Introduction aux capteurs quantiques

Vincent JACQUES
The first quantum revolution (1900 – 1940)

Deep modifications of ideas and concepts in Physics

The « fathers » of quantum physics at the Solvay congress 1927
The first quantum revolution (1900 – 1940)

Deep modifications of ideas and concepts in Physics

→ Led to *unexpected* groundbreaking technologies

**laser**

**transistor**

Bell lab, 1947
A second quantum revolution (1980 – ??)

Observation and manipulation of individual quantum systems (atoms, ions, photons, superconducting circuits…)

Chain of individual ions (R. Blatt, Innsbruck)
Observation and manipulation of individual quantum systems (atoms, ions, photons, superconducting circuits…)

A second quantum revolution (1980 – ??)

D. Wineland

S. Haroche

Nobel Prize 2012

New fundamental studies

• Quantum superposition
• Entanglement
• Decoherence
• Wave-particle duality
• …

New applications ??????

• Quantum information
• Sensing
• Quantum simulator
• Bioapplications
• …??????…??????…???
A large number of promising quantum systems

Neutral Atoms

Ions in a Paul trap

Quantum dot

Superconducting circuits

Defects in semiconductors
A large number of promising quantum systems

- Neutral Atoms
- Ions in a Paul trap
- Superconducting circuits
- Quantum dot
- Defects in semiconductors
Deep defects in wide-bandgap materials
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- Quantum cryptography
- Single photon interference

**Single Photon Source**

Conduction band

"Artificial Atom"

Valence band

Laser

Fluorescence
Deep defects in wide-bandgap materials

- Single Photon Source
  - Quantum cryptography
  - Single photon interference

- Fluorescent Biomarkers

- Conduction band

- "Artificial Atom"

- Valence band

- Single Photon Source

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- Laser
Deep defects in wide-bandgap materials

Single Photon Source
- Quantum cryptography
- Single photon interference

Fluorescent Biomarkers

Deep defects in wide-bandgap materials

- Conduction band
- Valence band

"Artificial Atom"

Laser

Fluorescence

|↑⟩

|↓⟩

Deep defects in wide-bandgap materials

Single Photon Source
- Quantum cryptography
- Single photon interference

Fluorescent Biomarkers

Quantum Information
- Spin physics
- Spin/photon interface

Quantum sensing
\[ \propto B, E, T, P, \ldots \]

Conduction band

Valence band

“Artificial Atom”

Laser

Fluorescence
Deep defects in wide-bandgap materials

- **Single Photon Source**
  - Quantum cryptography
  - Single photon interference

- **Fluorescent Biomarkers**

- **Quantum Information**
  - Spin physics
  - Spin/photon interface

- **Conduction band**
  - "Artificial Atom"
  - Laser
  - Fluorescence
  - e-spin

- **Valence band**

- **Quantum sensing**
  - \( \propto B, E, T, P \ldots \)
Magnetic field sensing with a single spin

**Single e-spin**

**Electron Spin Resonance (ESR)**

![Diagram showing single e-spin and electron spin resonance](Diagram.png)

- PL [a.u.]
- MW frequency [GHz]
- Magnetic field sensing with a single spin
Magnetic field sensing with a single spin

**Single e-spin**

Electron Spin Resonance (ESR)

\[ PL \propto B \]

MW frequency [GHz]

2.87

2.97
Magnetic field **imaging** with a single spin

**Single e-spin**

Electron Spin Resonance (ESR)

AFM tip

\[ \uparrow \leftrightarrow \downarrow \propto B \]

**Seminal proposal:** Chernobrod and Berman

“Spin microscope based on optically detected magnetic resonance”


Can be realized with **NV defects in diamond**

A “perfect” diamond would not absorb visible light…

… but more than 500 defects are optically active

Color centers

The « Hope » diamond

(Washington)

B-doped

The « Hortensia » diamond

(Louvre, Paris)

NV-doped?
Nitrogen-Vacancy (NV) defect in diamond

- An artificial atom "nestled" in the diamond lattice
An artificial atom “nestled” in the diamond lattice

Nitrogen-Vacancy (NV) defect in diamond

- Conduction band
- Valence band
- Laser
- Fluorescence
Nitrogen-Vacancy (NV) defect in diamond

- An artificial atom “nestled” 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

A. Tallaire and J. Achard (Villetaneuse)

2012

NV defect engineering through nanoscale ion implantation

Meijer group (Leipzig)
Engineering NV defect in diamond

1997

High purity diamond using CVD growth

A. Tallaire and J. Achard (Villetaneuse)

Focused Ion Beam (FIB) for nanoscale implantation of NV defects

Lesik et al., PSSA 210, 2055 (2013)
Spin properties

- Artificial atom with a spin triplet (S=1) ground state

- Excited state

- Photoluminescence (~25%)

- Single spin detection

- NV = e-spin qubit

- Coherence time $T_2 \sim \text{ms} @ \text{room T}$
Spin properties

Artificial atom with a spin triplet ($S=1$) ground state

- $|m_s = 0\rangle$
- $2g\mu_B B_{NV}$
- $|m_s = +1\rangle$
- $|m_s = -1\rangle$

Spin-dependent fluorescence

NV defect = magnetometer
Various experimental configurations

- Magnetic sensing with an ensemble of NV defect

\[ \eta \propto \frac{1}{C \sqrt{NRT^*}} \]

Sensitivity

- ESR contrast
- Number of NVs
- Collection efficiency
- Coherence time

See recent review – arXiv:1903.08176

- Sensitivity down to few nT Hz\(^{-1/2}\)

Sturnèr, DRM (2019)
Various experimental configurations

- Magnetic sensing with an ensemble of NV defects
- Magnetic **imaging** with an ensemble of NV defects

requires *NV-doped layers close to the surface*

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Some applications

- Paleomagnetism – Fu, Science (2014)
- Neuron activity - Barry, PNAS (2016)

Spatial resolution limited by diffraction (~ 500 nm)
Scanning-NV magnetometry

- Quantitative and vectorial (sensitivity - $1 \mu T/Hz^{1/2}$)
- No magnetic back-action
- Operation from 4K to 300K
- Spatial resolution limited by the probe-to-sample distance $d$

Related works
Harvard, Basel, Stuttgart, Ulm, ETHZ, UCSB…
Scanning-NV magnetometry

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First experiments with nanodiamonds

$\delta \sim 100 \text{ nm}$


Related works
Harvard, Basel, Stuttgart, Ulm, ETHZ, UCSB…

All-diamond scanning probe tips

$\delta \sim 30-50 \text{ nm}$

Commercially available since 2018
Physics of spin textures in ultrathin ferromagnets

Applications for a new generation of spintronic devices

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

*Parkin et al., Science 320, 190 (2008)*
Physics of spin textures in ultrathin ferromagnets

Thermal jumps of domain walls
Tetienne, Science (2014)

DW inner structure
Bloch vs Néel

From DW to skyrmions
Emerging field of antiferromagnetic spintronics

Special focus, Nature Physics (2018)

- Higher switching frequency (THz vs GHz for ferromagnets)
- Almost no magnetic field generated,
  - Highly stable devices
  - No cross-talk between neighboring cells (high density device)
Imaging spin textures in antiferromagnets (AFs)

Second Harmonic Generation (SHG) microscopy

Fiebig et al., JOSA B 22, 96-118 (2005) – review paper

A recent example

M. Viret group, CEA Saclay
J. Y. Chauleau et al., Nat. Mater. 16, 803 (2017)

diffraction-limited resolution (~500 nm)
Imaging spin textures in antiferromagnets (AFs)

Spin-polarized STM

Wiesendanger, Rev. Mod. Phys. 81, 1495 (2009)

Mn monolayer on W(110)


Atomic scale resolution!!!!!

...but limited to conductive samples and requires UHV conditions.

Antiferromagnetic order in multiferroics

BiFeO$_3$ : ferroelectricity....

S. Fusil
V. Garcia
A. Barthélémy
M. Bibes

G. Catalan and J.F. Scott
Adv. Mater. 21, 2463 (2009)
Antiferromagnetic order in multiferroics

BiFeO$_3$: ferroelectricity….

BiFeO$_3$ structure diagram with labeled atoms:
- Bi
- O
- Fe

Phase image labeled:
- 360°
- 0°

PFM (Piezoresponse Force Microscopy) image:
- 30-nm thick BFO film
- 1 μm scale bar

71° Domain wall

References:
S. Fusil, V. Garcia, A. Barthélémy, M. Bibes
G. Catalan and J.F. Scott
Adv. Mater. 21, 2463 (2009)
BiFeO$_3$: ferroelectricity...

...+ antiferromagnetism @ 300 K

Propagation direction $k$ is perpendicular to the ferroelectric polarization vector $P$
Imaging antiferromagnetic order in BFO

First real-space observation of the cycloidal antiferromagnetic order in BFO

Iso-B image

30 nm thick (001)-BiFeO$_3$

microscope objective

diamond tip

MW

NV e-spin

Iso-B signal [a.u.]

100 nm
Imaging antiferromagnetic order in BFO

First real-space observation of the cycloidal antiferromagnetic order in BFO
Controlling the spin cycloid in BFO
Controlling the spin cycloid in BFO

Controlling the spin cycloid in BFO

Controlling the spin cycloid in BFO


P FM images

NV images

200 nm

50 nm

200 nm

50 nm

\[ \lambda = 72 \pm 2 \text{ nm} \]

\[ \lambda = 73 \pm 2 \text{ nm} \]
A multimode sensor

Magnetic field

\[
\text{Full } B \text{ image}
\]

\[
\mu T
\]

\[
-50 - - 50
\]

\[
\propto B
\]

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

\[
100 \text{ nm}
\]
A multimode sensor

Magnetic field

Electric field

A multimode sensor

Magnetic field

Electric field

Temperature


A multimode sensor

Magnetic field

Dolde, Nat. Phys. 7, 459 (2011)

Electric field

N. Yao – Berlekey
J.-F. Roch – ENS Cachan

Pressure

N. Yao – Berlekey
J.-F. Roch – ENS Cachan

Temperature


$\propto B, E, T, P$

$\uparrow \rangle$

$\downarrow \rangle$
Other directions in quantum sensing

**Matter waves** in a « Mach-Zehnder » interferometer
Other directions in quantum sensing

**Matter waves** in a « Mach-Zehnder » interferometer

Philippe Bouyer, LP2N, Bordeaux
Other directions in quantum sensing

**Matter waves** in a « Mach-Zehnder » interferometer

Philippe Bouyer, LP2N, Bordeaux

Highly sensitive gravimeters and gyroscopes
Other directions in quantum sensing

Commercial products already available!!
Thank you for your attention