Quantum sensing and Quantum Materials

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Diamond Nitrogen-Vacancy center

Defects add unique properties to diamond

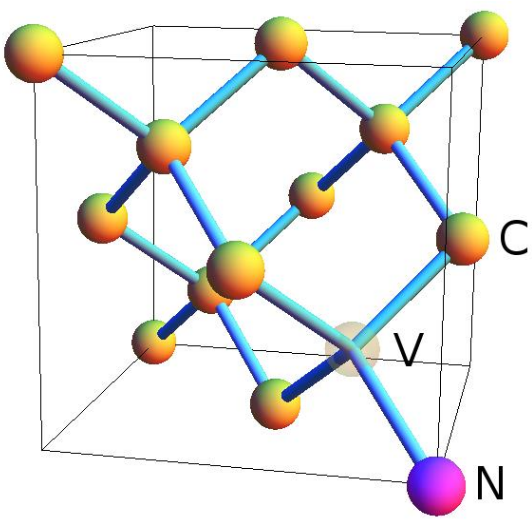
Tiffany's gemstone

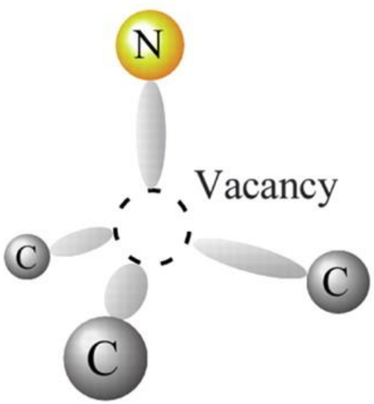
Nitrogen defects

Boron defects

Hydrogen defects

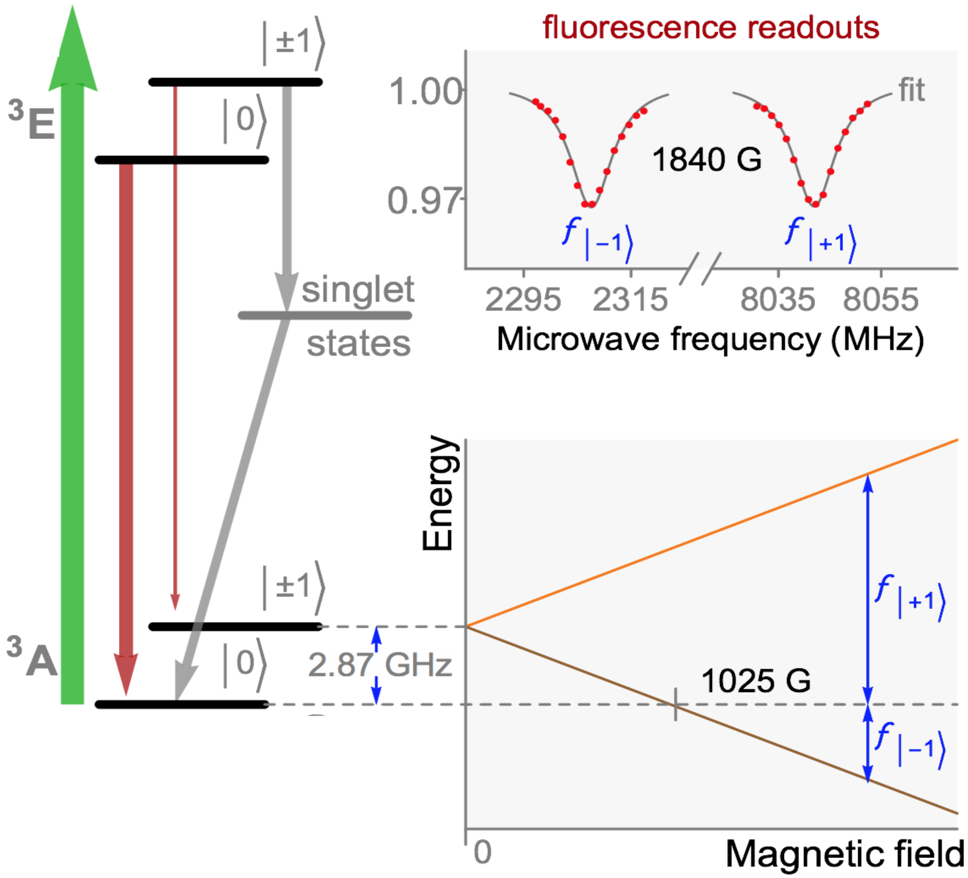
Diamond lattice with Nitrogen-Vacancy (NV)



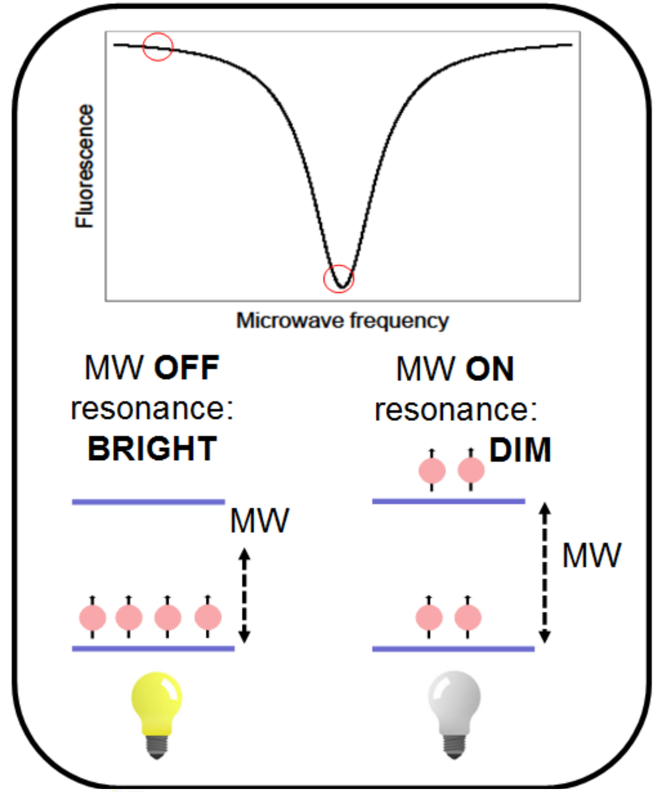


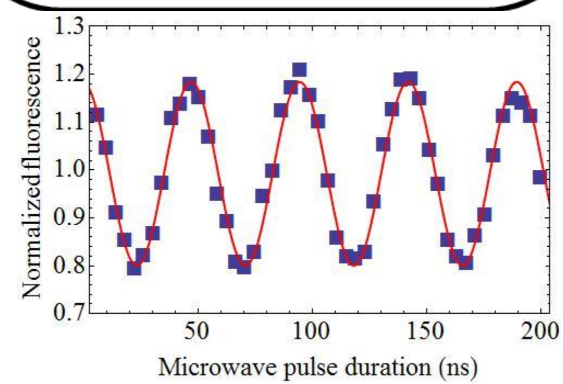
- C3v symmetry
- NV0, **NV-**
- 6 e-, 2 unpaired (gs)

Nitrogen-Vacancy center: detailed picture



Optically-detected magnetic resonance (ODMR)





Why NV centers?:

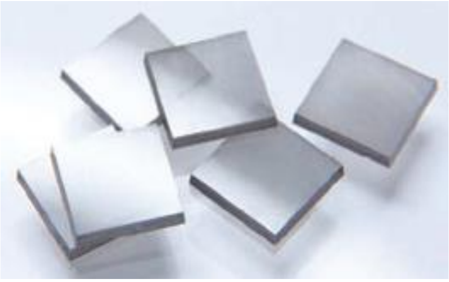
1. S=1 ground state
2. Optical initialization/readout
3. T_2>1 ms at 0-300+ K
4. Optical coherence (low T)
5. Atomic wavefunction (<1 nm)
6. **Semiconductor Fab**

Marcus W. Doherty, et al., Physics Reports 528, 1–45 (2013)

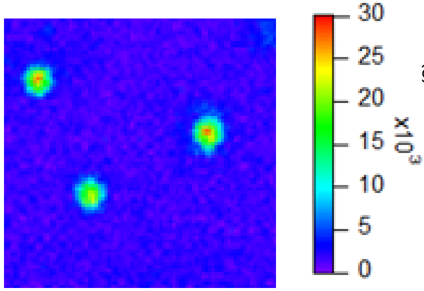
NV engineering in diamond

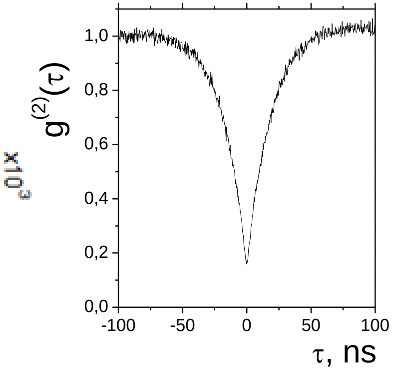
Single-crystal CVD growth

- $1\text{-}10^5$ nm layers
- 99 % C-12 (I=0)
- Defect densities < 10 ppb



http://www.vivialdiamonds.com/

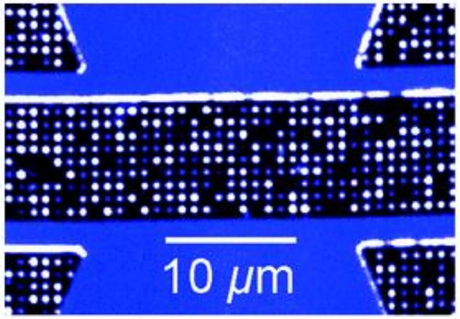


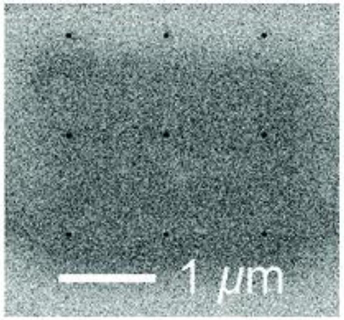


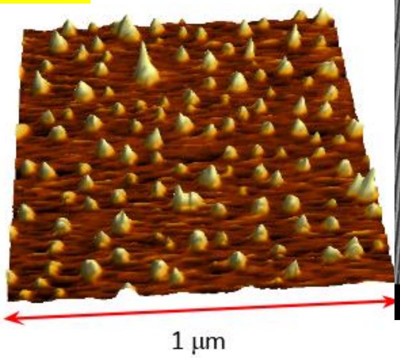
Single photon emission from isolated NVs

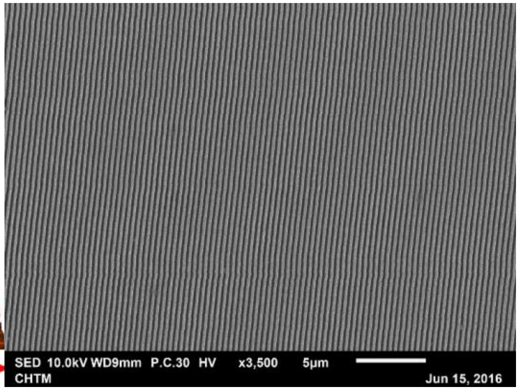
- **Nitrogen, He, + annealing, + nanopatterning**
- Single-center addressability
- Nanometer placement

nanodiamonds/nanopillars









M. Toyli, D. D. Awschalom, et al., ***Nano Lett.***10, 3168 (2010)

Trusheim, Li, **Laraoui**, et al., ***Nano Lett.***, 14 (1), 32-36 (2014)

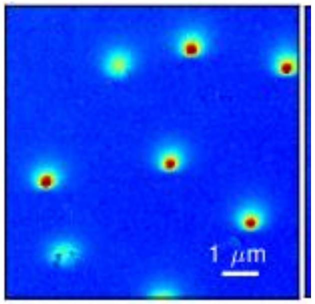
Kehayias, **Laraoui**, et al., ***Nature Comms.*** 8, 188 (2017).

NV centers in diamond: Quantum sensing

$$\frac{\mathcal{H}}{\hbar} = \underbrace{D\left(S_z^2 - \tfrac{2}{3}\right)}_{\text{zfs}} + \underbrace{\gamma \mathbf{B}\cdot\mathbf{S}}_{\text{magnetic}} + \underbrace{\epsilon_z E_z\left(S_z^2 - \tfrac{2}{3}\right) + \epsilon_{xy}\{E_x\left(S_x S_y + S_y S_x\right) + E_y\left(S_x^2 + S_y^2\right)\}}_{\text{electric}}.$$

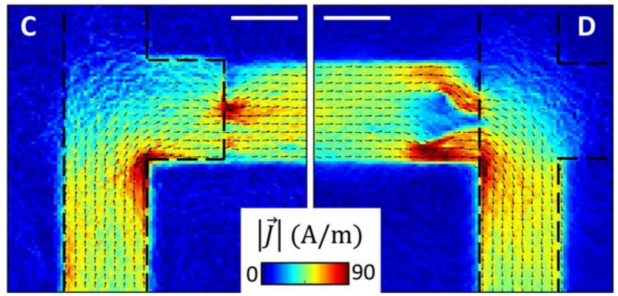
Temperature, strain, pressure

Superconductivity



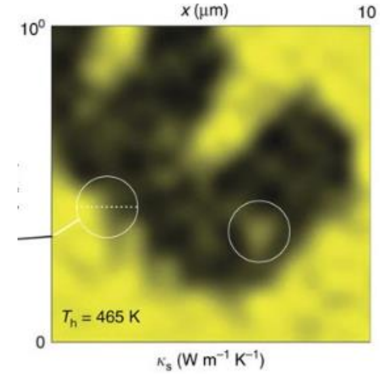
Thiel et *al.*, ***Nature Nano.*** (2016)

Graphene current imaging



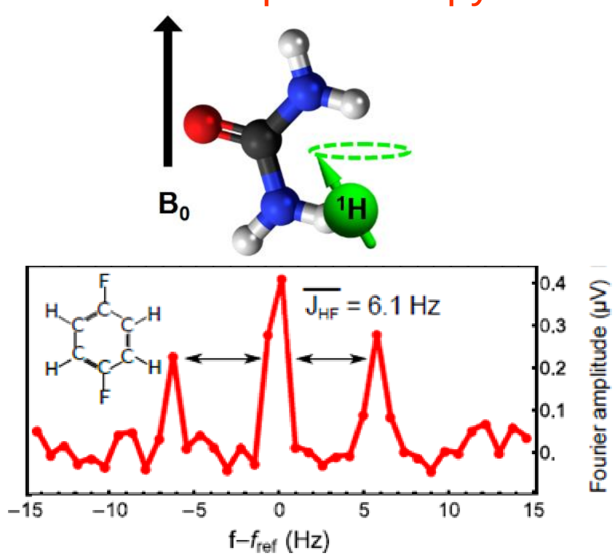
Tetienne et al. ***Science Adv.*** (2017)

Thermal conductivity



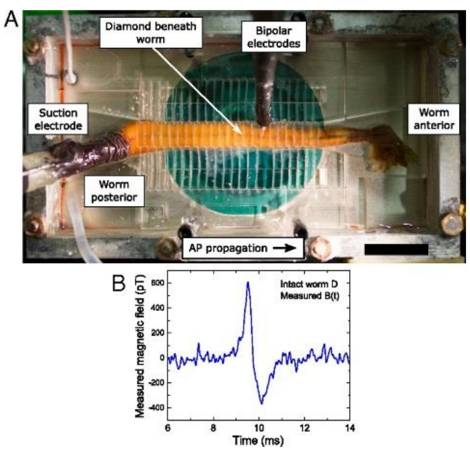
Laraoui et al. ***Nat Comms*** (2015)

NMR spectroscopy



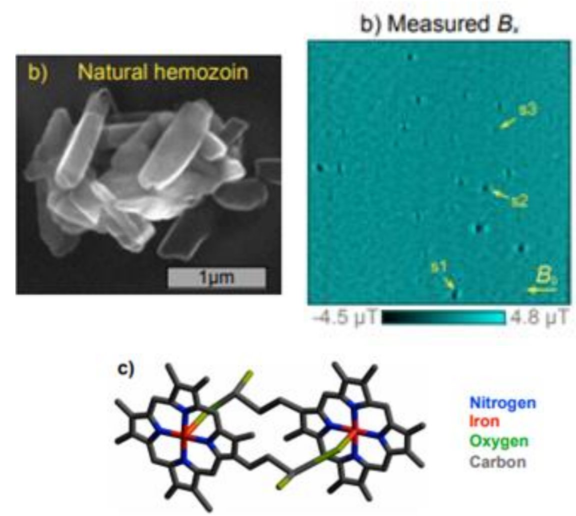
Laraoui, et al, ***Nature comms*** (2013)
Smit, **Laraoui**, et al. ***Science Advances*** (2019)

Neuron recording



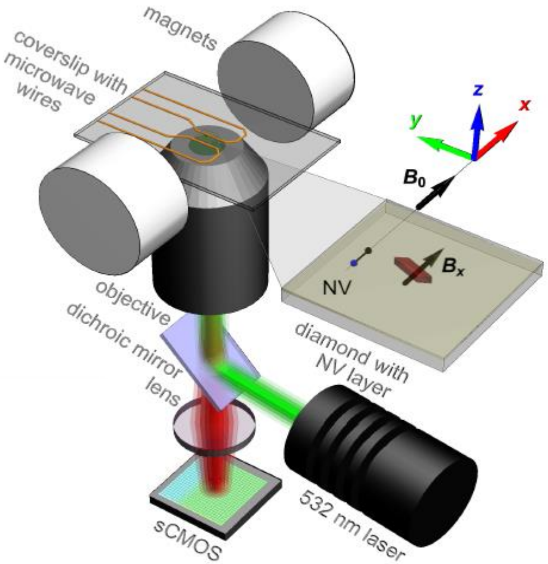
Barry et al. ***PNAS*** (2016)

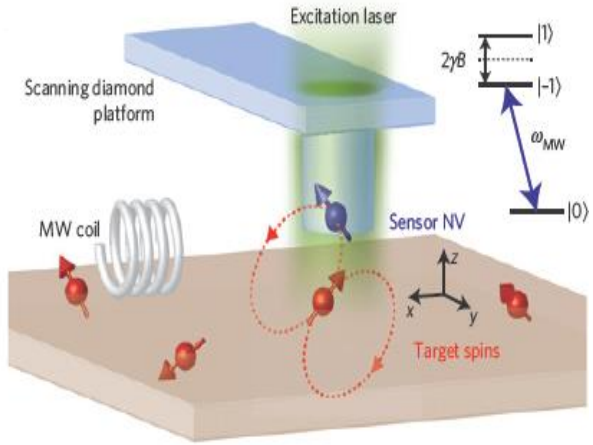
Malarial biocrystals imaging



Fescenko, **Laraoui**, et al, ***Science Advances***, *under review*

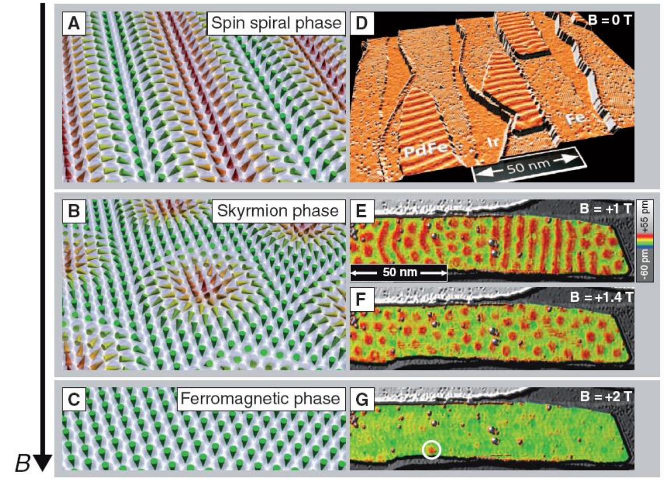
Project 1: diamond quantum sensing



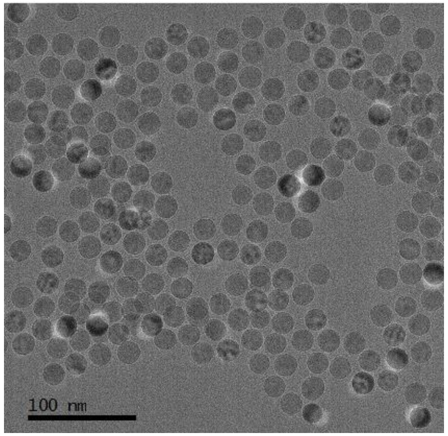


NV-microscopy: far-field, nearfield (AFM)

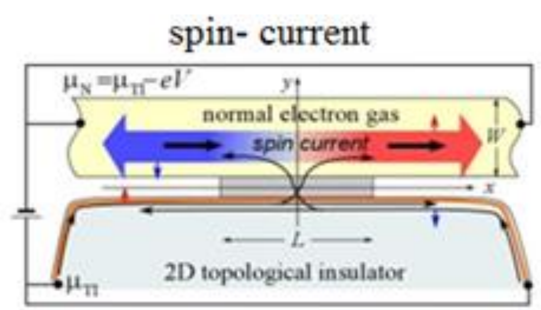
2D skyrmion-topological states in FeGe, PdFe,…



- **Nanoscale (sub-nm) resolution**
- **Super-sensitivity**: single spin detection, sub-pT magnetic field, sub-mK temperature,…
- **Flexibility:** 1-1000 K, KHz-THz, 0-3T, optical/electrical readout, …



Transition-metal nanoparticles, size < 20 nm for application in bioimaging, high-density data storage



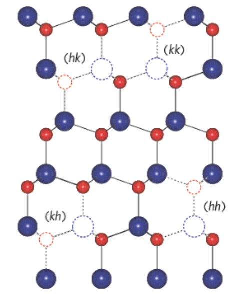
Surface spin current in topological insulators (bismuth selenide, …)

Many physical phenomena are not explored at the nanometer scale: spin textures, heat transfer, electron/spin transport, physical properties of low-dimensional materials, …

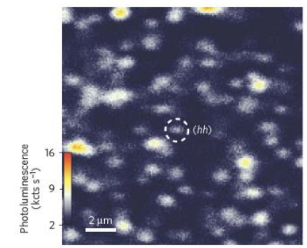
Project 2: Study new quantum materials (defects in WDG semiconductors/ 2D materials)

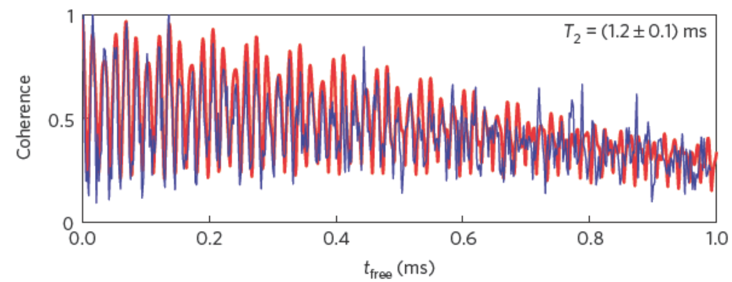
Table I. Relevant properties of potential host materials.

Material	Bandgap (eV)	Spin-Orbit Splitting (meV)	Stable Spinless Nuclear Isotope
Diamond	5.5	6	Yes
3C-SiC	2.2	10	Yes
4H-SiC	3.2[38]	6.8	Yes
6H-SiC	2.86	7.1	Yes
AlN	6.13	36[41]	No
GaN	3.44	17	No
AlP	2.45	50 (theory)[42]	No
GaP	2.27	80 (RT)	No
AlAs	2.15	275 (RT)	No
ZnO	3.3[39]	–3.5	Yes
ZnS	3.68[40]	64 (RT)	Yes
ZnSe	2.82	420 (RT)	Yes
ZnTe	2.25	970	Yes
CdS	2.48	67	Yes



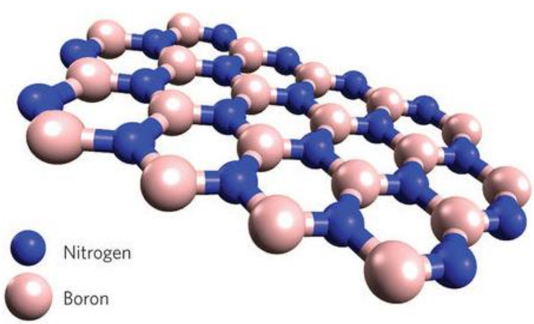
4H-SiC lattice



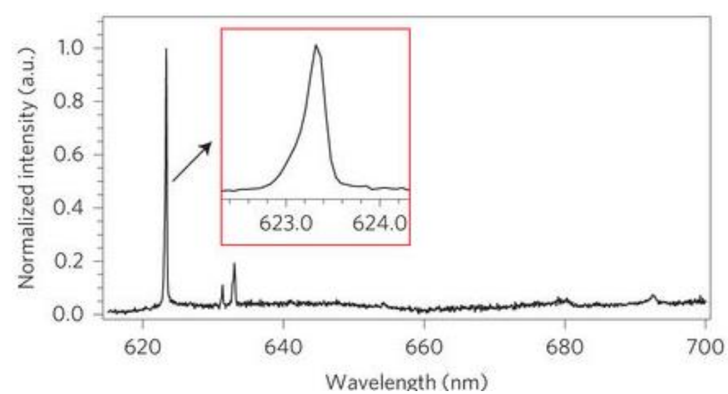


D. J. Christle, et al. ***Nature Materials***, 14, 160 (2015).

2D materials: hBN, Transition metal dichalcogenide(MoS_2, WS2, WSe_2, $MoTe_2$



T. Tran, et *al.*, *Nature Nanotech*. 11, 37–41 (2016).



Very emerging field: origin of defects not well understood, spin coherence mechanisms, integration to devices (eg. optoelectronics), scalable quantum networks,…

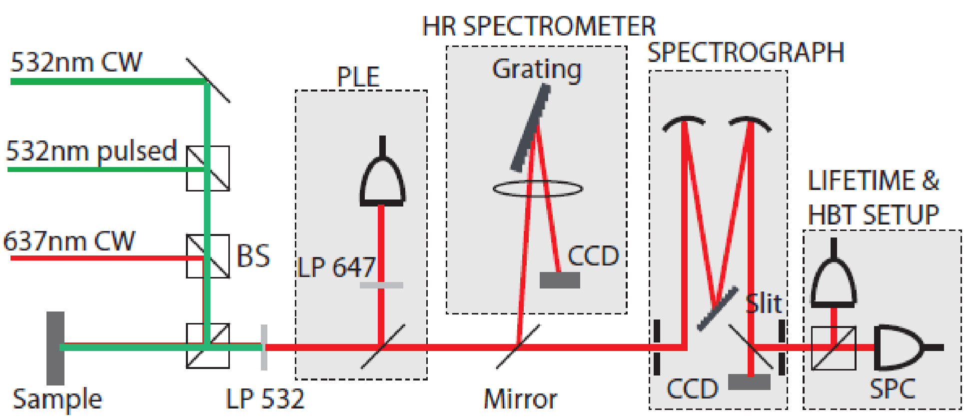
Project 2: Study new quantum materials (defects in WDG semiconductors/ 2D materials)

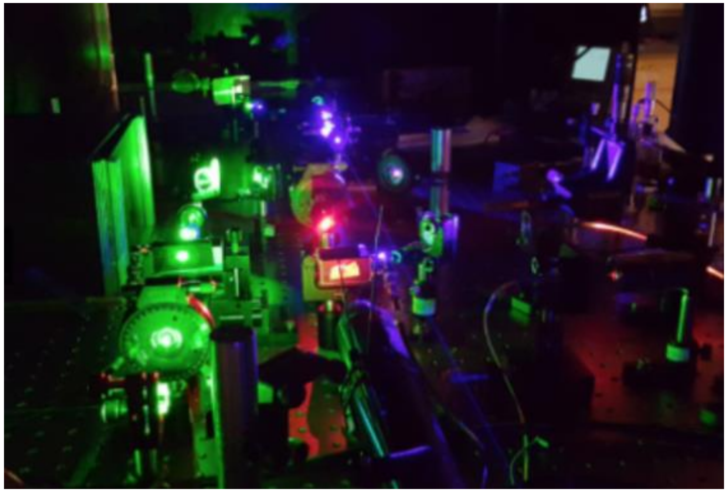
Samples: WBG: SiC (SiV, 6H, transition-metal ions), ZnO, AlN, GaN,…
2D: CVD + exfoliated monolayer/multilayer flakes from bulk hBN, WSe_2, MoS_2, …

Projetcs: ***1)*** study the origin of defects, ***2)*** measure the spin decoherence lifetime, ***3)*** explore single photon emission for integration to optoelectronic devices, ***4)*** develop new characterization techniques tailored to varieties of excitations (optical, electrical, magnetic, thermal, strain, etc.), ***5)*** build quantum networks based on their quantum properties.

Applications: innovative device designs and sensors based on their novel properties, scalable quantum systems for computing, optoelectronics, spintronics, etc

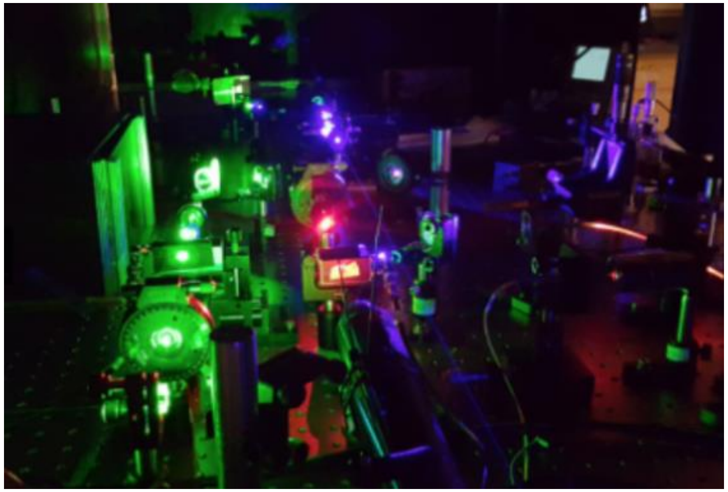
Setup: Confocal fluorescence microscope (single-photon sensitivity, high spectral resolution ~100 MHz, T = 4 – 300 K, B = 0-1 T)

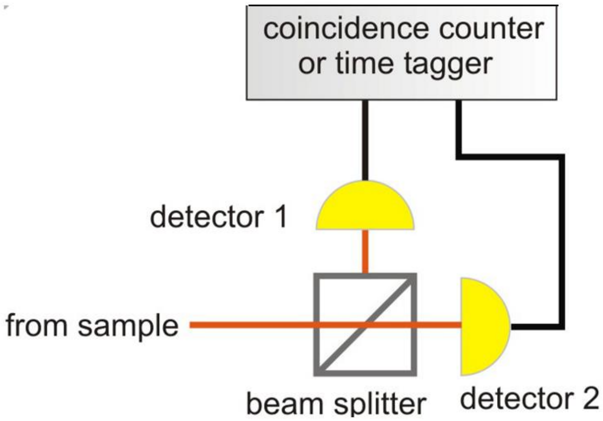


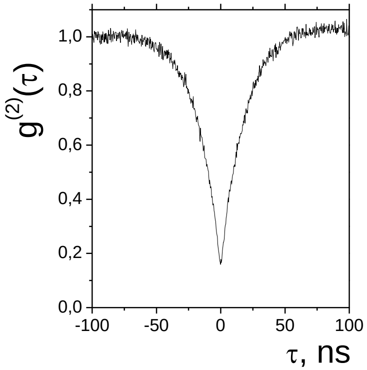


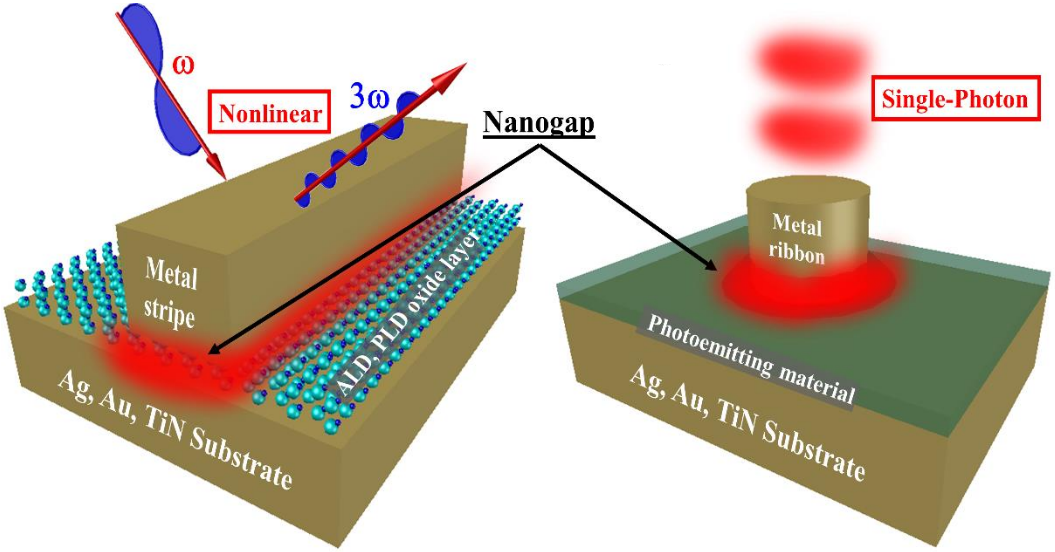
Built similar setups at CCNY, Univ. Strasbourg, UNM from scratch to full operation

Project 2: Applications of new quantum materials: nanophotonics





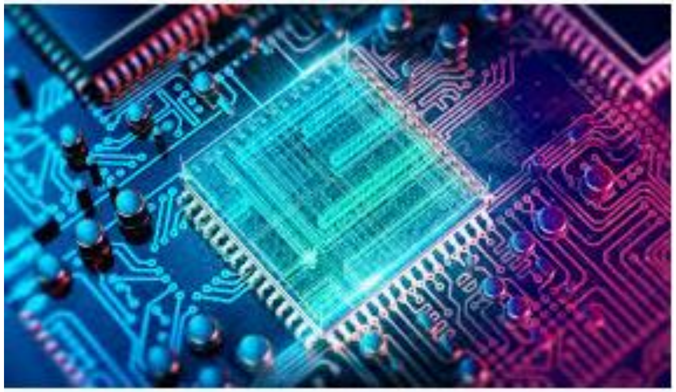


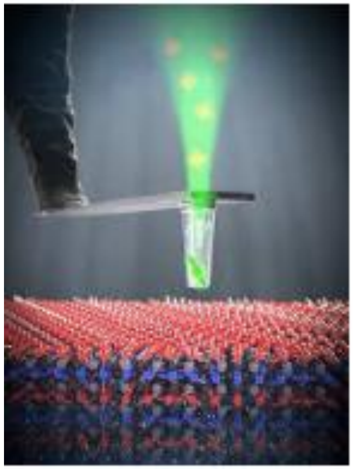


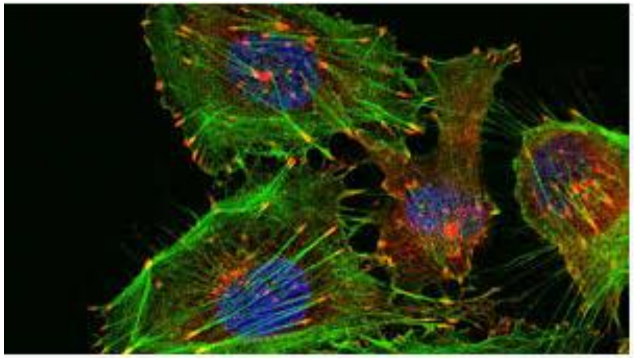
Enhanced nonlinear and quantum optical effects based on localized gap-plasmon nanomaterials

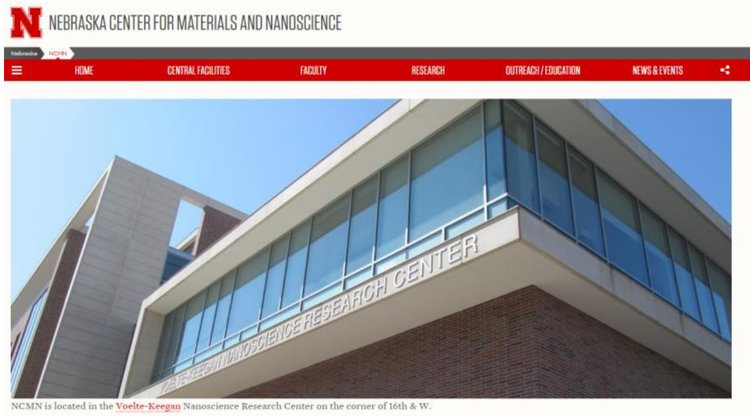
Students/postdocs wanted!

If you want to get trained as a quantum engineer and learn new skills in quantum optics, quantum materials, and quantum (bio) sensing, please contact us.









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