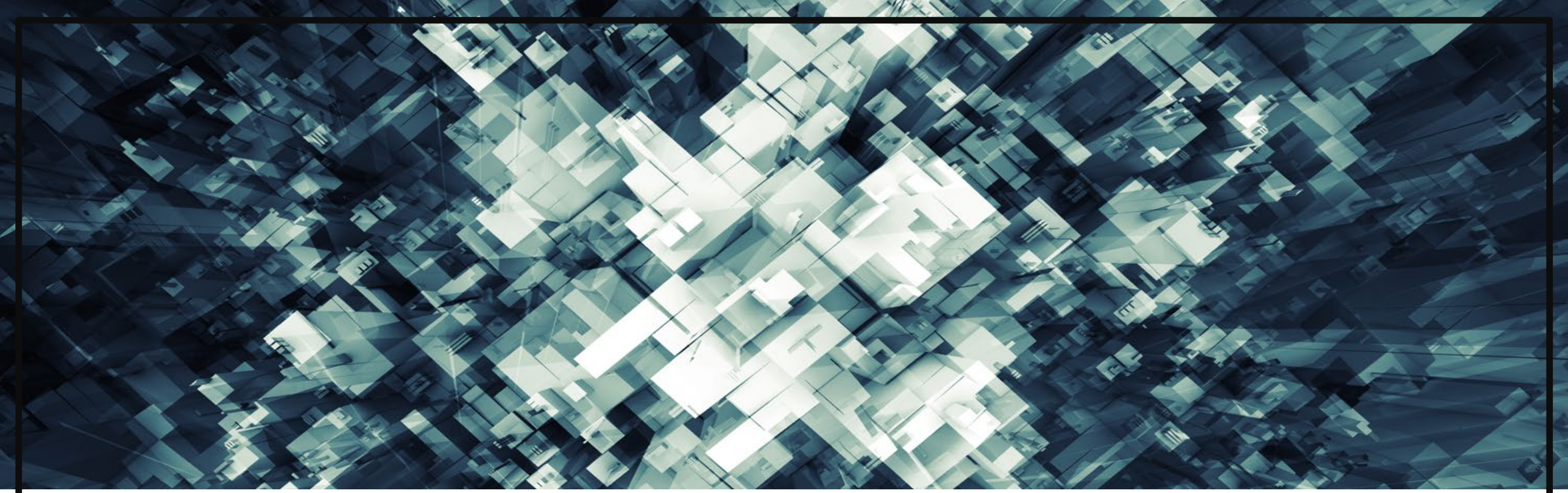

Photoelectric readout of electron spin qubits in diamond at room temperature

E. Bourgeois[1,2], M. Gulka[1], J. Hruby[1], M. Nesladek[1,2]

[1]Institute for Materials Research (IMO), Hasselt University, Belgium

[2]IMOMEC division, IMEC, Belgium

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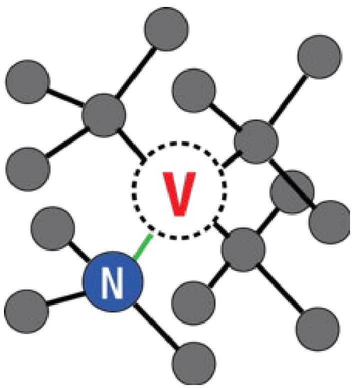
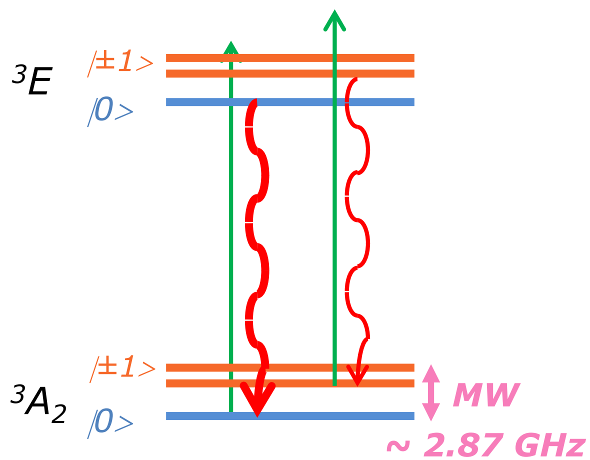
Meeting of Cost action NQO – Brussels, 4 April 2019

NV centres in diamond for quantum technologies



NV^{+} (4 electrons)
NV^{0} (5 electrons)
NV^{-} (6 electrons)

NV^{-}: triplet spin system



- Spin state of NV^{-} GS :
  - Optical initialization into m_s = 0
  - MW manipulation
  - Optical read-out
- NV^{-} in ultra-pure, isotopically purified diamond: T_2 ~ 1 ms at RT
  [N_s^0] < 1 ppb
  [^{13}C] < 0.01 %

→ NV^{-} ground state can be used as RT qubit for

- Quantum information processing
- Quantum computation
- Quantum sensing

(Magnetometry, electric field sensing, thermometry, nanoscale NMR, gyroscopy, quantum sensing in biological environment, etc.)

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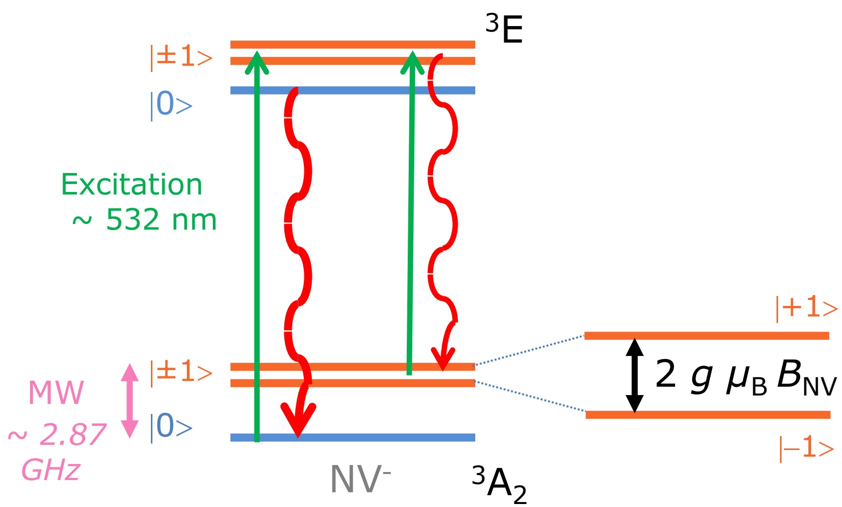
NV centres for quantum sensing

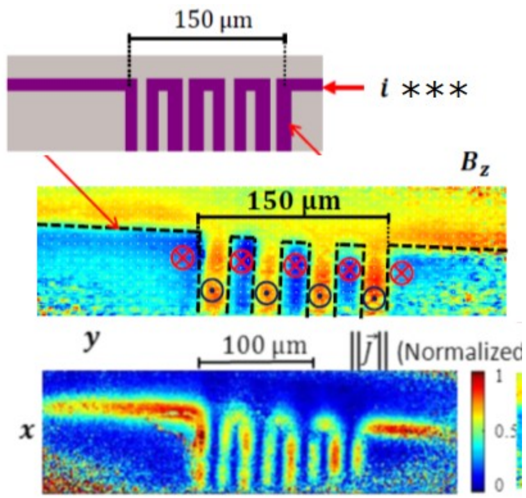
Applications of NV centers for quantum sensing:

- Magnetometry,
- Electric field sensing,
- Thermometry,
- Strain and pressure sensing, etc.

Zeeman splitting between |+1> and |–1> spin sublevels under external magnetic field

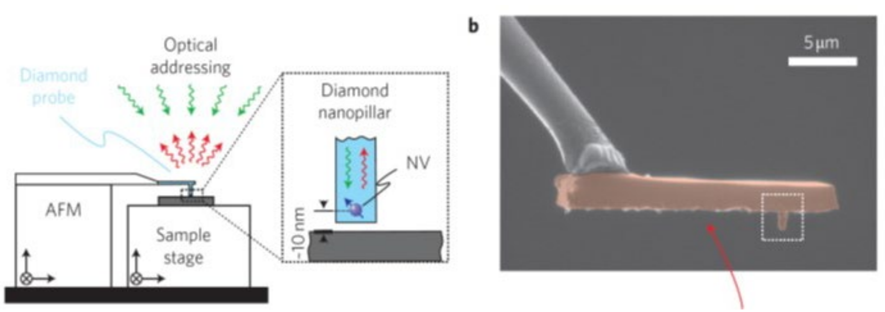


Ultra-sensitive sensing with NV ensembles*



Vector magnetometry with NV ensembles

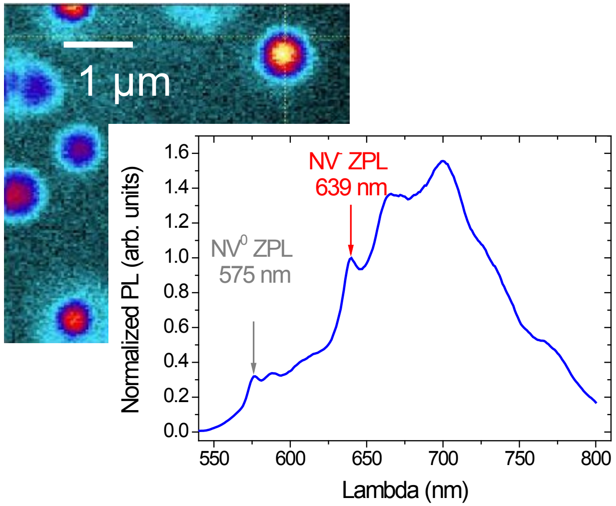
Nanoscale sensing with a single NV centre**



*A. Nowodzinski *et al.*, ***Microelectronics reliability* 55** (2015)

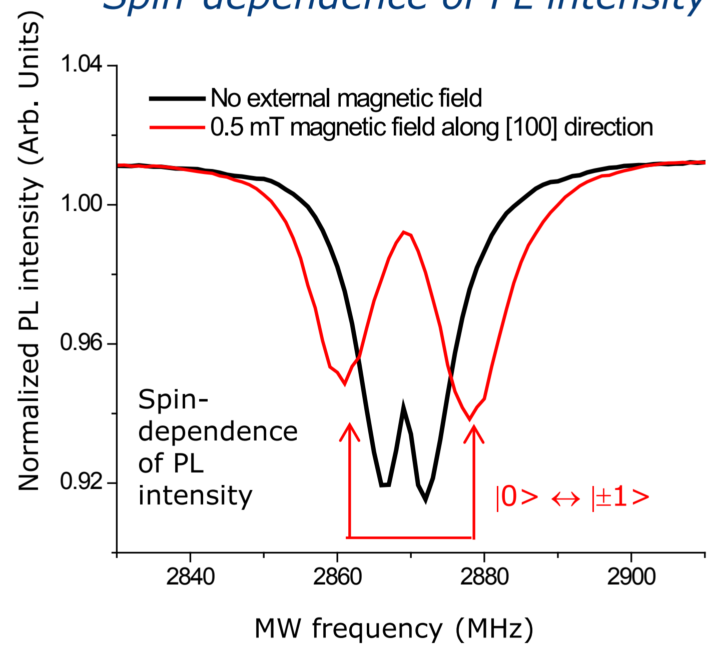
Maletinski P. *et al.*, ***Nature Nanotechnology* 7, 320–324 (2012)

Optical detection of NV^- magnetic resonances (ODMR)

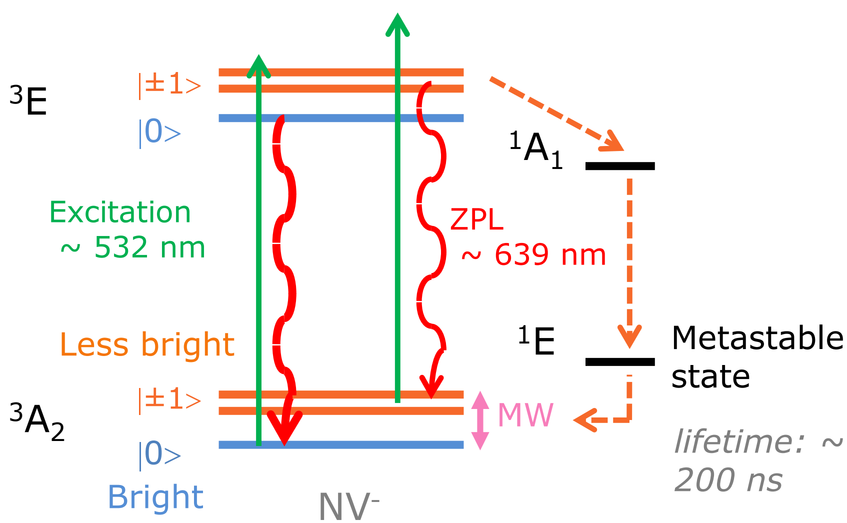


- Photostability (no photobleaching)
- High PL yield (single NV detection)

Spin-dependence of PL intensity



Spin-selective transitions to NV^- metastable state



Limitations of ODMR

- Spatial resolution limited by optical diffraction
- High photon collection efficiency requires complex microfabrication

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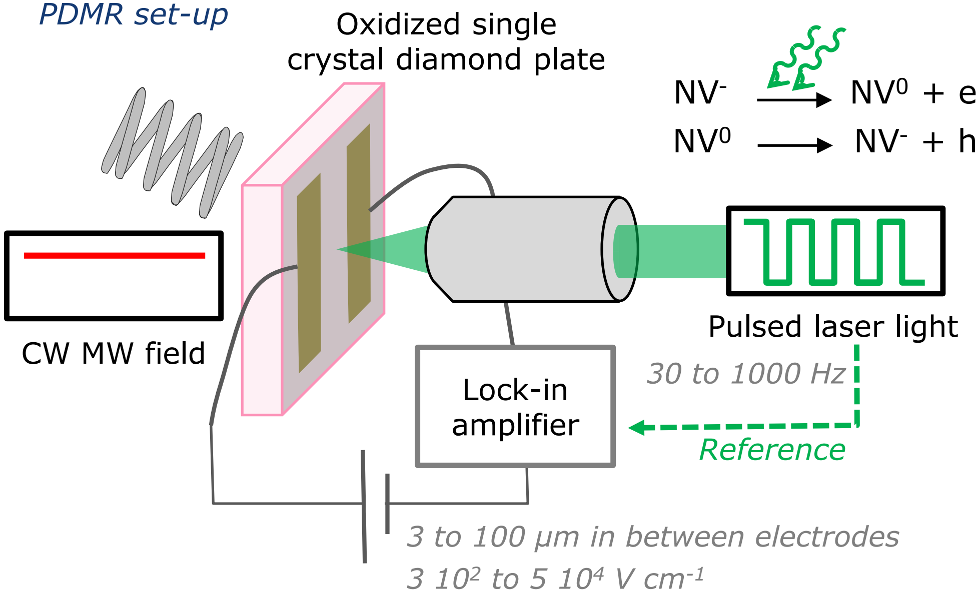
Objective NA: 0.95, 532 nm excitation, 2 mW, LP650

Photoelectric detection of magnetic resonances (PDMR)

Alternative to ODMR for readout of NV spin state:

Direct detection of spin-dependent photocurrent induced by ionization of NV⁻

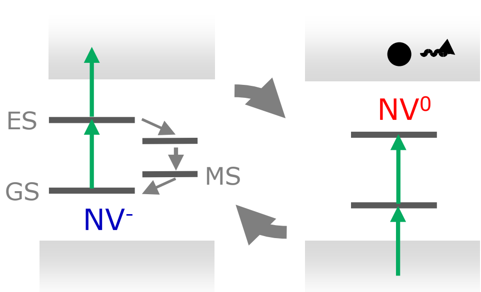
PDMR set-up



NV⁻ ionization induced by laser light

DC electric field in between coplanar electrodes

PDMR set-up



2-photon:

- Ionization of NV⁻
- Back-conversion from NV⁰ to NV⁻

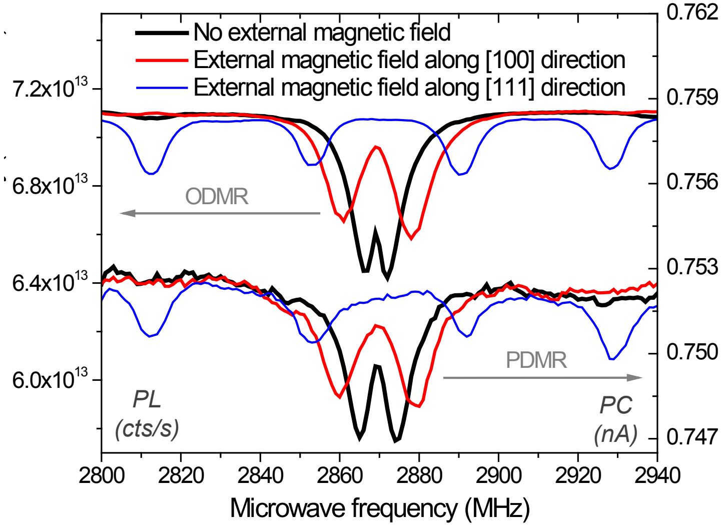
Advantages compared to ODMR:

- Direct integration of NV to electronic chip
- More compact and easily scalable
- Readout of single NV centers closer than the diffraction limit
- High detection rates without complex microfabrication

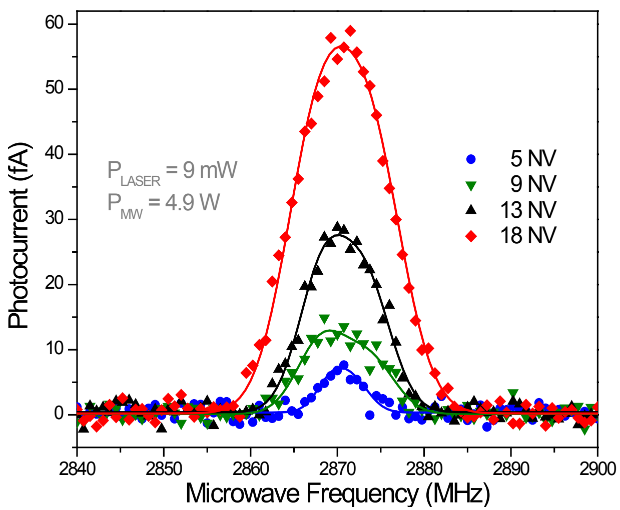
Photoelectric readout of NV⁻ spin ensembles

CW PDMR on large NV ensembles[1]

CW PDMR on ~10^9 NVs in irradiated Ib-diamond[1]

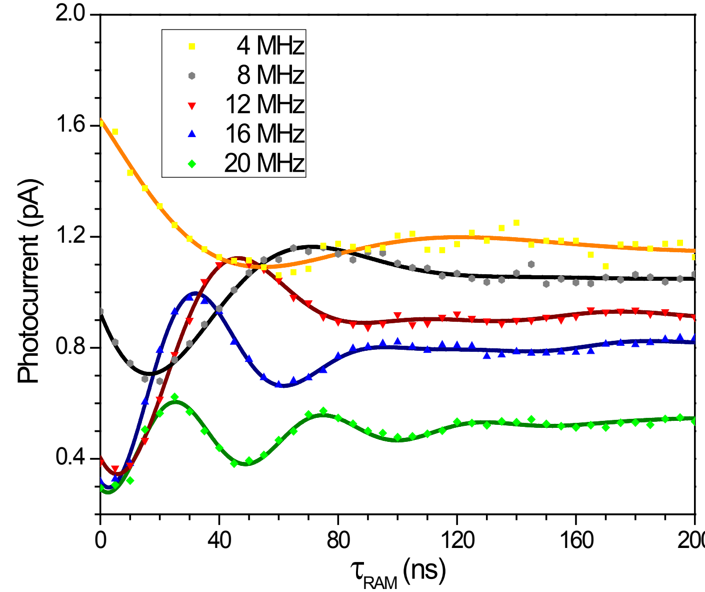


Downscaling of PDMR to small NV ensembles[2]



Pulsed MW-triggered PDMR on ensembles of ~ 5 to 20 NVs implanted in electronic grade diamond[2]

Photoelectric readout of coherently driven NV centres[2]



Ramsey fringes detected on ~ 10^3 shallow NVs implanted in electronic grade diamond[2]

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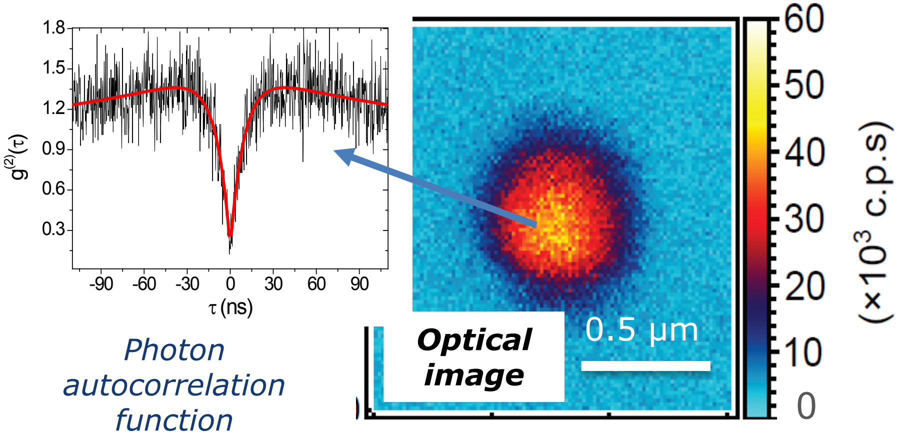
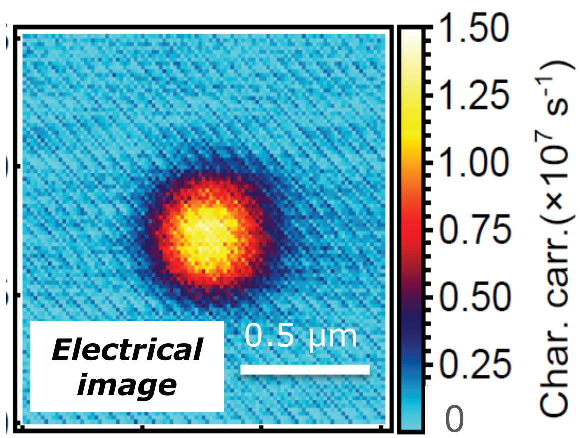
[1]E. Bourgeois *et al.* ***Nat. Commun.* 6** (2015)
[2]M. Gulka *et al.* ***Phys. Rev. Applied* 7** (2017)

Detection of photoelectric signal from a single NV centre

Photoluminescence and photoelectric mapping of a single NV⁻ centre in electronic grade diamond (~ 15 µm depth)

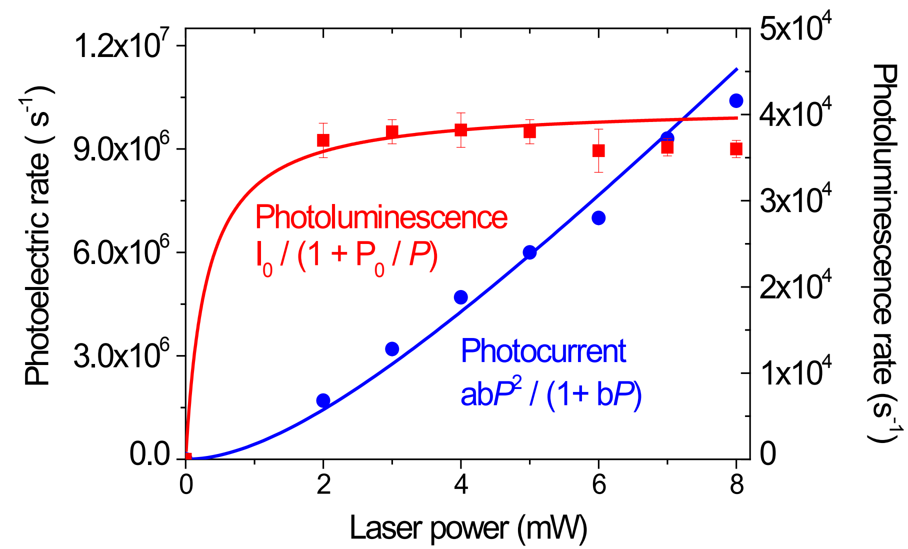


Photon autocorrelation function



DC detection of PC after ultra-low noise amplification

Comparison between optical and photoelectric detection rates



→ Photoelectric imaging of a single NV⁻ centre

→ Detection rates **increased by a factor ~ 10³** compared to optical readout

No saturation of photocurrent under high excitation power

Laser : 532 nm, 9 mW. Objective N.A.: 0.95
Voltage: 80 V, inter-electrode distance: 50 µm

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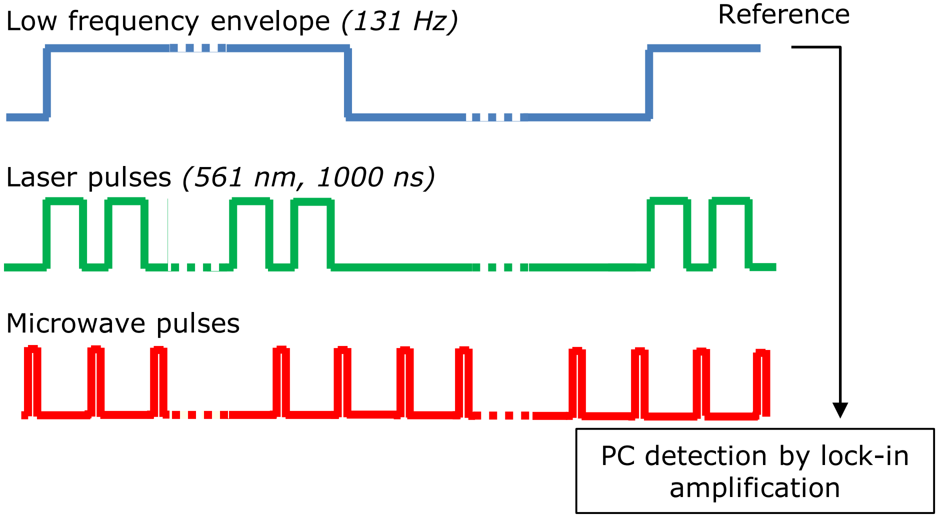
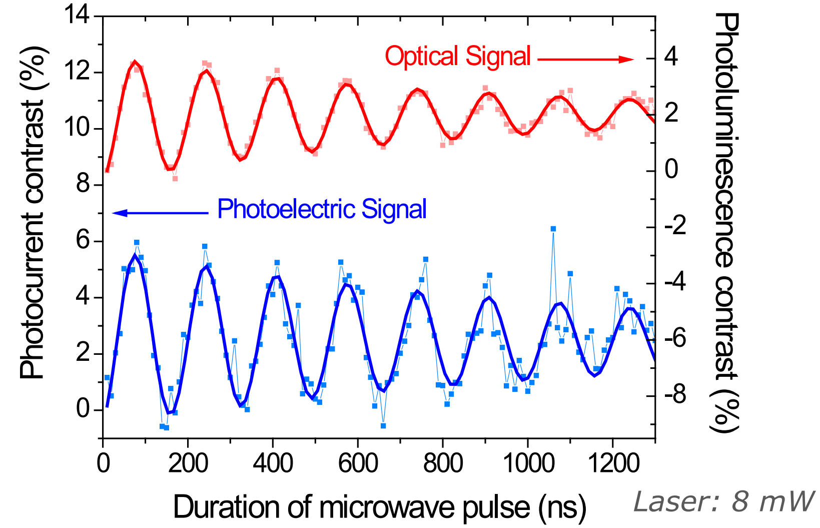
P. Siyushev, M. Nesladek, E. Bourgeois *et al.* ***Science* 363** (2019)

Photoelectric readout of a coherently driven single NV⁻ spin: detection of Rabi oscillations

*Pulsed detection scheme**

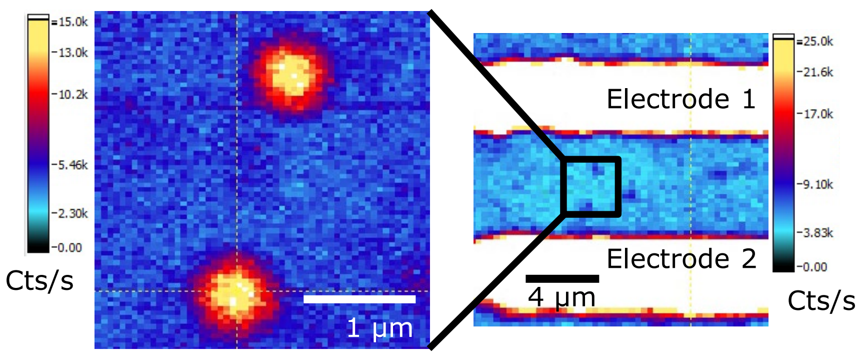


Photoelectric detection of Rabi oscillations on a single NV⁻ centre



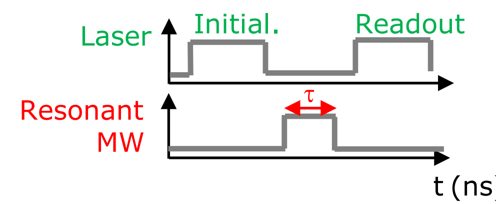
Laser: 8 mW

MW: 16 W



Voltage: 22 V

Inter-electrode distance: 6 µm



→ Photoelectric readout of a coherently manipulated single NV⁻ electron spin has been achieved

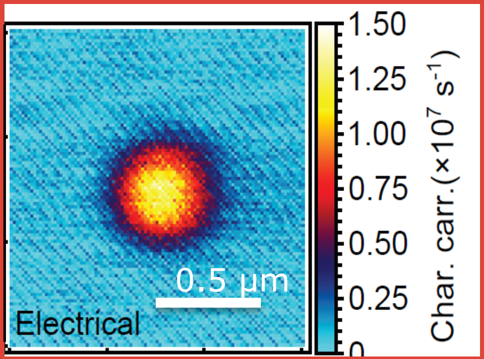
Highlights

- Photoelectric detection of NV⁻ magnetic resonance (PDMR) based on two-photon ionization of NV⁻

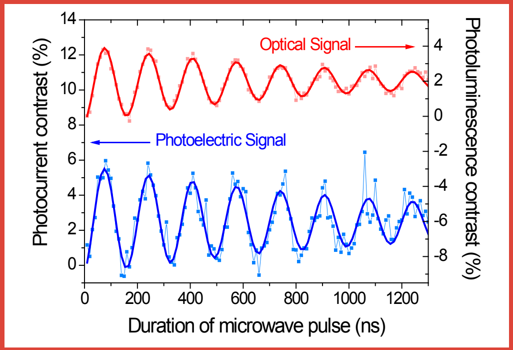
- Direct photoelectric readout of a coherently driven single NV⁻ spin, with photoelectric detection rate exceeding optical detection rate

  → **Electrically readout diamond quantum chips** integrated with electronics

Photoelectric imaging of a single NV⁻ centre



Photoelectric detection of Rabi oscillations on a single NV⁻ centre



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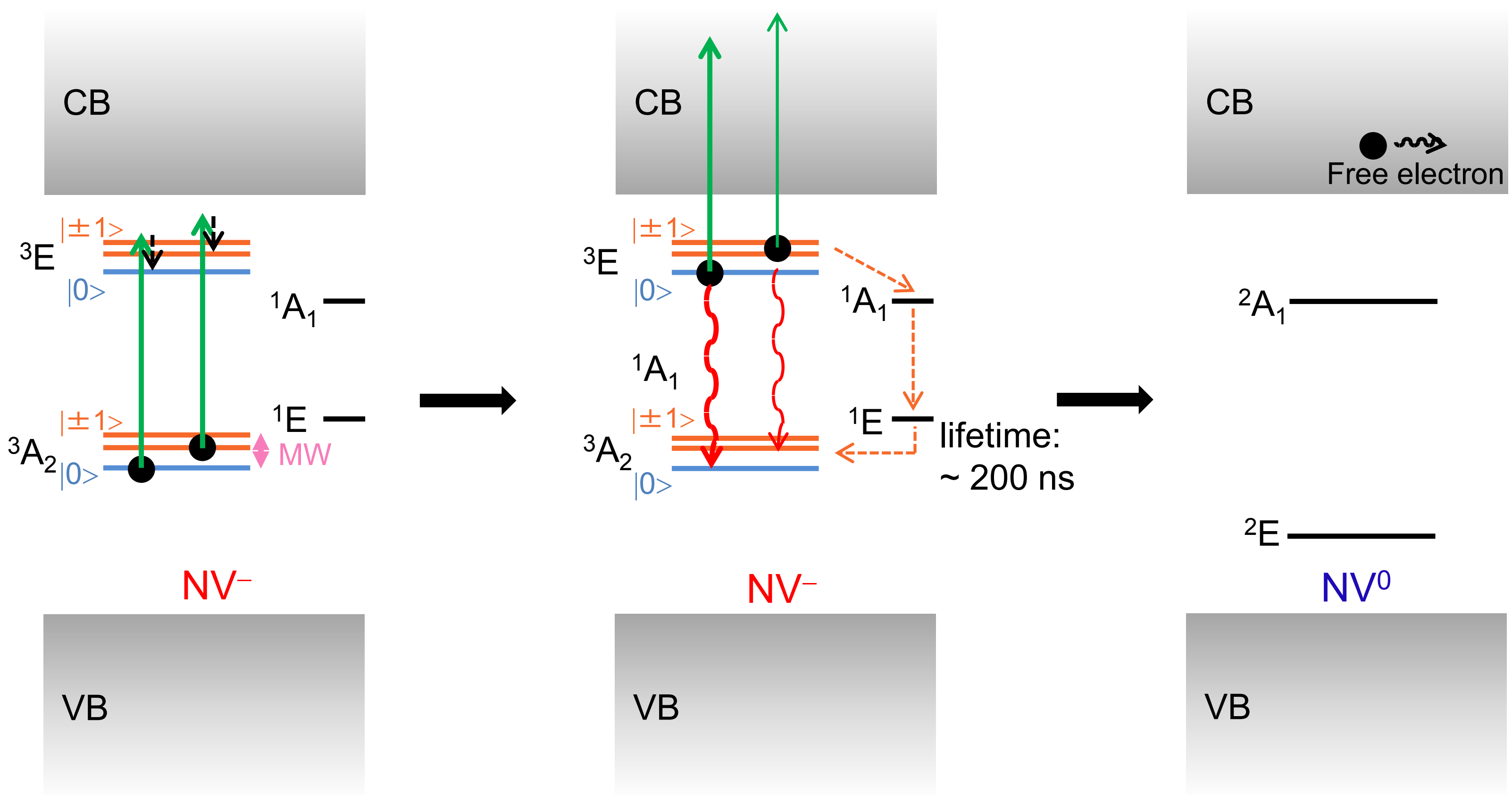
Ionization of NV⁻ – Origin of PDMR contrast



Spin-selective transitions to the metastable state

→ Temporary decrease in the occupation of NV⁻ ground state