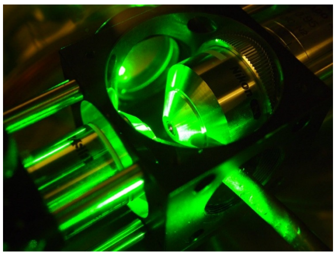
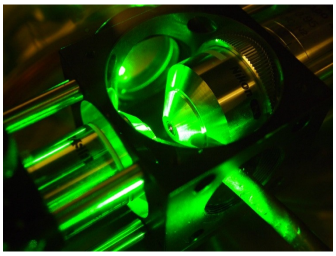
Experiments with spin qubits in diamond



Gavin W Morley
University of Warwick

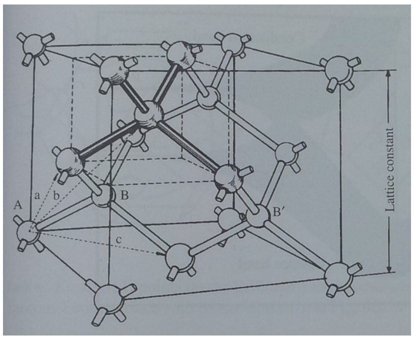
Experiments with spin qubits in diamond: overview

- Diamond
  - Nitrogen-vacancy (NV) centre
    1. Properties
    2. Applications
       a) magnetometry
       b) thermometry
       c) electrometry
       d) in a tractor beam?
       e) violating Bell's inequality
  - Silicon-vacancy (SiV) centre



Diamond

Face-centred cubic (FCC)
with two atom basis



Diamond crystal structure. Page 37, Singleton, Band Theory and Electronic Properties of Solids, OUP 2001

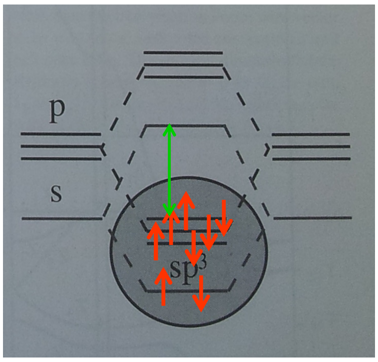
Diamond Science Technology Centre

EPSRC CDT:
Warwick (host)
Oxford
Imperial
Bristol
Cardiff
Strathclyde
Newcastle
Aberystwyth

Diamond

- tight-binding model

Carbon:
$1s^2\ 2s^2\ 2p^2$



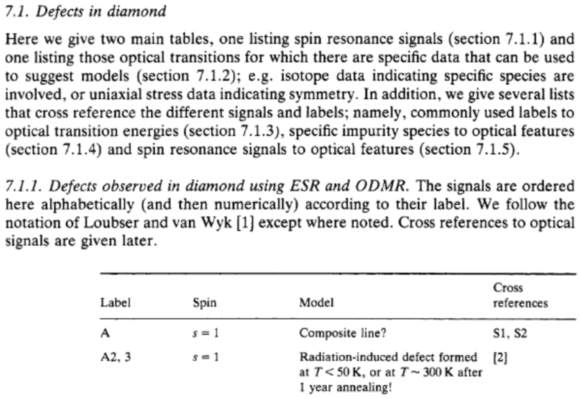
Schematic of the formation of sp^3 hybrid bonding states in diamond. Page 37, Singleton, Band Theory and Electronic Properties of Solids, OUP 2001

5.5 eV band gap

Diamond is an insulator:
”a place where electrons can be hermits”

Diamond defects

F Bridges, G Davies, J Robertson and AM Stoneham,
Journal of Physics-Condensed Matter **2**, 2875 (1990)



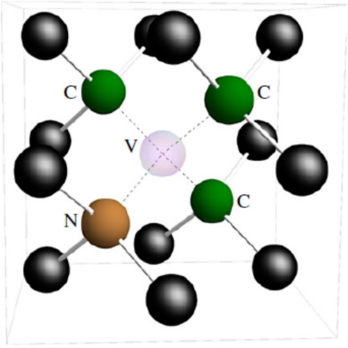
7.1. Defects in diamond

Here we give two main tables, one listing spin resonance signals (section 7.1.1) and one listing those optical transitions for which there are specific data that can be used to suggest models (section 7.1.2); e.g. isotope data indicating specific species are involved, or uniaxial stress data indicating symmetry. In addition, we give several lists that cross reference the different signals and labels; namely, commonly used labels to optical transition energies (section 7.1.3), specific impurity species to optical features (section 7.1.4) and spin resonance signals to optical features (section 7.1.5).

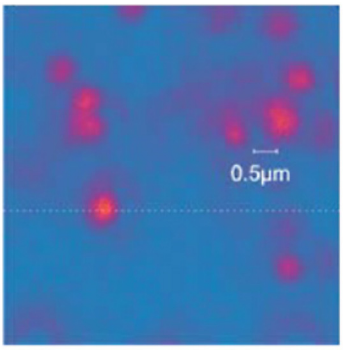
7.1.1. Defects observed in diamond using ESR and ODMR. The signals are ordered here alphabetically (and then numerically) according to their label. We follow the notation of Loubser and van Wyk [1] except where noted. Cross references to optical signals are given later.

Label	Spin	Model	Cross references
A	$s = 1$	Composite line?	S1, S2
A2, 3	$s = 1$	Radiation-induced defect formed at $T < 50$ K, or at $T \sim 300$ K after 1 year annealing!	[2]

The nitrogen-vacancy (NV) centre in diamond



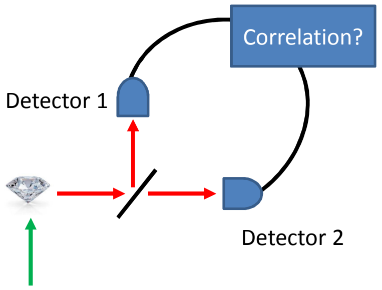
Confocal microscope image



MW Doherty, NB Manson, P Delaney, F Jelezko, J Wrachtrup, LCL Hollenberg, Phys Rep **528**, 1 (2013)

Single nitrogen-vacancy centres

Hanbury Brown and Twiss (HBT) experiment

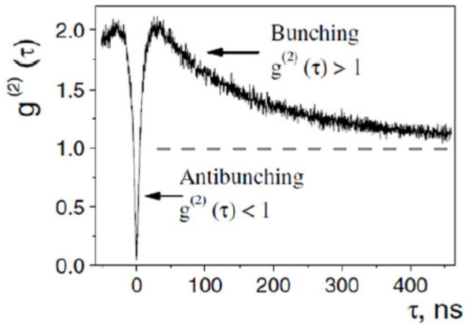


Correlation?

Detector 1

Detector 2

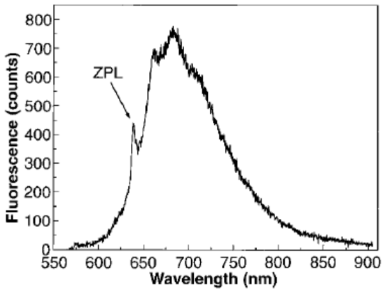
Green excitation

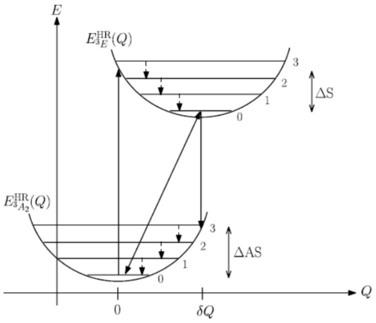


MW Doherty, NB Manson, P Delaney, F Jelezko, J Wrachtrup, LCL Hollenberg, Phys Rep **528**, 1 (2013)

Single nitrogen-vacancy centres

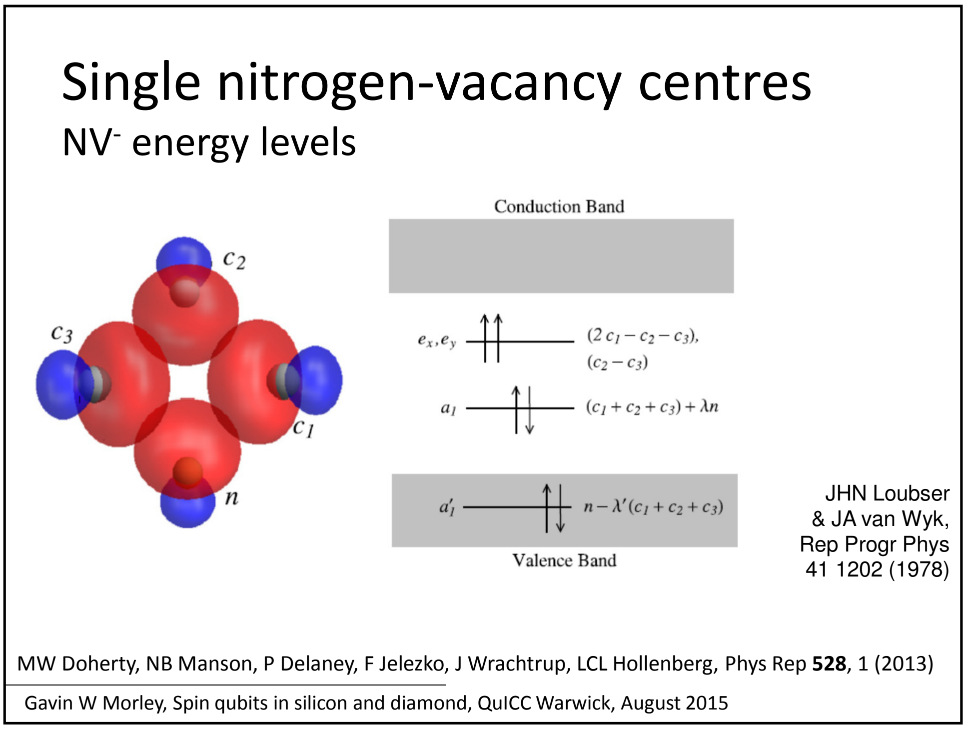
NV$^-$ optical spectroscopy





Green excitation in, red florescence out

See also: M Fox, Optical Properties of Solids, Second Edition, OUP 2013, Section 8.2, page 218-224.
A Gruber, A Drabenstedt, C Tietz, L Fleury, J Wrachtrup*, C. von Borczyskowski, Science **276**, 2012 (1997).
MW Doherty, NB Manson, P Delaney, F Jelezko, J Wrachtrup, LCL Hollenberg, Phys Rep **528**, 1 (2013).



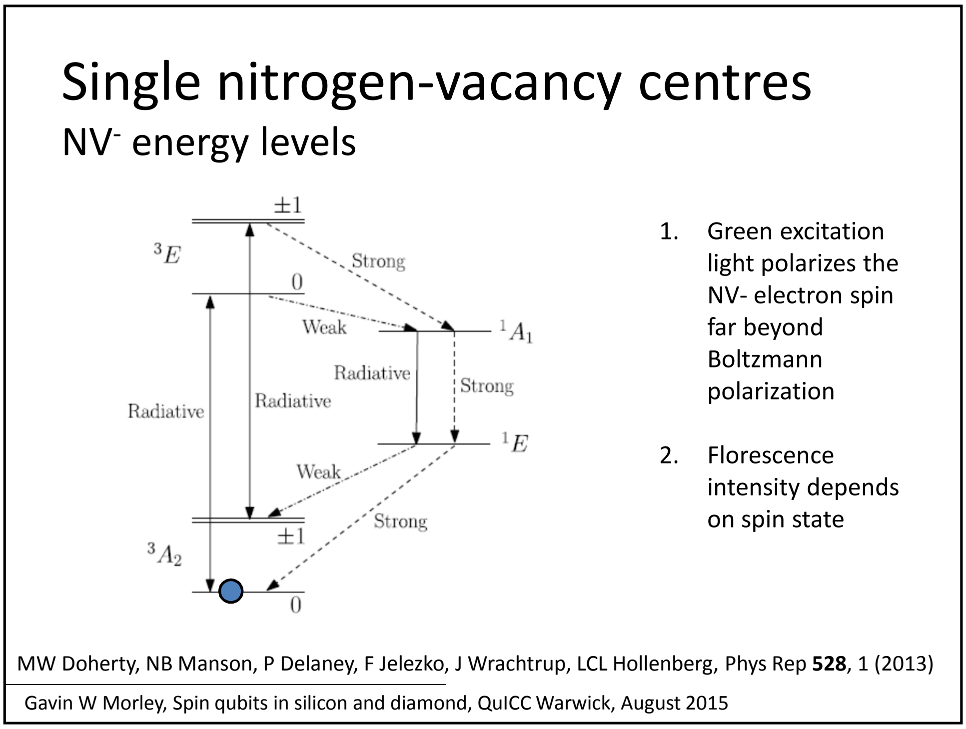
Single nitrogen-vacancy centres

NV$^-$ energy levels

JHN Loubser
& JA van Wyk,
Rep Progr Phys
41 1202 (1978)

MW Doherty, NB Manson, P Delaney, F Jelezko, J Wrachtrup, LCL Hollenberg, Phys Rep **528**, 1 (2013)

Gavin W Morley, Spin qubits in silicon and diamond, QuICC Warwick, August 2015



Single nitrogen-vacancy centres

NV$^-$ energy levels

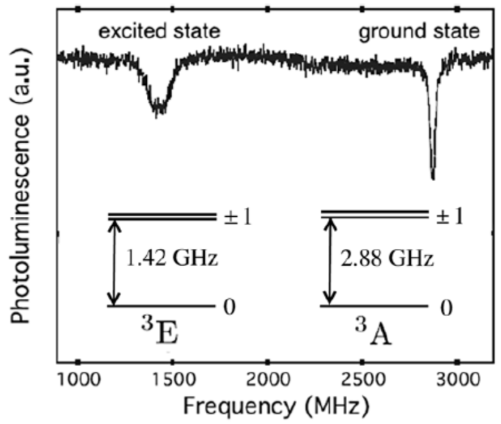
1. Green excitation light polarizes the NV- electron spin far beyond Boltzmann polarization
2. Florescence intensity depends on spin state

MW Doherty, NB Manson, P Delaney, F Jelezko, J Wrachtrup, LCL Hollenberg, Phys Rep **528**, 1 (2013)

Gavin W Morley, Spin qubits in silicon and diamond, QuICC Warwick, August 2015

Single nitrogen-vacancy centres

NV$^-$ optically-detected magnetic resonance



1. Green excitation light polarizes the NV- electron spin far beyond Boltzmann polarization
2. Florescence intensity depends on spin state

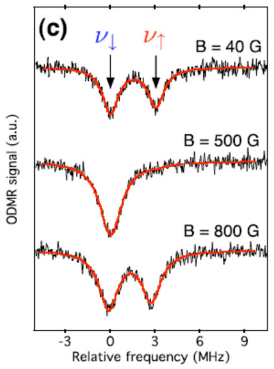
MW Doherty, NB Manson, P Delaney, F Jelezko, J Wrachtrup, LCL Hollenberg, Phys Rep **528**, 1 (2013)

Single nitrogen-vacancy centres

Initialize nuclear spins as well as electrons

Mini-overview

- NV fabrication
- Qubit initialisation
- Readout
- Control
- Coherence times



V Jacques *et al*, Physical Review Letters **102**, 057403 (2009)

Single nitrogen-vacancy centres

Single shot readout using nuclear spins

Mini-overview
- NV fabrication
- Qubit initialisation
- Readout
- Control
- Coherence times

L. Jiang *et al*, Science **326**, 267 (2009)
P Neumann *et al*, Science **329**, 542 (2010)
E Togan *et al*, Nature **478**, 497 (2011)

MW Doherty, NB Manson, P Delaney, F Jelezko, J Wrachtrup, LCL Hollenberg, Phys Rep **528**, 1 (2013)

Single nitrogen-vacancy centres

Quantum control of electron and nuclear spins

Mini-overview
- NV fabrication
- Qubit initialisation
- Readout
- Control
- Coherence times

L. Jiang *et al*, Science **326**, 267 (2009)
P Neumann *et al*, Science **329**, 542 (2010)
E Togan *et al*, Nature **478**, 497 (2011)

Microwaves to control electron spin
and
radiowaves to control nuclear spins

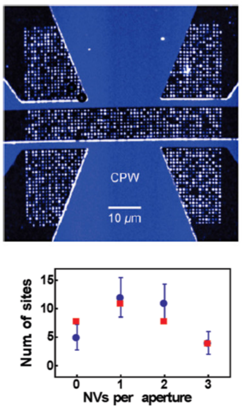
eg three spin quantum error correction:
G Waldherr *et al*, Nature **506**, 204 (2014)

MW Doherty, NB Manson, P Delaney, F Jelezko, J Wrachtrup, LCL Hollenberg, Phys Rep **528**, 1 (2013)

Single nitrogen-vacancy centres

Ion implantation for fabrication

Mini-overview
- NV fabrication
- Qubit initialisation
- Readout
- Control
- Coherence times



Very imperfect arrays:
- up to 50% yield for NV- after nitrogen ion implantation
- Worse for shallow NV-
- ~50 nm precision
- Repeat-until-success?

DM Toyli *et al*, Nano Lett **10**, 3168 (2010)

Single nitrogen-vacancy centres

Spin coherence times

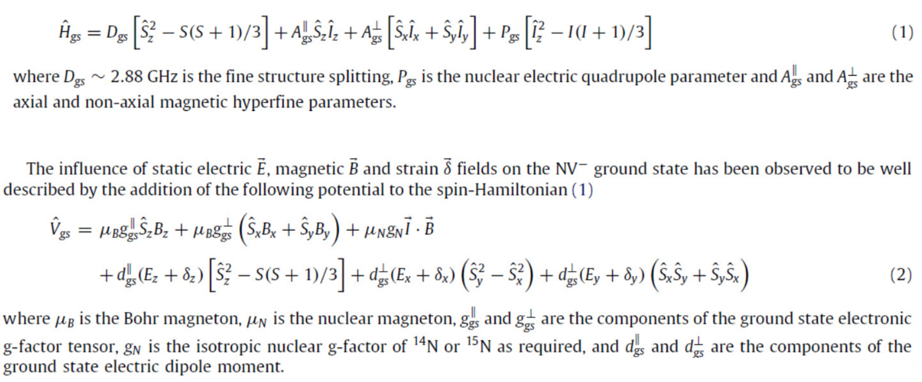
Mini-overview
- NV fabrication
- Qubit initialisation
- Readout
- Control
- Coherence times

	Electron spin in ^{12}C	**Nuclear spin**
Room temperature T_2	1.8 ms	1 s
77 K T_2	0.6 s (with dynamic decoupling)	

1.8 ms: G Balasubramanian *et al*, Nature Materials **8**, 383 (2009)
0.6 s: N Bar-Gill *et al*, Nat Commun **4**, 1743 (2013)
1 s: PC Maurer *et al*, Science **336**, 1283 (2012)

Nitrogen-vacancy centres: Applications

- Magnetometer, Electrometer, Thermometer…



$$\hat{H}_{gs} = D_{gs}\left[\hat{S}_z^2 - S(S+1)/3\right] + A_{gs}^{\parallel}\hat{S}_z\hat{I}_z + A_{gs}^{\perp}\left[\hat{S}_x\hat{I}_x + \hat{S}_y\hat{I}_y\right] + P_{gs}\left[\hat{I}_z^2 - I(I+1)/3\right] \quad (1)$$

where $D_{gs} \sim 2.88$ GHz is the fine structure splitting, P_{gs} is the nuclear electric quadrupole parameter and $A_{gs}^{\parallel}$ and $A_{gs}^{\perp}$ are the axial and non-axial magnetic hyperfine parameters.

The influence of static electric $\vec{E}$, magnetic $\vec{B}$ and strain $\vec{\delta}$ fields on the NV^- ground state has been observed to be well described by the addition of the following potential to the spin-Hamiltonian (1)

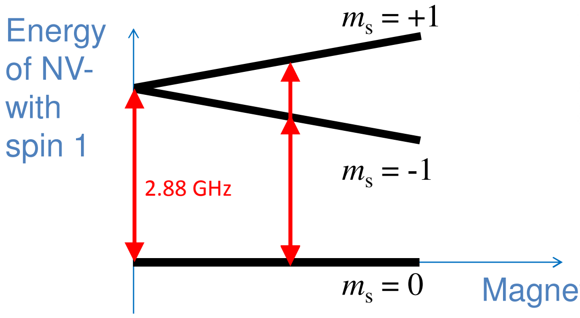
$$\begin{aligned}\hat{V}_{gs} = {} & \mu_B g_{gs}^{\parallel}\hat{S}_z B_z + \mu_B g_{gs}^{\perp}\left(\hat{S}_x B_x + \hat{S}_y B_y\right) + \mu_N g_N \vec{I}\cdot\vec{B} \\ & + d_{gs}^{\parallel}(E_z + \delta_z)\left[\hat{S}_z^2 - S(S+1)/3\right] + d_{gs}^{\perp}(E_x + \delta_x)\left(\hat{S}_y^2 - \hat{S}_x^2\right) + d_{gs}^{\perp}(E_y + \delta_y)\left(\hat{S}_x\hat{S}_y + \hat{S}_y\hat{S}_x\right) \quad (2)\end{aligned}$$

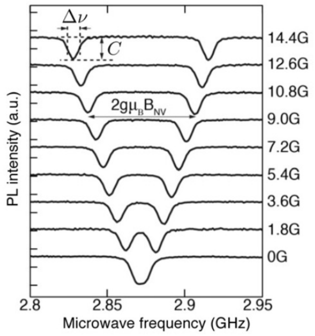
where μ_B is the Bohr magneton, μ_N is the nuclear magneton, $g_{gs}^{\parallel}$ and $g_{gs}^{\perp}$ are the components of the ground state electronic g-factor tensor, g_N is the isotropic nuclear g-factor of ^{14}N or ^{15}N as required, and $d_{gs}^{\parallel}$ and $d_{gs}^{\perp}$ are the components of the ground state electric dipole moment.

MW Doherty, NB Manson, P Delaney, F Jelezko, J Wrachtrup, LCL Hollenberg, Phys Rep **528**, 1 (2013)

Nitrogen-vacancy centres: Applications

- DC Magnetometer

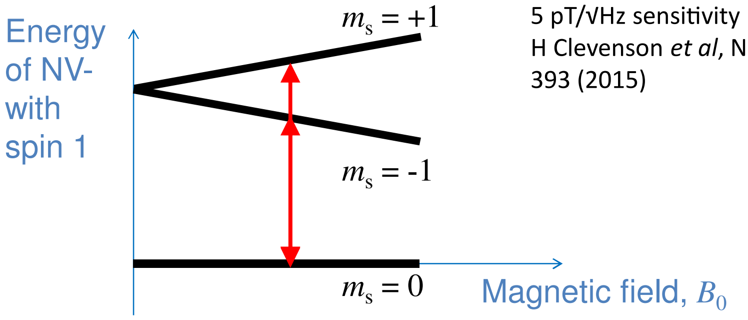




Review:
L Rondin *et al.*, *Magnetometry with nitrogen-vacancy defects in diamond*, Rep Prog Phys **77**, 056503 (2014)

Nitrogen-vacancy centres: Applications

- DC Magnetometer



Energy of NV- with spin 1

$m_s = +1$

$m_s = -1$

$m_s = 0$

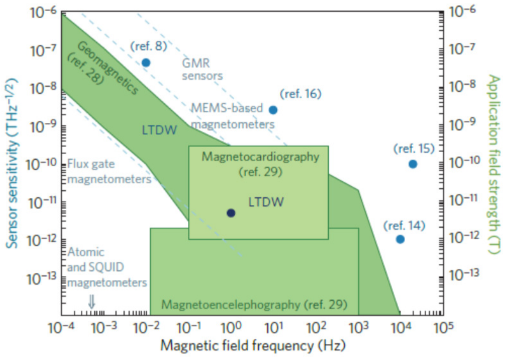
Magnetic field, B_0

5 pT/√Hz sensitivity at 1 Hz:
H Clevenson *et al*, Nat Phys **11**, 393 (2015)

- lock-in detection
- monitor temperature shifts by recording average of the split peaks
- large ensemble of NV- (sacrificing nanoscale spatial resolution)
- multiple passes of light though the diamond

Nitrogen-vacancy centres: Applications

- DC Magnetometer

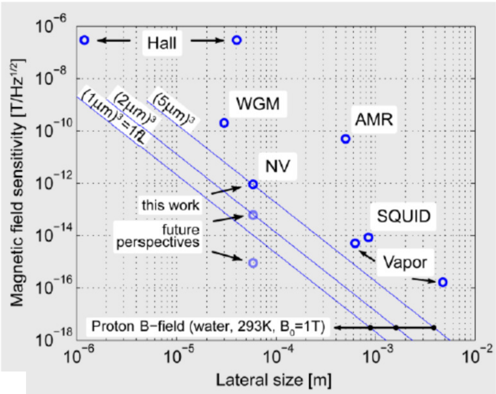


5 pT/√Hz sensitivity at 1 Hz:
H Clevenson *et al*, Nat Phys **11**, 393 (2015)

- lock-in detection
- monitor temperature shifts by recording average of the split peaks
- ensemble of ~10^{13} NV- (sacrificing nanoscale spatial resolution)
- multiple passes of light though the diamond

Nitrogen-vacancy centres: Applications

- AC Magnetometer

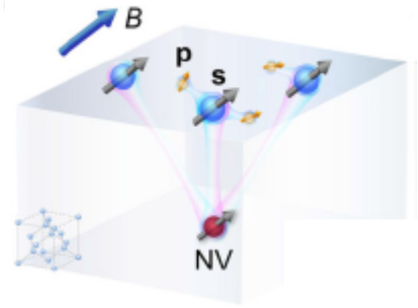


0.9 $\mathrm{pT}/\sqrt{\mathrm{Hz}}$ sensitivity at 10 kHz:
T Wolf *et al*, arXiv:1411.6553 (2014)

- Spin echo on the NV- centre allows through chosen frequency of interest
- Control noise in laser and microwave sources
- Ensemble of $\sim 10^{11}$ NV-

Nitrogen-vacancy centres: Applications

- Nanoscale AC magnetometer for single spin NMR

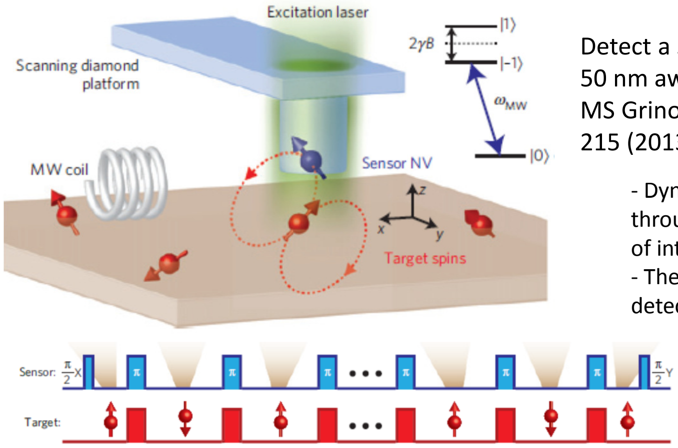


Single proton spin on surface of diamond:
AO Sushkov *et al*, Phys Rev Lett **113**, 197601 (2014)

- Spin echo on the NV- centre allows through chosen frequency of interest
- Single NV- detects a reporter spin

Nitrogen-vacancy centres: Applications

- Nanoscale AC magnetometer for scanning over a sample

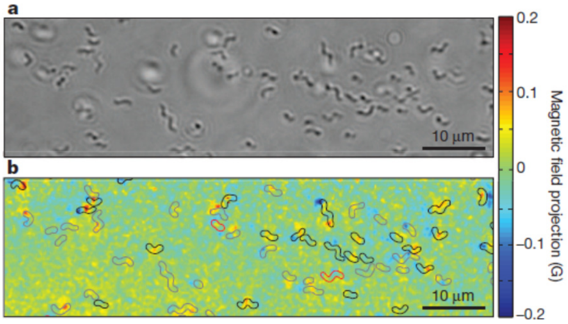


Detect a single electron spin 50 nm away from NV- sensor: MS Grinolds *et al*, Nat Phys **9**, 215 (2013)

- Dynamic decoupling allows through chosen frequency of interest
- The electron spin being detected was another NV-

Nitrogen-vacancy centres: Applications

- Wide-field magnetometry

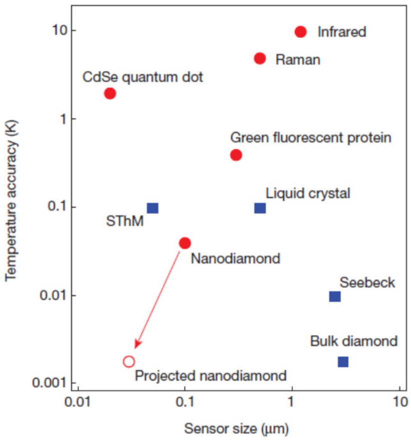


Optical magnetic imaging of living cells, D Le Sage *et al*, Nature **496**, 486 (2013)

Diamond is bio-compatible

Nitrogen-vacancy centres: Applications

- Nanoscale thermometry for inside living cells & computer chips



G Kucsko *et al*, Nature **500**, 54 (2013)

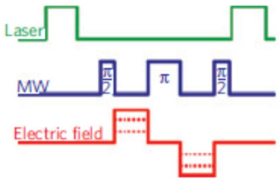
P Neumann *et al*, Nano Lett **13**, 2738 (2013)

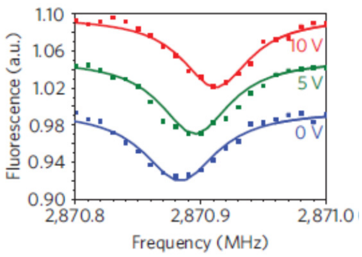
DM Toyli *et al*, PNAS **110**, 8417 (2013)

Nitrogen-vacancy centres: Applications

- Electrometry: Stark shift

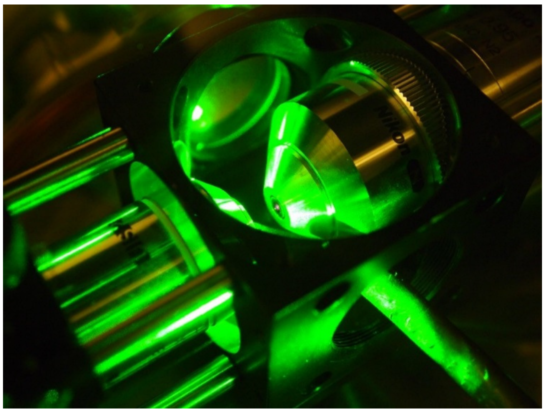
F Dolde *et al*, Nat Phys **7**, 459 (2011)





Nitrogen-vacancy centres: Applications

- In a tractor beam?

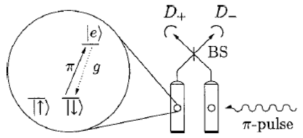


Proposal for testing spatial quantum superposition with 100 nm diamond:
- M Scala *et al*, Physical Review Letters **111**, 180403 (2013)
- C Wan *et al*, arXiv:1509.00724 (2015)

See also:
- LP Neukirch *et al*, Optics Letters **38**, 2976 (2013)
- Z-q Yin *et al*, Physical Review A **88**, 033614 (2013)

Nitrogen-vacancy centres: Applications

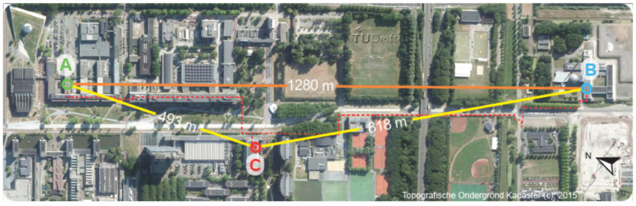
- Violating Bell's inequality



Proposal for entangling remote NV-
SD Barrett and P Kok, Physical Review A **71**, 060310 (2005)

The first experiment in which the "detection" and "locality" loopholes have both been closed

B Henson *et al*, arXiv:1508.05949 (2015)

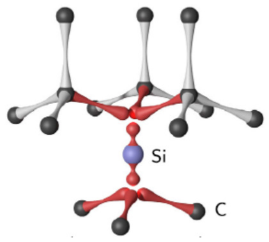


Silicon-vacancy centres

- Better optical properties, worse spin properties (spin T_2* ~ 45 ns)
  - 70% of the florescence from the SiV- is in the zero phonon line (ZPL), compared with 4% for NV- at low temperature

Spin control with coherent population trapping:

- B Pingault *et al*, Physical Review Letters **113**, 263601 (2014)
- LJ Rogers *et al*, Physical Review Letters **113**, 263602 (2014)



Experiments with spin qubits in diamond: overview

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  - Silicon-vacancy (SiV) centre