Solid-State Quantum Magnetometers*

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Agenda

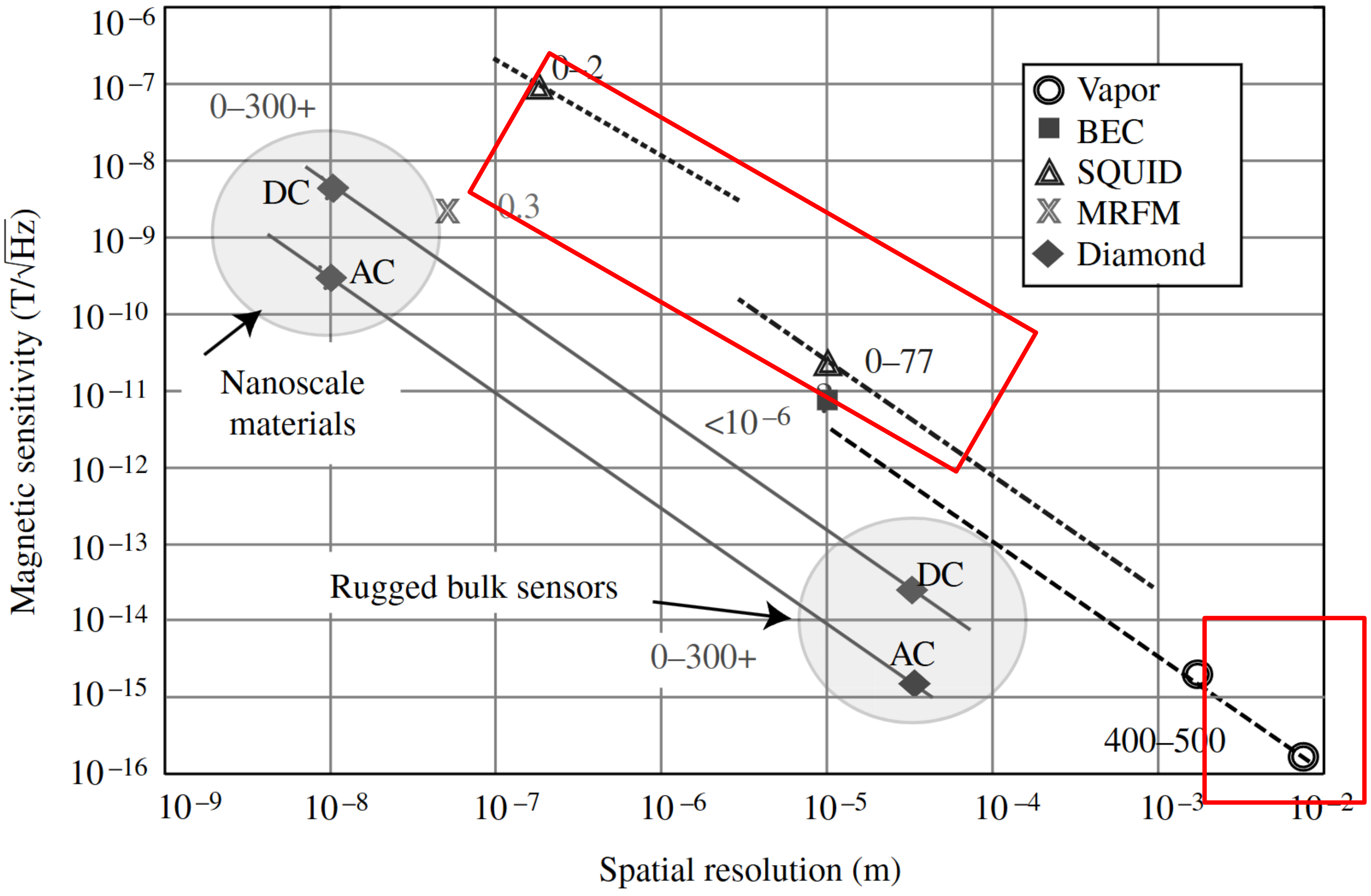
- The need for solid-state quantum magnetometers
- State of the art in magnetometers
  - Nitrogen-vacancy center in diamond as the prototype solid-state magnetometer
- Defect center in SiC semiconductor as a quantum magnetometer
- Advantages of SiC as potential platform for quantum magnetometers

Magnetometers: State of the art and Limitations/Challenges

Superconducting
(SQUID)
sensitivity
Complicated

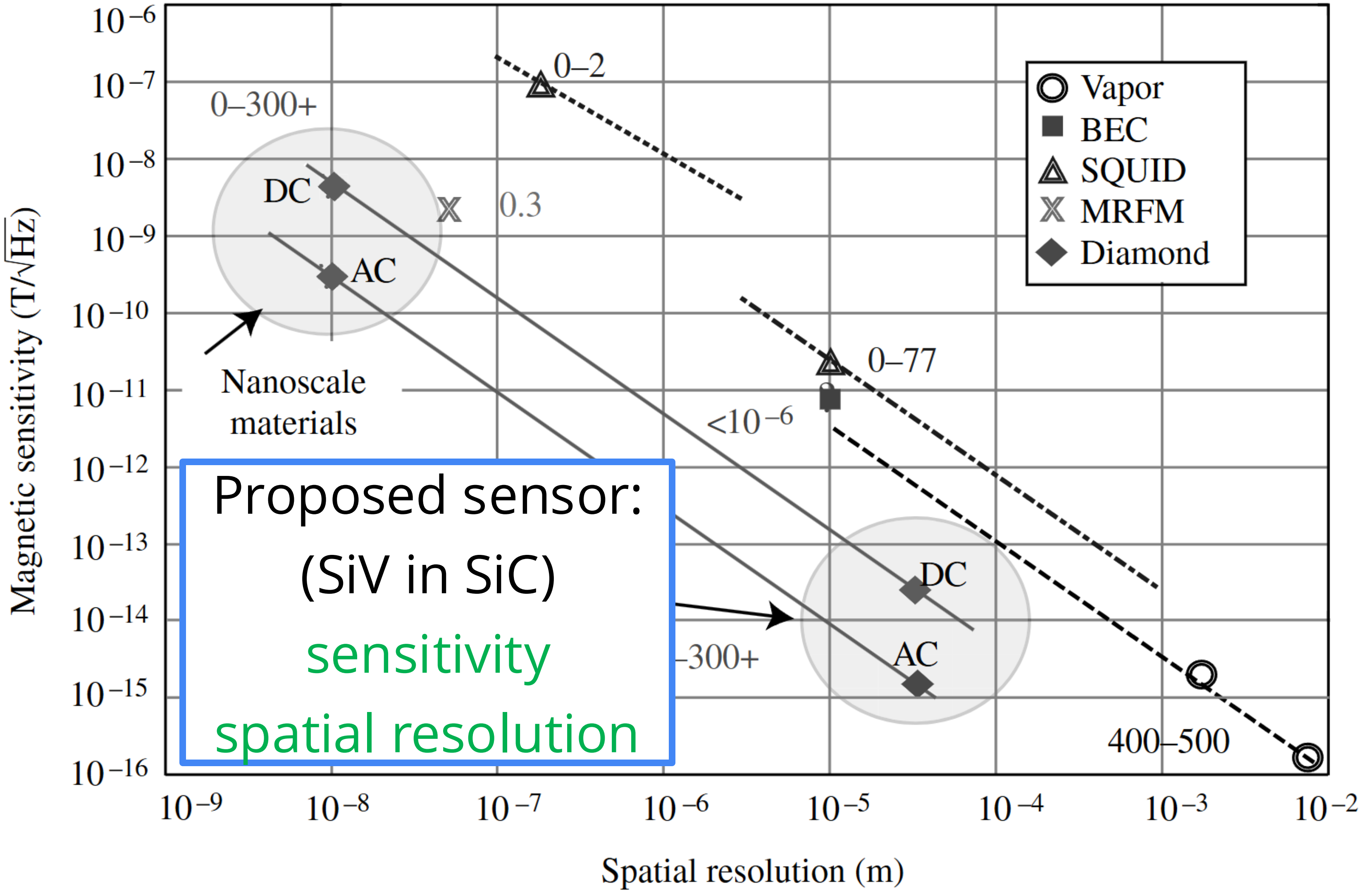
Newer Solutions

OPM
(Solid state)
Room temperature
spatial resolution



D. Budker and D. F. Jackson Kimball, Eds., Optical Magnetometry, 2013

Semiconductor Solid-state Sensors



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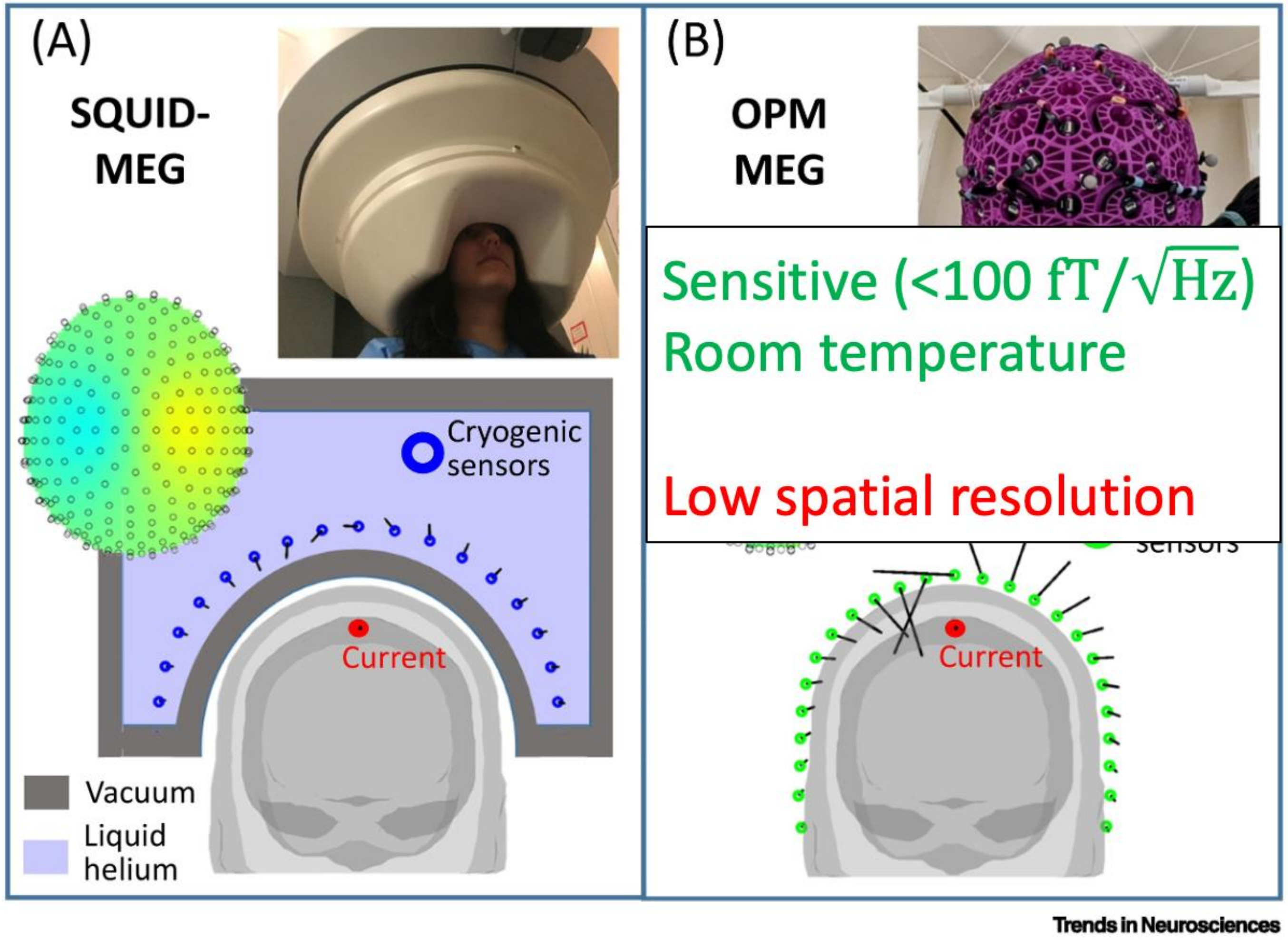
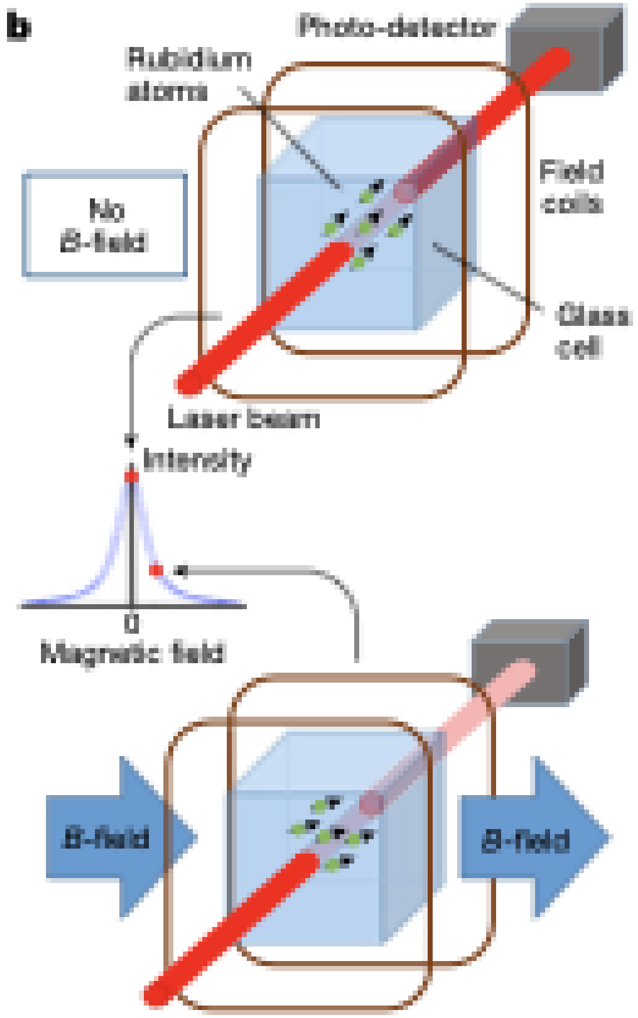
SQUID-Based MEG and Optically-Pumped MEG





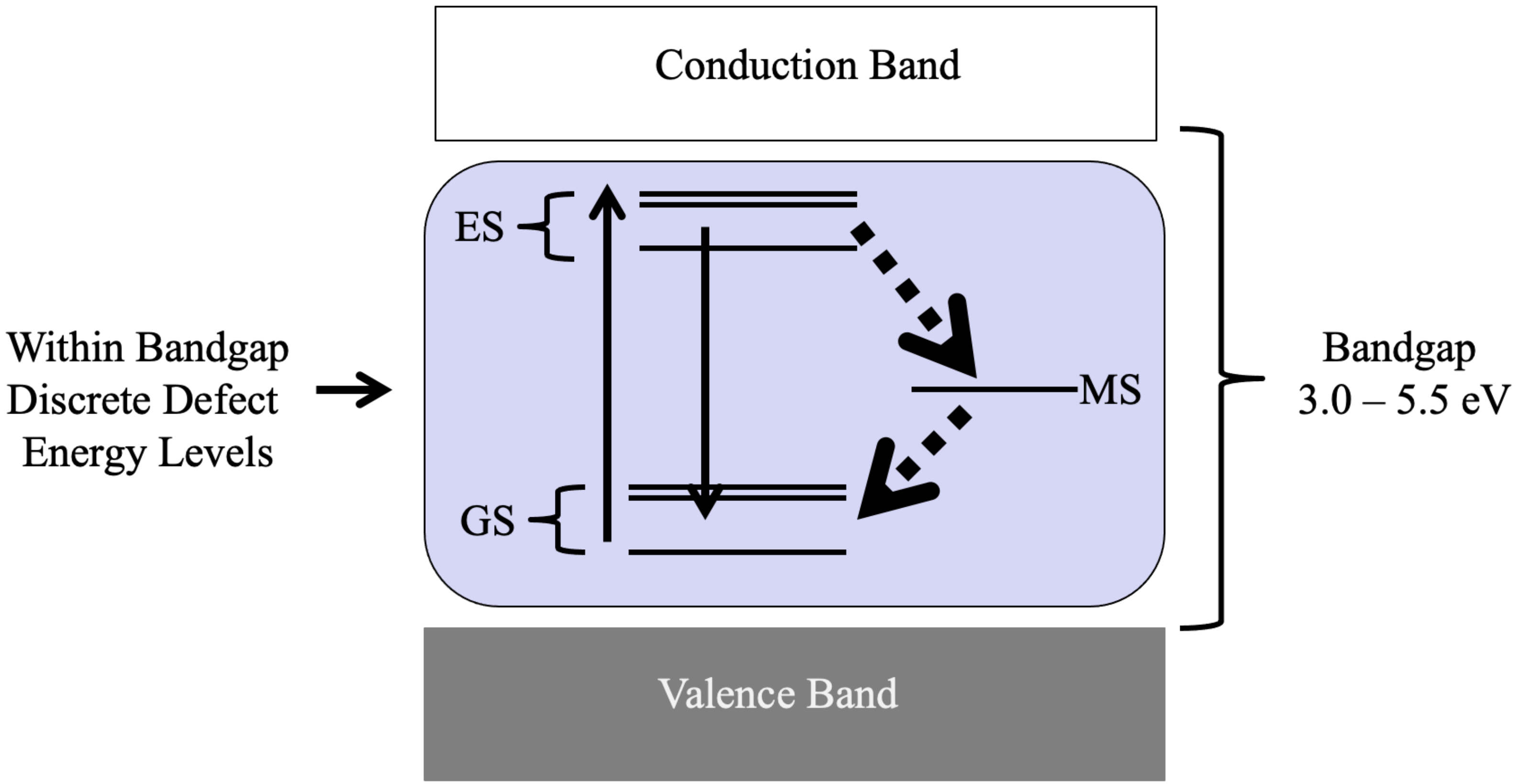
M. Brookes et al. *Trends in Neuroscience* **45** (8) 621-634 (2022).

Criteria for an Ideal Quantum Sensing Platform

- Two-level system that can exhibit superposition, and can be scaled to form an array that can be entangled to provide high sensitivity and precision beyond classical limits;

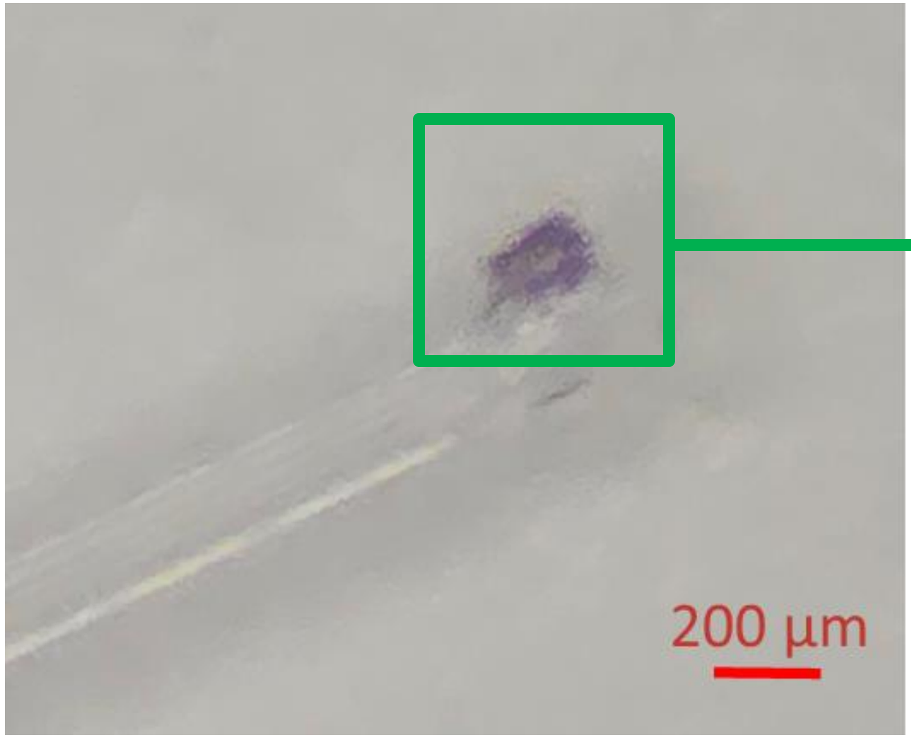
- Low and high energy levels that are accessible by (optical or electrical) excitation; transition from the high energy to low energy level is typically by spontaneous relaxation;
    - Initialization of the system into a definite state must be possible;
    - Coherent state manipulation is typically by time-dependent (electric or magnetic) fields;
    - Must have an efficient readout mechanism for measured response.

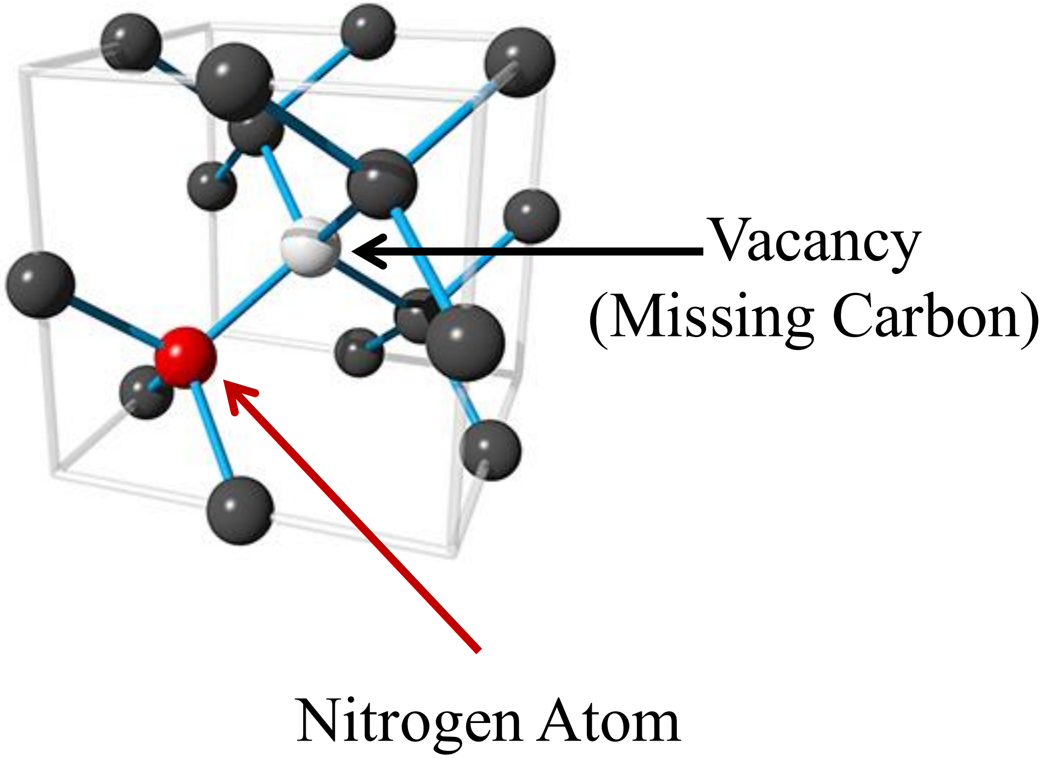
Band Structure of Ideal Host Semiconductor for Defects



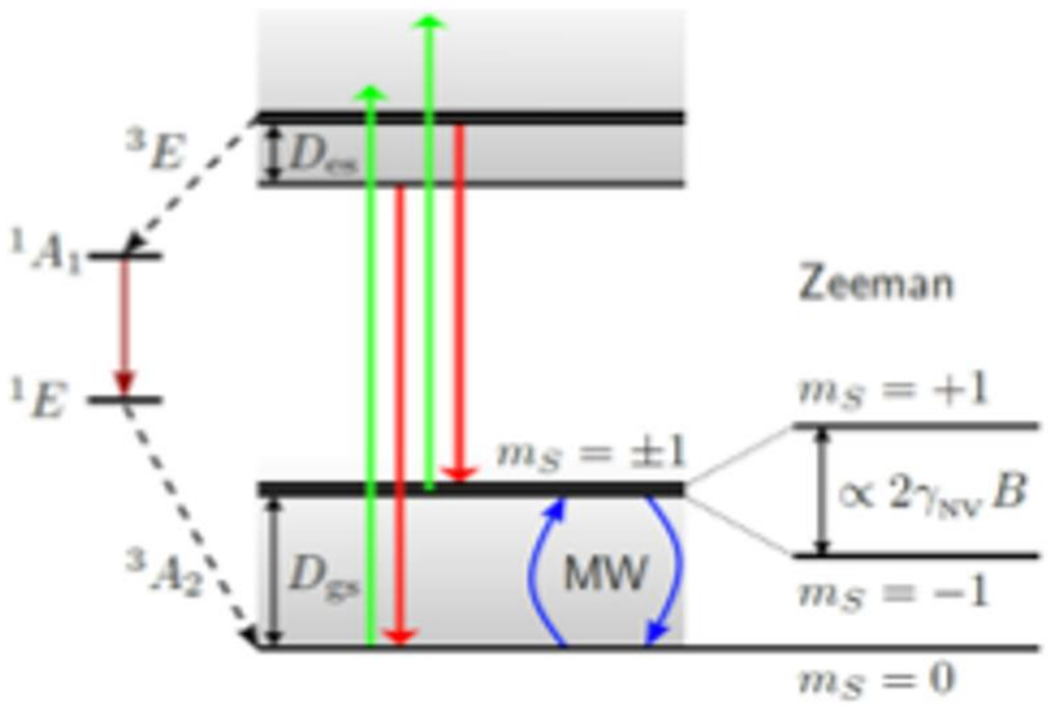
Nitrogen-Vacancy Center in Diamond

- Microphotograph of diamond sample with quantum defects
- Wide band gap ~ 5.4 eV





Energy Structure of the NV Center in Diamond



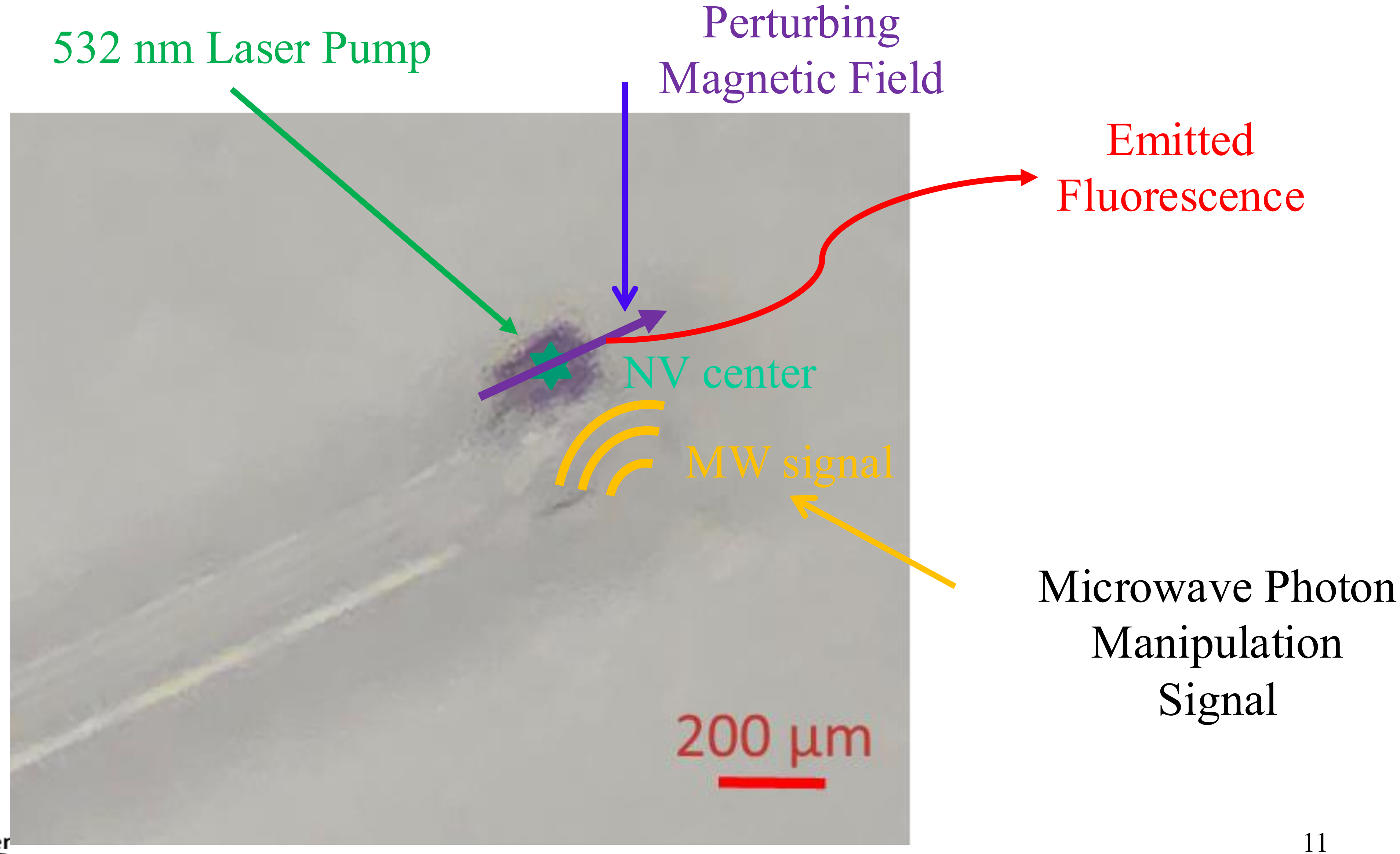
Sturner et al. Adv. Quantum Tech. **4**(4) 2000111 (2021)

- Optical behavior of defect depends on how its state is initialized;
- From the ground state $|m_s\rangle = 0$, it can be pumped to the excited state $|m_s\rangle = \pm 1$, from where it relaxes back to the ground state, emitting intense fluorescence.
- When it is pumped from the ground state $|m_s\rangle = \pm 1$, it can either relax non-radiatively or radiatively as indicated on the diagram to the left.

State Initialization Procedures

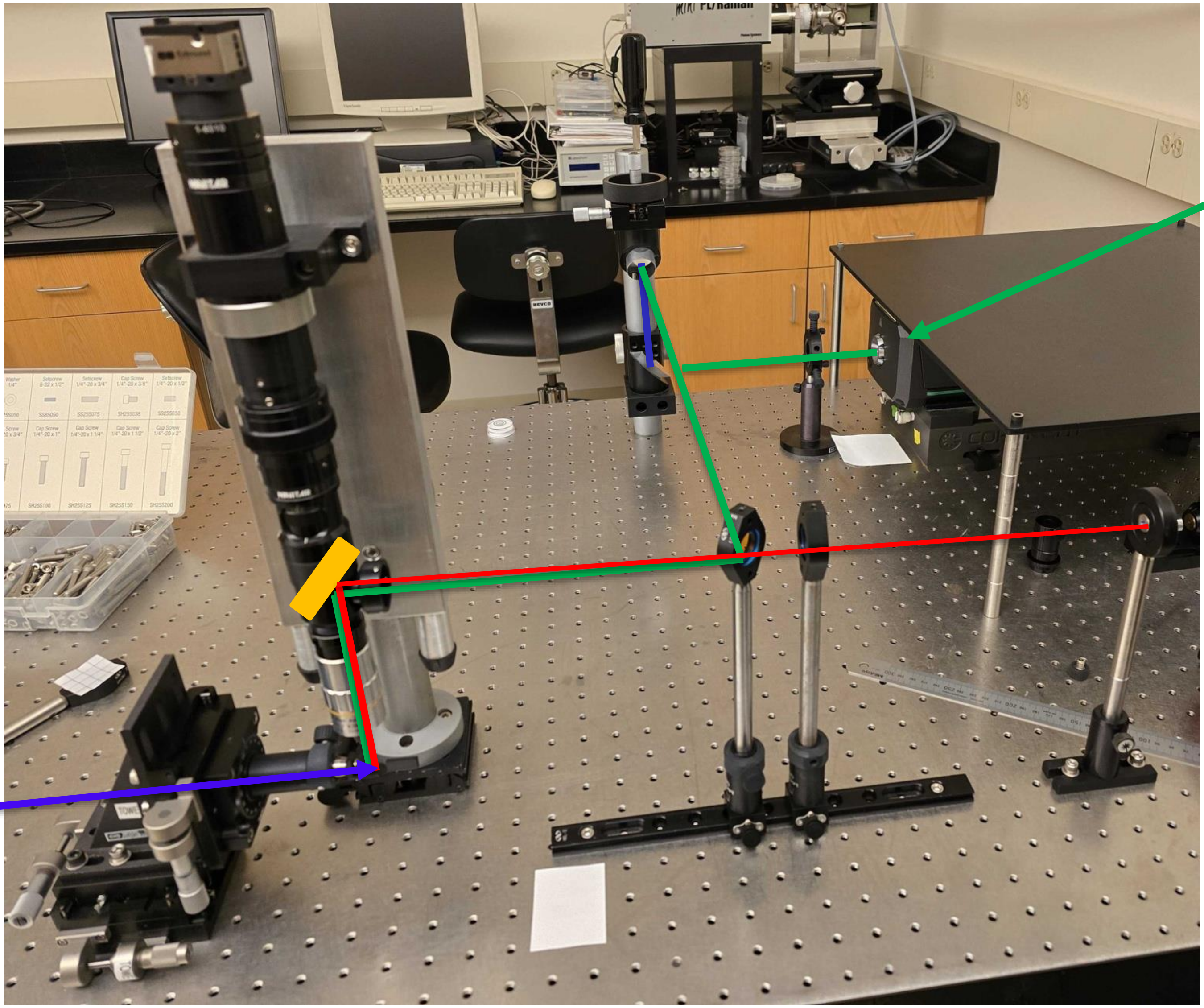
- Qubits are encoded as the spin of an electron within the platform vacancy;
- This spin evolves as a function of the Hamiltonian of the system;
  - **Zeeman interaction** (due to external magnetic fields;
  - **Strain and electric field** effects (modifying energy level;
  - **Hyperfine interactions** (coupling with nearby nuclear spins);
- Quantum control is needed to initialize the qubit into a “known” state/spin.

Free-Space NV Diamond Magnetometer Experiment



Preliminary Experimental Setup

532 nm Laser Pump

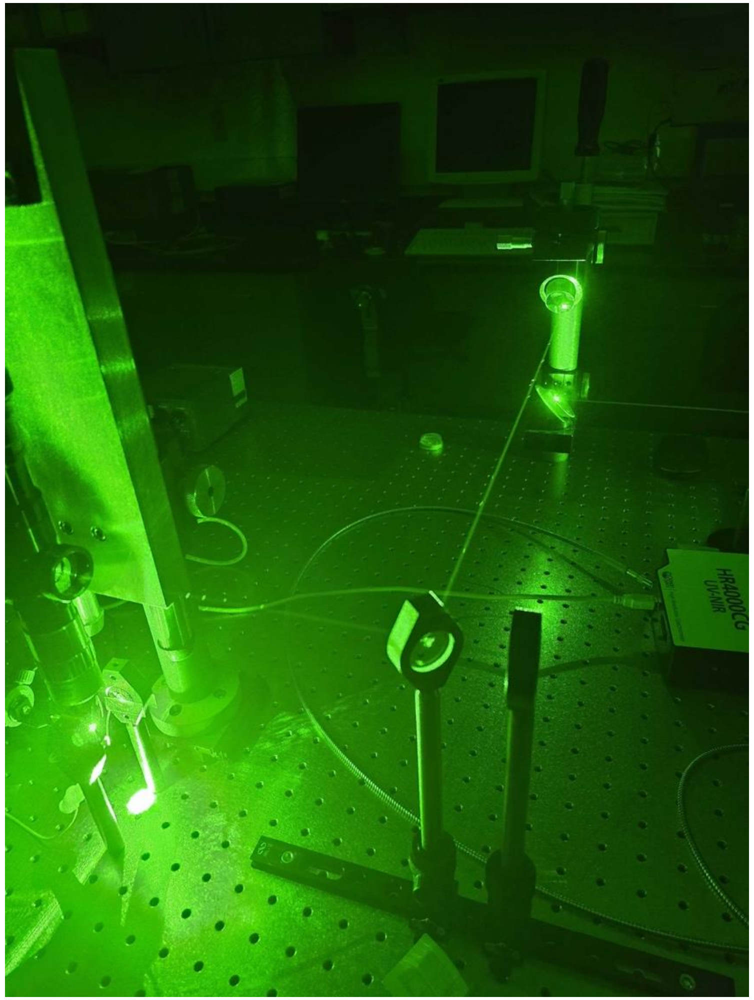


Fluorescence

NV Center Diamond Sample

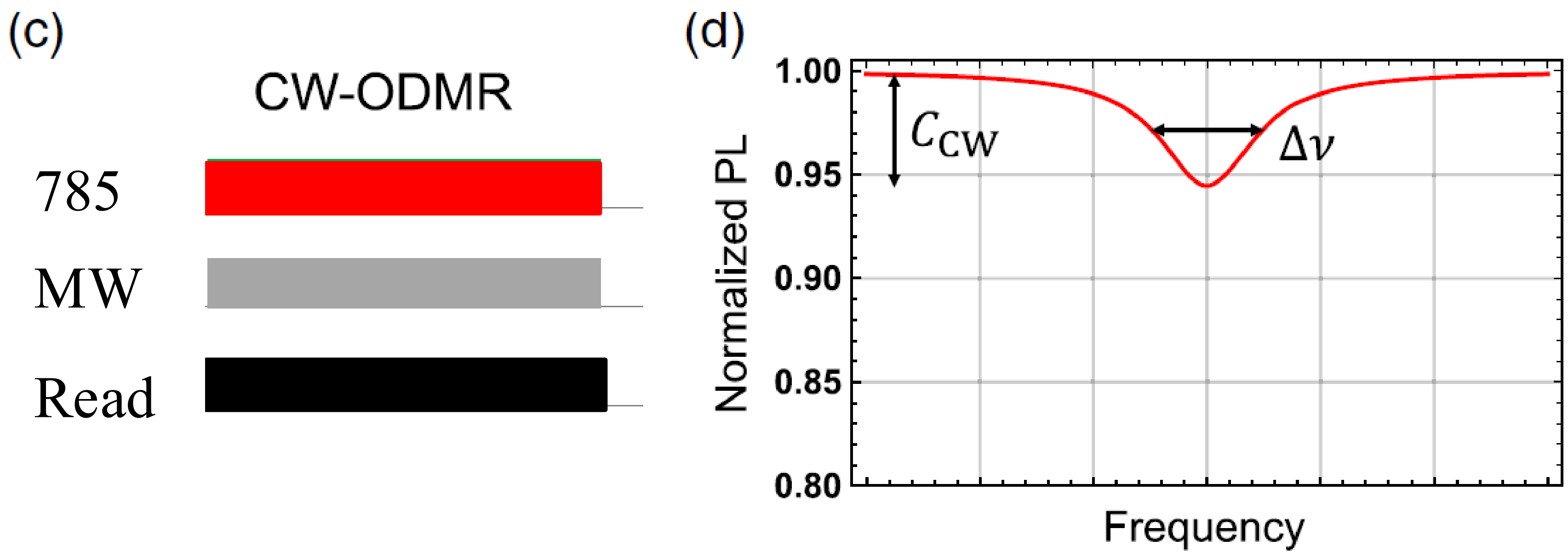
Pumping and Emission of NV Center

Pumping



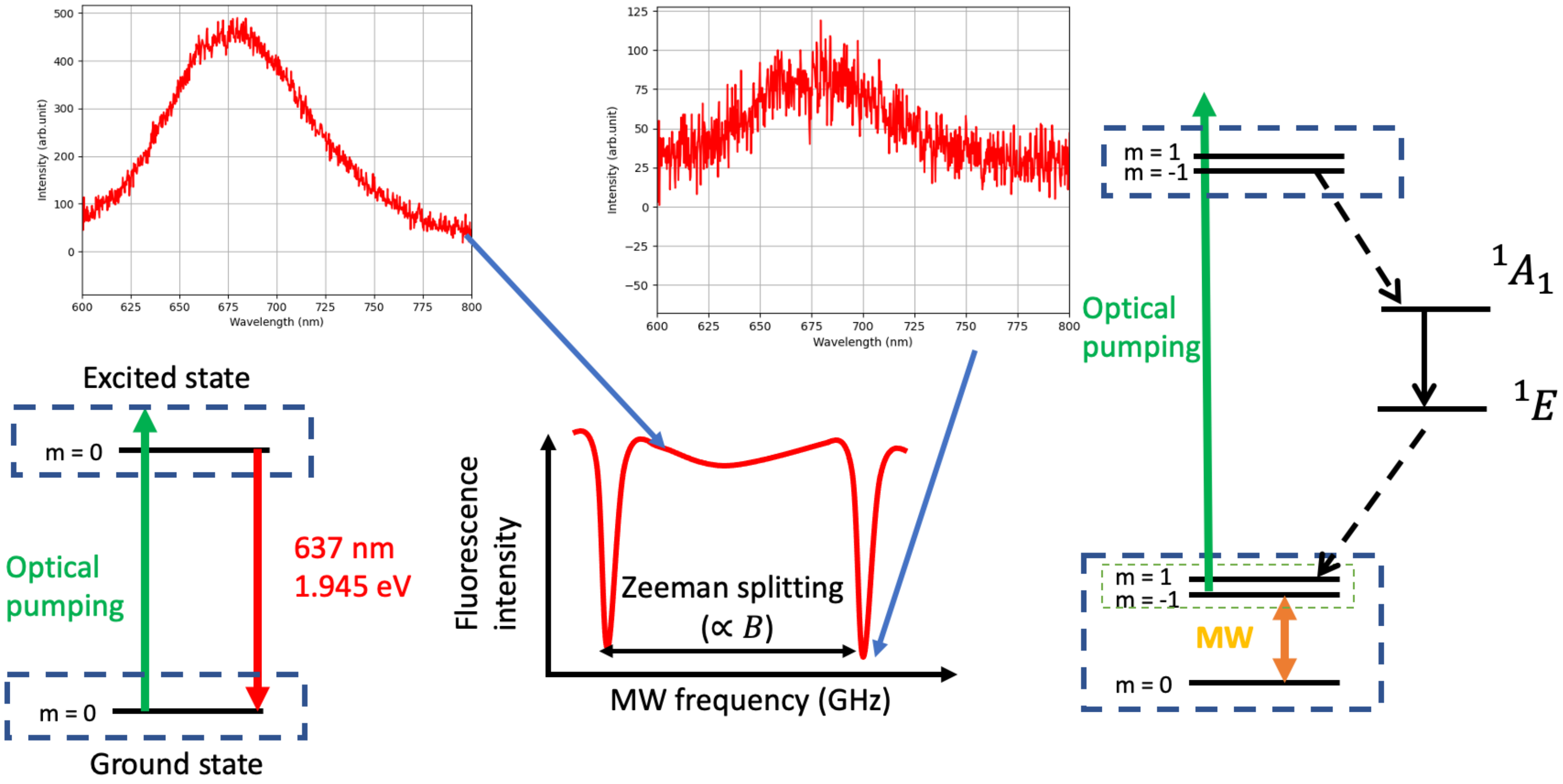
Filtered image of emission process

Continuous Wave Experimental Process



1. Green laser continuously excites color center, generating steady fluorescence.
2. Microwave signal applied, and frequency is swept to find the resonance.
3. Fluorescence intensity decreases when microwave signal drives the spin transition, creating resonance dips in the measured signal.

Fluorescence Change as a Function Microwave Frequency

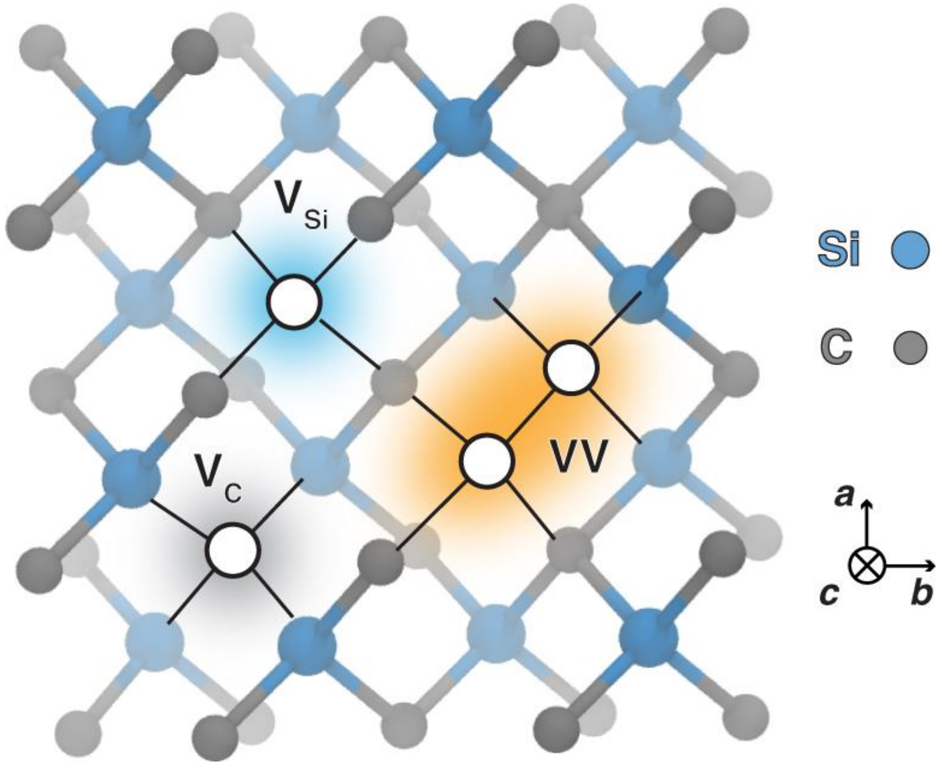


Silicon Carbide (SiC) Semiconductor

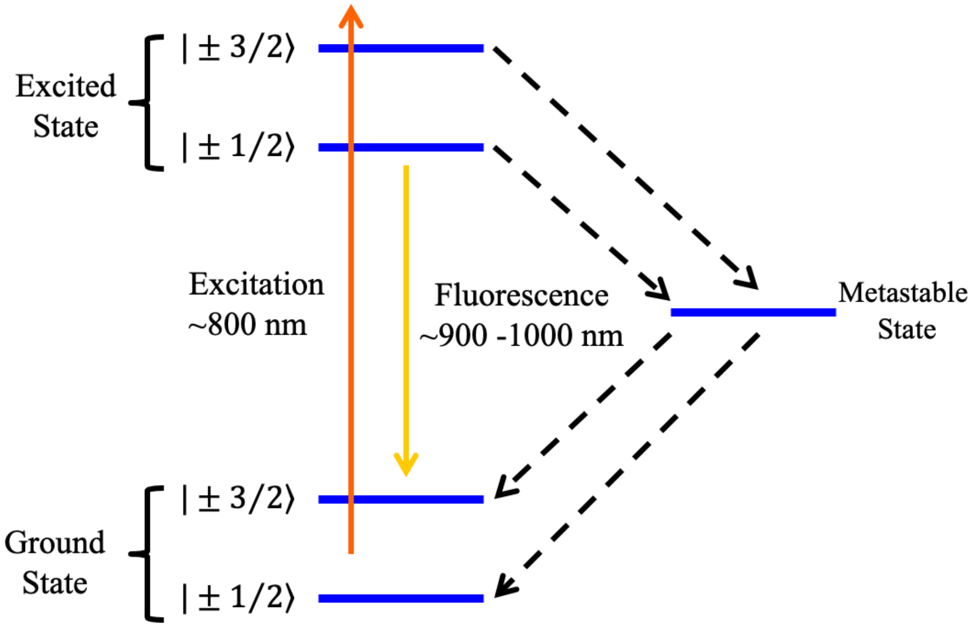
- A missing atom/impurity in the crystal lattice can trap an electron, forming a stable quantum system (spin qubit):
    - A vacancy or impurity creates energy levels within the bandgap;
    - Electrons trapped in defect states can absorb photons, which can promote the electron to an excited state; relaxation from the excited state is by emission of a photon;
    - Electrons trapped in defect energy states can be manipulated by optical or microwave fields;

- SiC is compatible with existing microelectronics fabrication processes, potentially simplifying the transition of quantum sensors based on it to real-world applications.

Silicon Vacancy in SiC



E. Lee, et al, Nature Communications **12** (1) 6325 (2021).

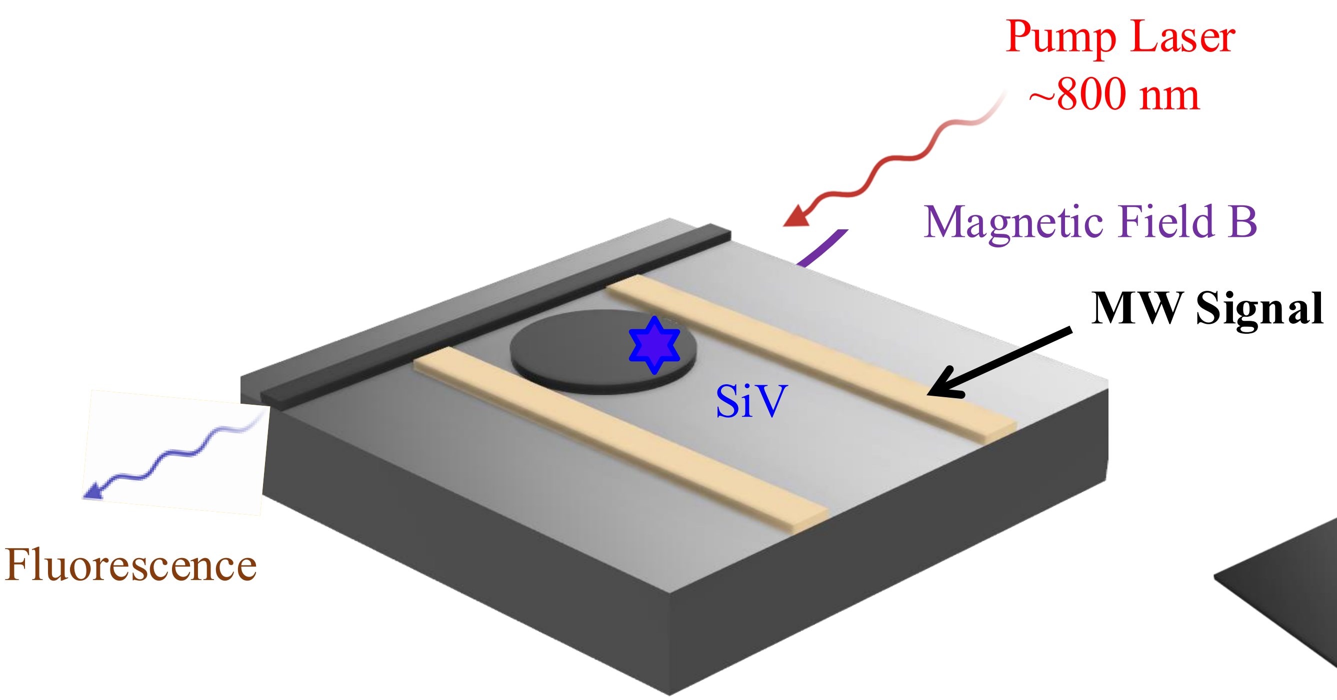


Energy level scheme of silicon vacancy (V_{Si}) in 4H-SiC.

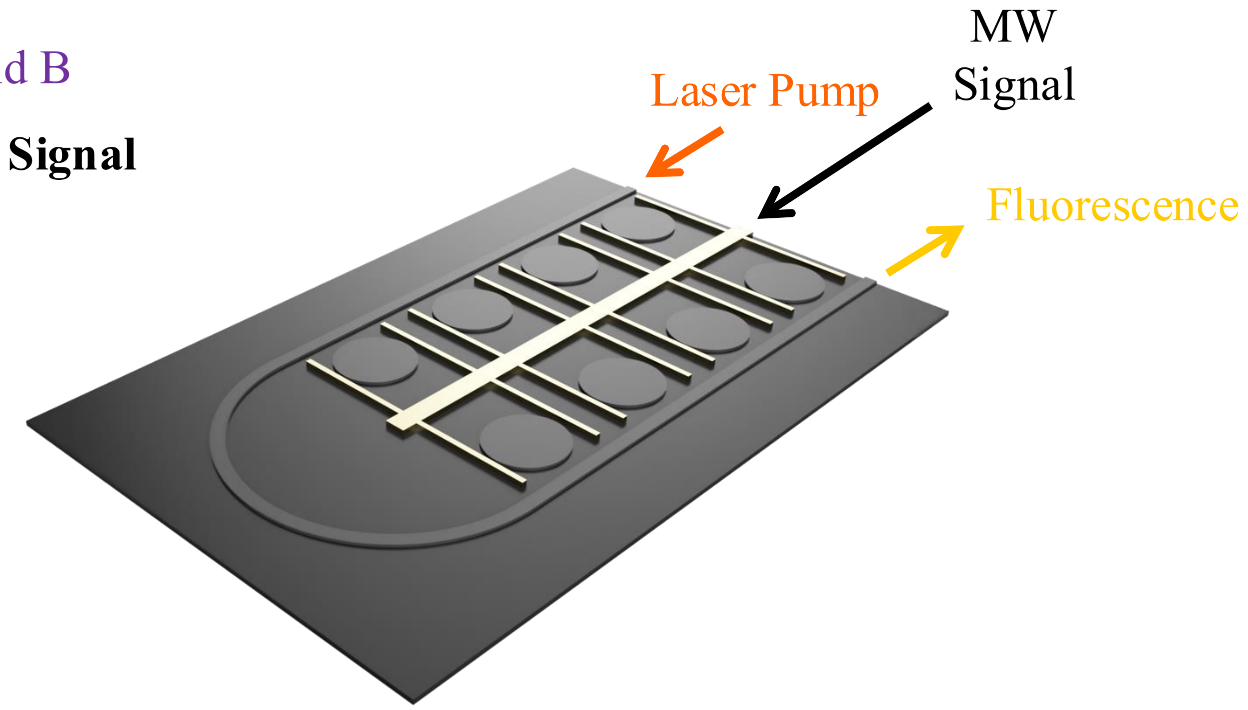
Requirements for SiC-Based Sensor Control

- Electronic and Optical Control:
  - Precision microwave/optical control for state manipulation;
  - FPGA/DSP-based pulse sequencing for quantum operations;
  - Phase-locked loops (PLLs) for stable frequency generation;
- Feedback and Stabilization:
  - Active stabilization of laser and microwave power;
  - Real-time feedback loops for noise compensation;
  - PID control for temperature regulation of SiC chip ;
- Data Acquisition and Processing:
  - High-speed photodetectors for real-time photoluminescence readout;
  - ADCs and fast data acquisition cards for signal digitization;
  - AI/ML for dynamic optimization.

Envisioned Design of a Si Vacancy SiC Sensor



Single Sensor



Sensor Array

State Detection and Optical Readout

- Optical Pumping - repeated laser pulses with prescribed polarization can polarize the system into a well-defined spin state, ensuring reliable state preparation for subsequent sensing;

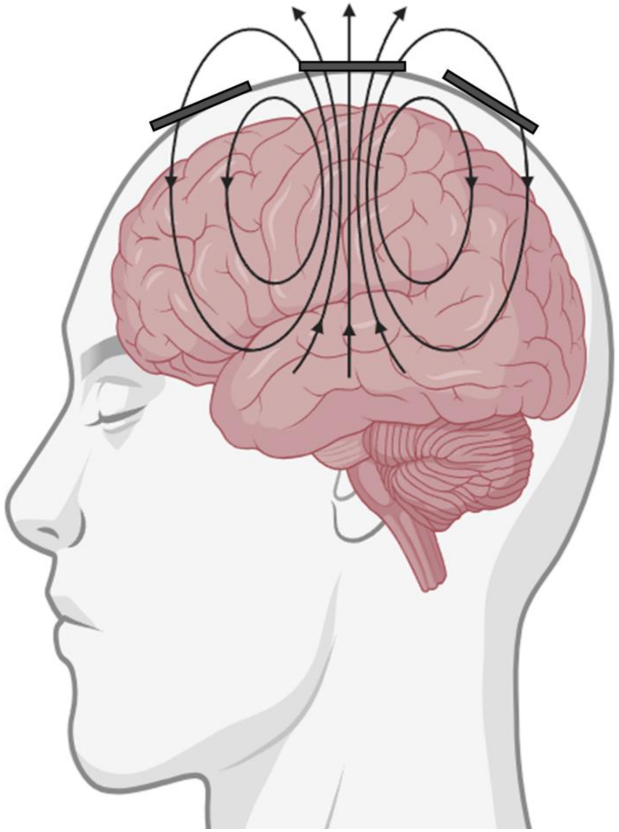
- A spin in certain state interacts with optical excitation in ways characteristic of the state;
  - Certain states exhibit higher fluorescence intensity, enabling non-invasive measurement
- A laser properly tuned to an allowed transition excites the qubit to a higher energy level;
  - If the spin is in a bright state, one detects fluorescence;
  - If spin is in a dark state, a non-radiative transition (no fluorescence) occurs.

Common Quantum Control Schemes

- Manual calibration techniques:
  - Rabi oscillations: Basic qubit transitions with fixed microwave pulses; particularly fundamental to initialization process;
  - Spin Echo (Hahn Echo): Apply pi-pulse halfway through evolution time to refocus the spin state, combat slow environmental drift;
  - $j\frac{\partial|\psi\rangle}{\partial t} = \hat{H}|\psi\rangle$
- With RL-optimized control:
  - Adaptive Rabi Control Feature: Adjust pulses to maintain optimal transitions;
  - Noise-Resilient Pulse Shaping Feature: ability to generate custom dynamical decoupling sequences.

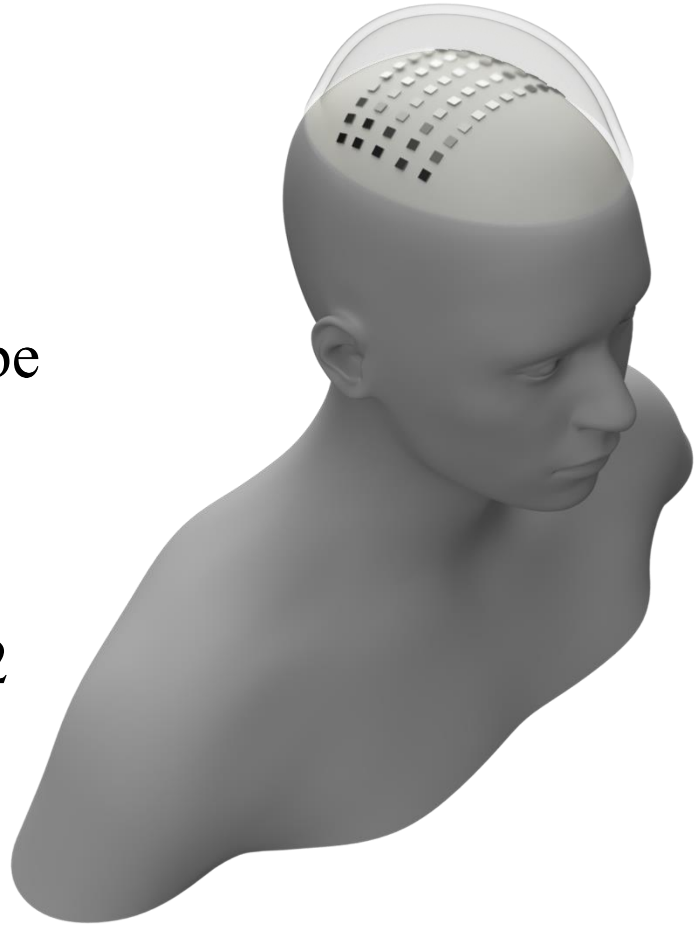
$$\hat{H} = H_0 + H_V(t) + H_{contr}(\mathrm{t})$$

Future Solid-State SiC Magnetometer Arrays



- Neural action potential voltage spikes generate magnetic field spikes;
- Magnetic field spikes can be sensed with SiC qubit magnetometer array;
- Wide bandgap of SiC (~3.2 eV) enables room-temperature operation.

Wearable Cap



Summary

- Reviewed solid-state semiconductor magnetometers
  - Discussed diamond as the representative state of the art
- Discussed preliminary plan and setup for SiC defect qubit magnetometer
  - Reviewed benefits of SiC platform
- Quantum magnetometers as prototype qubit systems with special control requirements and protocols