Diamond-based devices
From detectors to bio-sensors and single-photon emitters

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Cogne, 14 February 2014

Outline

- Diamond
- IBL in diamond
  - → Basic concepts
  - → State of the art
- Current research activities @ UniTo & INFN-To
  - → **Electrical** features
  - → Radiation detection
  - → Biosensing
  - → Quantum Optics
- Conclusions

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- IBL in diamond

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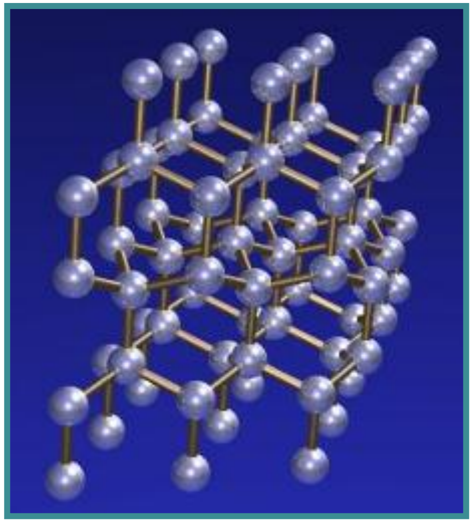
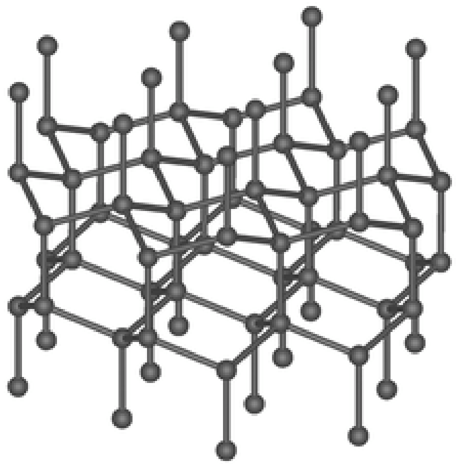
Diamond

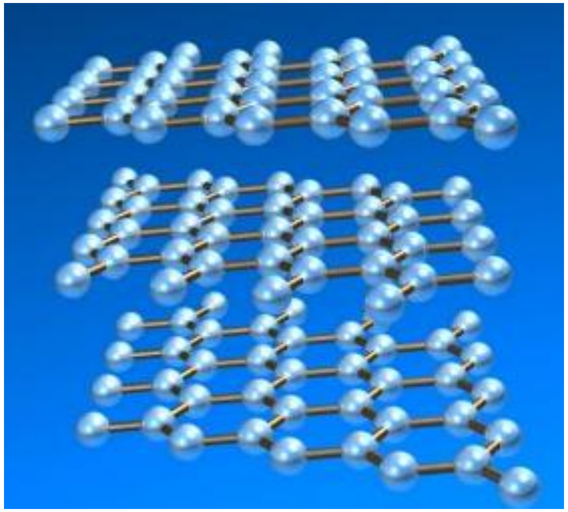
αδάμας (indestructible)



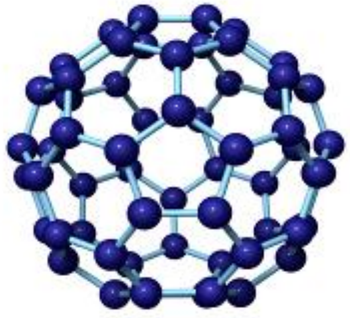
diamond



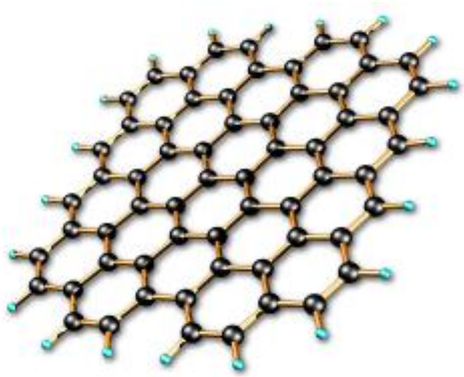
londsaelite



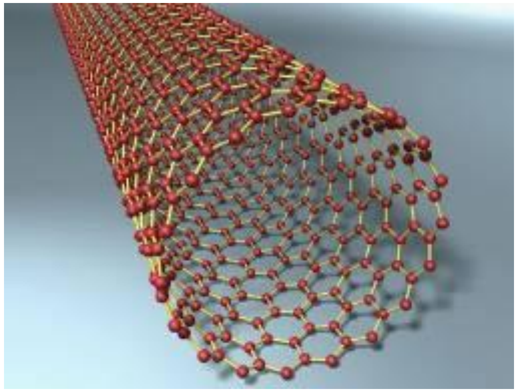
graphite



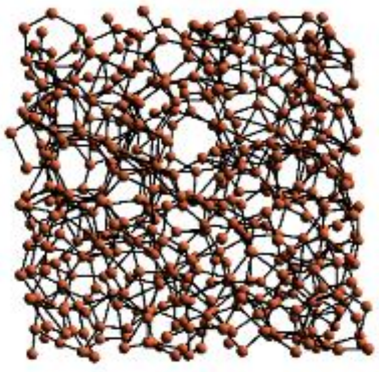
fullerene



graphene



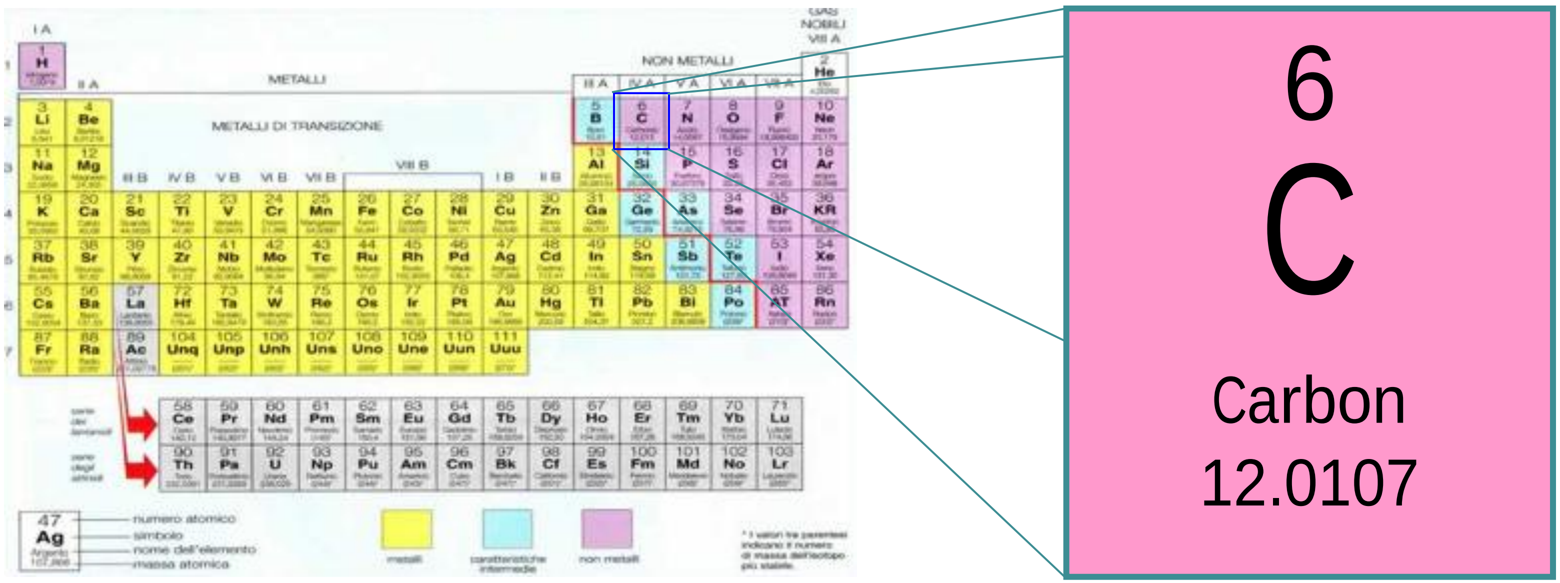
nanotube



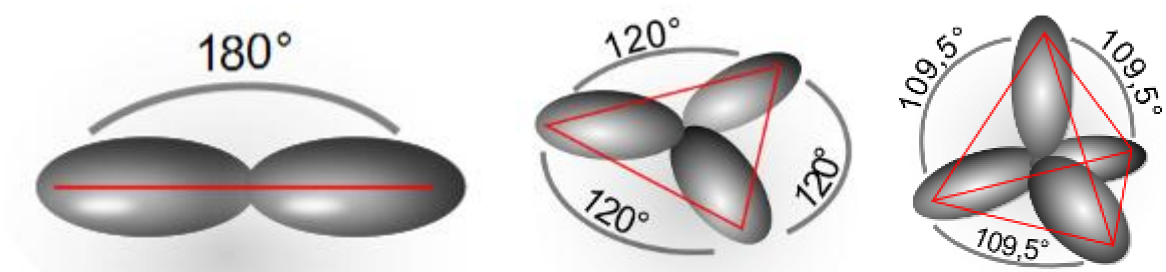
amorphous carbon

Diamond

Carbon



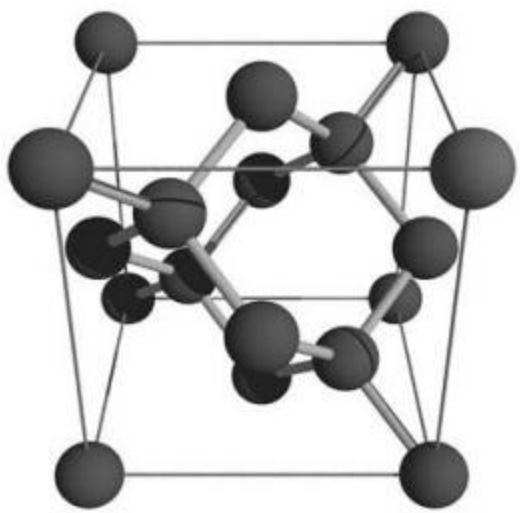
Three types of hybrid orbitals



sp^1 sp^2 sp^3

Diamond

Crystal structure

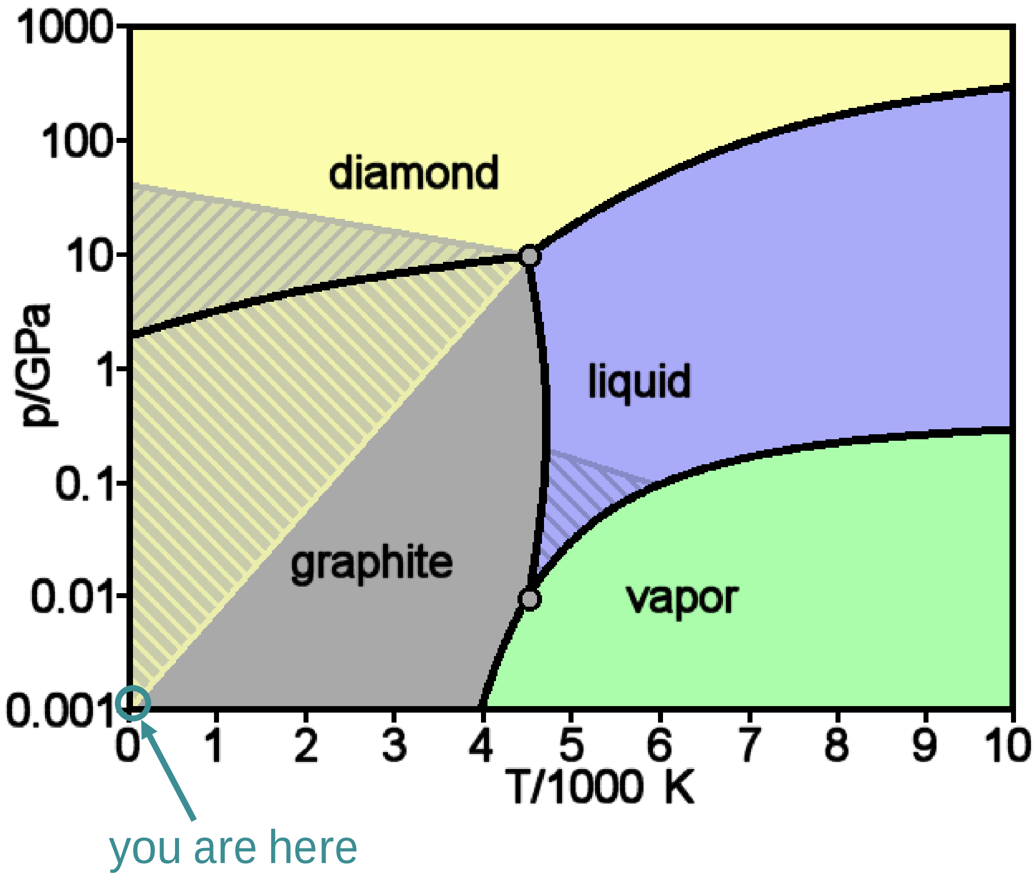


- Lattice: face-centered cubic
- Base: { (0, 0, 0); (¼a, ¼a, ¼a) }
- Crystal: diamond

- Bond length: 1.54 Å
- Cell parameter: 3.57 Å
- Atomic density: 1.77×10^{23} atoms cm^{-3}

Diamond

Phase diagram of Carbon



Room pressure and temperature: diamond is meta-stable

Natural diamond forms at high pressure and temperature

Diamond

Synthesis techniques

High Pressure High Temperature (HPHT)

- growth from a diamond seed
- graphite with catalytic elments (Ni, Fe**, ...)**
- single-crystals: good structural properties, impurities

Diamond

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Chemical Vapor Deposition (CVD)

- low pressure and temperature
- C- and H-containing plasma
- selective etching of non-diamond phases
- homoepitaxial **growth → high purity** single crystals

Diamond

Classification

Structure: single-crystal
polycrystalline
nanocrystalline

Impurities: type I: N in aggregates
- Ia: [N] = 100-1000 ppm
- Ib: [N] = 10-100 ppm

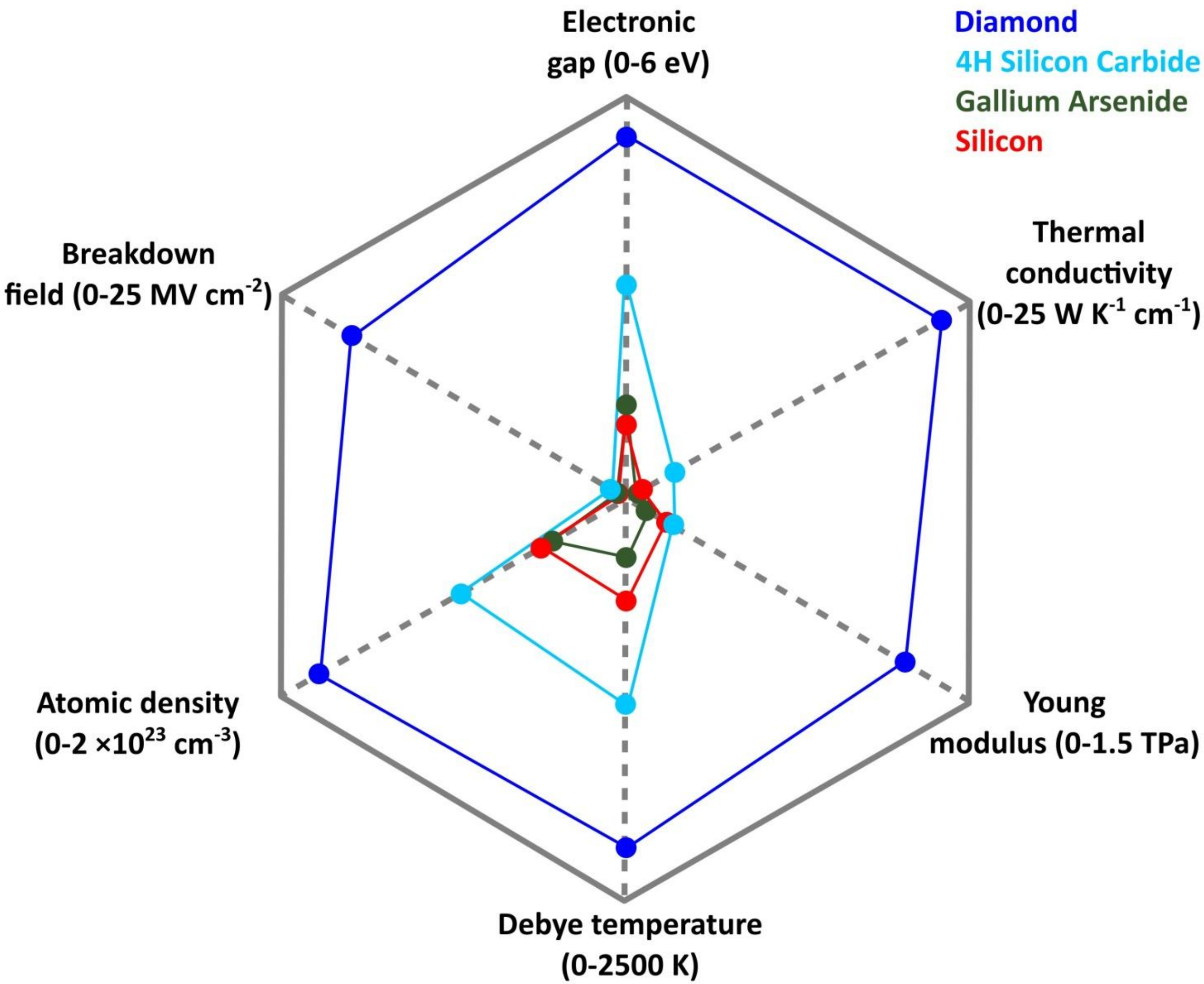
type II: substitutional B
- IIa: [N] < 1 ppm
- IIb: [N] < 1 ppm, B doping

Applications: quantum grade
detector grade
electronic grade
optical grade
thermal/mechanical grade

↑ crystal quality

Diamond

Extreme physical properties



Diamond

Other properties

- high carriers mobility
- high breakdown field
- radiation hardness
- wide band-gap $\rightarrow$ broad transparency, low leakage currents
- chemical inertness
- bio-compatibility
- tissue-equivalence
- surface functionalization $\rightarrow$ negative electron affinity, 2D hole gas
- appealing luminescent centers
- ...

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IBL in diamond

Diamond: a hard material for micro-fabrication:

- Mechanical hardness
- Chemical inertness
- Optical transparency

Ion beam lithography

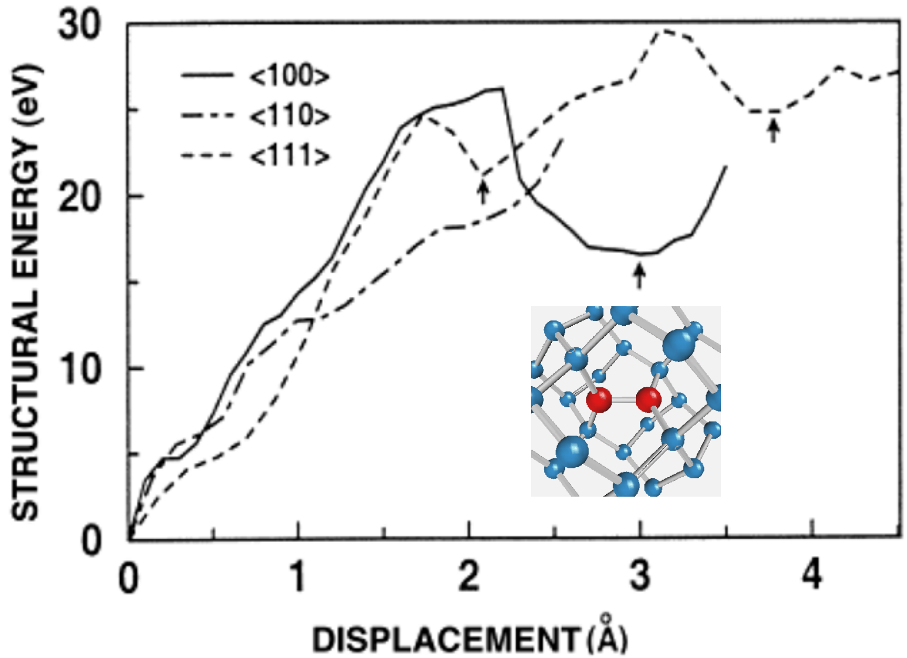
IBL in diamond

Electronic energy loss →

No effects (thermal spikes, coulomb explosions) reported so far

Nuclear energy loss →

Significant structural effects on a meta-stable material



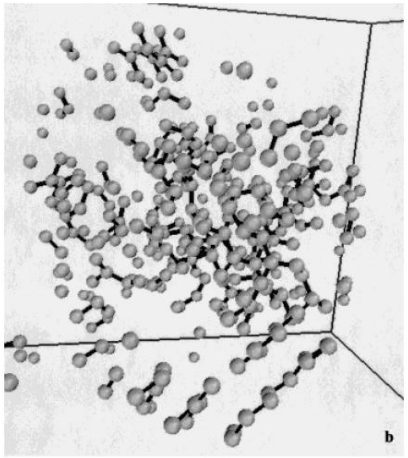
Atom displacement → Formation of an sp^2-bonded split interstitial

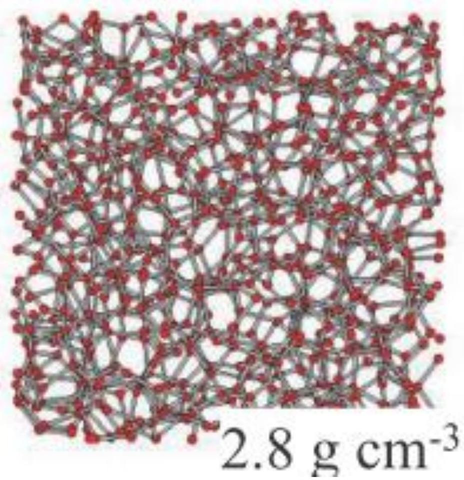
IBL in diamond

A crude linear approximation: $\boldsymbol{\rho}_{vac}$ = (linear damage density $)_{SRIM}$ × (fluence)

[$\#_{vac}$ cm^{-3}] [$\#_{vac}$ $\#_{ion}^{-1}$ cm^{-1}] [$\#_{ion}$ cm^{-2}]

- Non-linear effects (defect-defect interaction, self-**annealing, …) are ignored.**
- At high implantation fluences the defect density is not realistic (over-estimated density of point-defects)
- More advanced approaches: Atomistic simulations





IBL in diamond

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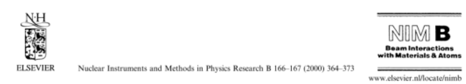
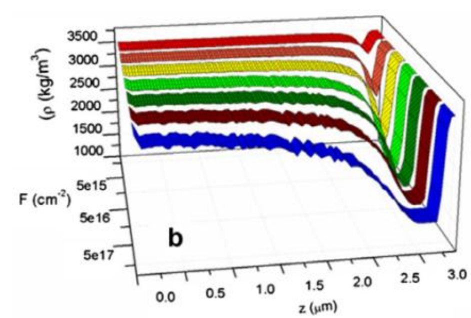
- At high implantation fluences the defect density is not realistic
  (over-estimated density of point-defects)
- More advanced approaches: Semi-analytical / empirical models

Crystal-TRIM (04/1D - last revision May 2004)
developed by Matthias Posselt [1) 2)]


Nuclear Instruments and Methods in Physics Research B 166-167 (2000) 364-373
NIM B Beam Interactions with Materials & Atoms
www.elsevier.nl/locate/nimb

Radiation defects and their annealing behaviour in ion-implanted diamonds

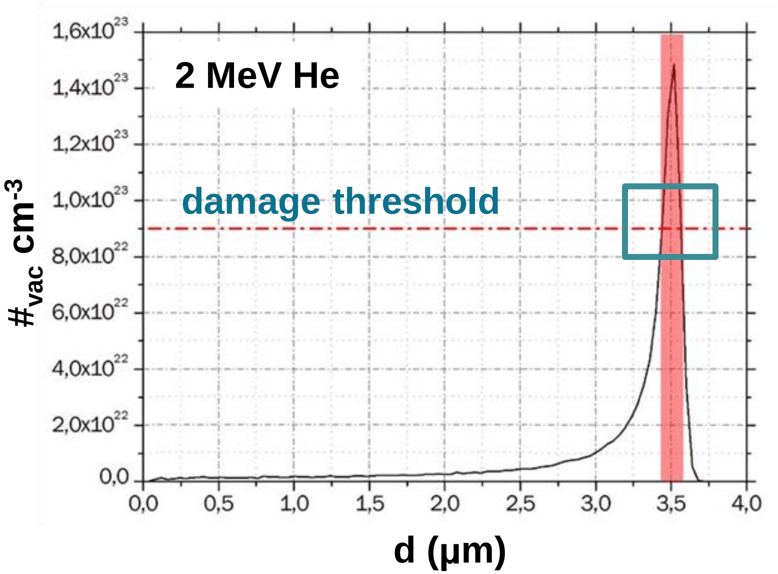
Johan F. Prins [a,*], Trevor E. Derry [b]

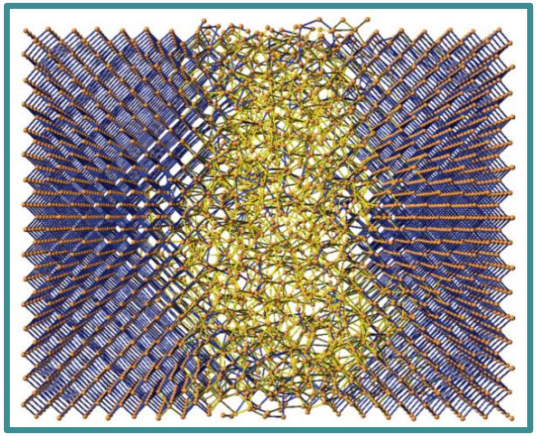


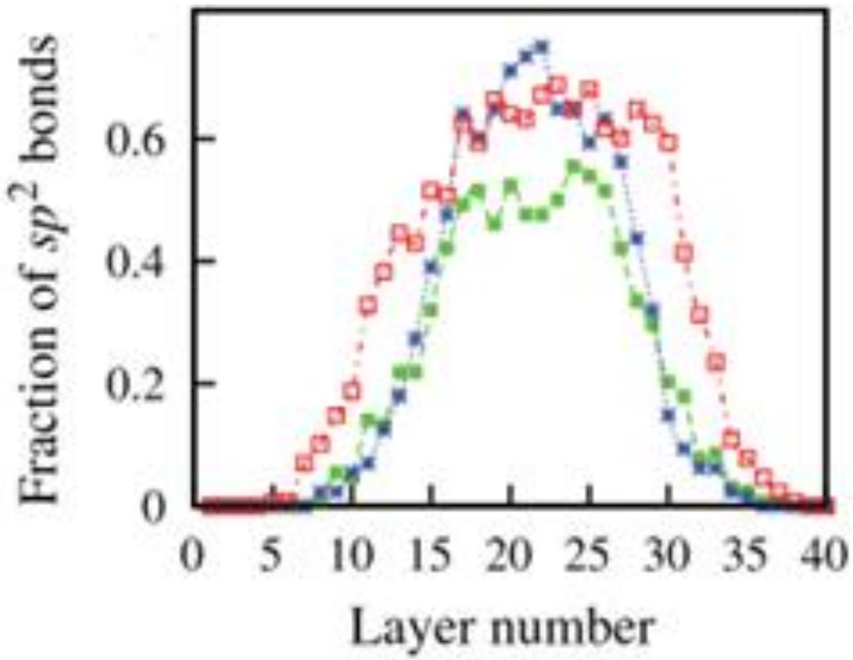
@ : Institute of Ion Beam Physics and Materials Research (Dresden),
Department of Physics – University of Pretoria, Solid State Physics Group – University of Torino

IBL in diamond

High fluence implantation → Formation of an amorphous carbon layer
where the damage density exceeds a threshold value



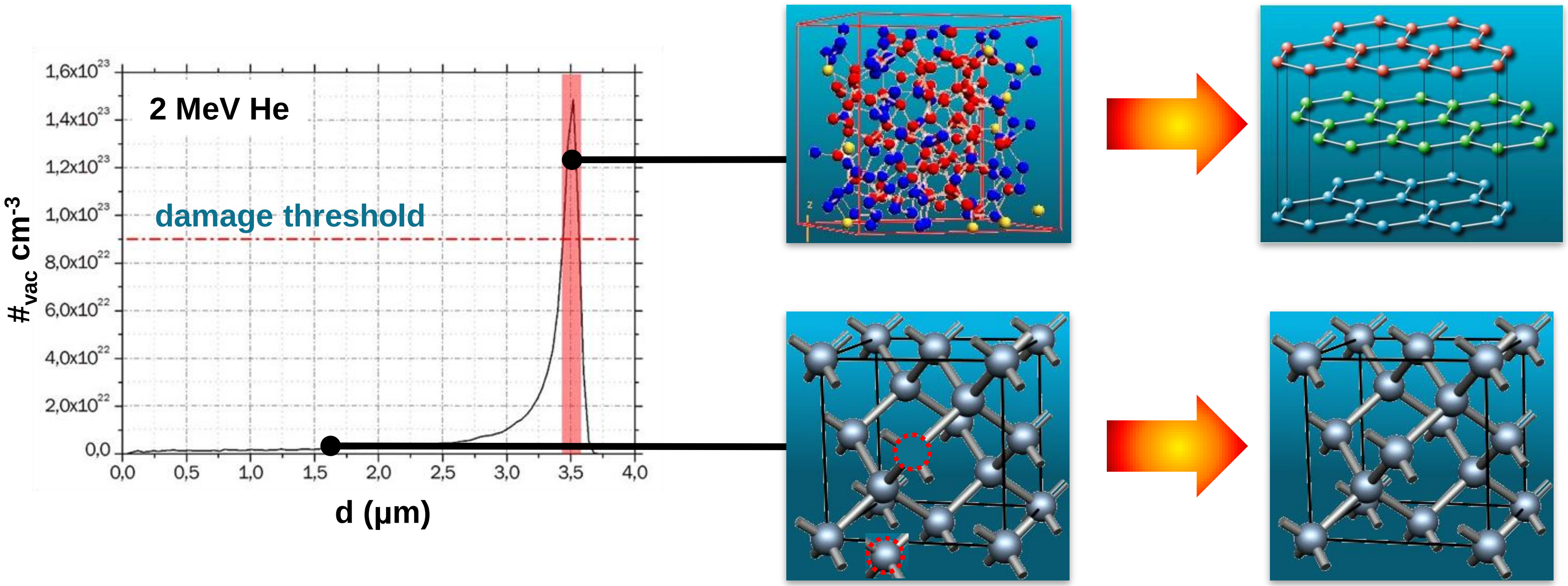




@ : SRIM Monte Carlo code, Technion – Israel Institute of Technology

IBL in diamond

Thermal annealing

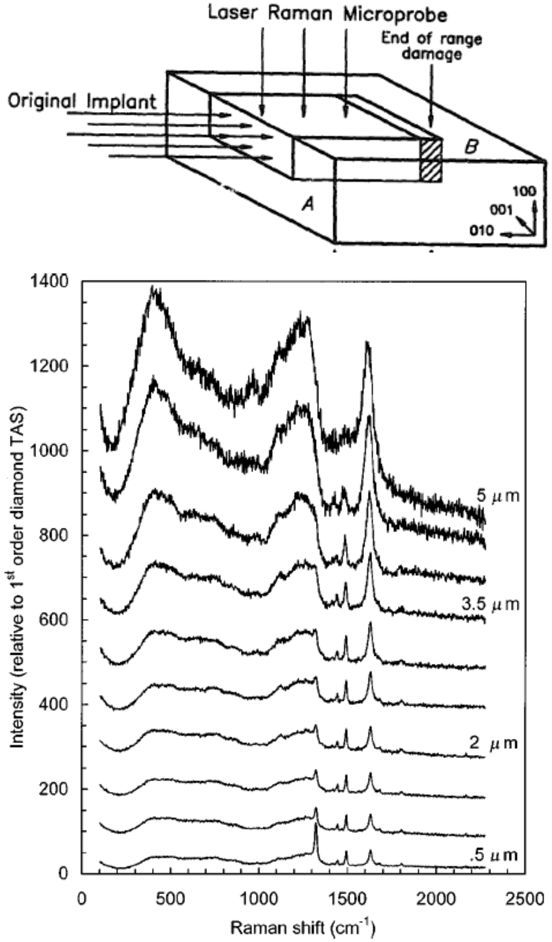


- Above threshold: amorphous carbon → **polycrystalline graphite**
- Below threshold: diamond with Frenkel defects → **diamond**

IBL in diamond

Experimental evidences

Cross-sectional **μ**-Raman



IBL in diamond

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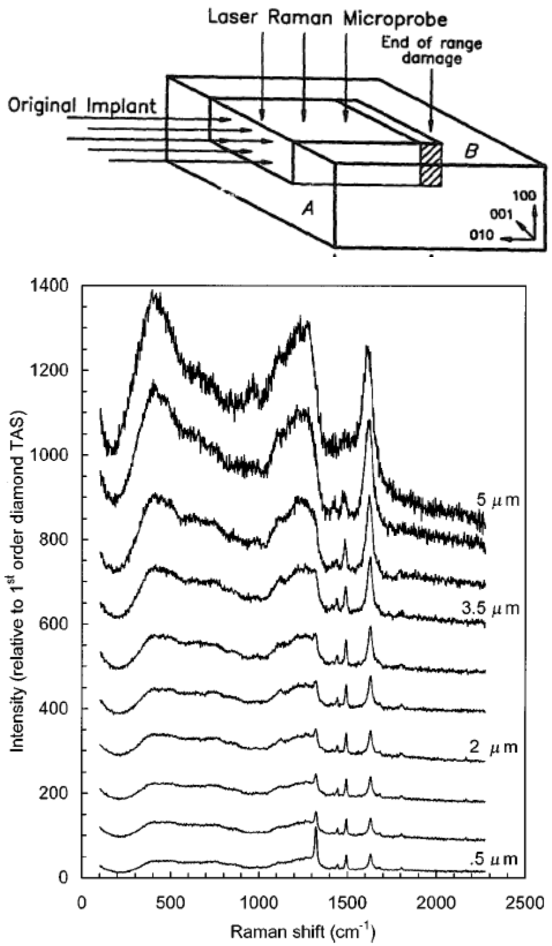
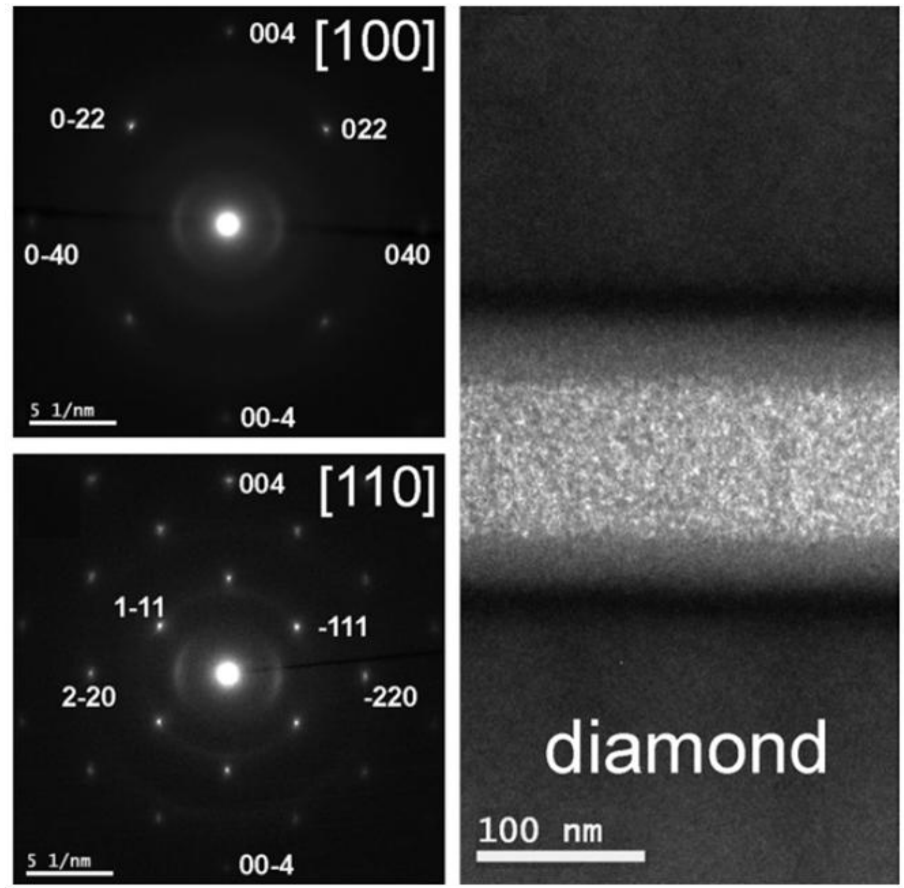
Cross-sectional μ-Raman



Cross-sectional TEM



IBL in diamond

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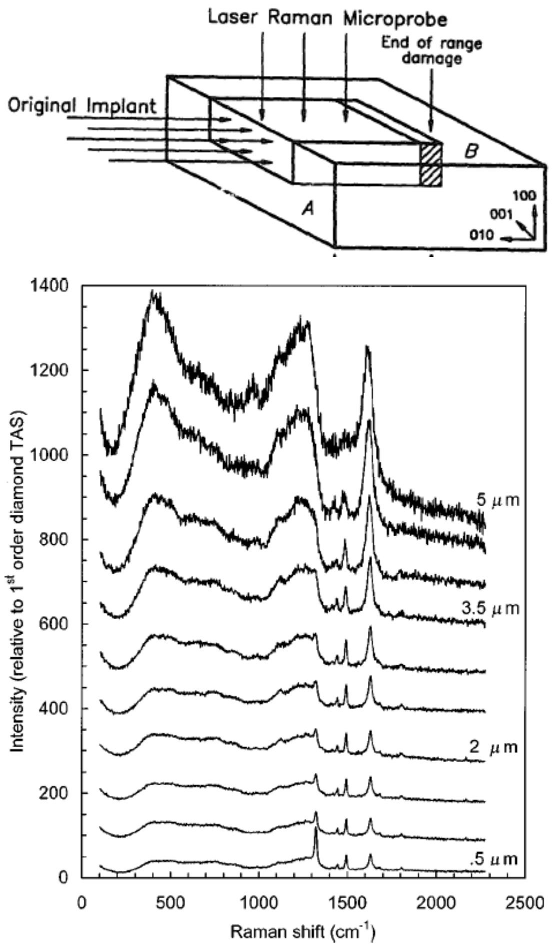
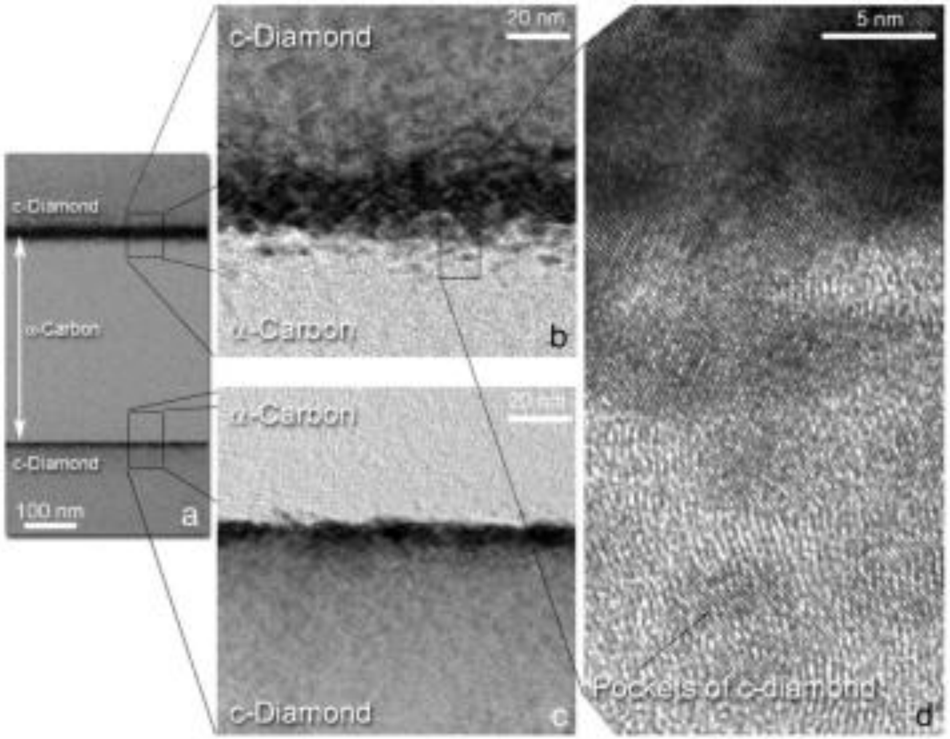
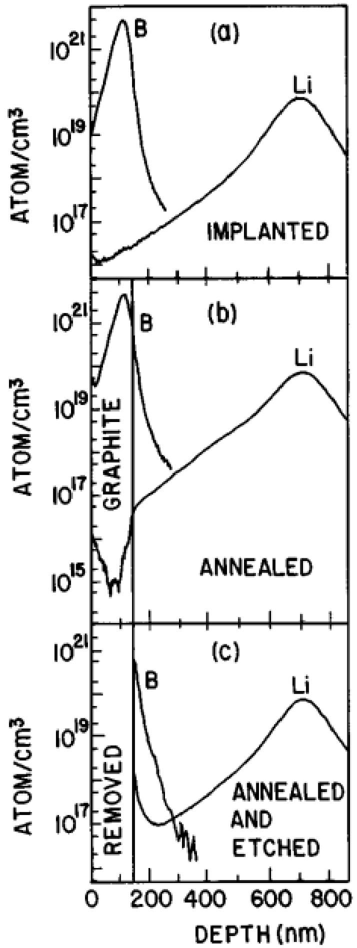


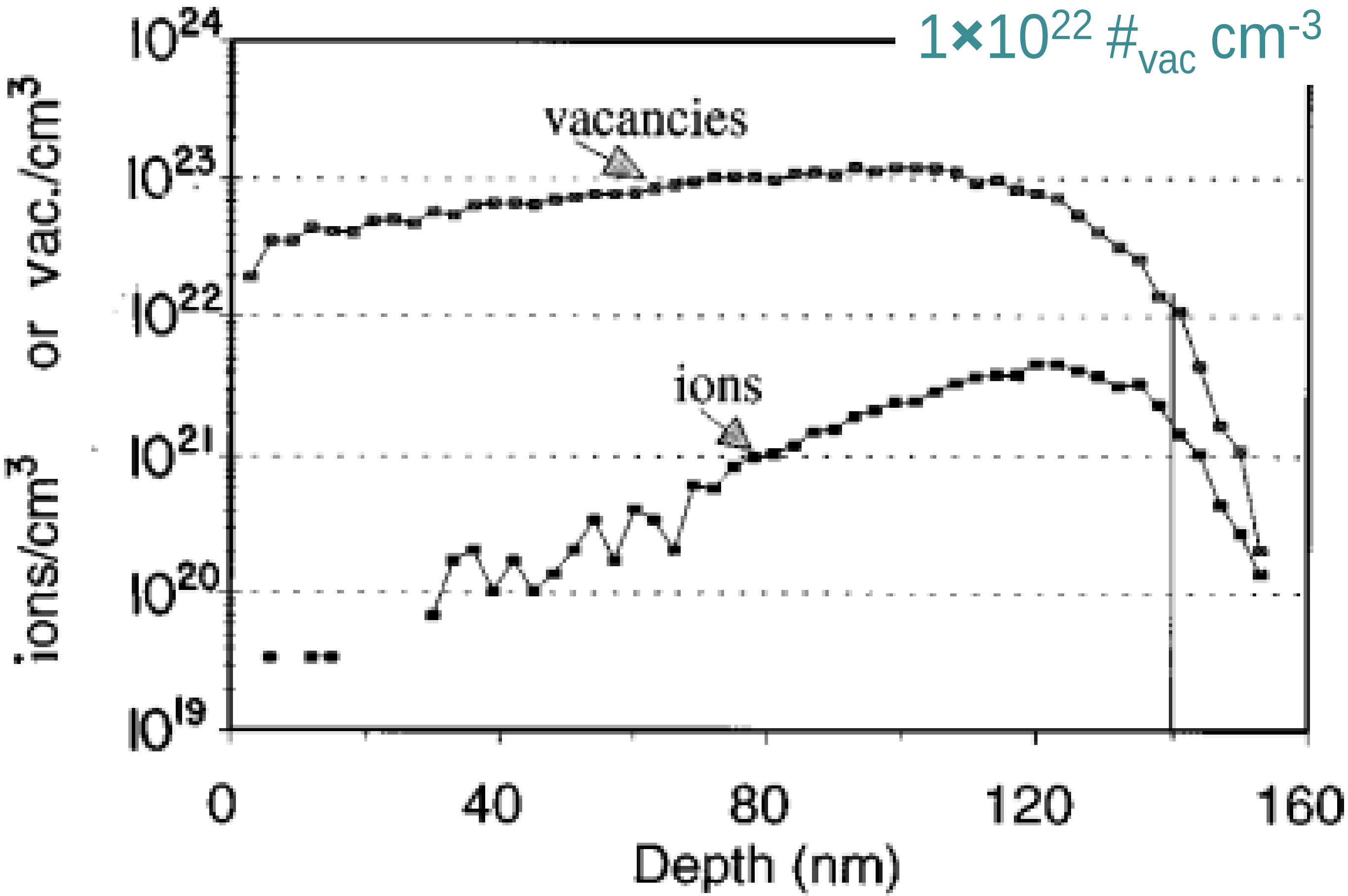
Cross-sectional TEM



IBL in diamond

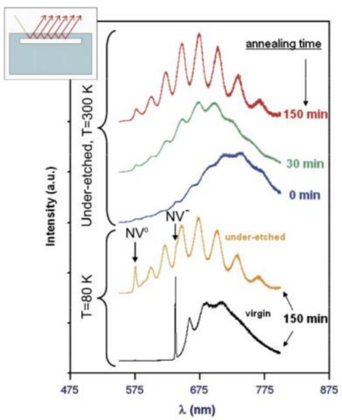
Graphitization threshold

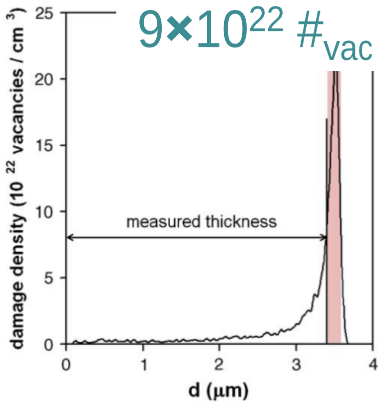




IBL in diamond

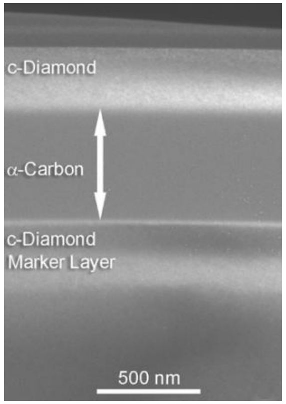
Graphitization threshold

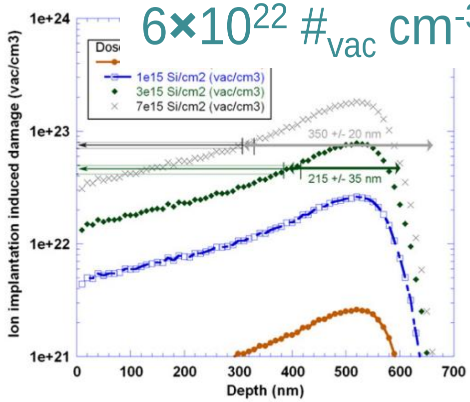




$9{\times}10^{22}\ \#_{vac}\ cm^{-3}$

@ : School of Physics – University of Melbourne

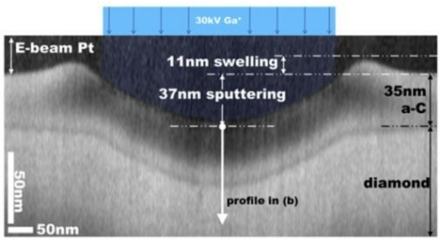


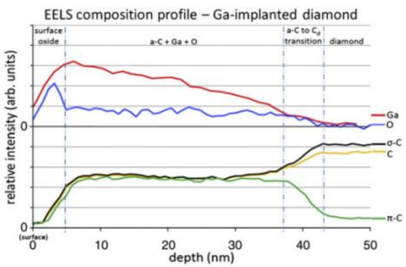


$6{\times}10^{22}\ \#_{vac}\ cm^{-3}$

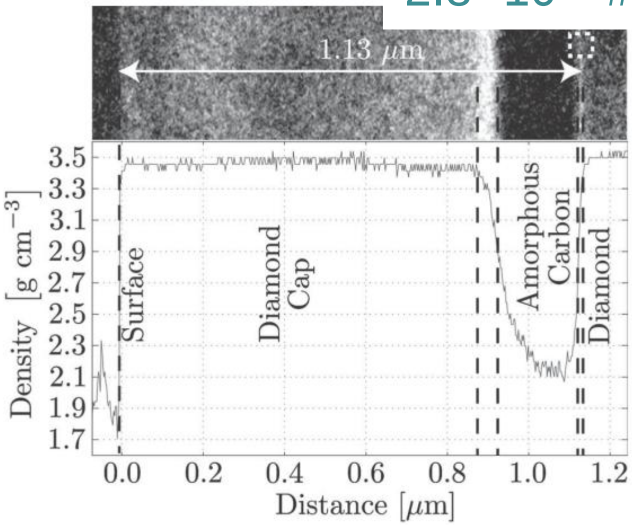
@ : Uni. of Florida & Australian National Uni.

$2{\times}10^{22}\ \#_{vac}\ cm^{-3}$





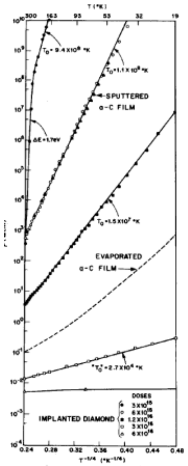
$2.8{\times}10^{22}\ \#_{vac}\ cm^{-3}$



@ : University of New South Wales

@ : School of Physics – University of Melbourne

IBL in diamond



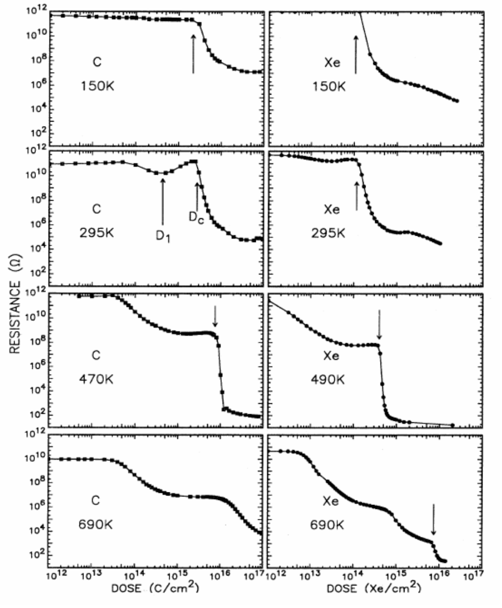
Electrical properties

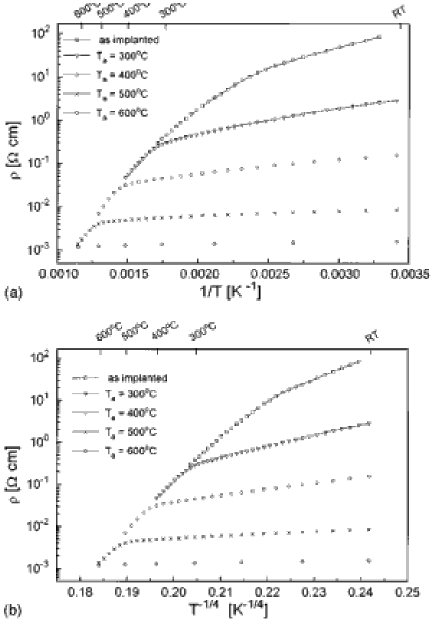
→ First works on ion-implantation-**induced graphitization (70’s)**

V. S. Vavilov et al., Radiat. Eff. 22, 141 (1974)

J. J. Hauser et al., Appl. Phys. Lett. 30, 129 (1977)

→ Studies on conduction mechanisms in graphitized / heavily damaged diamond



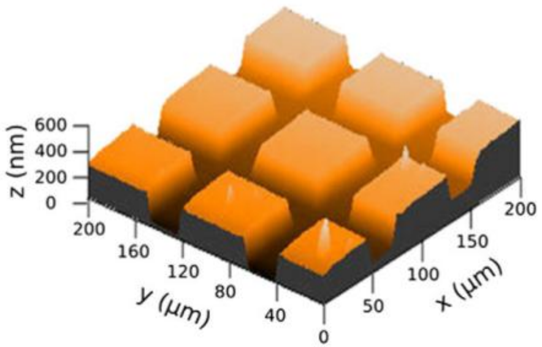


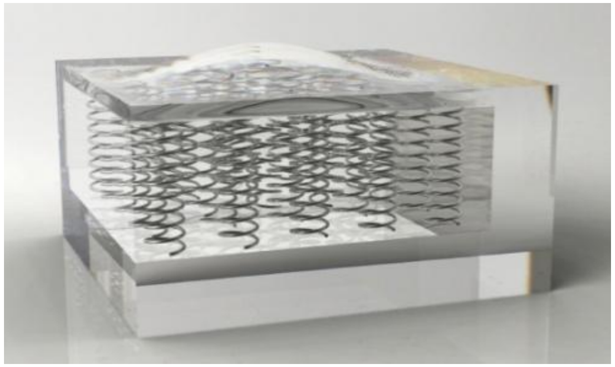
S. Prawer et al., Phys. Rev. B 51, 15711 (1995)

IBL in diamond

Deformation and stress

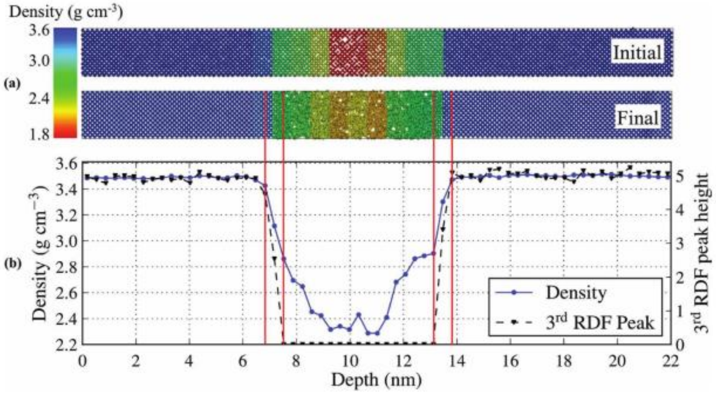
→ Surface swelling





@ : UniTo, INFN Torino

→ Internal stresses and graphitization



B. A. Fairchild et al., Adv. Mater. 24, 2024 (2012)

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IBL in diamond – State of the art

The diamond lift-off technique

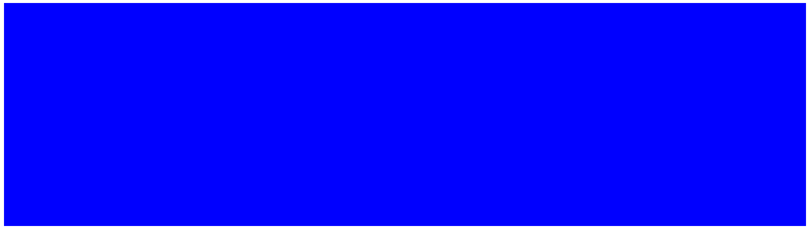
Single-crystal diamond plate liftoff achieved by ion implantation and subsequent annealing

N. R. Parikh, J. D. Hunn, E. McGucken, and M. L. Swanson
University of North Carolina, Chapel Hill, North Carolina 27599-3255

C. W. White
Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831-6048

R. A. Rudder, D. P. Malta, J. B. Posthill, and R. J. Markunas
Research Triangle Institute, Research Triangle Park, North Carolina 27709-2194

Appl. Phys. Lett. **61** (26), 28 December 1992 3124



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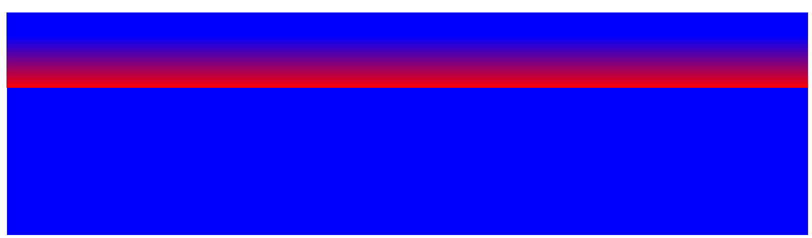

- MeV ion implantation

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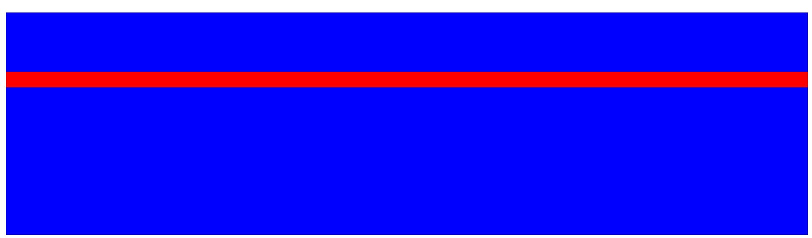

- MeV ion implantation
- Thermal annealing

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- MeV ion implantation
- Thermal annealing
- Selective graphite etching

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- MeV ion implantation
- Thermal annealing
- Selective graphite etching
- Lift-out

IBL in diamond – State of the art

Selective graphite etching

$C + 2O \rightarrow CO_2$

- Wet chemical etching

  i.e.: 1:1:1 H_2SO_4 : HNO_3 : $HClO_4$ boiling acid

- Annealing in oxygen atmosphere

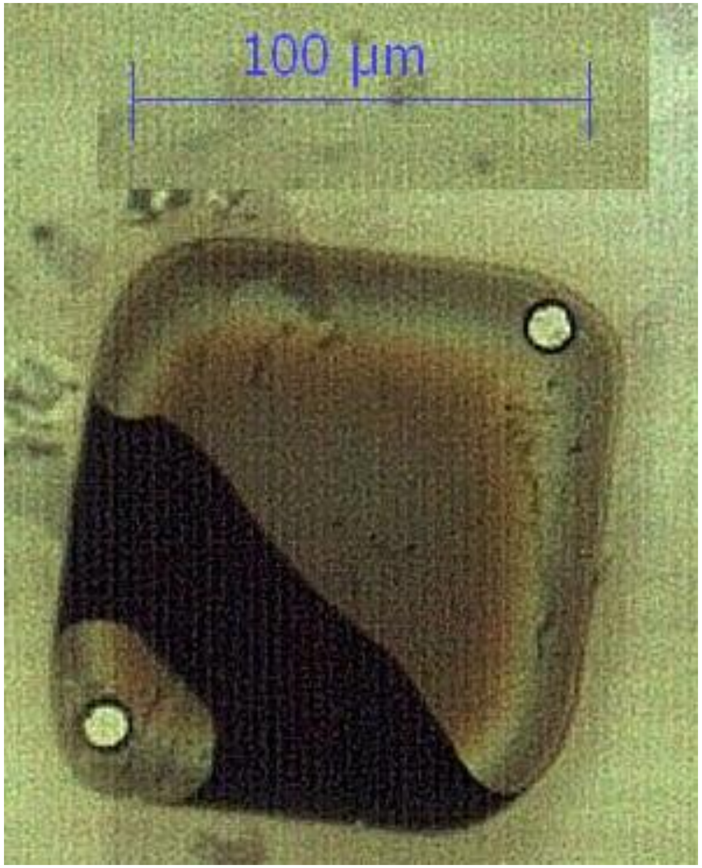
  T = 550 – 580 °C in air

- Annealing in ozone atmosphere

  T = 500 – 550 °C in air under UV illumination

- Electrochemical etching

  H_3BO_3, non-contact Pt electrodes, V ≅ 200 V



IBL in diamond – State of the art

Lift-off + laser micro-cutting

Fabrication of single-crystal diamond microcomponents

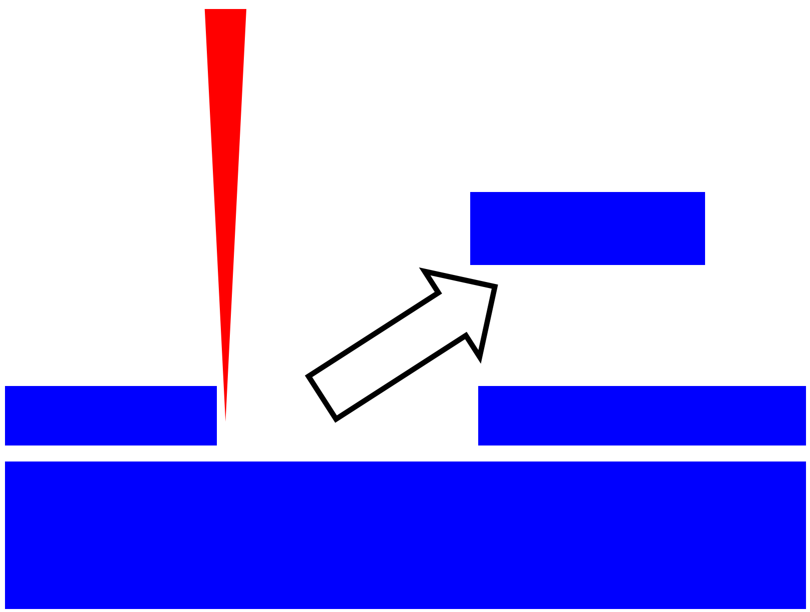
John D. Hunn, S. P. Withrow, C. W. White, R. E. Clausing, and L. Heatherly
Oak Ridge National Laboratory, Bldg 5500 MS-6376, Oak Ridge, Tennessee 37831-6376

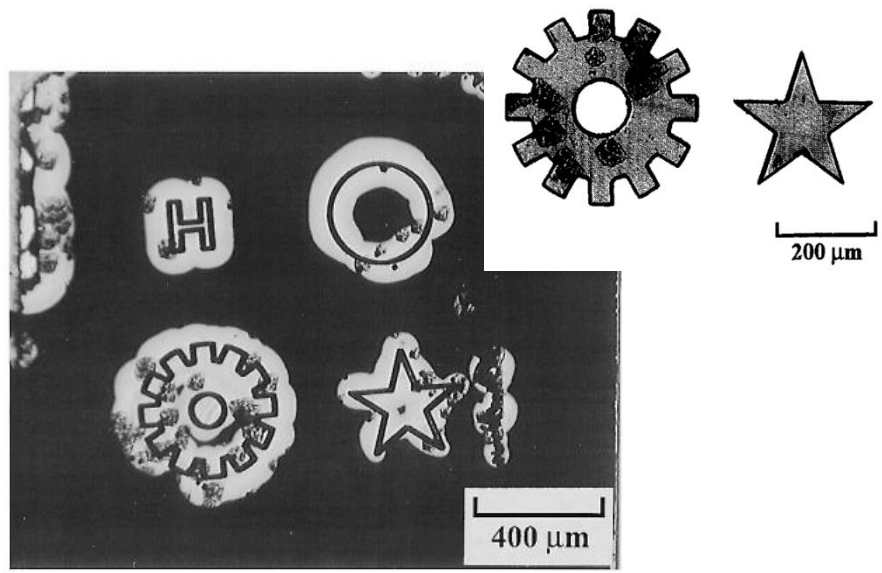
C. Paul Christensen
Potomac Photonics, Lanham, Maryland 20705

(Received 26 August 1994; accepted for publication 7 October 1994)

We have combined a technique for the lift-off of thin diamond films from a bulk diamond with a technique for engraving diamond with a focused excimer laser to produce free-standing single-crystal diamond microstructures. One microcomponent that has been produced is a 12 tooth gear ~400 μm in diameter and ~13 μm thick. Other microstructures have also been demonstrated, showing the versatility of this method. This process should be applicable to producing diamond microcomponents down to spatial dimensions (width and thickness) of a few micrometers.

3072 Appl. Phys. Lett. **65** (24), 12 December 1994





IBL in diamond – State of the art

Lift-off + CVD growth

Diamond & Related Materials 20 (2011) 616–619

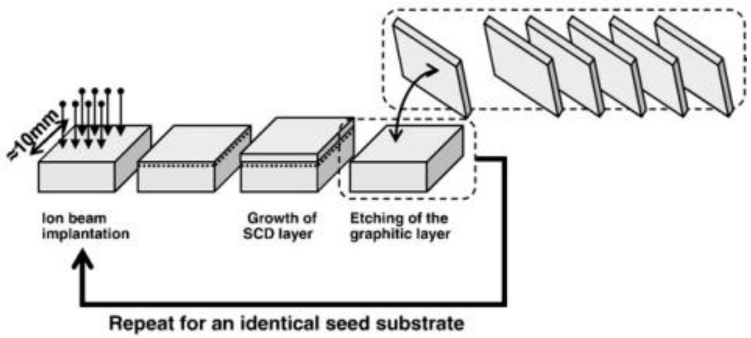
Contents lists available at ScienceDirect

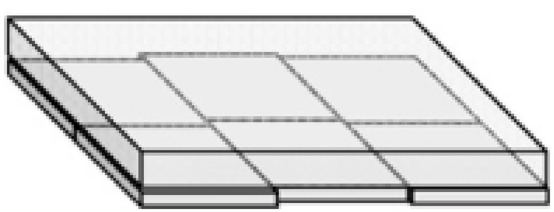
Diamond & Related Materials

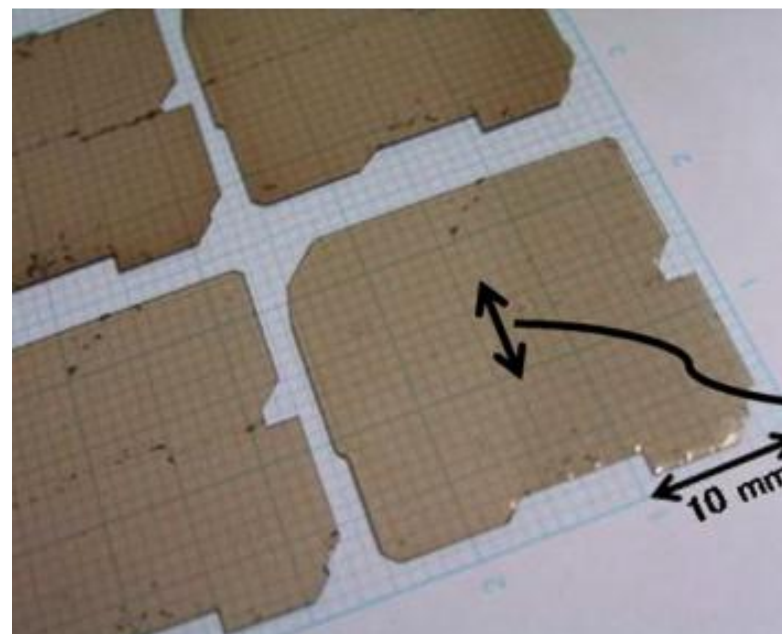
journal homepage: www.elsevier.com/locate/diamond

Developments of elemental technologies to produce inch-size single-crystal diamond wafers☆

Hideaki Yamada *, Akiyoshi Chayahara, Yoshiaki Mokuno, Nobuteru Tsubouchi,
Shin-ichi Shikata, Naoji Fujimori [1]







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Lift-off + CVD growth

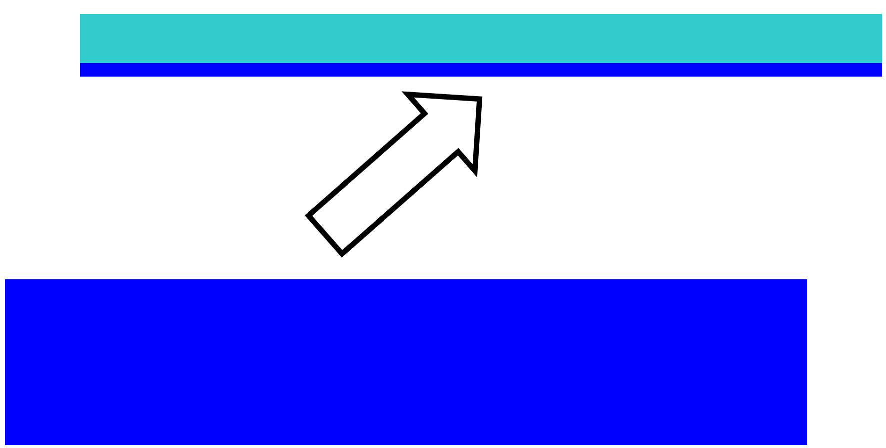
Diamond & Related Materials 24 (2012) 74–77

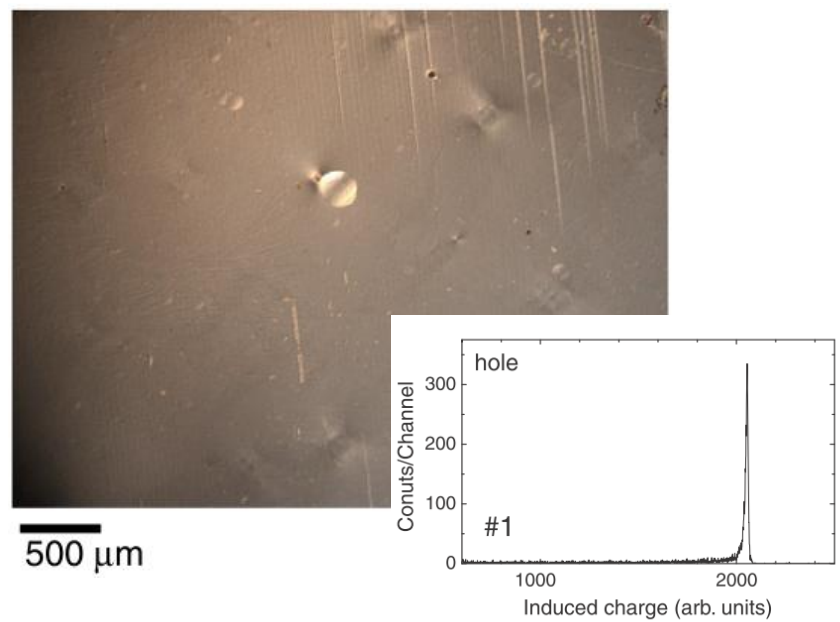
Contents lists available at SciVerse ScienceDirect

Diamond & Related Materials

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

Characterization of a sandwich-type large CVD single crystal diamond particle detector fabricated using a lift-off method☆





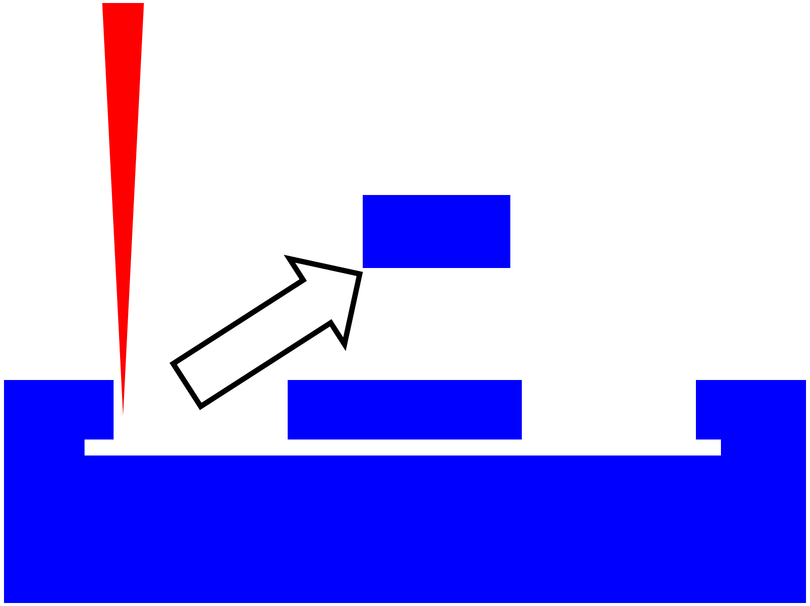
IBL in diamond – State of the art

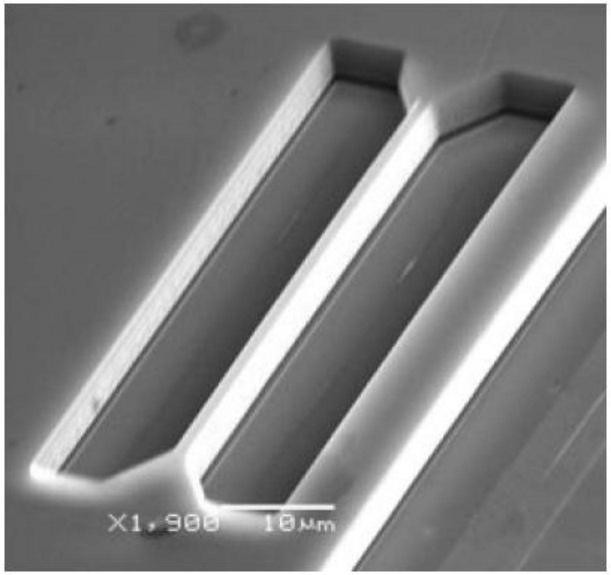
Lift-off + Focused Ion Beam (FIB) milling

Ion-Beam-Assisted Lift-Off Technique for Three-Dimensional Micromachining of Freestanding Single-Crystal Diamond**

By *Paolo Olivero*,* *Sergey Rubanov*, *Patrick Reichart*, *Brant C. Gibson*, *Shane T. Huntington*, *James Rabeau*, *Andrew D. Greentree*, *Joseph Salzman*, *David Moore*, *David N. Jamieson*, and *Steven Prawer*

Adv. Mater. **2005**, *17*, 2427–2430





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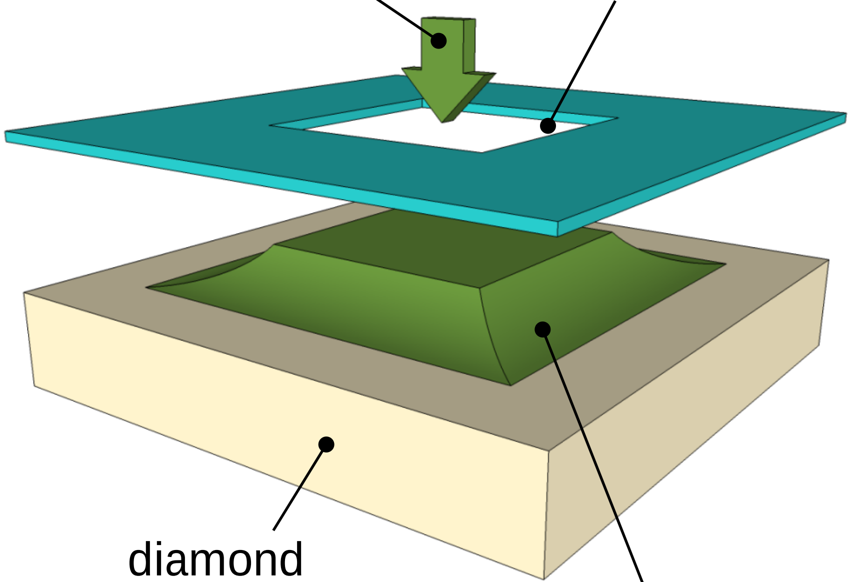
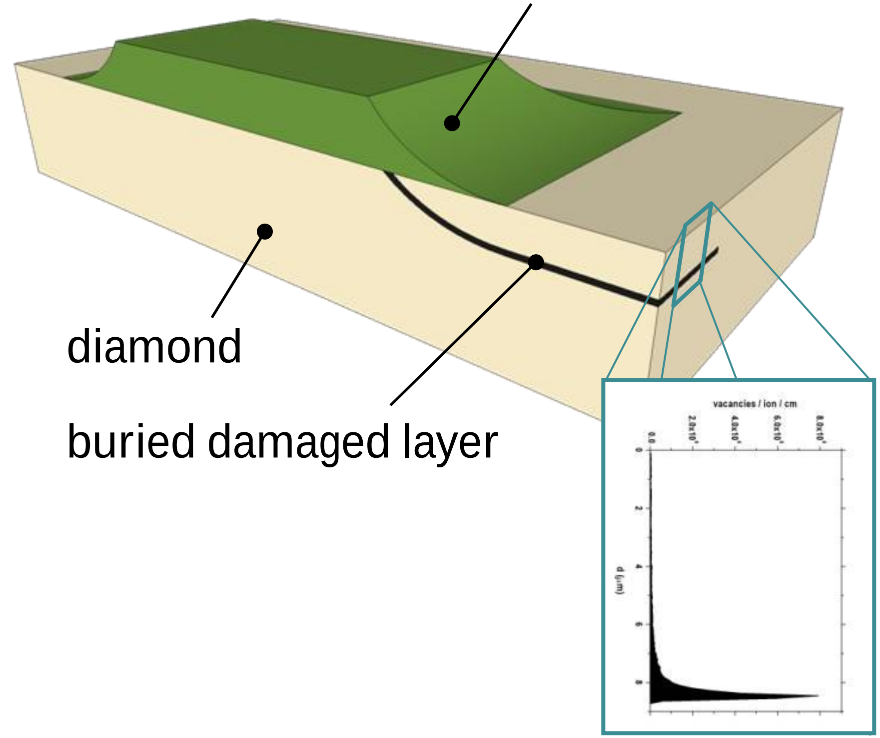
  - → **Electrical** features
  - → Radiation detection
  - → Biosensing
  - → Quantum Optics
- Conclusions

Electrical features

Implantation with a scanning MeV ion micro-beam through graded-thickness mask

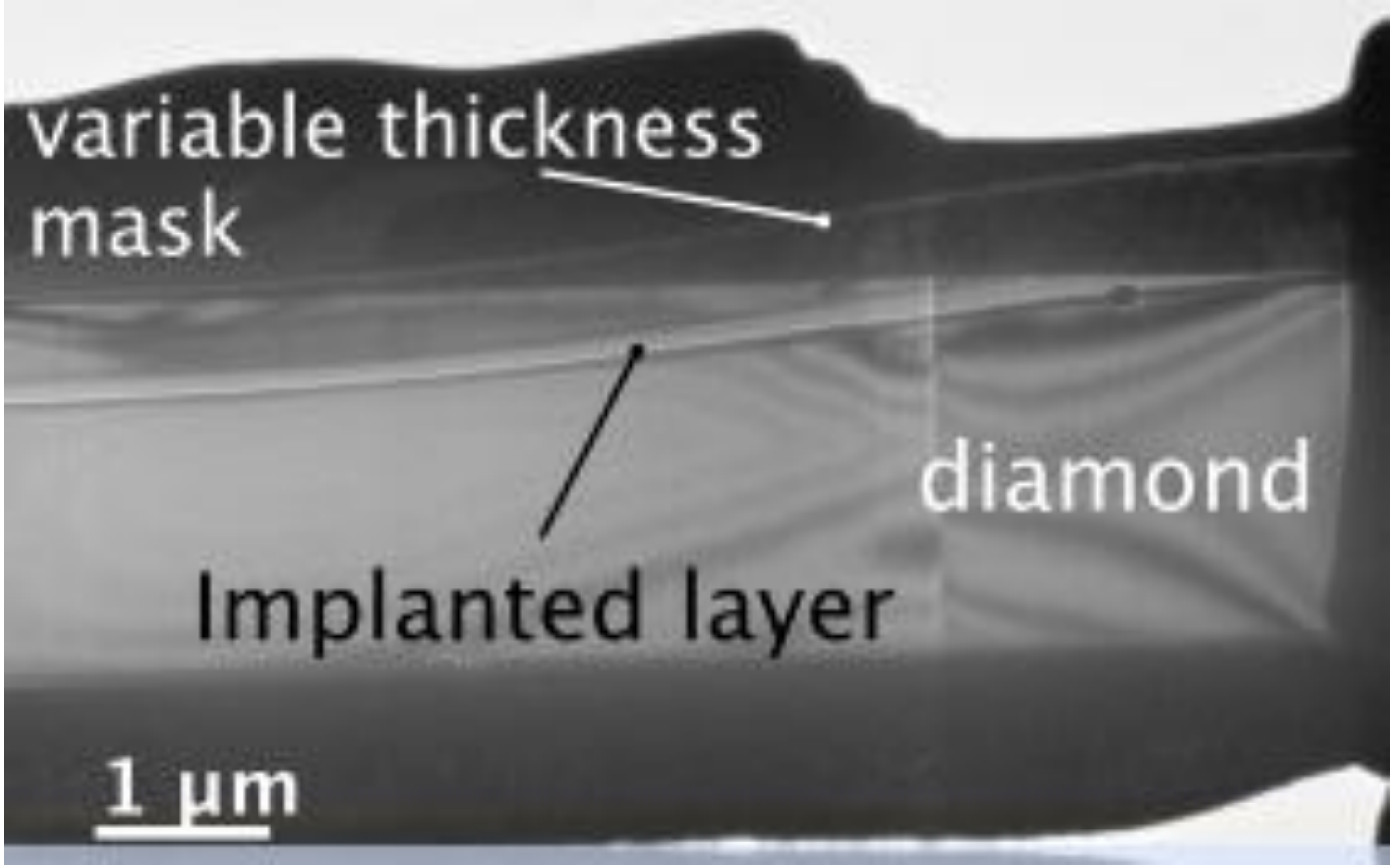




→ **direct writing of** sub-superficial conductive microchannels in single-crystal diamond

Electrical features

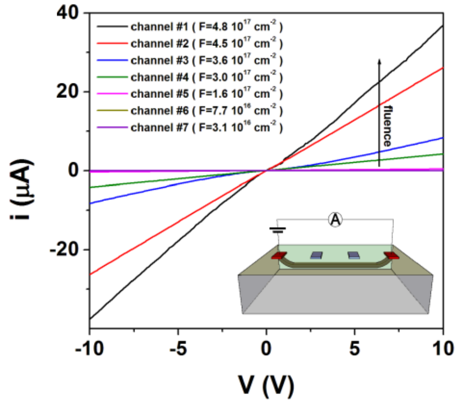
TEM microscopy



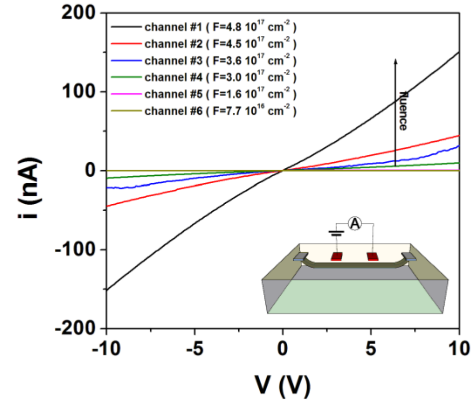
Electrical features

IV curves @ increasing fluences

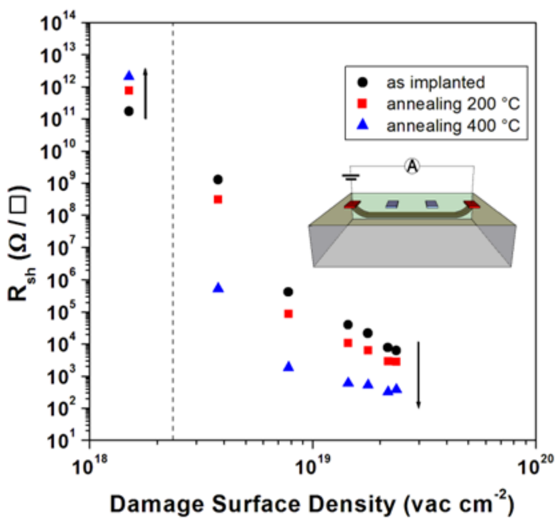
endpoints

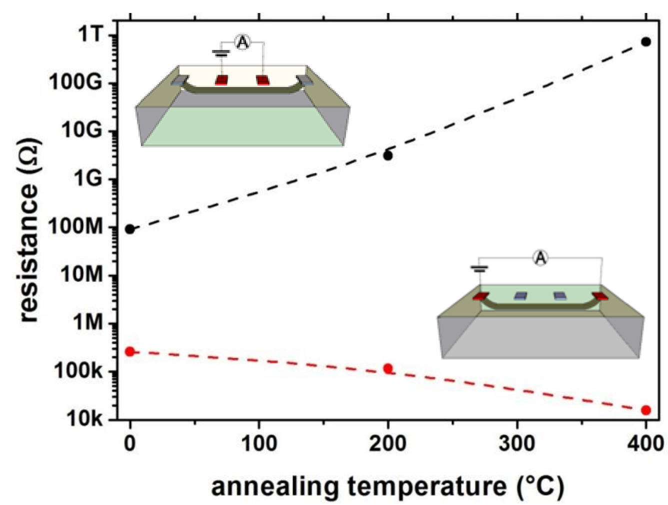


test



Annealing behavior

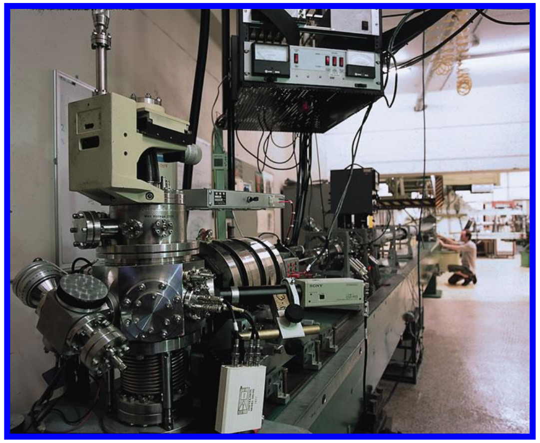


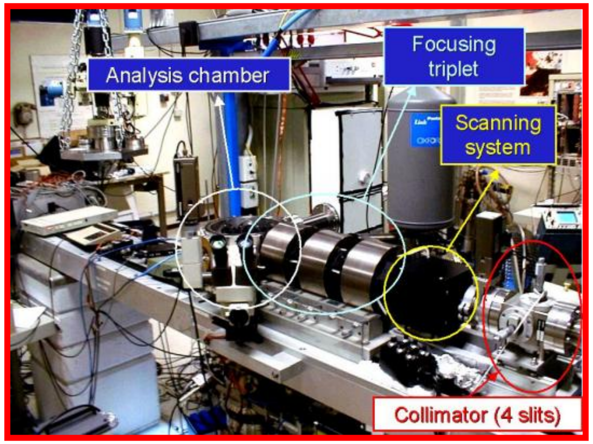


F. Picollo et al., New Journal of Physics 14, 053011 (2012)

Electrical features

Ion implantation performed at the
MP2-UniMelb, LNL-AN200 and **Ruđer Bošković Institute** ion microbeam lines



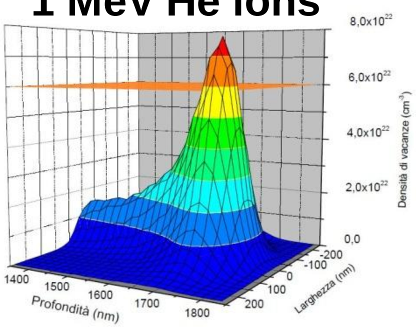


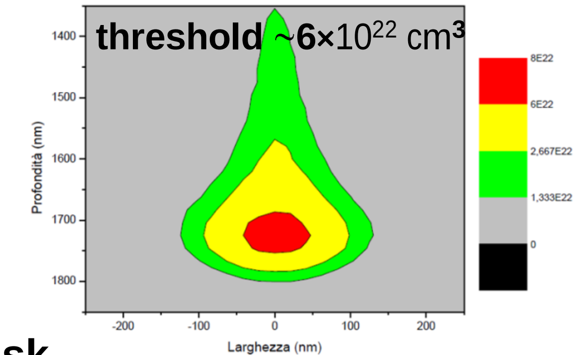
Structural TEM characterization	Cellular bio-sensing 3D particle detectors	3D particle detectors
0.5 MeV He^{+} $F=1\times10^{17}$ cm^{-2}	1.8 MeV He^{+} $F=1\text{-}10\times10^{16}$ cm^{-2}	6 MeV C^{3+} $F=4\times10^{16}$ cm^{-2}

Electrical features

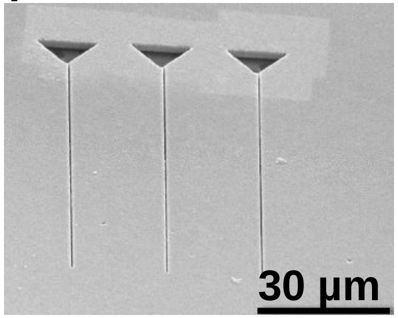
High-resolution FIB-machined metal contact masks

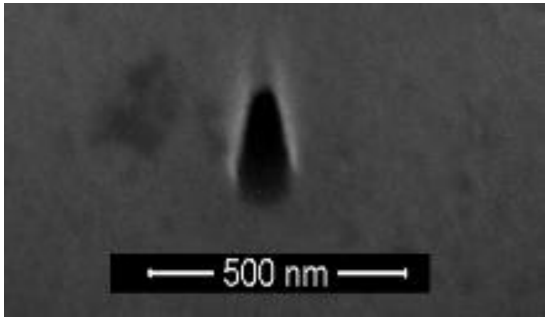
1 MeV He ions



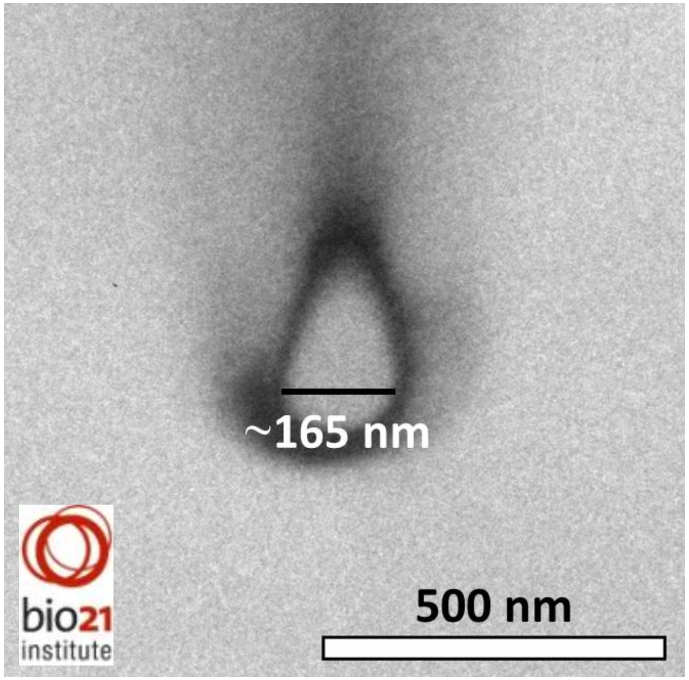


2 μm thick metal mask





unpublished



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Radiation detection

“DIARAD” & “DIAMED” INFN projects

Coordinated Research Project F11016

Ettore Vittone

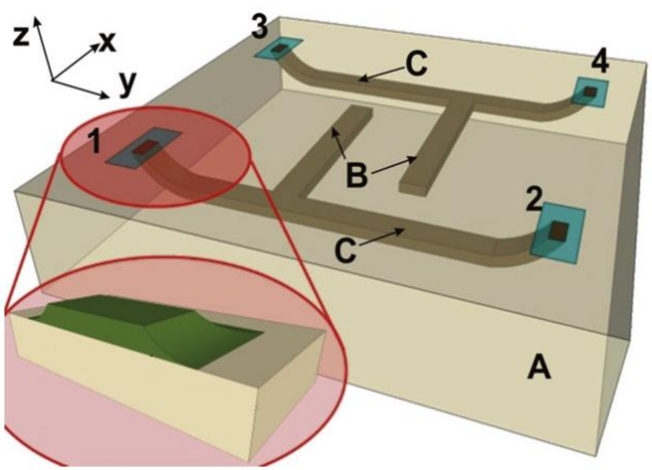
Radiation detection

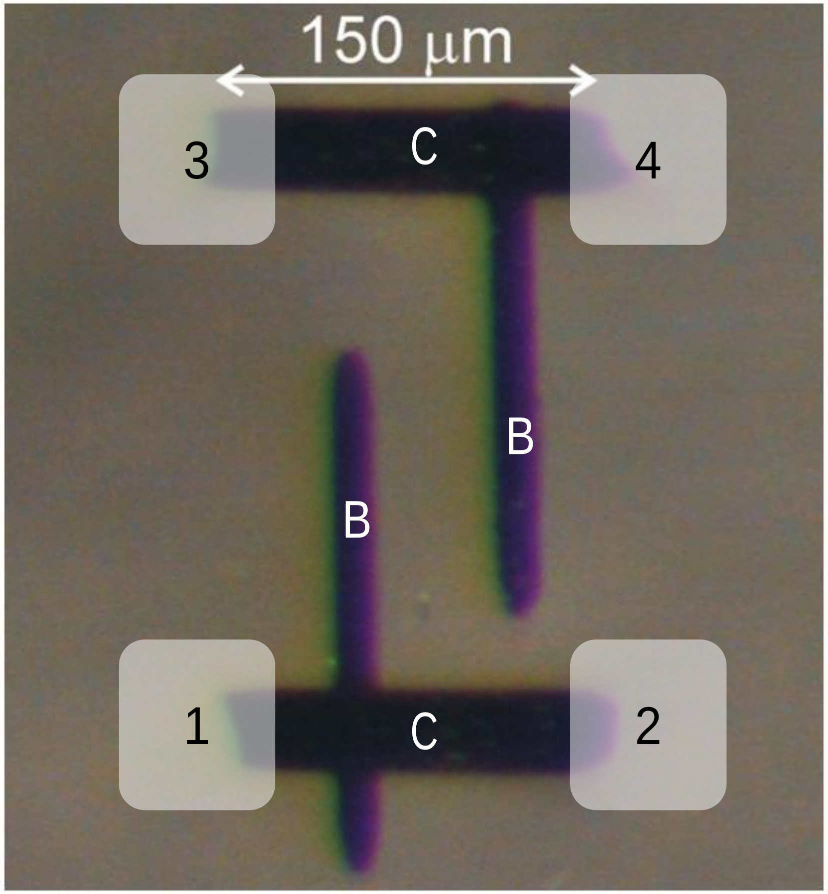
Sample #1

- free-standing homoepitaxial single-crystal **"electronic grade" CVD diamond grown by** ElementSix™
- [N], [B] < 5 ppb

Ion-beam microfabrication

- ion **μ**-beam line @ **Ruđer Bošković** Institute
- ions: 6 MeV C^{3+} (range ~3 **μ**m)
- ion fluence: 4×10^{16} cm^{-2}
- annealing: 2 hrs @ 950 °C in Ar



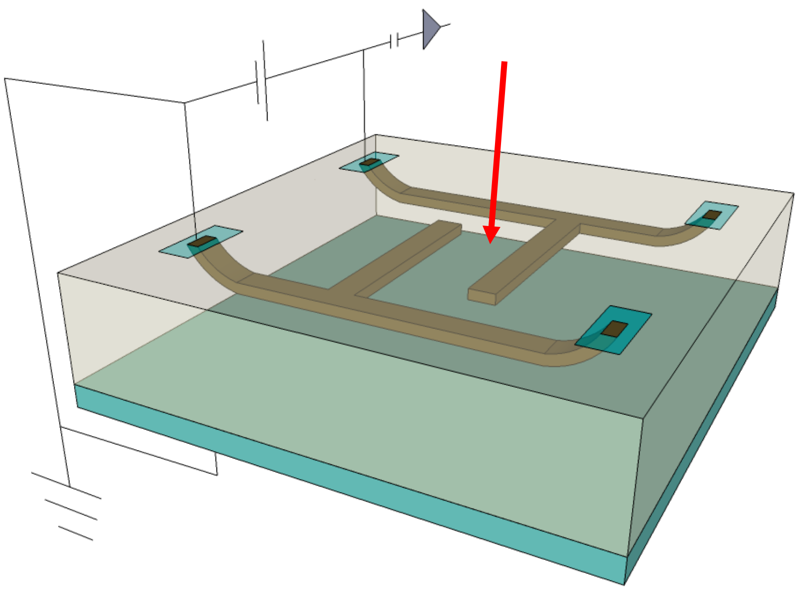


- R_{1-3}, R_{2-4} ~10 T**Ω**
- R_{1-2}, R_{3-4} ~1 k**Ω** → ρ_C ~10 m**Ω** cm
- ohmic contacts

Radiation detection

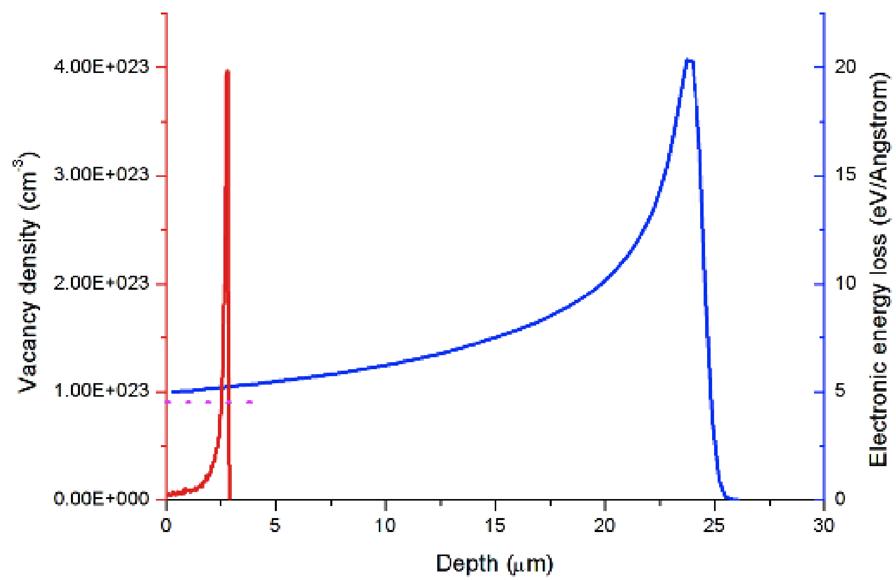
Sample #1

- free-standing homoepitaxial single-crystal **“electronic grade” CVD diamond grown by** ElementSix™
- **[N], [B] < 5 ppb**

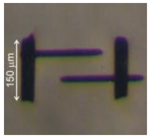


IBIC measurements

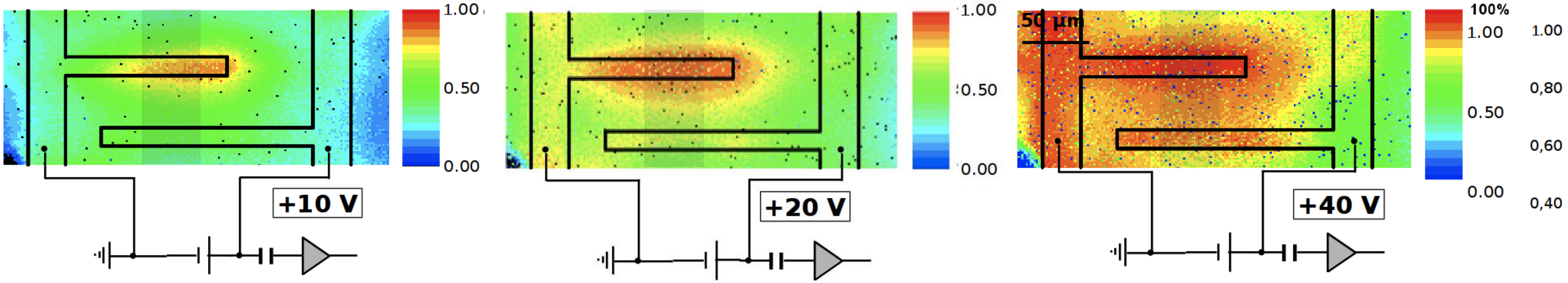
- ion **μ**-beam line @ **Ruđer Bošković** Institute
- ions: 2 MeV H^+ (range ~25 **μ**m)
- ∅ ~2 **μ**m
- frontal geometry



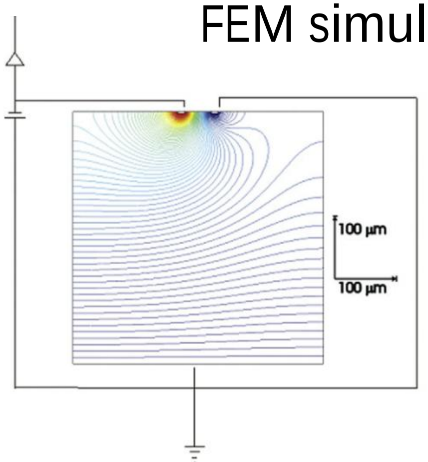
Radiation detection

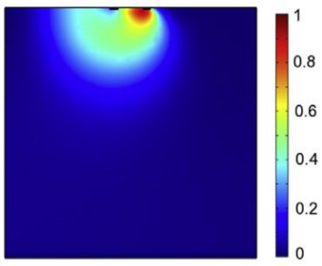


IBIC maps @ different V_{bias}



FEM simulations



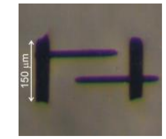


Gunn's weighting potential

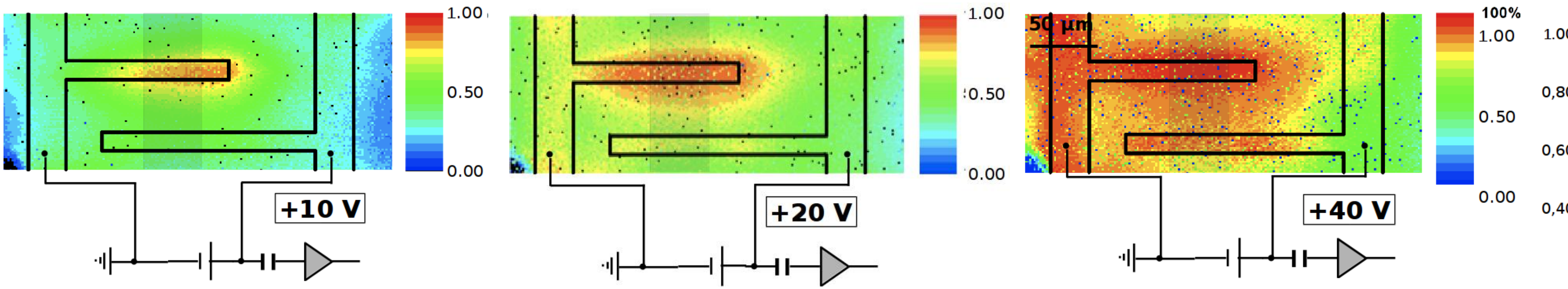
CCE

P. Olivero et al., Nucl. Instr. Meth. Phys. Res. B 269, 2340 (2011)

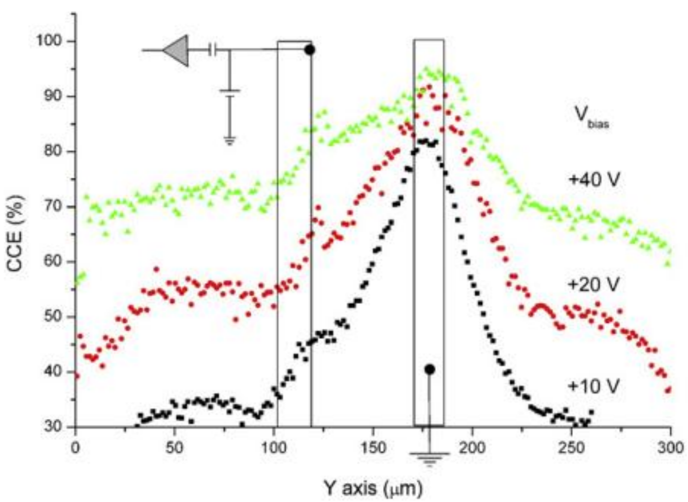
Radiation detection



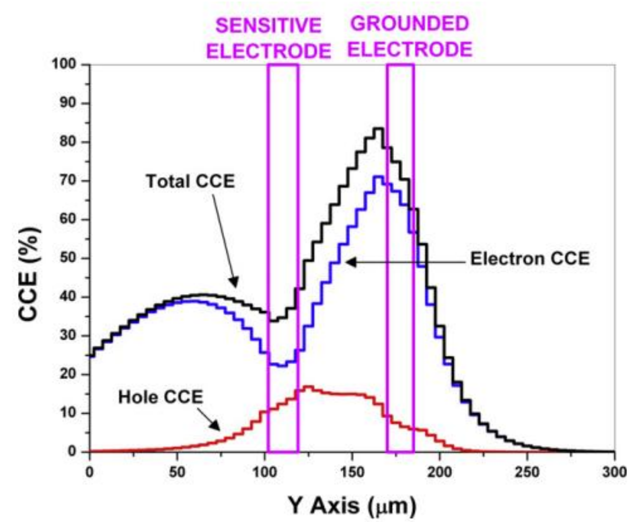
IBIC maps @ different V_{bias}



IBIC profiles @ different V_{bias}



Numerical predictions



P. Olivero et al., Nucl. Instr. Meth. Phys. Res. B 269, 2340 (2011)

Radiation detection

Sample #2

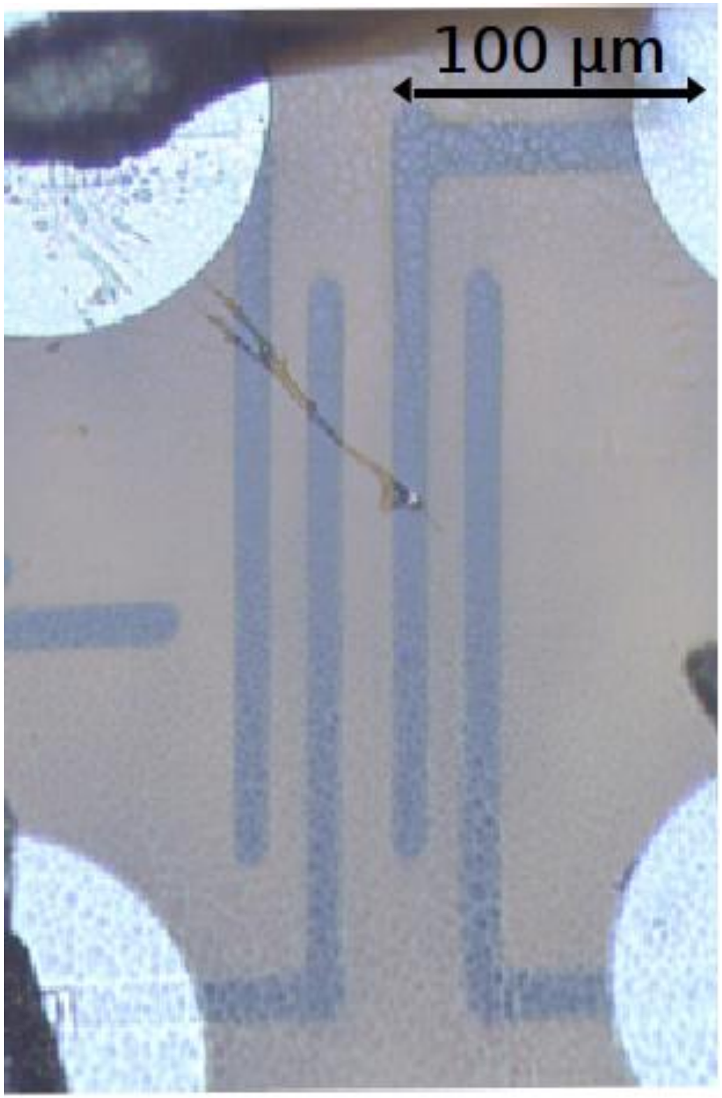
- homoepitaxial single-crystal CVD diamond grown @ UniRoma **"Tor** Vergata**"**
- **50 μ**m thick intrinsic layer on HPHT substrate
- [N], [B] < 5×10^{14} cm^{-2}

Ion-beam microfabrication

- ion **μ**-beam line @ Legnaro National Laboratories
- ions: 2 MeV He^+ (range ~3 **μ**m)
- ion fluence: 1.5×10^{17} cm^{-2}
- annealing: 2 hrs @ 1100 **°**C in vacuum

UNIVERSITA' degli STUDI di ROMA TOR VERGATA

INFN



Radiation detection

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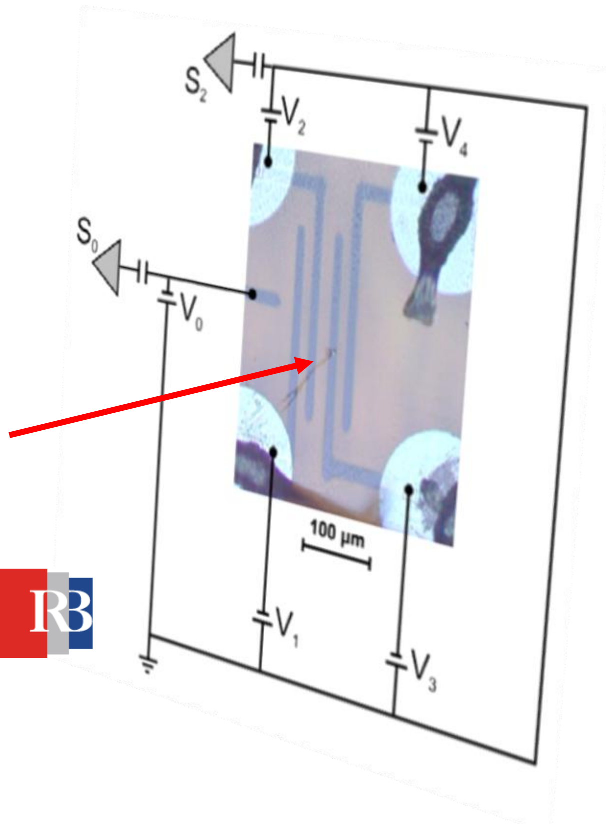
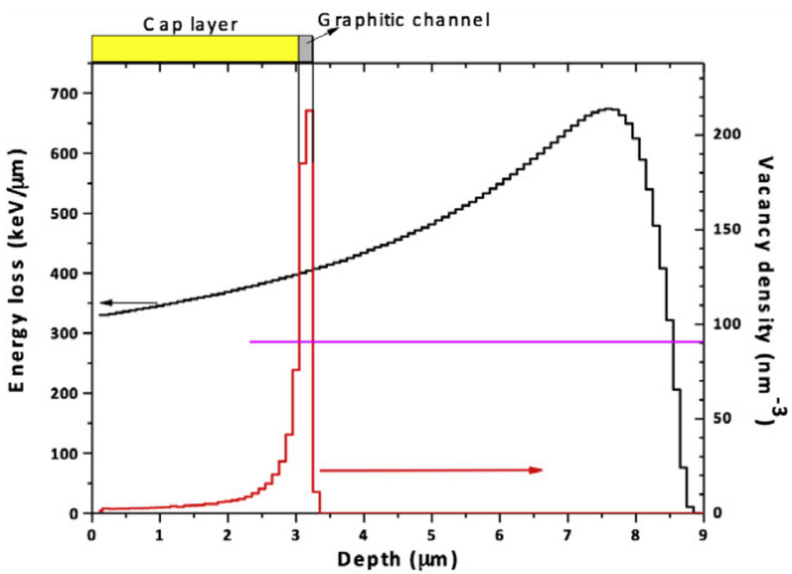


IBIC measurements

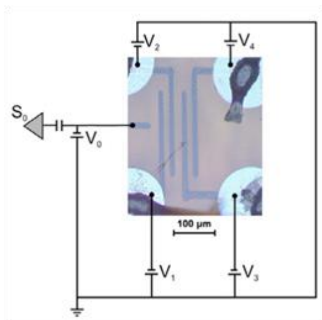
- ion **μ**-beam line @ **Ruđer Bošković** Institute
- ions: 4 MeV He$^+$ (range ~8 **μ**m)
- ∅ ~4 **μ**m
- frontal geometry

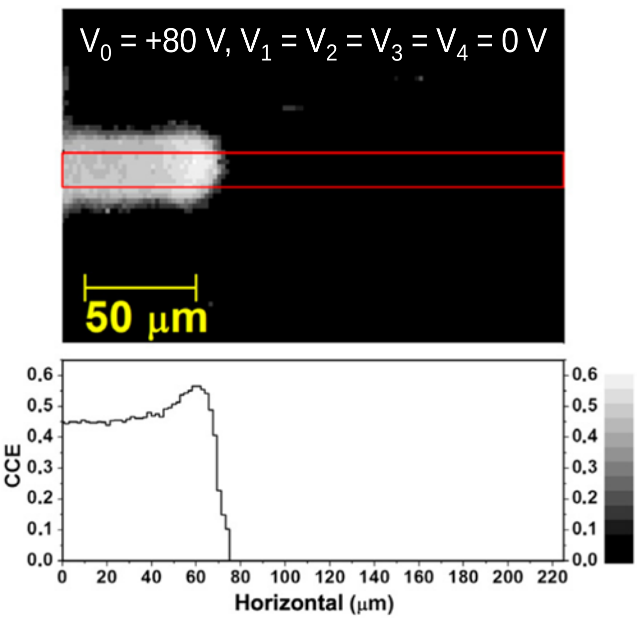


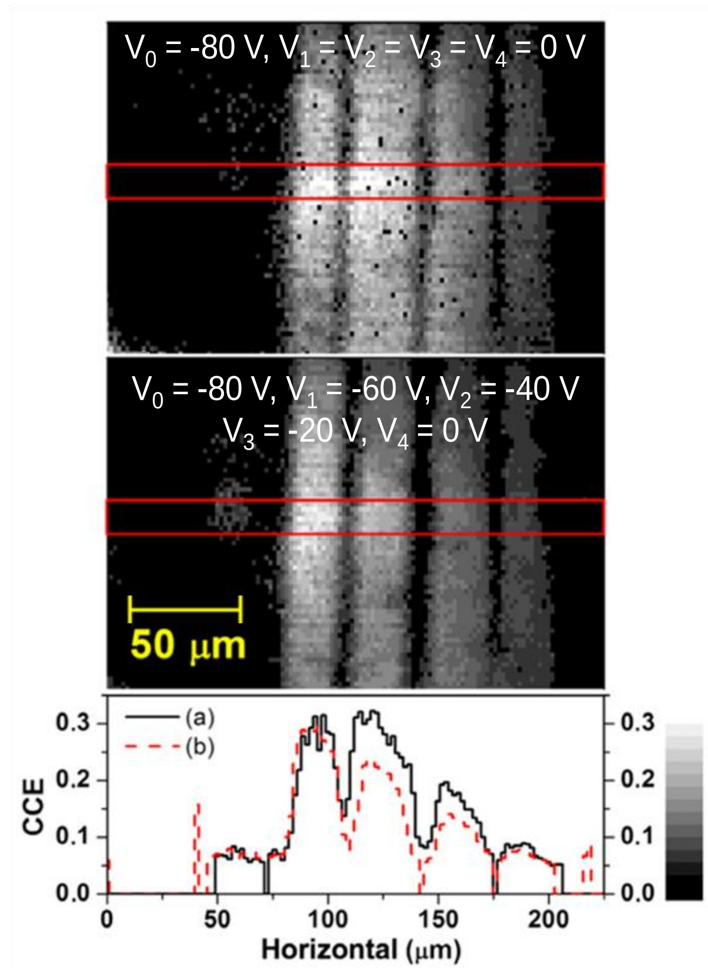
Radiation detection

IBIC maps & profiles @ different V_{bias} configurations

Sensitive electrode: S_0





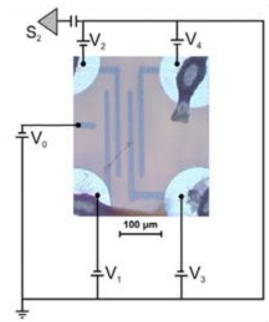


J. Forneris et al., Nucl. Instr. Meth. Phys. Res. B 306, 181-185 (2013)

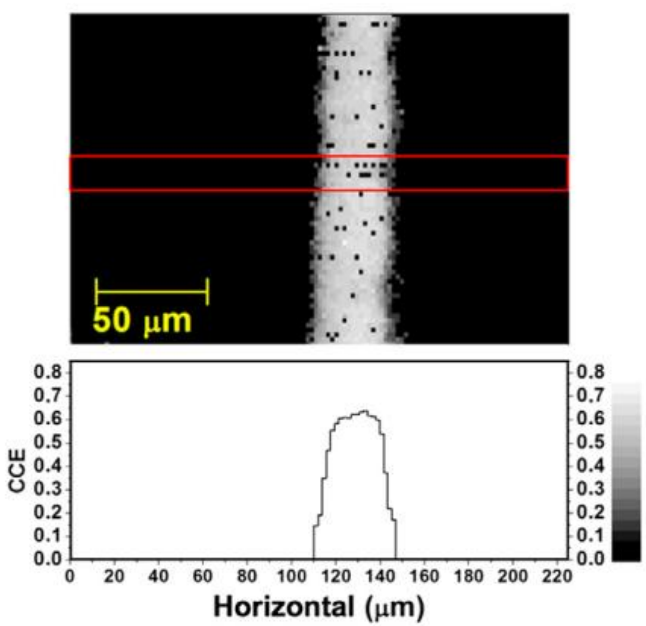
Radiation detection

IBIC maps & profiles @ different V_{bias} configurations

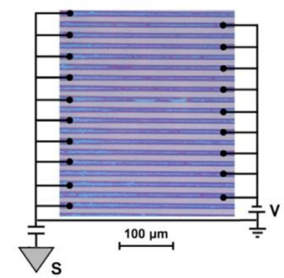
Sensitive electrode: S_2



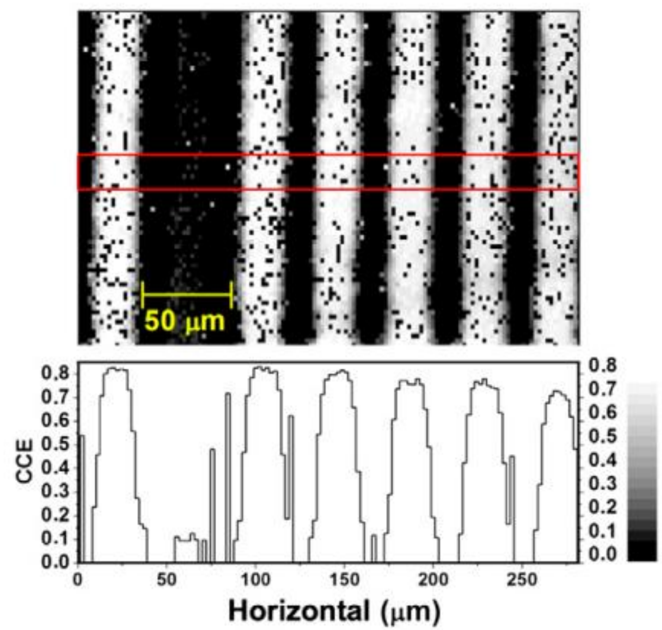
$V_0 = V_2 = V_4 = 0$ V, $V_1 = V_3 = -100$ V



Reference detector with planar Ti/Pt/Au electrodes



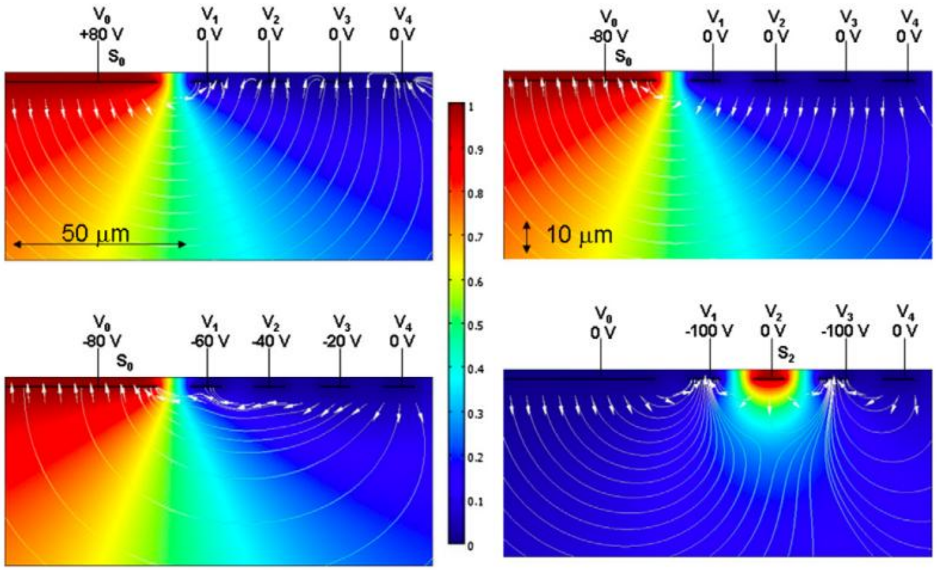
$V_S = 0$ V, $V = -100$ V



J. Forneris et al., Nucl. Instr. Meth. Phys. Res. B 306, 181-185 (2013)

Radiation detection

FEM numerical simulations



Weighting potential and electric field lines

Remarks:

- good ohmic contacts
- good consistency with FEM simulations
- predominant hole contribution
- **residual damage in the "cap layer"**

J. Forneris et al., Nucl. Instr. Meth. Phys. Res. B 306, 181-185 (2013)

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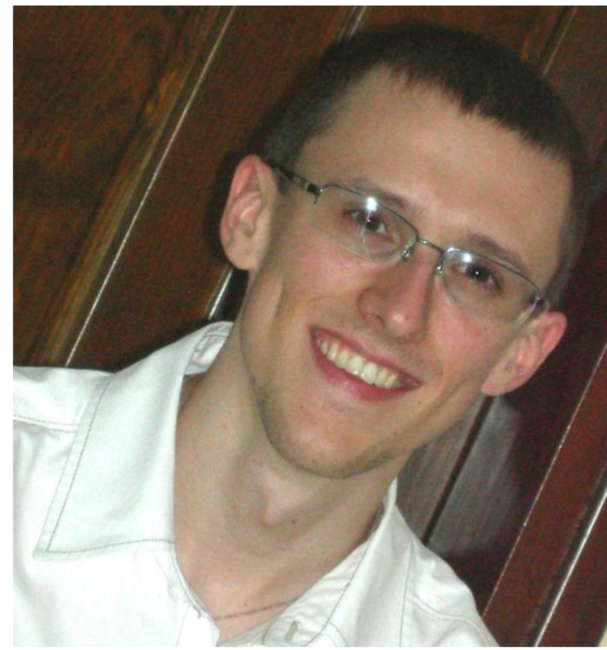
Biosensing

INFN projects “DINAMO” & “DIACELL”

F. Picollo



Federico Picollo

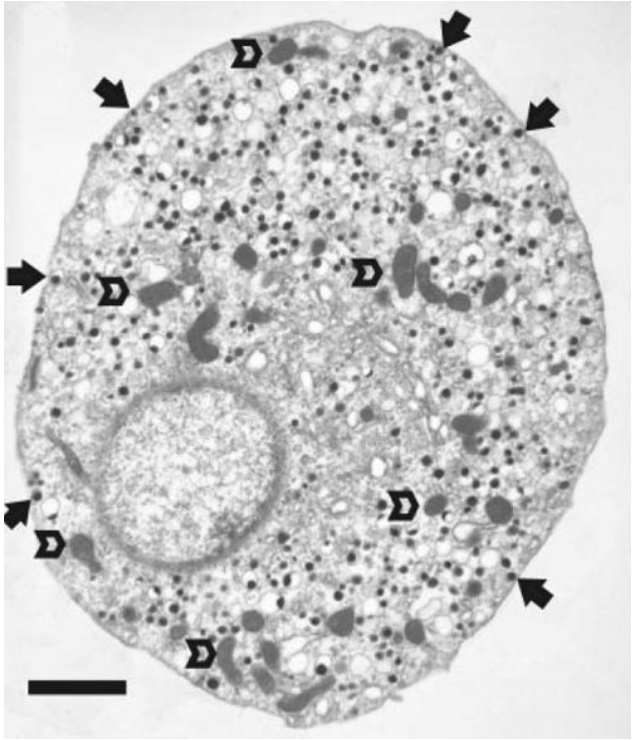
Biosensing

A viable model of neuronal excitation-secretion

- ✓ Easily available, large dimensions (>10 µm)
- ✓ Voltage-gated Ca^{2+} channels
- ✓ Electrically excitable
- ✓ Containing chromaffin granules

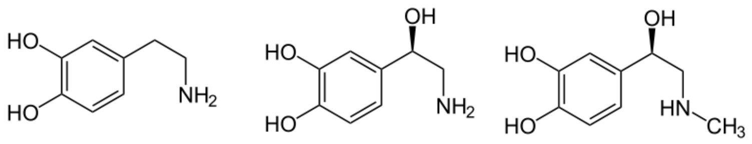
Diameter = 50-300 nm

Catecholamines concentration = 0.5-1 M
(~10^6 molecules each granule)



C. Grabneret al., J. Neurophysiol 94, 2093 (2005)

Catecholamines



dopamine noradrenaline adrenaline

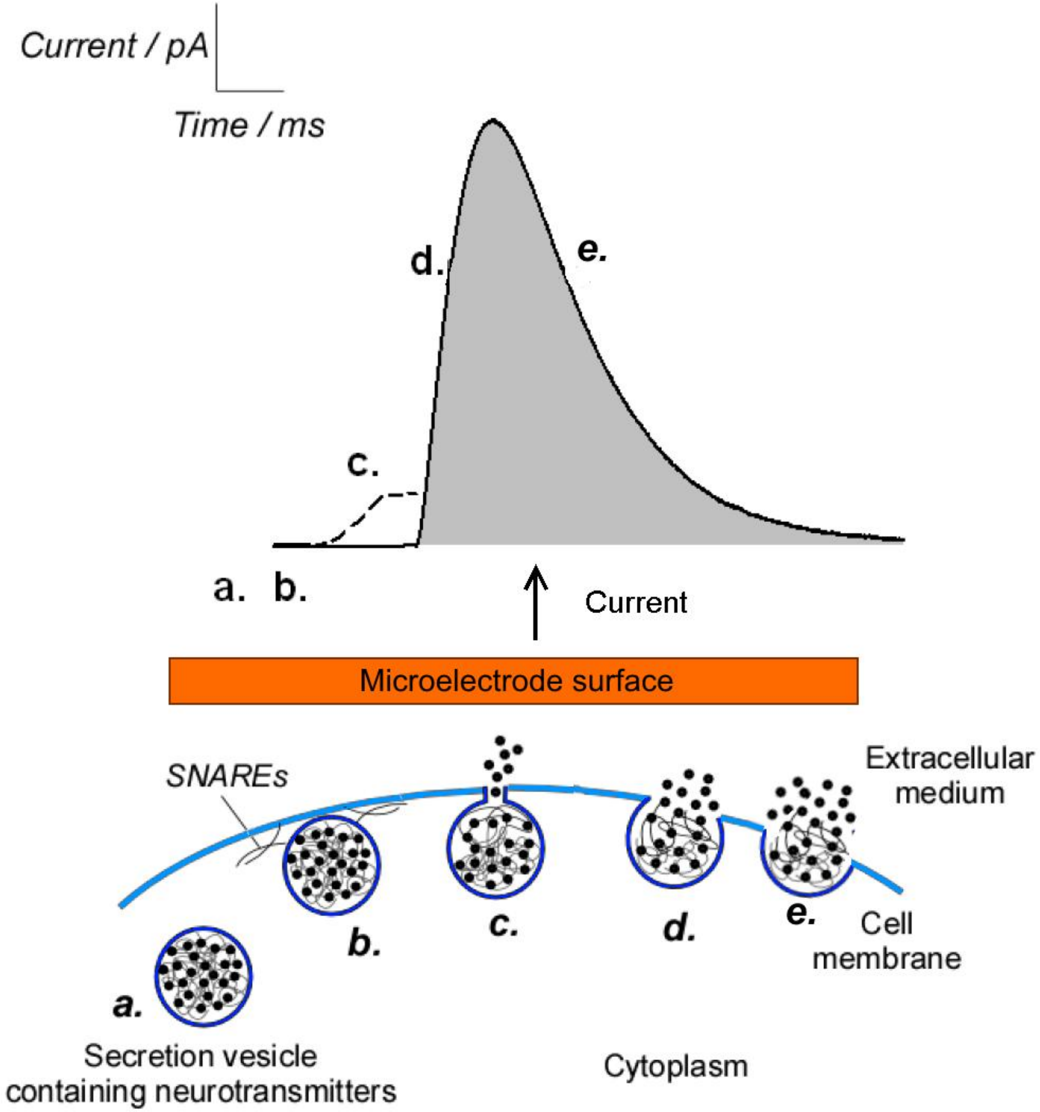
Biosensing

✓ Secretion of catecholamines from vesicles in which they are highly concentrated → strong signal

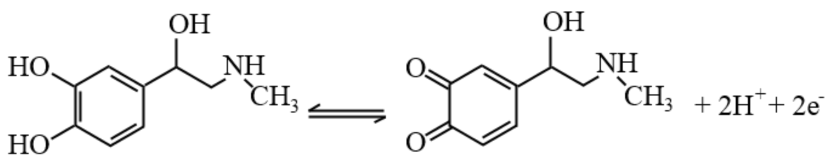
✓ Time duration: 50-100 ms

✓ Amperometric detection of the oxidized species in correspondence of a biased μ-electrode

✓ Electrical or chemical stimulation



Adrenaline oxidation



F. Lemâtre et al., Electrochim. Acta 140, 457 (2014)

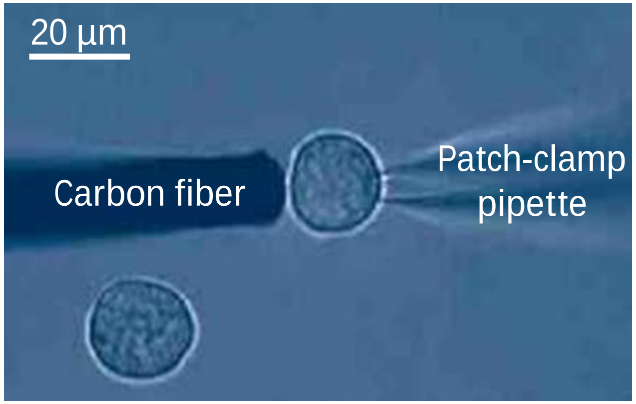
Biosensing

Carbon fibers

Biased carbon fiber microelectrode bought in close physical proximity of a single cell held by a patch-clamp pipette:

✓ not easily scalable

✓ **manipulation (→ stress) of the cell,** and of the CF



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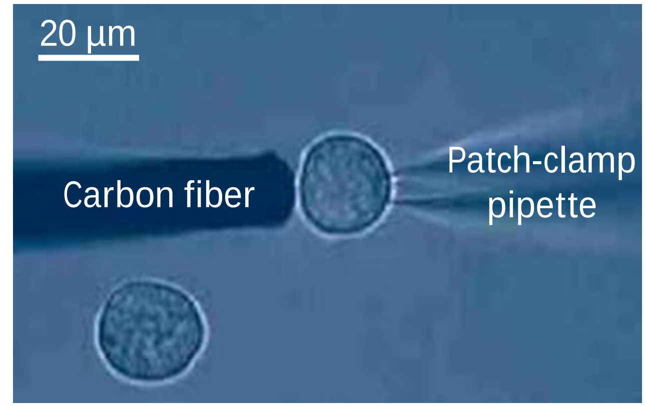
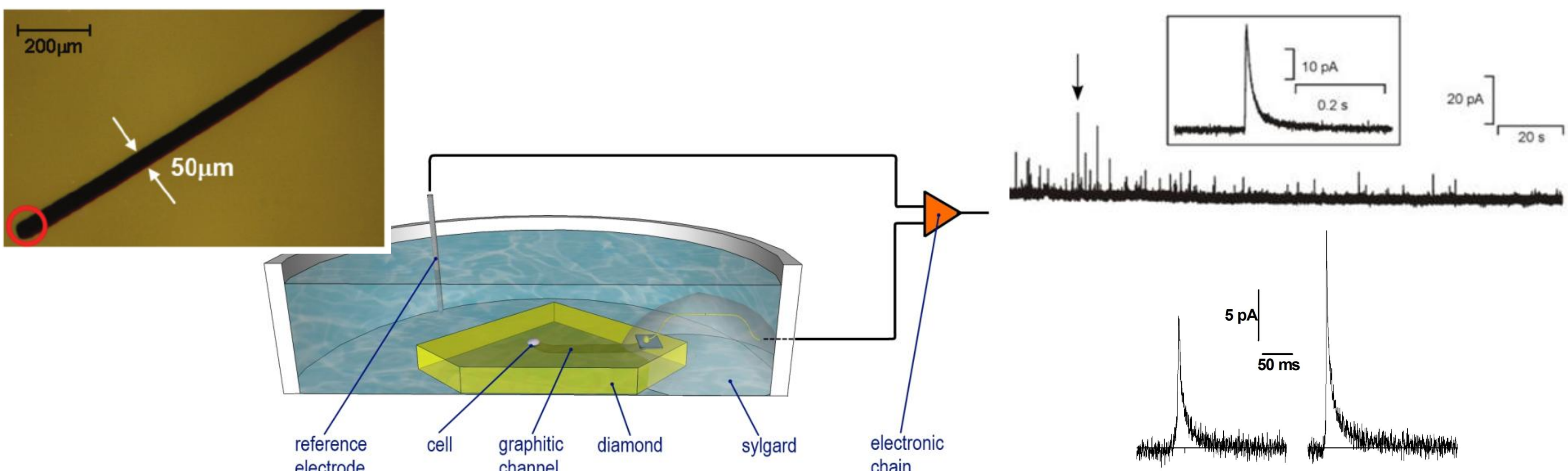


Single-electrode integrated device in diamond

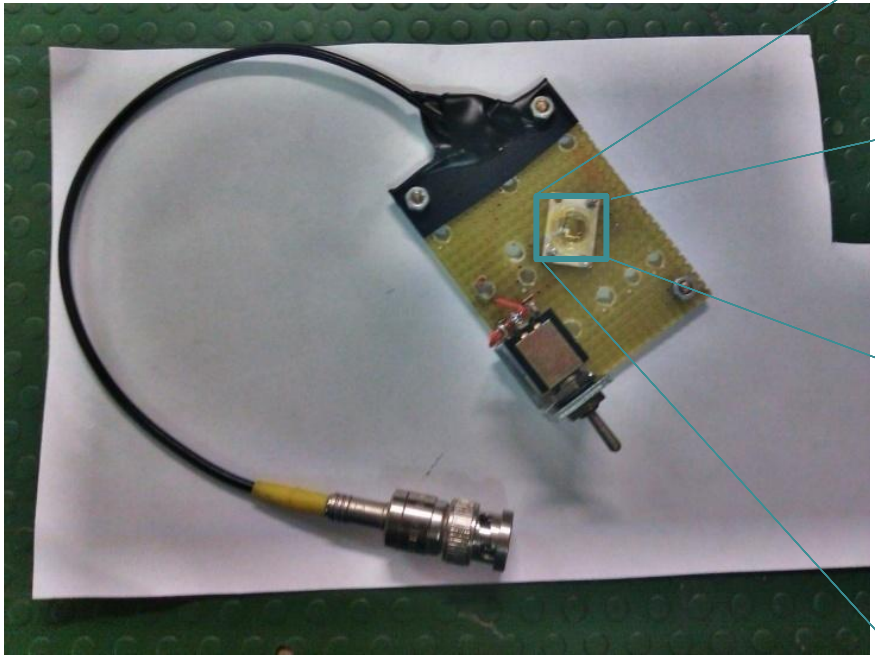


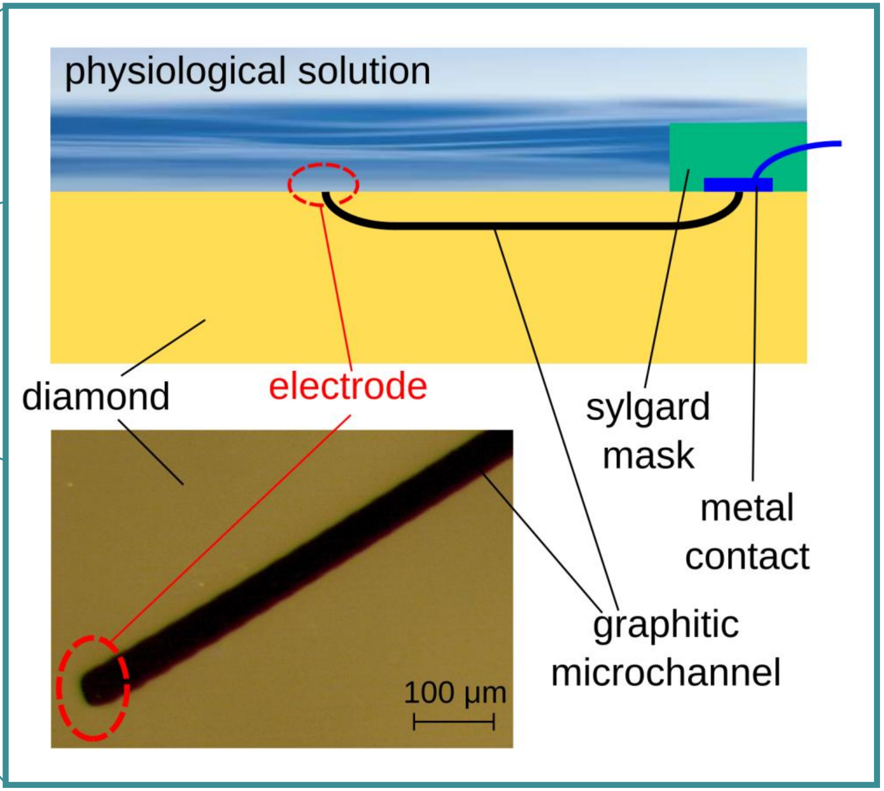
F. Picollo et al., Adv. Mater. 25, 4696 (2013)

Biosensing

Device fabrication

- 3×3×1.5 mm^2 type Ib single crystal HPHT diamond
- 1.8 MeV He^+ implantation at 5×10^{17} cm^{-2} fluence @ INFN Legnaro National Labs
- 1100 °C annealing for 2 hrs in vacuum
- mounting and contacting

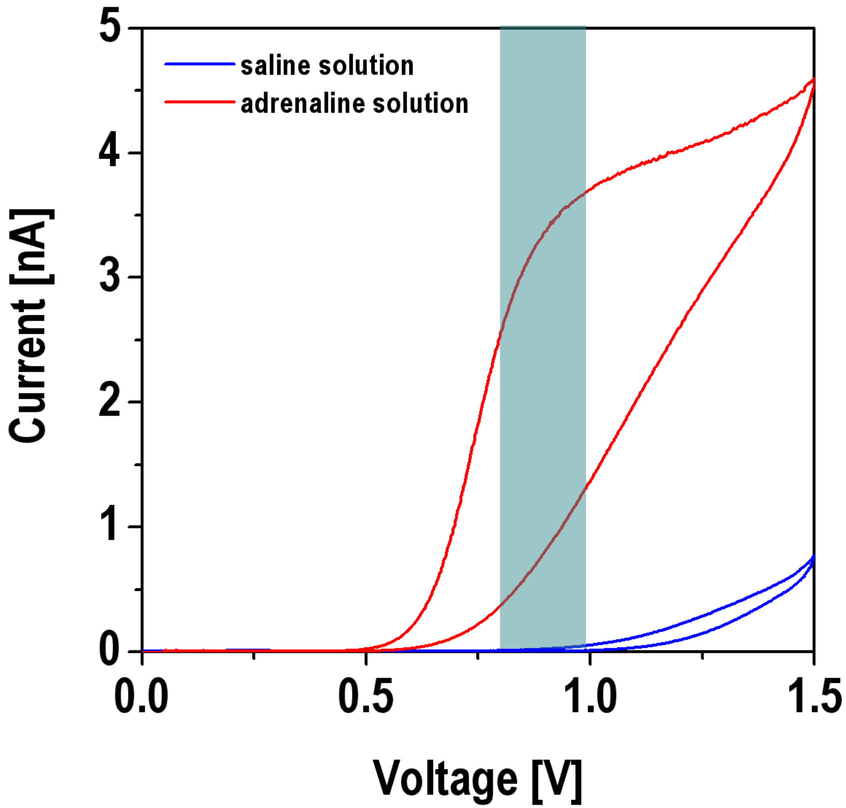


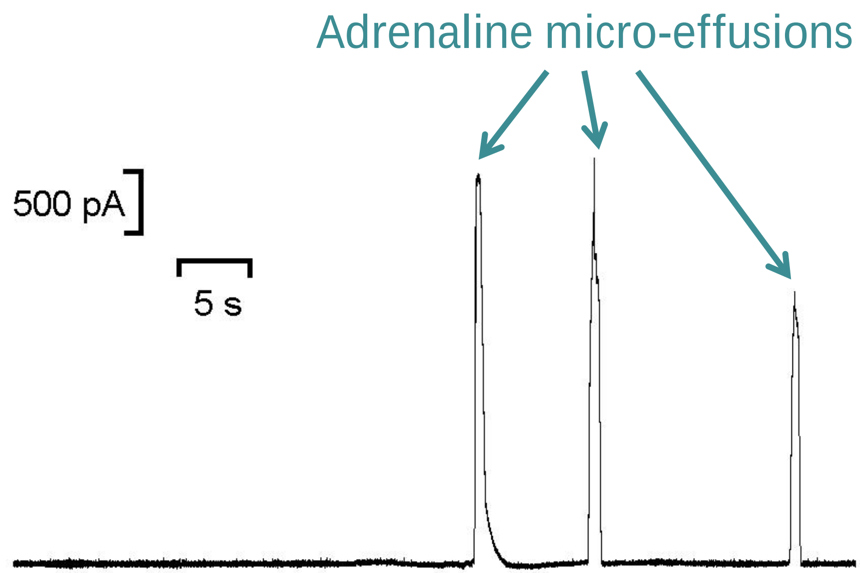


Biosensing

Cyclic voltammetry: oxidation of adrenaline at the biased electrode

Preliminary sensitivity test: micro-effusion of adrenaline with a syringe





Saline solution (in mM): 128 NaCl, 2 $MgCl_2$, 10 glucose, 10 HEPES, 10 $CaCl_2$. 4 KCl
Adrenaline solution: saline solution + adrenaline (10 mM)

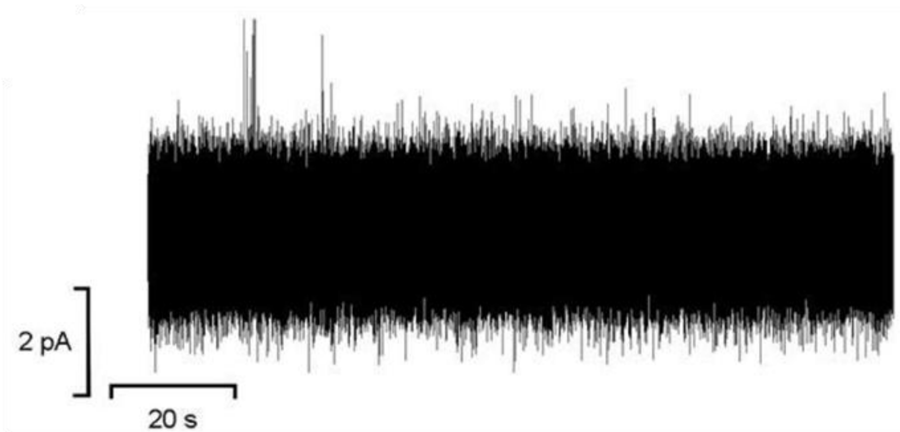
DSTF DIPARTIMENTO DI SCIENZA E TECNOLOGIA DEL FARMACO UNIVERSITÀ DEGLI STUDI DI TORINO

Biosensing

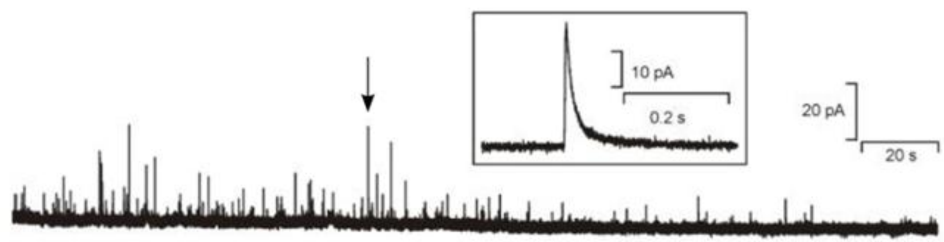
Exocytosis detection from a single chromaffin cell

Cell manipulation and positioning: glass patch-clamp pipette

Non-stimulated cell



Stimulated cell



Solution (in mM): 128 NaCl, 2 $MgCl_2$, 10 glucose, 10 HEPES, 10 $CaCl_2$, 4 KCl

Solution (in mM): 100 NaCl, 2 $MgCl_2$, 10 glucose, 10 HEPES, 10 $CaCl_2$, 30 KCl

F. Picollo et al., Advanced Materials 25 (34), 4696-4700 (2013)

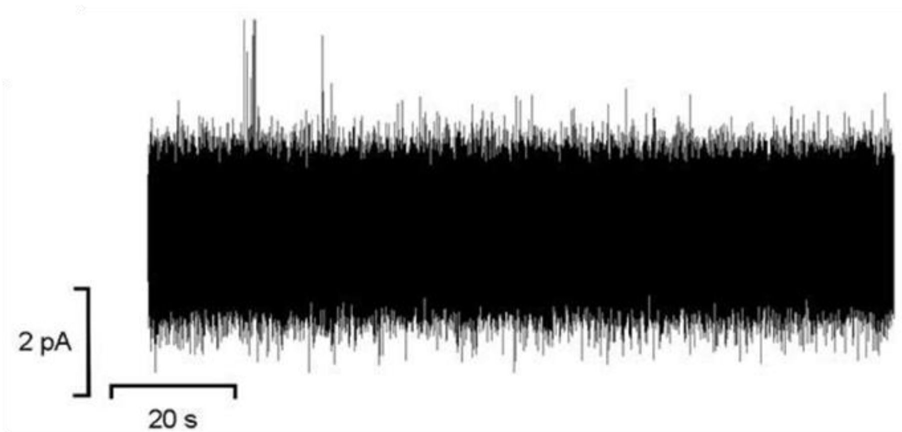
DIPARTIMENTO DI SCIENZA E TECNOLOGIA DEL FARMACO
UNIVERSITÀ DEGLI STUDI DI TORINO

Biosensing

Exocytosis detection from a single chromaffin cell

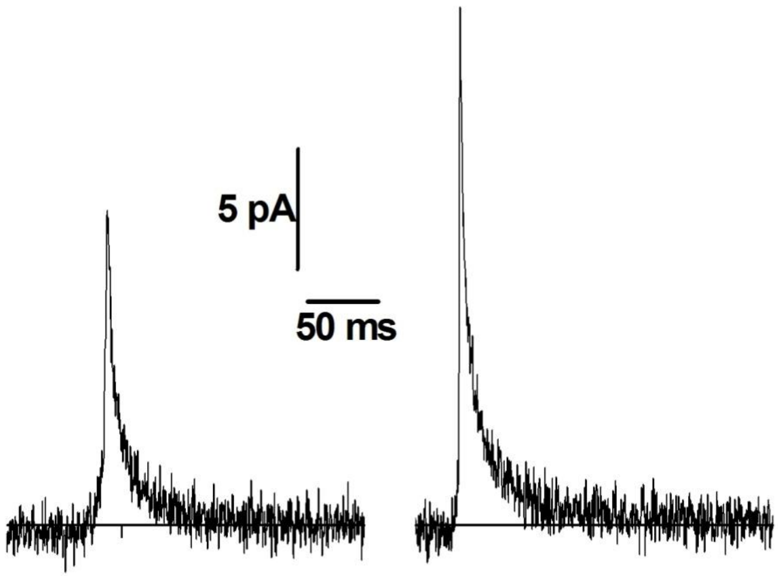
Cell manipulation and positioning: glass patch-clamp pipette

Non-stimulated cell



Solution (in mM): 128 NaCl, 2 $MgCl_2$, 10 glucose, 10 HEPES, 10 $CaCl_2$, 4 KCl

Stimulated cell



Solution (in mM): 100 NaCl, 2 $MgCl_2$, 10 glucose, 10 HEPES, 10 $CaCl_2$, 30 KCl

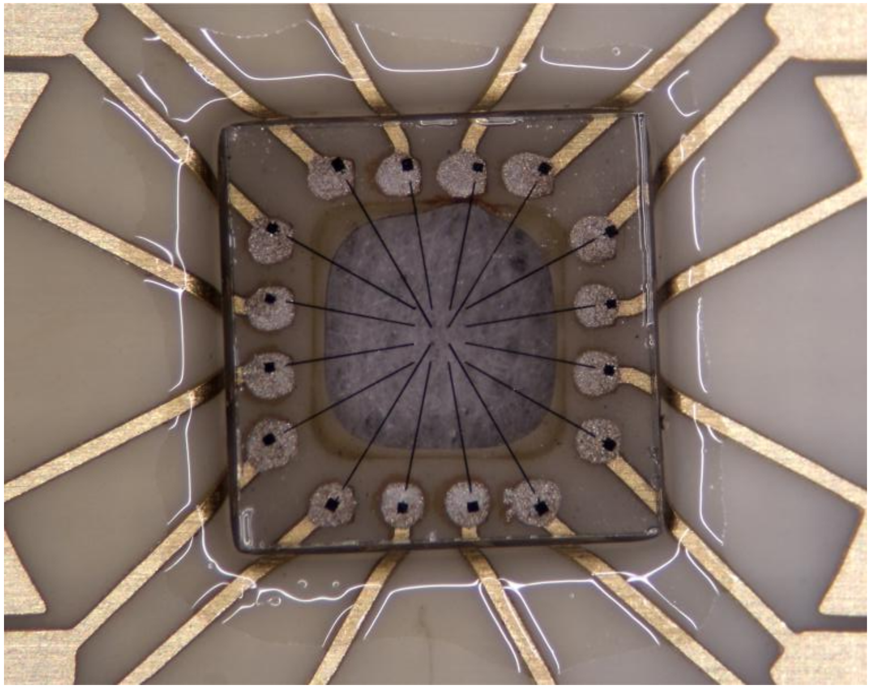
F. Picollo et al., Advanced Materials 25 (34), 4696-4700 (2013)

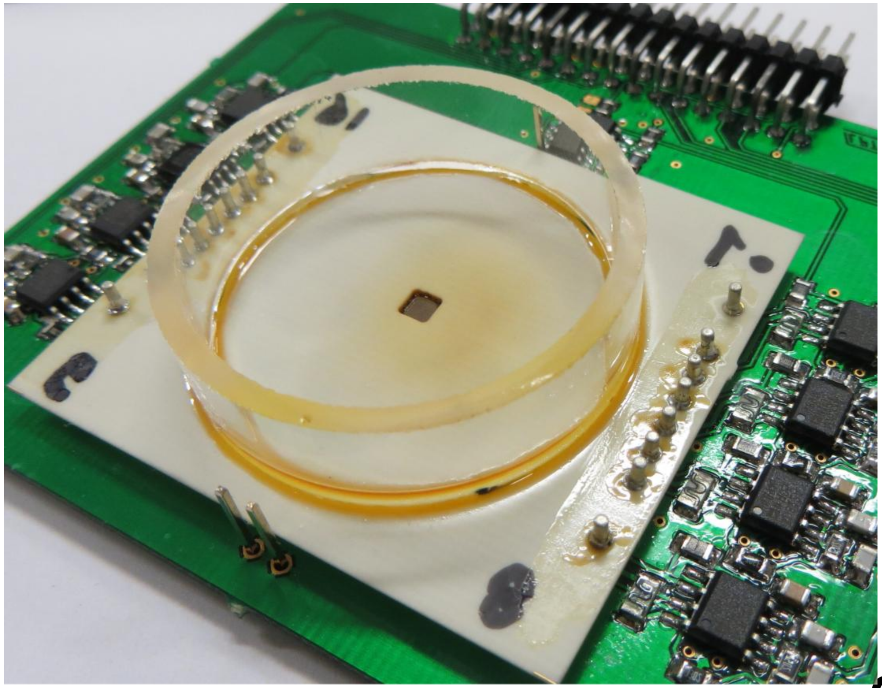
Biosensing

Samples:
- single-crystal type IIa CVD from ElementSix™
- $4.5 \times 4.5 \times 0.5$ mm^3

Ion implantation:
- He^+ @ 1.2 MeV
- fluence 1.2×10^{17} cm^{-2}
- penetration depth: ~2 μm

Thermal anealing:
- vacuum
- 950 °C
- 2 hrs

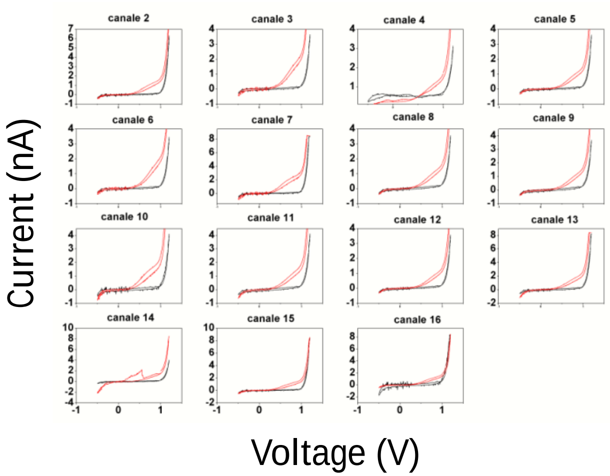




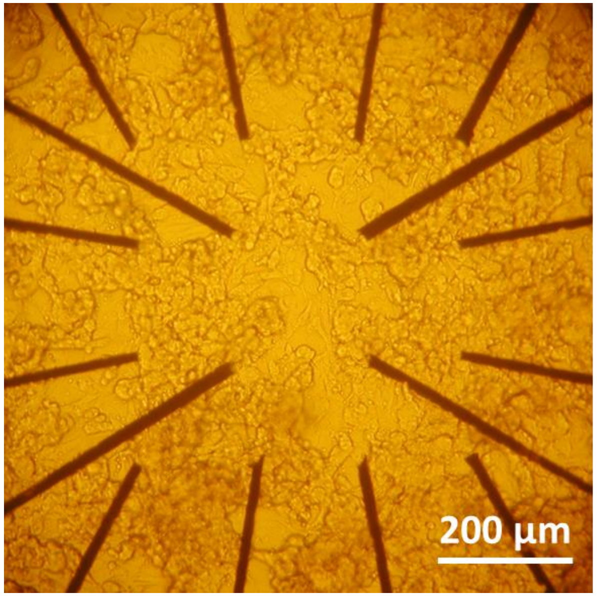
Biosensing

Exocytosis detection from a cultured chromaffin cells

Cyclic voltammetry:
- solution: tyrode / tyrode + 100 µm adrenaline
- 0.8 V: adrenaline oxidation

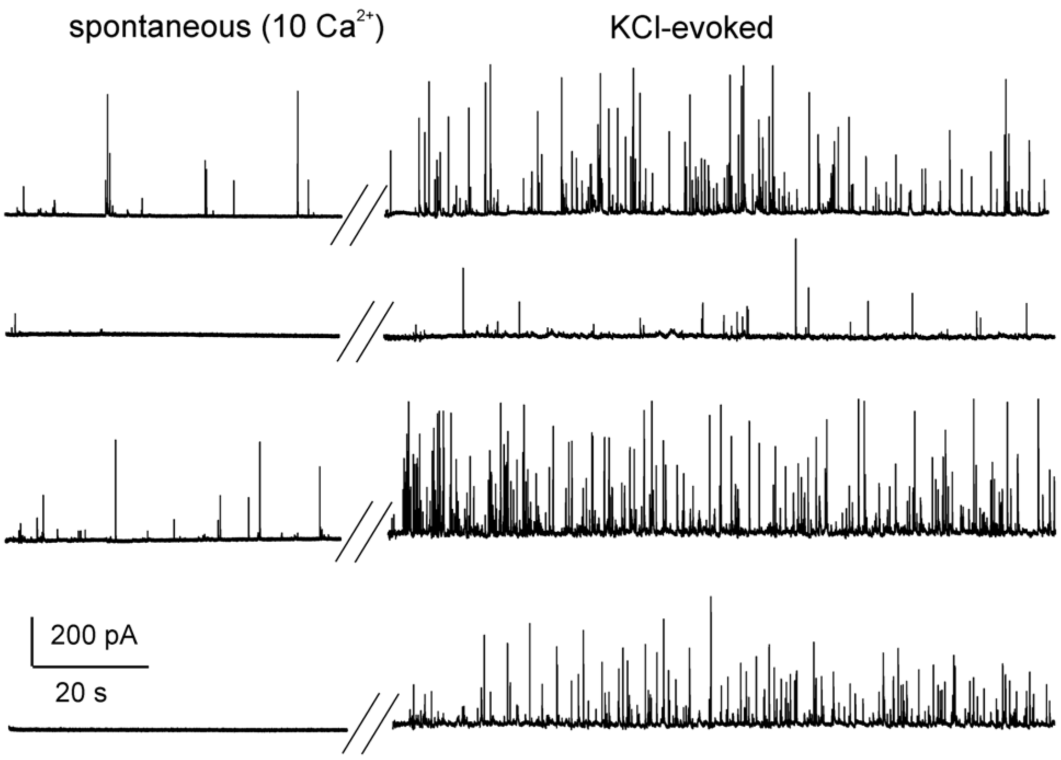


Plated chromaffin cells:
- from bovine adrenal glands
- ~150.000 cells plated on chip
- cultured for 4 days (37 °C, H_20-saturated atmosphere with 5% CO_2)



Biosensing

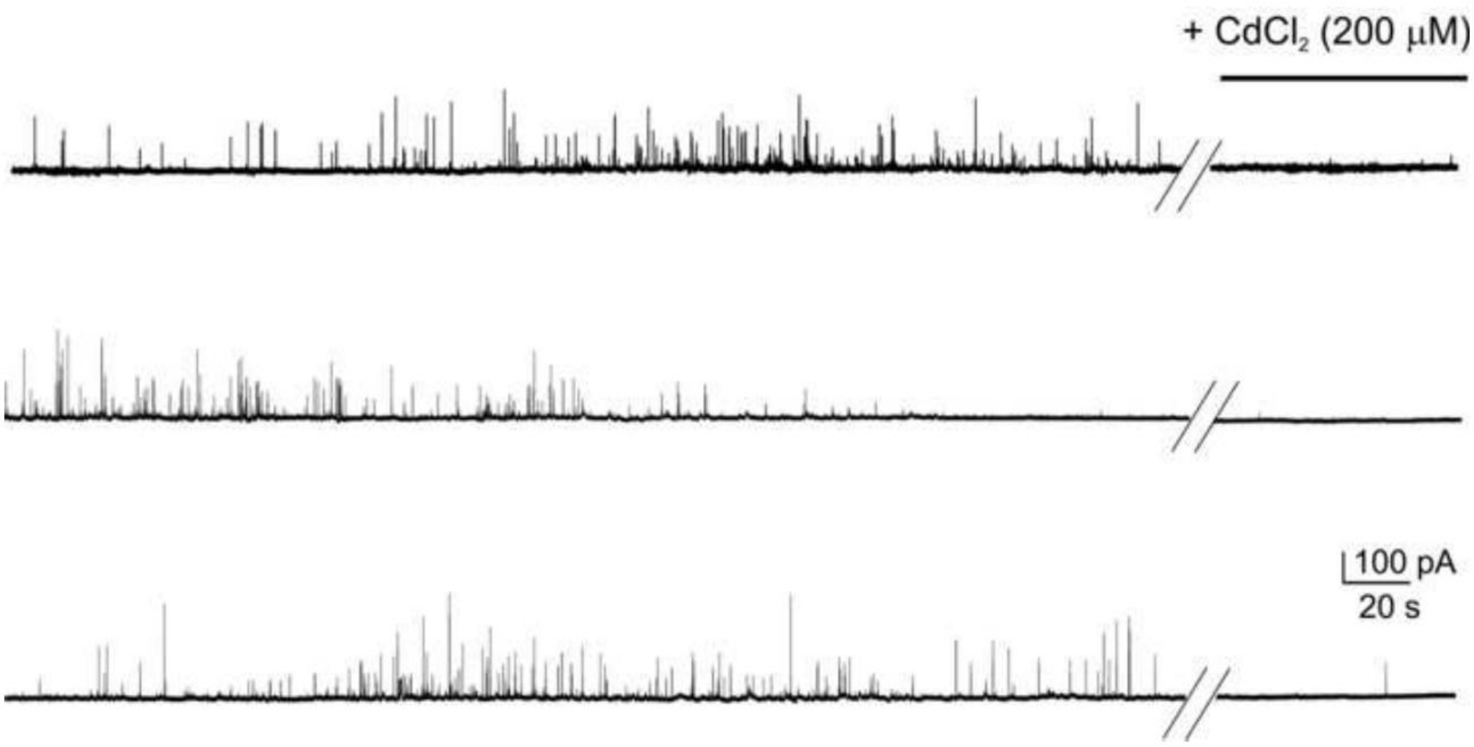
Chrono-amperometric recordings



- ✓ Bias voltage: +800 mV
- ✓ Individual cells in close proximity of the electrode
- ✓ Spontaneous activity in 10 mM Ca^{2+} solution (0.08 Hz)
- ✓ Chemical stimulation with 30 mM KCl solution (0.9 Hz)

Biosensing

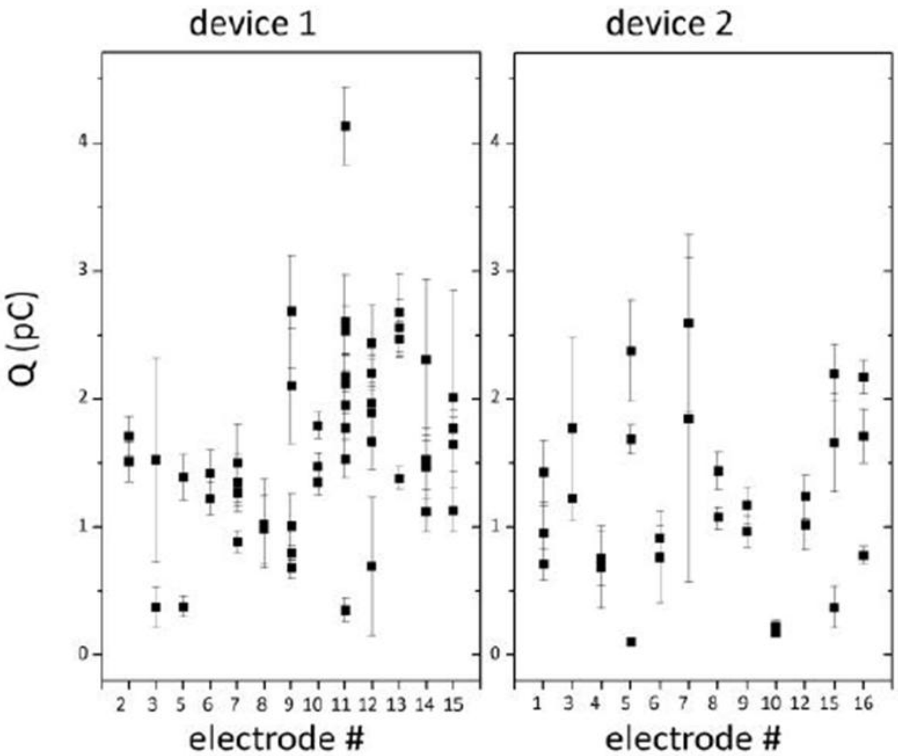
Chrono-amperometric recordings

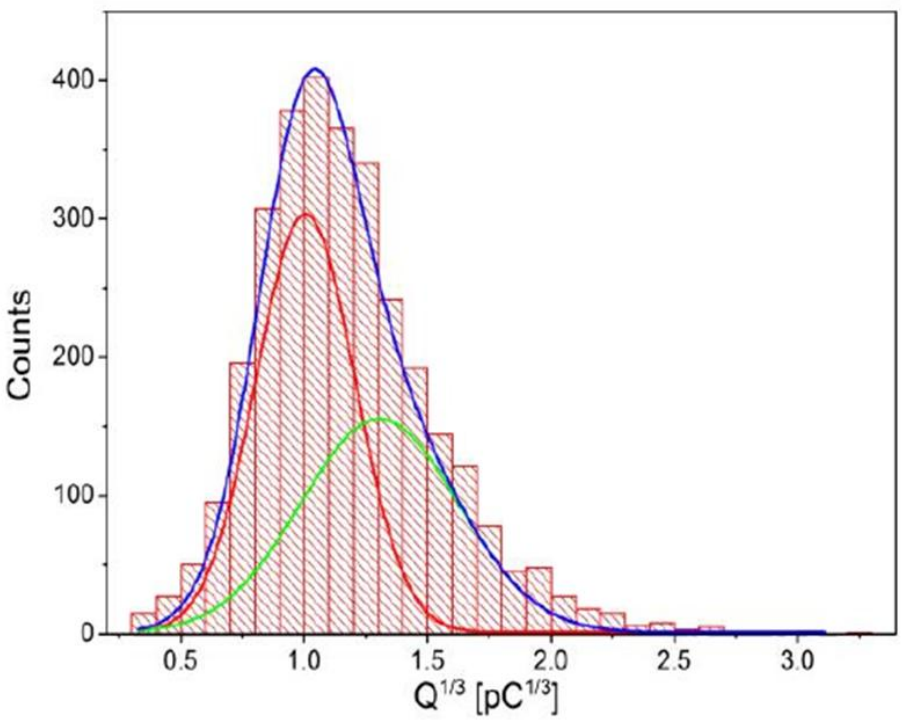


- ✓ Bias voltage: +800 mV
- ✓ Individual cells in close proximity of the electrode
- ✓ Chemical suppression in 200 μm $CdCl_2$ solution

Biosensing

Signal statistics



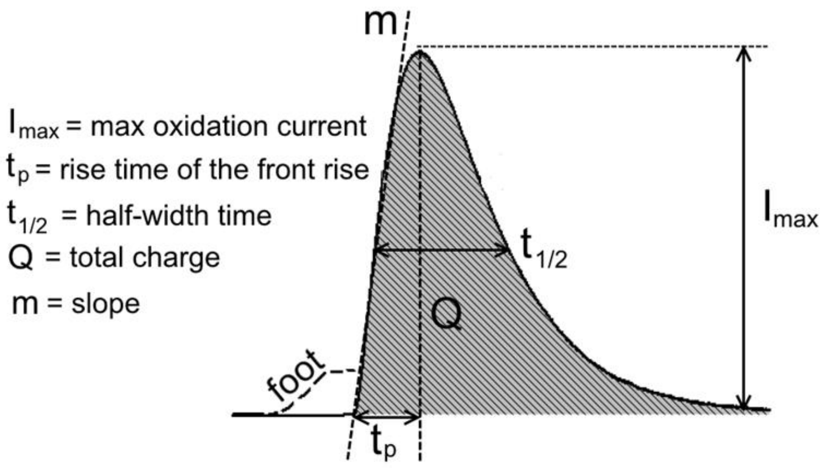


- ✓ Device reproducibility
- ✓ Variations due to cell behavior

- ✓ Full fusion events
- ✓ **“Kiss**-and-**run” events (smaller** events with faster kinetics)

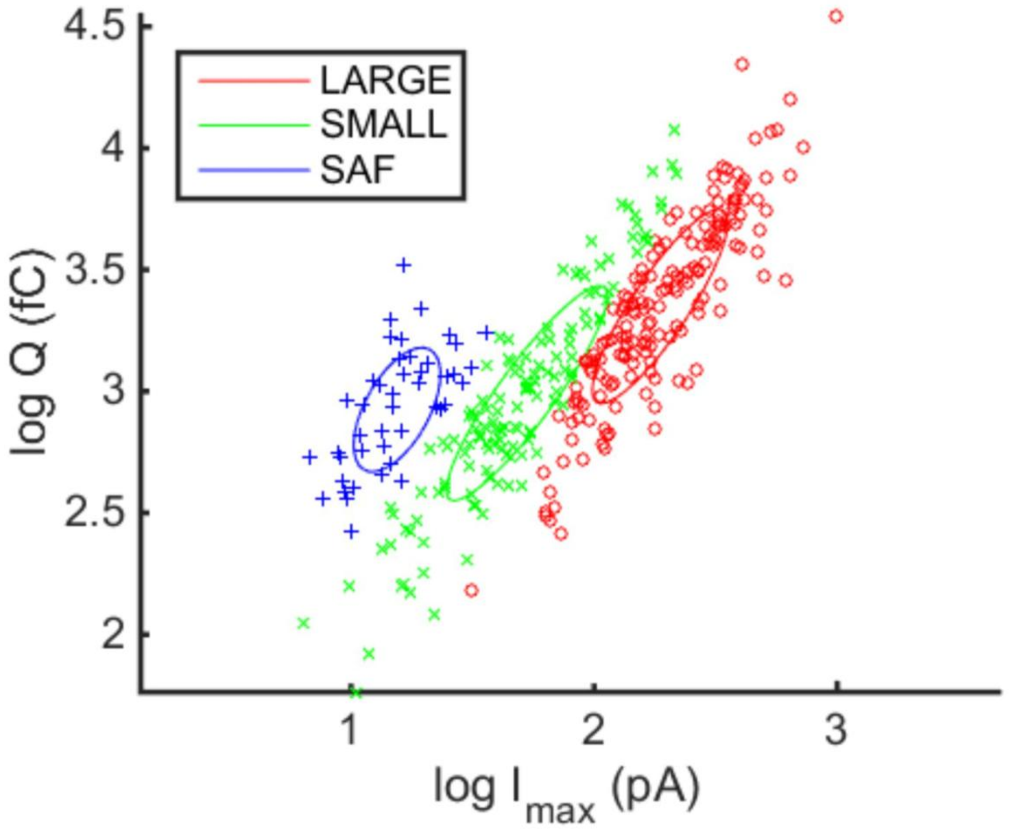
Signal statistics

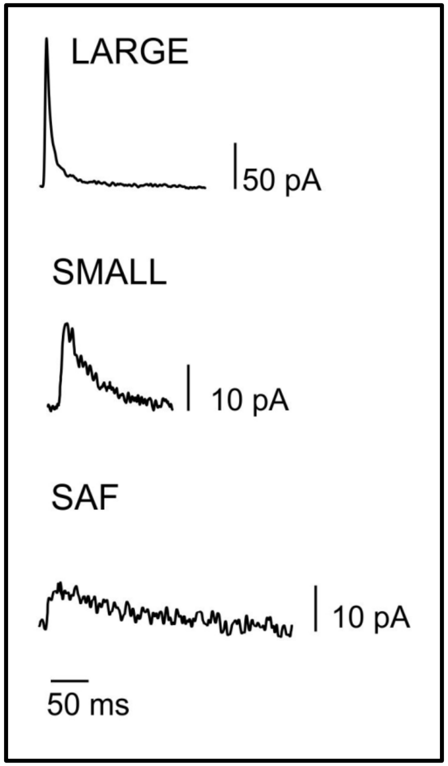
	I_{max} (pA)	Q (pC)	$Q^{1/3}$ ($pC^{1/3}$)	$t_{1/2}$ (ms)	m (nA s^{-1})	t_p (ms)	# spikes	# cells
SCD-MEA: cultured cells	74	1.56	1.06	17.0	21	8.3	3003	70
	±5	±0.09	±0.02	±0.7	±2	±0.4		
CFE (cultured cells on diamond plate)	82	1.4	0.97	17.2	33	8.0	495	14
	±13	±0.2	±0.05	±1.6	±6	±0.8		
Literature ‡ and §	73 ‡	1.40 ‡	1.06 §	16.0 ‡	24.2 ‡	18.2 ‡	778 ‡	12 ‡
	±3	±0.06	±0.04	±0.5	±1.1	±1.0		



‡ J. D. Machado et al., Mol. Pharmacol. 60, 514 (2001)
§ J. M. Finnegan et al., J. Neurochem. 66, 1914 (1996)

Signal statistics

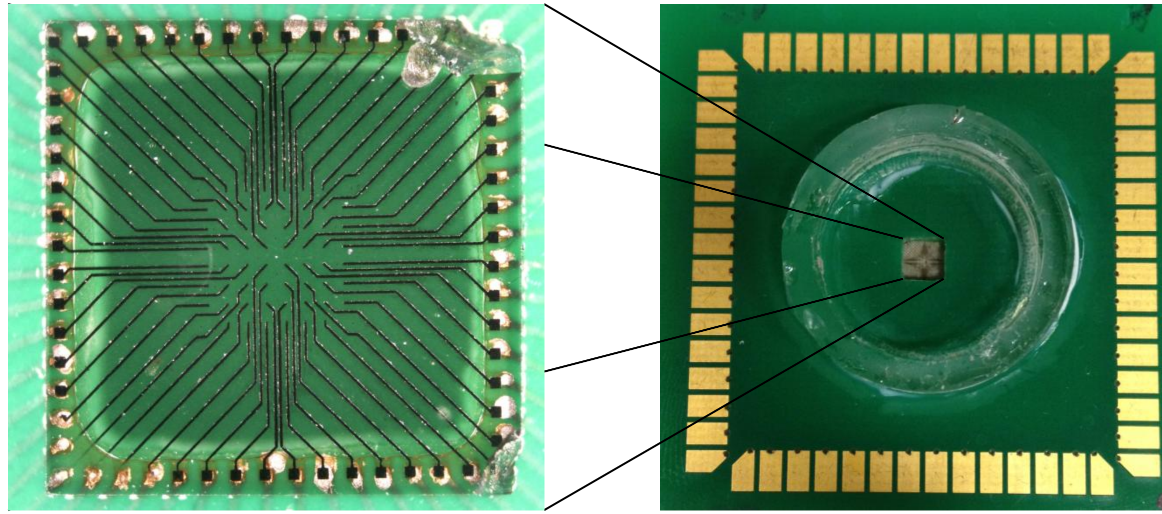




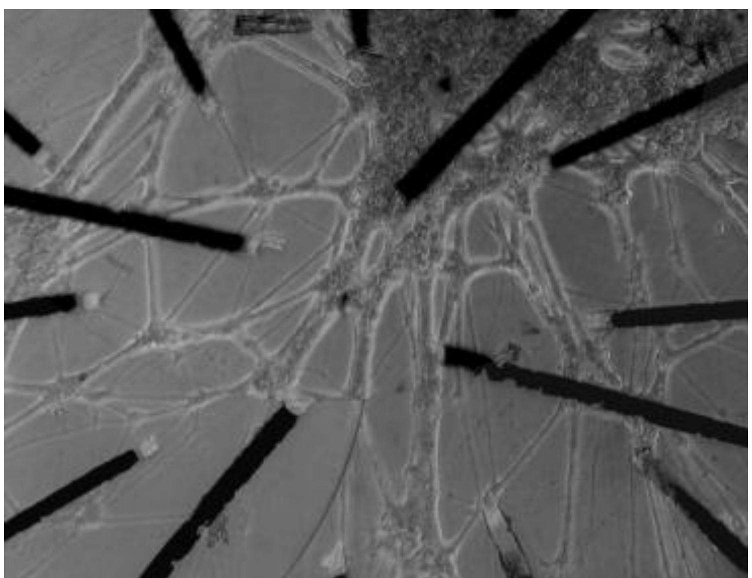
- ✓ 2D Gaussian mixture analysis
- ✓ 3-**modal distribution: large ("full fusion"), small ("kiss**-and-**run") and** stand-**alone foot ("kiss**-and-**stay") events**

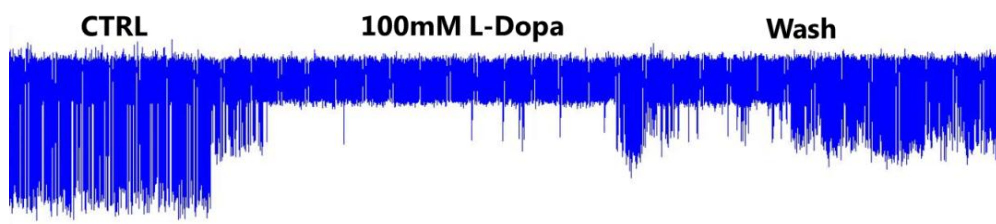
Biosensing

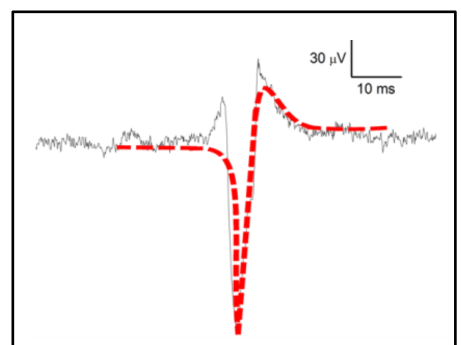
64 channels
micro-electrode array



substantia nigra neurons

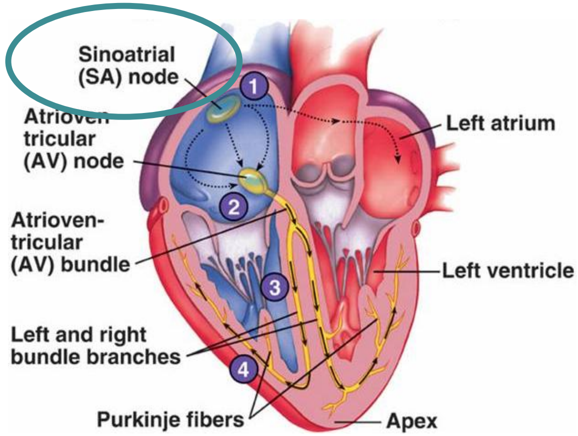


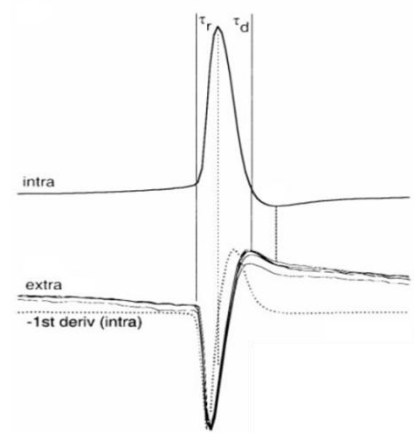


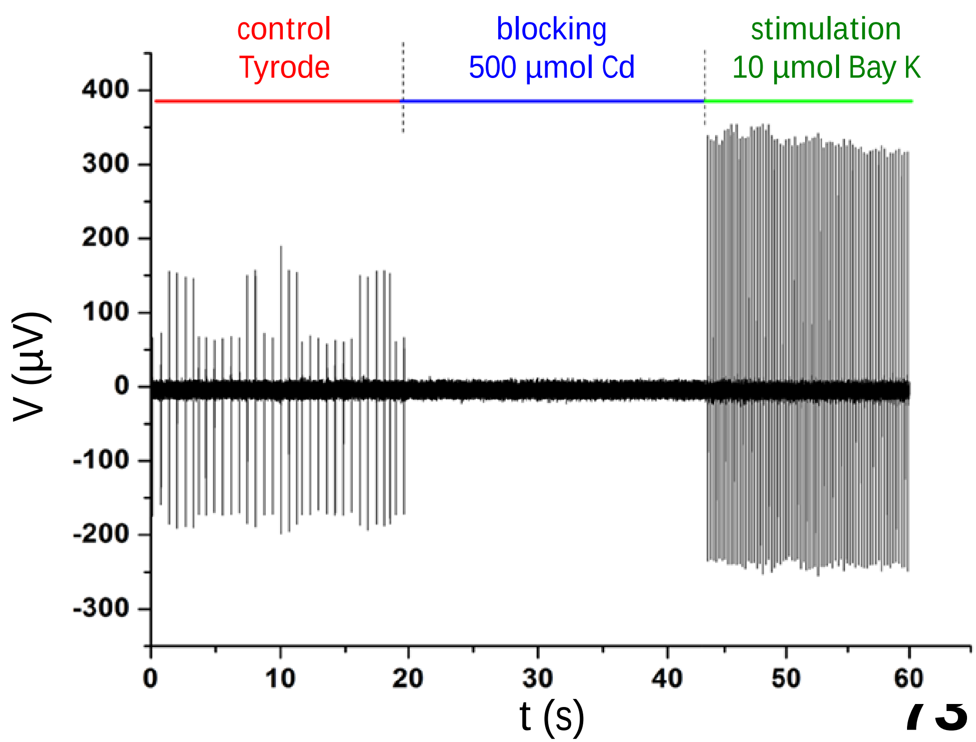


Biosensing

Detection of the
action potential

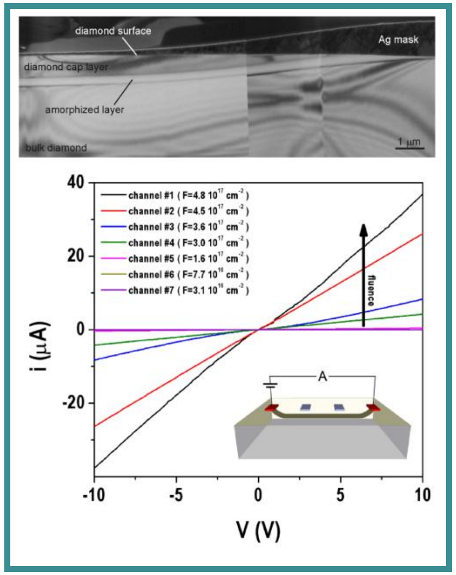




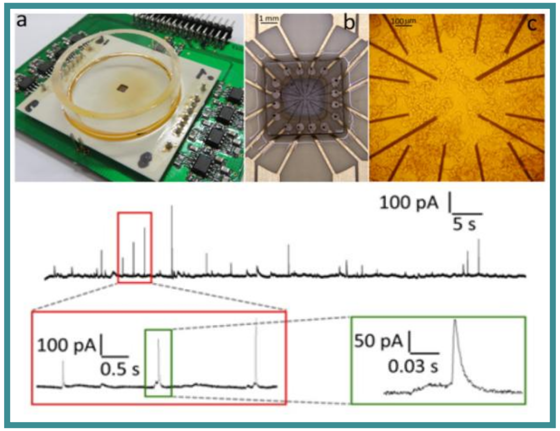


Biosensing

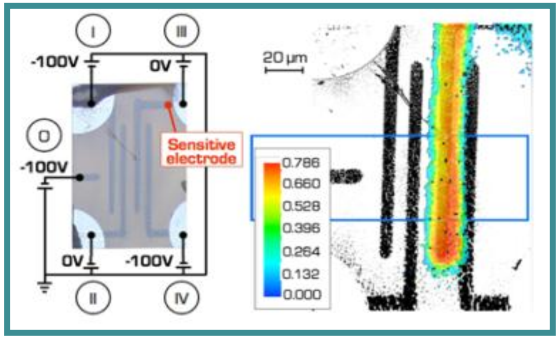
DIACELL: development of artificial diamond devices for the simultaneous detection of cell signals and ionizing radiation for applications in micro-radiobiology



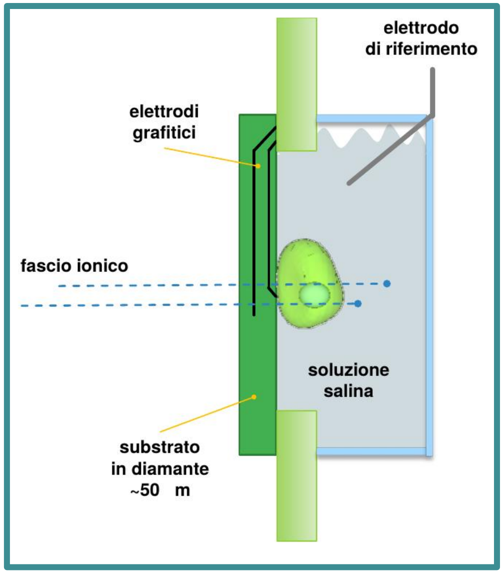
Deep ion beam lithography



Cellular bio-sensors
(→ DiNaMo)



Radiation detectors
(→ DiaRad)

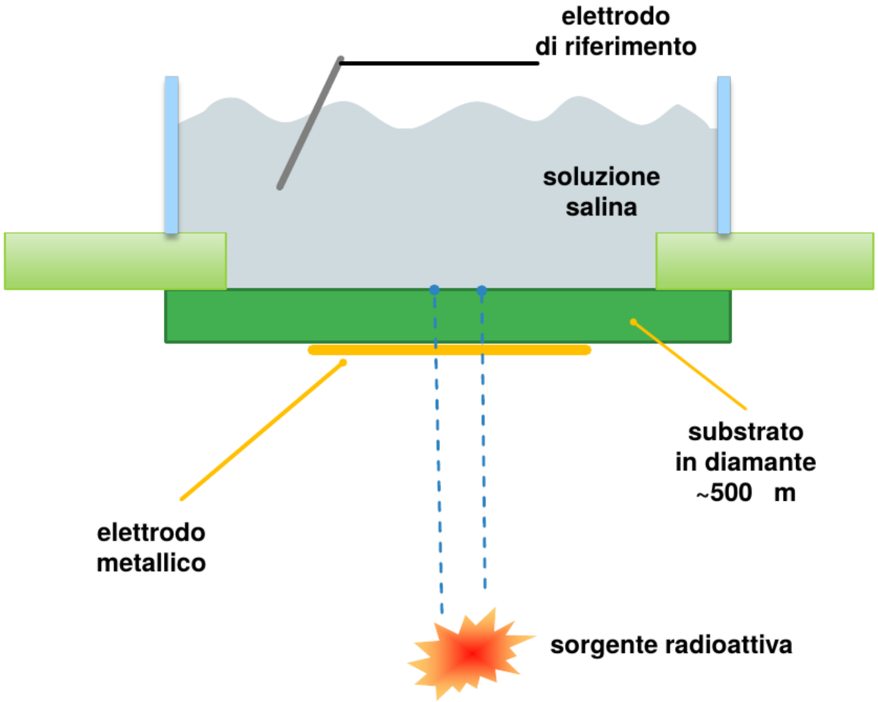


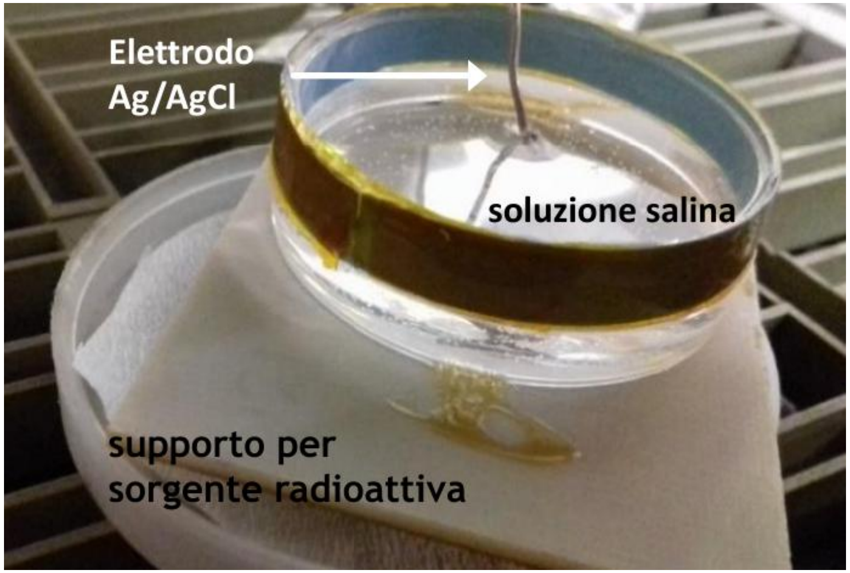
Integrated device

Biosensing

DIACELL: preliminary results

Counter-electrode in solution

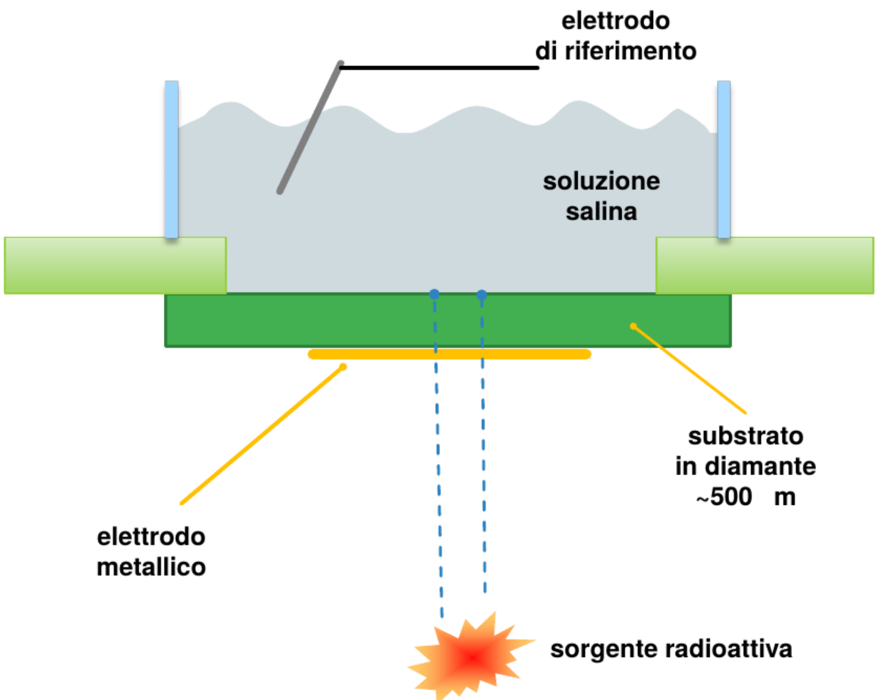


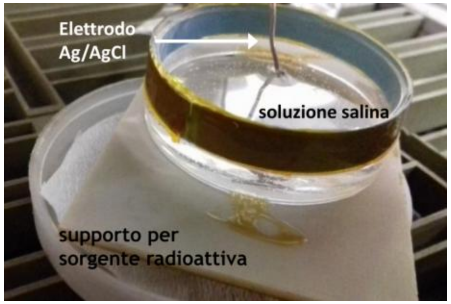


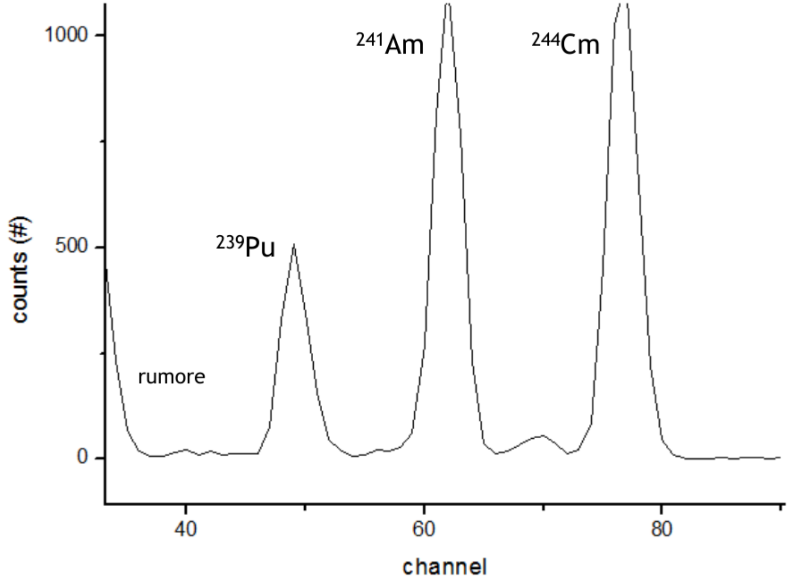
Biosensing

DIACELL: preliminary results

Counter-electrode in solution



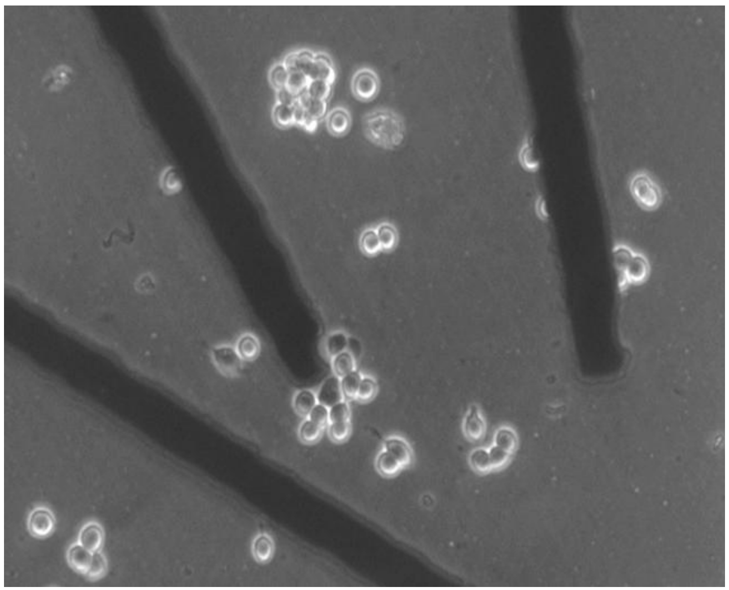


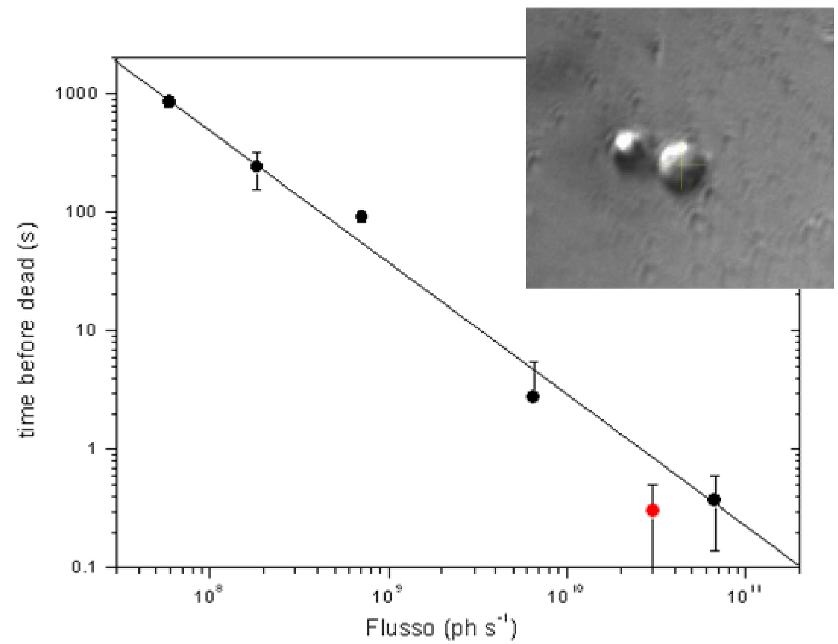


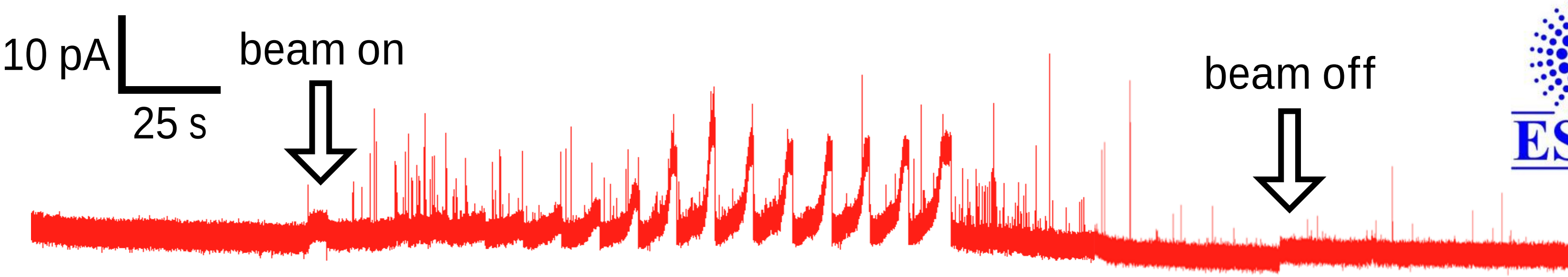
Biosensing

DIACELL: preliminary results

Test run @ ESRF: 17 keV photons, 10^8 - 10^{11} photons s^{-1}, $\varnothing_{beam}$ = 20-200 nm







ESRF

- Diamond
- IBL in diamond
  - → Basic concepts
  - → State of the art
- Current research activities @ UniTo & INFN-To
  - → **Electrical** features
  - → Radiation detection
  - → Biosensing
  - → Quantum Optics
- Conclusions

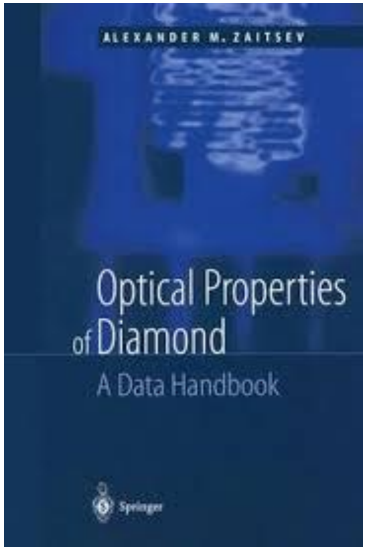
Quantum optics

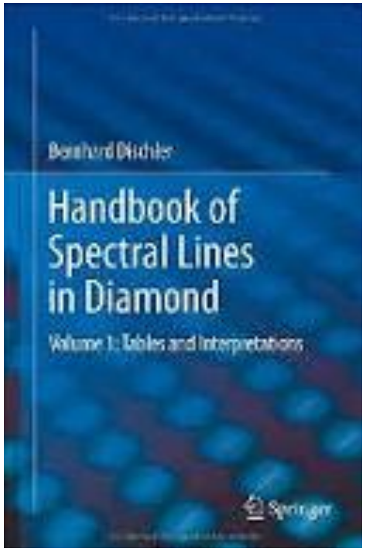
INFN project “DIESIS”

J. Forneris

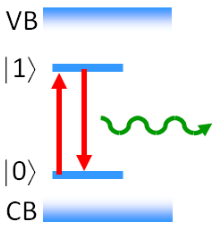
Jacopo Forneris

Quantum optics

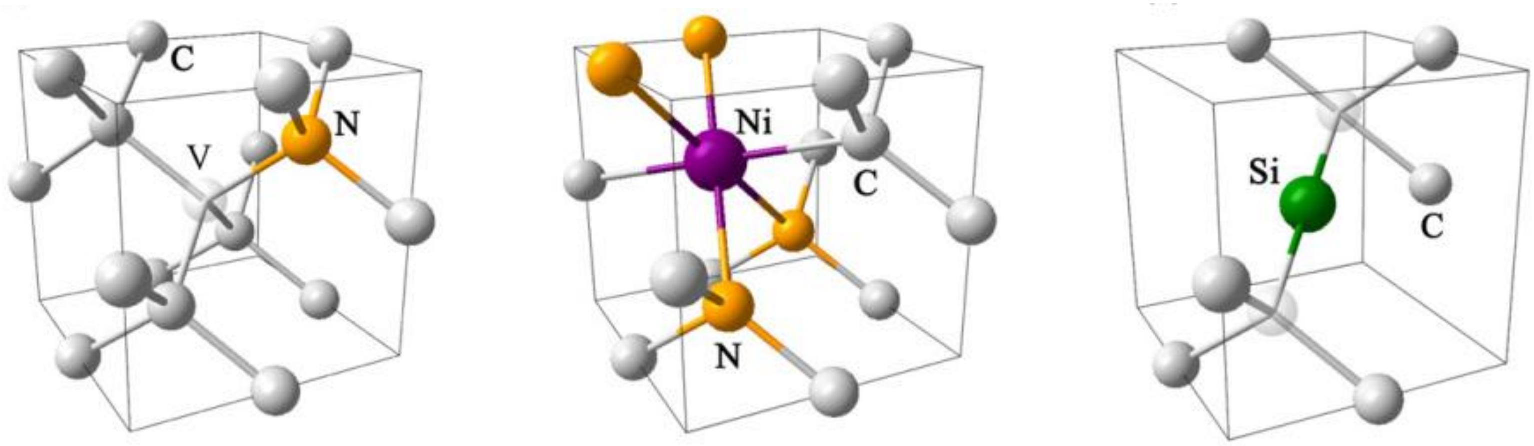




Eg = 5.49 eV
range of defects and impurities
low phonon density

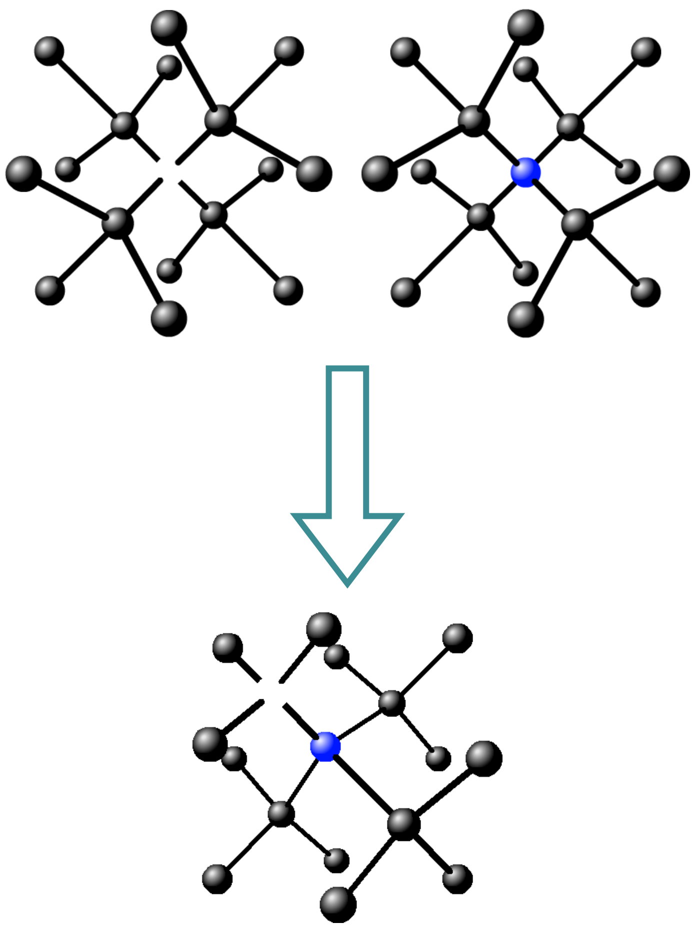


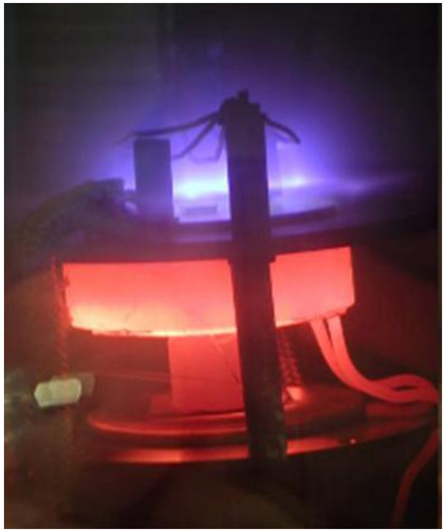
wide transparency from NUV to far IR
>150 vibrational & >500 electronic optically active centers
many centers are characterized by high quantum efficiency and photo-stability at room temperature
some centers display a convenient level structure for spintronics

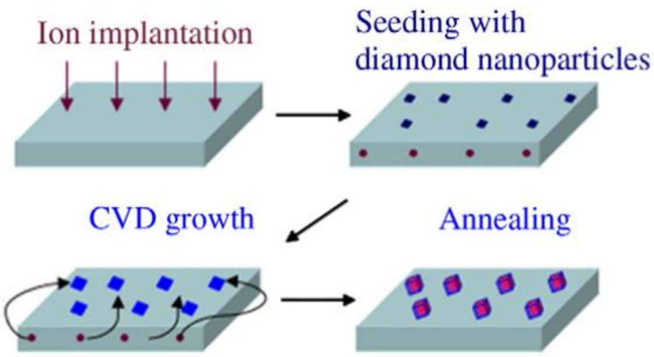


→ single photon emitters (quantum cryptography, quantum optics)

Creation of NV centers via
CVD growth



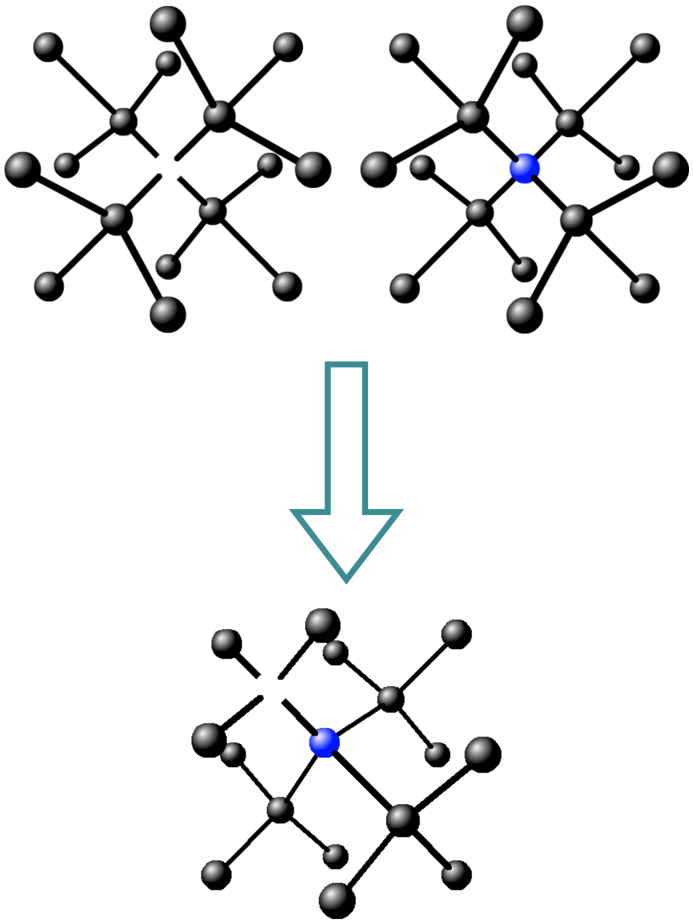


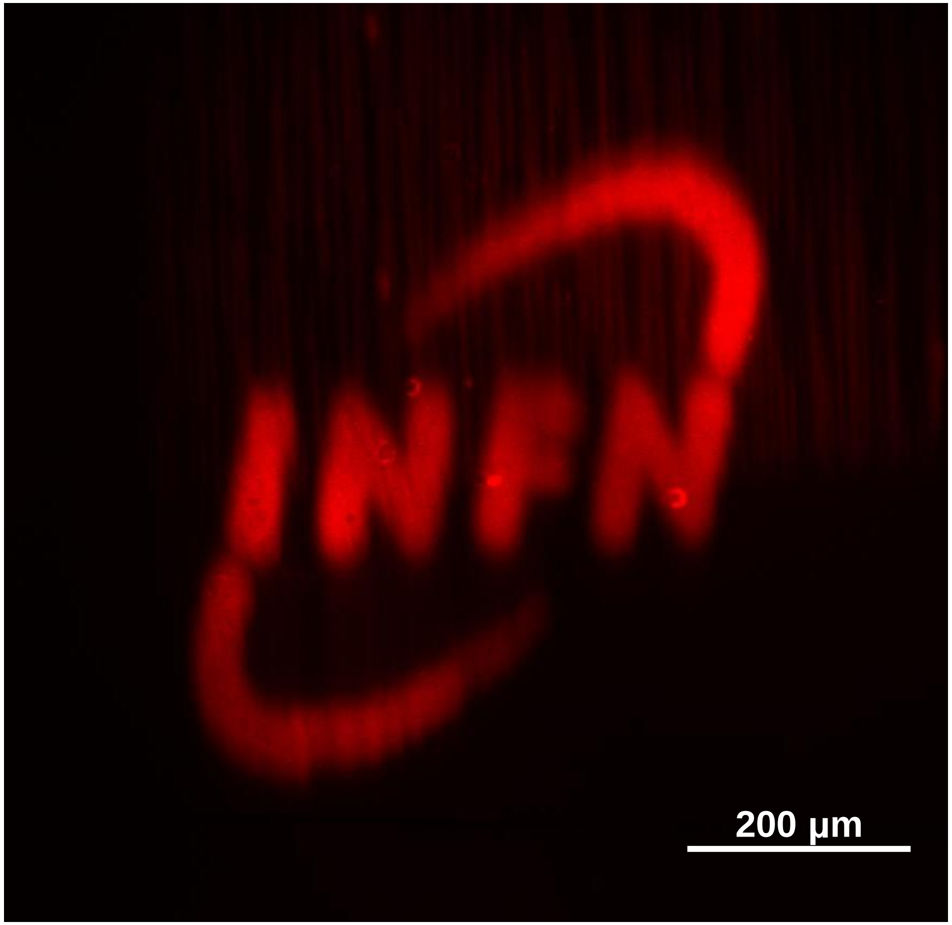


I. Aharonovic, S. Prawer, Diamond Relat. Mater. 19, 729 (2010)

Quantum optics

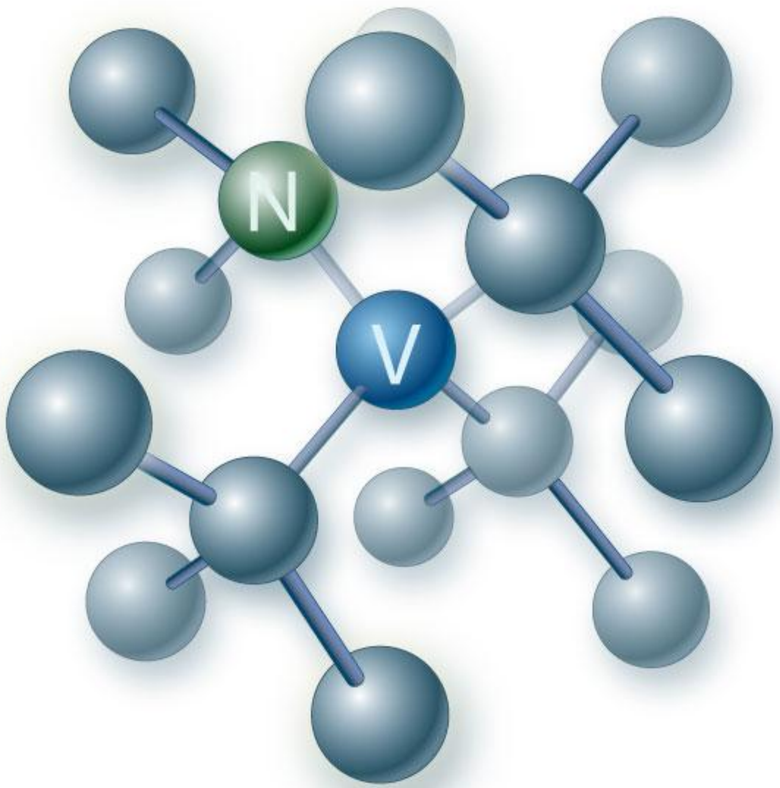
Creation of NV centers via
ion implantation & annealing

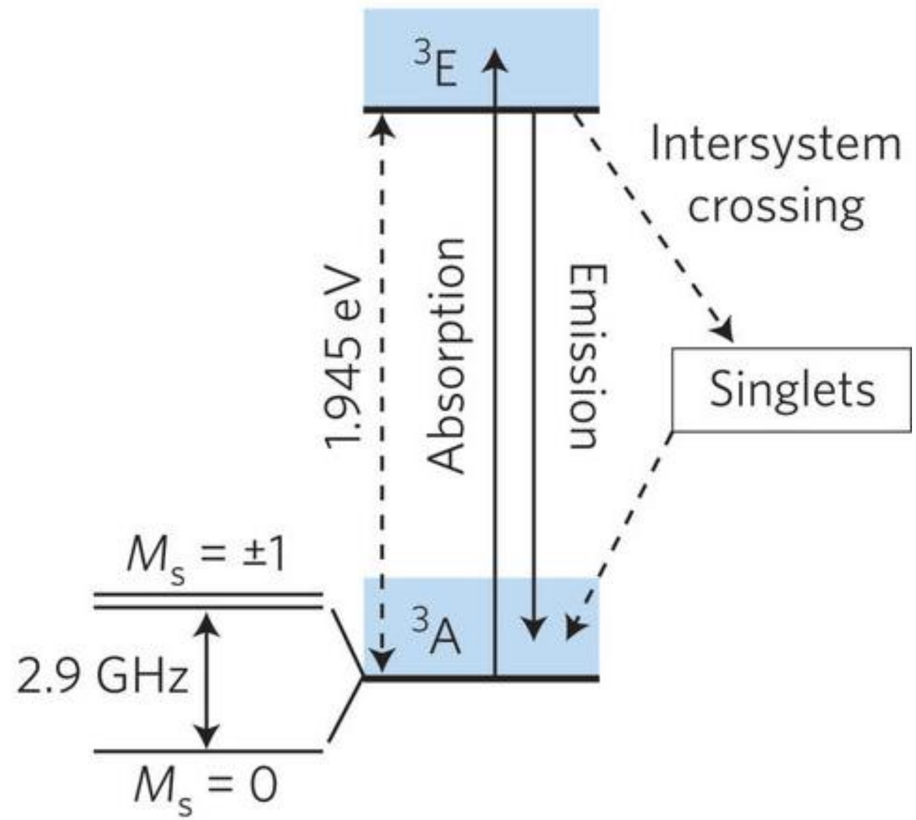




Quantum optics

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

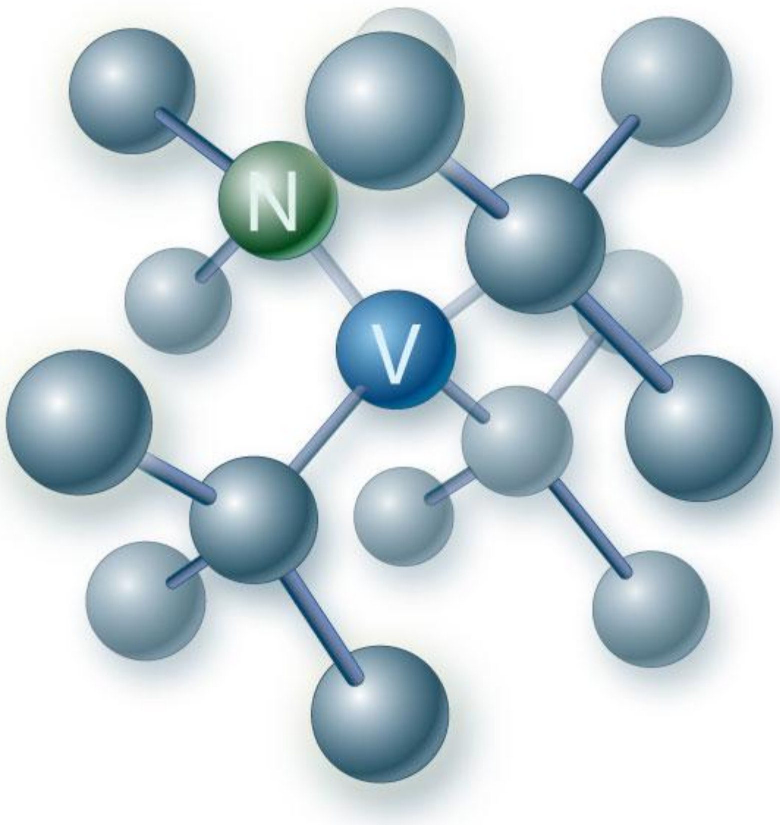


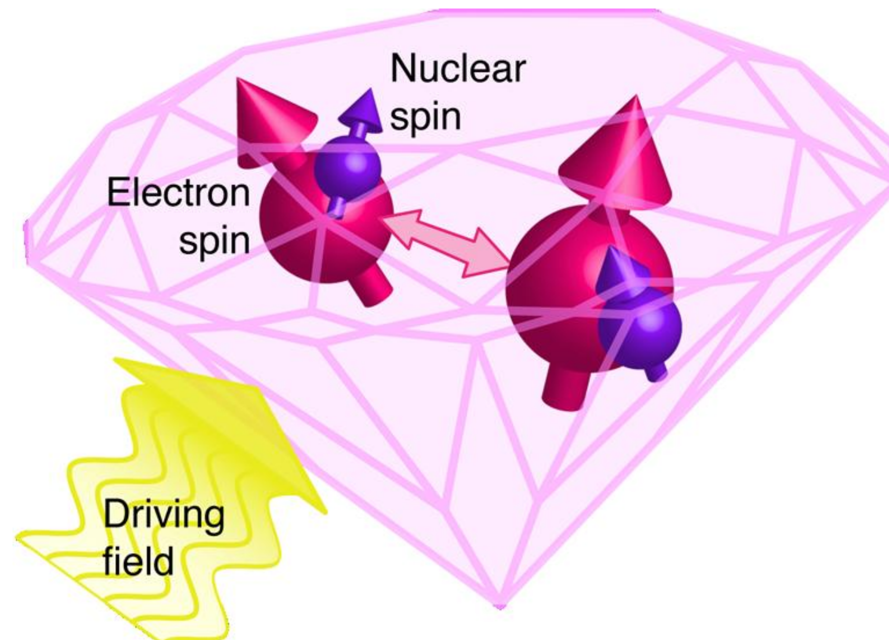


single-**spin selective transitions →** optically detected magnetic resonance (ODMR)

Quantum optics

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



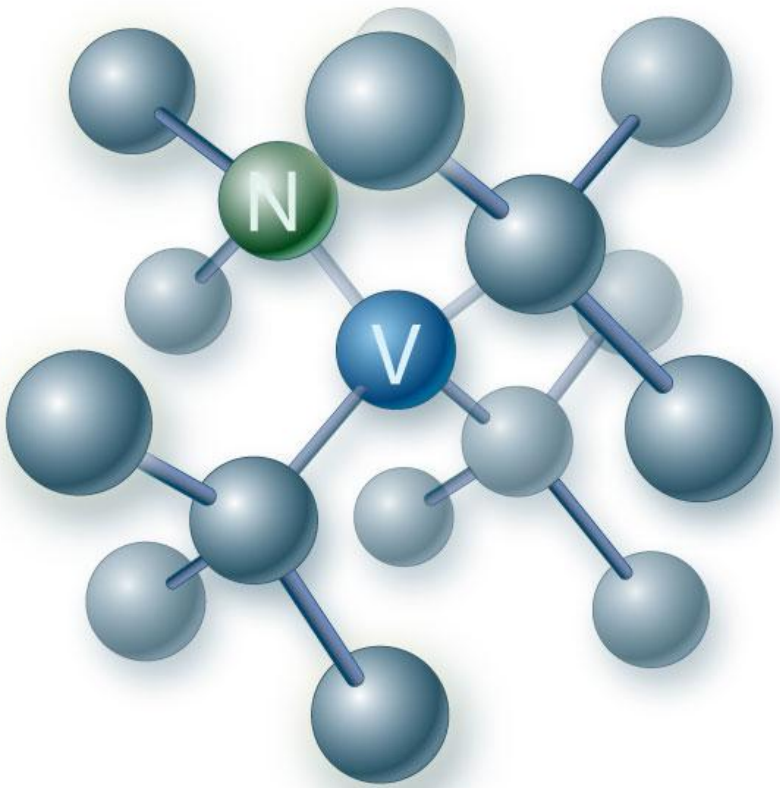


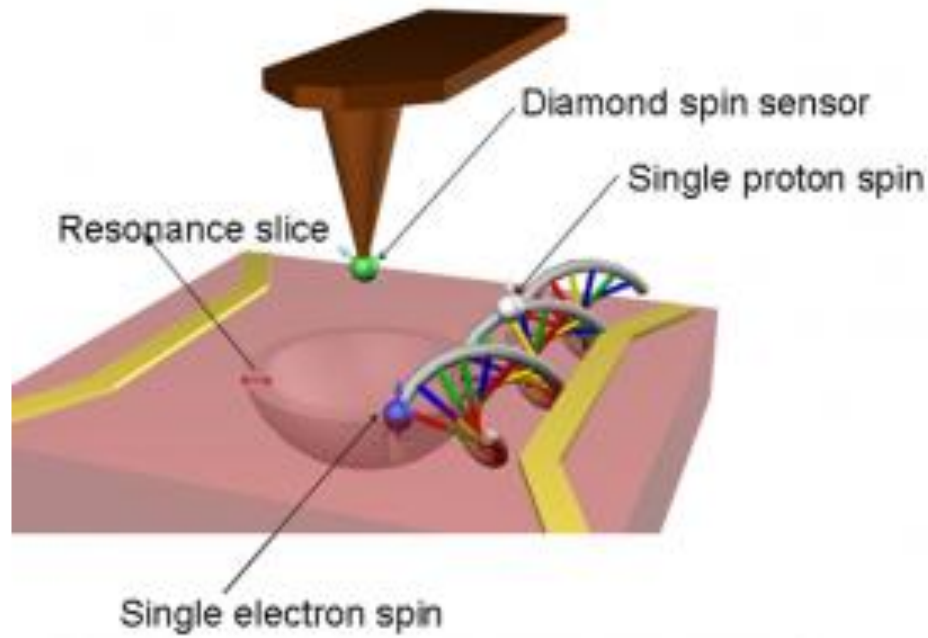
single-**spin selective transitions →** optically detected magnetic resonance (ODMR)

quantum information processing

Quantum optics

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

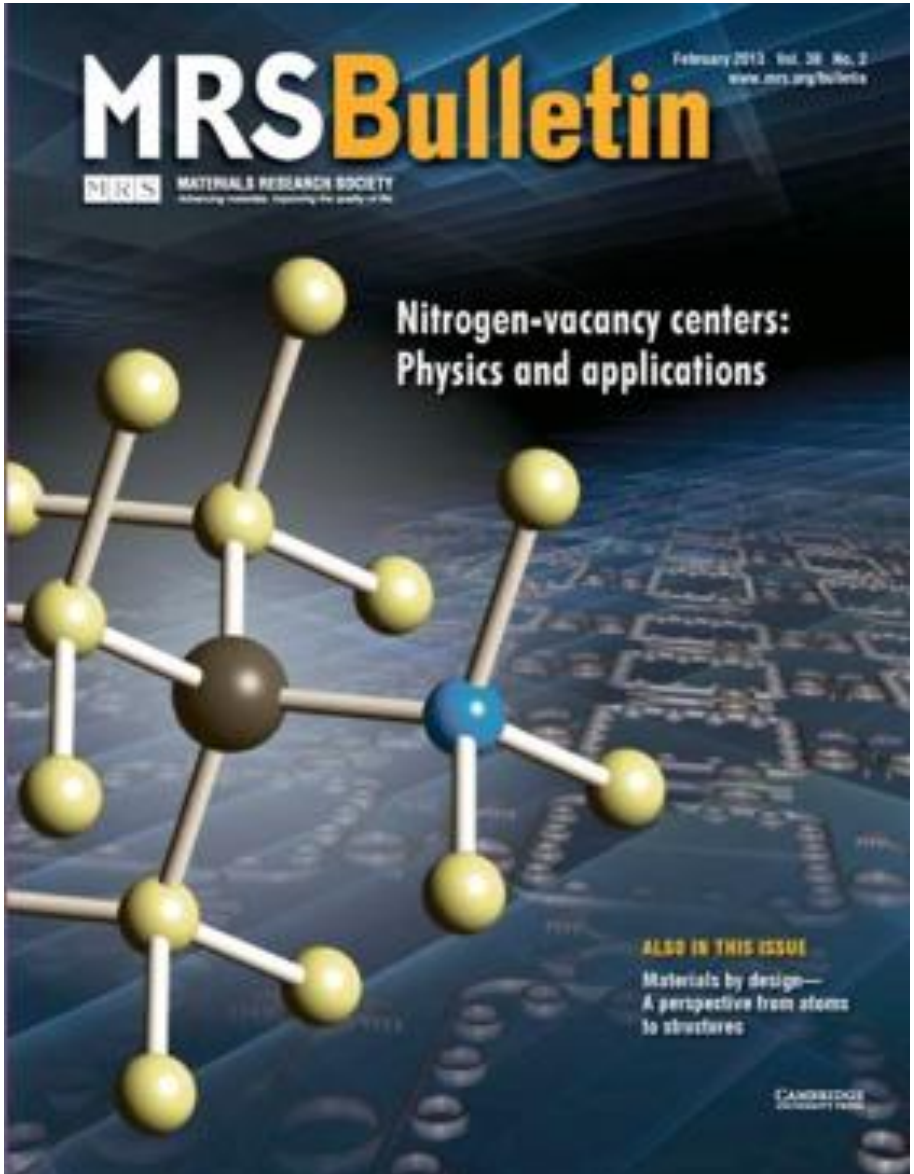


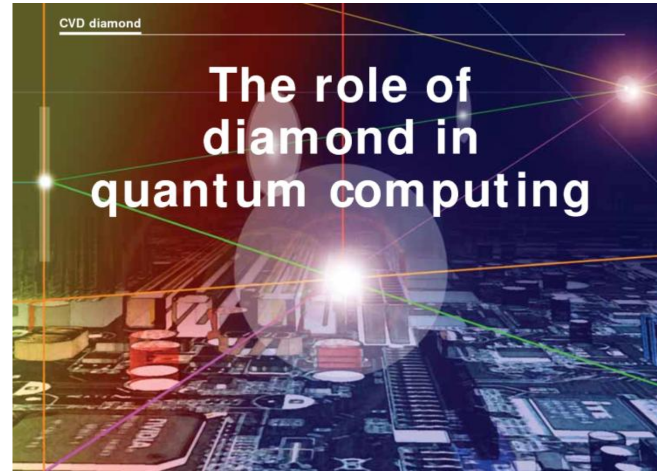


single-**spin selective transitions →**

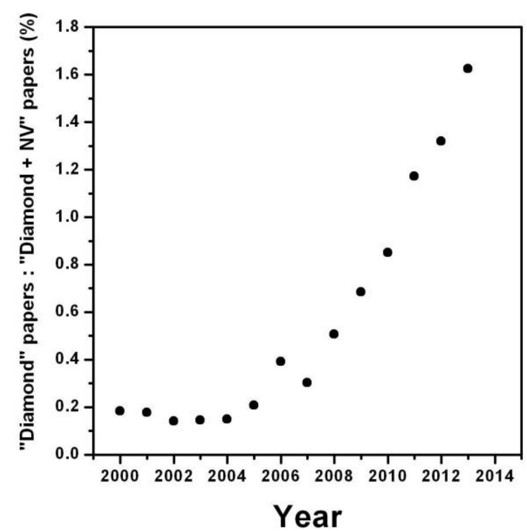
optically detected magnetic resonance (ODMR)
quantum information processing
high sensitivity & resolution magnetometry @ RT

Quantum optics



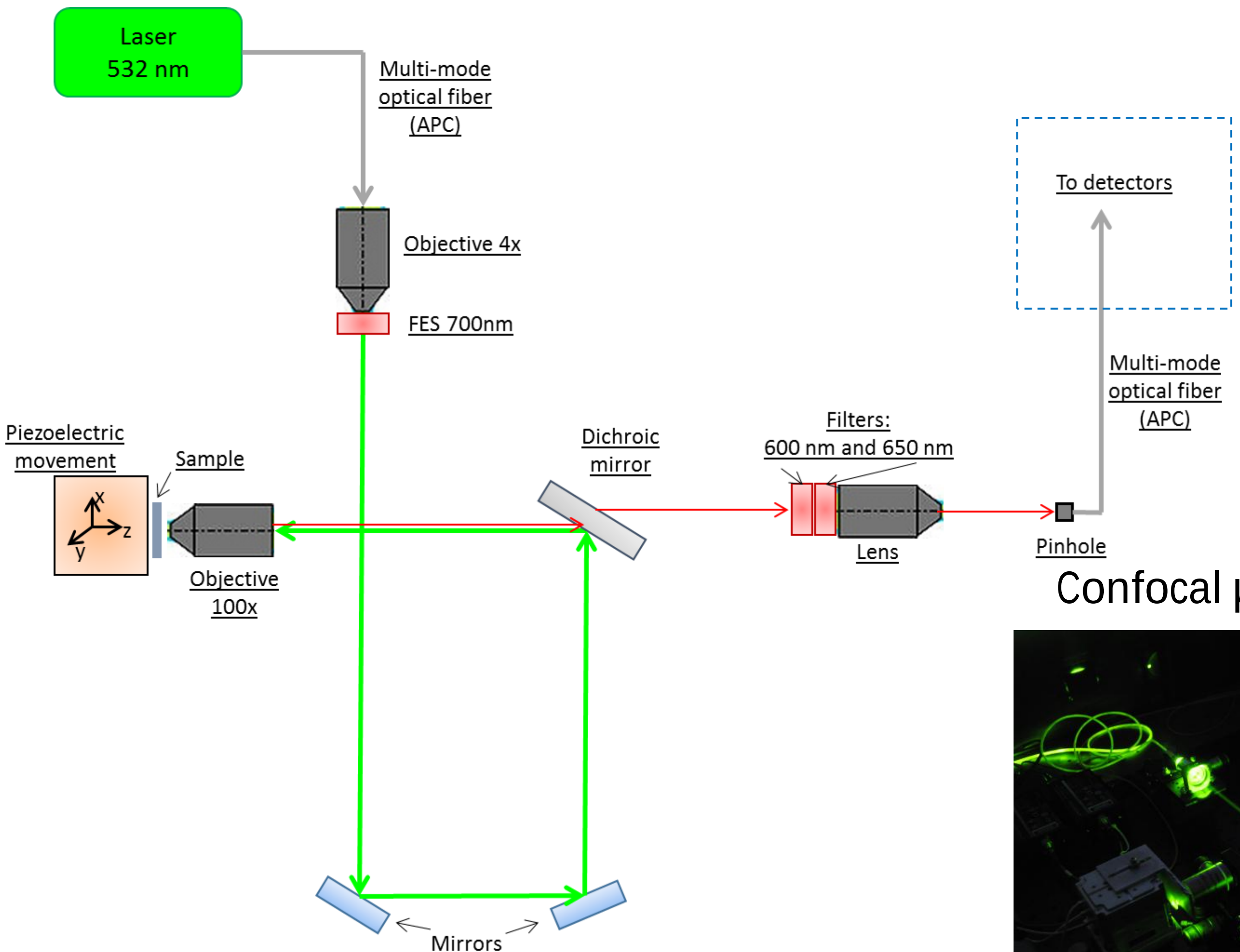


of “Diamond + nitrogen-vacancy” papers
: # of “Diamond” papers
(source: ISI Web)

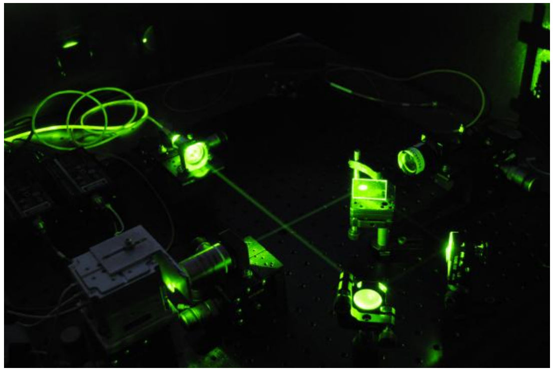


Quantum optics

Single-photon-sensitive confocal microscopy

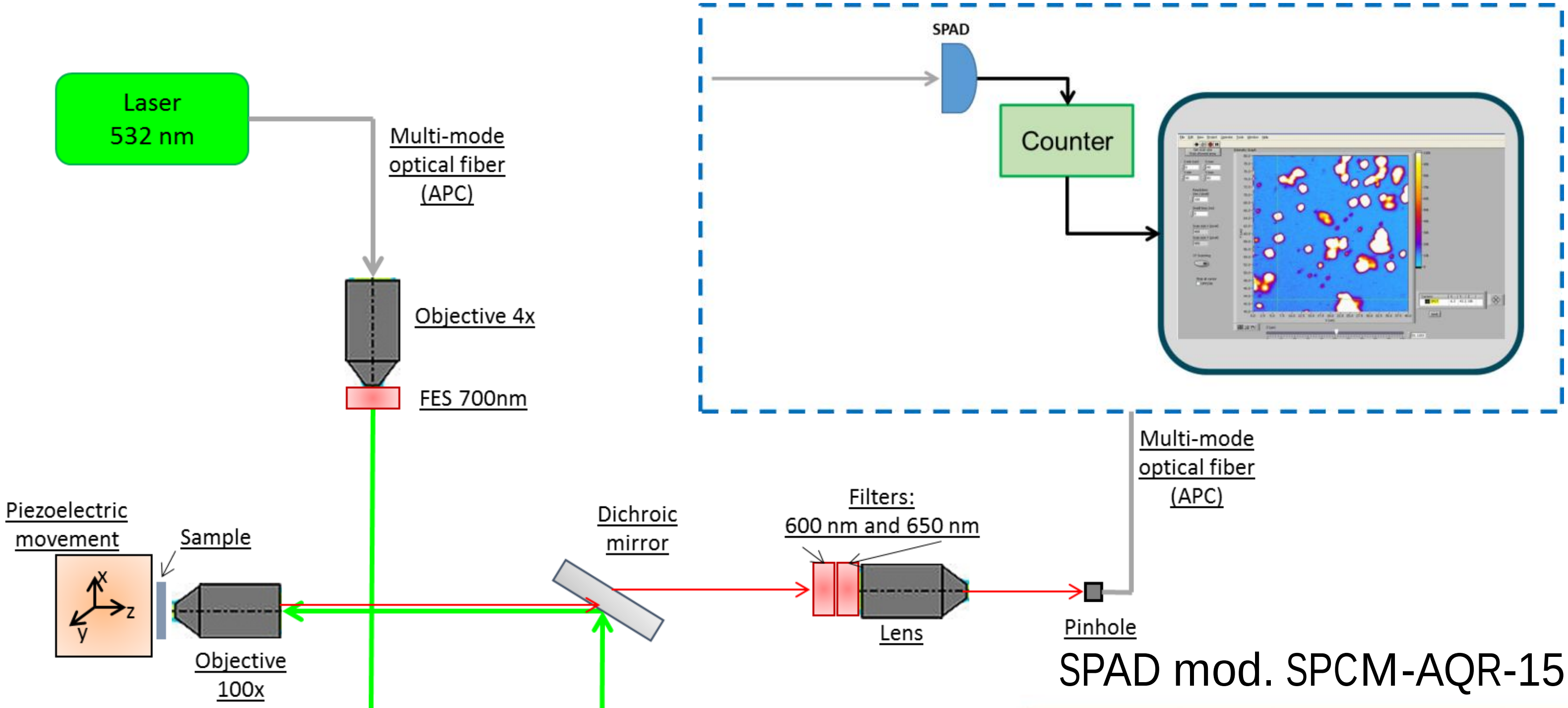


Confocal μ-scopy setup



Quantum optics

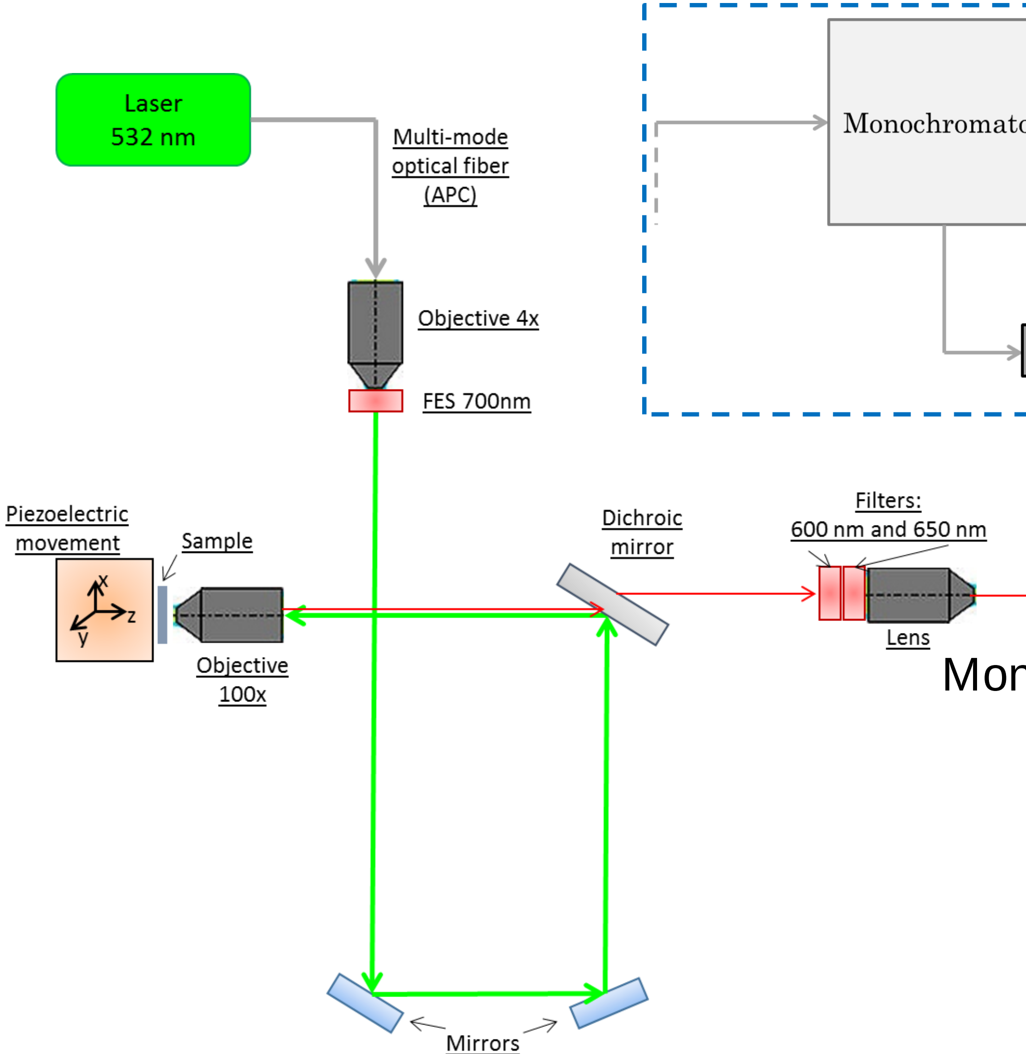
Single-photon-sensitive confocal microscopy



SPAD mod. SPCM-AQR-15

Quantum optics

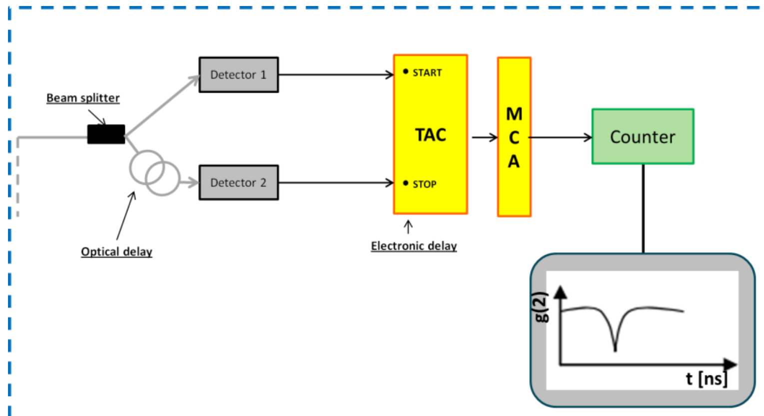
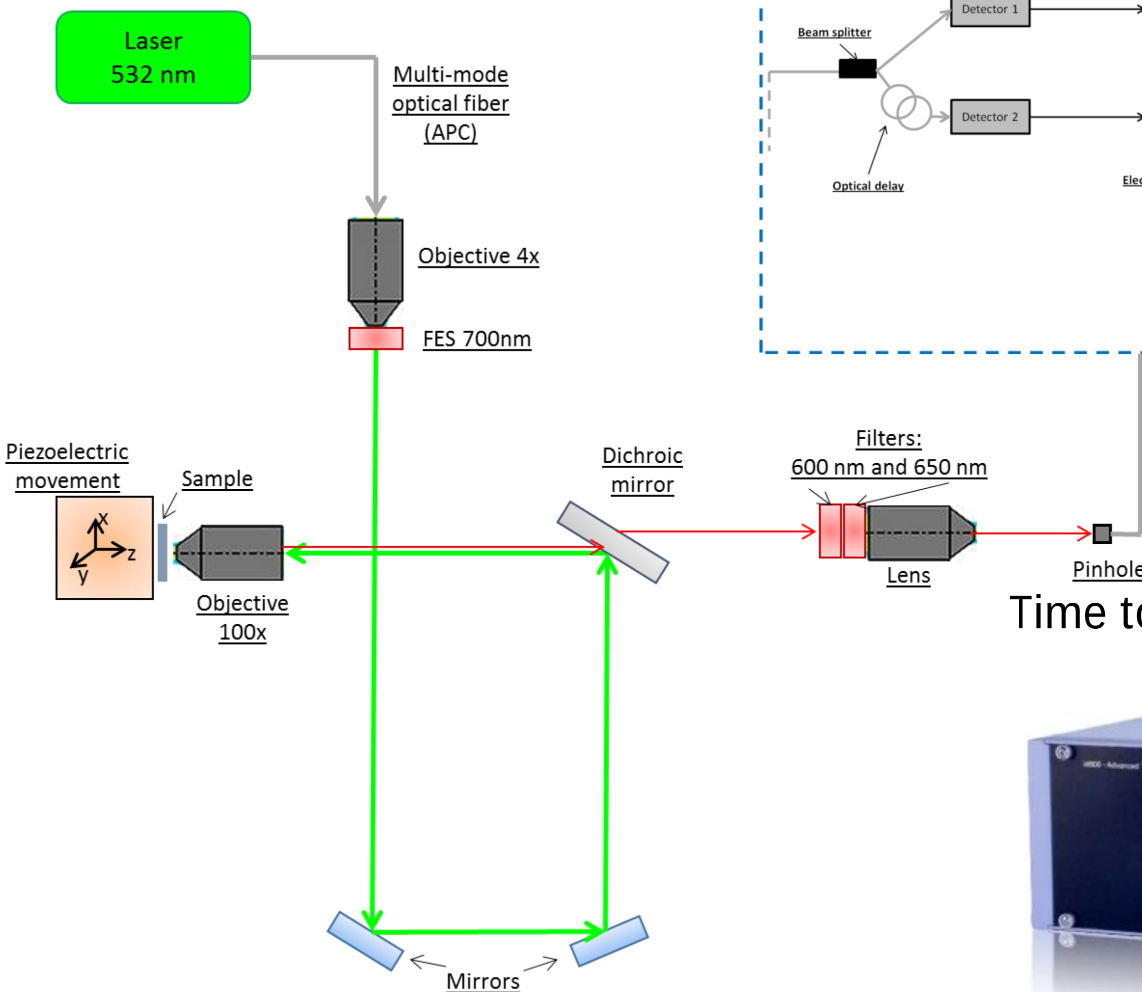
Single-photon-sensitive confocal spectroscopy



Monochromator mod. iHR320 HORIBA

Quantum optics

Hanbury-Brown-Twiss interferometry

Time to Digital Converter ID800

Quantum optics

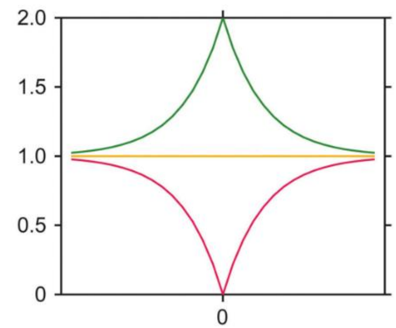
Hanbury-Brown-Twiss interferometry

2nd order auto-correlaion function

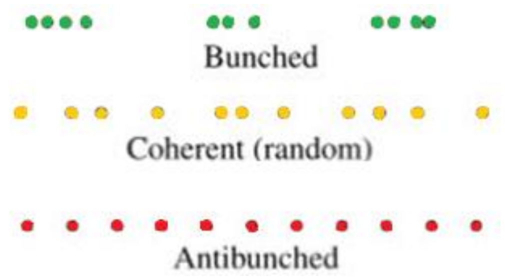
$$g^{(2)}(\tau) = \frac{< I(t) \cdot I(t+\tau) >}{< I(t) >^2}$$

$$g^{(2)}(0) = 1 - \frac{1}{n}$$

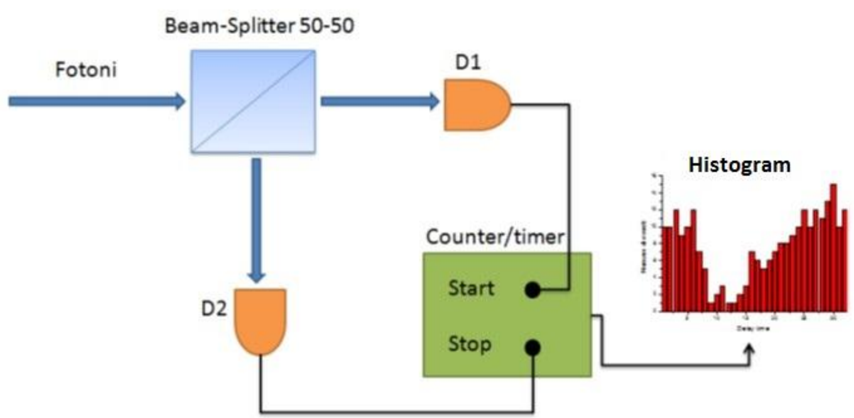
CW excitation



Delay time [ns]

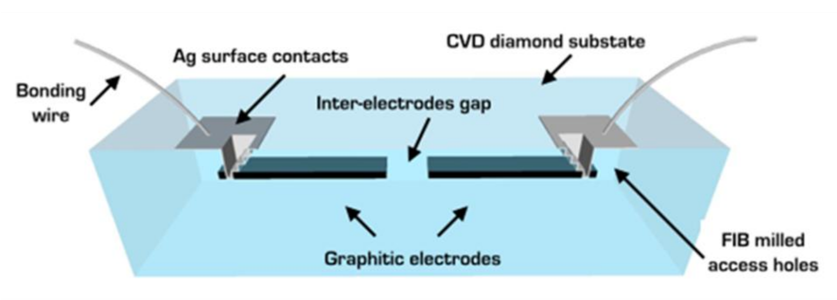


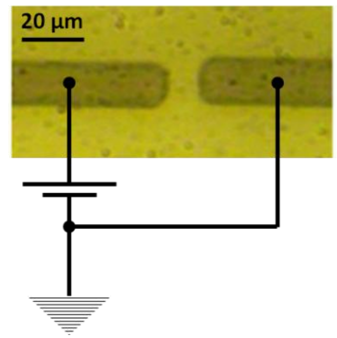
$g^{(2)}(0) < 0.5$ → **single**-photon emitter

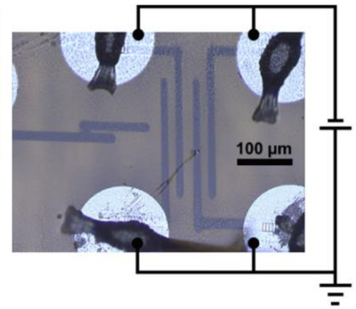


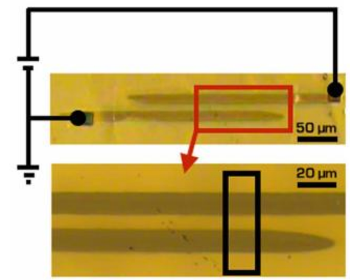
Quantum optics

The devices





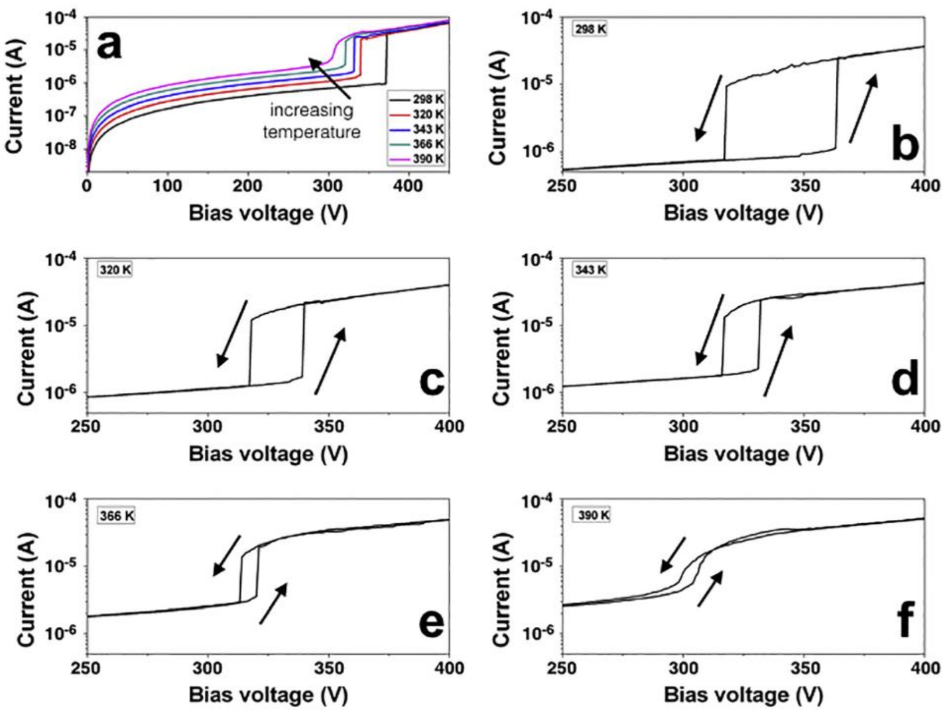




- IIa samples: optical / electronic grade from ElementSix, home grown
- ion beam lithography: 6 MeV C ions (RBI), 1.8 MeV He (INFN-LNL)
- penetration depth: ~3 µm
- post-implantation thermal processing: 950 °C, 2 hrs

Quantum optics

Electrical characterization

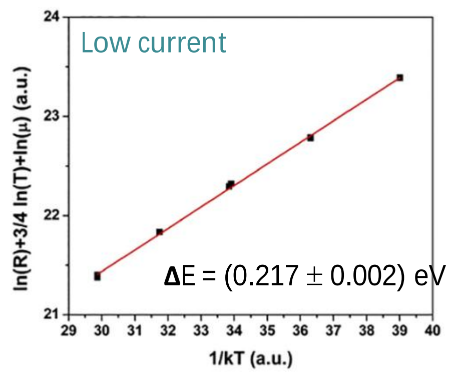


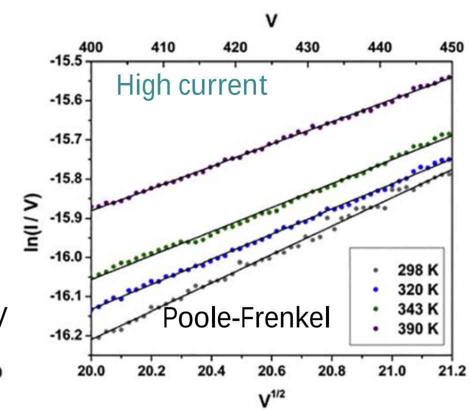
V < ~**350 V: “low current”, Space Charge Limited Current**
~350 V: abrupt current increase
V > ~**350 V: “high current”, Poole**-Frenkel

temperature-dependent study

“low-current” regime: NV charge state control, NV Stark shift

“high-current” regime: electroluminescence



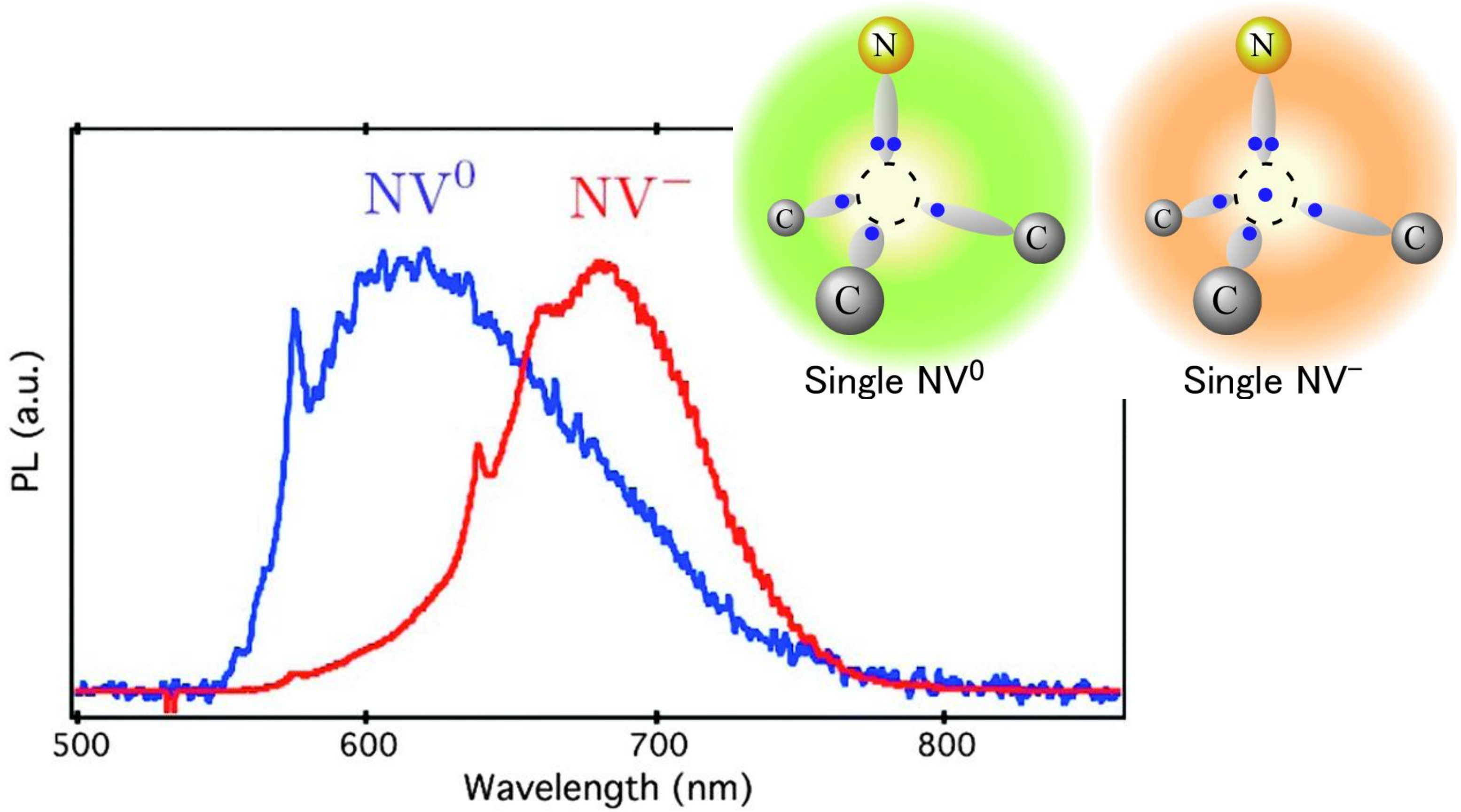


S. Ditalia et al., Diamond Relat. Mater. 74, 125 (2017)

Quantum optics

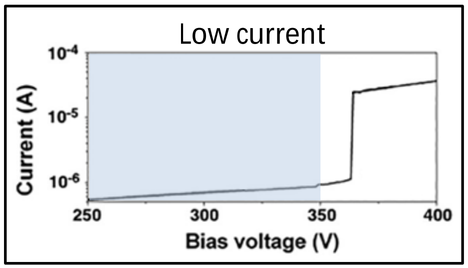
Open issues with NV defects:

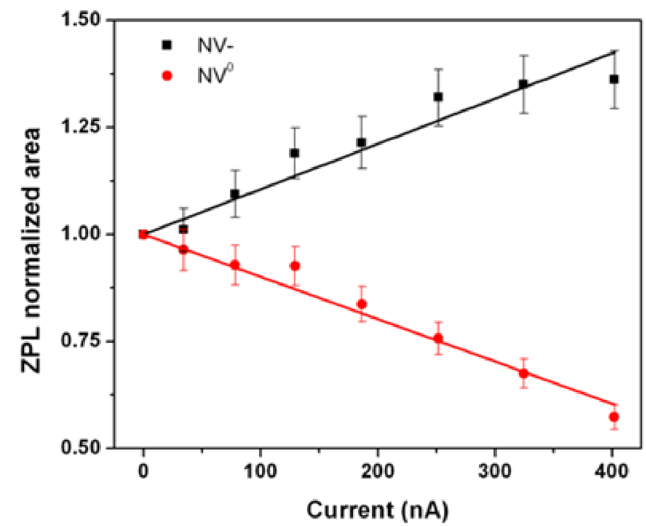
- ✓ Efficiency in defect formation
- ✓ **Spectral properties (inhomogeneous broadening, phonon coupling, …)**
- ✓ Charge state instability



Quantum optics

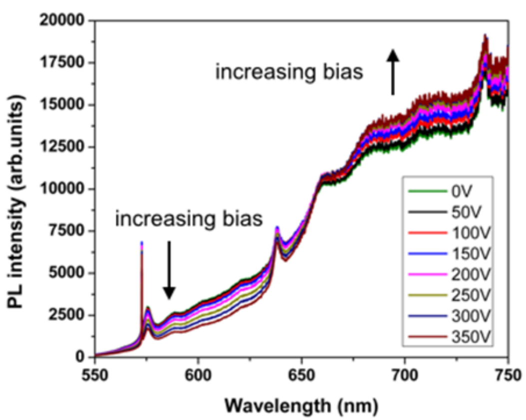
NV charge state control

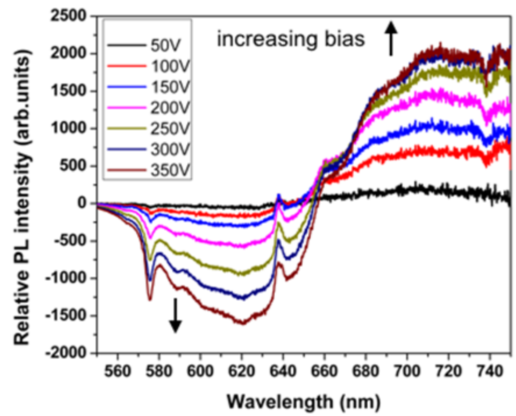


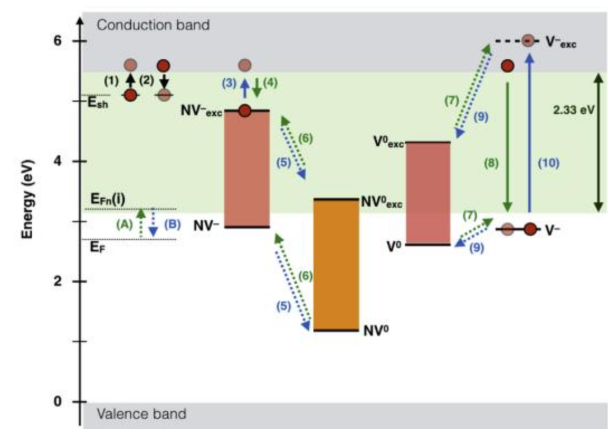


- optical grade sample, C ion beam
- steady laser excitation

- **λ = 532 nm**
- P = 21.6 mW



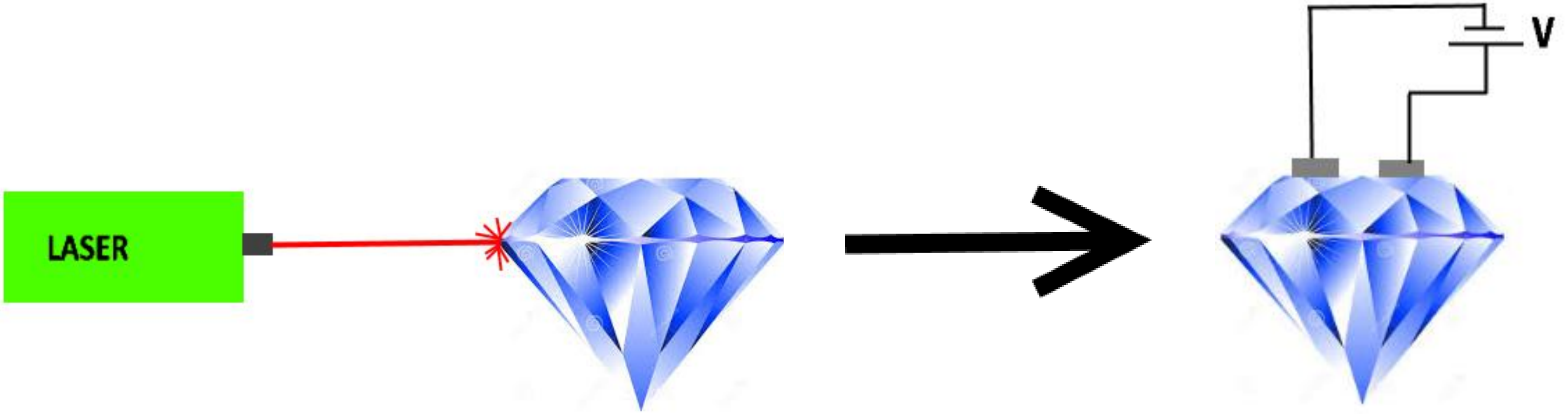




J. Forneris et al., Carbon 113, 76 (2017)

Quantum optics

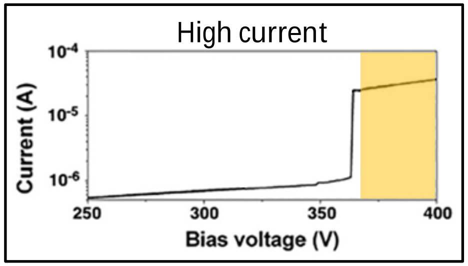
Electrical stimulation of luminescent emission

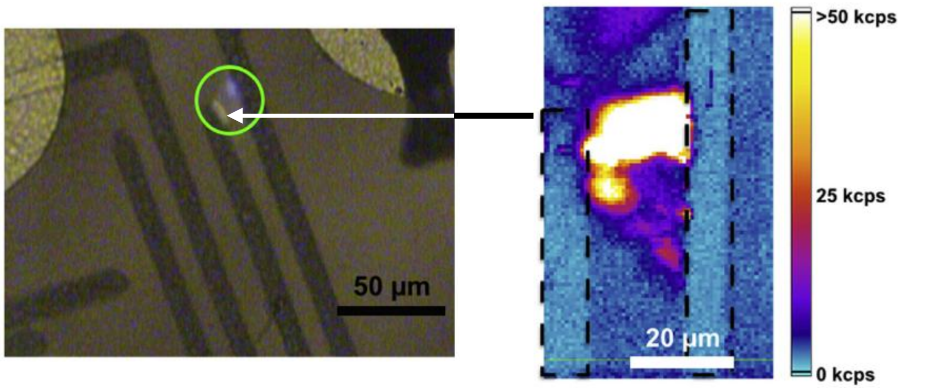


- ✓ Simpler device design
- ✓ No need for optical alignment
- ✓ Larger scalability and integrability

Quantum optics

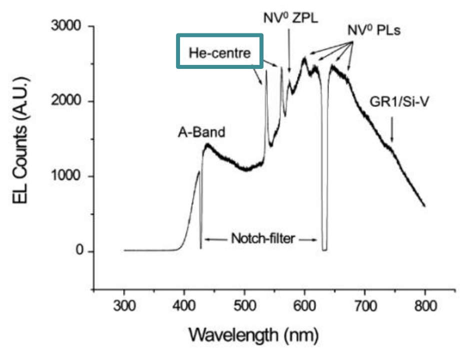
Ensemble emission regime

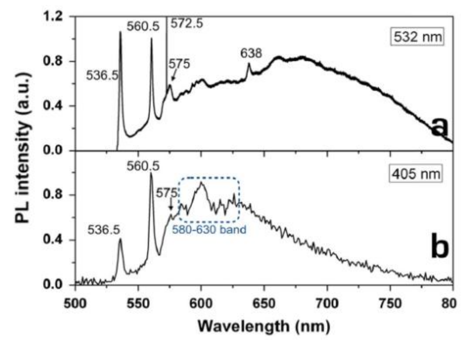




- CVD sample grown @Uni **Roma "Tor** Vergata**"**
- He ions irradiation with scanning µ-beam
- steady electrical stimulation

- observation of He-related color centers
- He-centers (536.5 nm, 560.5 nm) are both EL and PL active

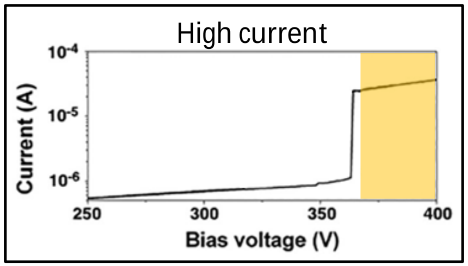


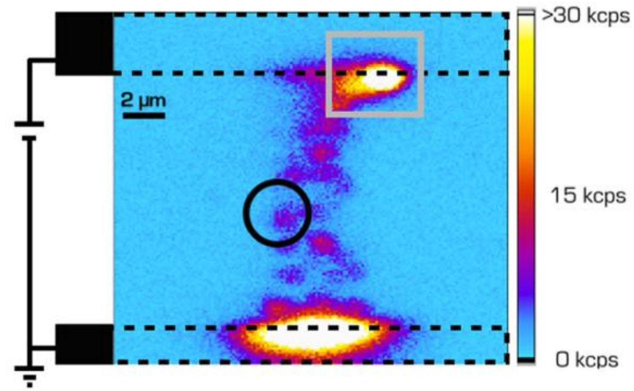


F. Forneris et al., Nucl. Instr. Methods B 348, 187 (2015)   F. Forneris et al., J. Lumin. 179, 59 (2016)

Quantum optics

Single-photon emission regime

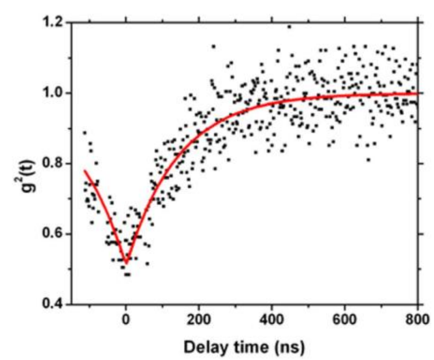




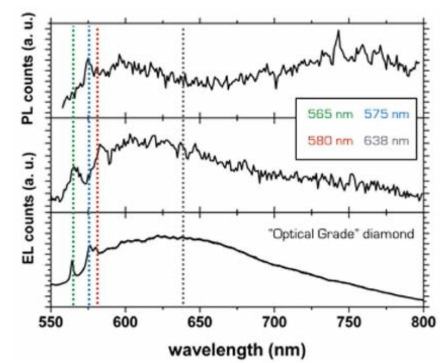
- electronic grade sample
- steady electrical stimulation

- $C_N(t) = 1 - a \cdot \exp(-\boldsymbol{\alpha}|t|)$
- $\boldsymbol{\alpha}^{-1} = (R + 1/\boldsymbol{\tau}) = (143 \pm 5)$ ns

2nd order auto-correlation function



emission spectrum



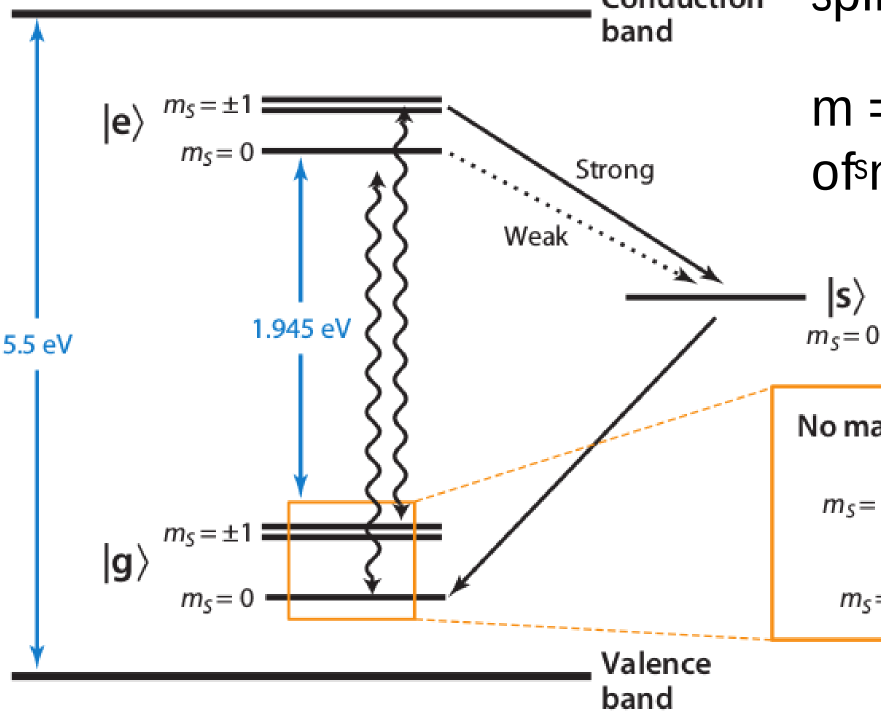
F. Forneris et al., Sci. Rep. 5, 15901 (2015)

Quantum optics

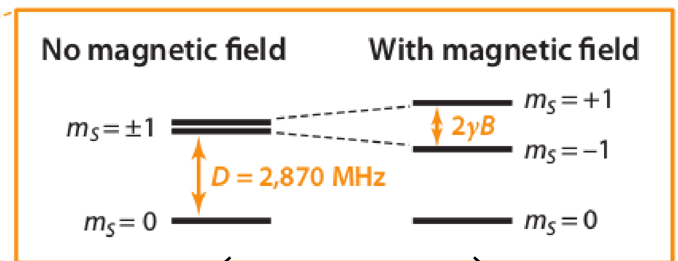
NV magnetometry

spin 1 system

$m_s = \pm1$ excited level: high probability of non-radiative relaxation



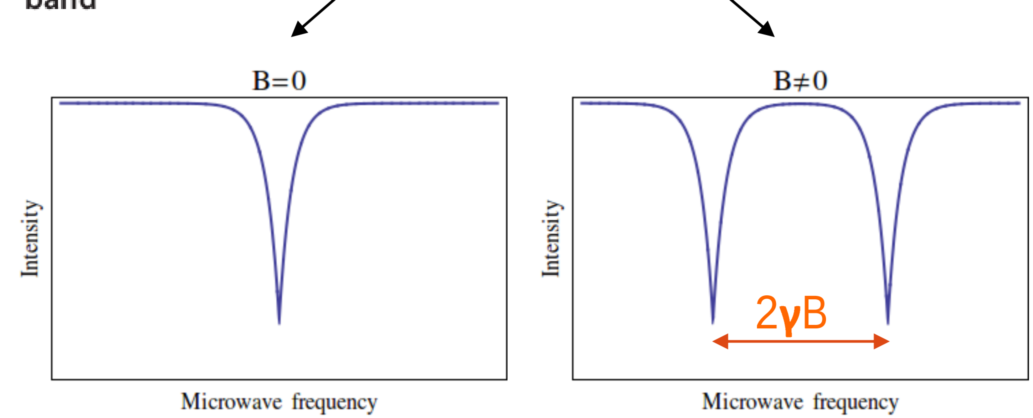
Microwaves promote transitions to the $m_s = \pm1$ state.



Zeeman effect

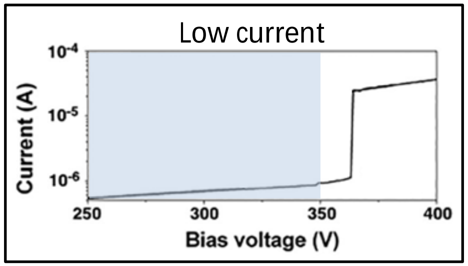
↓

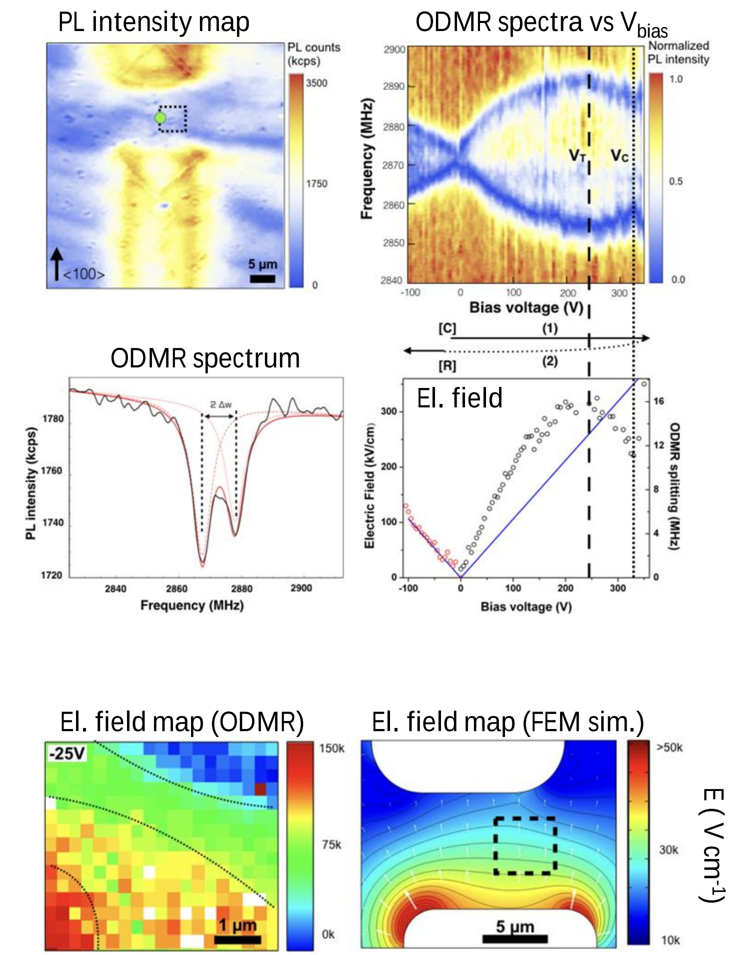
Magnetometry



Quantum optics

NV electrometry

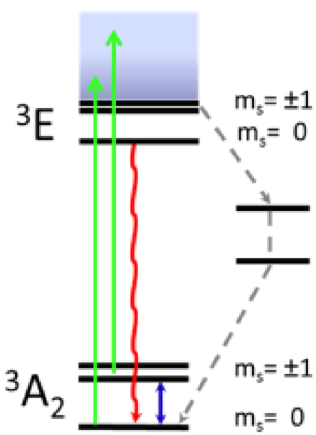




- optical grade sample, C ions
- steady laser excitation

- **λ** = 515 nm
- ODMR measurements

Stark shift of the |±1> states



$$H = H_0 + \underbrace{g\mathbf{S}\cdot\mathbf{B}}_{\alpha} + \underbrace{d_{\parallel}\left(E_z + F_z\right)\left[S_z^2 + S(S+1)/3\right]}_{\beta} - \underbrace{d_{\perp}\left(E_x + F_x\right)\left(S_xS_y + S_yS_x\right)}_{\gamma} - \underbrace{d_{\perp}\left(E_y + F_y\right)\left(S_x^2 - S_y^2\right)}_{\delta}$$

F. Forneris et al., arXiv:1706.07935 (2017)

- Diamond
- IBL in diamond
    - → Basic concepts
    - → State of the art
- Current research activities @ UniTo & INFN-To
    - → **Electrical** features
    - → Radiation detection
    - → Biosensing
    - → Quantum Optics
- Conclusions

Conclusions

- Ion beam lithography: a powerful technique for microfabricating

  “extreme” materials such as diamond

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- Nuclear damage:

  ⇩ point defect creation → **single color centers**

  amorphization & graphitization → **buried electrodes**

Conclusions

- Ion beam lithography: a powerful technique for microfabricating

  "extreme" materials such as diamond

- Nuclear damage:

  ⇩ point defect creation → **single color centers**

  amorphization & graphitization → **buried electrodes**

- Device applications:

  → **particle detectors**

  → **cellular biosensors**

  → **quantum**-optical devices

Acknowledgments

Sample processing and characterization University of Torino
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FIB micromachining and optical characterization National Institute of Metrologic Research
G. Amato, L. Boarino, G. Brida, I. Degiovanni, E. Enrico, M. Genovese, P. Traina

MeV ion implantation & IBIC measurements

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Optical / morphological characterization National Institute of Optics
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Development of microfabrication techniques in diamond for applications in bio-sensing and photonics
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CSP Foundation

Di.Na.Mo. – Diamond NanoModification
National Institute of Nuclear Physics

DIESIS – Electrically controlled diamond-based single photon sources
National Institut of Nuclear Physics

DIACELL – Diamond based detector for in vitro cellular radiobiology
National Institut of Nuclear Physics

MIRADS – New Micro-Radiobiology Devices for aeroSpace
CRT Foundation

Thanks for your attention!