Color Centers in Diamond

Slides and material courtesy of: Joerg Wrachtrup, Ronald Hanson, Lilly Childress, and Christian Degen as indicated
Reviews:


The Dopants

- Standard diamond lattice
- TR12 (interstitial Carbon)
  - PRB 72, 035214 2005
- NV (Nitrogen, Vacancy)
- NE8b (Nickel, Nitrogen)

6C
- Carbon
- 4 valence electrons
- sp3 hybridization

7N
- Nitrogen
- 5 valence electrons

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Level Scheme of Color Centers

Properties:
- Large band gap $E_g = 5.4 \text{ eV}$
- Defects form inter-gap states

Optical transition

Fluorescence $k_{21}$

1

2

CB

VB

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Shielding by the Diamond Lattice Provides Photostability

Slide material: Joerg Wrachtrup, Stuttgart
Level Structure of Color Centers

- Electron spin states are spectroscopically resolvable
- Defect behaves as a single atom, trapped in the diamond lattice
- Level structure similar to trapped ions or atoms
  - Diamond provides a solid state ion trap
  - Experimental power similar to trapped particles, but much easier to transform into certain applications, e.g. sensing and quantum networks
The NV Center

- Joint defect consisting of
  - Vacancy
  - Neighboring substitutional N
- Negatively charged (NV⁻)
- Six electron (= two hole) system

\[
\begin{align*}
\text{3E} & \quad \text{637nm} \\
\text{3A} & \quad 1.95 \text{ eV} \\
& \quad 470 \text{ THz} \\
& \quad 2.87 \text{ GHz}
\end{align*}
\]
The NV Center

Features:

• Initialization: Optical spin polarization of the ground state («Laser cooling»)

• Coherence: Narrow lines, $T_2 = 1$ ms, linewidth of ground state levels 1 kHz.

• Readout: Optical detection of the spin state
The NV Center

**Features:**

- **Initialization:**
  Optical spin polarization of the ground state («Laser cooling»)

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- **Readout:**
  Optical detection of the spin state
Experimental Setup for Optical Spin Readout

Confocal microscope with microwave access

Image of implanted diamond

Photon count rate (Hz)

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Wiring up NV Centers

CVD diamonds grown by Element6

10µm
deterministically placed silicon immersion lens (SIL)

dc Stark tuning:

high-fidelity spin control via magnetic resonance

Slide material: Ronald Hanson, TU Delft
Spin-Resolved Optical Excitation (T < 10K)

Early work by Stuttgart, Harvard, HP Labs
Slide material: Ronald Hanson, TU Delft
Initialization and Readout by Resonant Excitation

**Initialization**
- Fidelity $> 99.7\%$

**Single-Shot Readout**
- At the time at TU Delft: best fidelity $F \approx 98\%$
- $m_s=0$ \( <n> = 0.06 \)
- $m_s=\pm 1$ \( <n> = 8.5 \)

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Slide material: Ronald Hanson, TU Delft
Optically Detected Magnetic Resonance

Experimental Sequence:
• Set magnetic field
• Initialize optically
• Apply microwave with controlled frequency and amplitude
• Read out optically

\[ |0\rangle \quad |\pm 1\rangle \quad |1\rangle \quad |+1\rangle \]

\[ 2\gamma B \]

\[ 8.3 \text{ mT} \]

\[ 5.8 \text{ mT} \]

\[ 2.8 \text{ mT} \]

\[ B = 0 \]

\[ \gamma = 28 \text{ GHz/T} \]

Slide material: Christian Degen, ETHZ
Manipulating a Single Spin

Experimental sequence:

- Pulsed sequence consisting of laser cooling, spin manipulation by pulsed microwaves and detection
- Signal is <1photon/repetition => many repetitions
- Similar to ion trap, but experimentally easier
Features:

- **Initialization:**
  Optical spin polarization of the ground state («Laser cooling»)

- **Coherence:**
  Narrow lines, $T_2 = 1 \text{ ms}$, linewidth of ground state levels 1 kHz.

- **Readout:**
  Optical detection of the spin state

- **Single qubit gates:**
  Microwave pulses
## Three Approaches to Coupling NV Centers

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<thead>
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**Slide material:** Joerg Wrachtrup, Stuttgart
Coupling by Dipolar Interaction

ground state energy levels:

| 1⟩
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| 0⟩
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Idea:

- NV B interacts with the magnetic dipole of the electron spin of NV A
- Depending on the state NV A, NV B has another resonance frequency
Spin Hamiltonian: Coupled Spins

\[ \mathcal{H}_J = \hbar \sum_{i<j}^{n} 2\pi J_{ij} I_i^z I_j^z \]

Typical values for \( J \) depending on distance between spins:
- from kHz up to few 10 MHz for electron spins
- up to few 100 Hz for nuclear spins

\( J > 0 \): antiferro mag.
\( J < 0 \): ferro-mag.

Example with 5 nuclear spins:
Magnetic Dipole Coupled Spin Arrays

Single spin readout

Coherent interaction
Length scale ~ some10 nm,

Coupling vs. distance:

- Distance dependence of dipole coupling scales as $d^{-3}$

STED on NV: 10nm resolution: Hell et al., Nat. Phot. (2009)

Slide material: Joerg Wrachtrup, Stuttgart
Take Pure (CVD) Diamond and Implant Nitrogen!

*N+ ions, 2MeV

Surface

1.1µm depth

~ 200 nm FWHM

Success chance 1% to have two coherently interacting dimers

*Element Six Ltd., UK

Annealing at 900° C

10^3 N 10^4 N 10^5 N

10µm

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Two Defect Centers

Electron spin ground state:

\[ |0\rangle \]

\[ |+1\rangle \]

\[ |-1\rangle \]
Dipolar Coupling: Switching of Spin B

\[ |0\rangle \rightarrow \pi/2 \rightarrow |0\rangle \rightarrow \pi/2 \rightarrow |+1\rangle \]

Initial state $F \geq 85\%$

Switchable interaction! Coupling between defect: 0,5,10,20 kHz
Controlled-NOT for Spin-Spin Coupling

Before 

\begin{align*}
|0\rangle & \\
|0\rangle + |1\rangle & \frac{\sqrt{2}}{}
\end{align*}

After

\begin{align*}
|0\rangle & \\
|0\rangle + i|1\rangle & \sqrt{2}
\end{align*}

if spin B is \(\uparrow\)

\begin{align*}
Y_{90}^A & \\
\text{Delay} & \frac{1}{2}J_{AB}
\end{align*}

different rotation direction depending on control bit

time

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Bell State: Density Matrix Tomography

$$\Phi_+ = \frac{1}{\sqrt{2}}(|+\rangle + |–\rangle)$$

Fidelity $\Phi_+$: 0.67 (theoretically: 0.9)
# Three Approaches to Coupling NV Centers

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| • Transfer limited photons:  
  Batalov et al. PRL 08 | | • Couple nuclei via NV |
| • But: bad coupling efficiency | | • Read out single nuclei |
Coupling Nearby $^{13}$C Nuclei

- $^{12}$C has no nuclear spin ($I = 0$) and magnetic moment
- $^{13}$C nuclear spins ($I = \frac{1}{2}$, 1.1% abundance) create magnetic field at NV
- CNOT gate is implemented by selective microwave transition (flip nucleus if other nucleus is in $|0\rangle$)

Splitting of electron spin spectrum:

- Flip NV conditioned on nuclear state
- Flip nuclei conditioned on NV and nuclear state
Creation of Entangled States

- Creation of entangled states possible
  \[ |00\rangle \mp |11\rangle \]
  P. Neumann et al., Science \textbf{320}, 1326 (2008)
- Scaling up to four nuclear spins straightforward
- Combination of electron and nuclear spin states for quantum register
- Scaling to 10-20 spins presumably possible

Flip NV conditioned on nuclear state

Flip nuclei conditioned on NV and nuclear state
Different development: QND readout of nuclear spins

Readout of single quantum systems

• Standard readout
  • <1 photon per run limited by photon shot noise (at best)
  • Example: fluorescence detection of single NV

• Single shot readout
  • determine spin state in a single run but destroy the system or its quantum state
  • requires >1 photon per run limited by quantum shot noise
  • Example: Photon detection in Photomultiplier

• Quantum non demolition (QND) readout
  • >1 photon per run and preservation of the system and its spin state
  • Projective measurement
  • Example: Microwave photons in circuit QED
QND Readout of a Single Nuclear Spin

-1_e (dark)
0_e (bright)

|0_n⟩, |1_n⟩

-1_e <-> |1_e⟩

ESR π

fluorescence intensity (a.u.)

 correlate n- and e-spin
measure e-spin

n-spin state |Ψ⟩
esr π laser
time

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Observing Flips of a Single Nuclear Spin

Repetitive QND measurements reveal quantum jumps of a single nuclear spin (in diamond at room temperature)

Fidelity of Spin State Detection

- Two almost perfect Poissonians
- Threshold for state discrimination
  - Fidelity from overlap 99%
  - Fidelity to detect given state 92%
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- **Magnetic dipolar coupling**
  - Magnetic dipoles
  - \( d_{\text{coherent}} \propto \frac{3}{\sqrt{T_2}} \)

- **Use nuclear spin qubits**
  - Couple NV to surrounding nuclei
  - Couple nuclei via NV
  - Read out single nuclei

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