Imaging magnetism at the nanoscale with a single spin microscope

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Magnetic field sensing with a single spin

Single e-spin

Electron Spin Resonance (ESR)

![Diagram of a single spin and its energy levels with a peak in PL at 2.97 GHz and a drop at 2.87 GHz.](image)
Magnetic field sensing with a single spin

**Single e-spin**

\[ |\uparrow\rangle \propto B \quad |\downarrow\rangle \propto B \]

Electron Spin Resonance (ESR)

- PL [a.u.]
- MW frequency [GHz]

Magnetic field sensing with a single spin
Magnetic field sensing with a single spin

**Single e-spin**

\[ \propto B \]

Quantitative B field measurement within an atomic-size detection volume

Can be realized with the e-spin of a single NV defect in diamond

Electron Spin Resonance (ESR)

PL [a.u.]

MW frequency [GHz]

Can be realized with the e-spin of a single NV defect in diamond
Outline of the talk

1. The NV defect in diamond as an atomic-sized magnetic field sensor

2. Applications in nanomagnetism
   - From domain walls to skyrmions in ultrathin ferromagnets
   - Imaging antiferromagnetic order in multiferroics
Outline of the talk

1. The NV defect in diamond as an atomic-sized magnetic field sensor

2. Applications in nanomagnetism
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Nitrogen-Vacancy (NV) defect in diamond

- An artificial atom « trapped » in the diamond lattice

Detection at the single emitter level at room T — perfect photostability

Engineering NV defect in diamond

1997

High purity diamond using CVD growth

Gicquel and Achard group (Villetaneuse)

2012

NV defect engineering through nanoscale ion implantation

Meijer group (Leipzig)

Spinicelli et al., NJP 13, 025014
Engineering NV defect in diamond

1997

High purity diamond using CVD growth

Gicquel and Achard group (Villetaneuse)

2012

NV defect engineering through nanoscale ion implantation

Meijer group (Leipzig)
The ground state is a spin triplet (S=1)

- Optical polarization into $m_s = 0$
- **Spin-dependent fluorescence**

- Optical detection of the electron spin resonance

Photoluminescence (~25%)

Single spin detection

$\text{NV} = \text{e-spin qubit}$

Coherence time $T_2 \sim \text{ms} @ \text{room } T$
Optical detection of the electron spin resonance

- The ground state is a spin triplet ($S=1$)

- Optical polarization into $m_s = 0$
- Spin-dependent fluorescence

Scanning-NV magnetometry

**Principle**


- Atomic-sized detection volume
- Quantitative and vectorial
- No magnetic back-action
Scanning-NV magnetometry

**Principle**


- Atomic-sized detection volume
- Quantitative and vectorial
- No magnetic back-action

**Experiment**

Microscope objective

AFM tip

Sample

Magnetic structure

$2 \mu m$

$g^2(\tau)$

Delay $\tau$ (ns)
Imaging the core of a magnetic vortex

- Resolving power ~ 100 nm
  Limited by the probe-to-sample distance $d_{\text{min}}$

AFM image

NV image


Maletinsky group (Basel)
Outline of the talk

1. The NV defect in diamond as an atomic-sized magnetic field sensor

2. Applications in nanomagnetism

*From domain walls to skyrmions in ultrathin ferromagnets*

*Imaging antiferromagnetic order in multiferroics*
Ferromagnets “shrink” to few atomic layers...

- **Technological interest** (spintronic devices with low power consumption)
- **Rich new physics** mediated by the interface

*Interface interactions\* 
Surface energy \(\approx\) Volume energy 
Anisotropy, exchange…

- **e. g.** the domain wall (DW) “racetrack memory”

*Parkin et al., Science 320, 190 (2008)
Domain walls in ultrathin ferromagnets

One important issue
What is the effect of the interface on the DW structure?

Direct impact on DW motion

Bloch walls are predicted by elementary magnetostatic theory.
But inconsistencies in recent current-induced domain wall motion experiments are predicted by elementary magnetostatic theory.

- Bloch walls are predicted by elementary magnetostatic theory
- But inconsistencies in recent current-induced domain wall motion experiments

Miron et al., Nat. Mater. 10, 419 (2011)
Ryu et al., Nat. Nano. 8, 527 (2013)
But inconsistencies in recent current-induced domain wall motion experiments

- Miron et al., Nat. Mater. 10, 419 (2011)
- Ryu et al., Nat. Nano. 8, 527 (2013)

Interfacial Dzyaloshinskii-Moriya interaction proposed as a way to stabilize Néel walls

- Thiaville et al., EJP 100, 57002 (2012)
Determining the structure of the DW

Bloch wall = \[ \uparrow \uparrow \uparrow \uparrow \uparrow \uparrow \uparrow \uparrow \uparrow \downarrow \downarrow \downarrow \downarrow \downarrow \downarrow \downarrow + \]

Néel wall (right) = \[ \uparrow \uparrow \uparrow \uparrow \uparrow \uparrow \uparrow \uparrow \uparrow \downarrow \downarrow \downarrow \downarrow \downarrow \downarrow \downarrow + \]

Néel wall (left) = \[ \uparrow \uparrow \uparrow \uparrow \uparrow \uparrow \uparrow \uparrow \uparrow \downarrow \downarrow \downarrow \downarrow \downarrow \downarrow \downarrow + \]
Determining the structure of the DW

Bloch wall

Néel wall (right)

Néel wall (left)

@ $d = 100$ nm

$\Delta p \sim 10$ nm

$\frac{\Delta p}{d} \sim 10\%$
DW imaging with a scanning NV magnetometer

Magnetic wire
Ta / Co$_{40}$Fe$_{40}$B$_{20}$ (1 nm) / MgO

MW excitation

AFM image

Height (nm)
DW imaging with a scanning NV magnetometer

Magnetic wire
Ta / Co$_{40}$Fe$_{40}$B$_{20}$ (1 nm) / MgO

MW excitation

AFM image

B field distribution
Calibration of the experiment: $M_s$, $d$?

(1) Calibration determine $M_s$ and $d$. 

$M_s$, $d$?
Calibration of the experiment: $M_s, d$?

$M_s = 0.93 \pm 0.03$ MA/m
$d = 123 \pm 3$ nm

Extracting the structure of the domain wall

AFM

Zeeman shift (MHz)

500 nm
Extracting the structure of the domain wall

Zeeman shift (MHz)

Position x (µm)

M_{S}
Extracting the structure of the domain wall

![Diagram showing the domain wall and Zeeman shift graph]

Zeeman shift (MHz) vs. Position x (µm)

- Data
- Left Néel
- Bloch
- Right Néel

Extracting the structure of the domain wall...
Extracting the structure of the domain wall


**BLOCH Domain Wall**

No evidence of interfacial DMI

Ta/Co$_{40}$Fe$_{40}$B$_{20}$ (1 nm)/MgO

---

**ESRfreq. (MHz)**

500 nm

**Zeeman shift (MHz)**

Position x (µm)

-0.5 0 0.5

-106 -0.5 0 0.5

-106 -80 -60 -40 -20 0 20 40 60 80
What about Pt/Co(0.6nm)/AlOx?

I. M. Miron et al., Nat. Mater. 10, 419 (2011)

Domain-wall velocity (m s$^{-1}$) vs Current density ($\times 10^{12}$ A m$^{-2}$)
What about Pt/Co(0.6nm)/AlOx?
What about Pt/Co(0.6nm)/AlOx?

Pt/Co(0.6nm)/AlO_x

Zeeman shift (MHz)

Position (um)

Data
Left Néel
Bloch
Right Néel

SPINTEC Grenoble
G. Gaudin, M. Miron
What about Pt/Co(0.6nm)/AlOx?

Direct evidence of a sizable interfacial DMI at the Pt/Co interface.
Playing with the interface

Unique tool to probe interfacial DMI in thin films

Exploiting large interfacial DMI...

From DW to magnetic skyrmions...

- Topologically protected spin texture
- Efficient motion at low current densities
- Ultrahigh information-storage density

« Skyrmionics »

The sample – symmetric bilayer Pt/Co(1nm)/Au

Regime of strong off-axis magnetic field

Tetienne et al., NJP 14, 103033 (2012)

ESR contrast (%) vs. $B$ (mT)

$B > 20$ mT @ 50 nm
The sample – symmetric bilayer Pt/Co(1nm)/Au

Regime of strong off-axis magnetic field
Tetienne et al., NJP 14, 103033 (2012)

Can be exploited for all-optical magnetic imaging (MW free)
All-optical imaging of individual skyrmions

$B_z = 0$ mT

$B_z = 3$ mT

$B_z = 7$ mT

$B_z = 10$ mT

500 nm
All-optical imaging of individual skyrmions

-$B_z = 0 \text{ mT}$

-$B_z = 3 \text{ mT}$
All-optical imaging of individual skyrmions

$B_z = 0$ mT

$B_z = 3$ mT

$B_z = 7$ mT
All-optical imaging of individual skyrmions

$B_z = 0 \text{ mT}$

$B_z = 3 \text{ mT}$

$B_z = 7 \text{ mT}$

$B_z = 10 \text{ mT}$

Normalized PL

500 nm

100 nm

related work from A. Yacoby group

arXiv:1611.00673

In progress

Occurrence

skyrmion size [nm]
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Antiferromagnetic order in multiferroics

BiFeO$_3$: ferroelectricity….
BiFeO$_3$: ferroelectricity...

Antiferromagnetic order in multiferroics

S. Fusil, V. Garcia, M. Bibes

BiFeO$_3$ crystal structure

PFM image of a 30-nm thick BFO film

71° Domain wall
Antiferromagnetic order in multiferroics

BiFeO$_3$ : ferroelectricity...

...+ antiferromagnetism @ 300 K

S. Fusil, V. Garcia, M. Bibes

PFM image
30-nm thick BFO film

Phase
0°

360°

1 µm

71° Domain wall

λ ∼ 64 nm
Imaging antiferromagnetic order in BFO

Diamond tip - P. Maletinsky (Basel)


30 nm thick (001)-BiFeO$_3$
Imaging antiferromagnetic order in BFO

Diamond tip - P. Maletinsky (Basel)


**Figure:**
- **Microscope Objective:** Diagram showing the setup for imaging antiferromagnetic order in BFO using a diamond tip.
- **MW NV e-spin:** Diagram indicating the interaction of microwave (MW) frequency with NV (Nitrogen-Vacancy) spin.
- **1 μm single NV:** Image showing a single NV with PL intensity at different MW frequencies.
- **Normalized PL [a.u.]:** Graph illustrating the normalized PL intensity at various MW frequencies.

**Table:**

<table>
<thead>
<tr>
<th>MW Frequency [MHz]</th>
<th>PL [10^5 cts/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2790</td>
<td>0.8</td>
</tr>
<tr>
<td>2820</td>
<td>1.0</td>
</tr>
<tr>
<td>2850</td>
<td>2.0</td>
</tr>
</tbody>
</table>

**Note:** The diamond tip used is 30 nm thick (001)-BiFeO₃.
Imaging antiferromagnetic order in BFO

30 nm thick (001)-BiFeO$_3$

diamond tip

MV e-spin

MW

1 µm single NV

PL [$10^5$ cnts/s]

MW frequency [MHz]

ν$_1$

ν$_2$

 Iso-B image

100 nm
Imaging antiferromagnetic order in BFO

30 nm thick (001)-BiFeO$_3$

MW NV e-spin

$\nu_1$, $\nu_2$

1 $\mu$m single NV

$1 \times 10^5$ cnts/s

2850 2820 2790

Norm. PL [a.u.]

0 1 2

MW frequency [MHz]

Imaging antiferromagnetic order in BFO

Iso-B image

NV signal [a.u.]

0 2

100 nm
Controlling the spin spiral in BFO

PFM images
Controlling the spin spiral in BFO

PFM images

NV iso-B images
Controlling the spin spiral in BFO

PFM images

ISO-B signal [a.u.]

Distance [nm]

λ = 73 ± 7 nm

NV iso-B images
Controlling the spin spiral in BFO

PFM images

NV iso-B images

λ = 73 ± 7 nm

λ = 72 ± 7 nm
Quantitative analysis…

Full B image

Magnetic field $[\mu T]$

-200
-100
0
100
200

50 nm
Quantitative analysis...

- Full B image
- Magnetic field [μT]
- 50 nm

- 5 μB/Fe atom
- d=51±5 nm
- Cycloid periodicity λ = 70 nm
Quantitative analysis...

Full B image

- Magnetic field [µT]
  - 200
  - 100
  - 0
  - -100
  - -200

50 nm scale

Magnetic field [µT]
-200
-100
0
100
200

50 nm

Full B image

- 5 µB/Fe atom
- d=51±5 nm
- Cycloid periodicity λ = 70 nm

Calculation data

Distance [nm]
0
100
200
300

Magnetic field [µT]
-200
-100
0
100
200
Quantitative analysis…

Full B image

- Magnetic field [µT]
- Distance [nm]

- Calculation data
- Data

- 5 µB/Fe atom
- d=51±5 nm
- Cycloid periodicity λ = 70 nm
Conclusion

Magnetometry

\[ B \propto E, B, T \]

500 nm
Conclusion

Magnetometry

\[ \propto B \]

nanoMRI

Protein imaging

Shi et al., Science (2015)
Sushkov et al., PRL (2014)
Conclusion

Magnetometry

Electrometry

Thermometry

nanoMRI Protein imaging

Shi et al., Science (2015)
Sushkov et al., PRL (2014)

Kucsko et al., Nature 500, 54 (2013)