Padova, 21-01-2020

The SIQUST Project
Diamond-based single-photon sources as new quantum standards

Quantum Technologies within INFN: status and perspectives

Jacopo Forneris
Physics Department, University of Torino
Istituto Nazionale di Fisica Nucleare, Sez. Torino

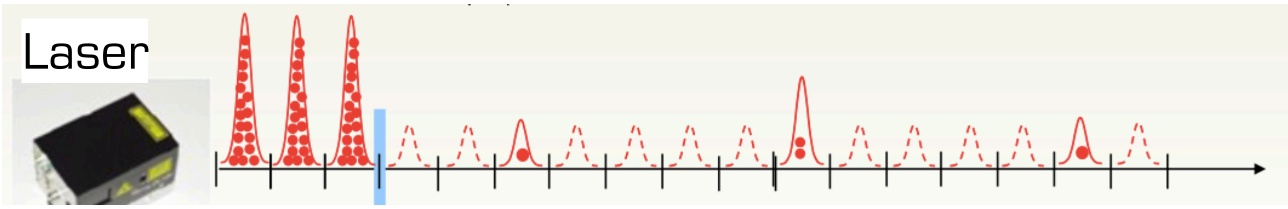
Single-photon sources

A single-photon source is a physical system which emits
one photon
on demand
with given physical properties (polarization, wavelength)

Enables quantum information using photons

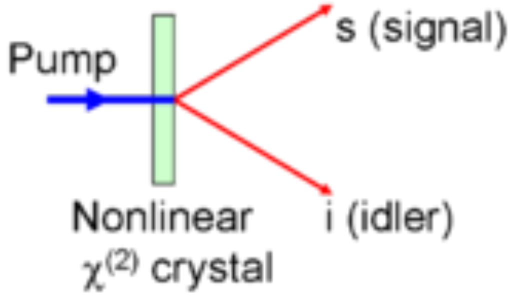
Probabilistic implementations

Attenuated lasers
Cheap
Highly monochromatic
High fraction of multi-photon (or no-photon) pulses

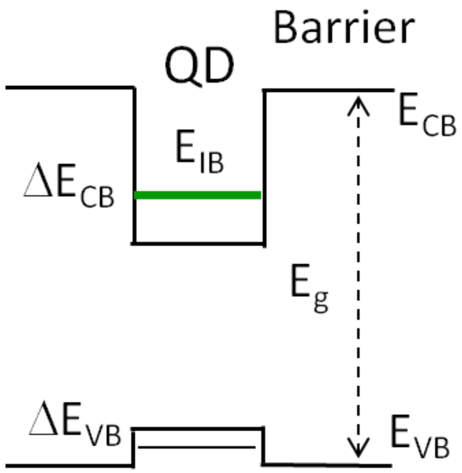


Attenuator

Parametric down-conversion
Conversion pump laser in entangled photon pairs
Post-selection: detection of the idler
Conversion process with small probability ($<10^{-10}$)

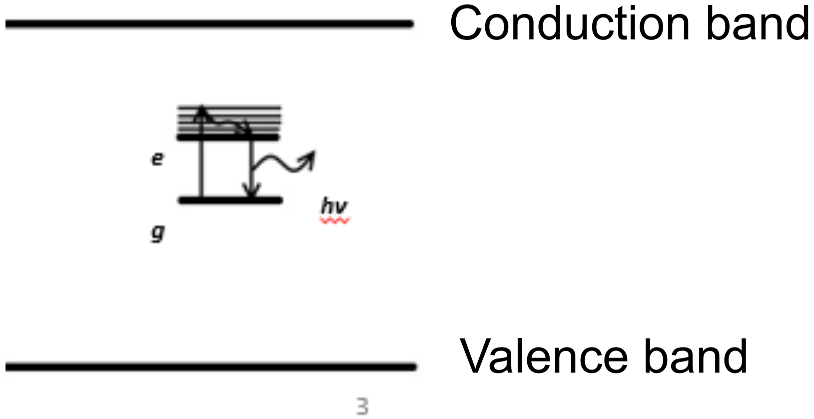


Solid-state single-photon sources



Quantum dots

Heterostructures, confinement, discrete energy levels
Wavelength: tunable with the QD size
Low temperature operation



Point defects in solids

Discrete energy levels in large band gap materials
Room temperature operation
Wavelength: system-dependent

Advantages
- Deterministic sources
- Compact (chip) size, portability, mass production
- Integration with existing micro-electronic technologies
- Tunability of the quantum systems by materials engineering

Challenges
- Fabrication strategies scalable to the industrial level
  - Significant retooling of ion implantation techniques
- Driving solid state quantum systems
  - Environmental noise, temperature
- Adequate single-photon detection systems
- Lack of established standards (specs, quality control, industry)

The SIQUST Research Project

EURAMET European Association of National Metrology Institutes
EMPIR: EU Metrology Programme for Innovation and Research
Integrated within H2020 scheme (2014-2020)
Joint research projects involving
- Metrological Institutes
- Industrial Organizations
- Academia

"To bring Europan measurement science to an internationally leading position"

SIQUST: Single-photon sources as new quantum standards

36 months (2018-2021), 1.8 M€ Consortium Budget

1. Solid state single-photon sources
10^6 s^{-1} rate, <2nm linewidth, 0.05 purity
Quantum dots, diamond color centers, organic molecules

2. Novel sensing and measurement techniques
Based on new classes of SPSs and on entangled photons

3. Measurement infrastructure
Complete metrological characterization
Traceability of detectors, amplifiers, radiometers
Portable sources

Project Leader

Physikalisch-Technische Bundesanstalt	D

6 **National Metrological Institutes**

AALTO University	FIN
Metrosert	EST
National Physical Laboratories	UK
Czech Metrological Institute	CZ
INRiM	I

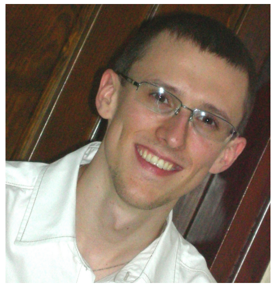
8 **External Partners**

VTT Technical Research Centre	FIN
Technische Universität Berlin	D
Universität des Saarlandes	D
Universität Nürnberg	D
Universität Stuttgart	D
Università di Torino	I
INFN sez. Torino	I
Consiglio Nazionale delle Ricerche	I
Consejo Superior de Investigaciones Cientificas	ES

The SIQUST Activities in Torino

UNIVERSITÀ DEGLI STUDI DI TORINO

INRiM ISTITUTO NAZIONALE DI RICERCA METROLOGICA

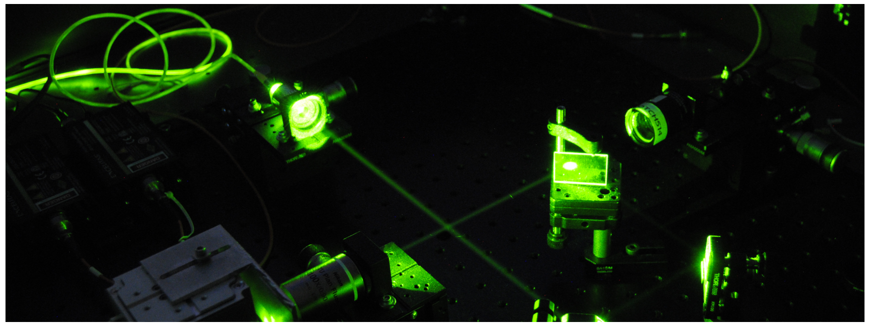


INFN Istituto Nazionale di Fisica Nucleare

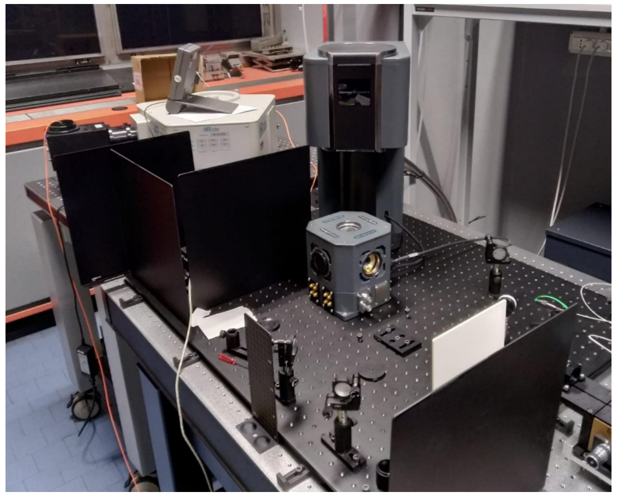
P. Aprà S. Ditalia Tchernij F. Picollo
A- Beraudo M. Monteno P. Olivero

M. Genovese I. Degiovanni E. Bernardi
P. Traina E. Moreva

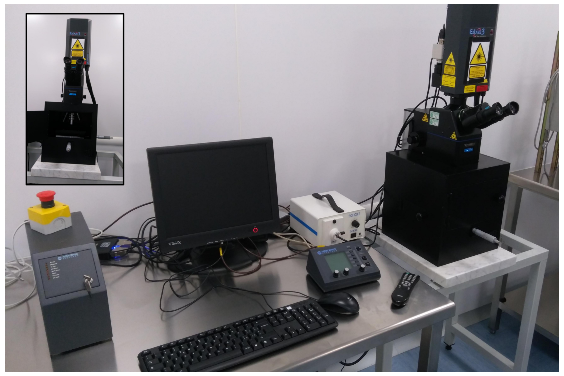
Cleanroom(s) for devices processing

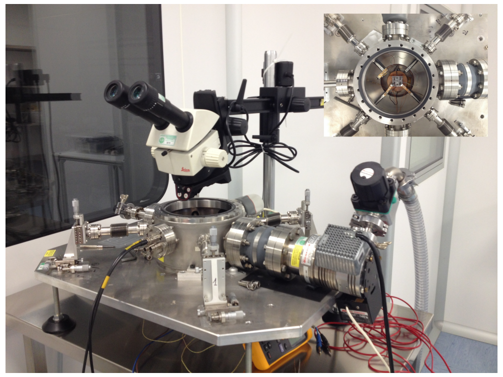


RT and 4K confocal microscopy setups



5-100 kV ion implanter, Univ. Torino
MIUR **Dept. of Excellence** Project
Irradiation chamber embedded in cleanroom environment





Photolitography, laser milling
Thermal processing, probe station

The SIQUST Activities in Torino

Diamond based single-photon sources

Exploration of novel classes of emitters
- Fabrication methods, ion implantation
- Characterization of emission properties

Integration in opto-electronic devices

Electroluminescent sources
Electrical tuning of emission spectra

Quantum enhanced sensing

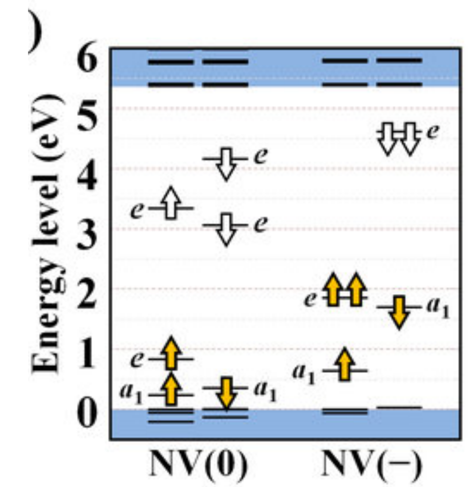
NV center
Electrometry
Thermometry
Bio-sensing

Alternative quantum emitters

Diamond color centers

Monoatomic crystal: control on defects formation

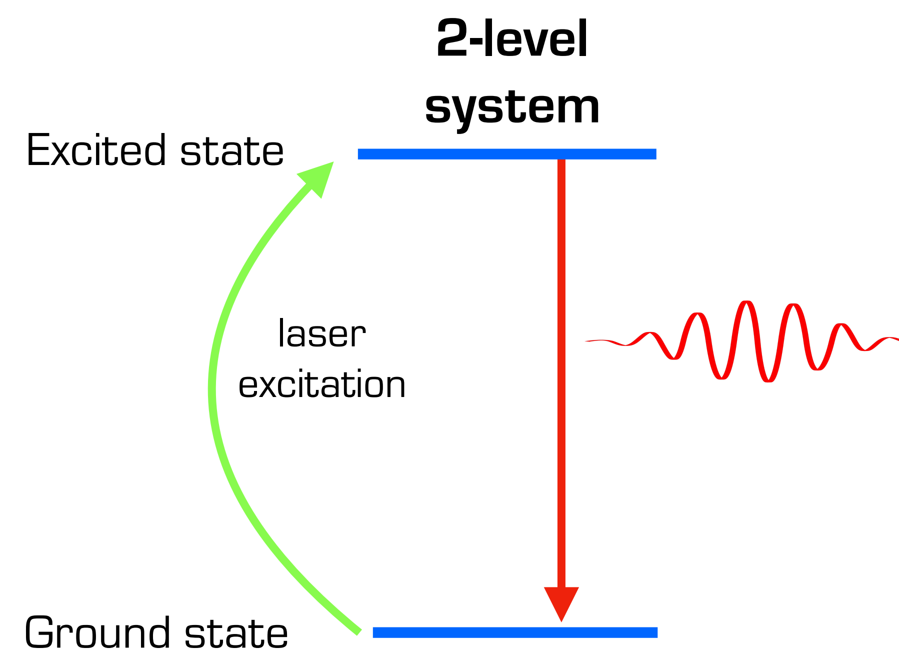
Point defects (vacancies, interstitials, substitutional impurities)
Formation of discrete energy levels with optical transitions



Individual defects: single-photon sources

Large band gap (5.5 eV):

- Emission in the visible light spectrum
- Operation at high temperatures

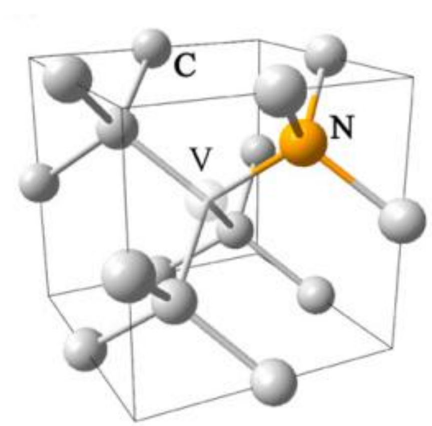


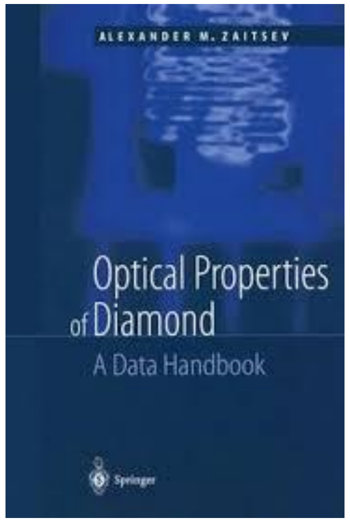
Hundreds of optically active defects

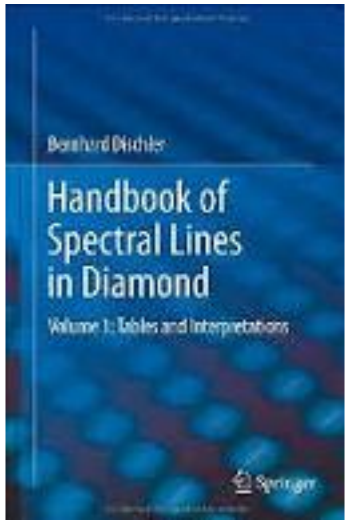
Many with **high quantum efficiency** and **RT photo-stability**

A **systematic study** is currently missing on

- fabricability
- emission properties characterization



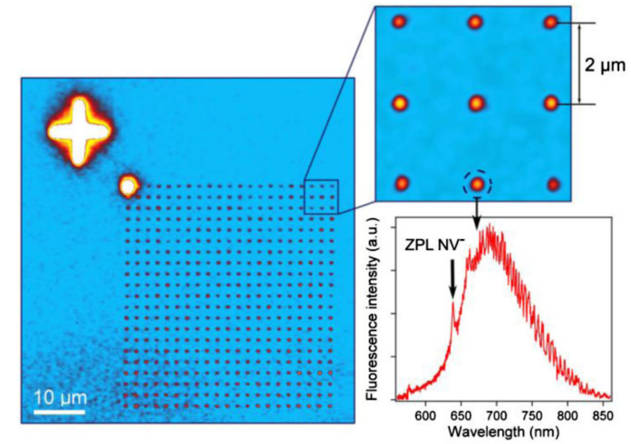




Ion implantation of diamond color centers

Key enabler for controlled fabrication of quantum emitters

Only viable path to large scale arrays of individual emitters



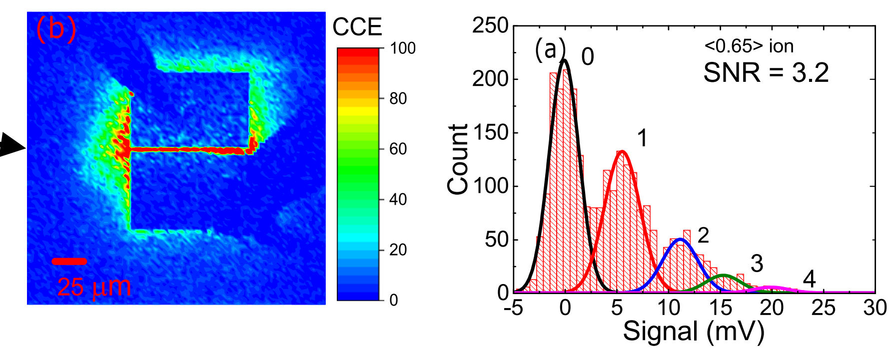
Leipzig, New J. Phys. 12 (2010) 065017

Control:

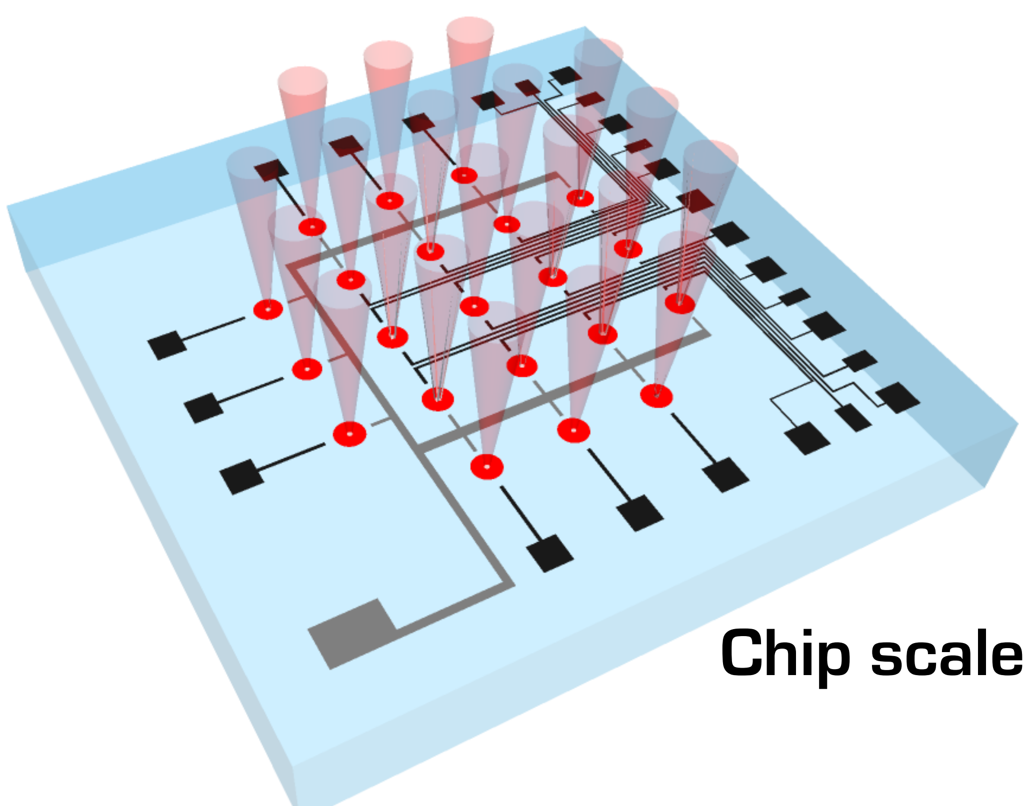
the position (~10 nm accuracy)

OR

the number (single ion detection, energies as low as 150 keV)



Sandia, APL 109 (2016) 063502



Reproducibility

Scalability

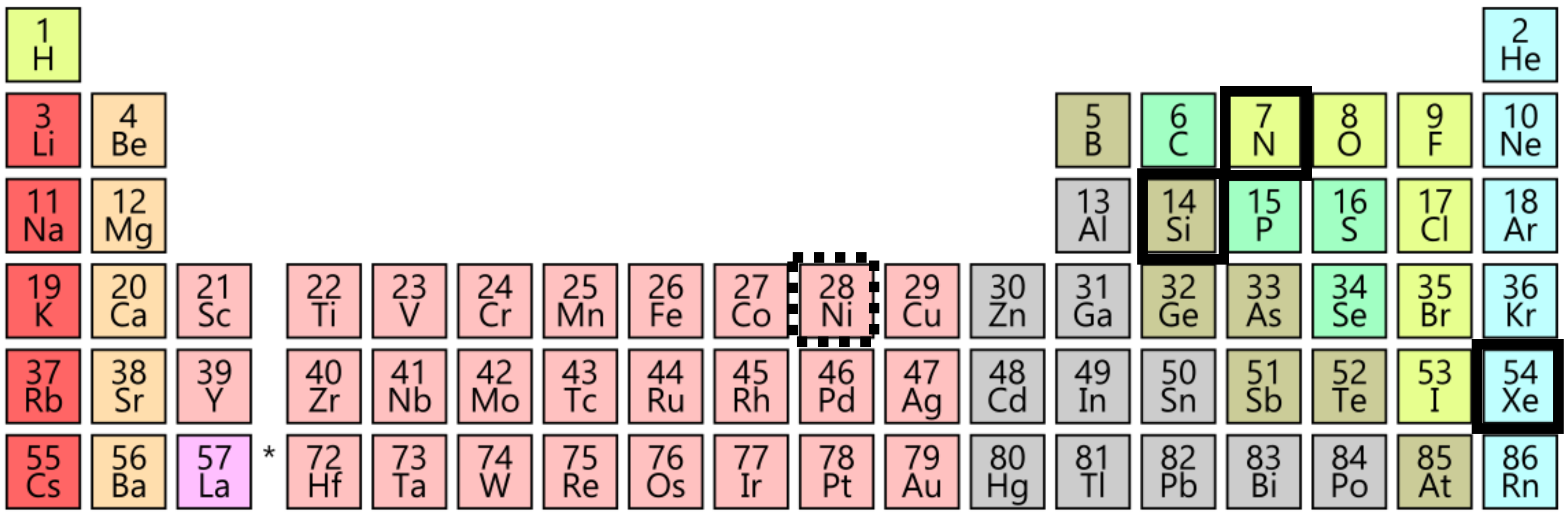
Integration in electronic/photonic structures

High spatial density

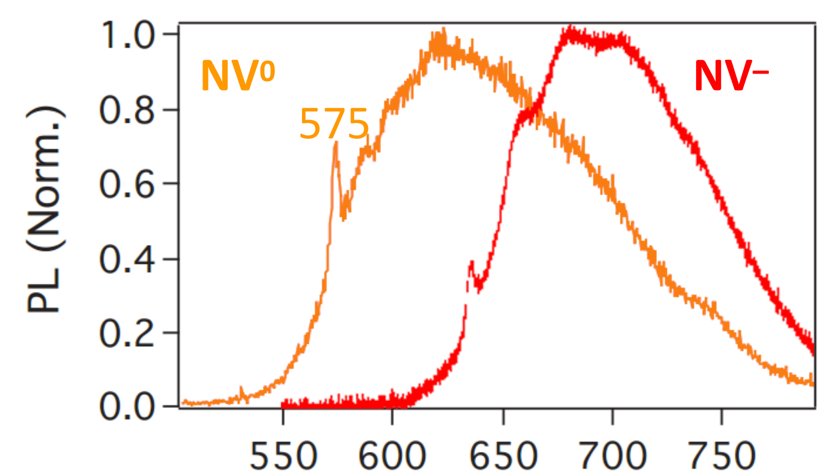
Chip scale fabrication with industrially available methods

Quest for optimal quantum emitters

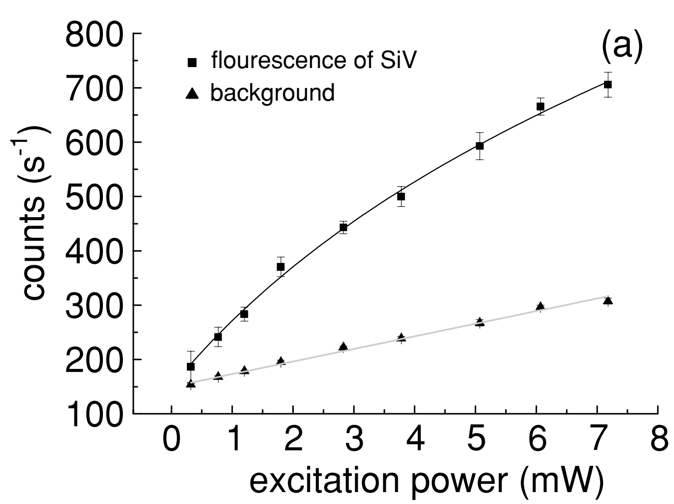
Luminescent defects in diamond fabricated upon ion implantation - 2014



NV center - J. Appl. Phys. 109, 083530 (2011)
SiV center - J. Phys. B 39 (2006) 37
Xe-center - J. Lumin 107 (2004) 26
NE8 Center - J. Appl. Phys. 107 (2010) 093512



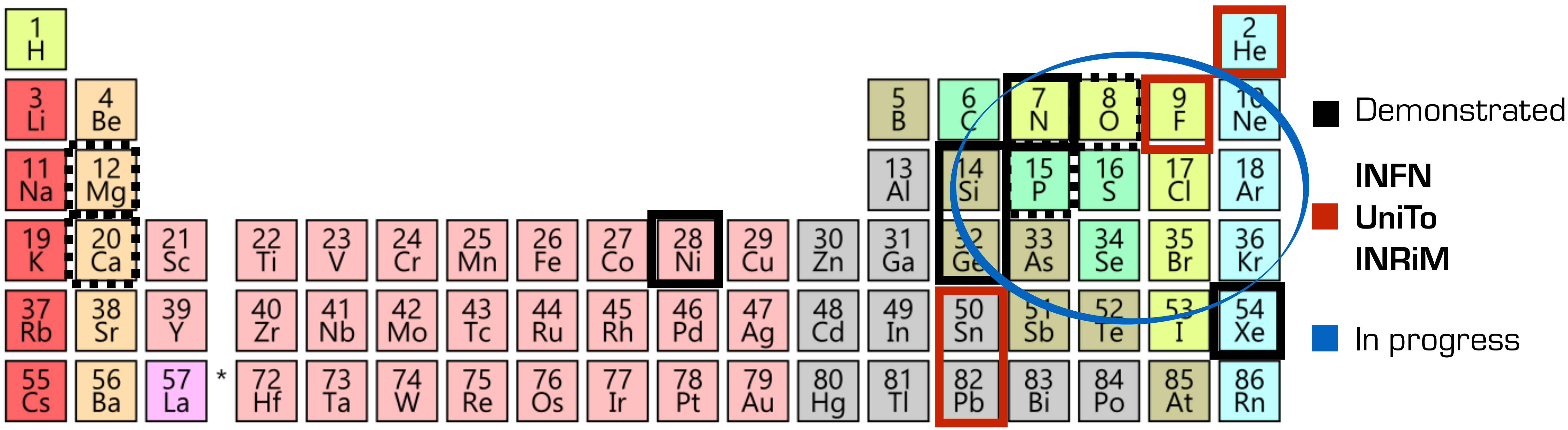
NV center - emission spectra



SiV center - RT emission intensity saturation

Quest for optimal quantum emitters

Luminescent defects in diamond fabricated upon ion implantation - 2019



NV center - J. Appl. Phys. 109, 083530 (2011)
SiV center - J. Phys. B 39 (2006) 37
Xe-center - J. Lumin 107 (2004) 26
NE8 Center - J. Appl. Phys. 107 (2010) 093512

SnV center - ACS Phot. 4 (2017) 2580
- PRL 119, 253601 (2017)
PbV center - ACS Phot. 5 (2018) 4864
He-center - J. Lumin 179 (2016) 59
F-center

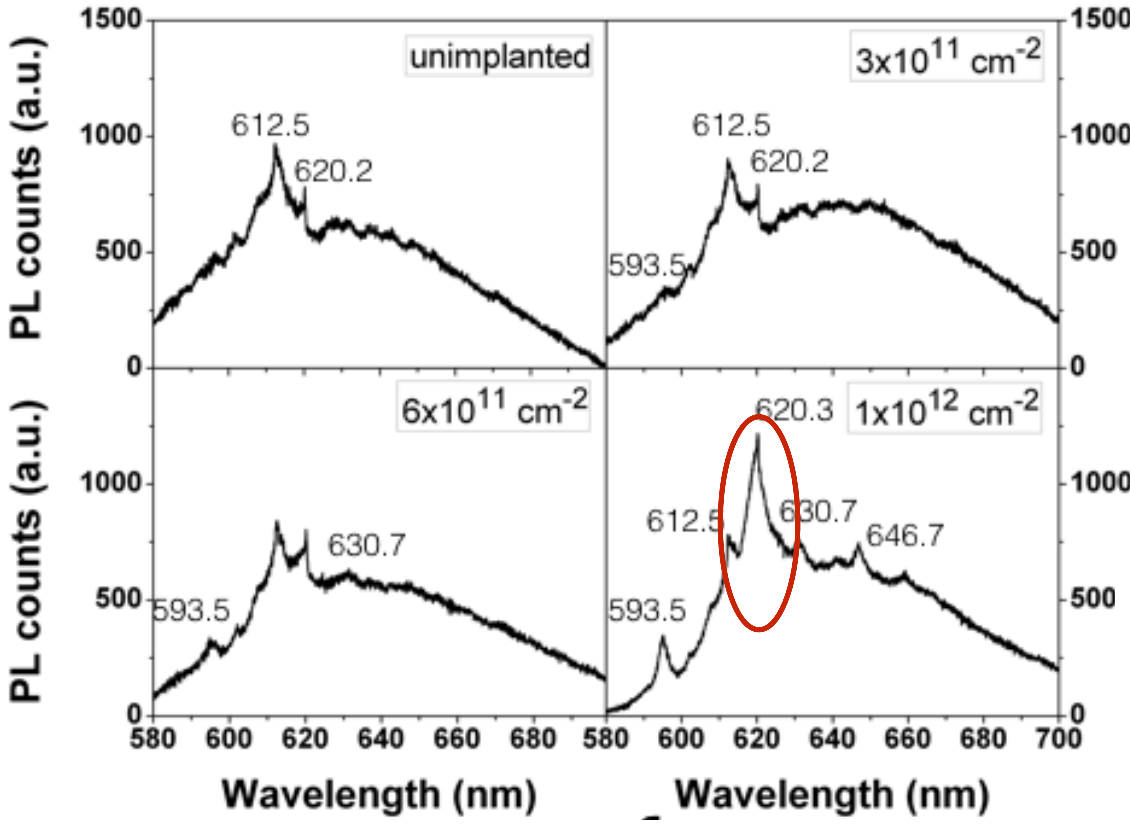
GeV center - Sci. Reports 5 (2015) 12882
- Sci. Reports 5 (2015) 14789

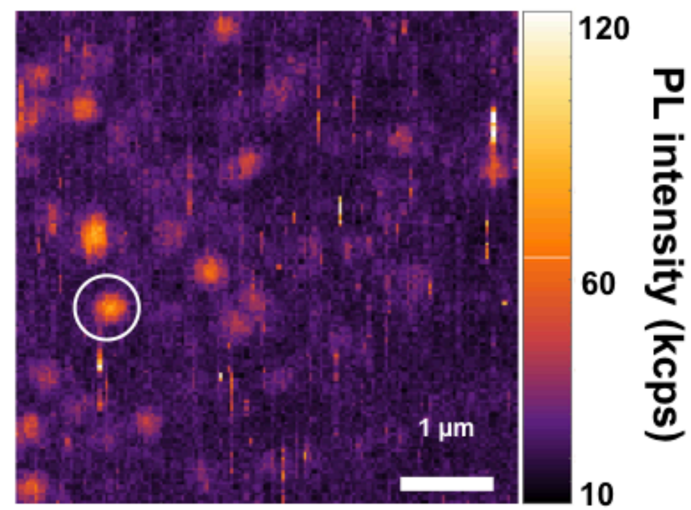
O-center - J. Phys. D 51 (2018) 483002
P-center Leipzig, ensemble
Ca-center
Mg-center
F-center

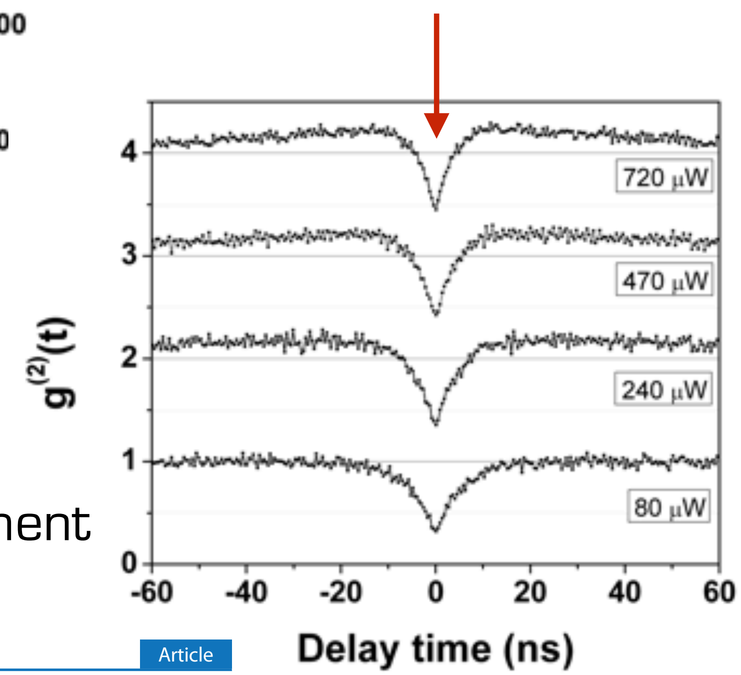
Demonstration of SnV center in diamond

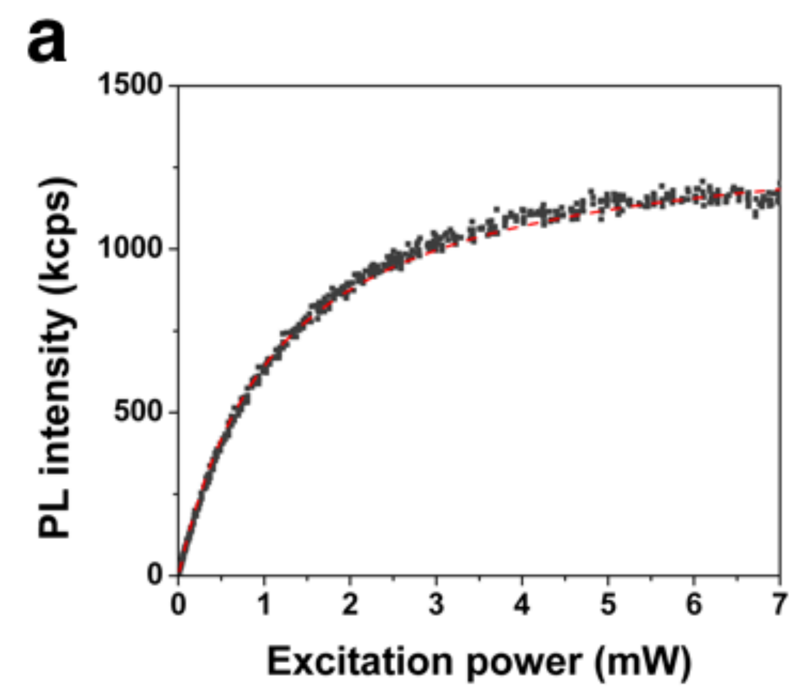
20 keV, 10 MeV Sn implantation and annealing (T>900 °C)
Main emission line at 620.3 nm

Correlation of PL intensity and implantation fluence









Single-photon emission assessment

ACS Photonics
Article
Cite This: ACS Photonics 2017, 4, 2580-2586
pubs.acs.org/journal/apchd5

Single-Photon-Emitting Optical Centers in Diamond Fabricated upon Sn Implantation

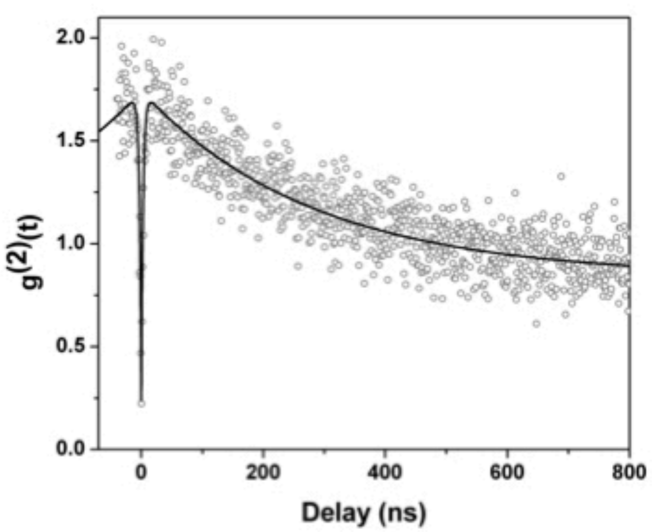
S. Ditalia Tchernij,[†,‡] T. Herzig,[§] J. Forneris,[*,‡,†] J. Küpper,[§] S. Pezzagna,[§] P. Traina,[∥] E. Moreva,[∥] I. P. Degiovanni,[∥] G. Brida,[∥] N. Skukan,[⊥] M. Genovese,[‡,∥] M. Jakšić,[⊥] J. Meijer,[§] and P. Olivero[†,‡]

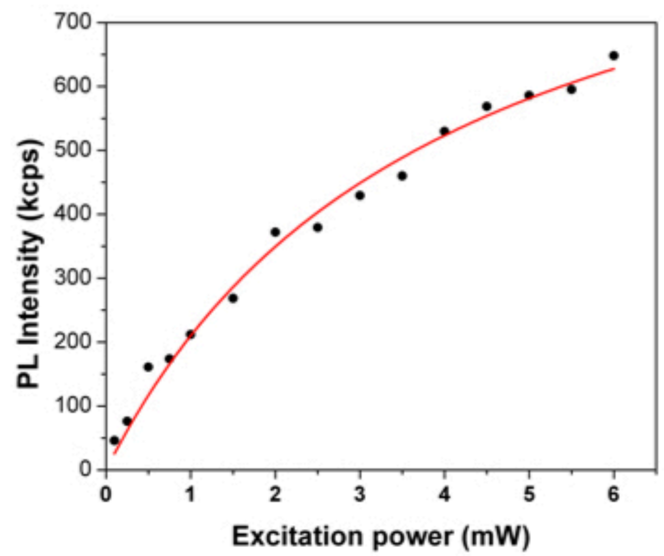
Highest intensity so far at room **temperature**
Saturation emission: (1.37 ± 0.01) x10^6 photons s^{-1}

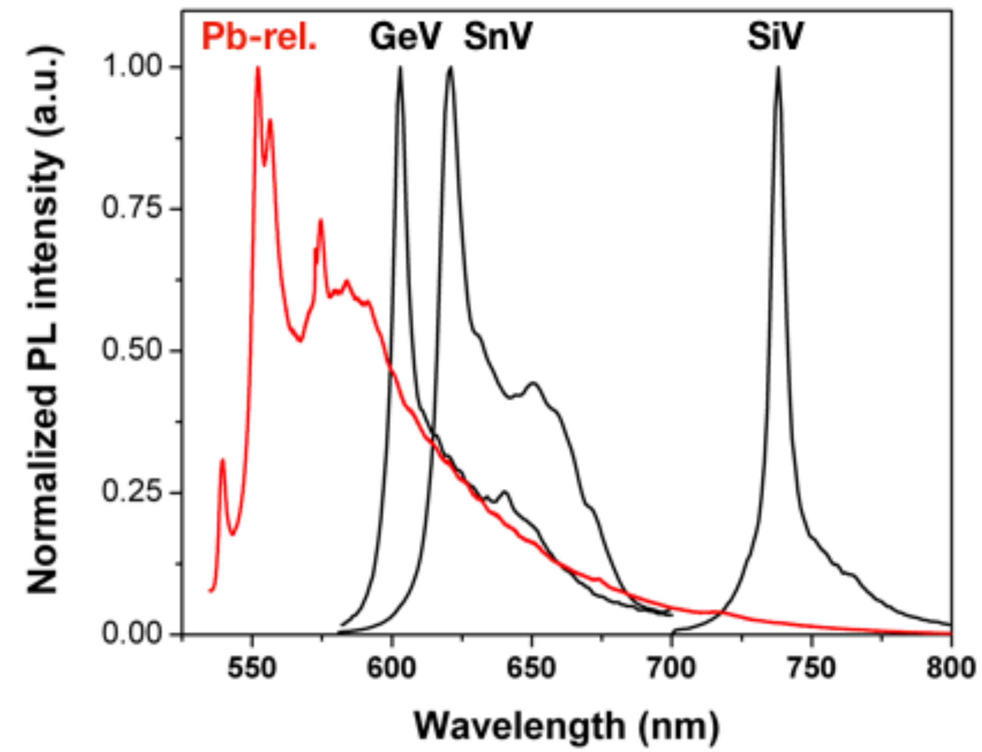
Pb-related emission in diamond

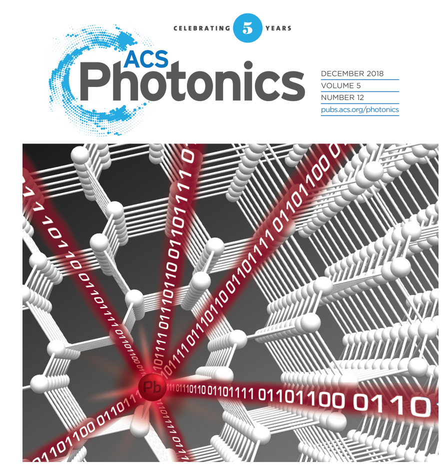
Fabrication with either Pb- (unstable beam, low ion currents)
PbO2-

PL excitability in the 405 nm - 532 nm range
Single-photon emitter demonstration
High count rate (1.04 ± 0.07) x10^6 photons s^{-1}









Emission lines at
538 nm (doublet)
552-556 nm (doublet?)
Theory: ZPL at either: 517 nm, 544 nm

Attribution and defect structure: still tentative

nature COMMUNICATIONS
PERSPECTIVE
https://doi.org/10.1038/s41467-019-13332-w OPEN
Quantum nanophotonics with group IV defects in diamond

ACS Photonics Article
Cite This: ACS Photonics 2018, 5, 4864−4871 pubs.acs.org/journal/apchd5

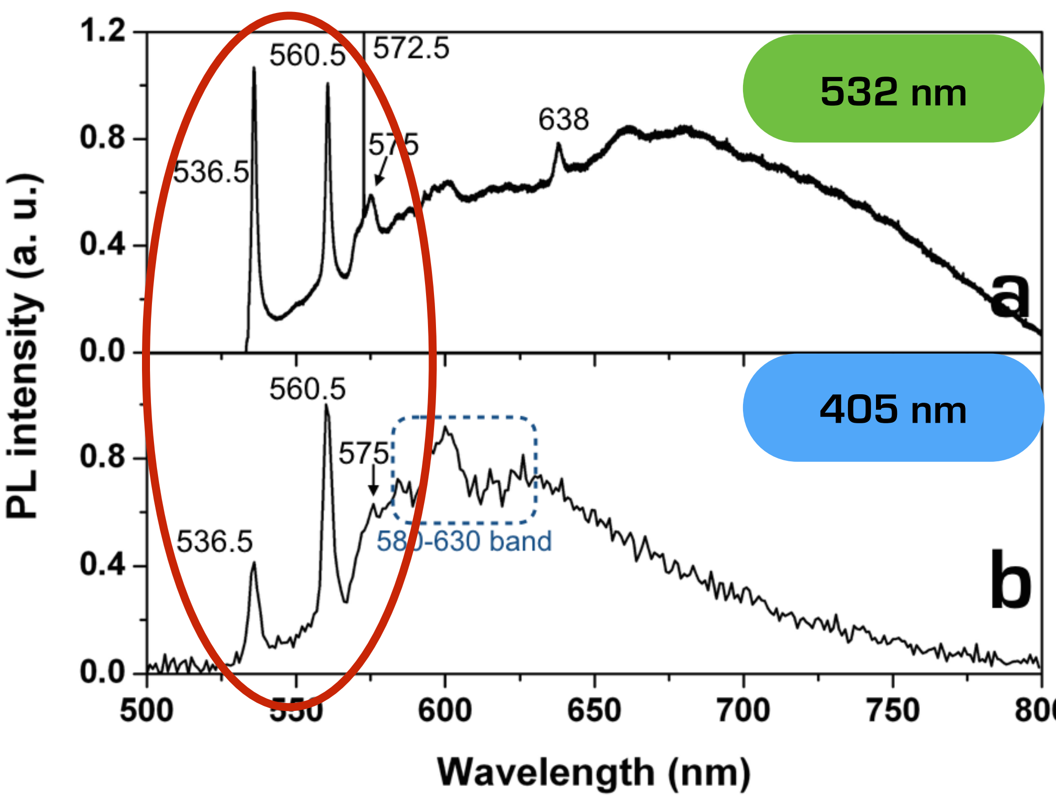
Single-Photon Emitters in Lead-Implanted Single-Crystal Diamond

S. Ditalia Tchernij,[†,‡,¶] T. Lühmann,[§,¶] T. Herzig,[§] J. Küpper,[§] A. Damin,[∥] S. Santonocito,[†] M. Signorile,[∥] P. Traina,[⊥] E. Moreva,[⊥] F. Celegato,[⊥] S. Pezzagna,[§] I. P. Degiovanni,[⊥] P. Olivero,[†,‡] M. Jakšić,[#] J. Meijer,[§] P. M. Genovese,[‡,⊥] and J. Forneris[*,‡,#]

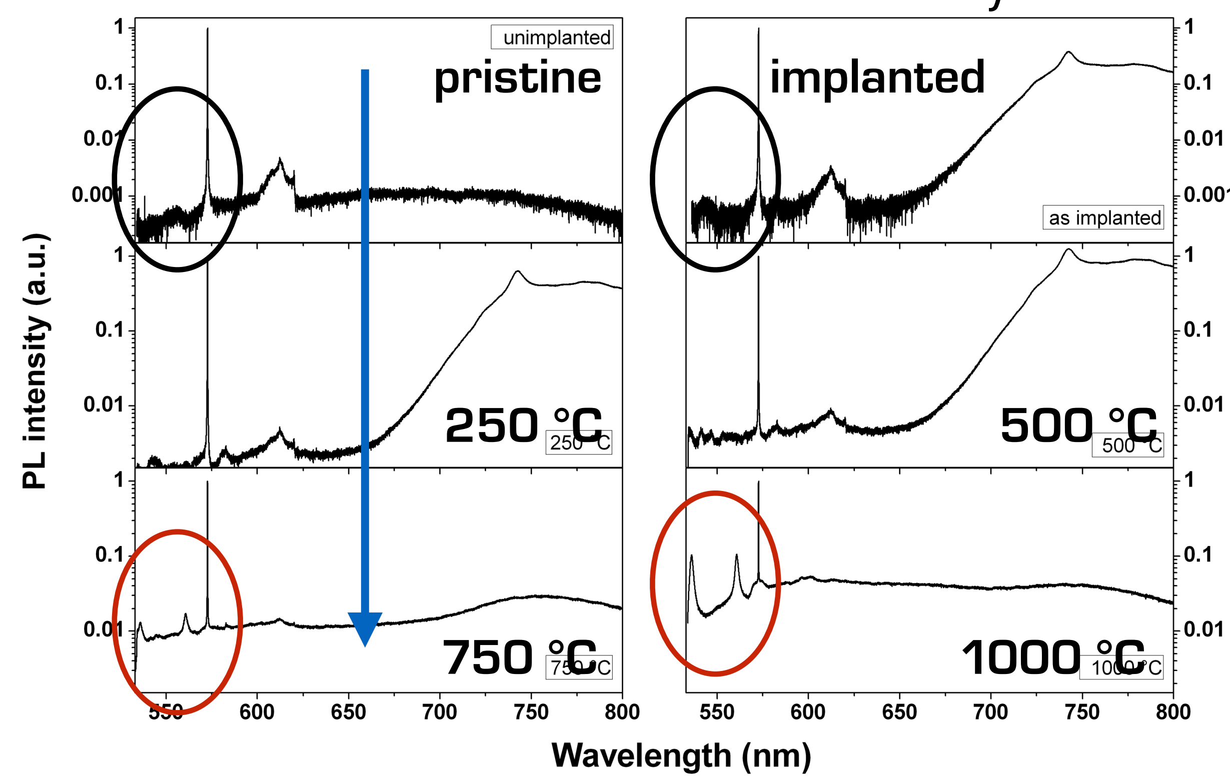
Optical activity of noble gases in diamond

Optical activity of noble gases in diamond

Narrow lines at 535.5, 560.5 nm in **He**-implanted diamond (E>1 MeV, annealing at >750 °C)



Formation at T>750° C, concurrent decrease in vacancies PL intensity



Contents lists available at ScienceDirect

Journal of Luminescence

journal homepage: www.elsevier.com/locate/jlumin

ELSEVIER

Full Length Article

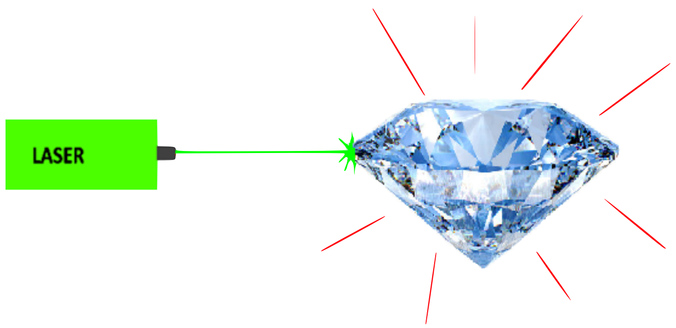
Creation and characterization of He-related color centers in diamond

J. Forneris [a,b,c,*], A. Tengattini [b,a,c], S. Ditalia Tchernij [b,a,c], F. Picollo [a,b,c], A. Battiato [b,a,c], P. Traina [d], I.P. Degiovanni [d], E. Moreva [d], G. Brida [d], V. Grilj [e], N. Skukan [e], M. Jakšić [e], M. Genovese [a,c,d], P. Olivero [b,a,c]

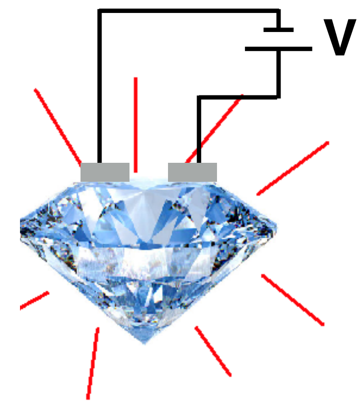
Ne, Xe-implanted diamond also exhibit CL lines, Phys. Stat. Sol. (b) 129 (1985) 129

Electrical control of diamond quantum emitters

Photoluminescence
Stimulation by electromagnetic radiation



Electroluminescence
Electrical current replaces the laser pump



Wide band gap semiconductor engineering

	Silicon	**Diamond**
Band gap	1.12 eV	5.5 eV
P-type acceptor	B	B
Energy from valence band (eV)	0.045	**0.37**
N-type: P 0.044 eV	P	P
Energy from conduction band (eV)	0.044	**0.6**
N-type resistivity	2 mΩ cm	1 kΩ cm
P-type resistivity	0.2-2 Ω cm	10-100 Ω cm

Alternative strategies to doping are needed

Electrical control of diamond quantum emitters

Dia.Fab Experiment

Deep Ion Beam Lithography

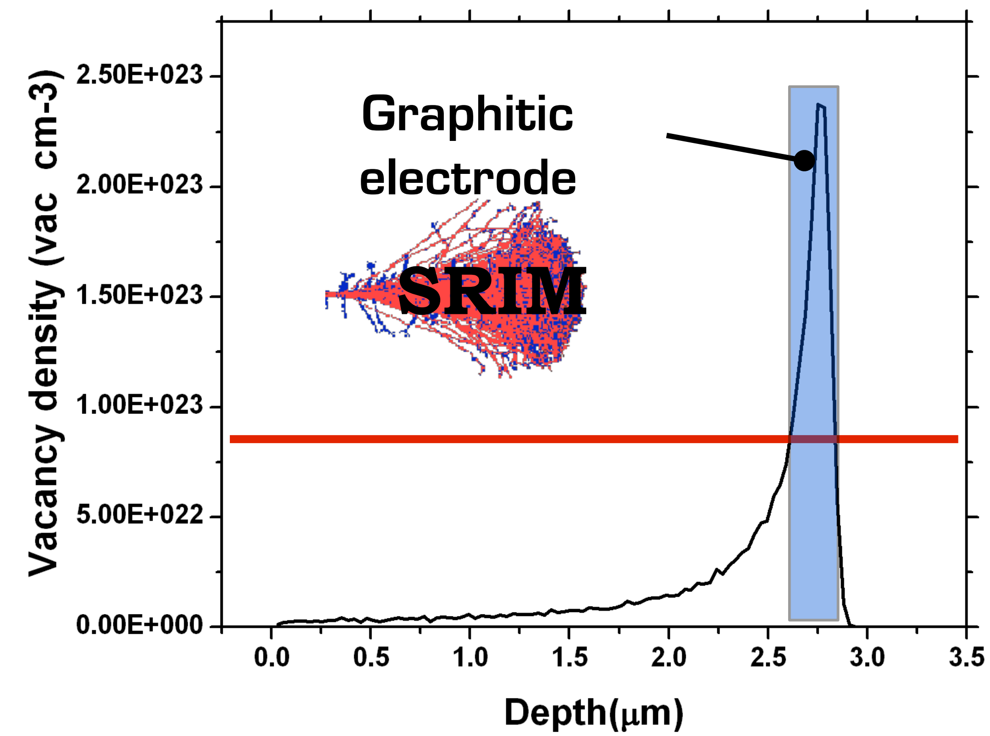
Exploitation of **MeV** ion nuclear energy loss

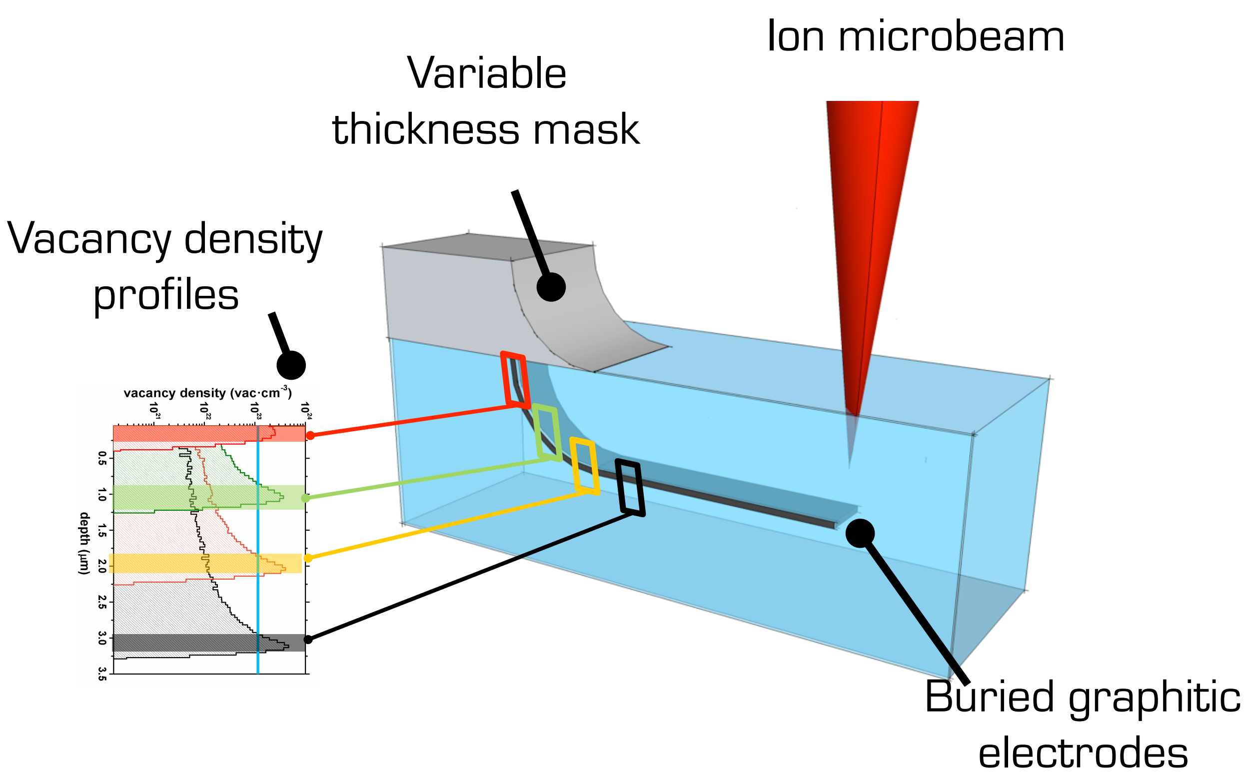
Cumulation of **damage** at the **end of ion range**

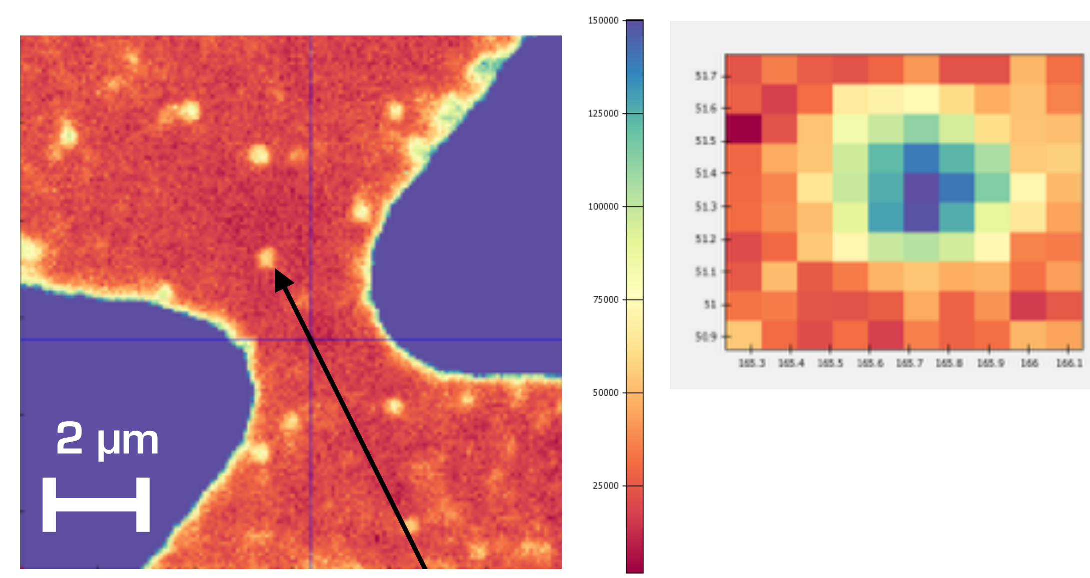
Amorphization of buried diamond layer

Thermal treatment: **Conductive channels** embedded in **insulating diamond**

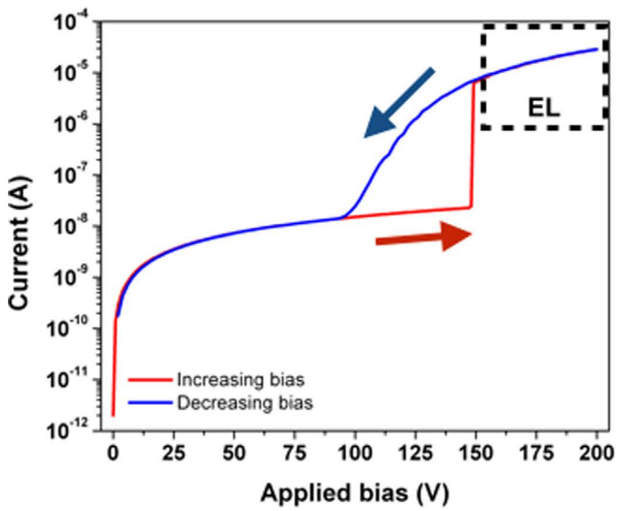
F. Picollo et al., New J. Phys. 14, 053011 (2012)

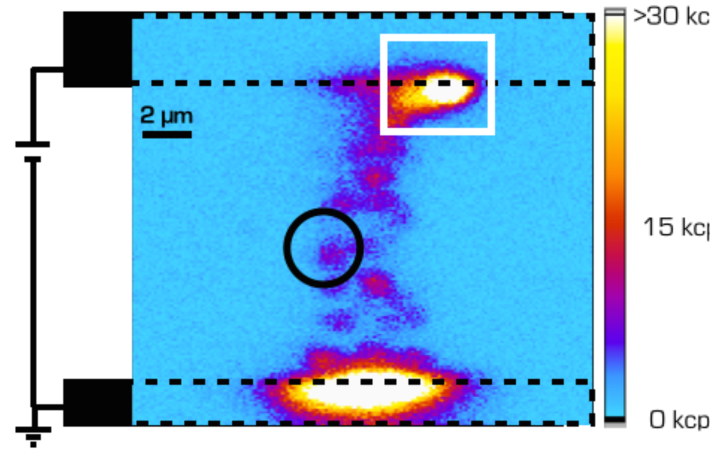


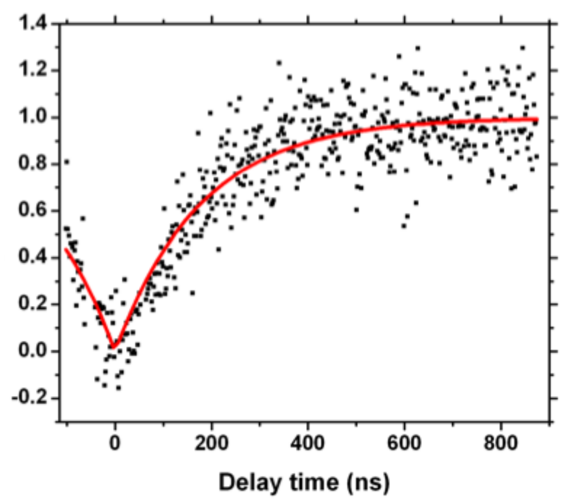




Emitters control with graphitic electrodes

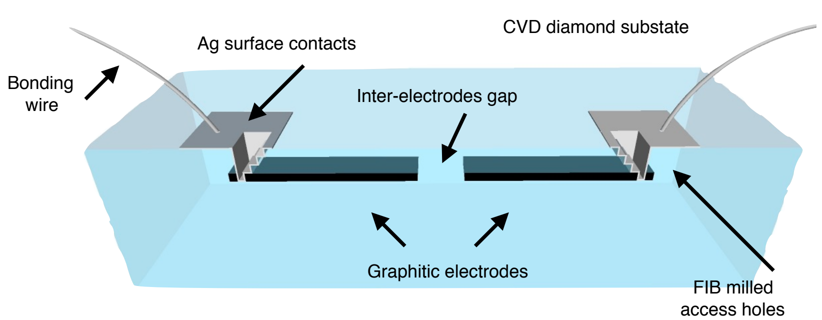


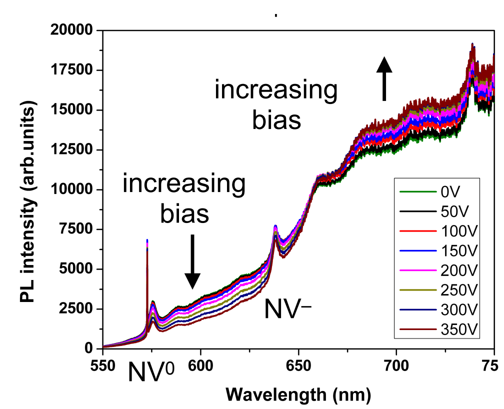




Single-photon EL, NV center, Sharp transition to carriers injection regime

Sci. Rep. 5 (2015) 15901





NV Center charge state control

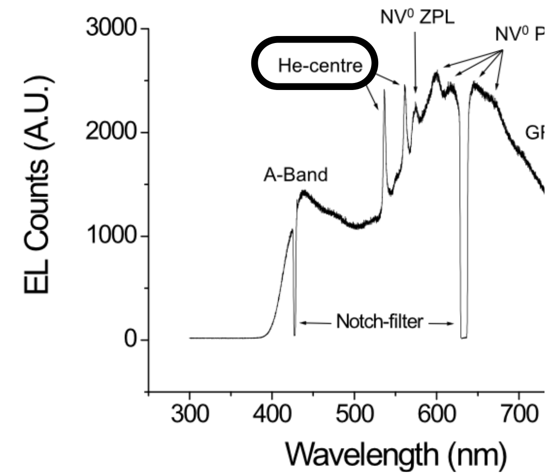
Low bias, linear I(V) regime

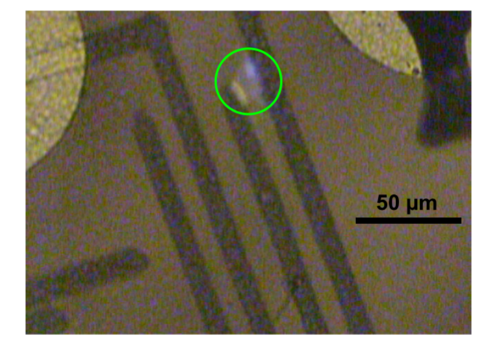
Carbon 113 (2017) 76

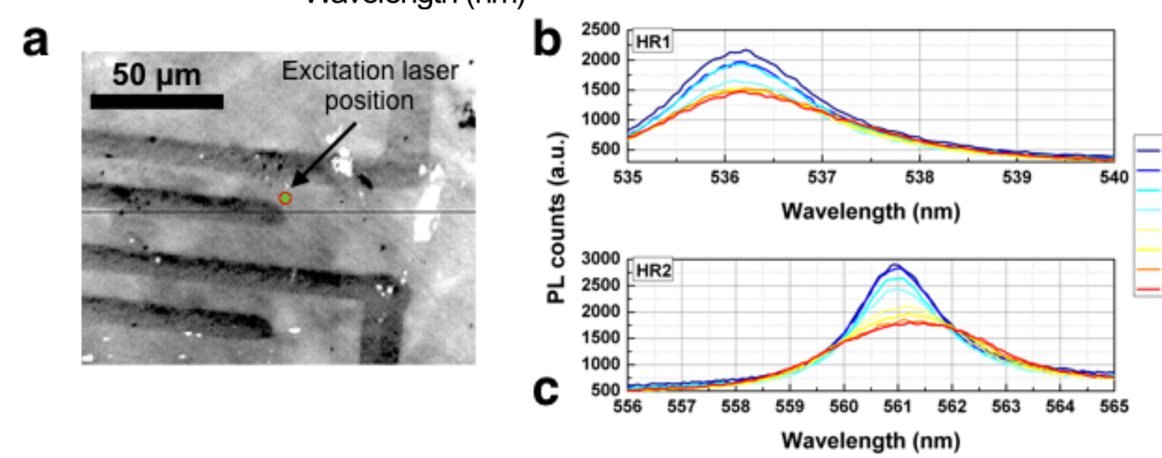
He-related center

Electroluminescence

NIM B 348 (2015) 187







Stark shift spectral tuning

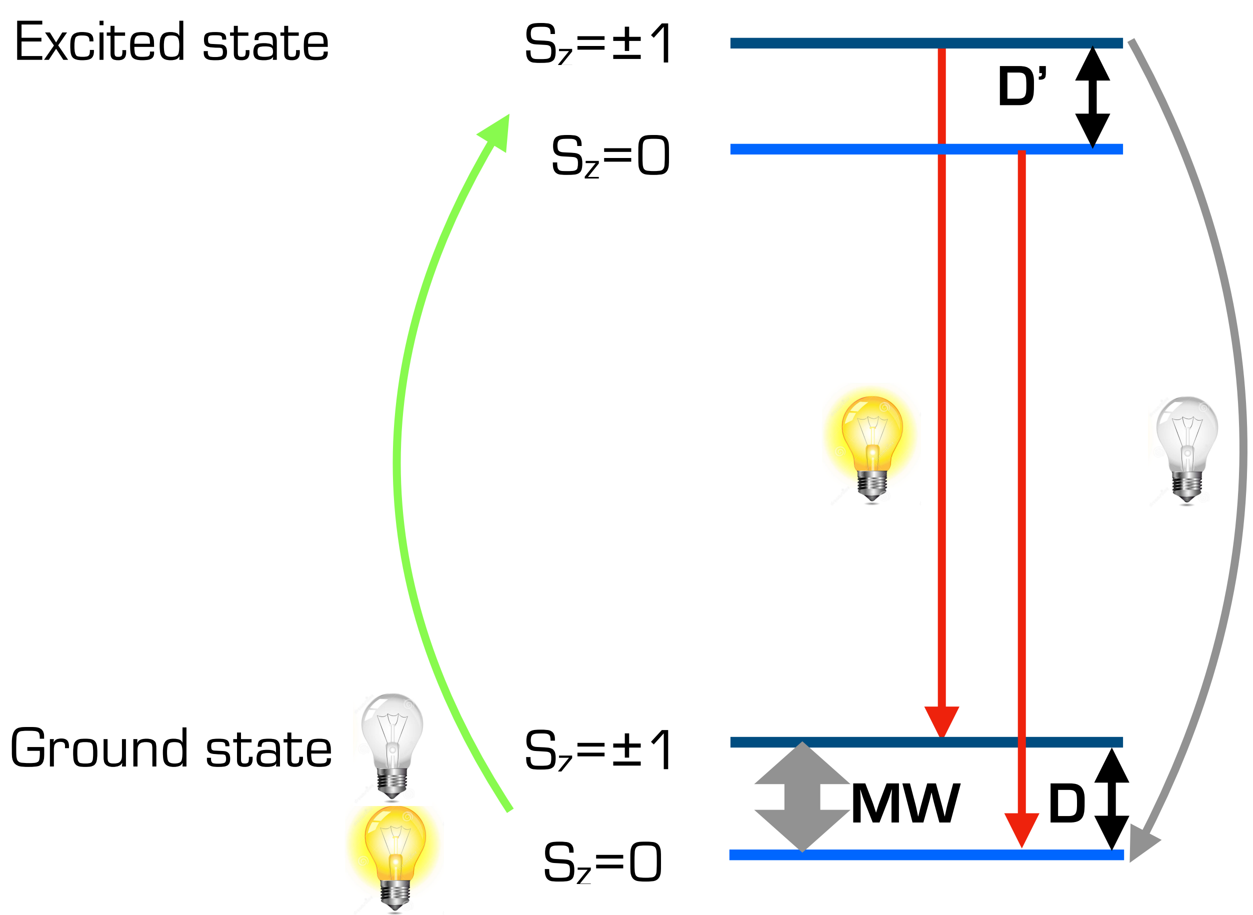
APL 111 (2017) 111105

CSN5 Young Researcher Grant

Diamond-based Electrically-controlled Single-photon Sources

Diamond-based quantum sensing: the NV⁻ center

Quantum information is encoded **in the emitting system**
emission rate, wavelength depend on the interaction with environment

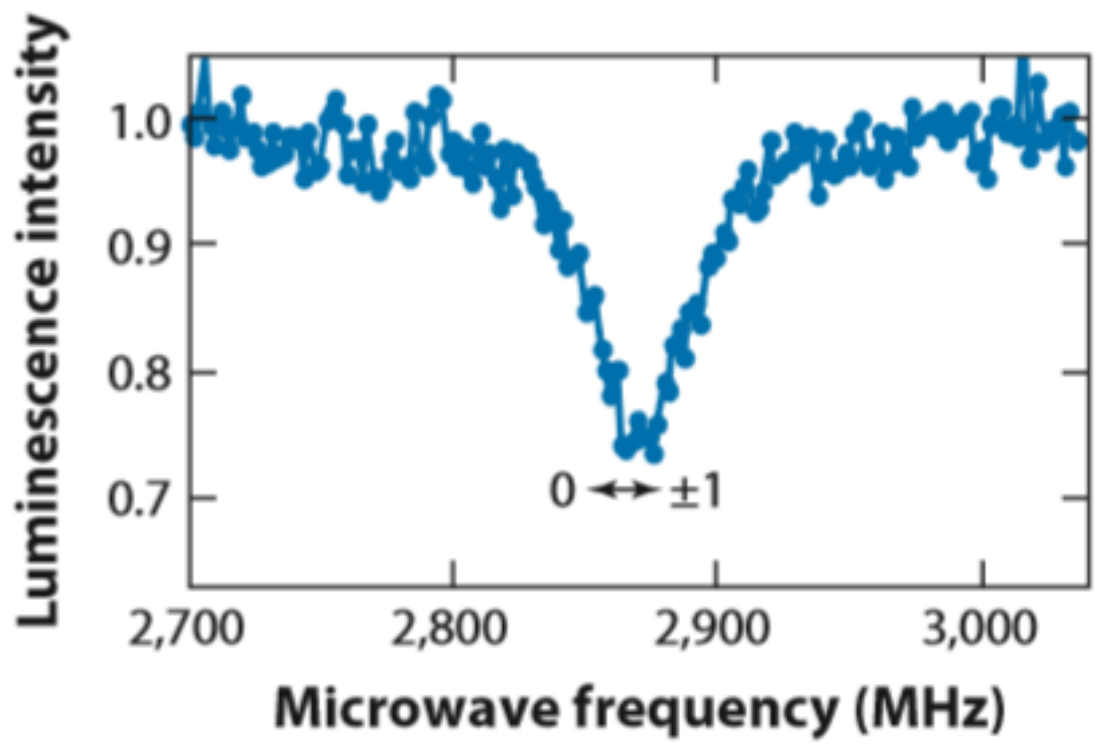


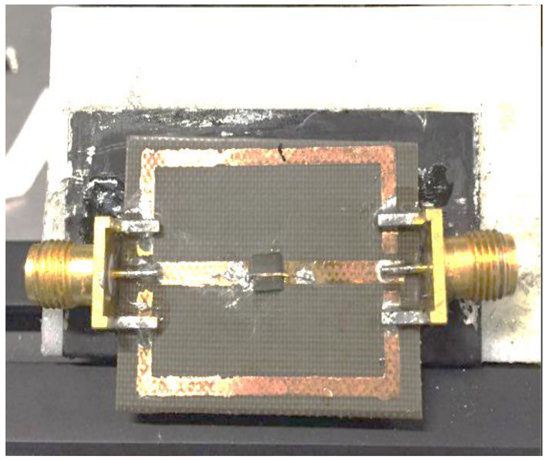
$$H = D\ (S_z{}^2 - S(S+1)/3\ ) + H_f$$

spin-spin interaction

D~2.88 GHz fine structure splitting

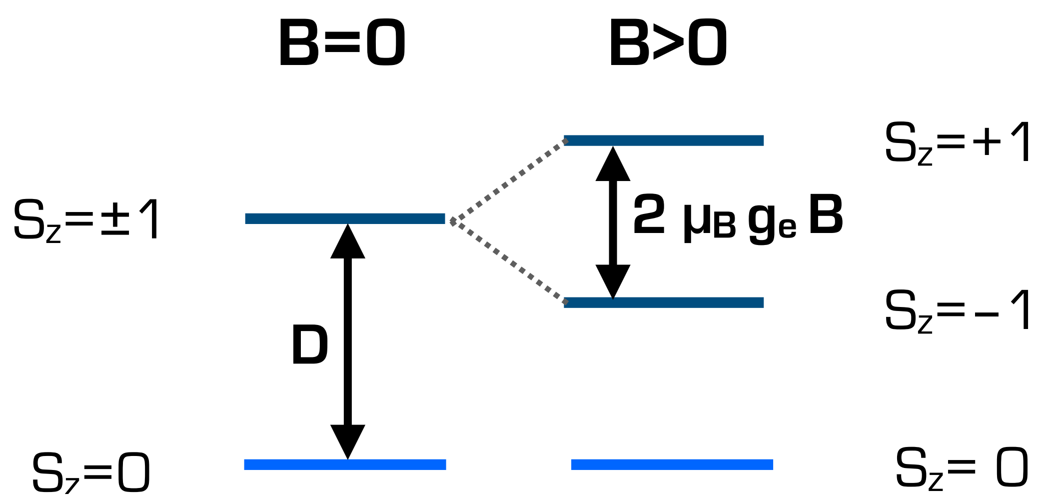
Optically detected magnetic resonance (ODMR)
Annu. Rev. Phys. Chem. 2014. 65:83



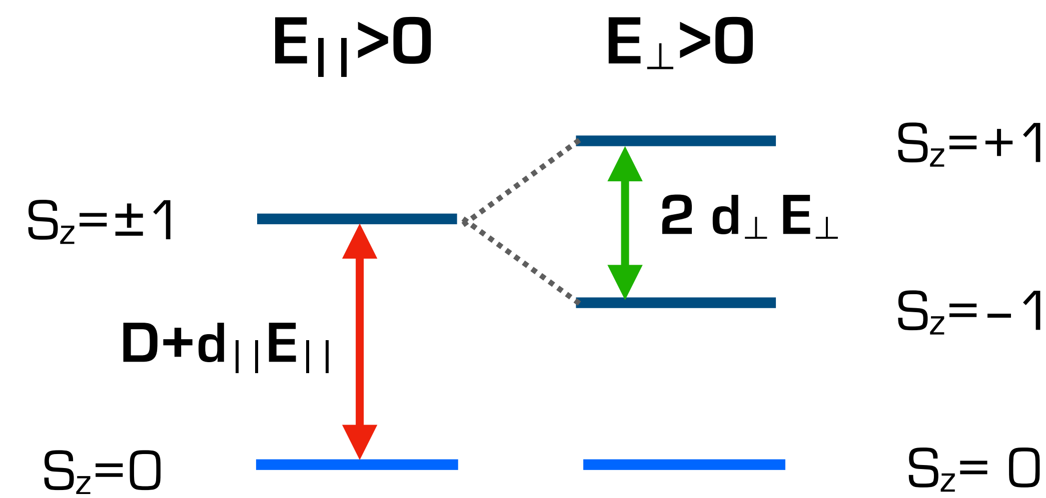


The NV$^-$ center as a nanoscale magnetometer

Magnetometry



Electrometry

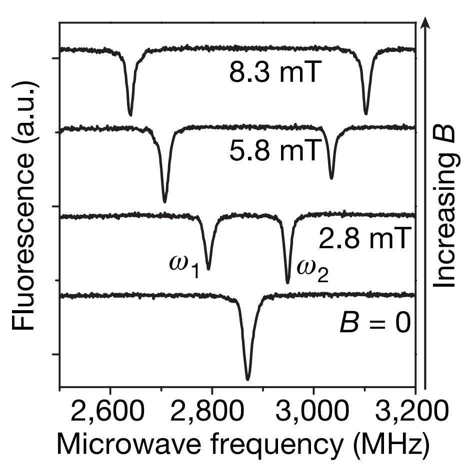


Hp: B≡0

Zeeman Effect

g_e electron g-factor
μ_B Bohr magneton

$$H = H_0 + \mu_B\, g_e\, \mathbf{S}\cdot\mathbf{B} + H_{f2}$$



1.2 10^{-4}eV/T

Stark Effect

$d_\perp$ = 17 Hz V^{-1} cm
$d_{||}$ = 0.35 Hz V^{-1} cm

Both shift and splitting of the resonance frequencies

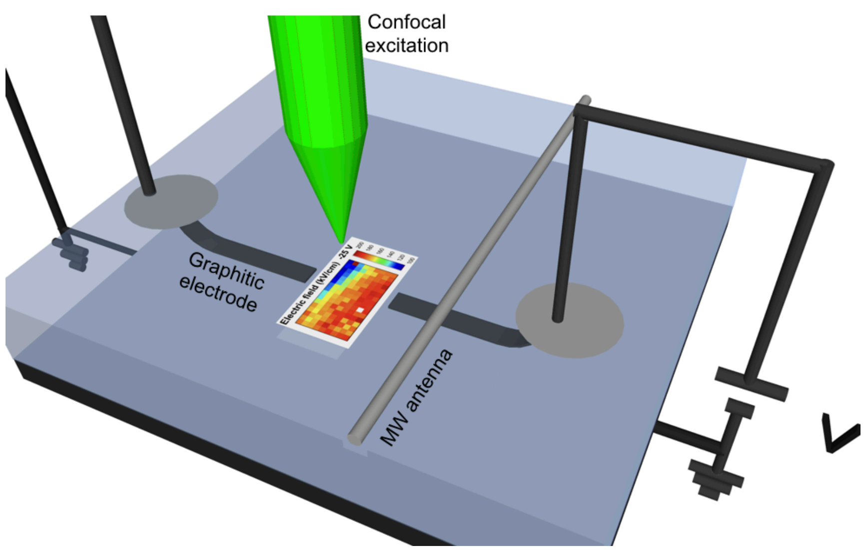
Stress fields (and thus temperature) display the same interaction Hamiltonian as electric field coupling

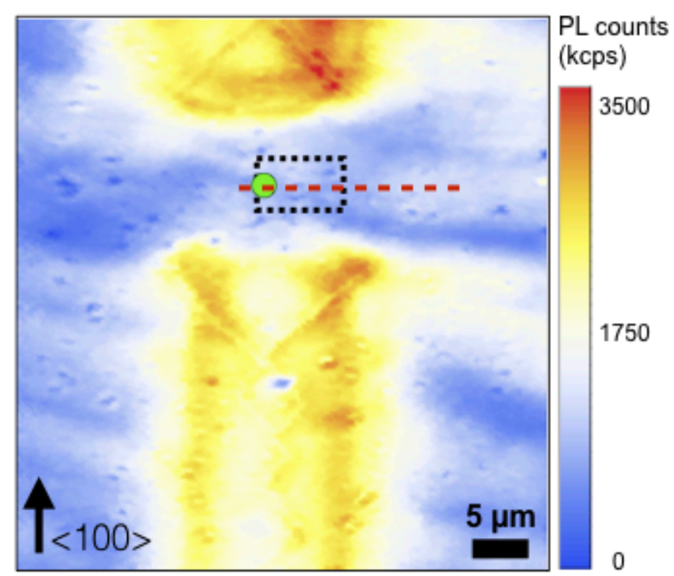
Electric field sensing: device diagnostics

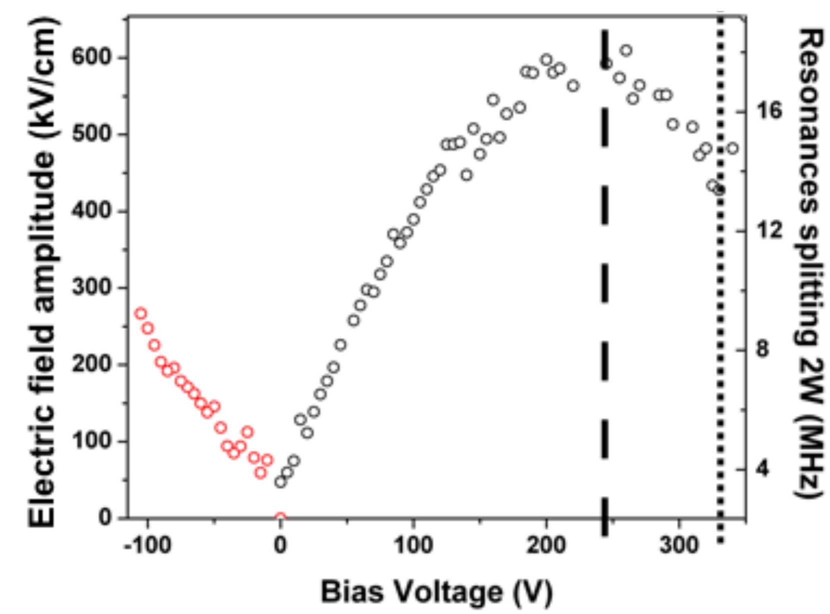
Direct measurement and **mapping** of the internal electric field in diamond devices
Experimental observation of **radiation-damage induced memory effects** diamond

NV ensembles

PL map of graphite-diamond-graphite junction







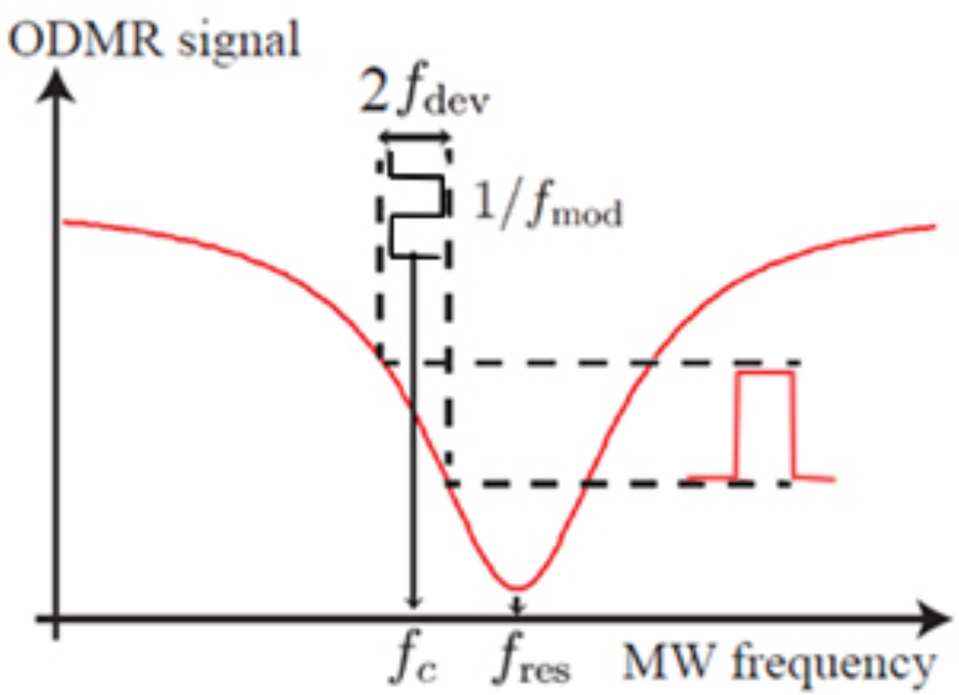
Internal electric field at the junction center
vs applied external bias

PHYSICAL REVIEW APPLIED **10,** 014024 (2018)

Mapping the Local Spatial Charge in Defective Diamond by Means of N-*V* Sensors—A Self-Diagnostic Concept

Advanced temperature sensing

ODMR Resonance



Sensitivity = 5 mK/Hz$^{1/2}$

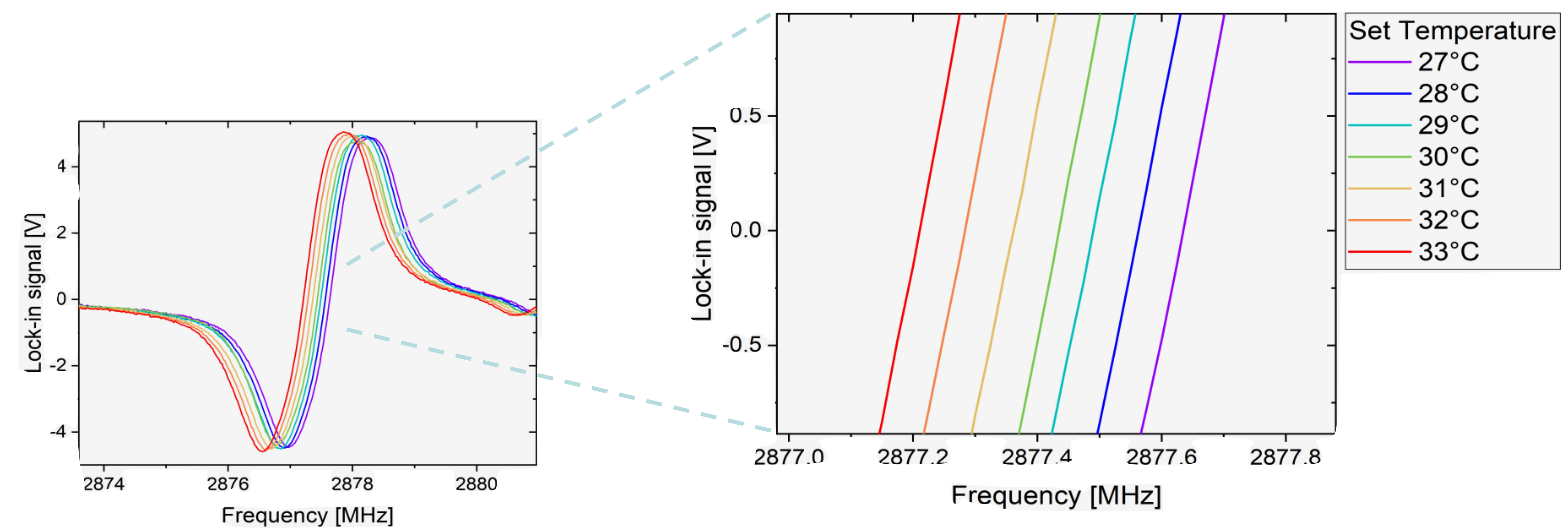
Thermocouple 10^{-9} m^3 volume
NV centers ensemble: **~10^{-20}** sensing volume

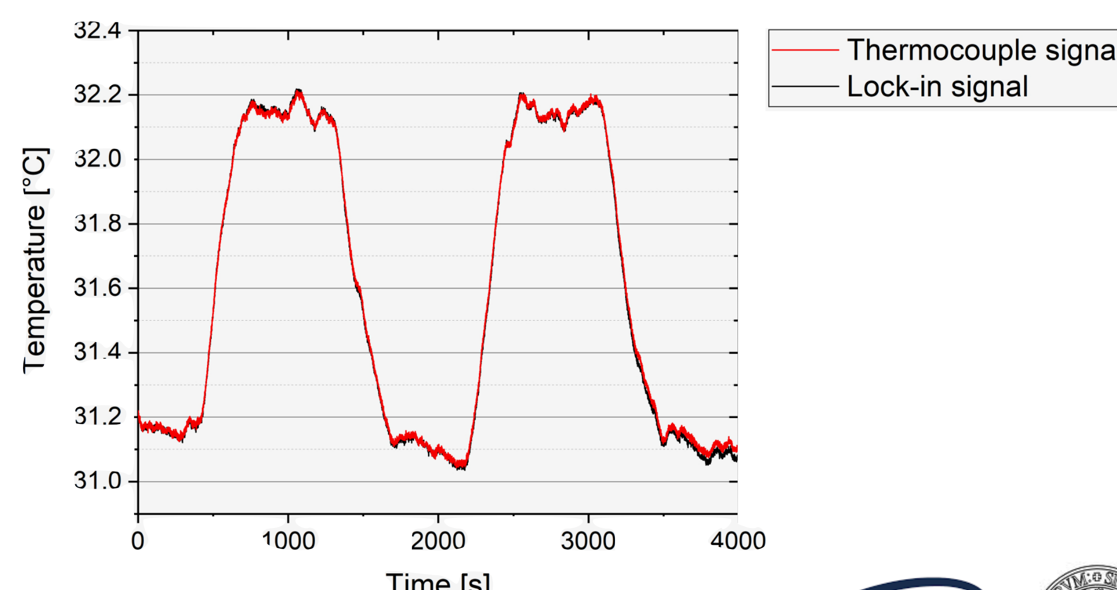
E. Moreva et al., arXiv:1912.10887 (2019)

Lock-in detection

Microwave excitation modulated by a square wave
Photodiode signal detected by a lock-in amplifier
Temperature-induced resonance shift -> lock-in signal variation

Lock-in Spectrum





Summary

Diamond color centers

Promising platform for technologies

- quest for optimal quantum emitters is still open
- need for scalable fabrication tools
- need for experimental techniques to assess defects structure and properties

Unique features for quantum sensing applications

- high sensitivity at the lattice constant spatial scale
  - magnetometry
  - electrometry
  - thermometry

Thank you for your kind attention!

UNIVERSITÀ DEGLI STUDI DI TORINO

INFN
Istituto Nazionale di Fisica Nucleare

P. Aprà
S. Ditalia Tchernij
P. Olivero
F. Picollo
E. Vittone

INRiM
ISTITUTO NAZIONALE DI RICERCA METROLOGICA

I. Degiovanni
M. Genovese
E. Moreva
G. Petrini
P. Traina

INFN LNL
Istituto Nazionale di Fisica Nucleare

V. Rigato
L. Latorre

Ruder Boskovic

M. Jaksic
N. Skukan

UNIVERSITÄT LEIPZIG

T. Herzig
J. Küpper
T. Luehmann
J. Meijer
S. Pezzagna

Università di Roma Tor Vergata

M. Marinelli
E. Milani
G. Prestopino
C. Verona
G. Verona Rinati

UNIVERSITÄT ULM

F. Jelezko
B. Naydenov

EMPIR EURAMET

Research Project "SIQUST"
Single-photon sources as new quantum standards