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

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

NV engineering in diamond

Single-crystal CVD growth
- 1-10^5 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


**Superconductivity**

\[
\frac{\mathcal{H}}{\hbar} = D \left( S_z^2 - \frac{2}{3} \right) + \gamma \mathbf{B} \cdot \mathbf{S} + \varepsilon_z E_z \left( S_z^2 - \frac{2}{3} \right) + \varepsilon_{xy} \left\{ E_x \left( S_x S_y + S_y S_x \right) + E_y \left( S_x^2 + S_y^2 \right) \right\}.
\]

Temperature, strain, pressure

**Graphene current imaging**


**Thermal conductivity**


**Neuron recording**


**NMR spectroscopy**


**Malarial biocrystals imaging**

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,

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>
<thead>
<tr>
<th>Material</th>
<th>Bandgap (eV)</th>
<th>Spin-Orbit Splitting (meV)</th>
<th>Stable Spinless Nuclear Isotope</th>
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<tbody>
<tr>
<td>Diamond</td>
<td>5.5</td>
<td>6</td>
<td>Yes</td>
</tr>
<tr>
<td>3C-SiC</td>
<td>2.2</td>
<td>10</td>
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<td><strong>4H-SiC</strong></td>
<td><strong>3.2</strong></td>
<td>6.8</td>
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<td>6H-SiC</td>
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<td>AlN</td>
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<td>GaN</td>
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<td>50 (theory)^b</td>
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<td>CdS</td>
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</table>

2D materials: hBN, Transition metal dichalcogenide(MoS$_2$, WS$_2$, WSe$_2$, MoTe$_2$)


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$_2$, …

**Projects:** 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. Strasbour, 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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