ADVANCED ION IRRADIATION STRATEGIES FOR THE ENGINEERING OF QUANTUM-LIGHT EMITTERS IN SOLID STATE

INFN sect. Torino

Physics Department University of Torino

Sviatoslav Ditalia Tchernij

Objective

Realization of a protocol for the controlled fabrication of individual defects in solid state

Why
• Fabrication of quantum devices based on individual defects with a scalable process • Overcoming of a significant technological limit (ions straggling, limited creation efficiency, no repruducibility)

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- Fabrication of quantum devices based on individual defects with a scalable process
- Overcoming of a significant technological limit (ions straggling, limited creation efficiency, no repruducibility)

How

- Employment of delta-doped crystals
- High resolution masking
- Ion beam implantation with high currents

Outline

Background

- **Motivation**
- **Nitrogen-Vacancy center in diamond (NV)**
- **Diamond-based Photonics & Quantum optics**

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- Motivation
- Nitrogen-Vacancy center in diamond (NV)
- Diamond-based Photonics & Quantum optics

Proposal

- Methodologies
- Team composition
- Costs

Increasing interest in quantum enabling technologies

- Participation in EU Quantum Flagship (QuantERA) and EMPIR (EuraMet) projects

- Several quantum-oriented funded projects (INFN Call, INFN grants, Experiments)

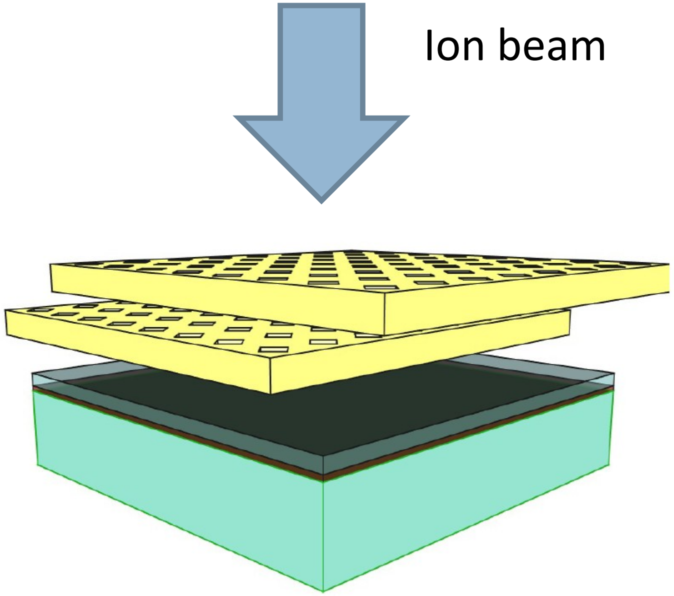
This project:

- Delivery of a method for the controlled fabrication of arrays of defects in solid state platforms

Perspectives:

- Spin based qubits & arrays of single photon sources

- Portability to several solid state platforms



Quantum technologies - Required scales

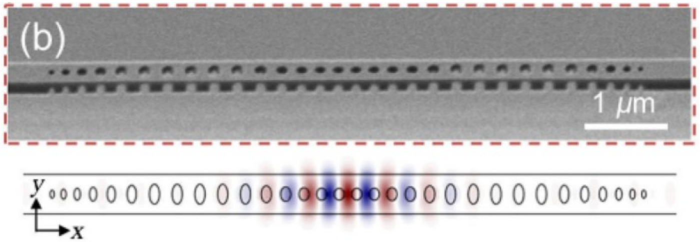
Applications: Metrology, Quantum computing, Quantum communications (cryptography, entanglement, etc.)

Required scales:

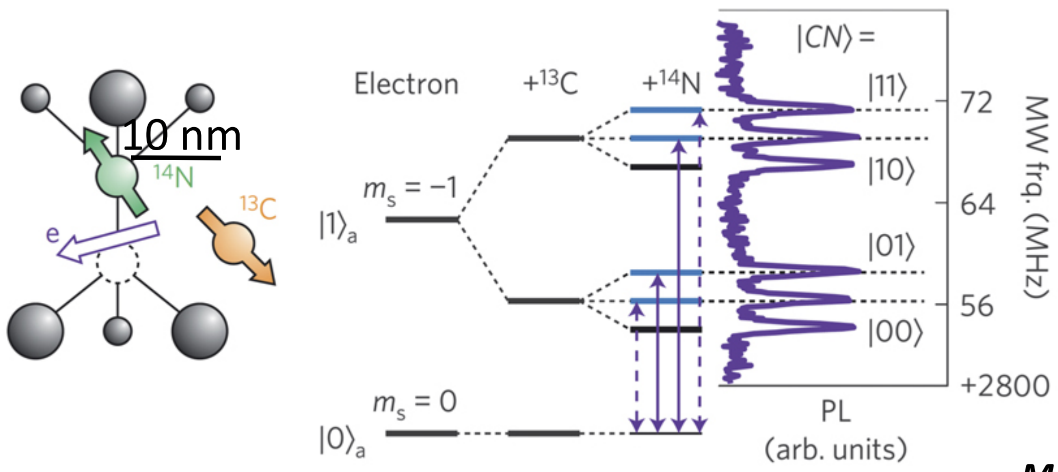
- **diamond photonics: 100s of nm**
- **spin based solid state qubits: 10s of nm**

Diamond nano-photonics

Si-V

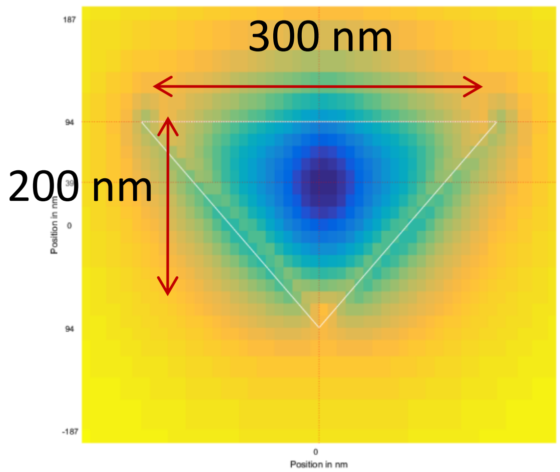


M. J. Burek et al., Phys. Rev. Applied 8, 024026 (2017)



L. Childress et al., MRS Bulletin 38, 134 (2013)

Ge-V



M. K. Bhaskar et al., Phys. Rev. Lett. 118, 223603 (2017)

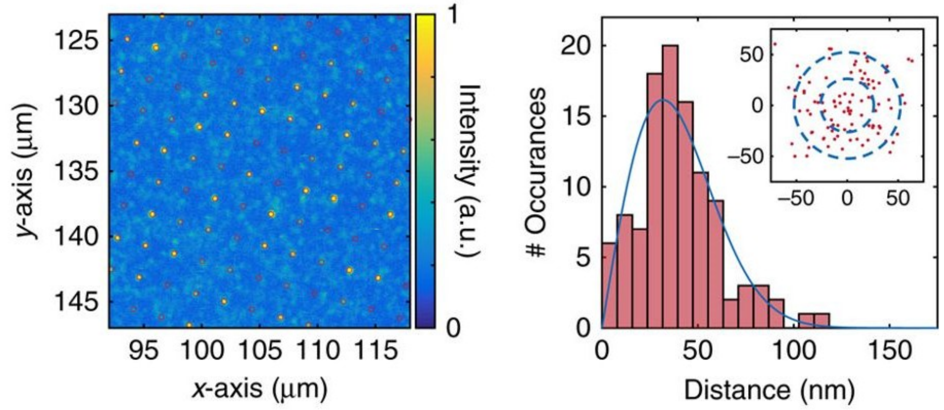
High resolution fabrication

Fabrication: **low energy ion implantation**

Limits:
- **low creation efficiency**
- **Statistical process**
- **Ion detection strictly required**

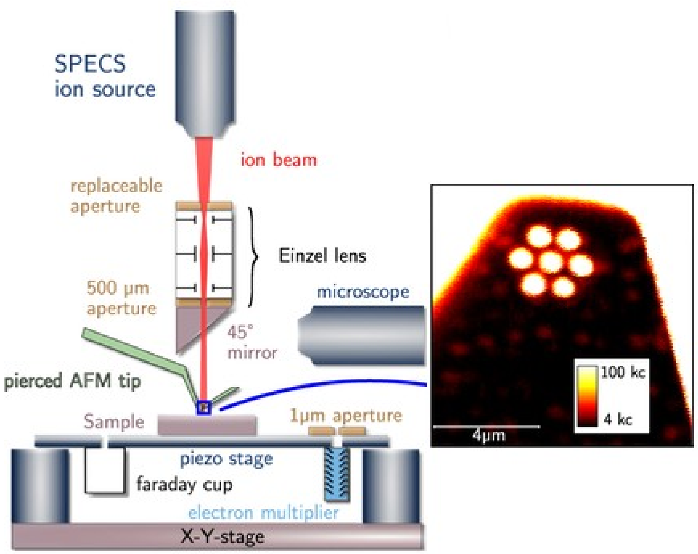
➡ **single ion implantation**

Focused beam (FIB) implantation (~ keV)

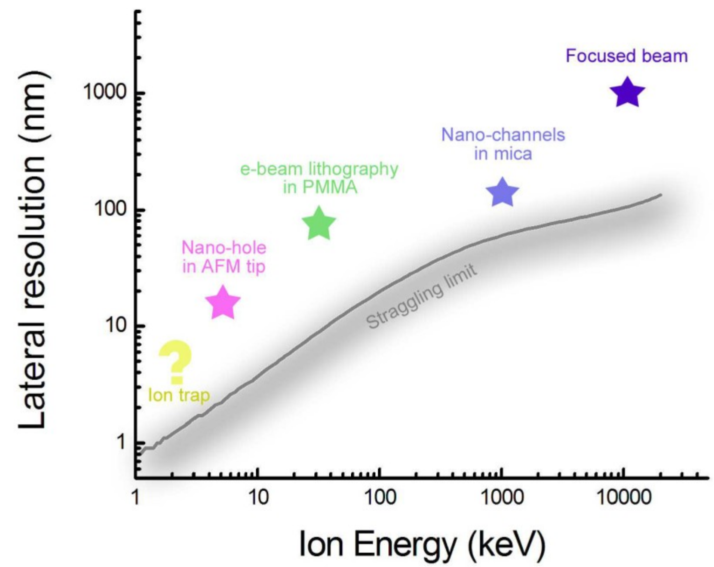


T. Schröder et al., Nature Communications 8,15376 (2017)

AFM tip implantation (~ eV)

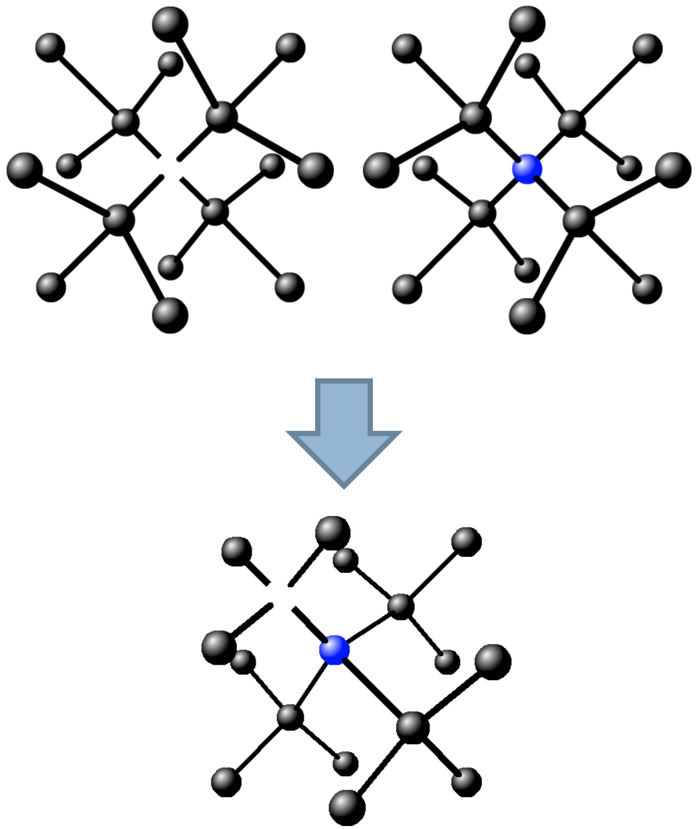


N. Raatz et al., PSSA 216, 21 (2019)

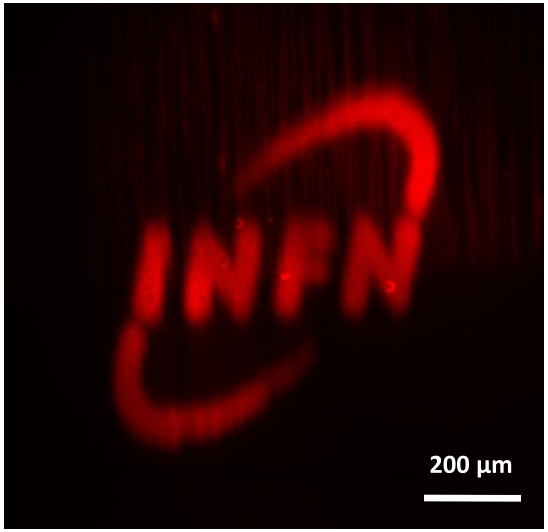


S. Pezzagna and J. Meijer, IntechOpen (2012)

Creation of NV centers via ion implantation & annealing

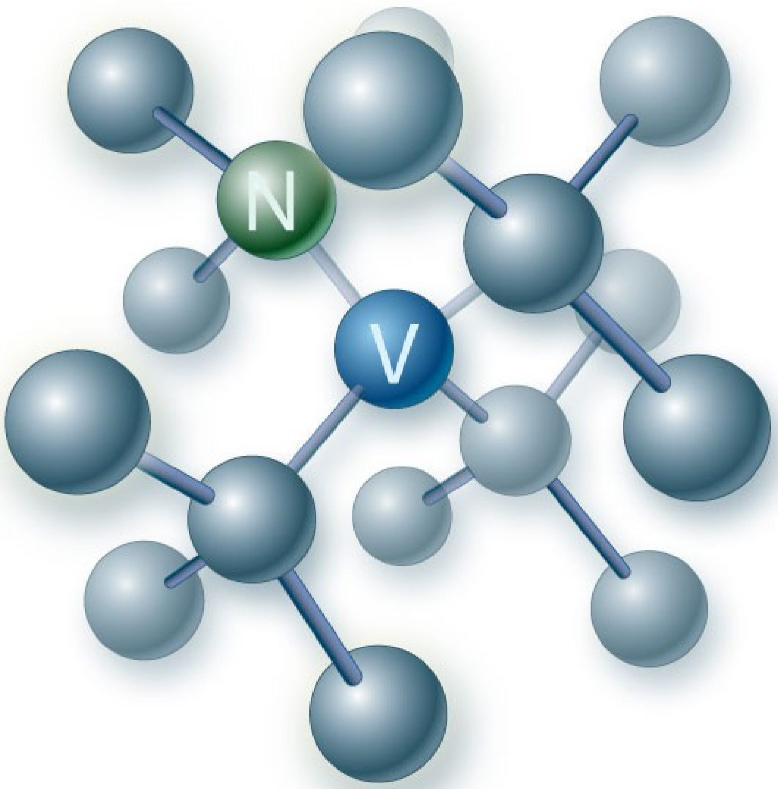


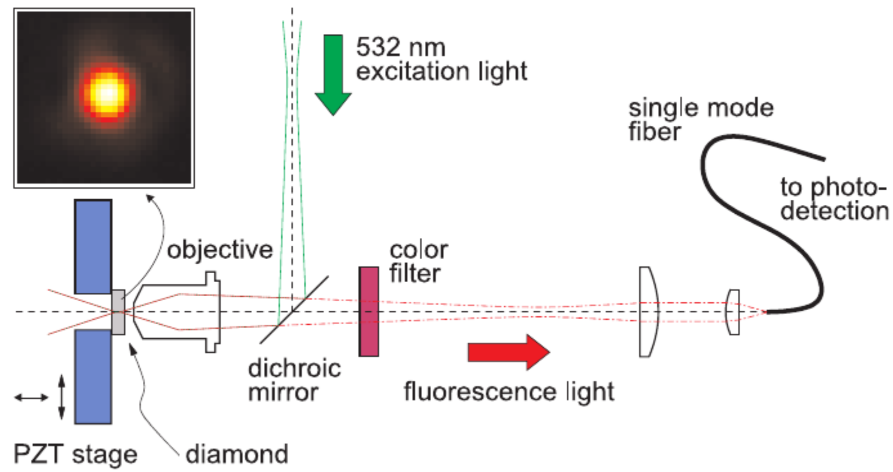
Photoluminescence image

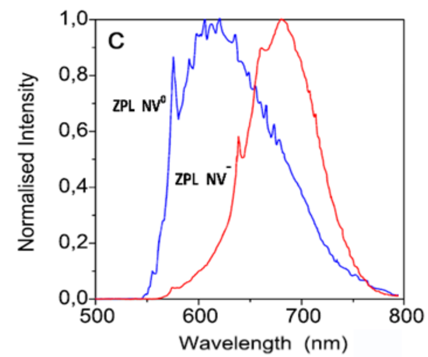


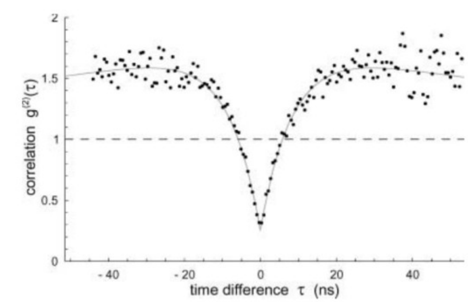
Ion implantation @ LNL INFN

The negatively-charged nitrogen-vacancy (NV^-) center









C. Braig et al., Appl. Phys. B 76, 113 (2003)

single-photon emission → **quantum cryptography, entanglement**

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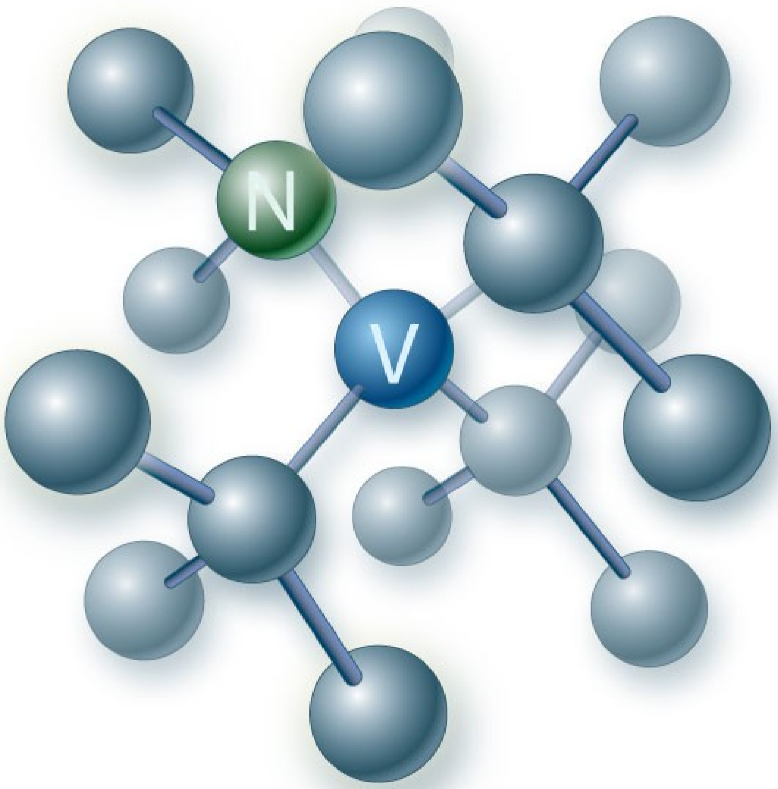

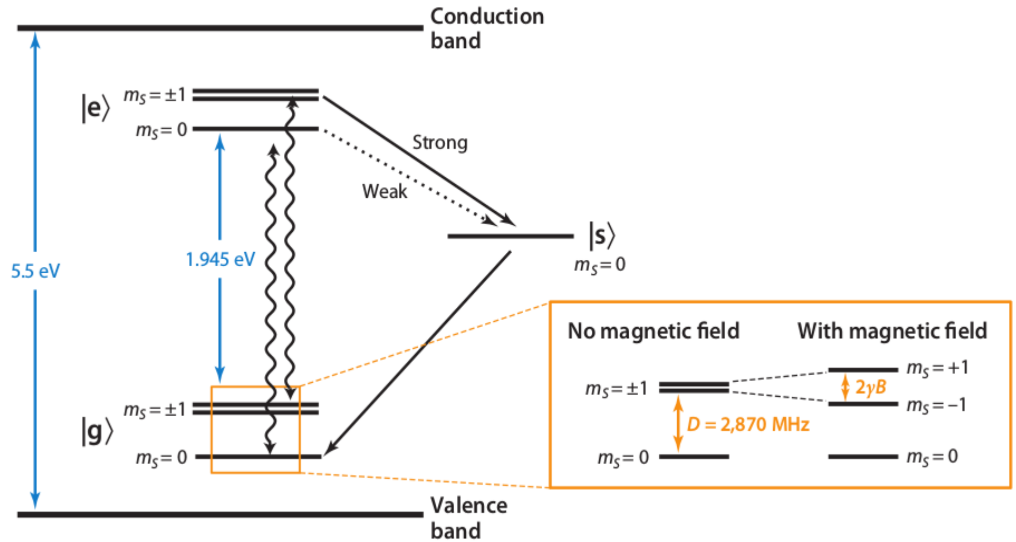

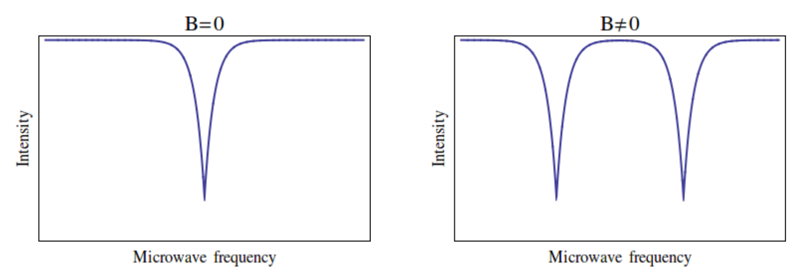

single-photon emission → **quantum cryptography, entanglement**

single-spin selective transitions → **optically detected magnetic resonance (ODMR)**

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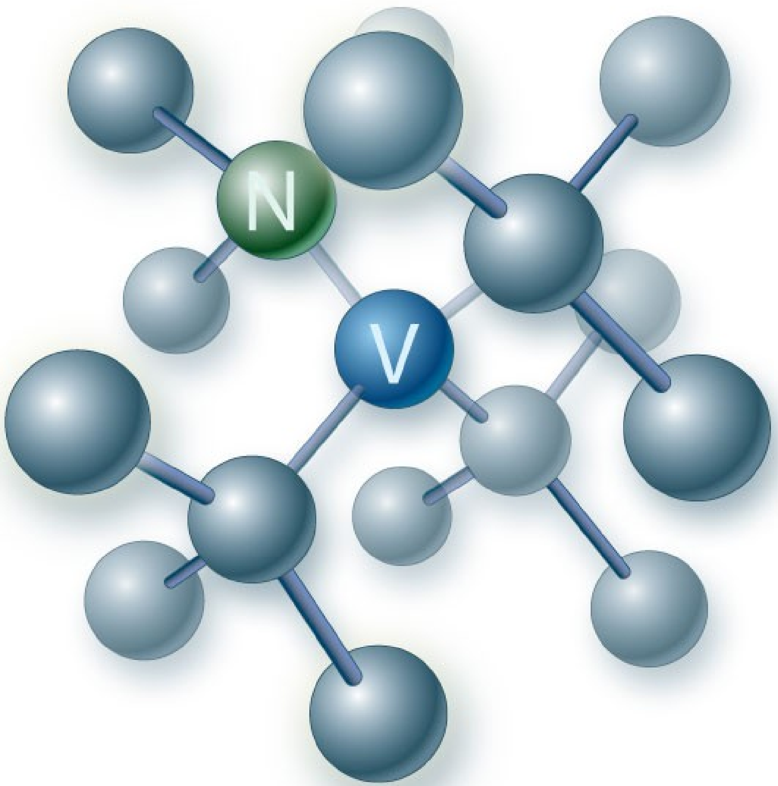
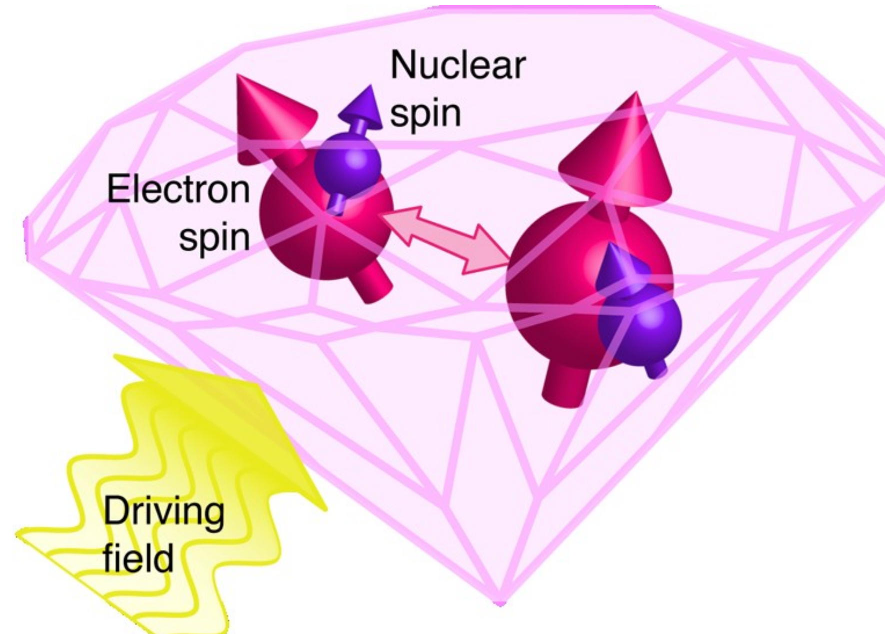




single-photon emission → **quantum cryptography, entanglement**

single-spin selective transitions → **optically detected magnetic resonance (ODMR)**

quantum information processing

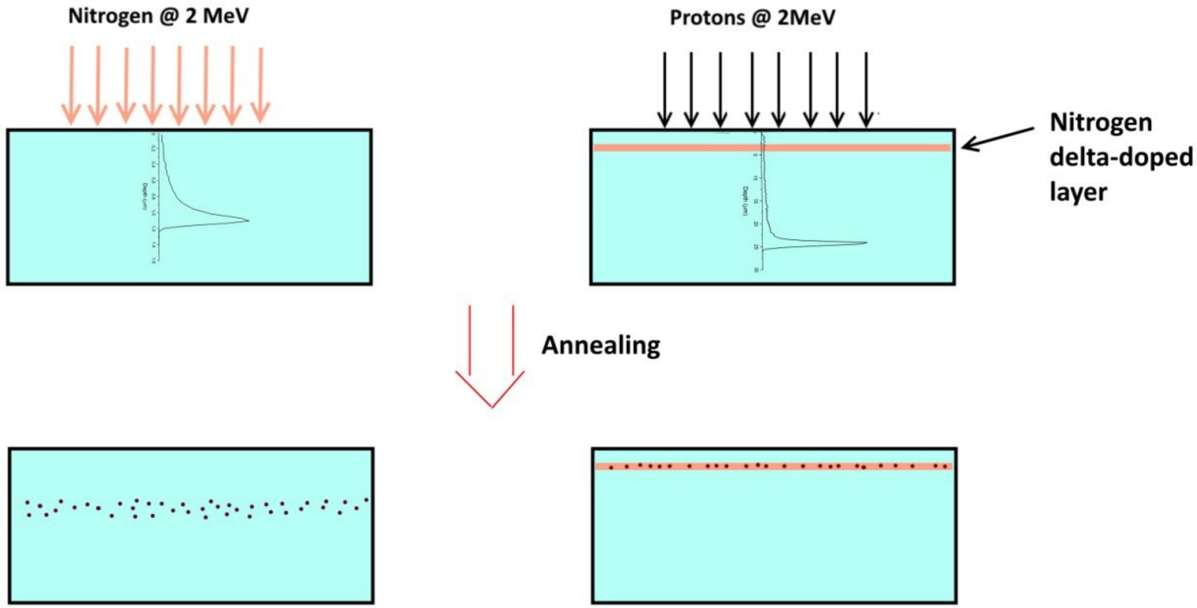
Irradiation scheme – state of the art comparison

Testbed: **Nitrogen-vacancy** centers in diamond

State of the art:
Low energy (eV - keV)
N ions implantation

Proposed technique:
High energy (**MeV**)
protons implantation on
delta-doped samples

⇒ **high in-depth placement resolution**



State of the art

- ions straggling
- low creation efficiency
- ion detection required

Current proposal

- use of MeV ions on superficial layers
- vacancies diffusion study and control
- high implantation fluence

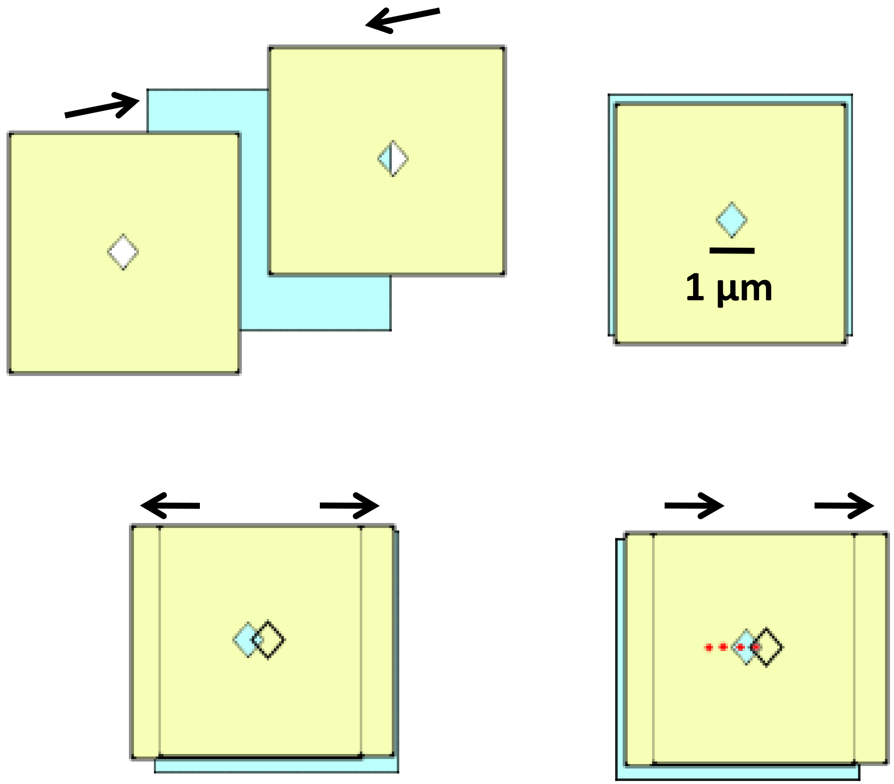
Irradiation scheme – procedure

Proposed scheme

Collimation control:
⇨ implantation masks

nanometric control required

1. **apertures alignment**
   - optical
2. **spot dimension selection**
   - optical
   - STIM (Scanning transmission ion microscopy)
   - PMMA irradiation tests
3. **array fabrication**
   - implantation masks traslation



Expected resolution

Lateral resolution:

- employment of 2 MeV protons
- low depth ⇒ max resolution
- limited only by the masks apertures

In-depth resolution:

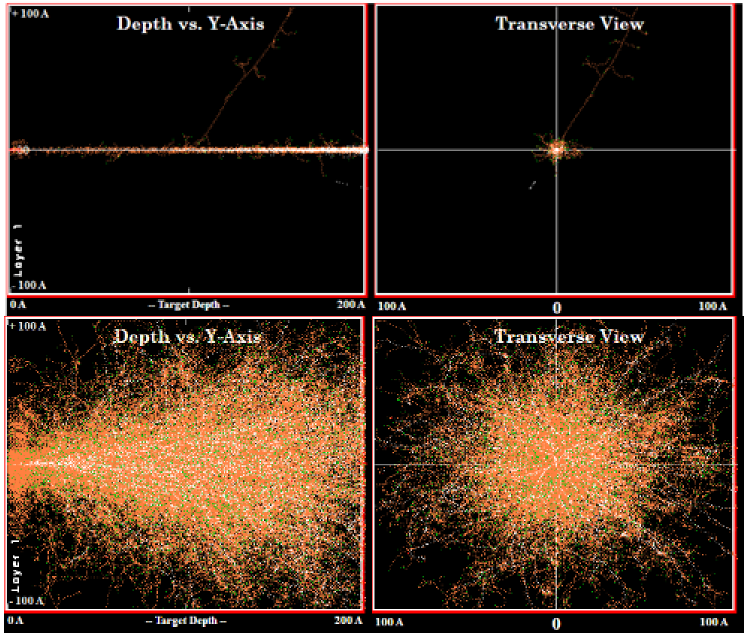
- provided by the delta doping
- damage out of plane not relevant
- vacancies diffusion

Fluence: 10^{13} ions · cm^{-2}

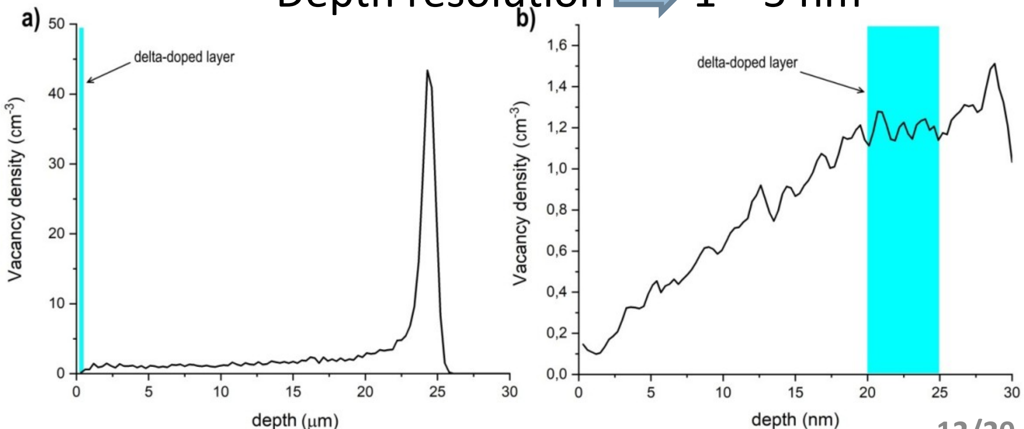
Ion beam lateral resolution ⇒ 1 – 2 nm

2 MeV protons

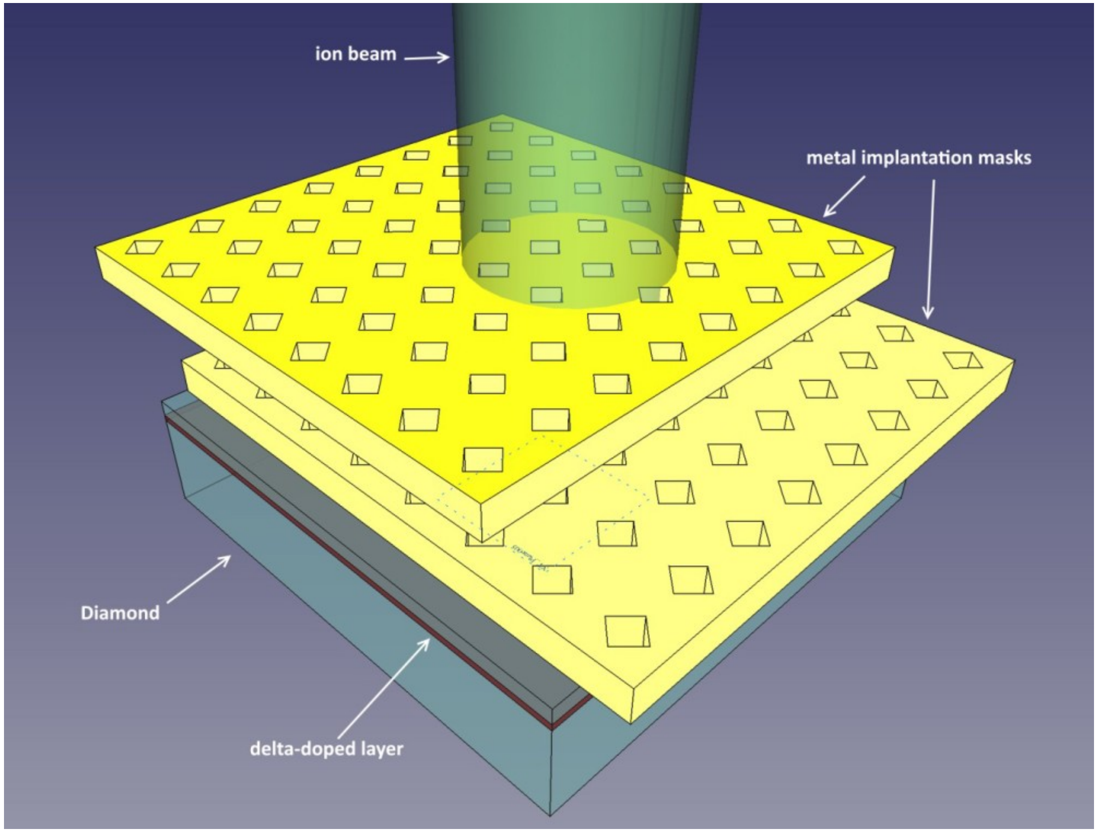
10 keV Nitrogen



Depth resolution ⇒ 1 – 5 nm



Irradiation masks



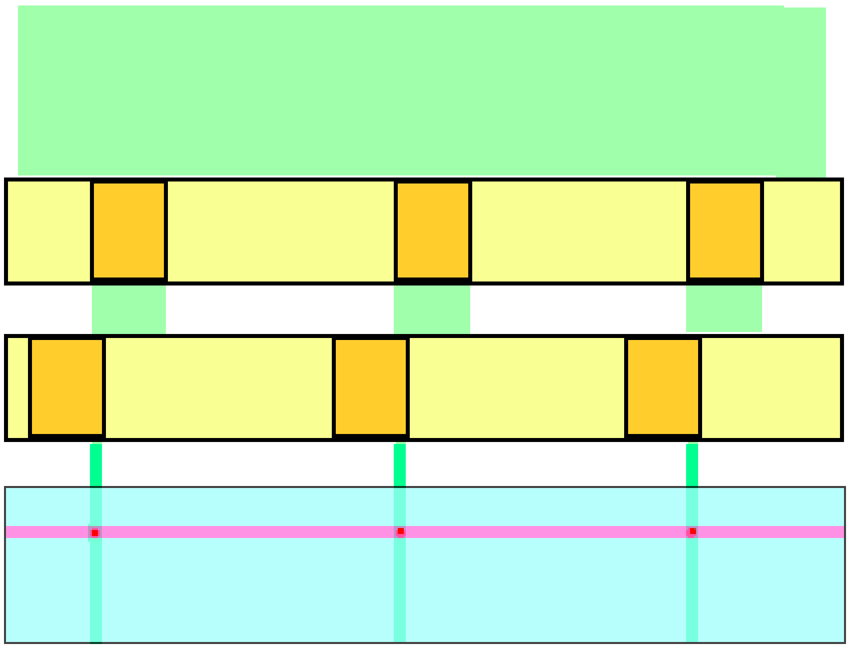
Lateral defects placement resolution provided by implantation masks:

- nanometric position control
- concurrent fabrication of several defects arrays
- Statistical approach: high level control on the process

⇒ **no single ion implantation/detection techniques**

⇒ **potential scalability**

Irradiation masks



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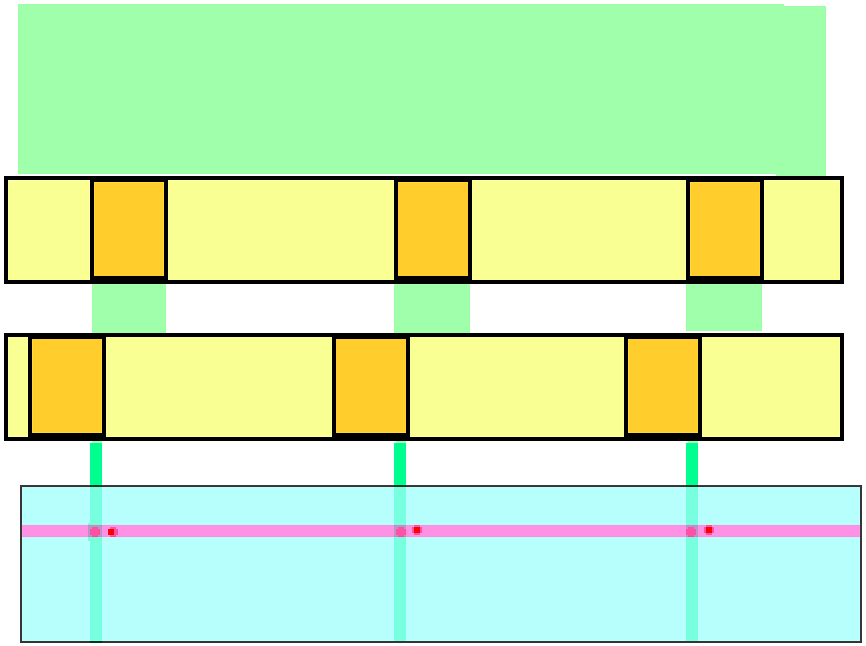

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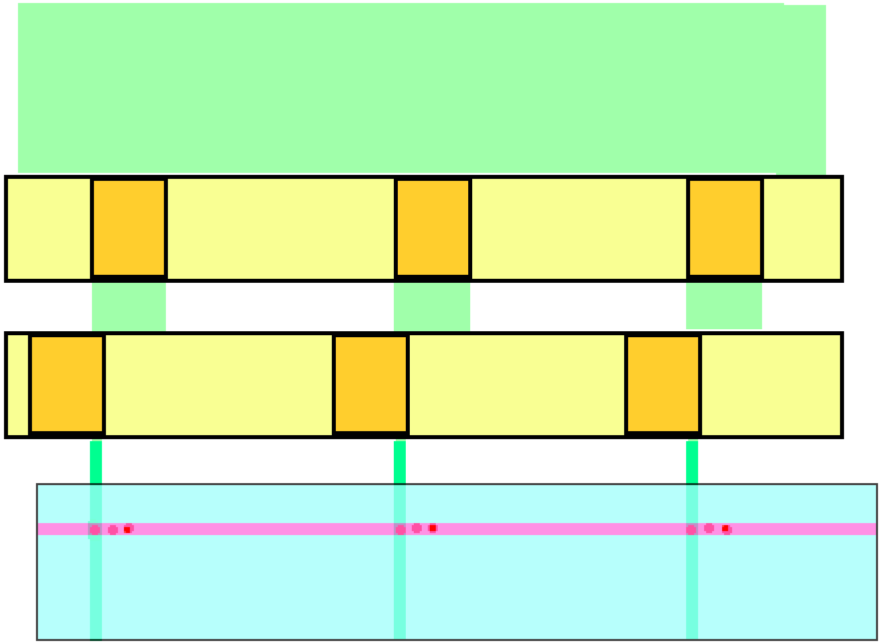

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Research group

Team A – INFN Sec. TO @ UniTo Physics Department, local coordinator: Sviatoslav Ditalia Tchernij
Composition**: 1 Post-doctoral fellow (PI), 3 PhDs, 3 researchers**

Tasks: Experiment design, ion implantation, photoluminescence characterization

Team B – INFN Sec. TO @ INRiM, local coordinator: Marco Genovese
Composition: **1 PhD, 3 researchers**

Tasks: photoluminescence characterizazion, magnetic resonance assessment of the fabricated defects (optically detected magnetic resonance)

Both Team A and Team B have a strong background on their tasks

Long standing scientific collaboration

Principal investigator - Background

3 years from PhD – 24 ISI papers on diamond non classical photon sources and ion beam technologies

Highlights

• “Single-Photon Emitters in Lead-Implanted Single-Crystal Diamond”, S. Ditalia Tchernij et al., **ACS Photonics 5(12), pp. 4864-4871 (2018) Paper selected for Journal cover**

• "Single-Photon-Emitting Optical Centers in Diamond Fabricated upon Sn Implantation", S. Ditalia Tchernij et al., **ACS Photonics, 4(10), 2580-2586 (2017)**

Invinted talks:

• “Ion-beam fabricated optically active color centers in diamond for quantum optics and quantum-enhanced sensing”, S. Ditalia Tchernij, **CAARI2018**, Grapevine, Texas, August 2018

• “Single photon sources based on diamond color centers”, S. Ditalia Tchernij, **ICQOQI 2019**, XVI International Conference on Quantum Optics and Quantum Information, Minsk, Belarus, May 2019

Awards:

National Prize "**Francesco Resmini**" 2019 awarded by the National Institute of Nuclear Physics (INFN) for the best PhD Thesis on particle accelerators physics and new technologies to: “Use of energetic ion beams for the engineering and control of quantum-optical emitters and sensors in artificial diamond”.

INFN Projects synergies

Know-how

• "DINAMO" INFN CSN5 young researchers Grant:
Diamond Masking for ion beam lithography techniques
Coordinator: F. Picollo

• "DiESiS" INFN CSN5 young researchers Grant:
Diamond color centers fabrication by means of ion beam implantation and photoluminescence characterization
Coordinator: J. Forneris

Potential synergies:

- SIQUST, EU-funded project involving INFN-TO: (non-deterministic) fabrication of color centers in diamond and related optical characterization
- SEQUME, EU-funded project involving INFN-TO: estimation of non-classicality parameters for solid-state-based single-photon sources
- PICS4ME INFN-funded project involving INFN-TO: advanced imaging techniques for photon emitters
- QUANTEP INFN-funded project involving INFN-TO: single photon sources integrated in silicon

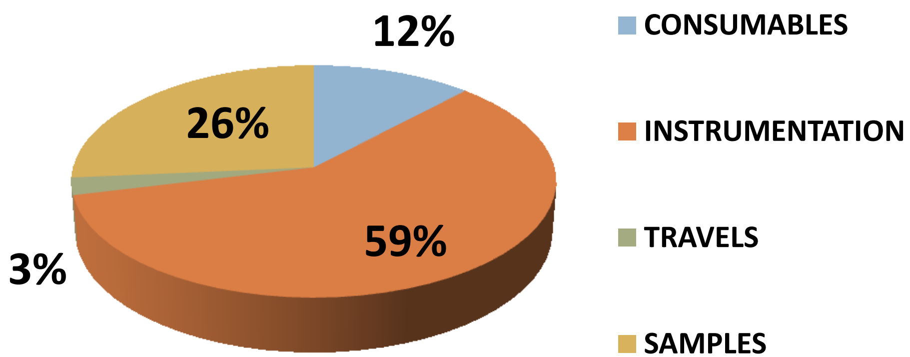
Time table

Task	Description	Team	Timetable							
			M3	**M6**	**M9**	**M12**	**M15**	**M18**	**M21**	**M24**
0	**Project coordination**	A	■	■	■	■	■	■	■	■
1.1	**Samples acquisition**	A	■	■						
1.2	**Masks caquisition**	A	■	■			■	■		
1.3	**Irradiation stage design and realization**	A		■	■					
2.1	**Ion irradiation (@AN 2000)**	A		■	■			■	■	
2.2	**Thermal annealing**	A			■				■	
3.1	**PL Characterization**	A,B			■	■	■		■	■
3.2	**ODMR measurements**	B					■	■		■
4	**Dissemination**	A,B				■	■	■	■	■

Planned costs

- 1° year:
  - Acquisition of samples and piezo positioners
  - Masks acquisition and design (2 different types will be adopted)
  - realization of the irradiation stage

- 2° year:
  - Acquisition of a dedicated imaging setup
  - Design of a wide-field photoluminescence setup



Detail	Year of acquisition	Cost
Samples	1 – 2	33 k€
Masks	1	2 k€
Piezo-positioners	1	25 k€
EmCCD camera	2	37 k€
Spectrograph	2	12 k€
Optical components	2	5 k€
Travels	1 – 2	3 k€
Consumables	1 – 2	8 k€
Total		125 k€

Access to facilities

- INFN LNL national laboratories. Participation in DiaFab experiment since 2016, **DiaFab coordinator since 2021**
    1. Ion implantation @ MeV energies

- Ruder Boskovic Institute (RBI). "Radiate" transational access to irradiation facilities, **coordinator of 2 experiments**
    1. Ion implantation @ MeV energies

- INFN sect. TO. **Scientific association since 2016**
    1. High precision mechanics support
    2. Quantum-optical characterization (DiESiS)

- Physics Department Univerity of Turin. **Employed since 2015**
    1. Ion implantation @ keV energies
    2. Laser lithography

- Nanofacility Piemonte & INRiM. Scientific collaboration since 2016, **scientific association since 2019**
    1. Focused ion beam lithography
    2. Quantum-optical characterization
    3. Magnetic resonance measurements (ODMR)

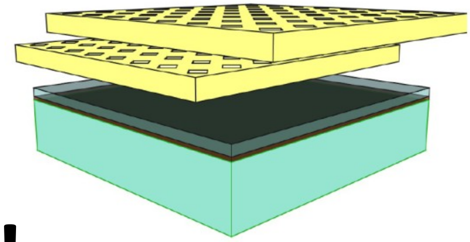
Challenges and output

Challenges

- **Fluence optimization** ⇨ determined experimentally
- **Thermal annealing process** ⇨ control over the vacancies diffusion range (single defects fabrication)
- **Potential scattering of the ions on mask apertures edges** ⇨ statistical approach relying on many ions, implantation halo should not represent a problem

Results

- Results assessment by means of optical characterization (luminescent defects)
- Project output ⇨ **development of a protocol for the fabrication of arrays / matrixes of defects in solid state** ⇨ **qubits / single photon sources**
- **Scalability to other solid state platforms**



Thank you for your attention!

INFN sect. Torino

Physics Department University of Torino

Research group - People

Team A – INFN Sec. TO @ UniTo Physics Department, local coordinator: Sviatoslav Ditalia Tchernij

Name	Age	Position	Involvement %
Sviatoslav DitaliaTchernij	32	Post-doctoral fellow	100
Emilio Corte	27	PhD	70
Greta Andrini	25	PhD	60
Elena Nieto Hernández	24	PhD	60
Jacopo Forneris	36	Associate Professor	30
Federico Picollo	37	Researcher	20
Paolo Olivero	44	Associate Professor	20

Team B – INFN Sec. TO @ INRiM, local coordinator: Marco Genovese

Name	Age	Position	Involvement %
Giulia Petrini	26	PhD	50
Ekaterina Moreva	40	Researcher	30
Ettore Bernardi	43	Researcher	30
Marco Genovese	54	Researcher	15

Vacancy density – Fluence optimization

Fluence: 10^{13} ions · cm^{-2}

Beam spot: 3x3 mm^2 = 0,09 cm^2

n° ions = F x A = 9 ·10^{11}

charge state = 1

Q = 9 ·10^{11} · 1,6 · 10^{-19} = 1,4 · 10^{-7}

I = 50 nA – 100 nA (typical values)

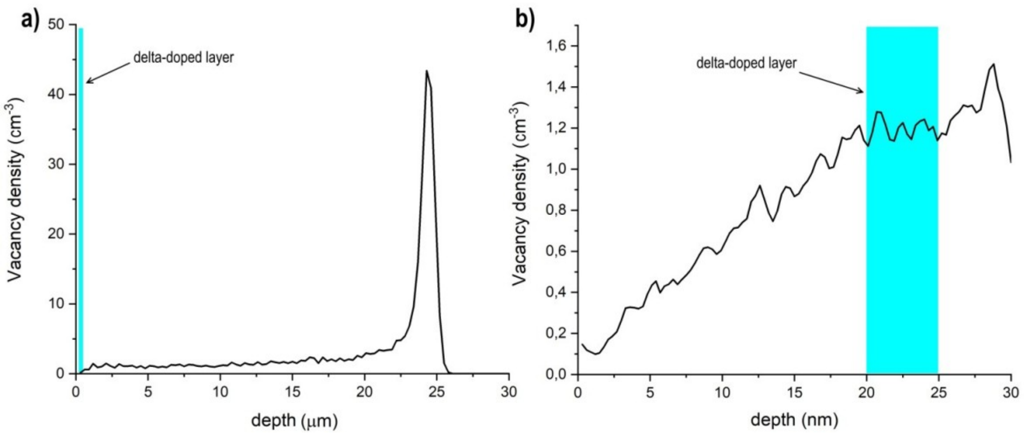
t = Q/I = 2,8 s – 5,6 s ⇨ very low fluence density

If Fleunce = 10^{16} ions · cm^{-2} ⇨

A = 0,09 cm^2
Q = 9 ·10^{11} · 1,6 · 10^{-19} = 1,4 · 10^{-7}
I = 500 nA
t = 2800 s < 1 h

3 orders of magnitude more vacancies

⇨ Irradiation times in a feasible range with typical operation currents



Vacancy density – diffusion

$$D = D_0 \exp\left(\frac{-E_a}{kT}\right)$$ vacancies diffusivity

$$D_0 = 3{,}6 \times 10^{-6}\ cm^2 s^{-1}$$ superficial vacancies diffusivity

$$E_a = 1{,}7 - 4\ eV$$ activation energy for bulk vacancies

$\Rightarrow$ $D = 1{,}82 \times 10^{-13}\ cm^2 s^{-1}$

Considering an annealing temperature of 900 °C and the lowest possible activation energy (from literature)

$$d \approx \sqrt{Dt}$$

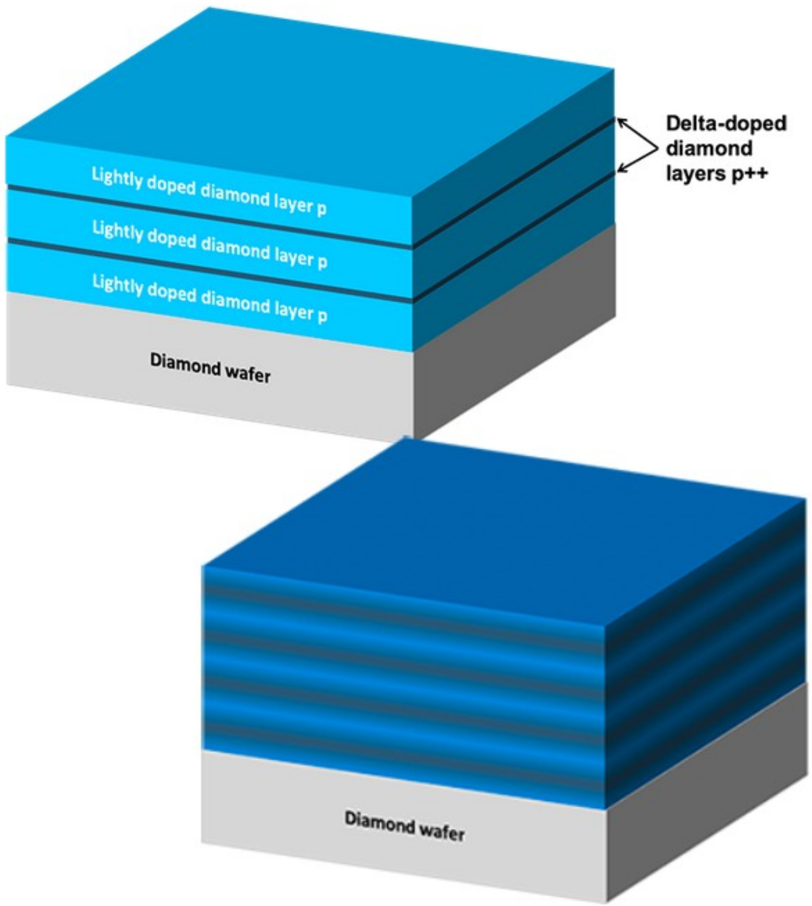
3600 s (1 h) annealing the maximum diffusion distance is ~ 260 nm

300 s annealing result in a maximum diffusion of ~ 75 nm

$\Rightarrow$ Over estimated. Activation energy may be higher

J. O. Orwa et al., Diamond and Related Materials 24, 6-10 (2012)

Samples



Some TAILOR-MADE product examples

Additionally to the standard products, we also provide:

- Nitrogen (N) doped layers
- Boron delta-doped layers (< 2nm)
- "Wavy" profil layers
- etc...

DIAMFAB

- Diamond doped layers design according to customer needs

- Layer characteristics for this proposal: Layer 1: 20 nm, [N] = $1\text{x}10^{18}$ cm^{-3} on $4\text{x}4\text{x}0.5$ mm^3 (100) diamond samples

- several doped layer thicknesses will be tested

Unit price:
4500 € + vat

Implantation masks

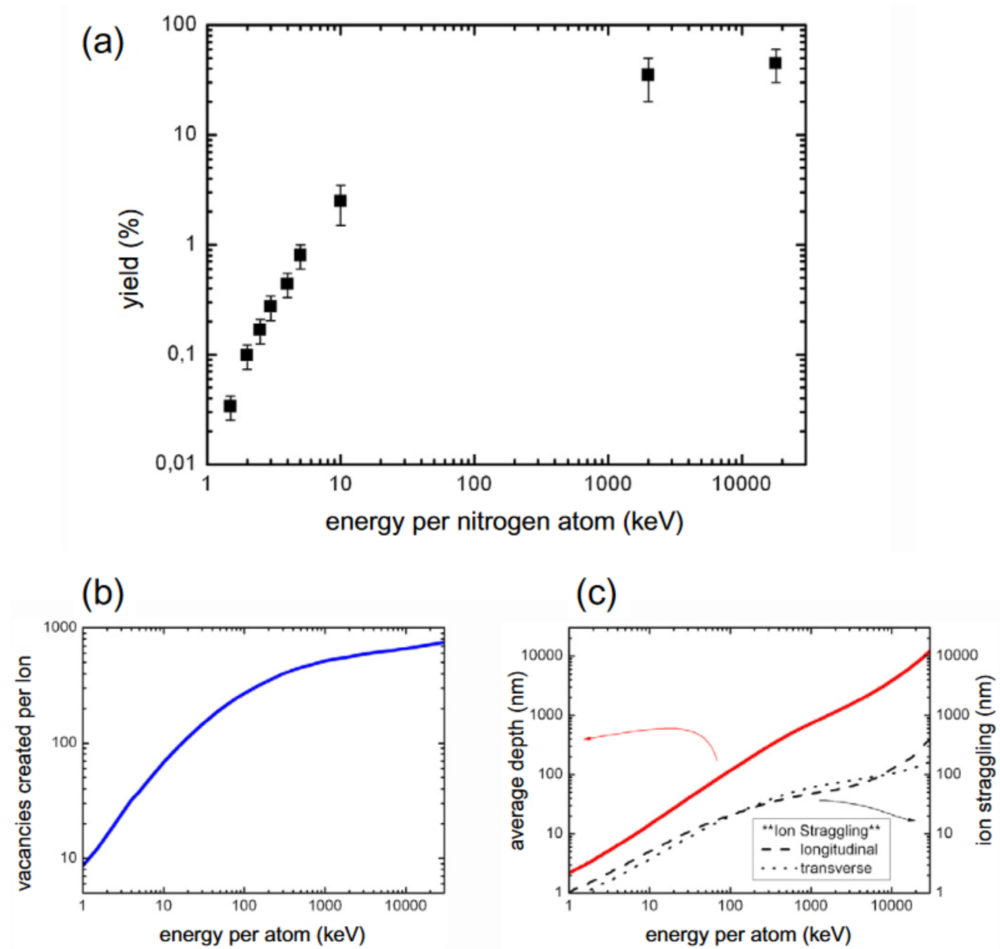
- Brass mask for the best aspect ratio of the holes
- hole diameter minimum: 1 micrometer

KIRANA
a beam of light for micromachining

Soluzioni: microforatura, microtaglio, microincisione, microstrutturazione, marcatura
Capacità: fori di diametro minimo fino a 1 micron, incisioni e tagli di larghezza minima fino a 5 micron.
Materiali: metalli, polimeri, vetro, silicio, ceramiche, compositi

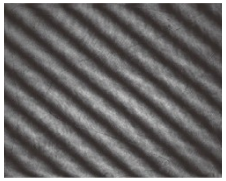
Nitrogen – vacancy creation efficiency

- high yield of 45% at 18 MeV
- < 1% yield at energies below 5 keV

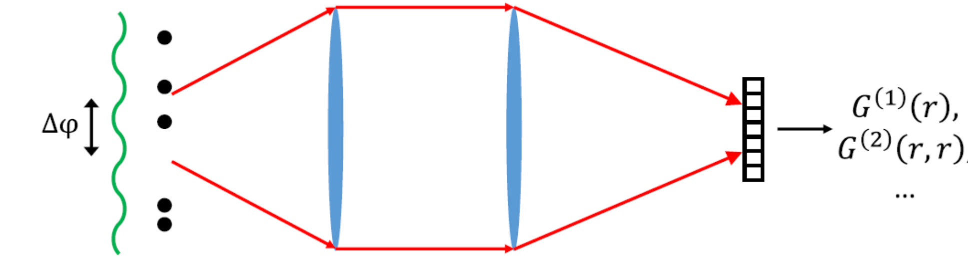


S.Pezzagna et al., New Journal of Physics 12 (2010)

Super resolved imaging



$$I_{\text{str}}(\mathbf{r},t) = I_0\left[\tfrac{1}{2} + \tfrac{1}{2}\cos(\mathbf{k}_0\mathbf{r}+\varphi)\right]$$



Resolution: $1/(K+\sqrt{K}) \times$ Diff. Lim.

Research Article Vol. 4, No. 6 / June 2017 / *Optica* 580

optica

Superresolution via structured illumination quantum correlation microscopy

Anton Classen,[1,2,*] Joachim von Zanthier,[1,2] Marlan O. Scully,[3,4,5] and Girish S. Agarwal[3,6]

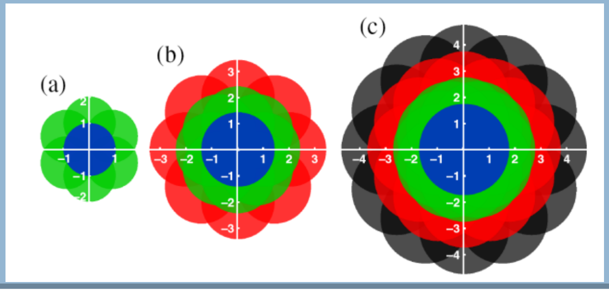
Super resolved imaging

5 phases

$$\varphi = 0, \frac{2\pi}{5}, \frac{4\pi}{5}, \frac{6\pi}{5}, \frac{8\pi}{5}$$

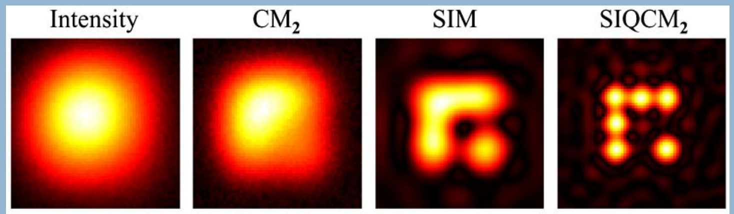
4 orientations

$$\alpha = 0, \frac{1\pi}{4}, \frac{2\pi}{4}, \frac{3\pi}{4}$$



4 phases X 5 orientations = 20 $g^{(2)}$

2D-map



Camera:

- EmCCD
- Single Photon
- Cooling to -100 °C
- EM gain up to 1000x