

Synthesis processes of materials for quantum technologies: diamond and oxide films

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IRCP, Chimie ParisTech

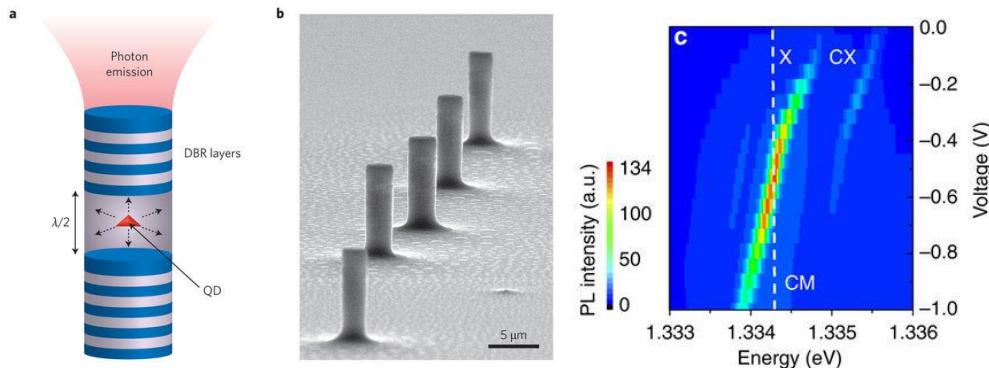
Ovidiu Brinza, Vianney Mille, Riadh Issaoui, **Jocelyn Achard**
LSPM-CNRS, University Paris 13



SIRTEQ kick-off meeting, Palaiseau, 20/10/2017

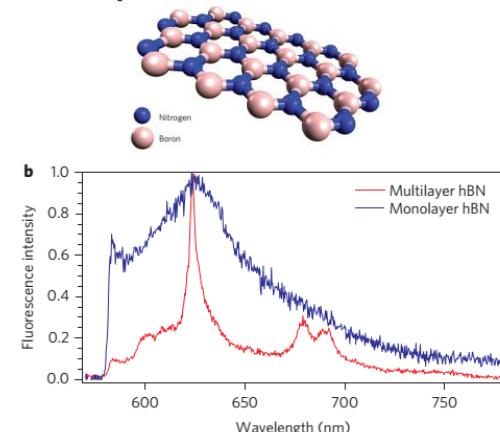
Many solid-state systems for QT...

InAs quantum dots



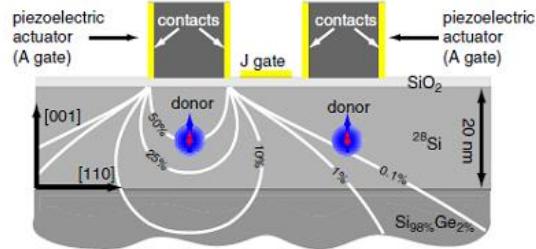
Nowak et al. *Nature Communication* 2014

h-BN single photon source



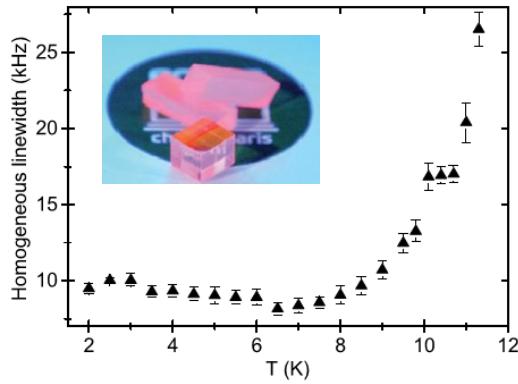
Ahoronovich *Nature Nanotech* 2016

Single P donors in Si



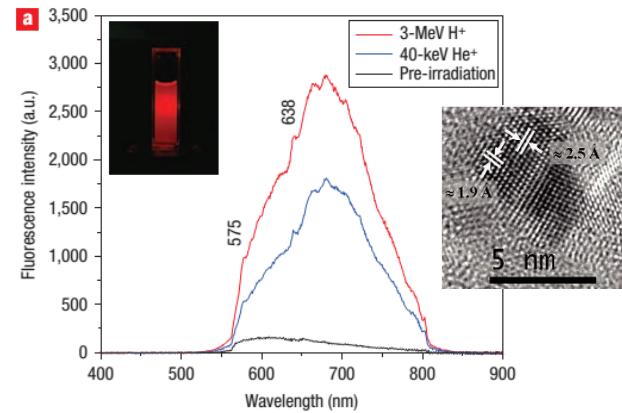
Dreher et al. *PRL* 2011

Rare earths in oxides



Kunkel et al. *APL Mat.* 2015

Fluorescent nanodiamonds

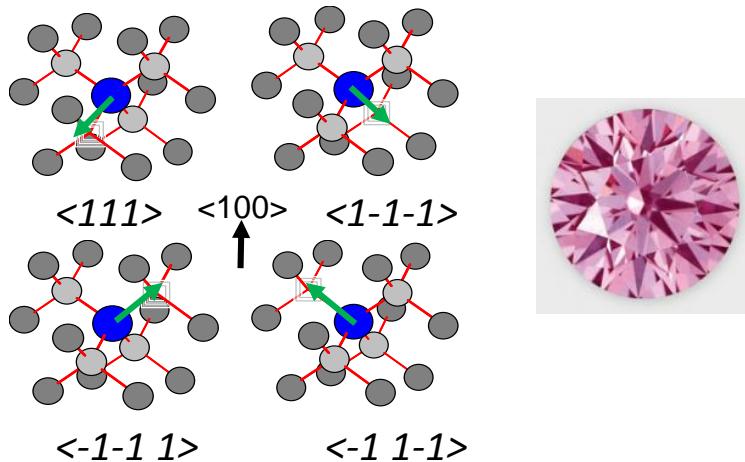


Chang *Nature Nanotech* 2008

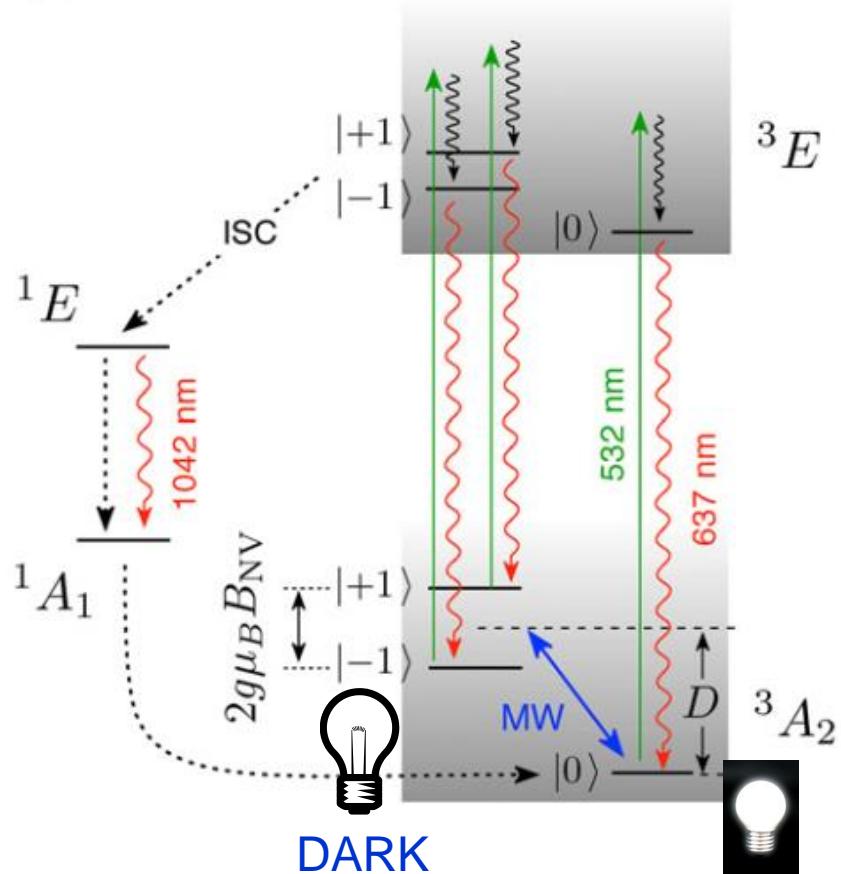
NV centres in synthetic diamonds: a useful system for QT

Nitrogen-Vacancy centres in diamond

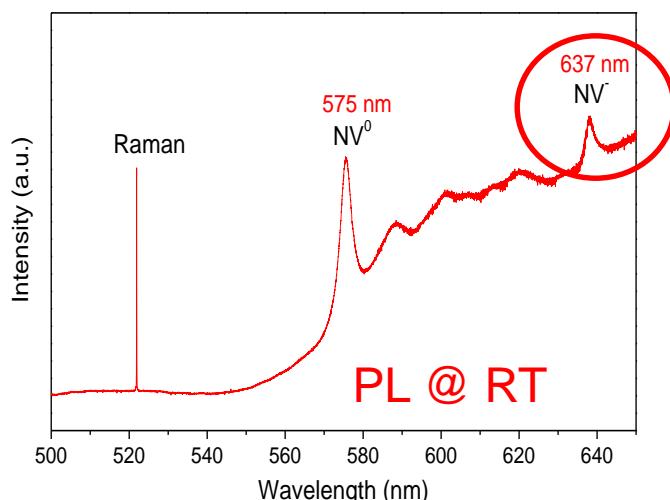
4 possible orientations



Electronic structure of the NV⁻ centre

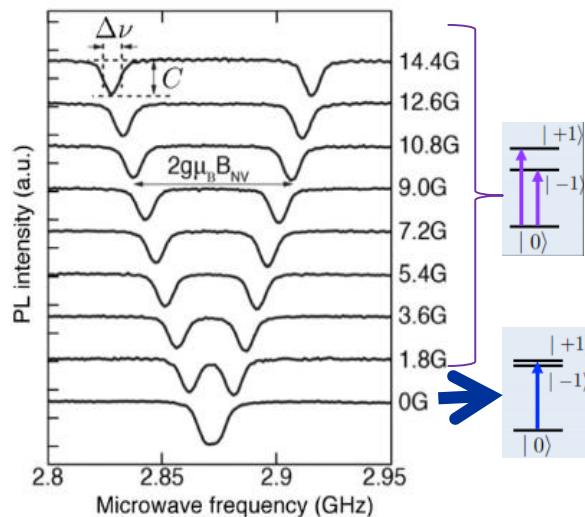


2 known charge states, neutral and negative



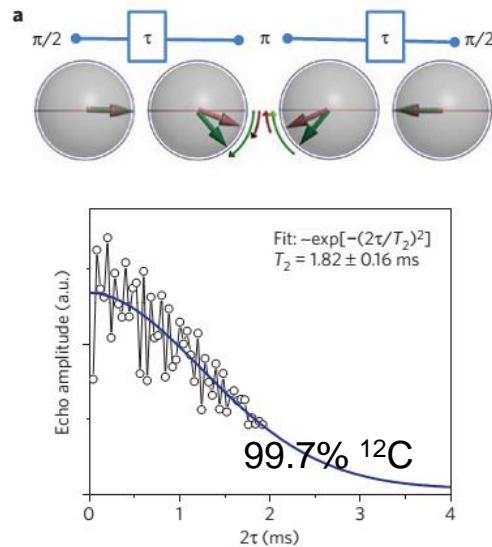
Properties of NV centres

Optically Detected Magnetic Resonance



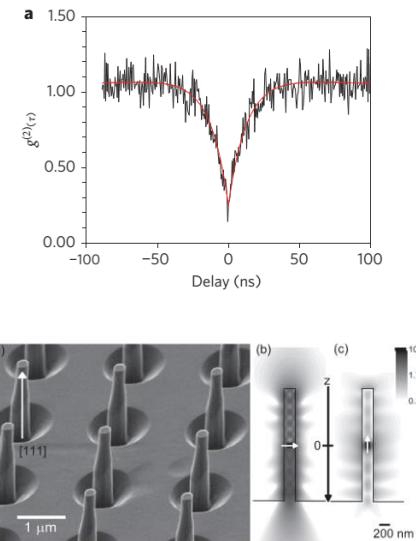
Gruber et al. Science 1997

Spin Echo: $T_2 = 2$ ms



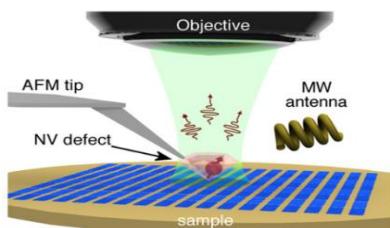
Balasubramanian et al. Nat. Materials 2009

Single photon emission



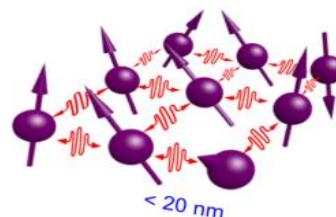
E. Neu et al. APL 2014

Nano-magnetometry



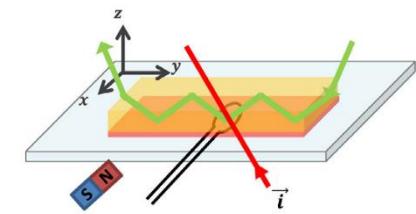
L. Rondin APL 2012

Quantum computing



M. Loncar MRS Bulletin 2013

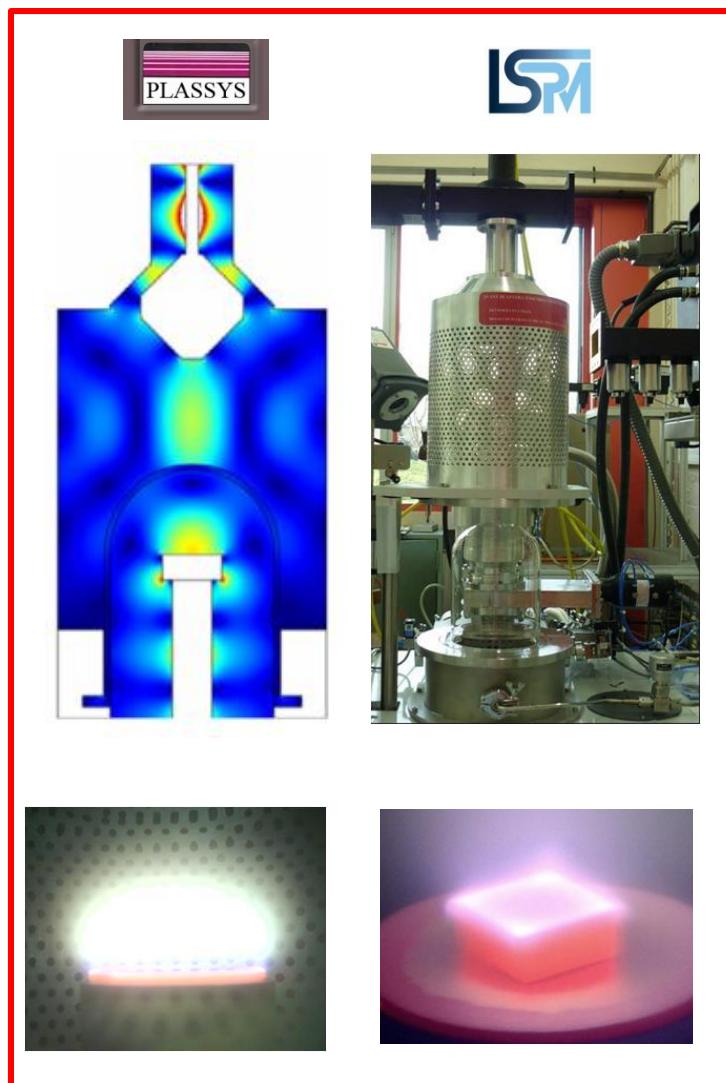
Wide field magnetic imaging



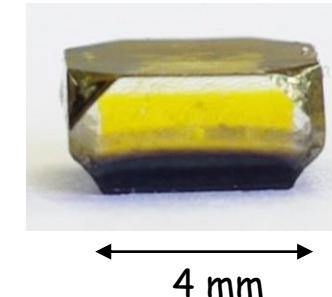
M. Chipaux et al. European Physical Journal 2015

Fabricating diamonds containing NVs for QT

PACVD: a KEY ENABLING TECHNOLOGY



MW plasma assisted chemical vapour deposition
Homoepitaxial growth on a high-pressure substrate
High plasma power
 H_2/CH_4 (95/5)
800-1000°C



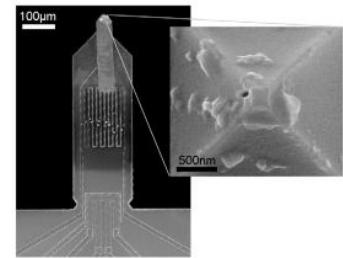
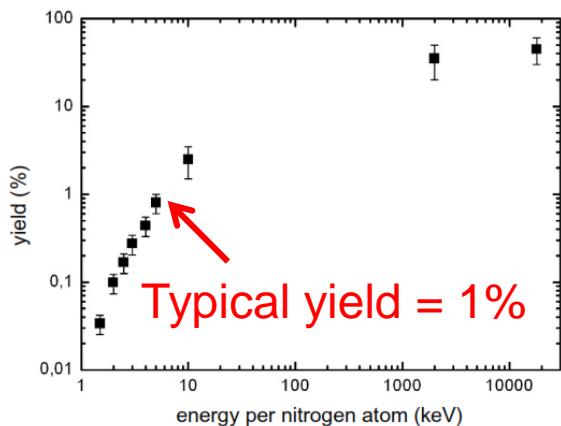
A. Tallaire et al. Comptes-rendus de physique 2013



Growth rates 1-10 $\mu\text{m}/\text{h}$

Creating NVs in CVD diamond

N implantation and annealing



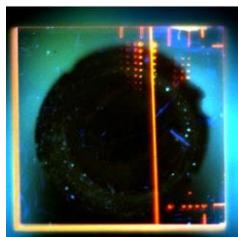
pierced -AFM tip or etched PMMA

Low yield and damage (shorter T_2)
but accurate positionning possible

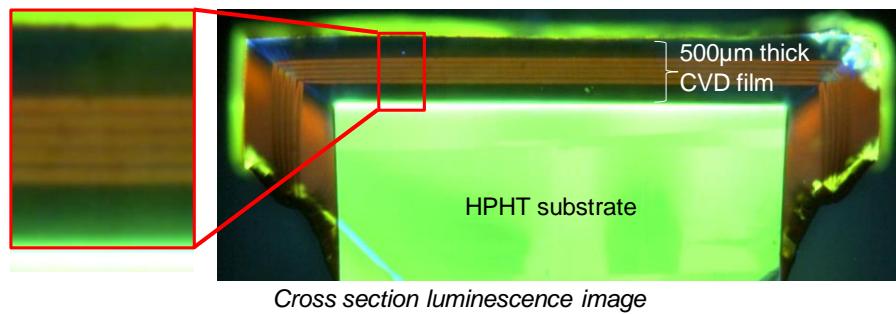
Pezzagna et al. New Journal of Physics
13, 035024 (2011).

vs

In-situ doping during growth



$10 \text{ ppm N}_2 \rightarrow 55 \text{ ppb N}_s$
 $\rightarrow 0.2 \text{ ppb NV}^-$



Stacking of layers with high NV doping

Moderate yield and longer T_2 but
localization difficult

A. Tallaire et al., Diam. & Relat. Mat.
15, 1700-1707 (2006)

Tuning NV properties in CVD diamonds

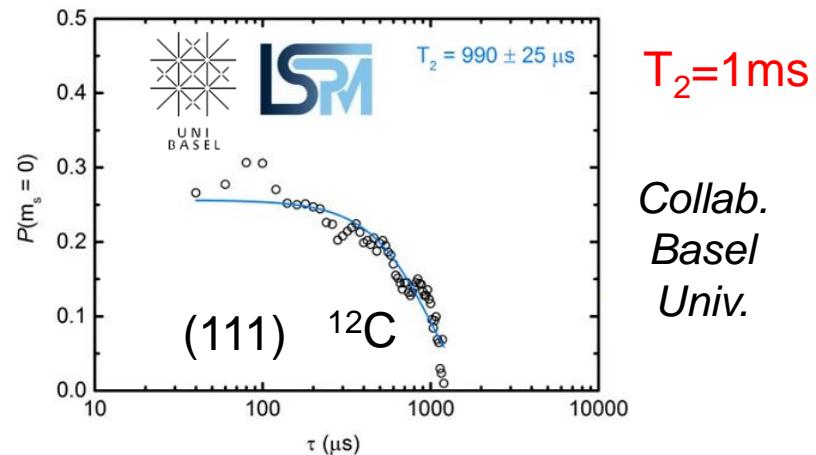
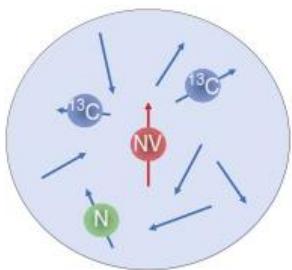
1. Tuning NV properties: environment

Isotopic purity control (^{13}C depleted)

$$\frac{1}{T_2} \approx \left(\frac{1}{T_2} \right)_{^{13}\text{C} \text{ flip-flop}} + \left(\frac{1}{T_2} \right)_{\text{nitrogen impurity}} + \left(\frac{1}{T_2} \right)_{\text{paramag defect}} + \left(\frac{1}{T_2} \right)_{\text{spin-lattice relaxation}}$$

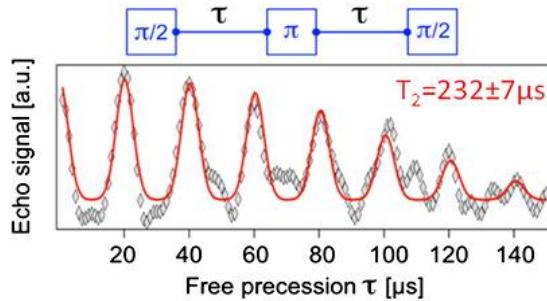
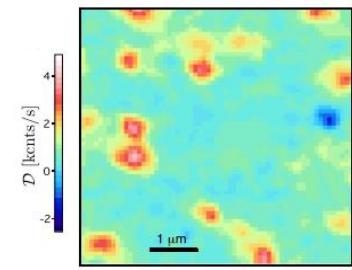
Sensitive to spin environment

Natural C = 98.9%
 $^{12}\text{C} + 1.1\% \ ^{13}\text{C}$



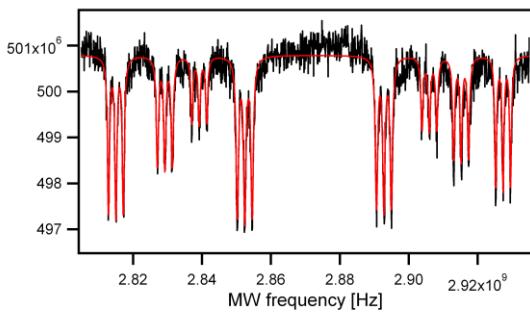
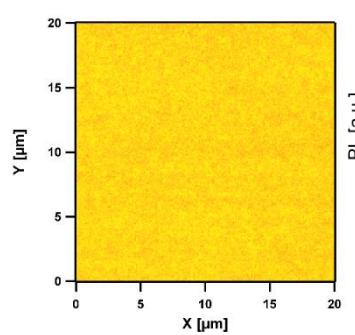
Control of NV density in a wide range

Single: 0.01 ppb NV-



Collab. LAC/ENS

Ensembles: 20 ppb NV-



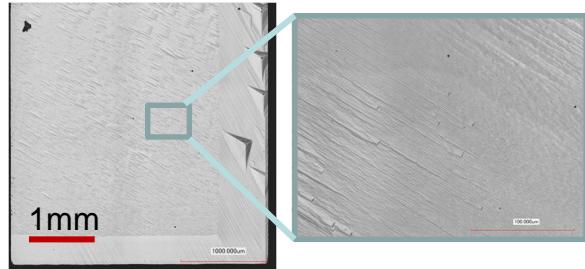
Collab. Thales



2. Tuning NV properties: orientation

[111]

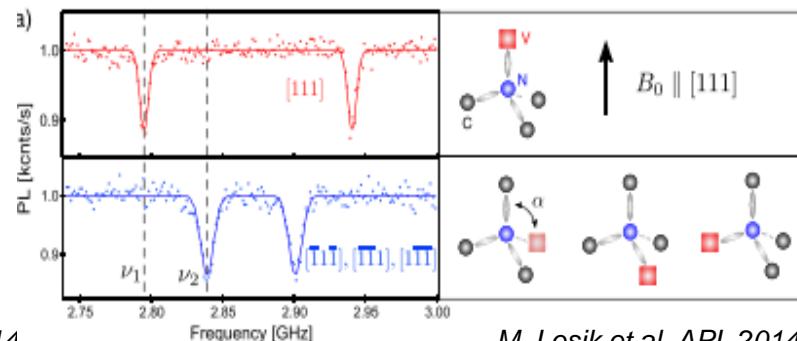
Optimized growth on [111]



Control of NV orientation

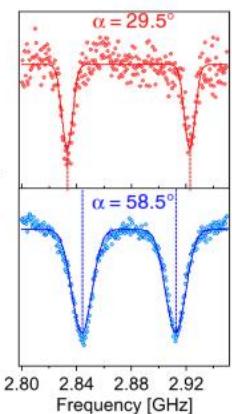
Collab. LAC/ENS

100% preferential orientation!

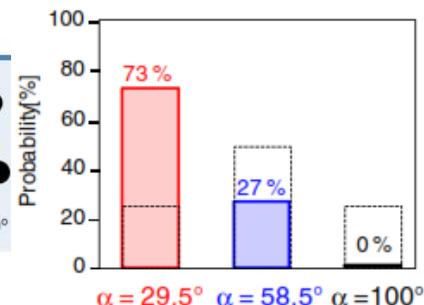
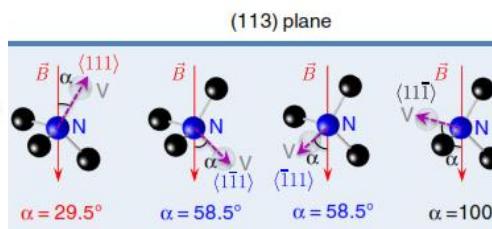


A. Tallaire et al. Diamond and Related Materials 2014

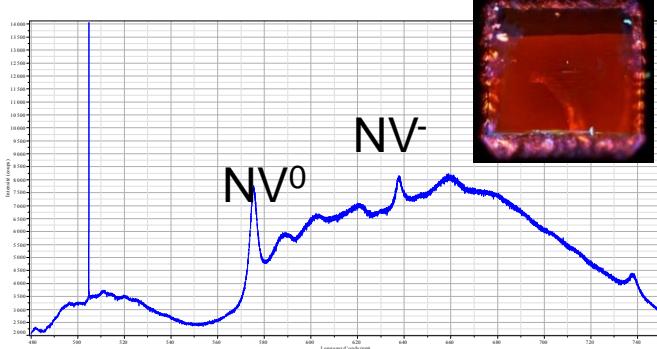
[113]



73% preferential orientation



High doping + thick material

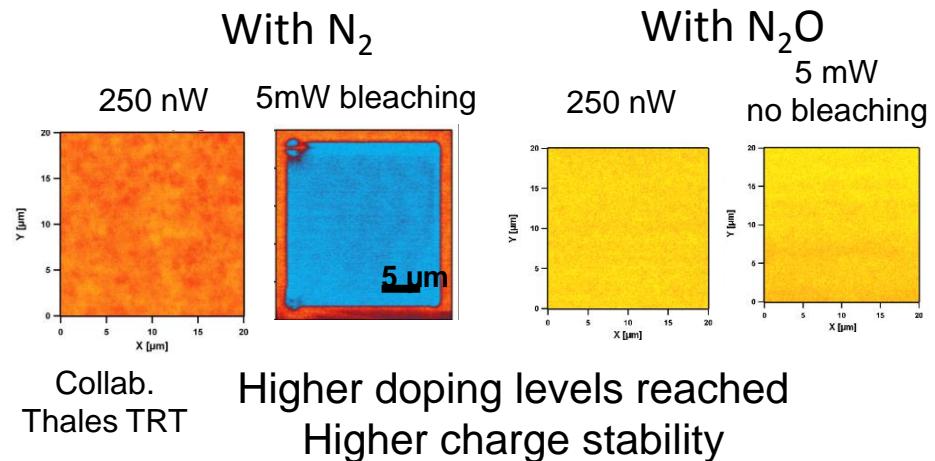
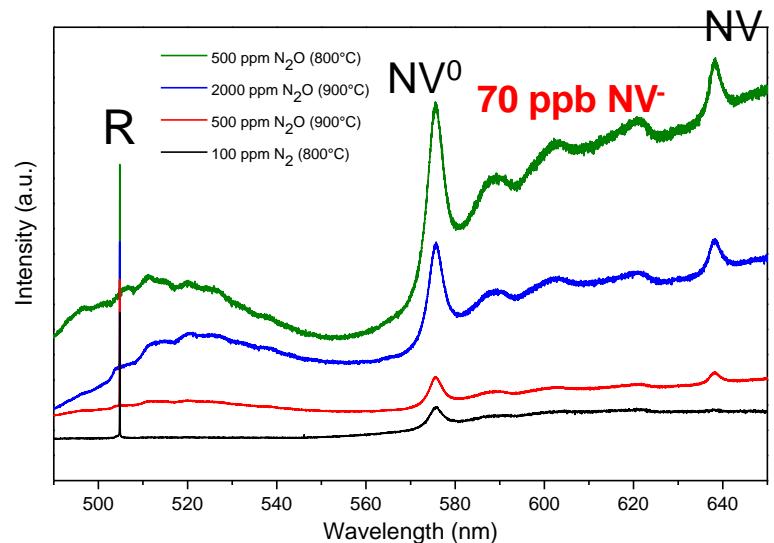


M. Lesik et al., Diam. & Relat. Mat. 2015

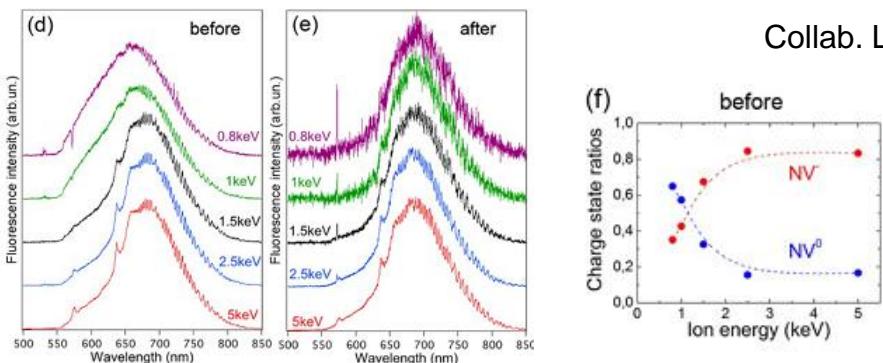
3. Tuning NV properties: stability

NV ensembles created by N₂O doping

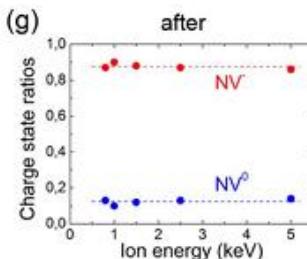
A. Tallaire et al. APL 2017



Overgrowing an implanted pattern with a thin CVD layer



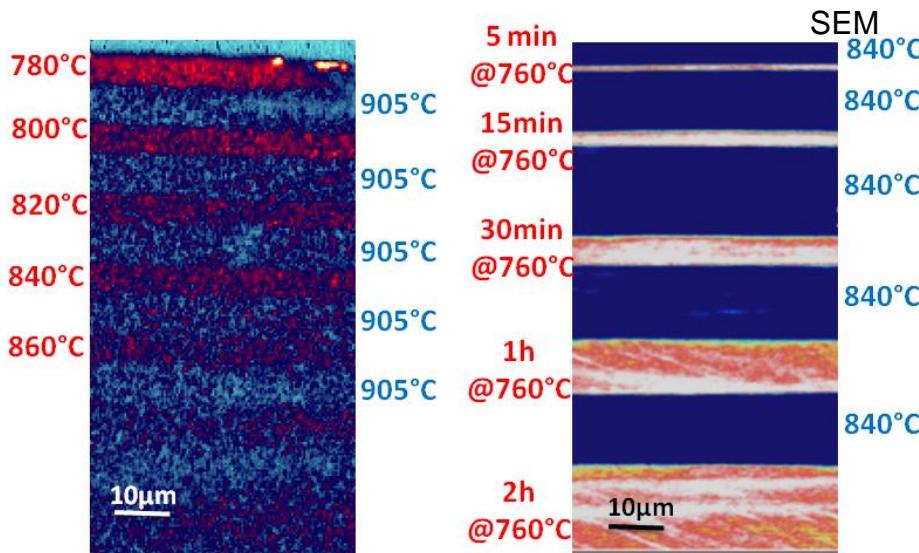
Collab. Leipzig Univ.



Stabilisation of the negative charge state

4. Tuning NV properties: spatial localisation

In-depth control



Low T → high NV

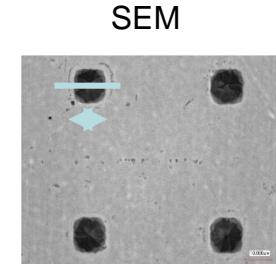
Quick change of T →
narrow NV layers

A. Tallaire et al., Diam. & Relat. Mat. 2015

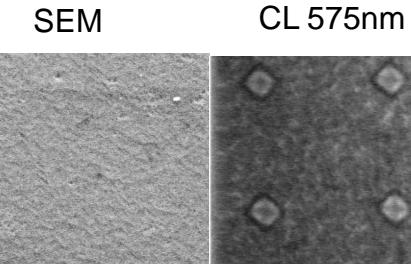
In-plane control

Overgrowth of micro-holes

Before growth

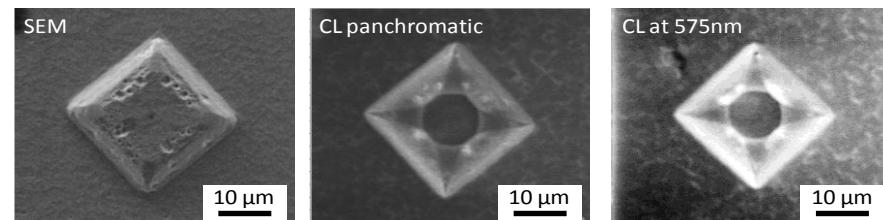


After growth



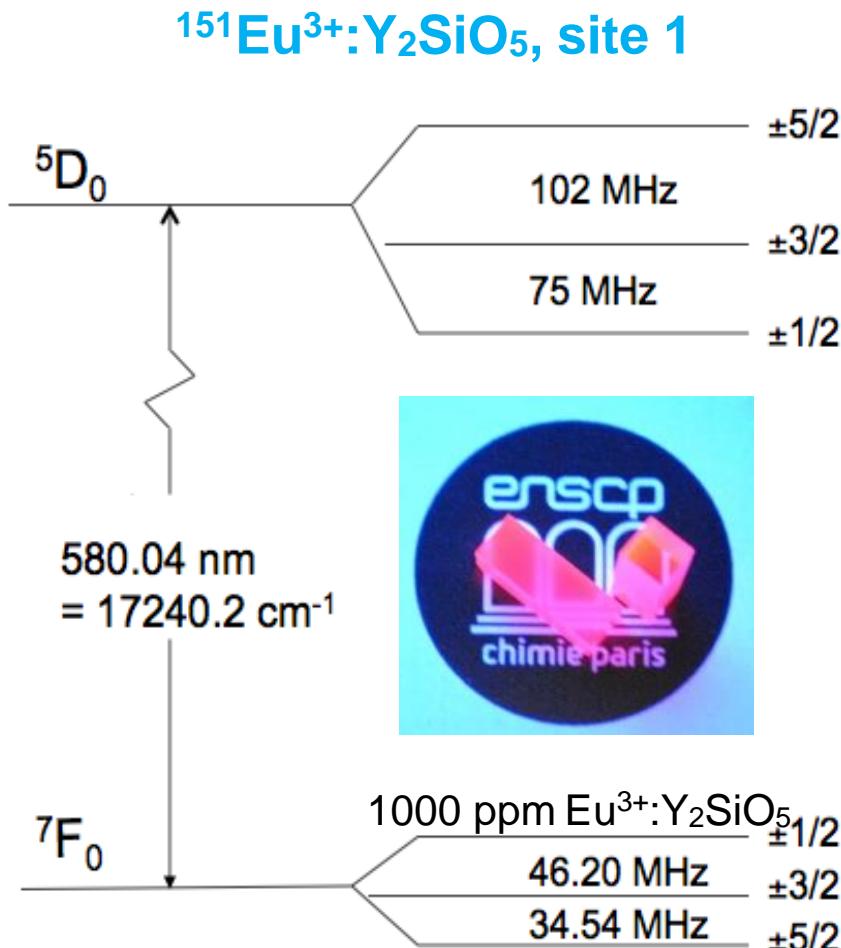
Overgrowth of micro-pillars

After growth



Other material system of interest: Rare earth ions in oxides

Rare earths in bulk oxides for QT



Shielding of the 4f electrons → isolated atoms naturally trapped into a solid host

- Optical coherence lifetime up to 4ms ($\text{Er}:\text{Y}_2\text{SiO}_5$)

T. Böttger et al., Phys. Rev. B 2009

- Spin coherence lifetimes up to 6 hours ($\text{Eu}:\text{Y}_2\text{SiO}_5$)

M. Zhong et al., Nature 2015

@ cryogenic temperature

P. Goldner, A. Ferrier, and O. Guillot-Noël, in Handbook on the Physics and Chemistry of Rare Earths, vol. 46, 2015

Bulk oxides grown by crystal pulling methods
(Czochralsky)



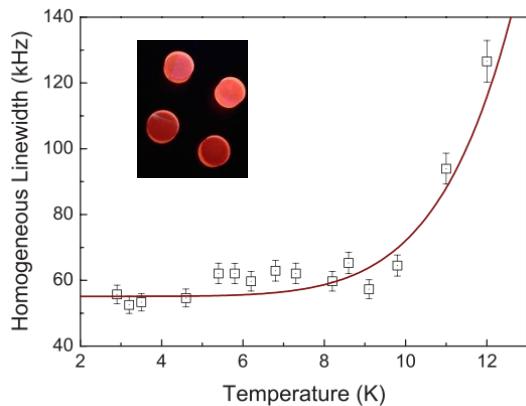
Oxides at the nanoscale for QT

Reproducing bulk RE-Ox properties at the nanoscale

→ Possibility to create hybrid systems

→ Develop a new and large platform for QIP

Sintered Eu: Y_2O_3 ceramics



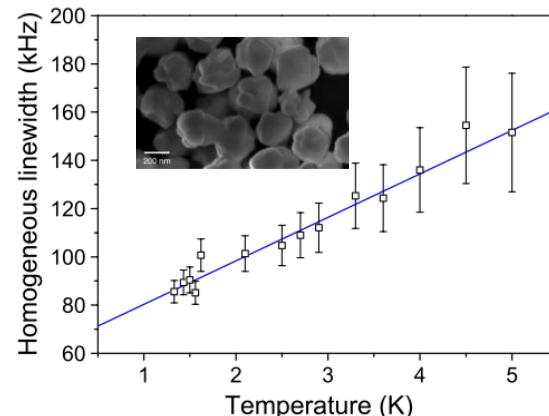
A. Ferrier et al.,
Phys. Rev. B 2013



Institut
de Recherche
de Chimie Paris

Lifetime of a spectral hole at 6K in a $\text{Y}_2\text{O}_3:\text{Eu}^{3+}$ ceramic > 15 min !

Eu: Y_2O_3 nanocrystals produced by homogeneous precipitation



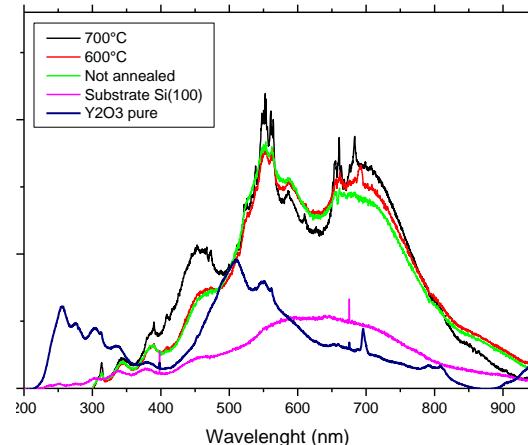
85 kHz linewidth!

A. Perrot et al.,
Phys. Rev. Lett.
2013

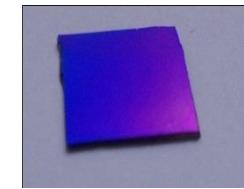


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de Recherche
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Er: Y_2O_3 thin films by ALD



M. Scarafaglio et al., thesis



Conclusion

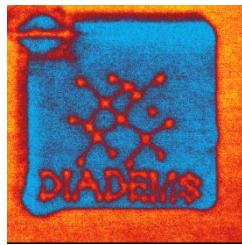
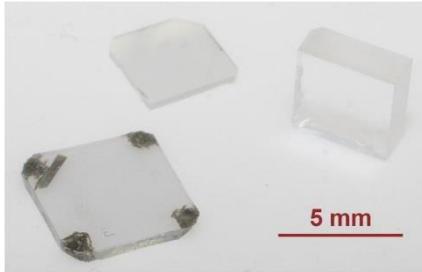
- Materials need to be designed on purpose for quantum applications → very high level of requirement (quality, purity, defect control etc.)
- Single crystal **diamond material** produced at LSPM with enhanced control on defects orientation, density, localisation
- **Rare earth in oxide crystals** produced at IRCP with the development of nanoscale approach: nanoparticles, thin films etc.
- New opportunities will emerge by combining materials with complementary properties → towards hybrid systems

The most exciting thing about a quantum-enhanced world is the promise of what it may yet bring

« *Here, there and Everywhere* » *The Economist* 09/03/2017

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**ENS-Cachan, Laboratoire Aimé Cotton, Basel
University, Thales TRT, Leipzig University,
Laboratoire Pierre Aigrain...**



European projects acknowledgements:



www.diadems.eu



www.nanoqtech.eu

Thank you for your attention