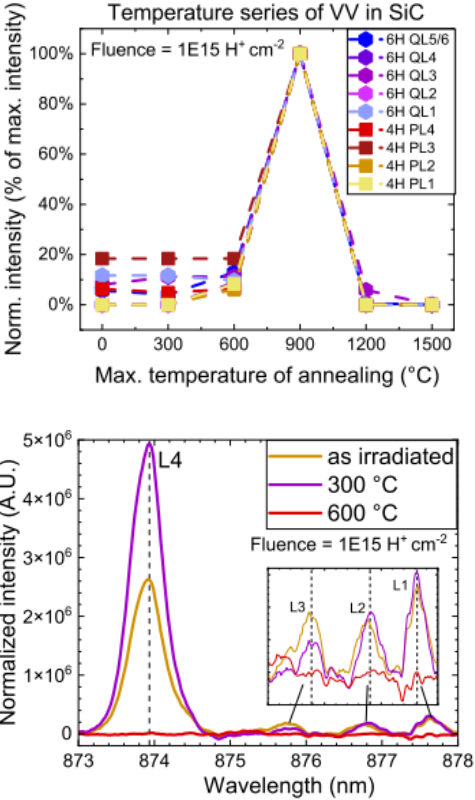
M. Bathen and L. Vines, *Advanced Quantum Technologies*, 4, 2100003 (2021)

M. Bathen, ... L. Vines and U. Grossner, *Defect and Diffusion Forum*, 425, 35 (2023)

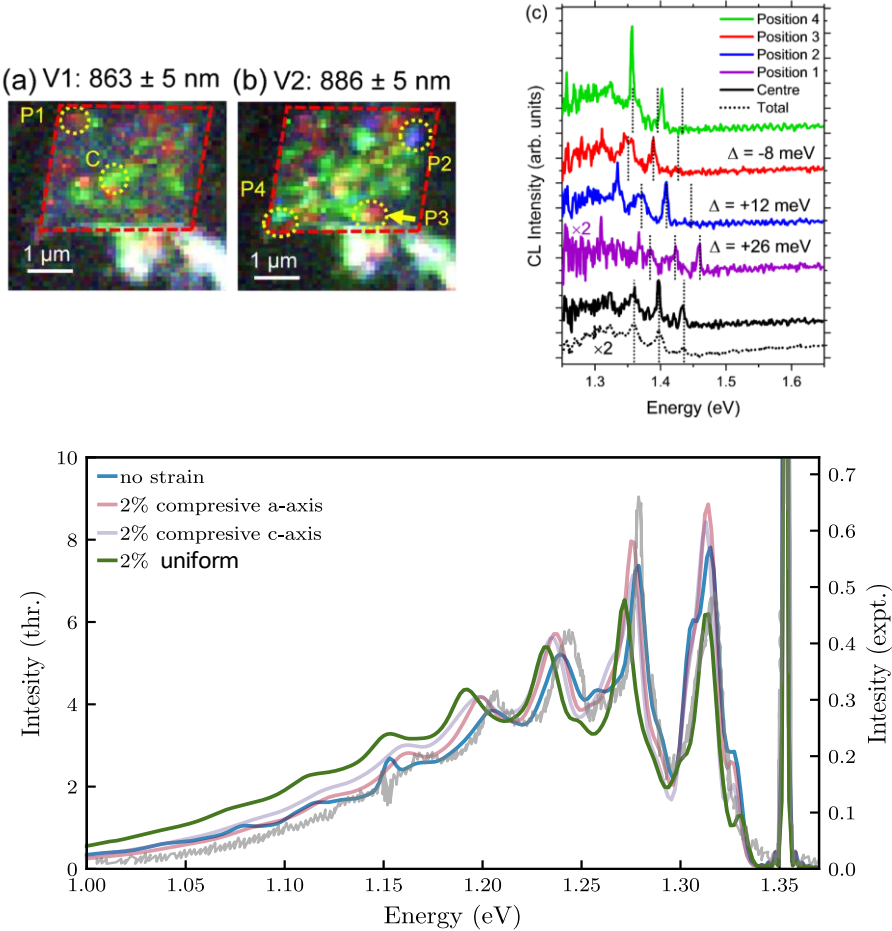
Ongoing projects

SPE's in SiC polymorphs and other materials

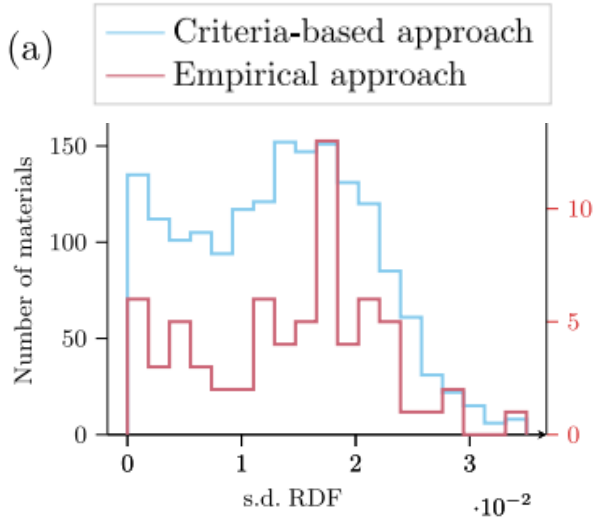
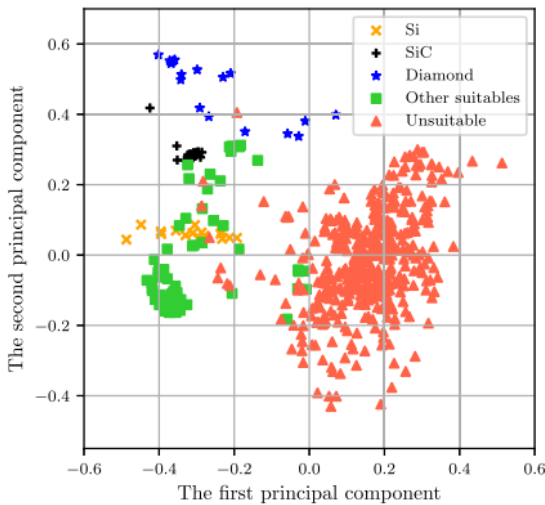
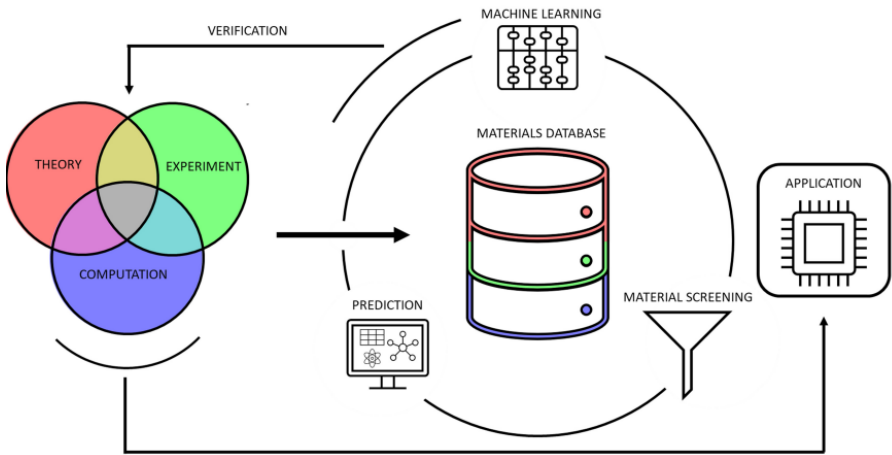
Emission wavelength (nm)	Proton fluence (cm ⁻²)	Annealing temperature (°C), 30 min
571.2	5E14 ^a	1200
586.5	5E14 ^a	900-1200
591.4	5E14 ^a	1200
606.8	5E14 ^a	1200
614.7	5E14 ^a	1200
615.4	5E14 ^a	1200
617.8	5E14 ^a	1200
621.7	5E14 ^a	1200
623.6	5E14 ^a	1200
631.8	5E14 ^a	1200
663.5	5E14 ^a	900 & 1200
671.6	5E14 ^a	0
746.7	5E14-1E15	900
762.9	5E14-1E15	1200
768.6	1E14-1E15	900
822.2	5E14 ^a	0
855.0	5E13-1E15	0
873.8	5E13-1E15	0-300
875.7	5E13-1E15	0-300
876.8	5E13-1E15	0-300
877.6	5E13-1E15	0-300
885.2	5E14 ^a	0
1095.7	5E13-5E14	1500
1100.6	5E14 ^a	1200
1105.1	5E14 ^a	1200
1108.0	5E14 ^a	900
1119.9	5E14 ^a	1200
1123.0	5E14 ^a	1200
1129.1	5E14-1E15	1200
1134.0	5E14 ^a	900
1144.3	5E14-1E15	1200
1146.8	5E14-1E15	1200
1162.7	5E14 ^a	1200
1173.1	5E14 ^a	900-1200
1183.4	5E14 ^a	1200
1186.5	5E14 ^a	0 & 600



Strain effect on emission lineshape



Predicting solid state material platforms for quantum technologies



Crystal structure from large datasets were used as a starting point to predict suitable material hosts for quantum emitters.

- Unconventional parameters was found to be important for the material selection
- Resulted in a list of potential material candidates for experimental investigation

Approach	Material	Crystal structure	MP code	Density (g cm ⁻³)	Band gap (eV)	a, b, c (Å)	α, β, γ (°)
Empirical approach to 0.85 confidence	CdSe	Hexagonal	mp-1070	5.3	0.6	4.4, 4.4, 7.2	90, 90, 120
	CuI	Hexagonal	mp-569346	5.8	1.2	4.3, 4.3, 7.0	90, 90, 120
	CuI	Cubic	mp-22895	5.8	1.2	4.3, 4.3, 4.3	60, 60, 60
	CdSe	Cubic	mp-2691	5.3	0.5	4.4, 4.4, 4.4	60, 60, 60
	BN	Cubic	mp-1639	3.5	4.6	2.6, 2.6, 2.6	60, 60, 60
	InAs	Cubic	mp-20305	5.3	0.3	4.4, 4.4, 4.4	60, 60, 60
	ZnCd ₃ Se ₄	Cubic	mp-1078597	5.3	1.7	6.1, 6.1, 6.1	90, 90, 90
	BC ₂ N	Tetragonal	mp-1008523	3.3	1.6	2.6, 2.6, 3.7	90, 90, 90
	BC ₂ N	Orthorhombic	mp-629458	3.4	1.8	2.5, 2.6, 3.6	90, 90, 90
All approaches to 0.75 confidence	CdSnP ₂	Tetragonal	mp-5213	4.6	0.7	7.2, 7.2, 7.2	131.1, 131.1, 71.7
	GeSe	Cubic	mp-10759	5.5	0.4	4.0, 4.0, 4.0	60, 60, 60
	InP	Cubic	mp-20351	4.6	0.5	4.2, 4.2, 4.2	60, 60, 60
	InP	Hexagonal	mp-966800	4.6	0.5	4.2, 4.2, 6.9	90, 90, 120
	SiSn	Cubic	mp-1009813	4.4	0.4	4.3, 4.3, 4.3	60, 60, 60
	ZnGeAs ₂	Tetragonal	mp-4008	5.2	0.6	7.0, 7.0, 7.0	131.4, 131.4, 71.2

Material properties for the 9 materials predicted by the empirical approach (>0.85 confidence) and the 6 materials predicted by all approaches (>0.75 confidence).



Andrej



Lasse



Augustinas



Vegard



Marianne



Christopher



David



Erlend



Alireza



Mariann

Luis Roberto
Jimenez Arteta

Joseph Panana Vera

Thank you for the attention!

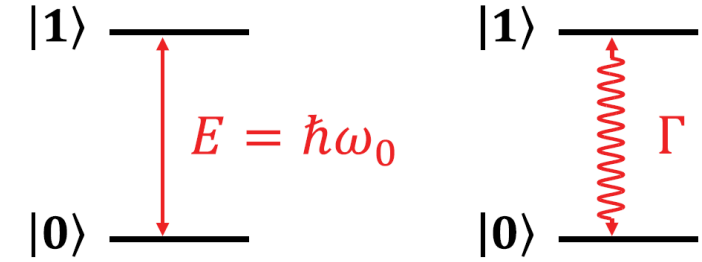
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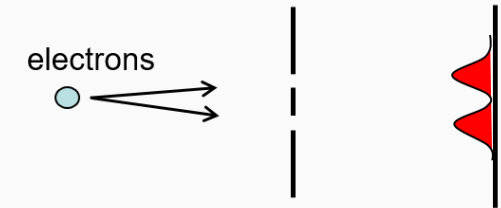
What is quantum sensing ?

Definitions:

1. Use of quantum system with quantized energy levels to measure a physical quantity
2. Use of quantum coherence (i.e., wavelike spatial or temporal superposition states) to measure a physical quantity.
3. Use of quantum entanglement to improve the sensitivity or precision of a measurement, beyond what is possible classically

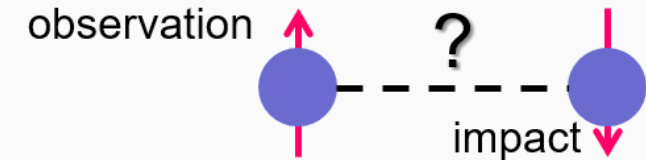


- Superposition

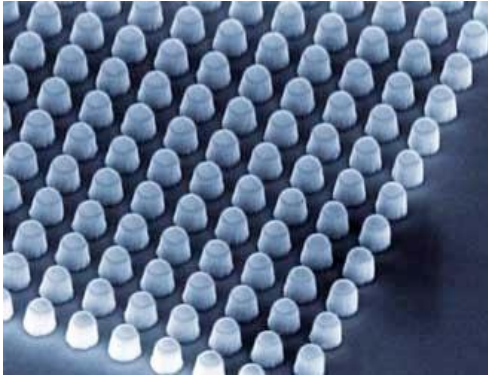


$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

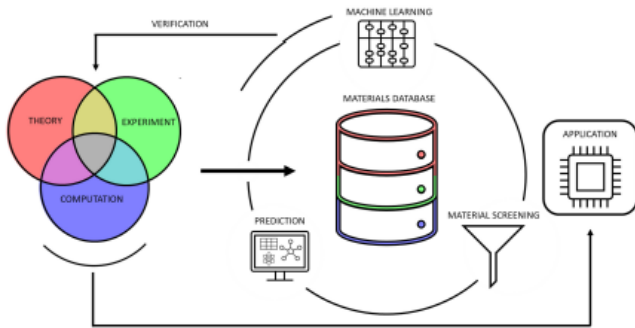
- Entanglement



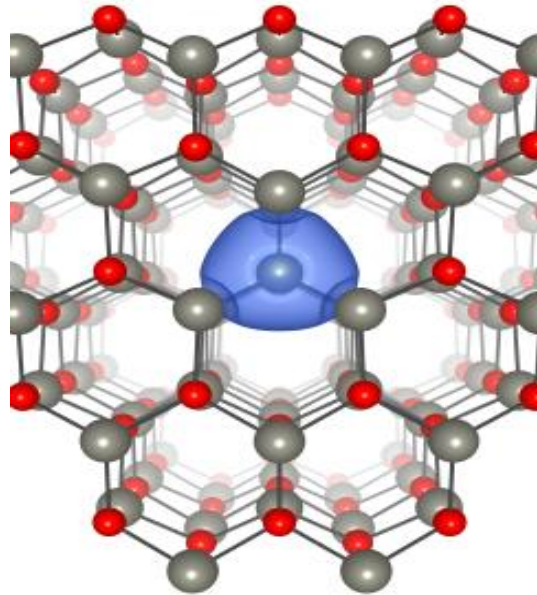
Ongoing QT research at the University of Oslo



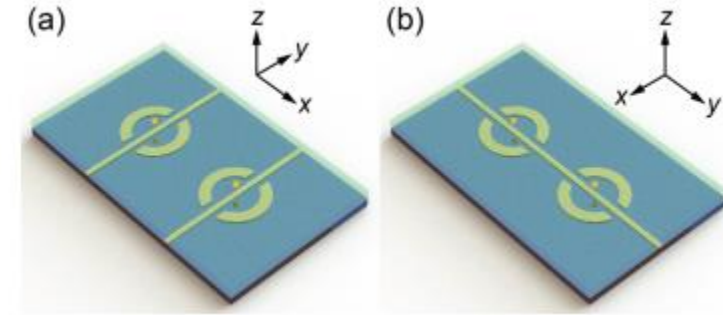
Nanoparticle and epitaxial quantum dots



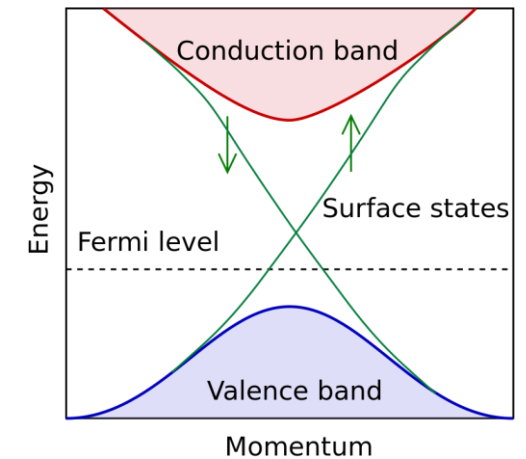
Machine learning for new quantum materials



Point defects

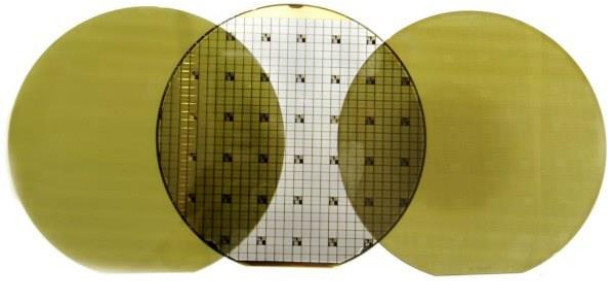


Liquid He quantum dots



Properties of quantum materials

Semiconductor materials for QT



Silicon carbide
Point defects



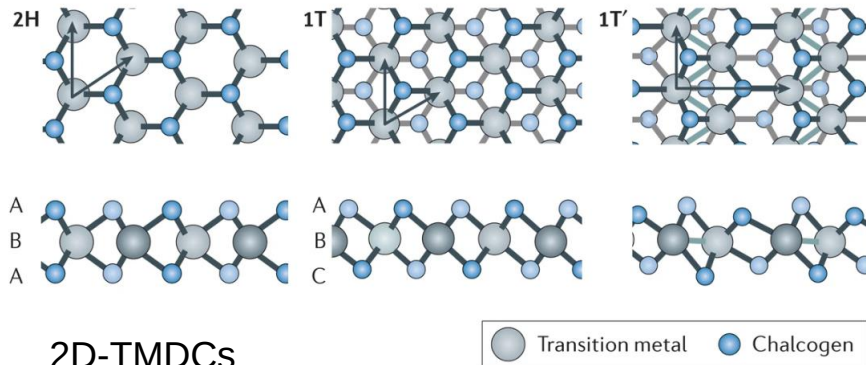
Diamond
Point defects



Silicon
Point defects
Spin qubit CMOS devices



Gallium arsenide
Quantum dots

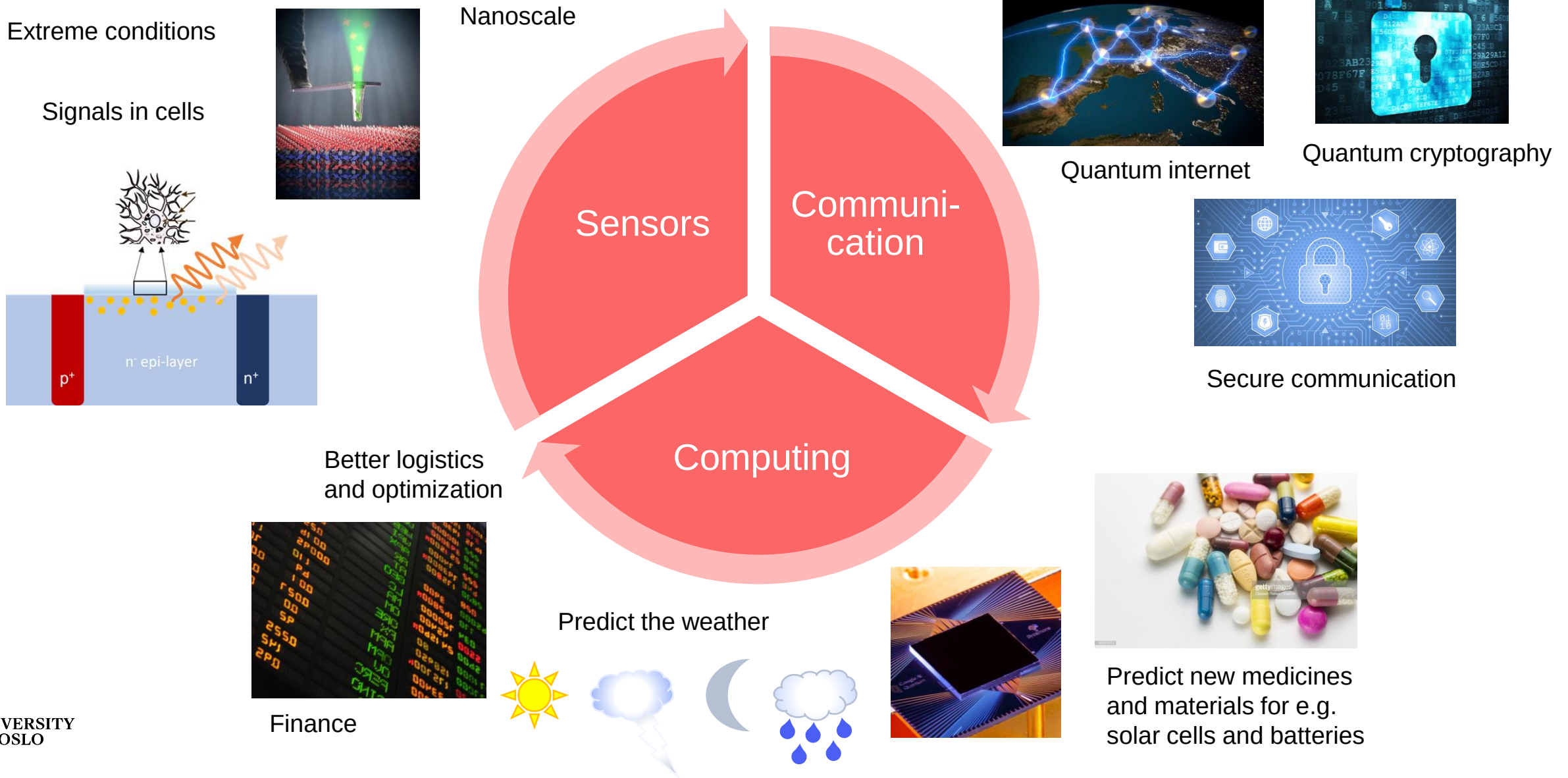


2D-TMDCs
Bound excitons



Hexagonal boron nitride
Point defects

Quantum technologies promise new capabilities





Questions?