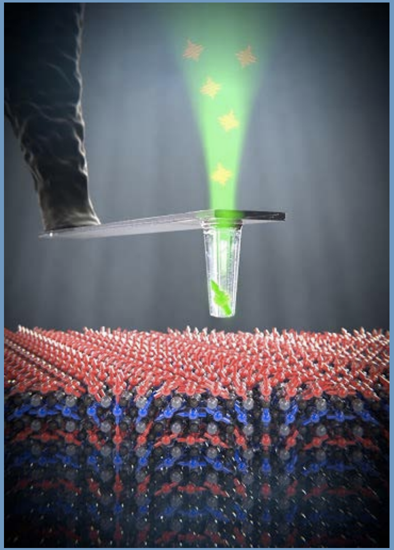
Exploiting impurities in diamond for nanoscale measurements

Isabelle PHILIP – Chercheur CNRS

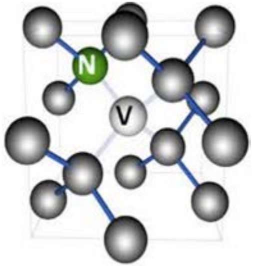
CNRS – Laboratoire Charles Coulomb



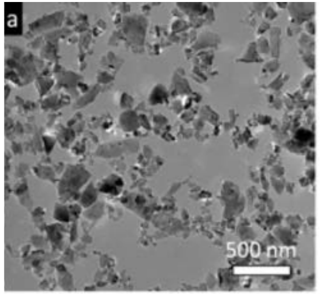
Vincent JACQUES

Aurore FINCO

The Nitrogen-Vacancy center



Nanodiamonds

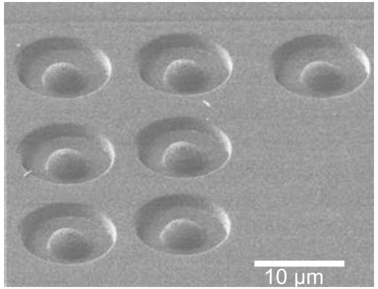


Sci. Report 5, 11661 (2015)

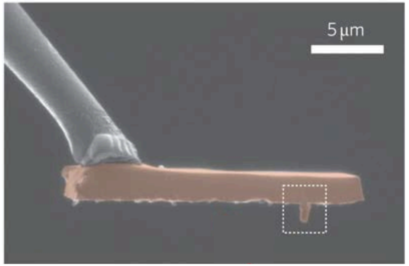
Bulk

elementsix
DE BEERS GROUP

Diamond nanostructures



Appl. Phys. Lett. 97, 241901 (2010)

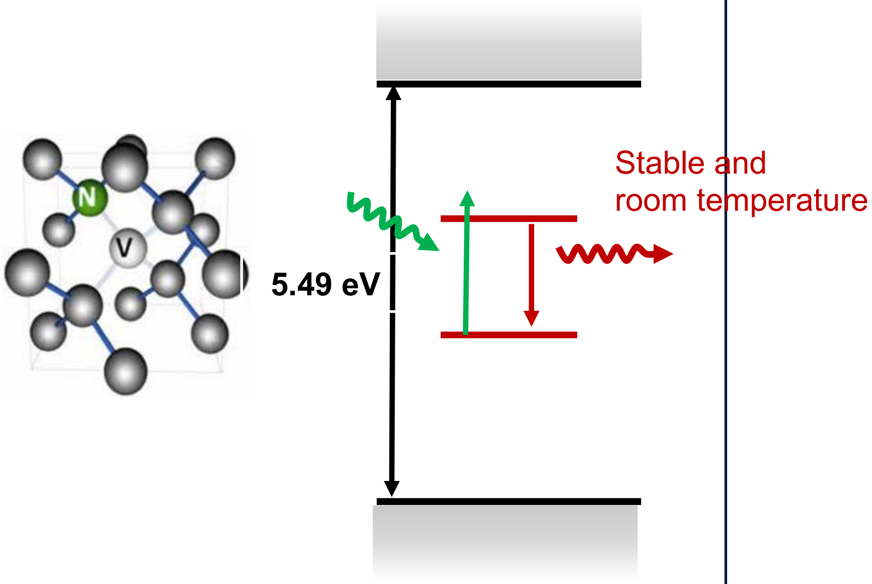


Nat. Nanotechnol. 7, 320 (2012)

cnrs

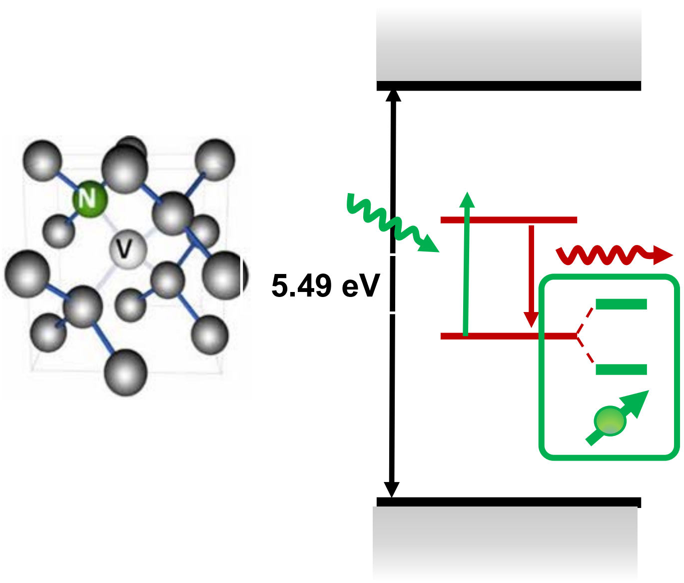
The Nitrogen-Vacancy center

Optical properties

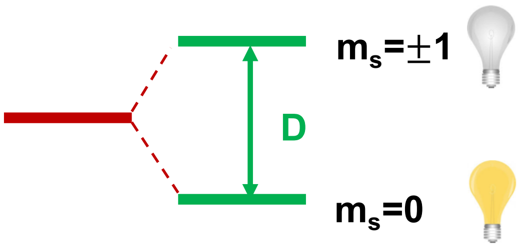


The Nitrogen-Vacancy center

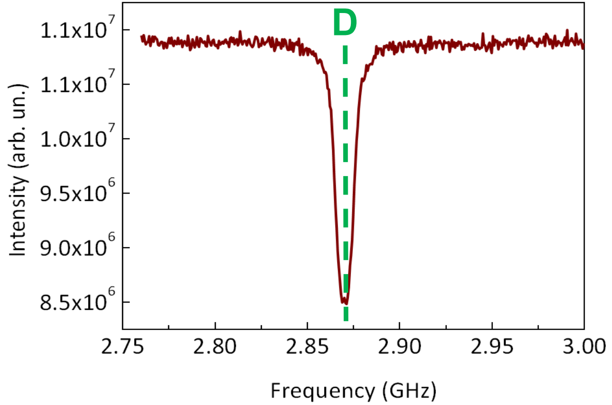
Optical properties



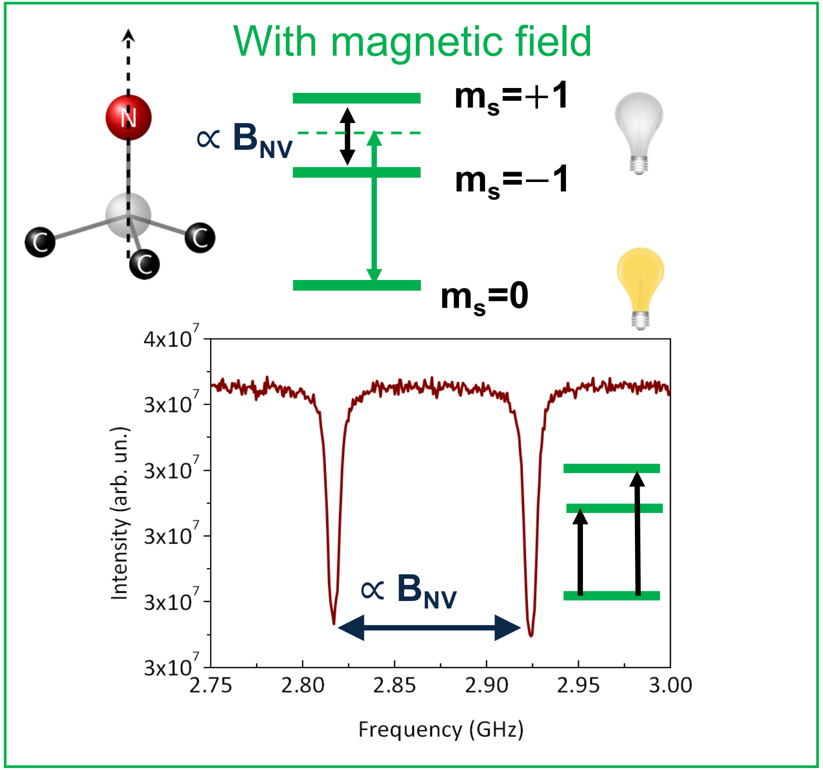
Spin properties

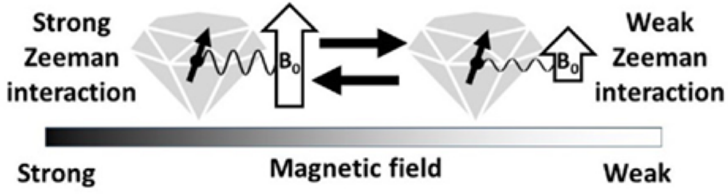


- Optical spin polarization into $m_s=0$
- Spin-dependent photoluminescence



The Nitrogen-Vacancy center for magnetic sensing





Prog. Nucl. Magn. Reson. Spectrosc.134–135, 20 (2023)

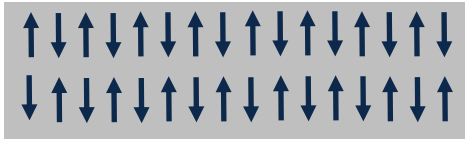
- Operates under ambient conditions
- Sensitivity $\sim 1\ \mu T/\sqrt{Hz}$
- Spatial resolution $\sim 50\ nm$
- Quantitative and vectorial measurements

The Nitrogen-Vacancy center for magnetic sensing

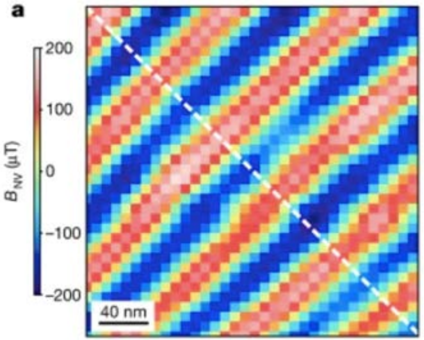
Condensed matter

Magnetic order in magnetic systems that, by nature, feature very small magnetization

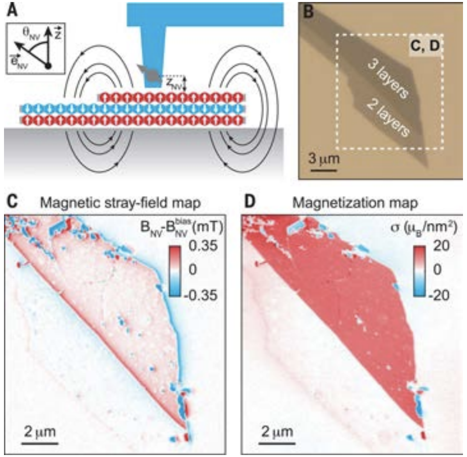
Spin spirals in antiferromagnets



Spin spirals in a multiferroic ultrathin layer
Nature 549, 252 (2017)



2D magnets

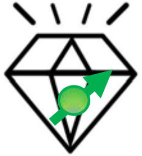


Vanishing magnetizion for even number of CrI3 layers
Science 364, 973 (2019)

The Nitrogen-Vacancy center as a sensor

Magnetic noise

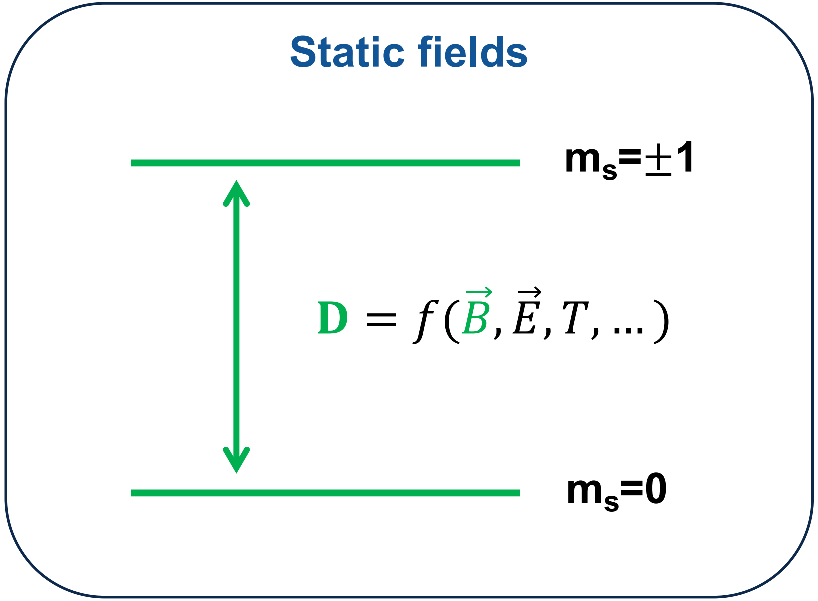
Magnetic fields

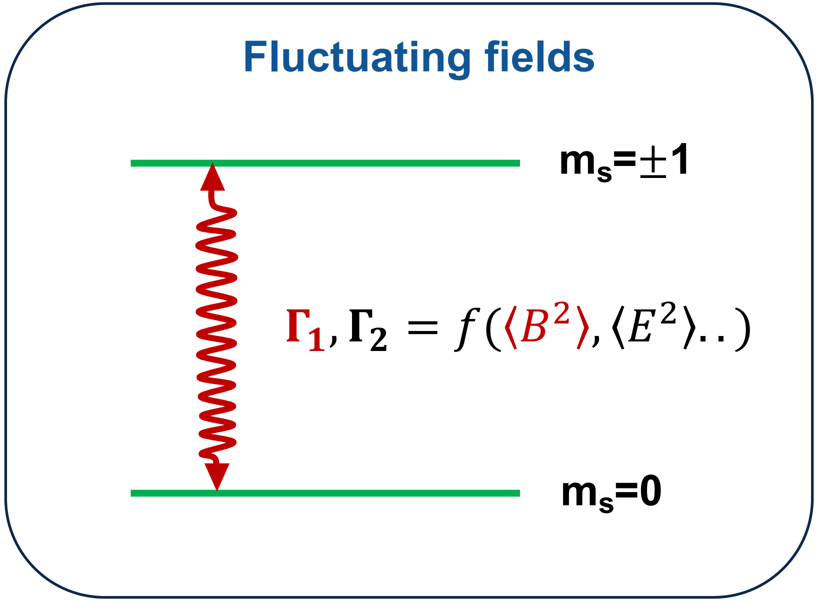


@ nanoscale and
room temperature

Temperature

The Nitrogen-Vacancy center for magnetic noise sensing

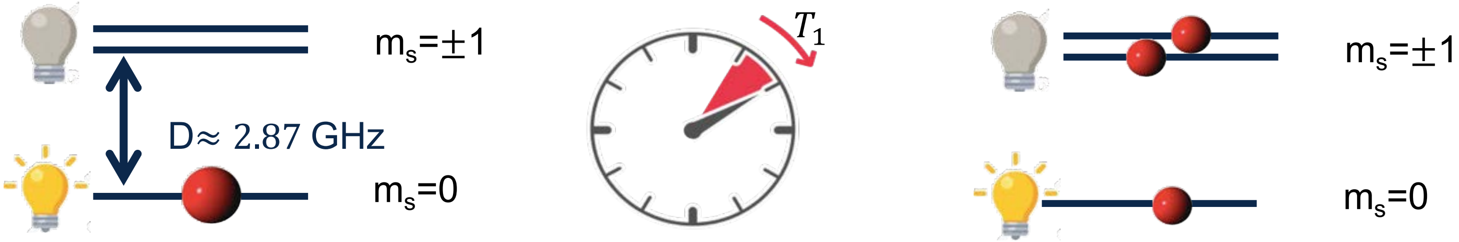


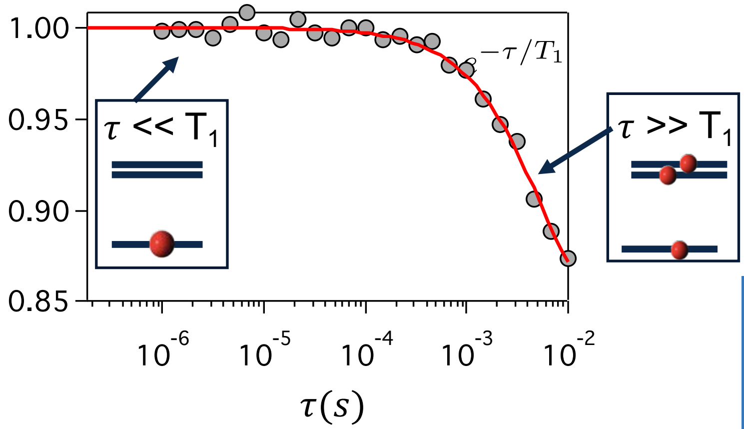


Rev. Mod. Phys. 89, 035002 (2017)

The Nitrogen-Vacancy center for magnetic noise sensing

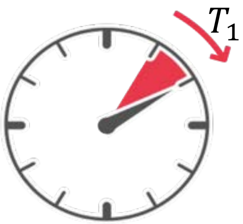
Detection of a magnetic noise

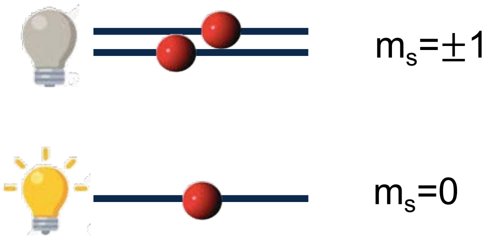




The Nitrogen-Vacancy center for magnetic noise sensing

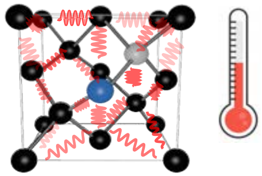
Detection of a magnetic noise





$$\frac{1}{T_1} = \frac{1}{T_1^0} + 3\gamma^2 S_{B_\perp}(D)$$

$\frac{1}{T_1^0}$ Interaction with the phonons



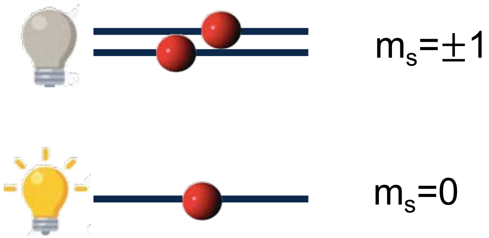
$T_1^0 \sim 1ms$

$3\gamma^2 S_{B_\perp}(D)$ Transverse magnetic noise at the resonance frequency of the NV

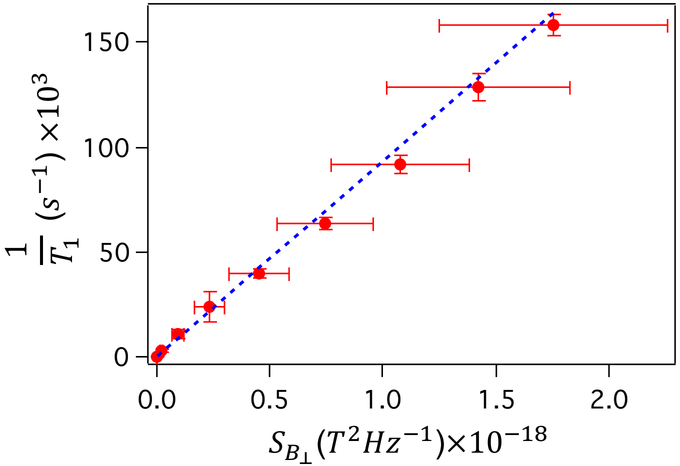
$\langle \boldsymbol{B}^2 \rangle$

The Nitrogen-Vacancy center for magnetic noise sensing

Detection of a magnetic noise



$$\frac{1}{T_1} = \frac{1}{T_1^0} + \boxed{3\gamma^2 S_{B_\perp}(D)}$$



Collaboration with
T. DEVOLDER

The Nitrogen-Vacancy center for magnetic noise sensing

Condensed matter

- Superparamagnetic nanoparticules

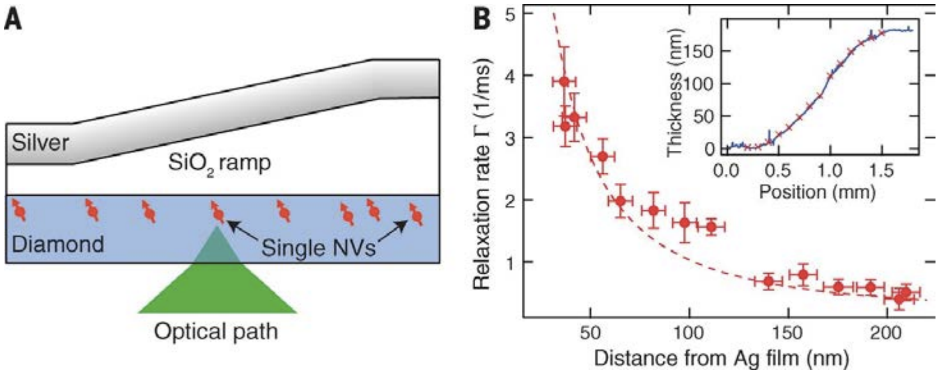
  Nano Lett. 15, 4942, (2015)

- Spin waves

  Science, 357, 195 (2017)

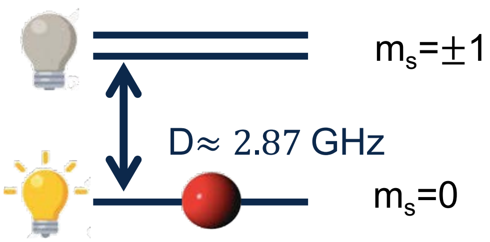
- Johnson noise

  Science 347, 1129 (2015)

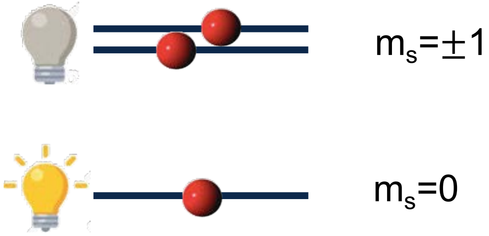


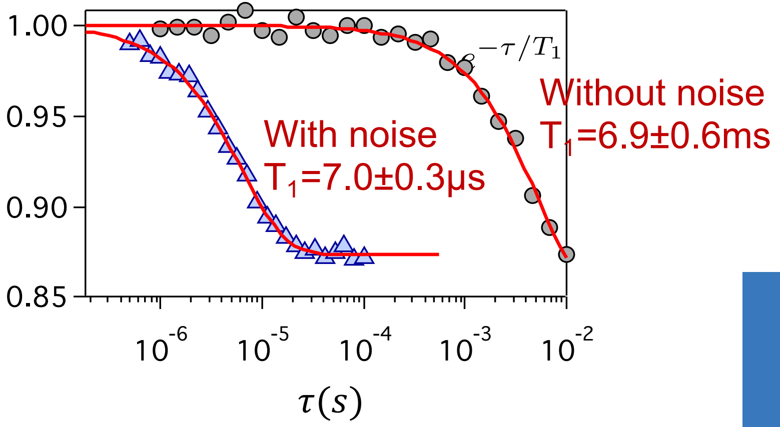
The Nitrogen-Vacancy center for magnetic noise sensing

Detection of a magnetic noise



$$\frac{1}{T_1} \propto \langle B^2 \rangle$$

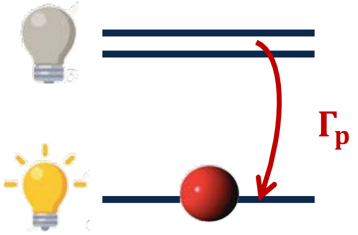




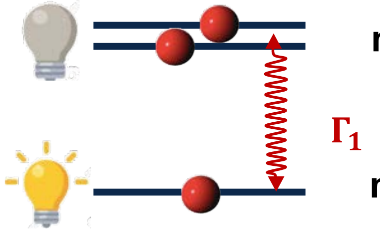
The Nitrogen-Vacancy center for magnetic noise sensing

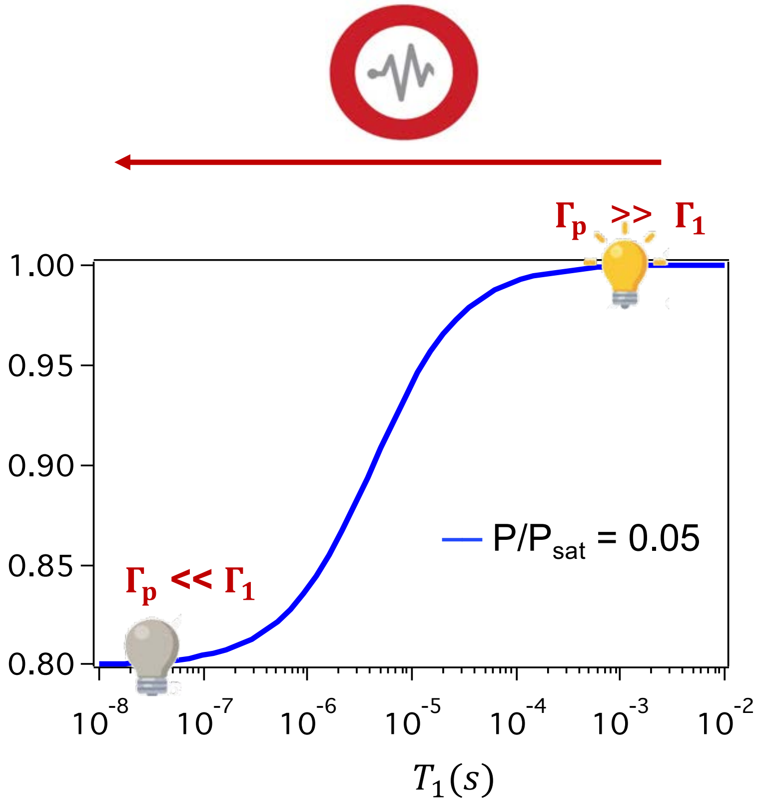
Fast optical detection of a magnetic noise

Spin polatization by optical pumping



Spin relaxation

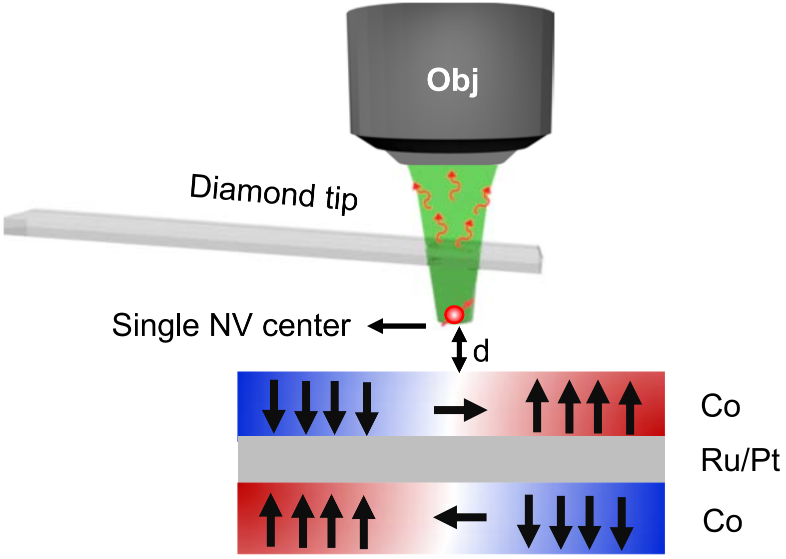




Phys. Rev. B 103, 235418 (2021)

The Nitrogen-Vacancy center for magnetic noise sensing

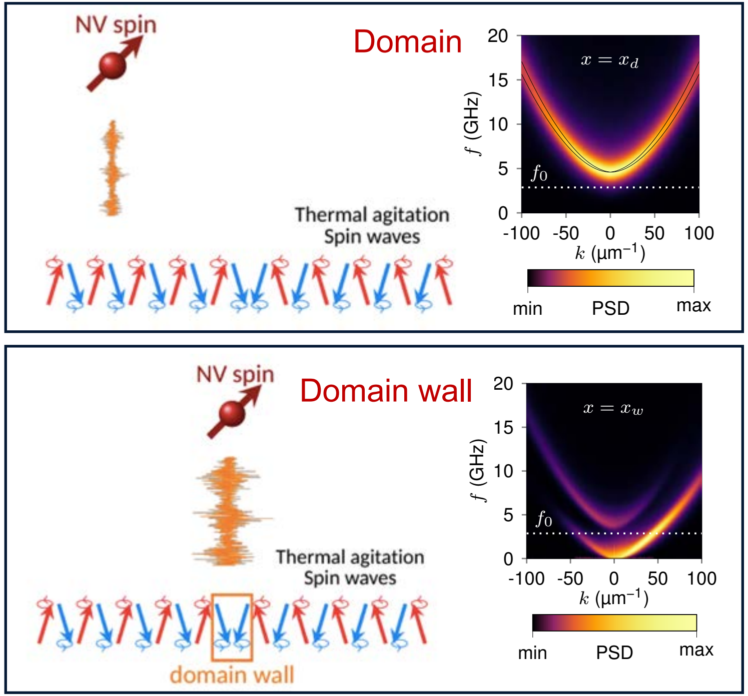
Fast optical detection of a magnetic noise



Collaboration with W. LEGRAND et al.

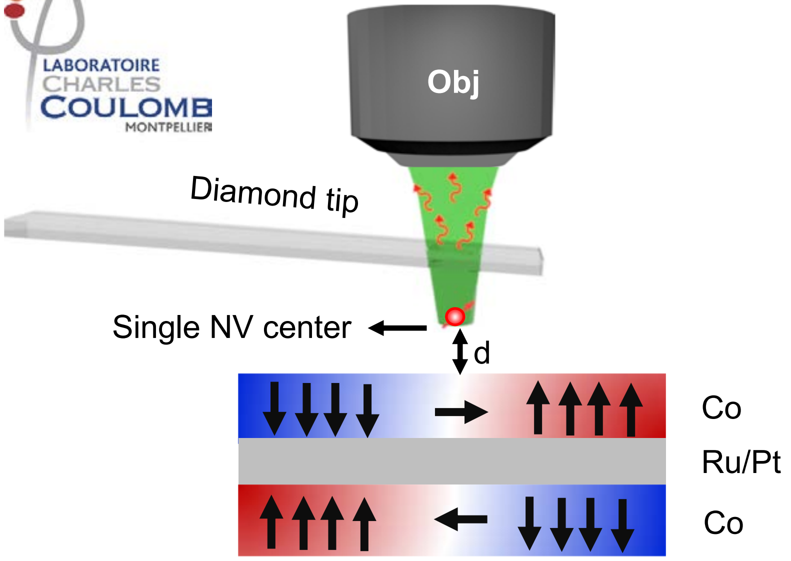
Different noise properties above domains and domain walls

Collaboration with J.-V. Kim



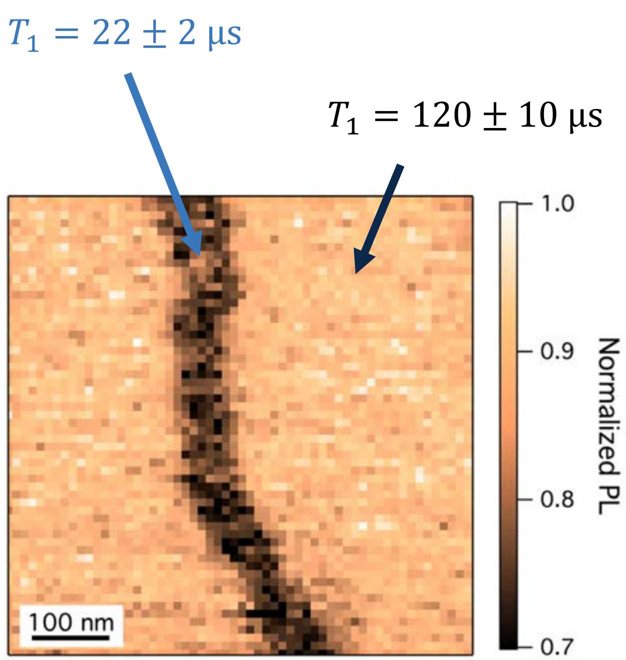
The Nitrogen-Vacancy center for magnetic noise sensing

Fast optical detection of a magnetic noise



Collaboration with W. LEGRAND et al.

Different noise properties above domains and domain walls

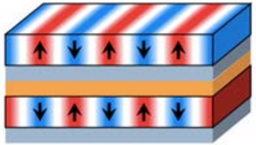


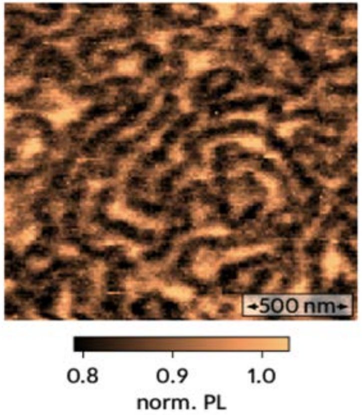
Nat. Commun. 12, 767 (2021)

The Nitrogen-Vacancy center for magnetic noise sensing

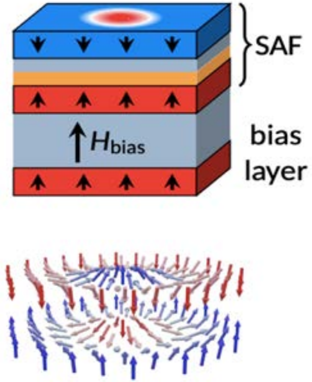
Fast optical detection of a magnetic noise

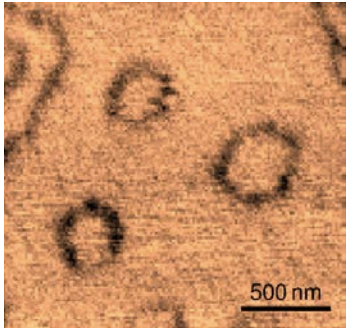
Spin spirals





Skyrmions



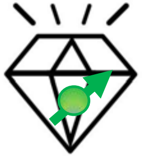


Nat. Commun. 12, 767 (2021)
APL Materials, 11, 100901 (2023)

The Nitrogen-Vacancy center as a sensor

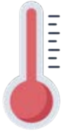
Magnetic noise

Magnetic fields

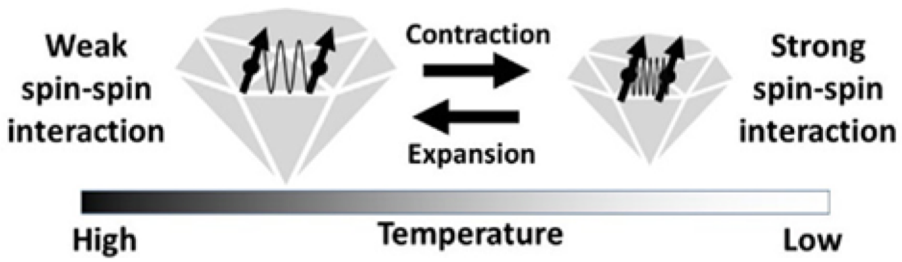


@ nanoscale and
room temperature

Temperature

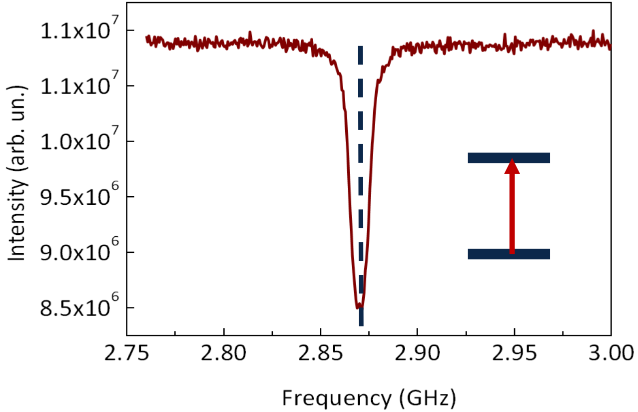


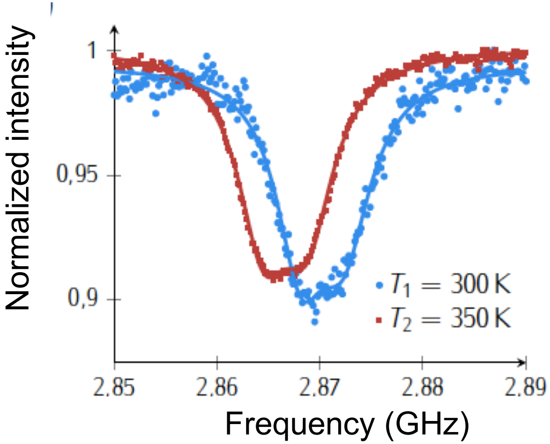
The Nitrogen-Vacancy center for temperature sensing

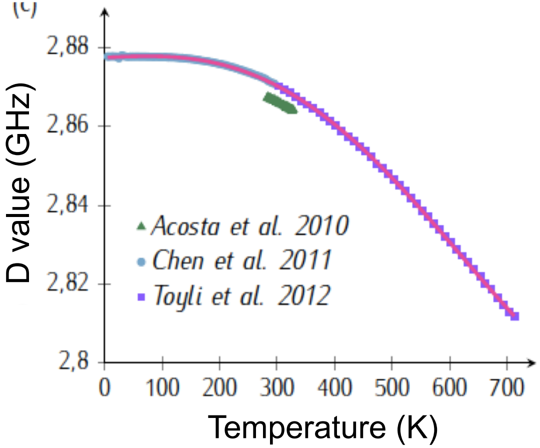


Prog. Nucl. Magn. Reson. Spectrosc.134–135, 20 (2023)

D(T)



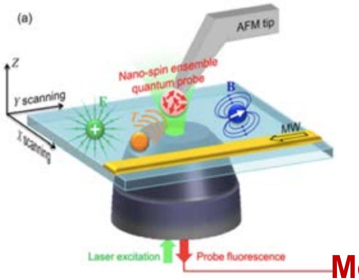




dD/dT=-68 kHz/K
around room temperature

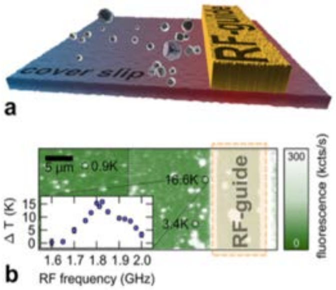
The Nitrogen-Vacancy center for temperature sensing

Condensed matter



Nano Lett. 16, 326 (2016)
Hollenberg et al.

Melbourne Univ.

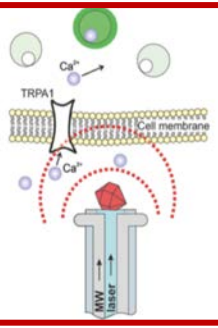


Nano Lett. 13, 2738 (2013)
Wrachtrup et al.

Stuttgart Univ.

Biological species

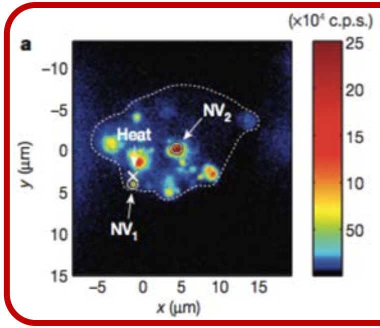
Cell membranes



Sci. Rep. 5, 1573 (2015)
Nat. Comm. 8, 15362 (2017)
Zheltikov et al.

Moscow State Univ.

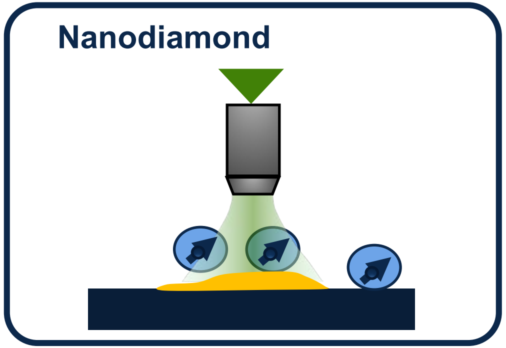
embryonic fibrobast cells



Nature 500, 54 (2013)
Lukin et al.

Harvard

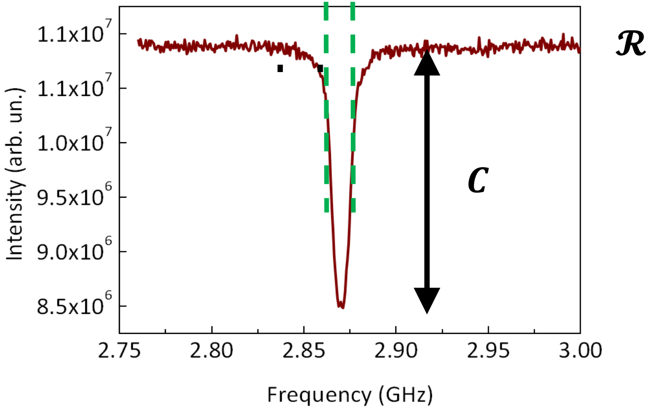
The Nitrogen-Vacancy center for temperature sensing



Perfect thermalisation
of the nanodiamonds with the probed sample

- Few K/Hz$^{1/2}$ → Limited by the coherence time T_2^* of about 100 ns
- Tens-hundreds nm

$\Delta\nu > 1/T_2^*$



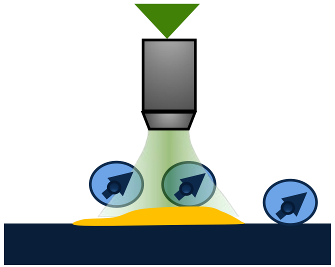
Thermal sensitivity

$$\eta_T \approx \frac{1}{\left|\frac{\mathrm{dD}}{\mathrm{dT}}\right|}\frac{\Delta\nu}{C\sqrt{\mathcal{R}}}$$

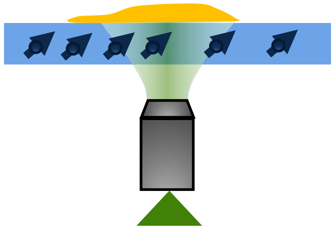
The Nitrogen-Vacancy center for temperature sensing

Sensor architecture

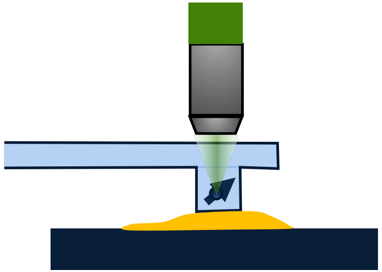
Nanodiamond



Diamond substrate



Scanning tip



Perfect thermalisation of the nanodiamonds with the probed sample
- Few K/$Hz^{1/2}$
- Tens-hundreds nm

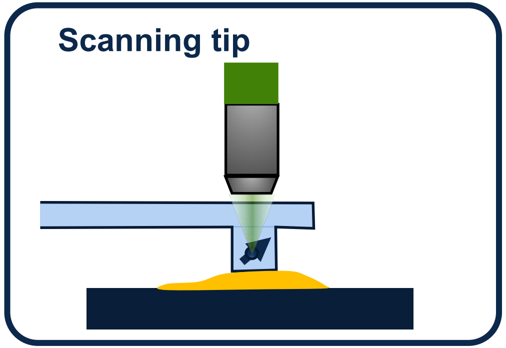
High thermal dissipation in the substrate that cools the probed sample

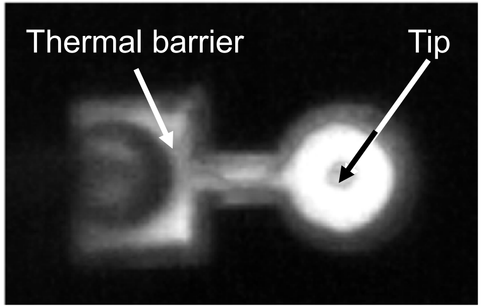
Good thermalisation of the tip provided an optimized tip geometry
- Sub-K/$Hz^{1/2}$
- Sub-100 nm

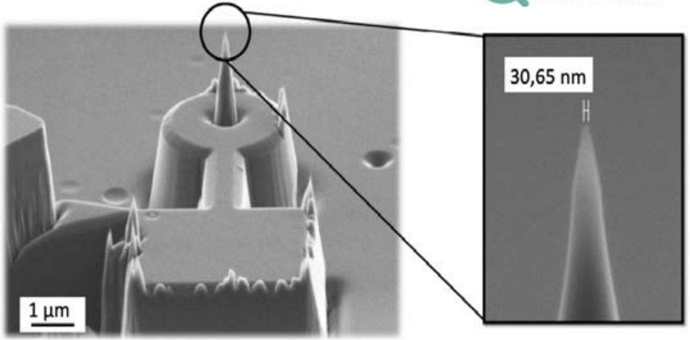
AIP Advances 10, 025027 (2020)

The Nitrogen-Vacancy center for temperature sensing

Sensor architecture





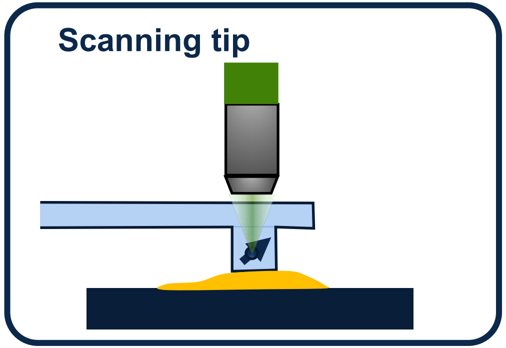


Thermal sensitivity

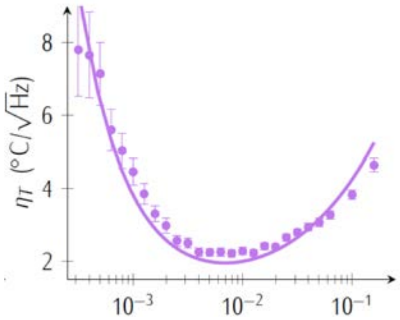
$$\eta_T \approx \frac{1}{\left|\frac{dD}{dT}\right|}\frac{\Delta\nu}{C\sqrt{\mathcal{R}}}$$

- Evolution of D as a function of T : dD/dT
- Number of collected photons out of resonance $\mathcal{R}$
  - Increased number of NVs → more emitted photons
  - Conical tip → more collected photons

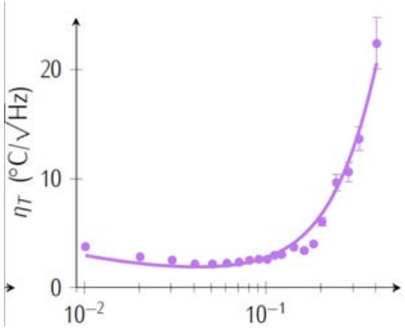
The Nitrogen-Vacancy center for temperature sensing



Sensor architecture



Microwave power (W)



Normalized optical power

Thermal sensitivity

$$\eta_T \approx \frac{1}{\left|\frac{\mathrm{dD}}{\mathrm{dT}}\right|}\frac{\Delta\nu}{C\sqrt{\mathcal{R}}}$$

- Evolution of D as a function of T : dD/dT
- Number of collected photons out of resonance $\mathcal{R}$
  - Increased number of NVs → more emitted photons
  - Conical tip → more collected photons
- Linewitdth $\Delta\nu$
- Contrast C

}
- Coherence time (about 1 µs)
- Laser and microwave powers

Perspectives

Electric fields

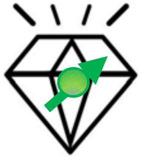
26 mV μm^{-1} $Hz^{-1/2}$ (AC)
2 V μm^{-2} $Hz^{-1/2}$(DC)
Sub-100 nm resolution

npj Quantum Information 8, 107 (2022)

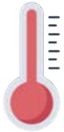
Nat. Comm.12, 2457 (2021)

Magnetic fields

From µT/$Hz^{1/2}$
down to tens nT/$Hz^{1/2}$
Sub-100 nm resolution



Temperature

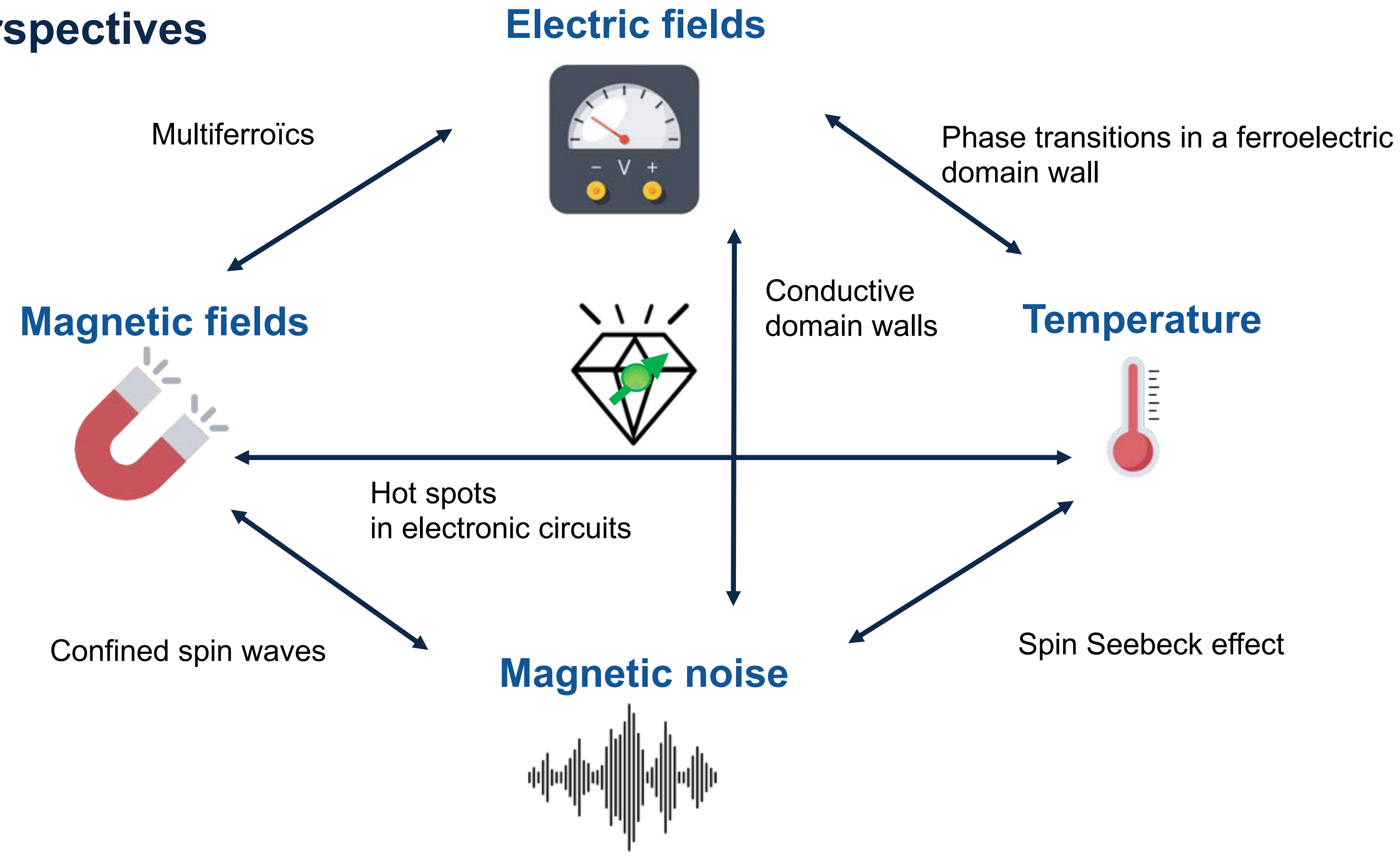


Sub-K/$Hz^{1/2}$
Sub-100 nm resolution

Magnetic noise

µT^2.MHz^{-1}/$Hz^{1/2}$
Sub-100 nm resolution

Perspectives

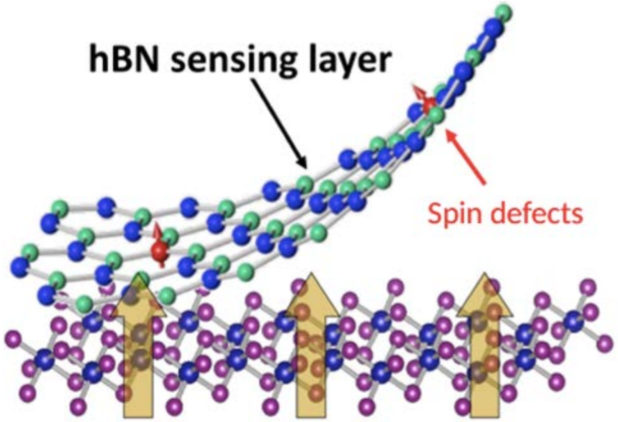


Perspectives

Novel defects in diamond
(SiV, GeV, SnV, G4V)

Defects in wide bandgap materials
(SiC, GaN…)

Defects in 2D materials



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