Quantum devices with diamond defects

Lilian Childress
Bates College, TU Delft, Yale University, McGill University

University of Toronto
November 8, 2012
A few applications of diamond defect centers

**Quantum information science**
- 2 qubit QC
- Long-lived nuclear spin quantum memory
- Electronic spin mediates gates
- And provides an optical interface
- for quantum repeaters and quantum networks

**Metrology**
- Spin as sensor of electric and magnetic fields, acceleration, time

**Optical devices**
- Single photon source
- Stable emitter for fluorescence markers

**Metrology**
- 25 nm resolution
- Metrology Stuttgart 2008
- Spin as sensor of electric and magnetic fields, acceleration, time

**Optical devices**
- 100 nm resolution
- Optical devices Gottingen 2009
- Stable emitter for fluorescence markers
The quest for quantum bits

Controllability vs coherence

Solid state quantum systems
- Fast electrical or optical gating
- Typically short coherence times
- Inconsistent fabrication outcomes

Atoms & molecules, isolated nuclear spins, photons
- Longest coherence times
- Excellent selection rules
- Difficult to prepare, control, and measure on fast timescales

Impurity-based electronic spins in solids
- Fast control possible with microfabricated gates
- Long coherence times in spinless hosts

NV diamond: An interface between nuclear spins and photons
The nitrogen-vacancy center in diamond

- Ground state electronic spin triplet
- Coherent interactions with proximal nuclear spins

Optical transitions: single-defect isolation, preparation & detection of the electronic spin and the nuclear spins with which it interacts

Recent results: Nuclear spin coherence times in the range of seconds (Harvard)

Precession of a single $^{13}$C nuclear spin

Ground state $S = 1$

Excited state $S = 1$

Fast control
~ ns (electron)
~ μs (nuclear)

Room temperature

Stuttgart, Harvard, U CSB, Canberra

Dutt et al. 2007
The nitrogen-vacancy center in diamond

- Ground state electronic spin triplet
- Coherent interactions with proximal nuclear spins

*an NMR molecule*

- Optical transitions: preparation & detection of the electronic spin

**Conventional approach:** non-resonant excitation

*Higher fluorescence from* $m_s = 0$

*Optical polarization into* $m_s = 0$

Enables measurements of a single NV spin

**Spin** $S = 1$

*electronic ground state*

$m_s = \pm 1$

$m_s = 0$

Stuttgart, Harvard, U

CSB, ANU

**A new arena for exploring quantum phenomena and investigating applications**
The nitrogen-vacancy center in diamond

The vision:
- A few-spin-qubit register with preparation, coherent control, and measurement
- Scalability via optical connections

Spin-photon entanglement
Togan et al. 2010

Quantum interference

Fast magnetic resonance based 1-2 qubit gates
Stuttgart, UCSB, Bates, Delft

Recent results:
- Grover search with decoherence-protected gates
  Van der Sar 2012 (Delft)
- , Harvard

Coincidence detection
→ leaves spins entangled
a quantum channel between the registers
1. Optical spin readout
2. Two photon quantum interference
1. Optical spin readout
1. Optical spin readout

**Challenge:**
High fidelity preparation and single-shot detection of multiple spins

**Conventional approach:** non-resonant excitation
- Higher fluorescence from $m_s = 0$
- Optical polarization into $m_s = 0$
- Time-averaging or repetition* required!

**Our approach:** resonant excitation
- Single shot readout of a nuclear spin, Neumann et al. Science 2010

*Single shot readout of a nuclear spin, Neumann et al. Science 2010

**Other approaches**
e.g. Buckley et al. Science 2010

Excited state $S = 1$

Ground state $S = 1$

$m_s = \pm 1$

$m_s = 0$
Resonant excitation of a single NV center at low temperature

Spin-selective transitions
- $f_0$ only excited from $m_s = 0$ ground state
- $f_1$ only excited from $m_s = \pm 1$ ground state

Mostly spin-conserving transitions
- Some spin-mixing within the excited state

Zero phonon line
- The good stuff

Excited state
- $S = 1$

Excitation
- Optical pumping mechanism
- $m_s = \pm 1$

Ground state
- $S = 1$
- $m_s = 0$
High fidelity spin preparation: Optical pumping

>99% preparation fidelity under $f_0$ excitation

Long spin-flip time

An order of magnitude reduction in error rate
Resonant readout of the NV center spin

Enhanced collection efficiency

Microfabricated SILs

Spin-selective transitions

f₀ only excited from ms = 0 ground state

f₁ only excited from ms = ±1 ground state

Readout mechanism

Mostly spin-conserving transitions

Some spin-mixing within the excited state

2.3% collection efficiency = 10x improvement

Challenge:

Can we collect enough photons to measure the spin before it flips? Yes!
Resonant readout of the NV center spin

Optical pumping  Spin readout

$f_0$  $f_1$

Fraction of occurrences

$m_s = \pm 1$

$m_s = 0$

$\langle N \rangle = 0.07$

$\langle N \rangle = 6.4$

NV A

Photon number

Fraction of occurrences

Photon number

Single shot detection

Fidelity (lower bound)

$F_{\text{avg}} = 93\%$
Resonant readout of the NV center spin

Optical pumping → Spin readout

Do the fluorescence levels indicate spin?

Single shot detection

Fidelity (lower bound)

$$F_{\text{avg}} = 93\%$$
How ideal is our quantum measurement?

Partially destructive: readout also optically pumps the spin

But:
The shorter the readout duration, the less likely a spin flip is to occur

Short duration readout:

Very short readout pulse (400 ns)

0 photons
=> Virtually no information about the spin state

1+ photons
=> Only if initially $m_s=0$

Probably still in $m_s=0$

Allows measurement-based quantum state preparation
Measurement-based initialization of a multi-spin register

The simplest system:
NV + host $^{14}$N nuclear spin ($I = 1$)

$^{14}$N hyperfine lines

Fluorescence

Microwave frequency (GHz)

Rotates electronic spin conditional on the nuclear spin state – a CNOT gate

$m_s = -1$

Nuclear spin projections

$m_s = 0$

Optical pumping readout

Probabilistic state preparation for the nuclear spin
Measurement-based initialization of a multi-spin register

The simplest system:
NV + host $^{14}$N nuclear spin ($I = 1$)

NV B:
No proximal $^{13}$C isotopic impurities

Straightforward extension to larger numbers of nuclear spins

No preparation

With preparation into

![Graph showing fluorescence vs. microwave frequency]
Measurement-based initialization of a multi-spin register

Three nuclear spins:

NV A:
Two proximal $^{13}$C isotopic impurities

No preparation
12 partially overlapping lines

With preparation into $\downarrow \uparrow \uparrow$

Initialization by measurement into 1 of 36 electron-nuclear spin configurations
Nuclear spin readout

\[ m_s = -1 \]
\[ m_s = 0 \]

No proximal $^{13}\text{C}$ isotopic impurities

Pioneering work with conventional detection: single-shot nuclear spin detection at room temperature
Neumann et al. 2010
See also Jiang et al. 2009

92% average fidelity

Compatible with sequential readout of electronic and nuclear spin
Preparation, manipulation, and single-shot readout of a two-spin quantum register

Measurement based state preparation

Driven spin rotations

Single shot electron spin qubit readout

Repetitive single shot readout of the nuclear spin qubit
Preparation, manipulation, and single-shot readout of a two-spin quantum register

Single-shot detection of two spin qubits
1. Single shot readout

2. Two photon quantum interference

Quantum interference between photons emitted by different NVs can be used to establish long-distance entanglement.

Indistinguishable photons => destructive interference.

Photons cannot emerge from different ports.
Resonant emission: Towards two photon quantum interference

532nm

Wanted: indistinguishable photons

Recipe:
1. Spectral filters to isolate ZPL
2. Spin pumping into $m_s=0$
3. Polarization filtering

But...
Inhomogeneity between NVs
Spectral diffusion in time

These two lines are orthogonally polarized

Robledo et al. 2010

Ey
Resonant emission: Towards two photon quantum interference

Solution # 1: Tune

Wanted: indistinguishable photons

Recipe:
1. Spectral filters to isolate ZPL
2. Spin pumping into $m_s=0$
3. Polarization filtering

Tunable optical transitions:
Strong DC Stark shifts
Resonant emission:
Towards two photon quantum interference

Solution # 2: Get lucky

Wanted: indistinguishable photons

Recipe:
1. Spectral filters to isolate ZPL
2. Spin pumping into $m_s=0$
3. Polarization filtering

But...
Inhomogeneity between NVs
Spectral diffusion in time

Natural linewidth = 15 MHz
Spectral diffusion broadened linewidth $\sim$ 500 MHz
Coping with spectral diffusion
Legero et al. 2003

Solution #3: Time resolution

Wanted: indistinguishable photons

Key idea: they only have to be indistinguishable to the detector

Record coincidence clicks as a function of $\tau$

Bin size $d\tau << 1/frequency$ difference

532nm picosecond pulse
Time = 0

Indistinguishable photons => destructive interference

NV 2 + filters

Click!
Time $= t + \tau$

NV 1 + filters

Click!
Time $= t$

within the $\tau=0$ bin the photons are indistinguishable!
Coping with spectral diffusion

Solution #3:
Time resolution

Wanted: indistinguishable photons

\[ \hat{a}_3 = \hat{a}_1 + \hat{a}_2 \]
\[ \hat{a}_4 = \hat{a}_1 - \hat{a}_2 \]

Initial state:
\[ \hat{a}_1^+ \hat{a}_2^+ |0\rangle = |1_1 1_2\rangle \]

Remaining photon state (immediately afterwards):
\[ \hat{a}_4 |1_1 1_2\rangle = |0_1 1_2\rangle - |1_1 0_2\rangle = -\hat{a}_4^+ |0\rangle \]

Probability to detect a photon at time = \( t + \tau \)

Click!
Time = \( t \)

Probability = 0 to detect in 3 at \( \tau=0 \)

\[ e^{-i\omega_2 \tau} |0_1 1_2\rangle - e^{-i\omega_1 \tau} |1_1 0_2\rangle \]

Probability oscillates as (\( \omega_1 - \omega_2 \))\( \tau \)
Time resolved two-photon quantum interference

Record time-resolved coincidence counts

Perpendicular polarization:

Parallel polarization:

Zero-free-parameter simulation

532nm ps-pulsed excitation (10 MHz)
Outlook: Eliminating luck

Both experiments "got lucky".

Electronic tuning is tricky in the presence of photoexcited carriers.

Barrett et al. 2011

Simulation using measured f di f f counts

$\text{f}_{\text{di f}}$ t $\text{f}_{\text{frequency}}$

$\Delta \text{r if}$ $\text{f}_{\text{ds}}$

$\text{incidence Gate}\,$ $\text{vol}$ $\text{t C}$

$\Delta \text{t}$ $\text{age}(\text{V})$

Detection time difference (ns)

Excitation detuning (GHz)

Avenues for improvement: better understanding of tuning dynamics, optimized excitation frequencies

Recent results: HP Group

Use Stark shifts to stabilize transition frequencies
Outlook: Integrated optics

Critical technology:
Collection efficiency typically << 1%
ZPL only 3% of total emission

Directed emission

Cavity quantum electrodynamics

Diamond ring resonator
Photonic crystal cavity

Also
Loncar, Fu, Becher, Barclay, A
wschalom, Englund

Emission on cavity resonance enhanced by

\[ F_P = \frac{3}{4 \pi^2} \left( \frac{\lambda}{n} \right)^3 \frac{Q}{V} \]

Quality factor
Mode volume

Diamond nanophotonics

Promising avenue to enhance ZPL emission fraction and improve collection efficiency
Summary

The vision:
• A few-spin-qubit register with preparation, coherent control, and readout
• Scalability via interactions between NV registers

Heading towards entanglement distribution for quantum communication and quantum networks
Thanks to

Lucio Robledo
Hannes Bernien
Bas Hensen
Toenov.d. Sar

$$ FOM, SOLID, Research Corporation $$

Anna Kashkanova
Donghun Lee
Jack Sankey
Andrew Jayich

Brian Yang
Mitchell Underwood
Jack Harris

McGill
Starting January 2013
...positions available!