The Abdus Salam International Centre for Theoretical Physics

2359-14

Joint ICTP-IAEA Workshop on Physics of Radiation Effect and its Simulation for Non-Metallic Condensed Matter

13 - 24 August 2012

Ion beam lithography - II

Paolo Olivero

University of Turin
Italy

Ion beam lithography - II

Paolo Olivero

Physics Department
NIS Centre of Excellence
University of Torino

INFN Section of Torino

CNISM Consortium

olivero@to.infn.it

ICTP-IAEA Workshop, Trieste, 13-24 August 2012

Outline

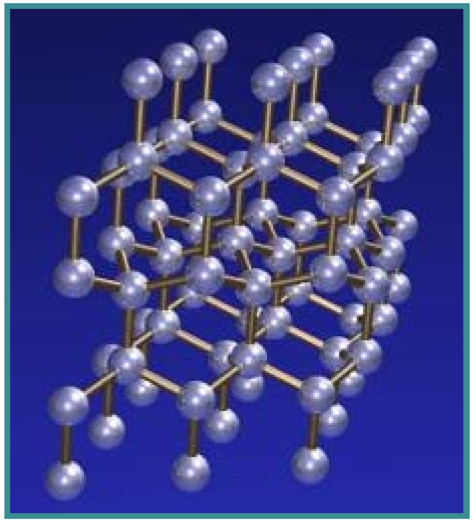
- Diamond
  - → Synthesis
  - → Properties
  - → Applications
- IBL in diamond
  - → MeV ion lithography in diamond
  - → keV ion beam lithography in diamond
- Activities at the University of Torino
  - → Electrical features
  - → Optical features
  - → Microfluidics

Outline

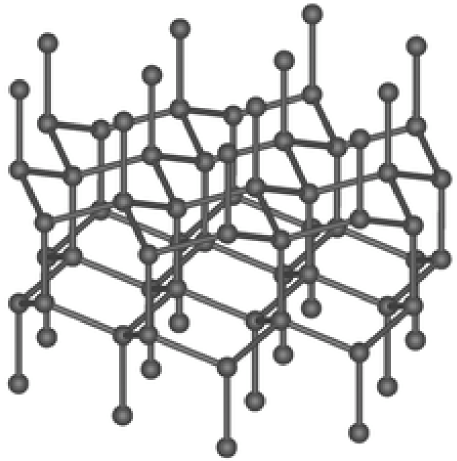
- **Diamond**
  - → **Synthesis**
  - → Properties
  - → Applications
- IBL in diamond
  - → MeV ion lithography in diamond
  - → keV ion beam lithography in diamond
- Activities at the University of Torino
  - → Electrical features
  - → Optical features
  - → Microfluidics

Diamond

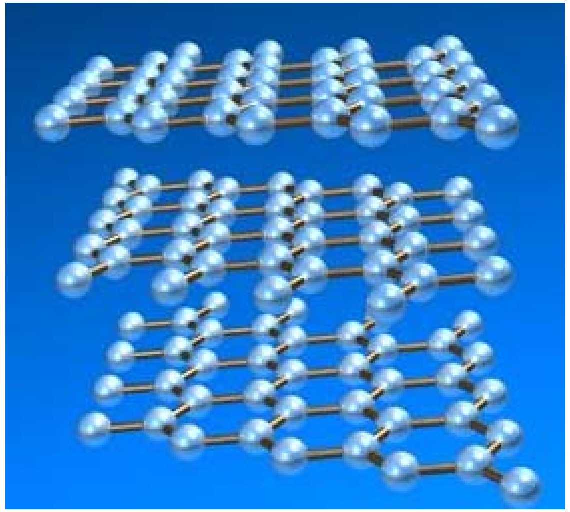
αδάμας (*indestructible*)



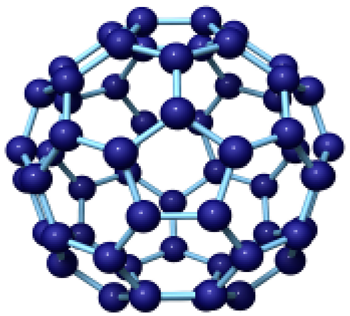
diamond



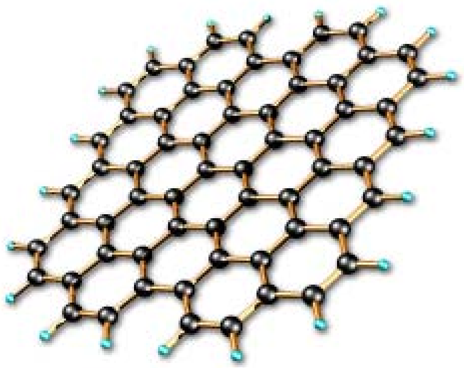
londsaelite



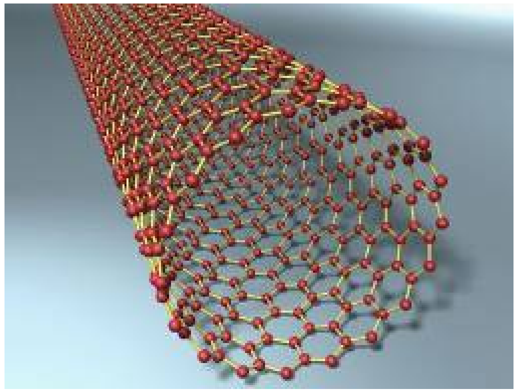
graphite



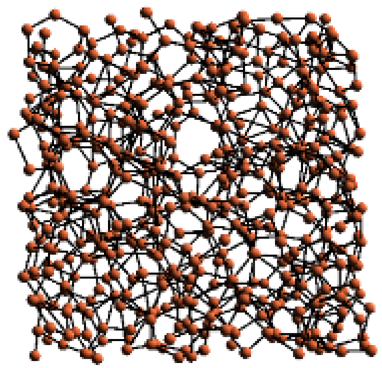
fullerene



graphene



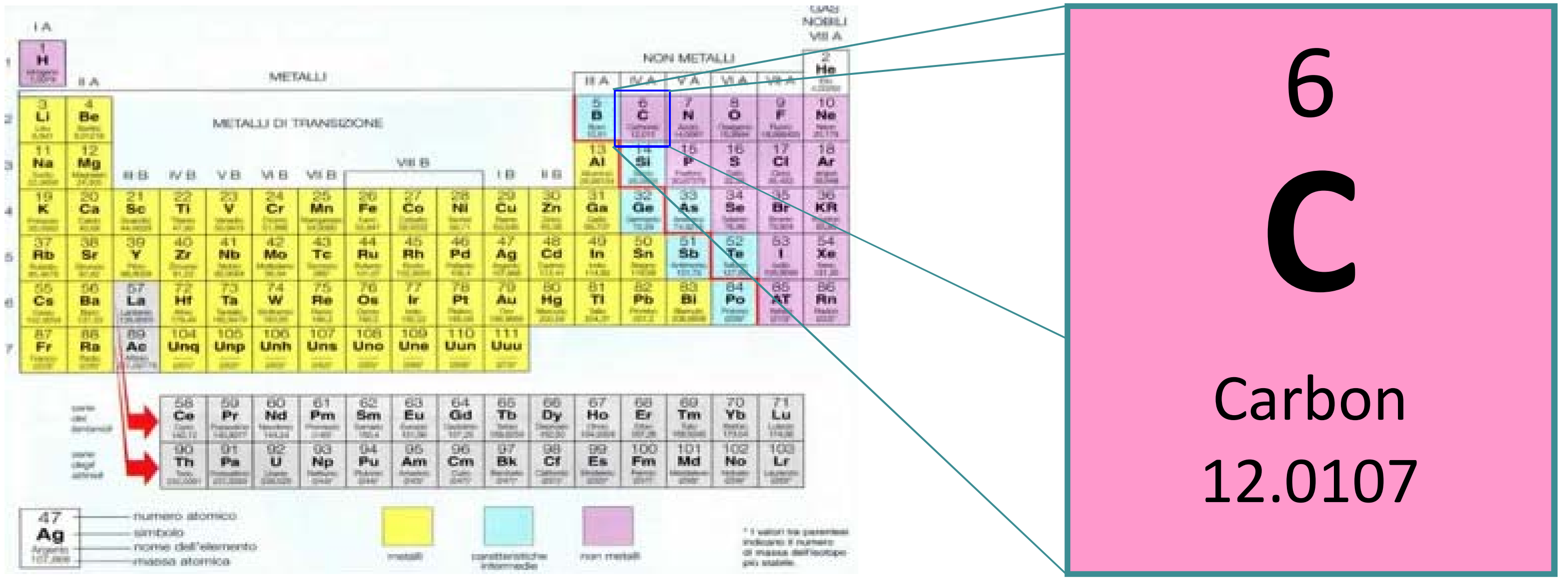
nanotube



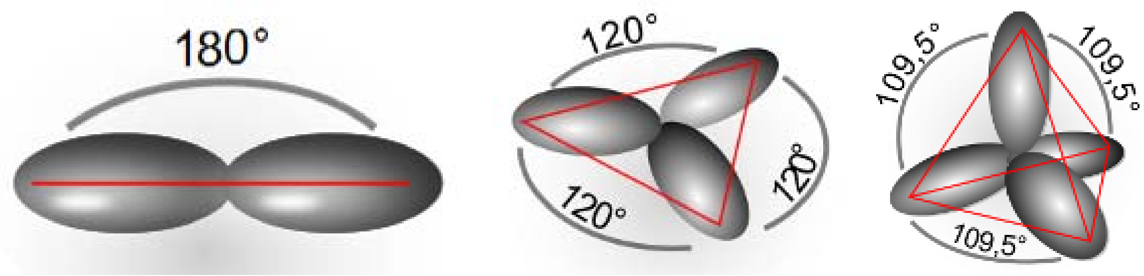
amorphous carbon

Diamond

Carbon



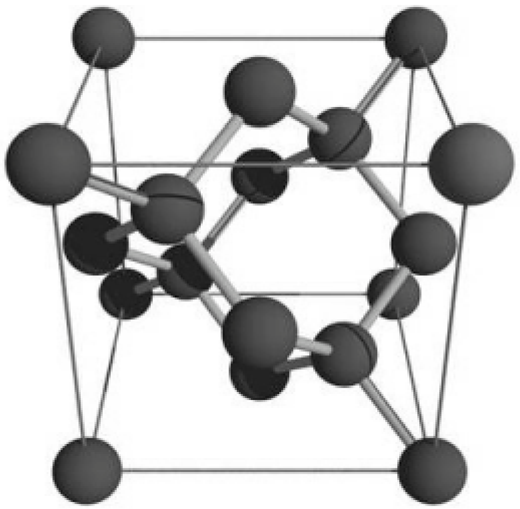
Three types of hybrid orbitals



sp¹ ***sp²*** ***sp³***

Diamond

Crystal structure

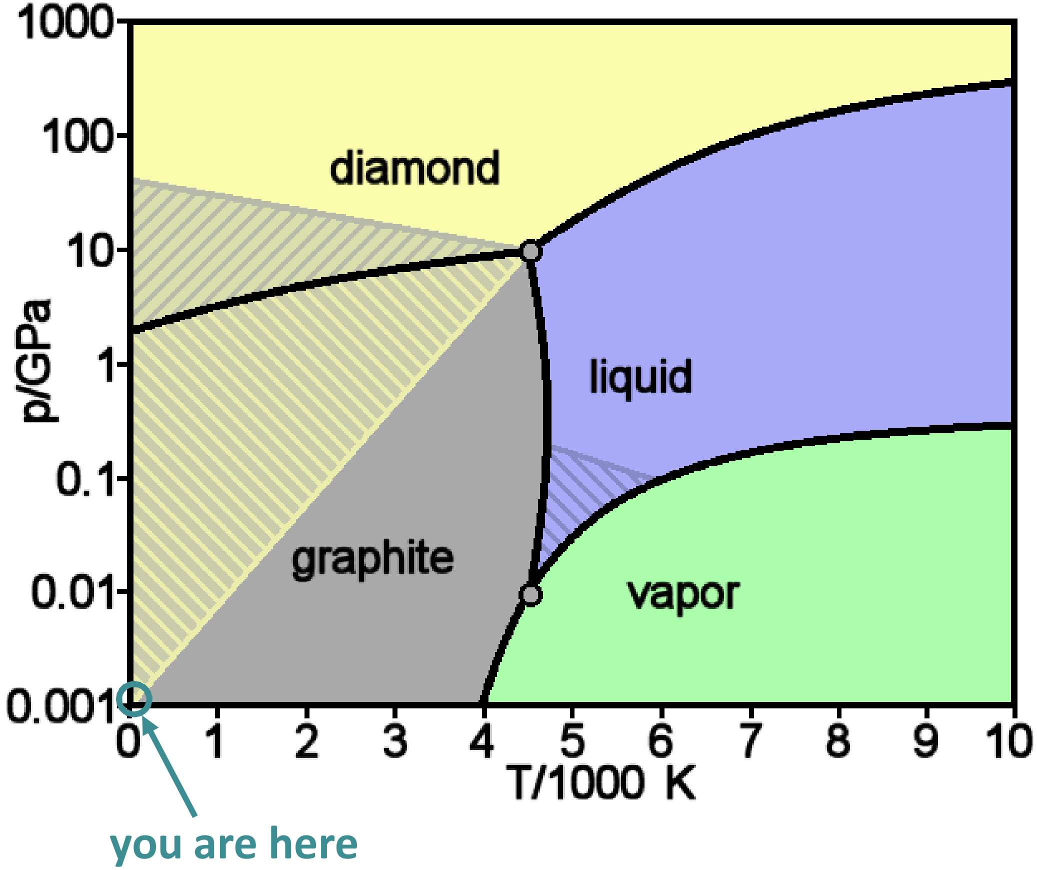


- Lattice: face-centered cubic
- Base: { (0, 0, 0); (¼a, ¼a, ¼a) }
- Crystal: diamond

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

Diamond

Phase diagram of Carbon



Room pressure and temperature: diamond is meta-stable

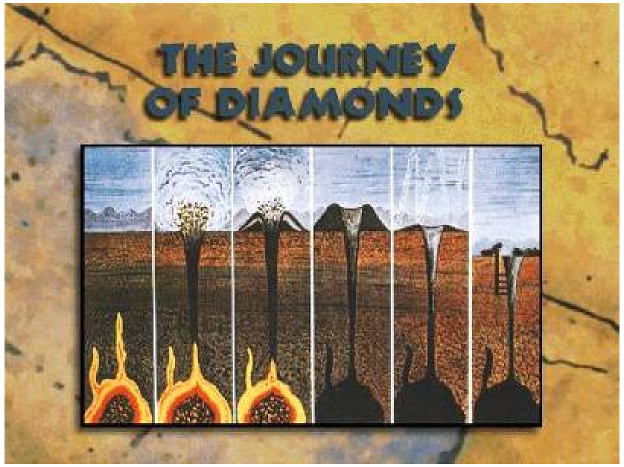
Natural diamond forms at high pressure and temperature

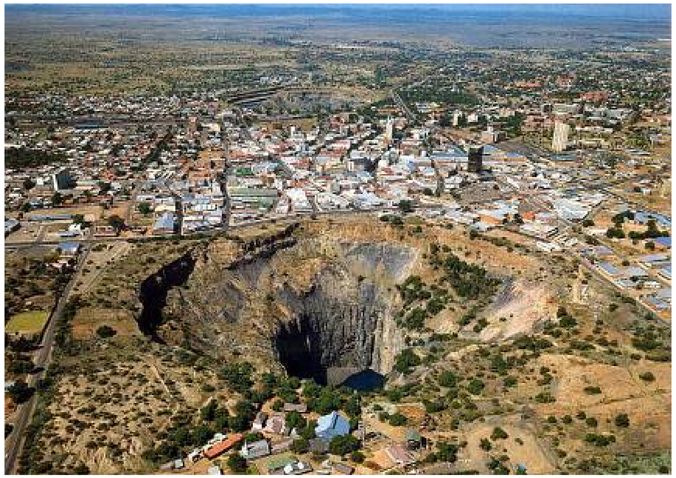
Diamond – Synthesis

Natural diamond

At the litosphere (140-190 km below the Earth surface):

- **pressure: 4.5 – 6 Gpa**
- **temperature: 900 – 1300 °C**





Kimberley Mine, the largest human hole on Earth

Transport to Earth surface: volcanic eruption from deep regions.

Diamond: included in rocks.

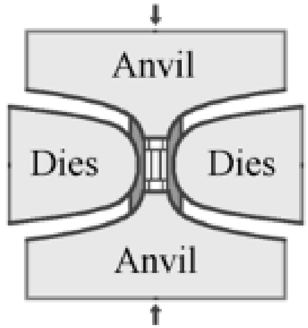
- **Primary sources: volcanoes**
- **Secondary sources: sites where diamonds are eroded from the rocks (kimberlite, lampronite)**

Diamond – Synthesis

High pressure high temperature synthesis

HPHT growth system
© Kobelco

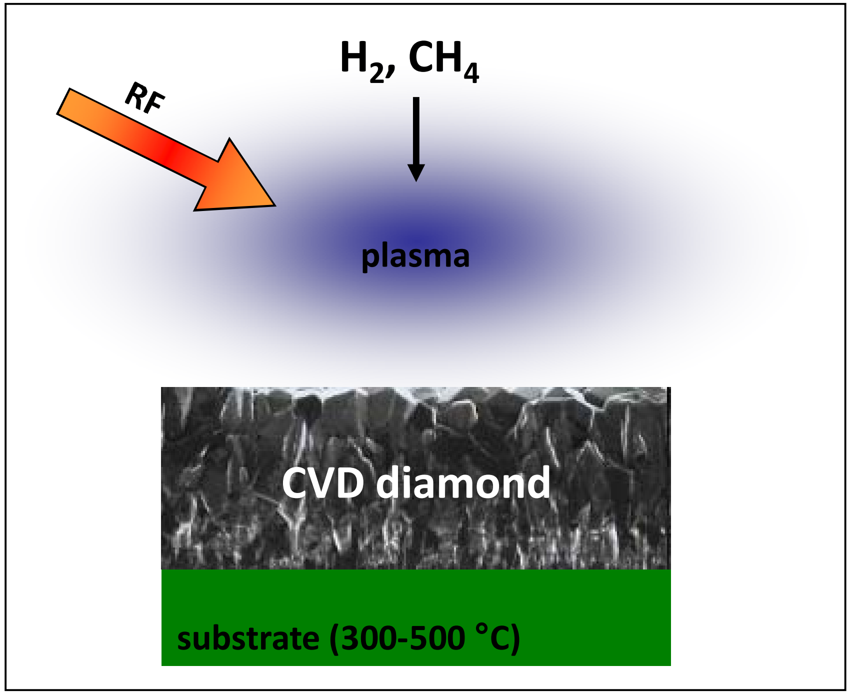
1954: General Electric obtains systematic and comrercially viable synthesis of diamond by HPHT.

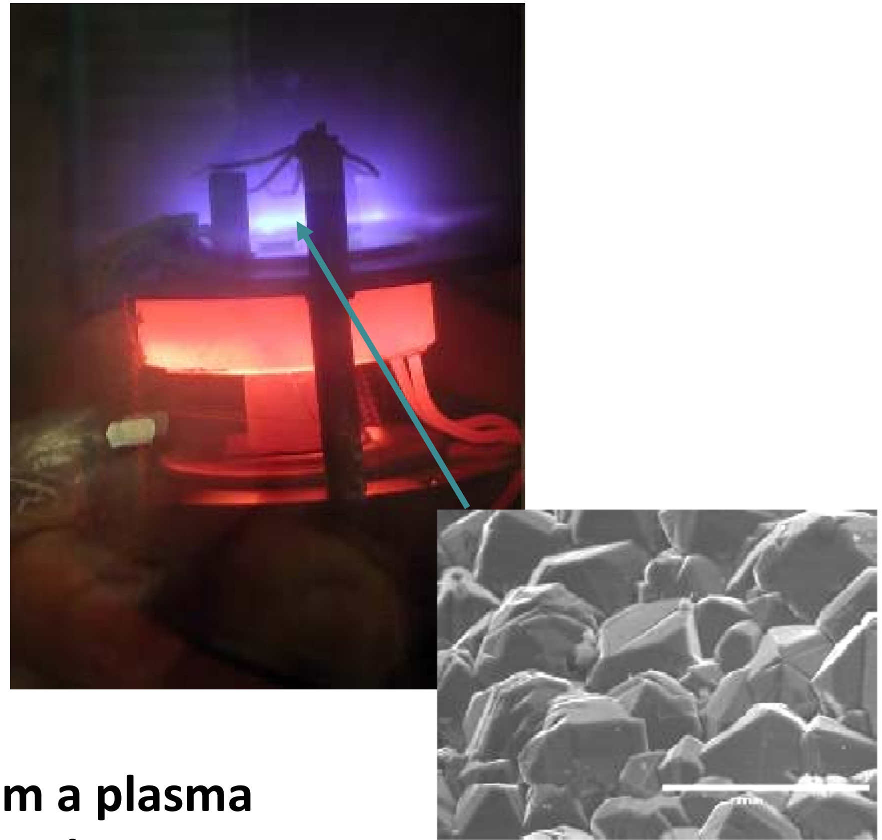


- growth from a diamond seed
- graphite with catalytic elments (Ni, Fe, …)
- single-crystals: good structural properties, impurities

Diamond – Synthesis

Chemical Vapour Deposition





- deposition of C on a “cold” substrate from a plasma
- selective etching of non-sp3 C by H in the plasma
- heteroepitaxial growth of polycrystalline samples
- homoepitaxial growth of single-crystals with high purity

Diamond – Synthesis

Classifications

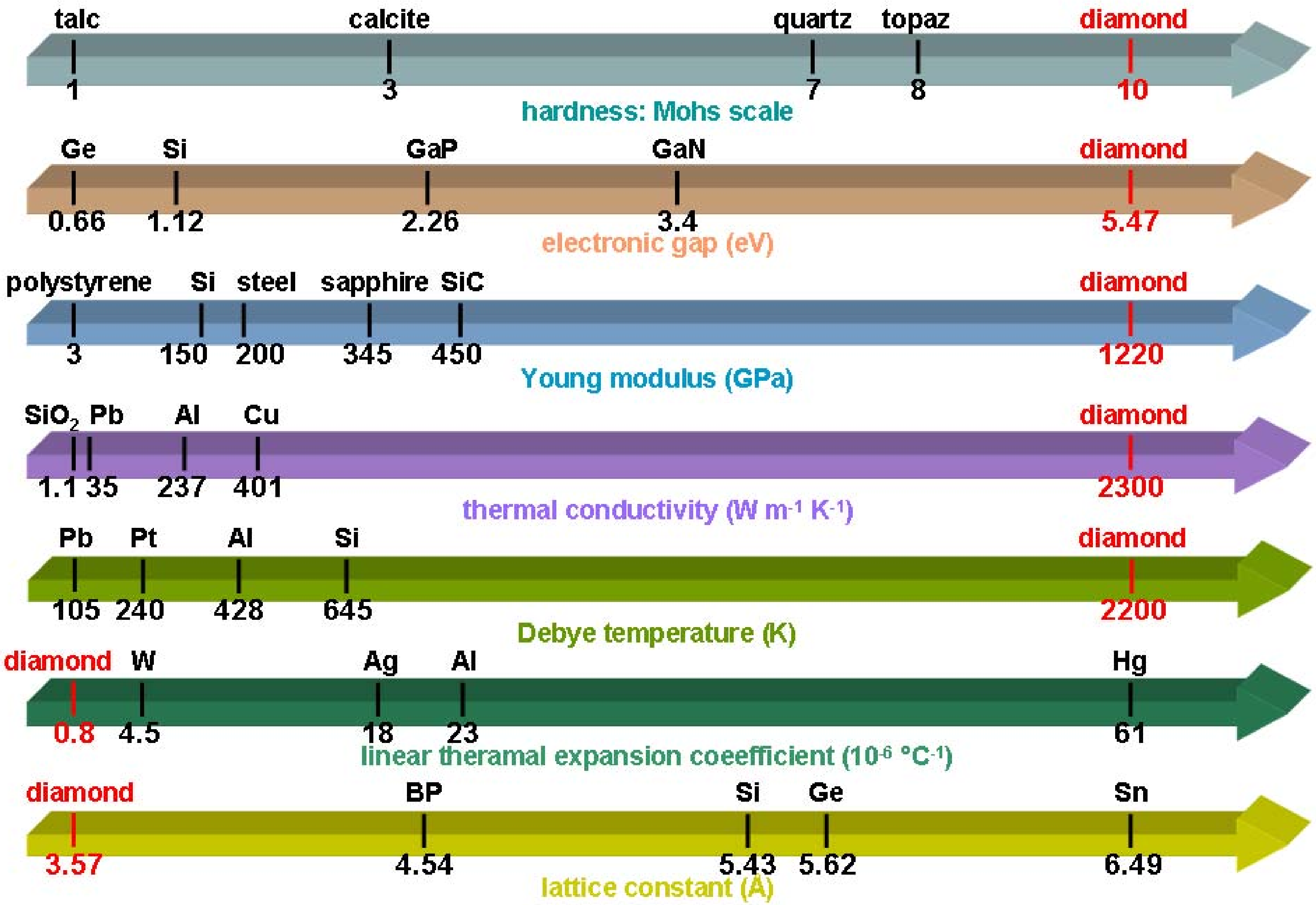
Structure:	**single-crystal**	
	polycrystalline	
	nanocrystalline	
Impurities:	**type I: N in aggregates**	**Ia: [N] = 100-1000 ppm**
		Ib: [N] = 10-100 ppm
	type II: substitutional B	**IIa: [N] < 1 ppm**
		IIb: [N] < 1 ppm, B doping
Applications:	**thermal/mechanical grade**	↓ **crystal quality**
	optical grade	
	electronic grade	
	detector grade	

Outline

- **Diamond**
  - → Synthesis
  - → **Properties**
  - → Applications
- IBL in diamond
  - → MeV ion lithography in diamond
  - → keV ion beam lithography in diamond
- Activities at the University of Torino
  - → Electrical features
  - → Optical features
  - → Microfluidics

Diamond – Properties

Extreme physical properties



Diamond – Properties

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
- efficient luminescent centers
- ...

Outline

- **Diamond**
  - → Synthesis
  - → Properties
  - → **Applications**
- IBL in diamond
  - → MeV ion lithography in diamond
  - → keV ion beam lithography in diamond
- Activities at the University of Torino
  - → Electrical features
  - → Optical features
  - → Microfluidics

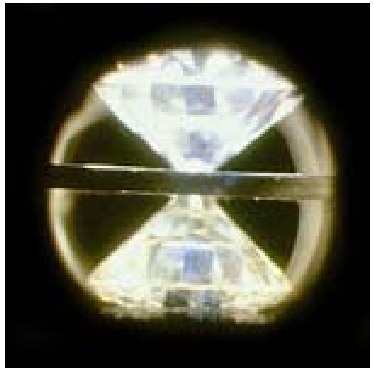
Diamond – Applications

Mechanical properties

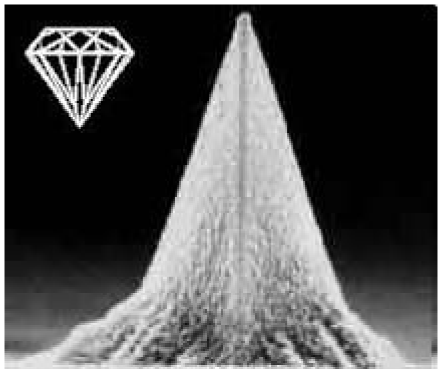
Cutting tools

Tweeters

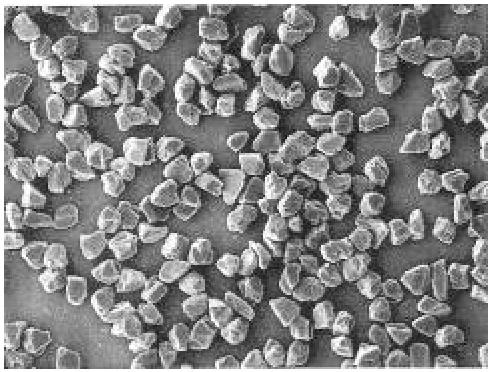
Anvil cells



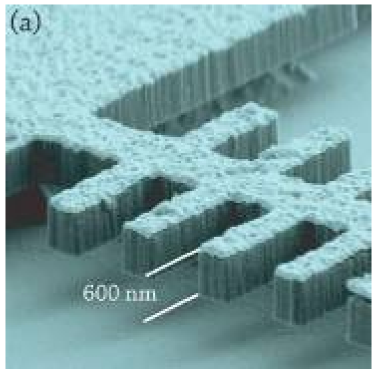
Scanning probe tips



Abrasive powders



MEMS

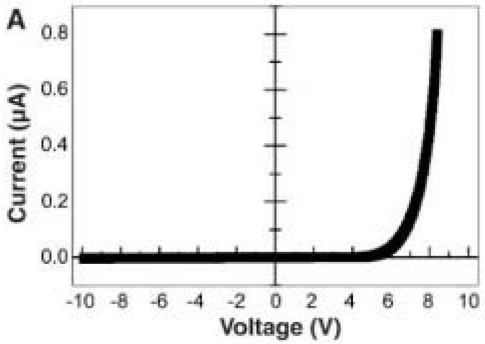


Diamond – Applications

Electronic properties

Particle detectors

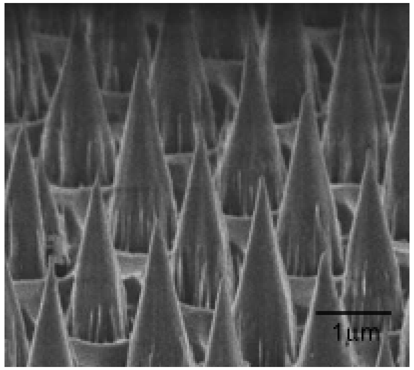
Power diodes



UV diodes

Dosimeters

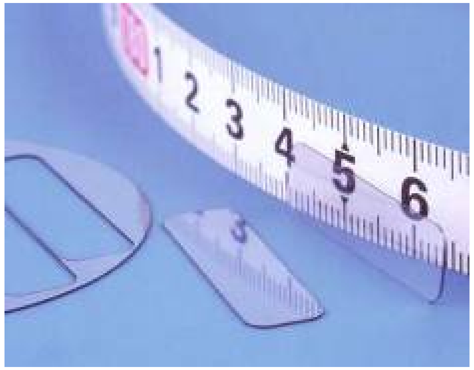
Field emitters

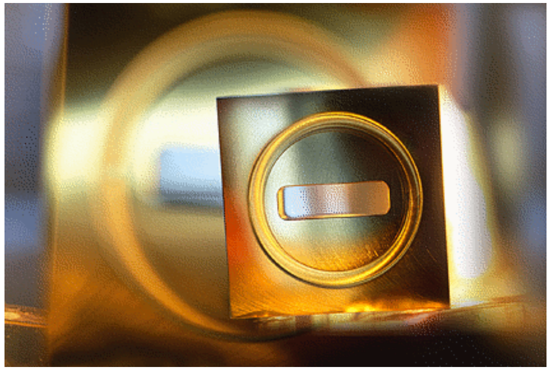


Diamond – Applications

Optical properties

High-power laser windows



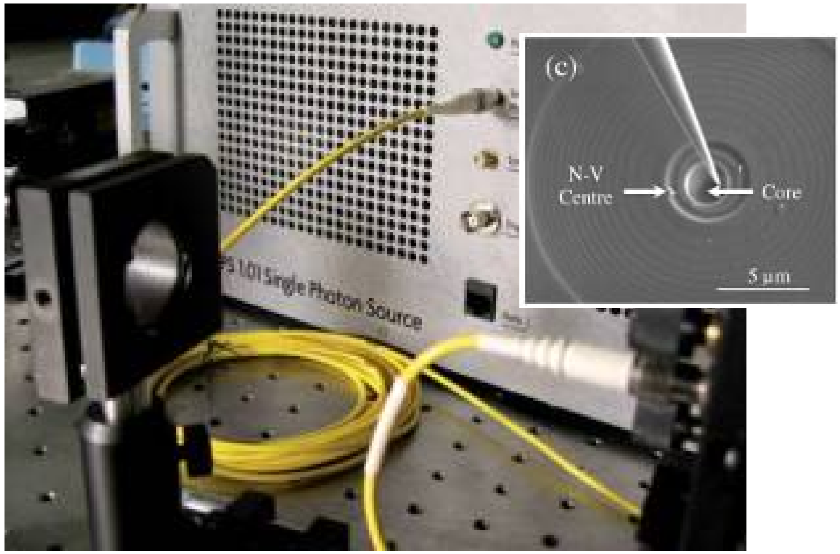


Heat sinks

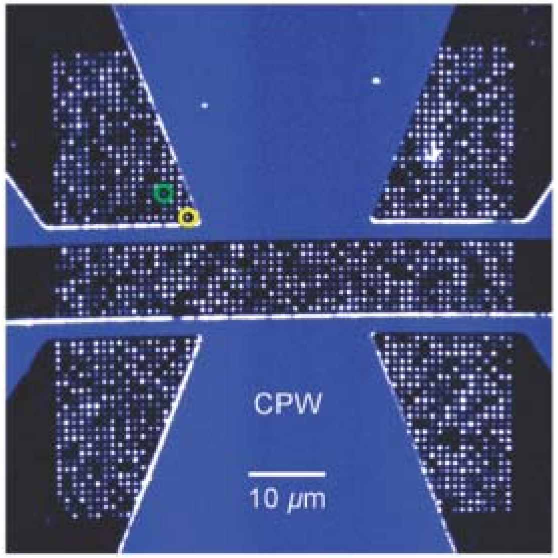
Diamond – Applications

Optical properties

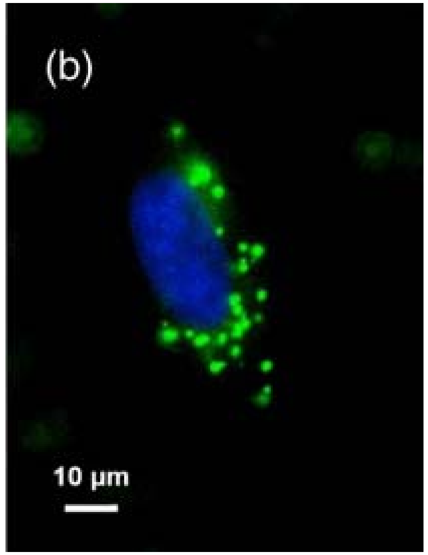
Single photon sources



Quantum computing



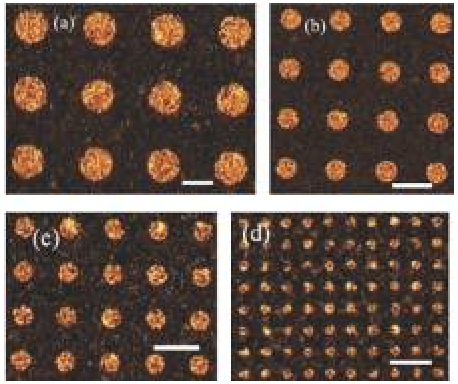
Luminescent markers

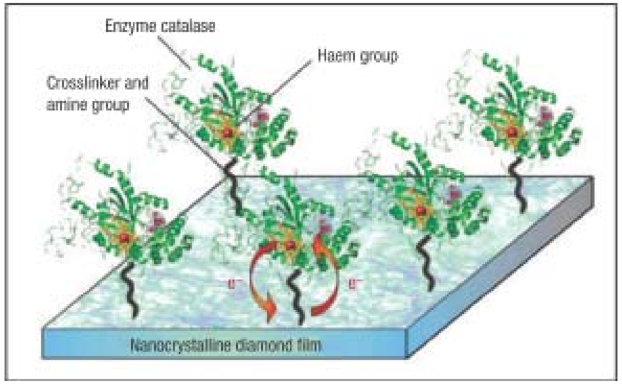


Diamond – Applications

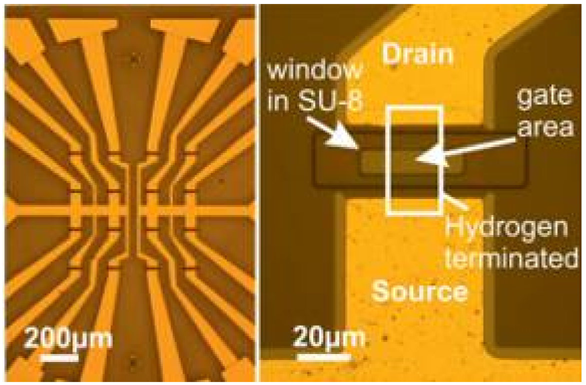
Bio-chemical properties

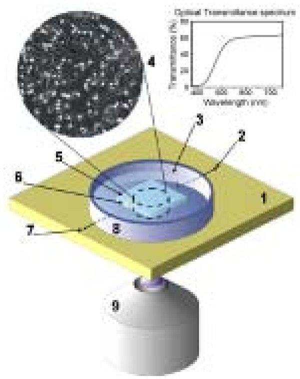
Molecular bio-sensors





Cellular bio-sensors





Diamond – Applications

Companies in diamond synthesis

elementsix

ALMAX INDUSTRIES
The high-precision diamond micro-polishing laboratory

Diamond Materials
Advanced Diamond Technology

SEKI DIAMOND SYSTEMS

SUMITOMO ELECTRIC

rhoBeSt

APOLLO diamond, inc.

QCV Quantum Communications Victoria

cividec

HRDAntwerp
Institute of Gemmology

ADVANCED DIAMOND TECHNOLOGIES, INC.
www.thindiamond.com

GEMESIS

Outline

- Diamond
  - → Synthesis
  - → Properties
  - → Applications
- **IBL in diamond**
  - **→ MeV ion lithography in diamond**
  - → keV ion beam lithography in diamond
- Activities at the University of Torino
  - → Electrical features
  - → Optical features
  - → Microfluidics

MeV ion implantation in diamond

Diamond: a *hard* material for micro-fabrication:

- **Mechanical hardness**
- **Chemical inertness**
- **Optical transparency**

⇩

Ion beam lithography

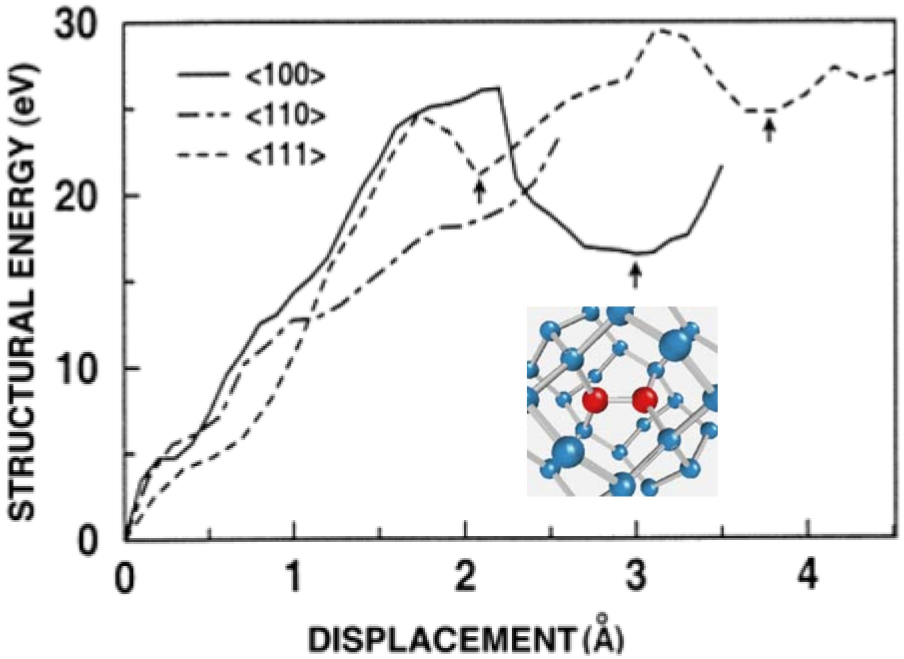
MeV ion implantation in diamond

Electronic energy loss →

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

Nuclear energy loss →

Significant structural effects on a meta-stable material



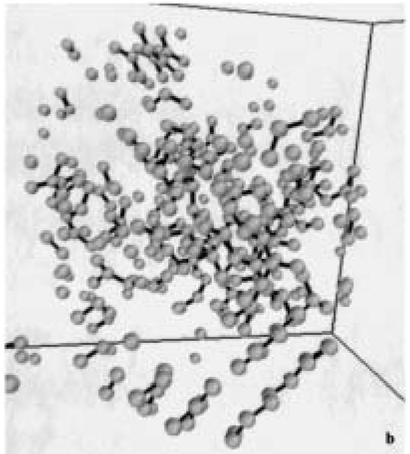
Atom displacement → Formation of an sp^2-bonded split interstitial

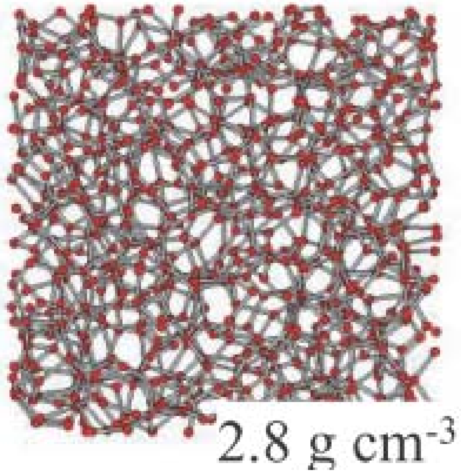
MeV ion implantation in diamond

A crude linear approximation: ρ_{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**





MeV ion implantation in diamond

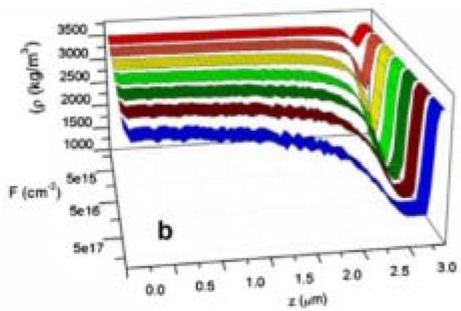
A crude linear approximation: ρ_{vac} = (linear damage density)$_{SRIM}$ × (fluence)

[$\#_{vac}$ 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: Semi-analytical / empirical models**

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

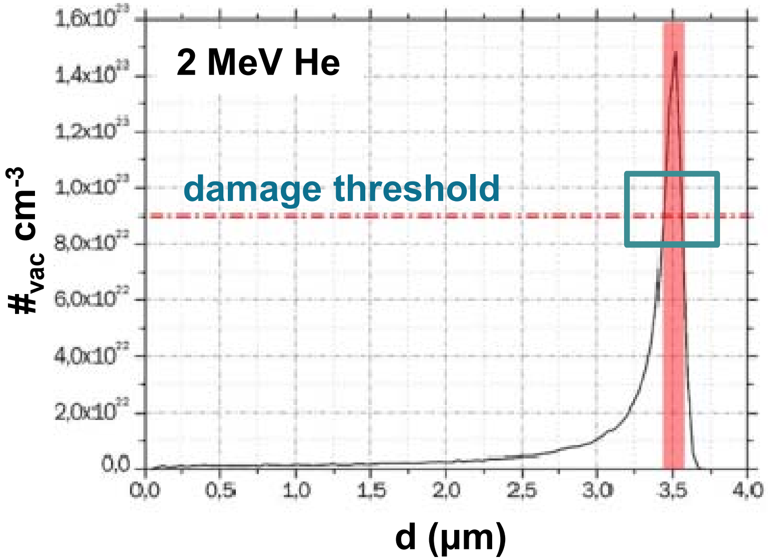

NIMB
Radiation defects and their annealing behaviour in ion-implanted diamonds
Johan F. Prins, Trevor E. Derry

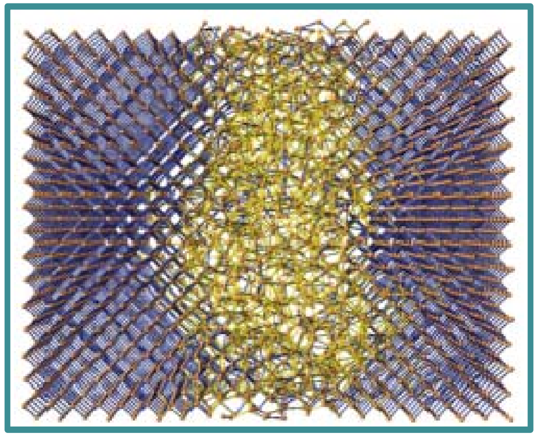


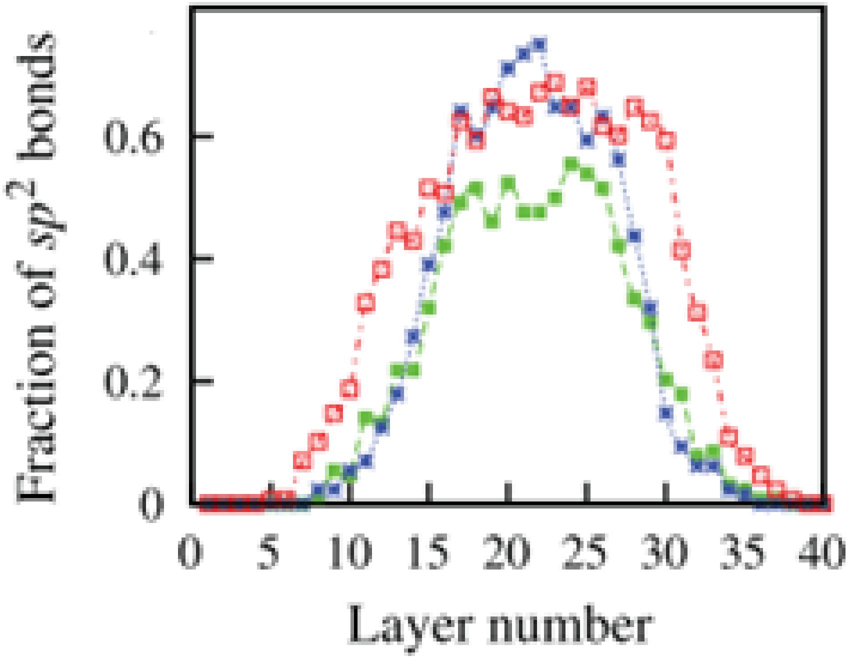
@ : **Institute of Ion Beam Physics and Materials Research (Dresden), Department of Physics – University of Pretoria, Solid State Physics Group – University of Torino**

MeV ion implantation in diamond

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



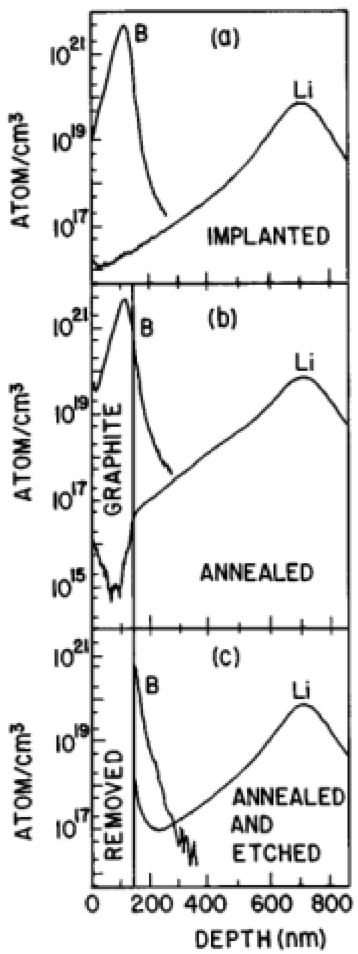


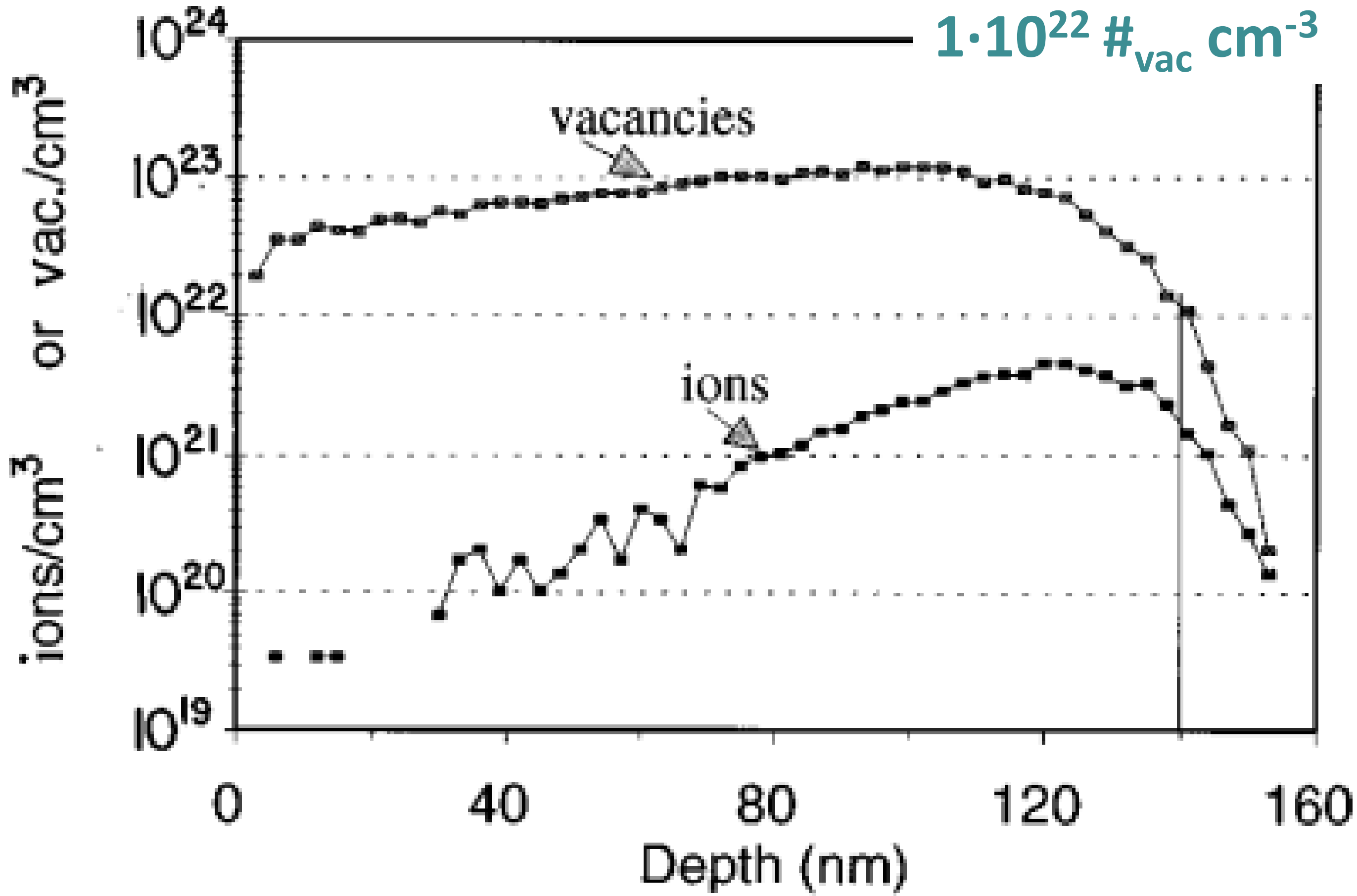


@ : SRIM Monte Carlo code, Technion – Israel Institute of Technology

MeV ion implantation in diamond

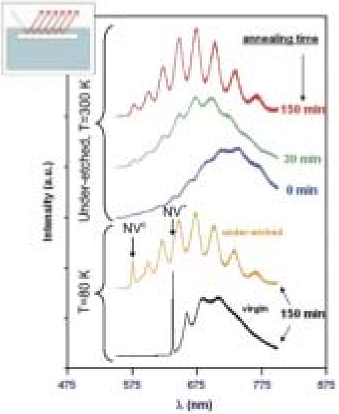
Graphitization threshold



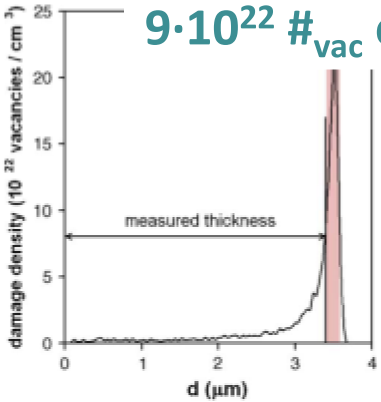


MeV ion implantation in diamond

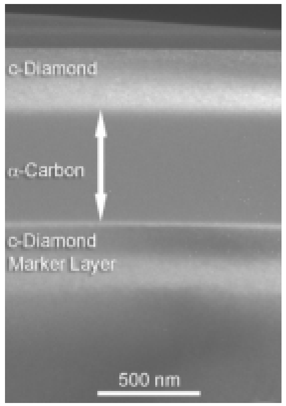
Graphitization threshold



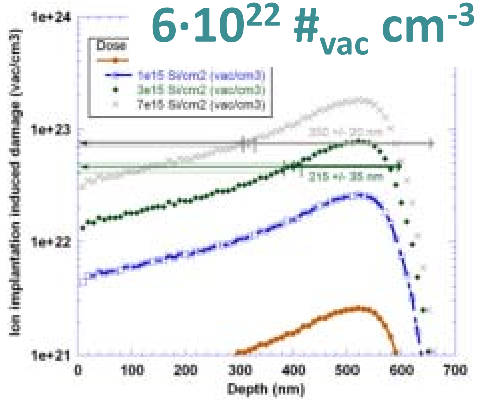
$9 \cdot 10^{22}$ $\#_{vac}$ cm^{-3}



@ : School of Physics – University of Melbourne

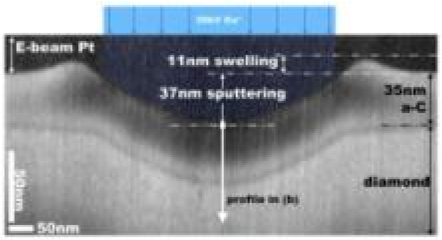


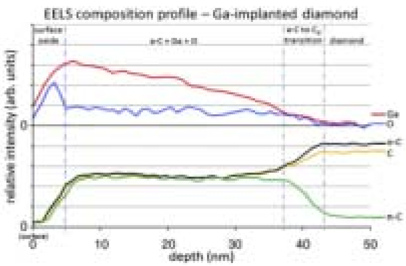
$6 \cdot 10^{22}$ $\#_{vac}$ cm^{-3}



@ : Uni. of Florida & Australian National Uni.

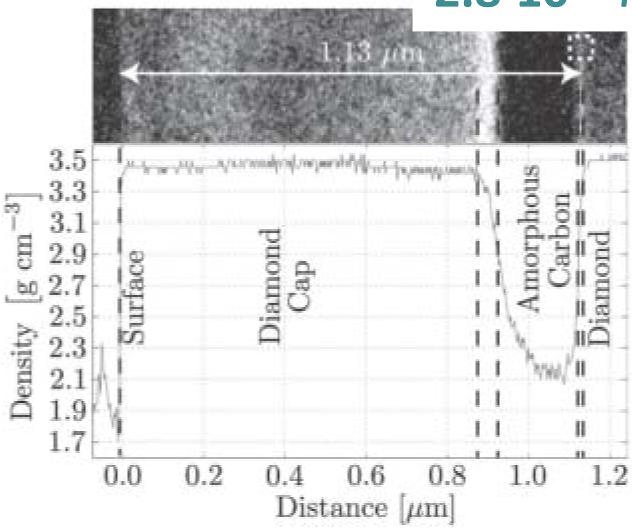
$2 \cdot 10^{22}$ $\#_{vac}$ cm^{-3}





@ : University of New South Wales

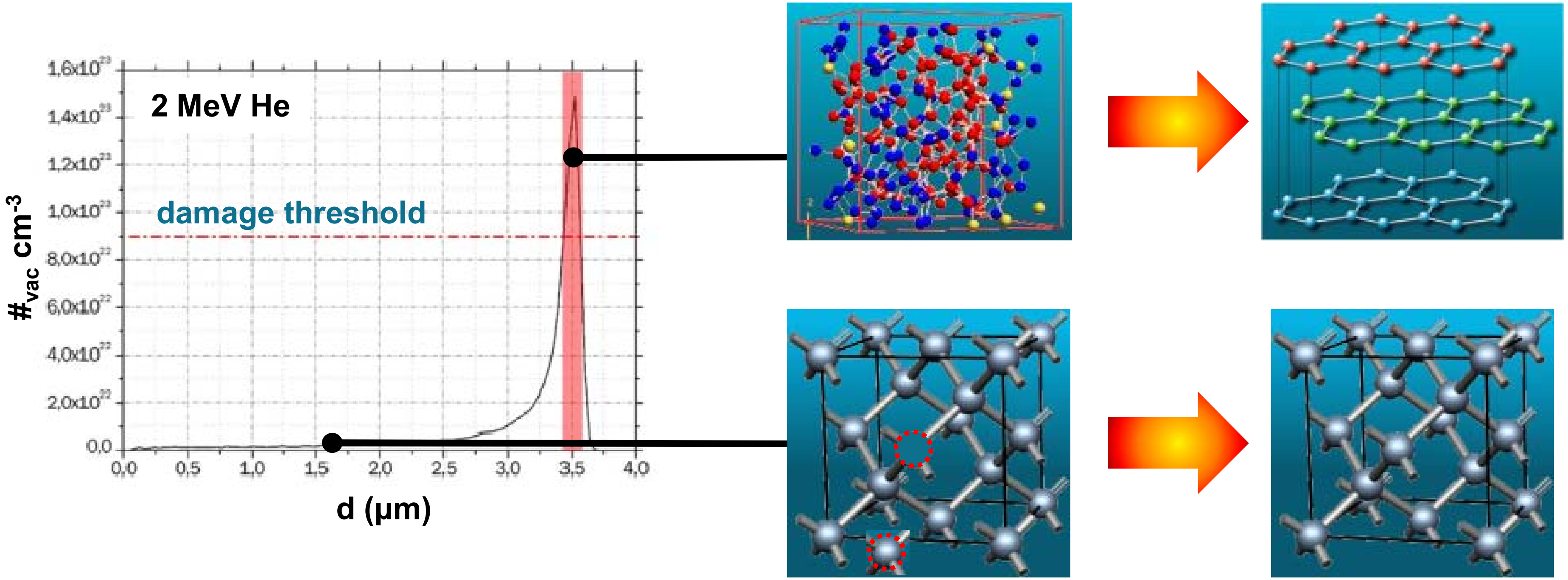
$2.8 \cdot 10^{22}$ $\#_{vac}$ cm^{-3}



@ : School of Physics – University of Melbourne

MeV ion implantation in diamond

Thermal annealing

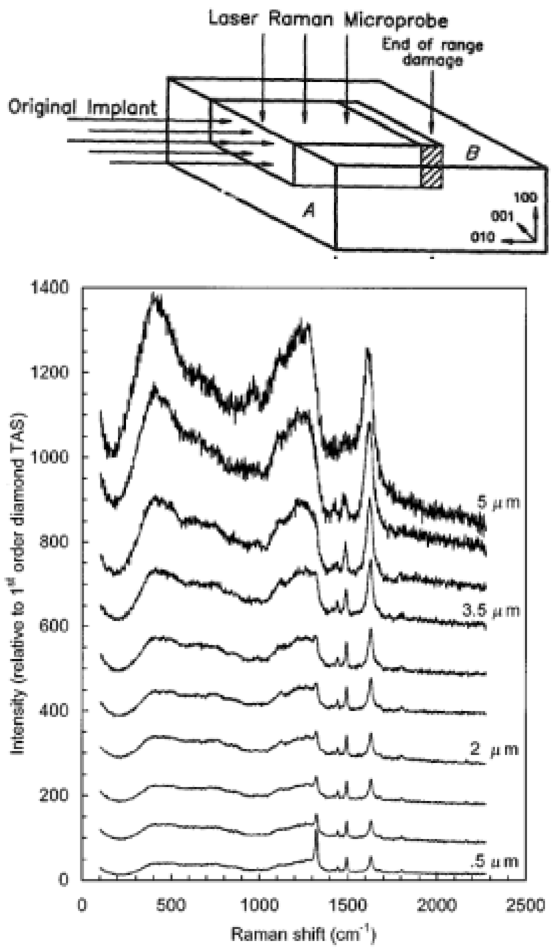


- **Above threshold: amorphous carbon** → **polycrystalline graphite**
- **Below threshold: diamond with Frenkel defects** → **diamond**

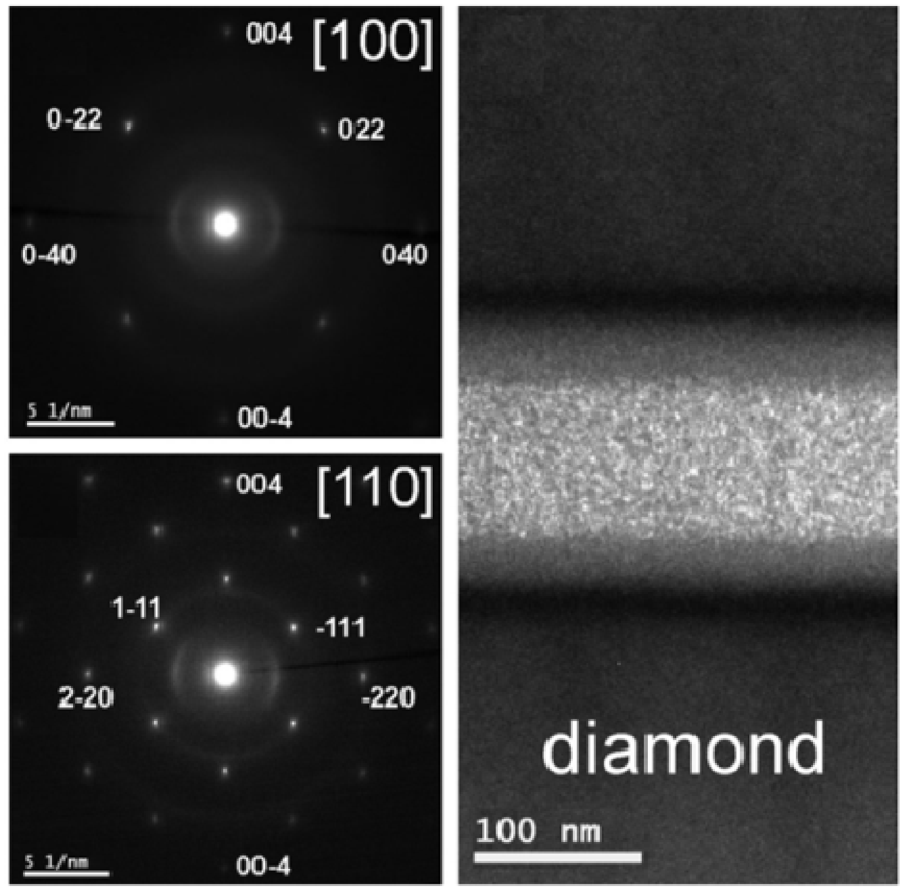
MeV ion implantation in diamond

Experimental evidences

Cross-sectional µ-Raman



Cross-sectional TEM



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

IBL in Diamond: State of the Art

The diamond lift-off Technique

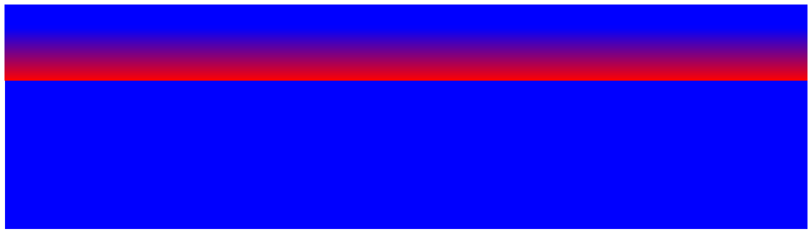
Single-crystal diamond plate liftoff achieved by ion implantation and subsequent annealing

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



- **MeV ion implantation**

IBL in Diamond: State of the Art

The diamond lift-off Technique

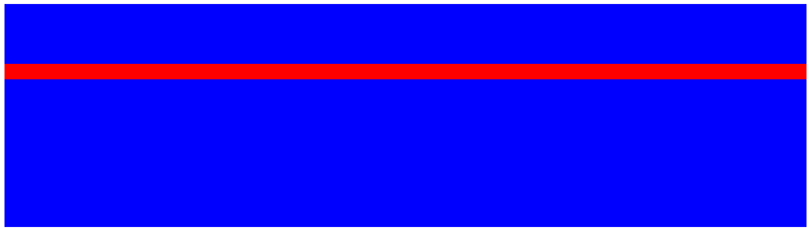
Single-crystal diamond plate liftoff achieved by ion implantation and subsequent annealing

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



- **MeV ion implantation**
- **Thermal annealing**

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

- **MeV ion implantation**
- **Thermal annealing**
- **Selective graphite etching**

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

- **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

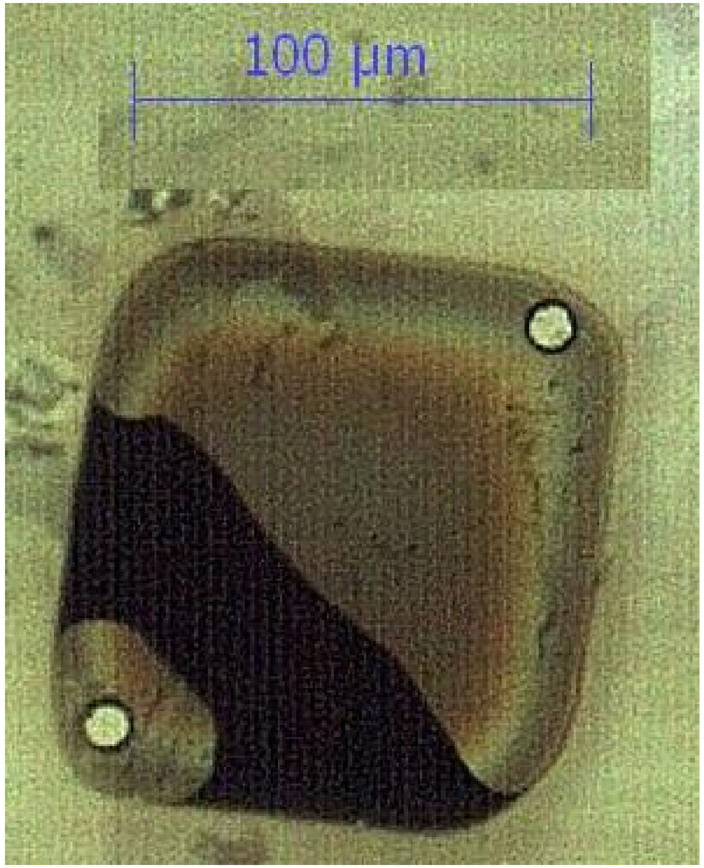
  T = 550 – 580 °C in air

- 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

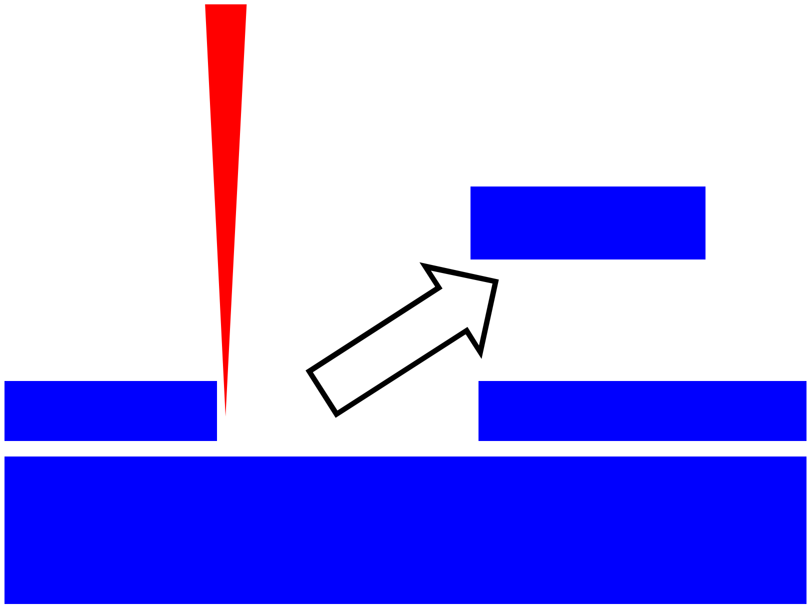
John D. Hunn, S. P. Withrow, C. W. White, R. E. Clausing, and L. Heatherly
Oak Ridge National Laboratory, Bldg 5500 MS-6376, Oak Ridge, Tennessee 37831-6376

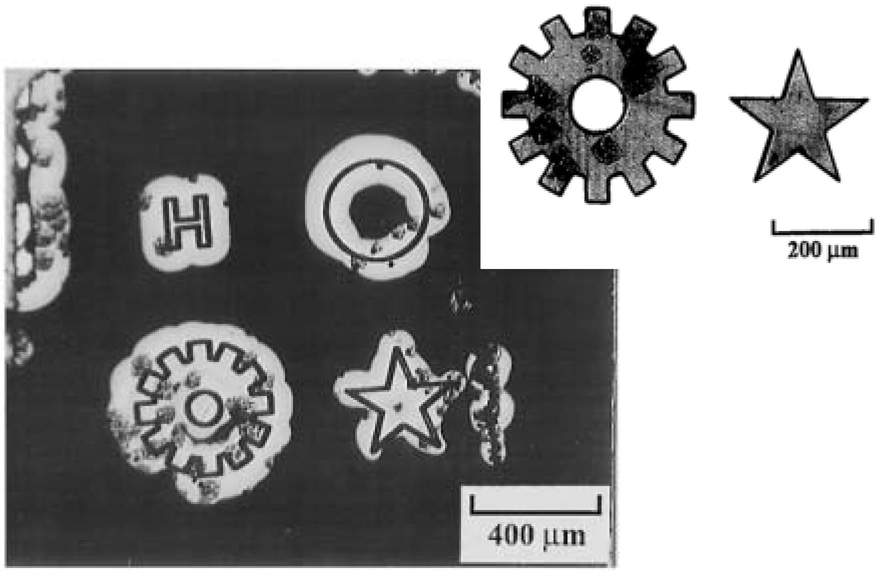
C. Paul Christensen
Potomac Photonics, Lanham, Maryland 20705

(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

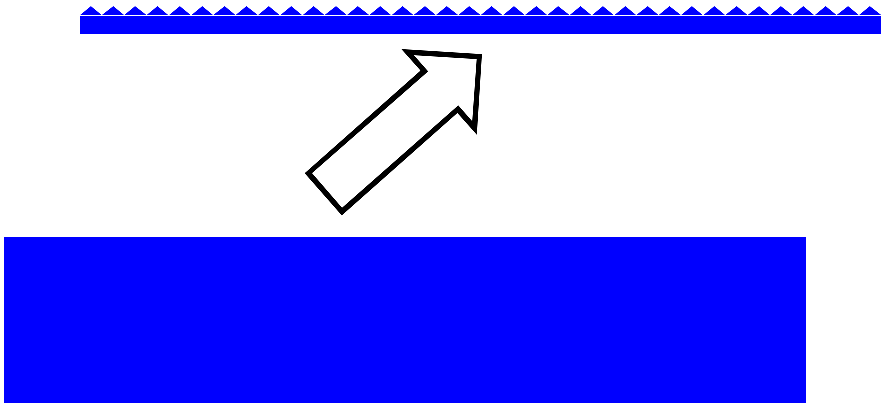
Surface smoothening

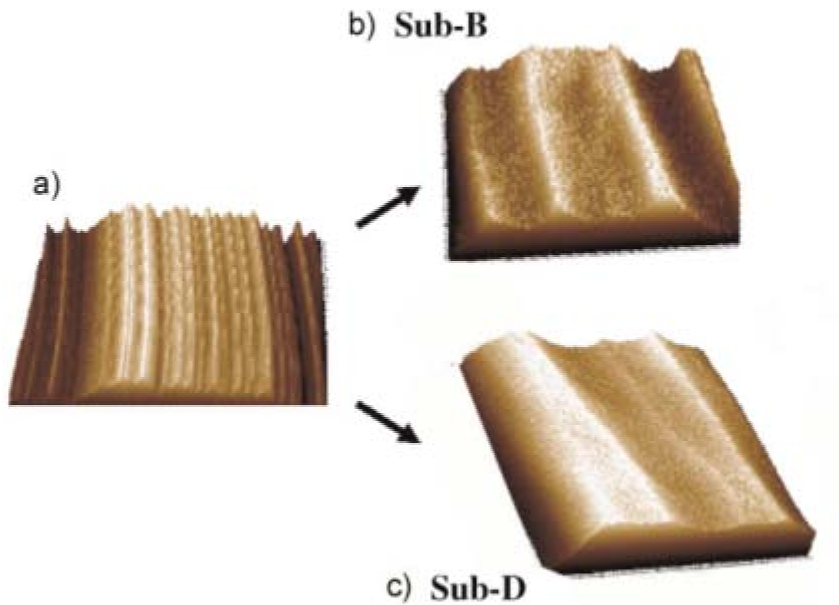
Phys. Status Solidi A **206**, No. 9, 1955–1959 (2009) / **DOI** 10.1002/pssa.200982232

physica status solidi a
www.pss-a.com
applications and materials science

High surface smoothening of diamond HPHT (100) substrates

C. Mer-Calfati[*,1], N. Habka[1,2], A. Ben-Younes[1], M.-A. Pinault[2], J. Barjon[2], and P. Bergonzo[1]





IBL in Diamond: State of the Art

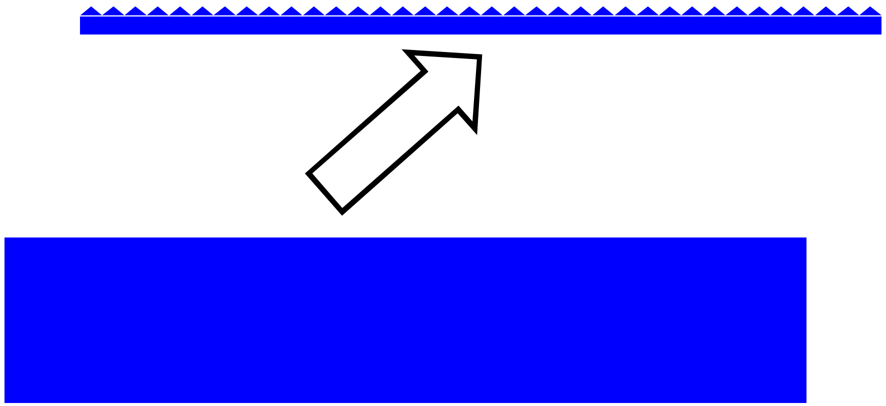
Surface smoothening

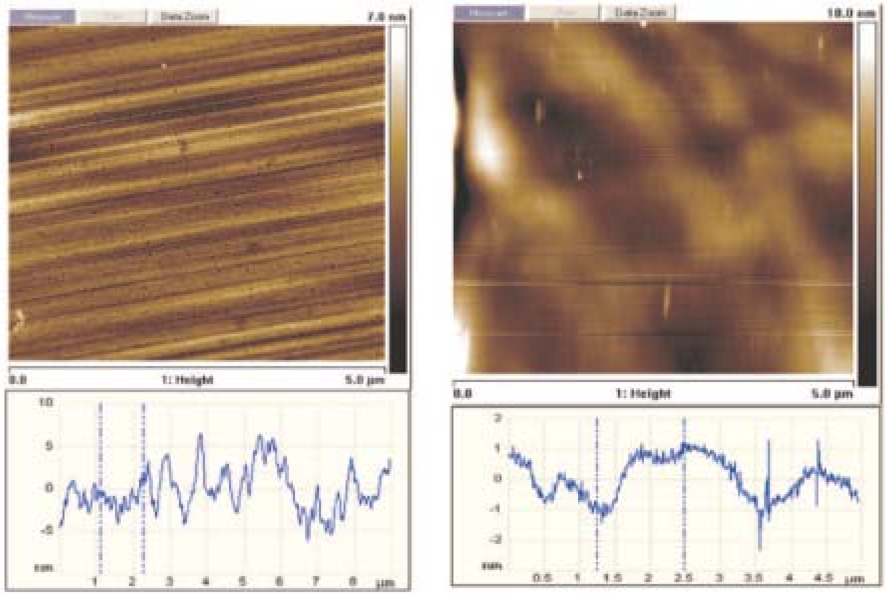
Phys. Status Solidi A **208**, No. 9, 2057–2061 (2011) / **DOI** 10.1002/pssa.201100038

physica status solidi a
www.pss-a.com
applications and materials science

Ultra-smooth single crystal diamond surfaces resulting from implantation and lift-off processes

T. N. Tran Thi[*,1], B. Fernandez[1], D. Eon[1], E. Gheeraert[1], J. Härtwig[2], T. Lafford[2], A. Perrat-Mabilon[3], C. Peaucelle[3], P. Olivero[4], and E. Bustarret[**,1]





IBL in Diamond: State of the Art

Lift-off + CVD growth

Diamond & Related Materials 20 (2011) 616–619

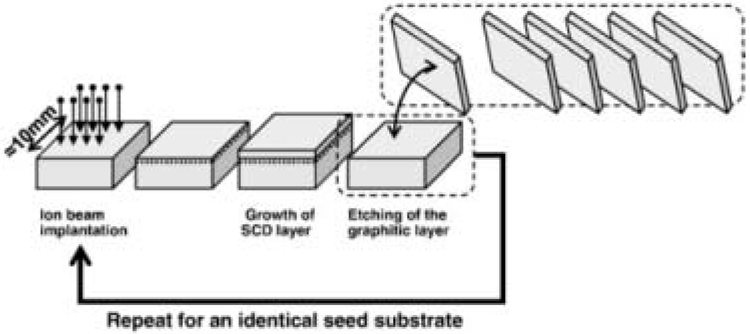
Contents lists available at ScienceDirect

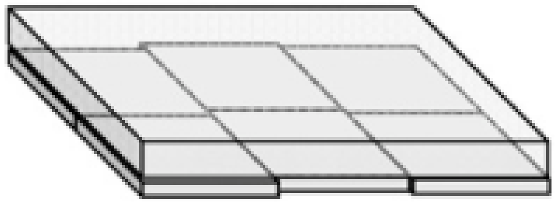
Diamond & Related Materials

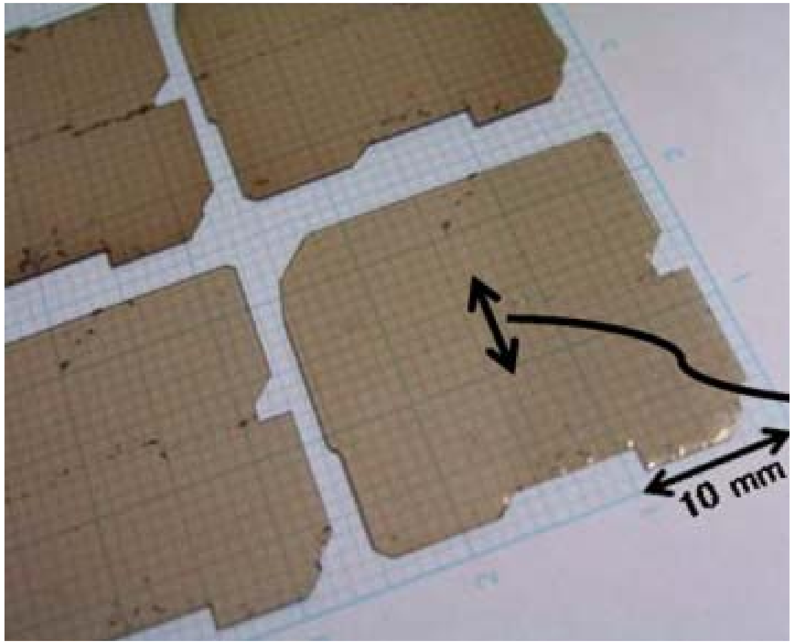
journal homepage: www.elsevier.com/locate/diamond

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]







IBL in Diamond: State of the Art

Lift-off + CVD growth

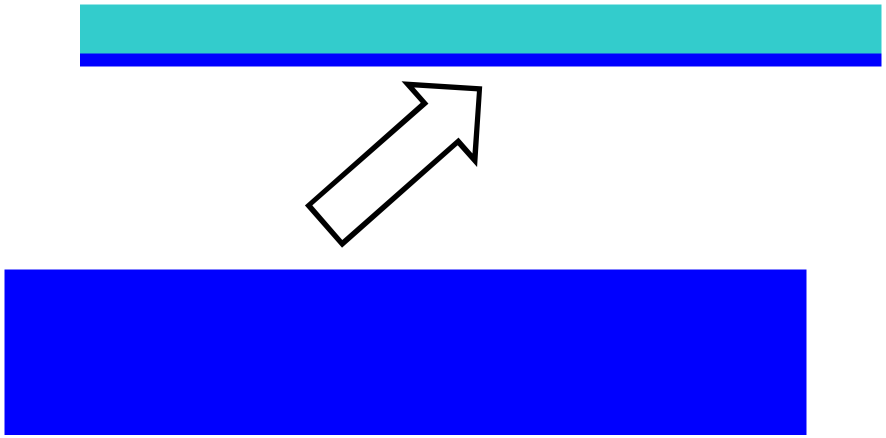
Diamond & Related Materials 24 (2012) 74–77

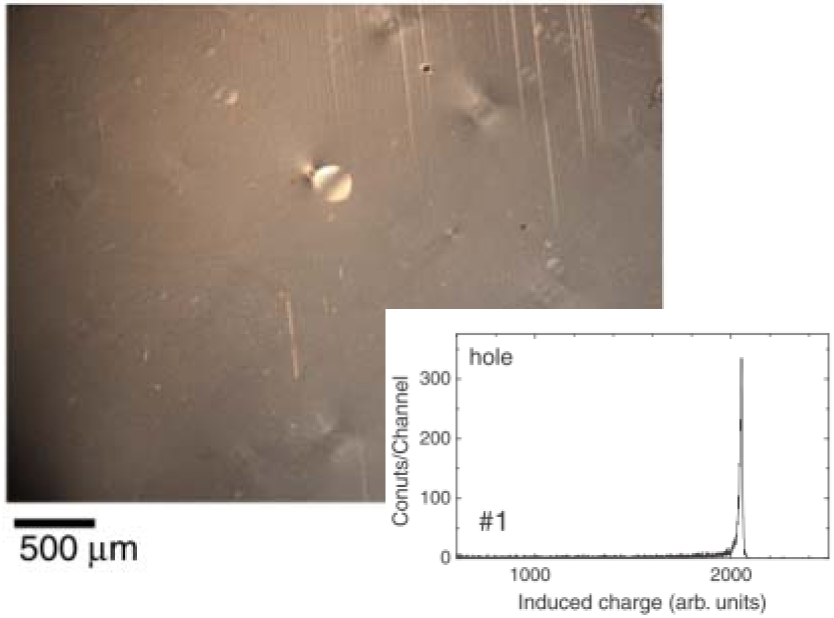
Contents lists available at SciVerse ScienceDirect

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 + CVD growth

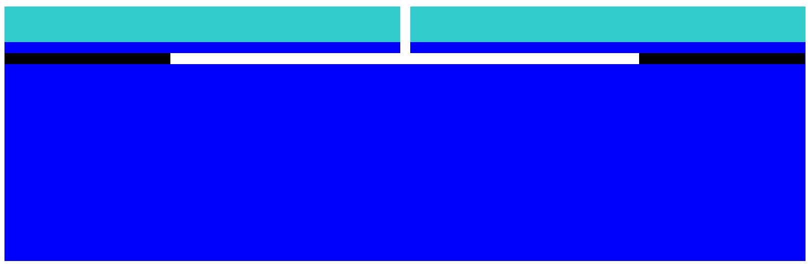
NANO LETTERS

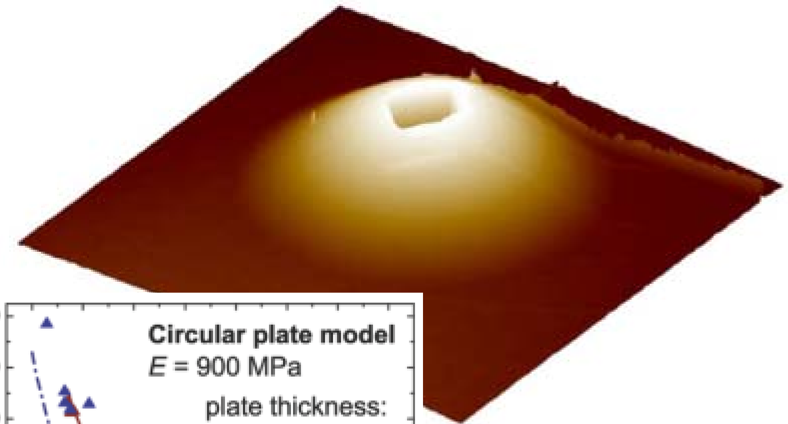
LETTER

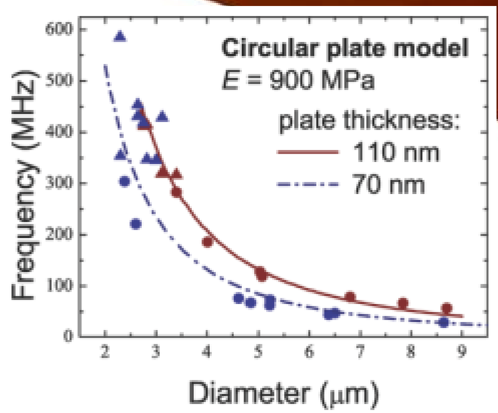
pubs.acs.org/NanoLett

Ultrathin Single Crystal Diamond Nanomechanical Dome Resonators

Maxim K. Zalalutdinov,*,† Matthew P. Ray,† Douglas M. Photiadis,† Jeremy T. Robinson,† Jeffrey W. Baldwin,† James E. Butler,§ Tatyana I. Feygelson,§ Bradford B. Pate,† and Brian H. Houston†







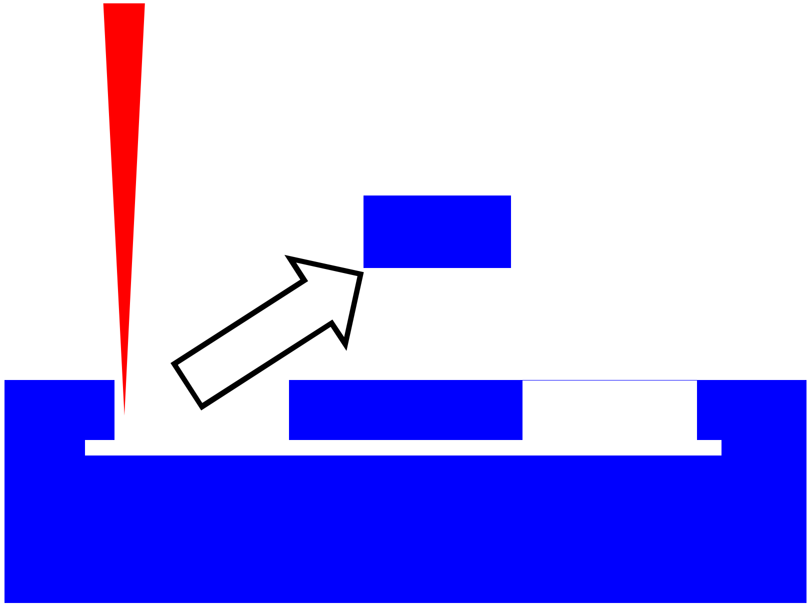
IBL in Diamond: State of the Art

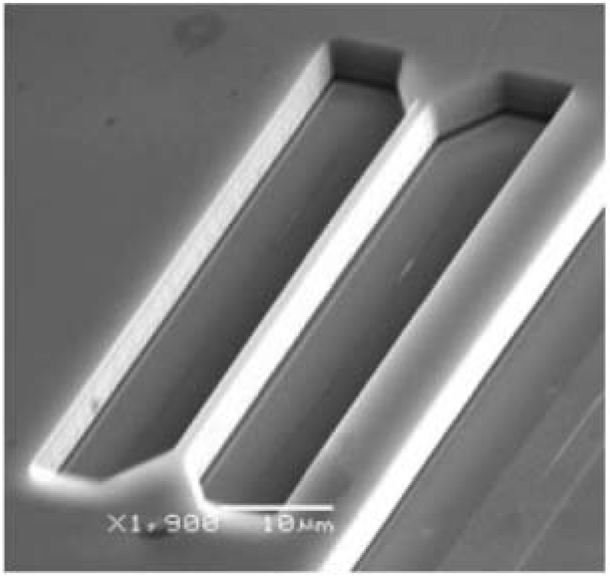
Lift-off + Focused Ion Beam (FIB) milling

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





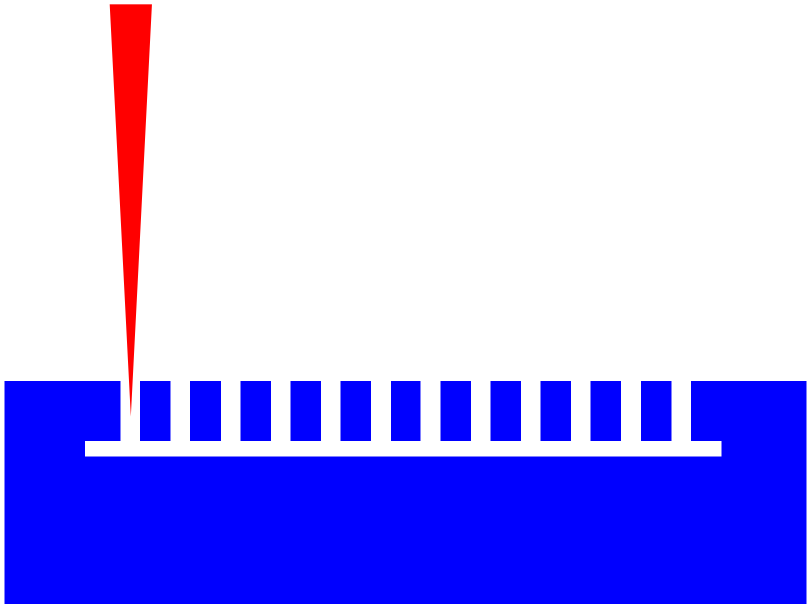
IBL in Diamond: State of the Art

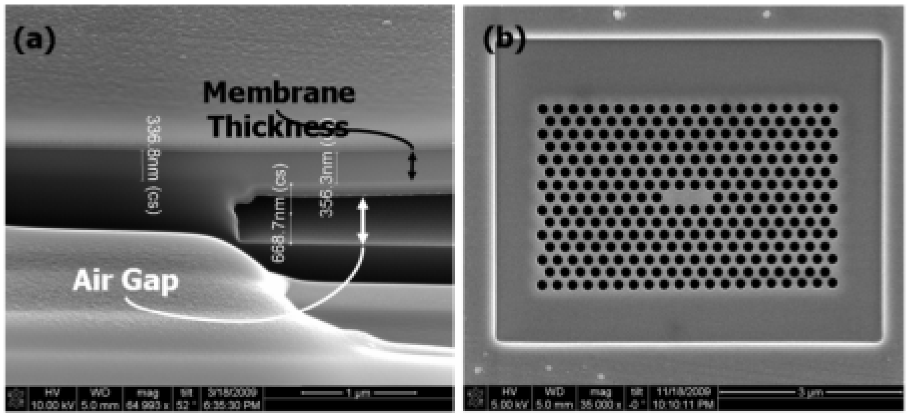
Lift-off + Focused Ion Beam (FIB) milling

New Journal of Physics
The open-access journal for physics

Triangular nanobeam photonic cavities in single-crystal diamond

Igal Bayn[1,3], Boris Meyler[1], Joseph Salzman[1] and Rafi Kalish[2]





IBL in Diamond: State of the Art

Lift-off + Focused Ion Beam (FIB) milling

Diamond & Related Materials 21 (2012) 16–23

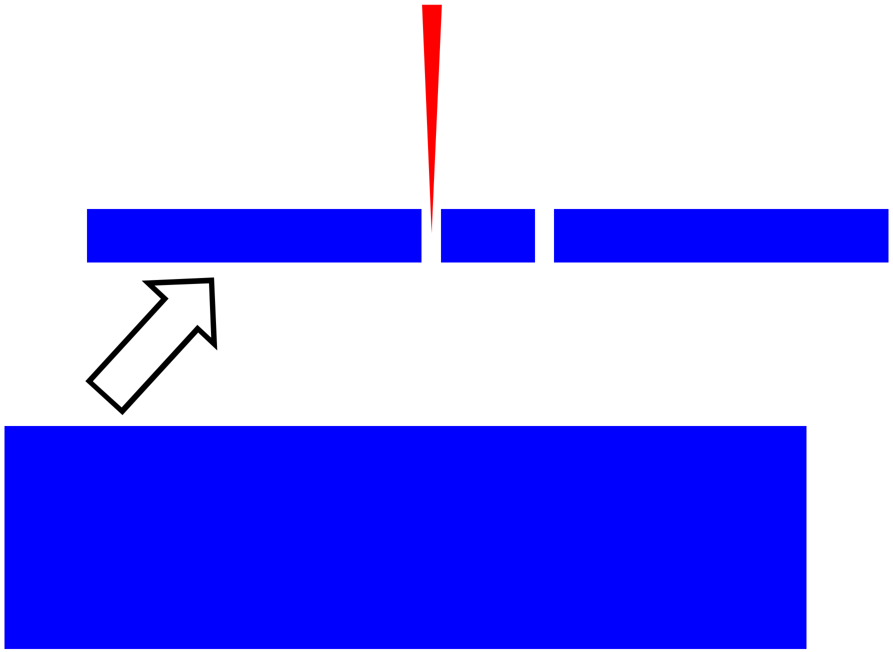
Contents lists available at SciVerse ScienceDirect

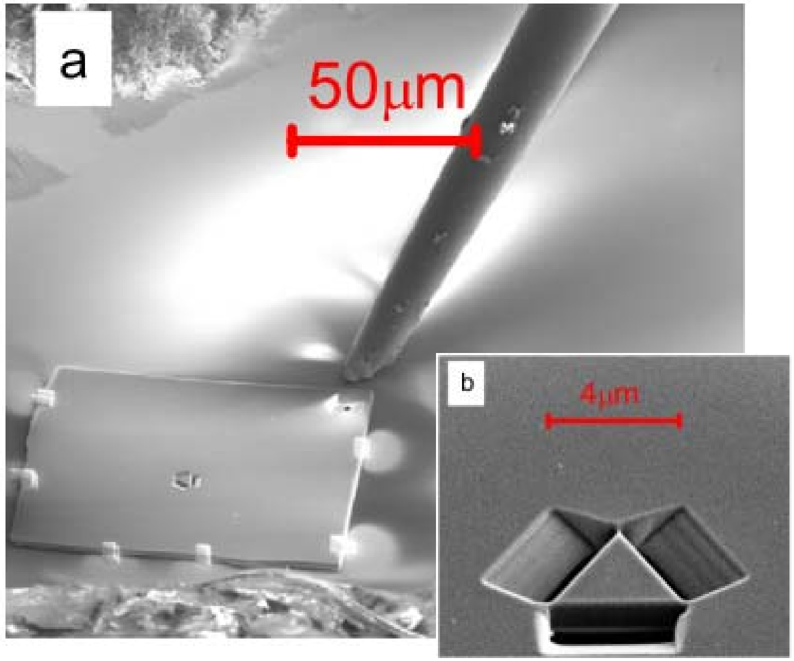
Diamond & Related Materials

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

Optical properties of single crystal diamond microfilms fabricated by ion implantation and lift-off processing

Brian R. Patton [a], Philip R. Dolan [a], Fabio Grazioso [a], Matthew B. Wincott [a], Jason M. Smith [a,*], Matthew L. Markham [b], Daniel J. Twitchen [b], Yanfeng Zhang [c], Erdan Gu [c], Martin D. Dawson [c], Barbara A. Fairchild [d], Andrew D. Greentree [d], Steven Prawer [d]





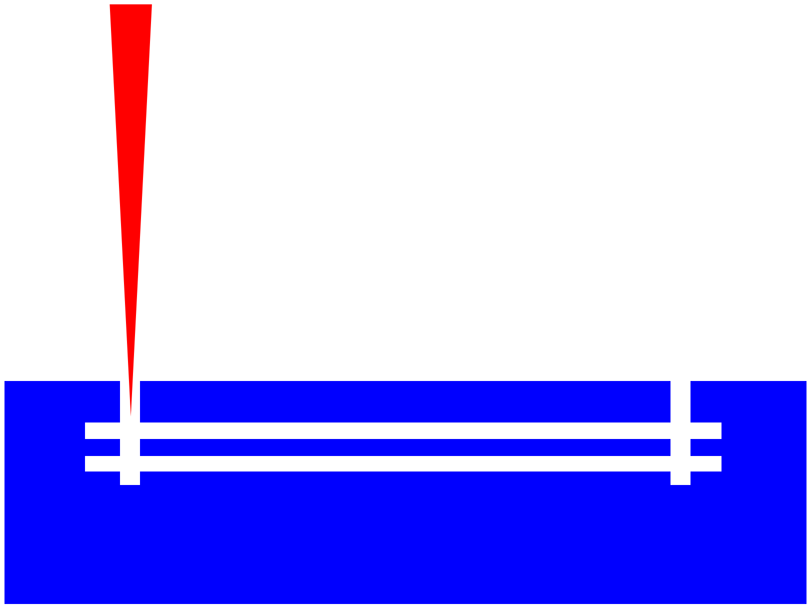
IBL in Diamond: State of the Art

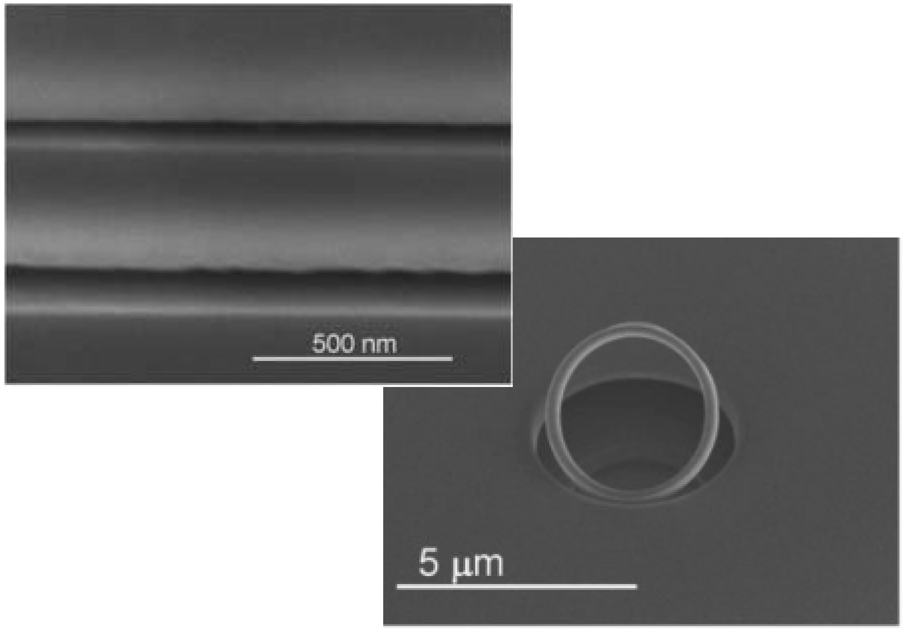
Lift-off (double implantation) + FIB

Fabrication of Ultrathin Single-Crystal Diamond Membranes**

By *Barbara A. Fairchild,** *Paolo Olivero, Sergey Rubanov, Andrew D. Greentree, Felix Waldermann, Robert A. Taylor, Ian Walmsley, Jason M. Smith, Shane Huntington, Brant C. Gibson, David N. Jamieson,* and *Steven Prawer*

Adv. Mater. **2008**, *20*, 4793–4798





IBL in Diamond: State of the Art

Lift-off (double implantation) + FIB

Diamond & Related Materials 20 (2011) 937–943

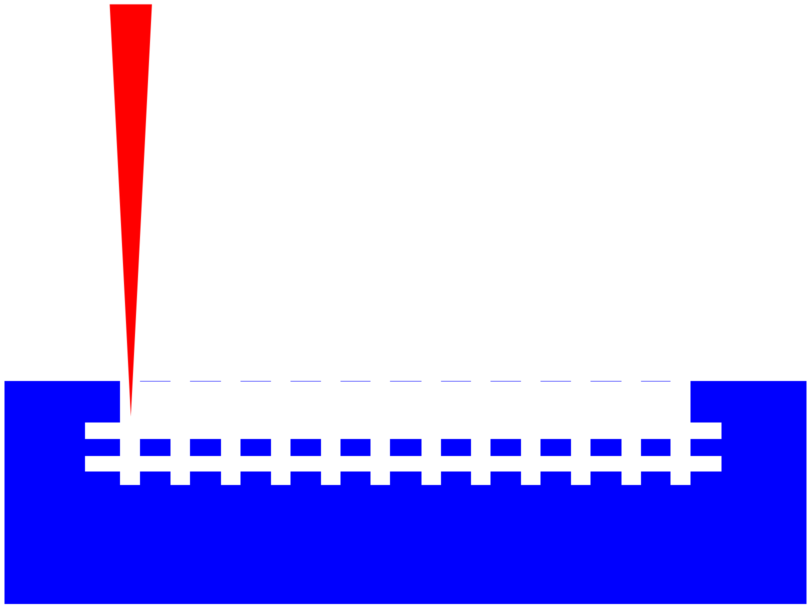
Contents lists available at ScienceDirect

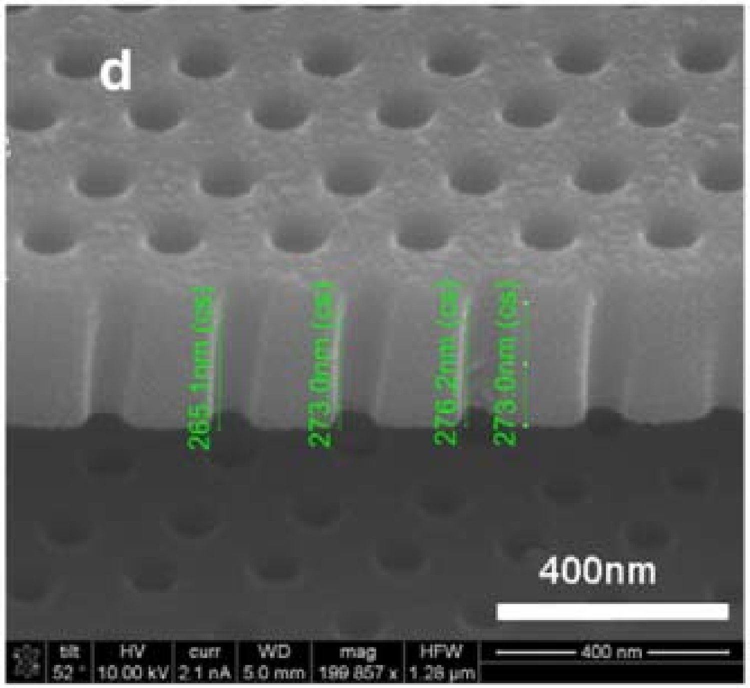
Diamond & Related Materials

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

Processing of photonic crystal nanocavity for quantum information in diamond

Igal Bayn [a,*], Boris Meyler [a], Alex Lahav [a], Joseph Salzman [a], Rafi Kalish [b], Barbara A. Fairchild [c], Steven Prawer [c], Michael Barth [d], Oliver Benson [d], Thomas Wolf [e], Petr Siyushev [e], Fedor Jelezko [e], Jorg Wrachtrup [e]





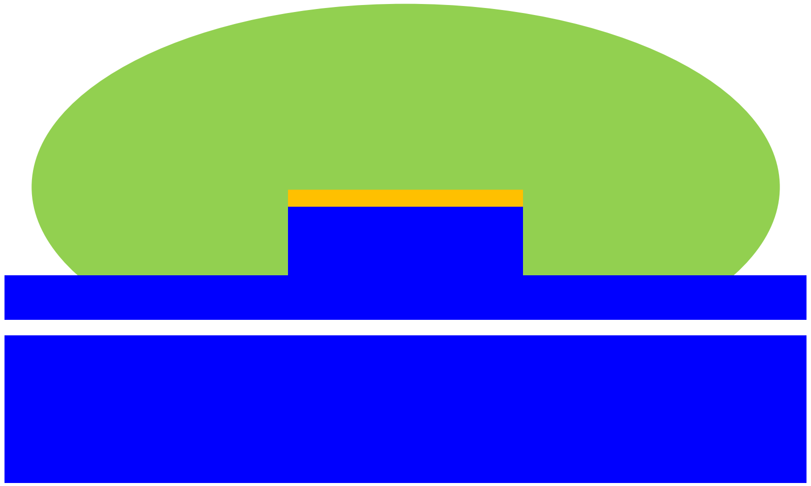
IBL in Diamond: State of the Art

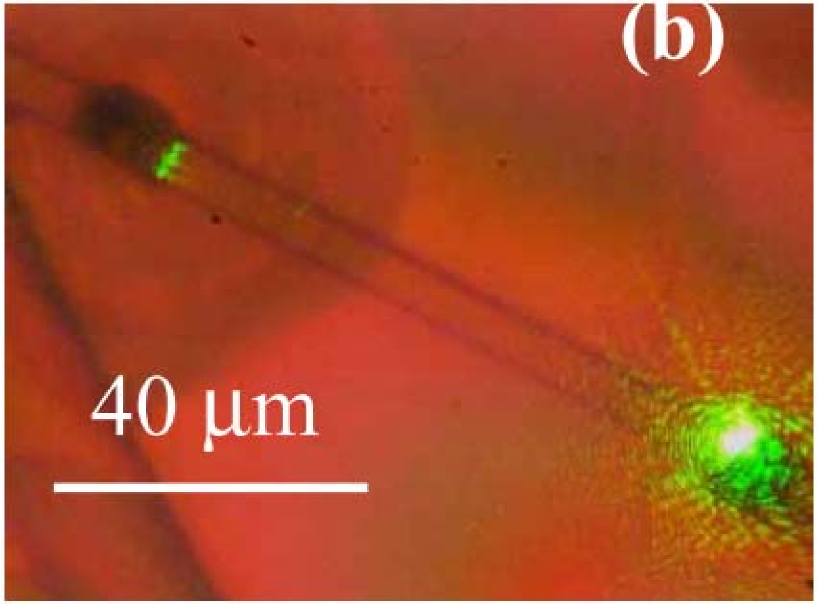
Lift-off + Reactive Ion Etching (RIE)

Diamond waveguides fabricated by reactive ion etching

Mark P. Hiscocks[1], Kumaravelu Ganesan[2], Brant C. Gibson[3], Shane T. Huntington[2], François Ladouceur[1], and Steven Prawer[3]

24 November 2008 / Vol. 16, No. 24 / OPTICS EXPRESS 19512





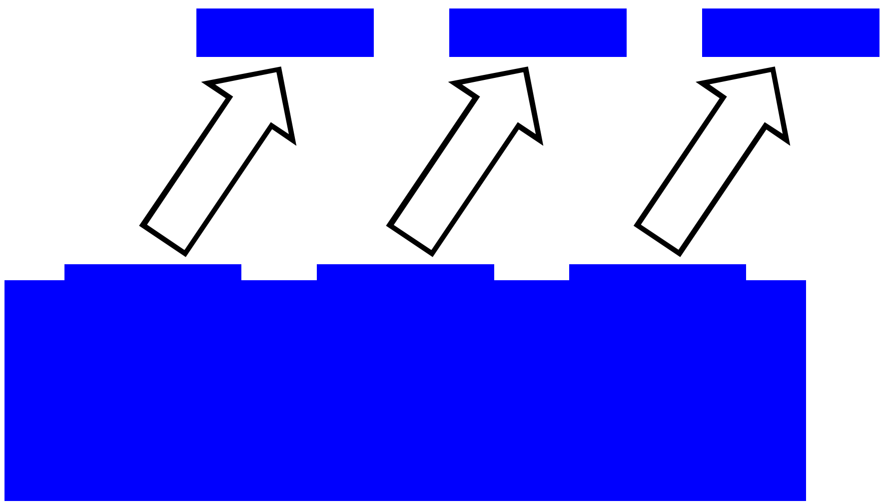
IBL in Diamond: State of the Art

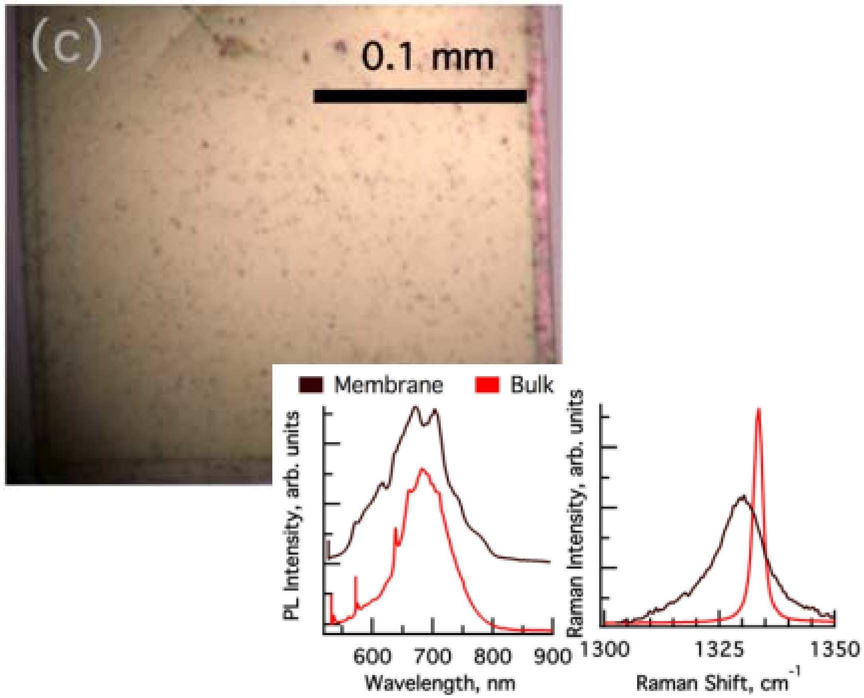
Lift-off + Reactive Ion Etching (RIE)

APPLIED PHYSICS LETTERS **99**, 081913 (2011)

Fabrication of thin, luminescent, single-crystal diamond membranes

Andrew P. Magyar,[1] Jonathan C. Lee,[1] Andi M. Limarga,[1] Igor Aharonovich,[1] Fabian Rol,[1]
David R. Clarke,[1] Mengbing Huang,[2] and Evelyn L. Hu[1,a)]





IBL in Diamond: State of the Art

Lift-off + CVD growth + RIE

Fabrication of suspended single crystal diamond devices by electrochemical etch

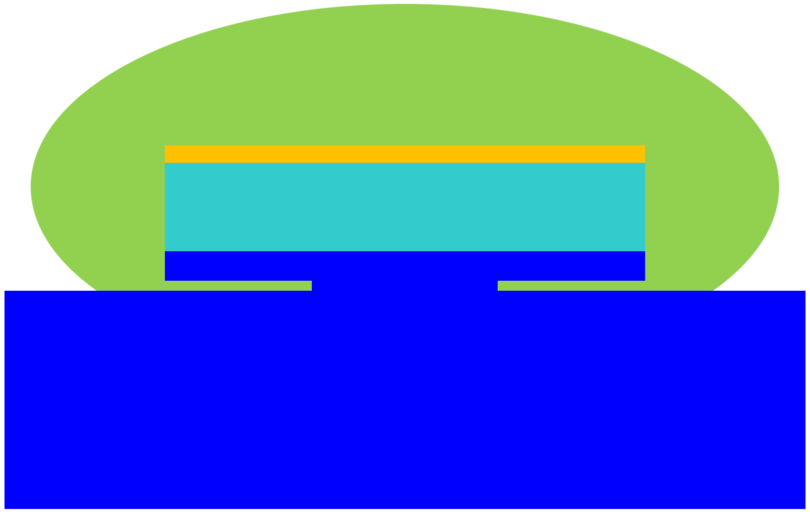
C. F. Wang[a)]
Department of Physics, University of California, Santa Barbara, California 93106

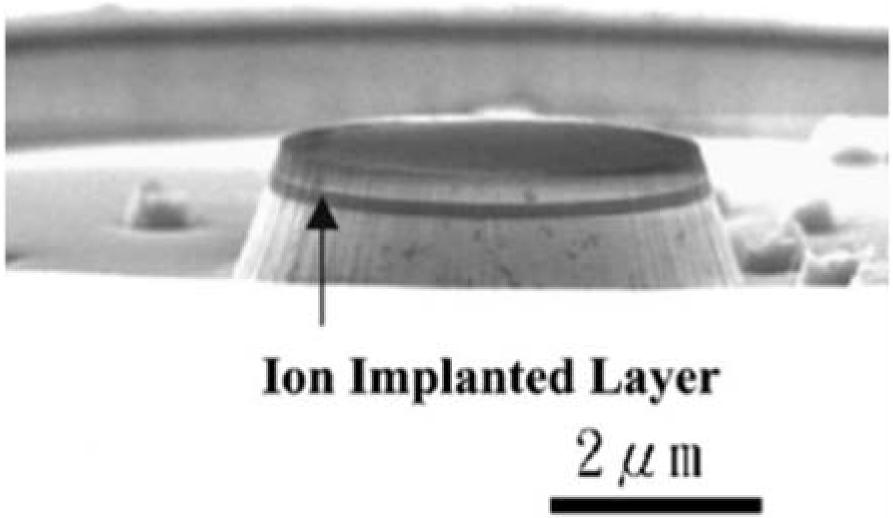
E. L. Hu
Department of Electrical and Computer Engineering, University of California, Santa Barbara, California 93106 and Materials Department, University of California, Santa Barbara, California 93106

J. Yang
Gas/Surface Dynamics Section, Naval Research Laboratory, Washington, DC 20375 and NOVA research, Inc., Alexandria, Virginia 22308

J. E. Butler
Gas/Surface Dynamics Section, Naval Research Laboratory, Washington, DC 20375

730 J. Vac. Sci. Technol. B 25(3), May/Jun 2007





IBL in Diamond: State of the Art

Lift-off + CVD growth + RIE

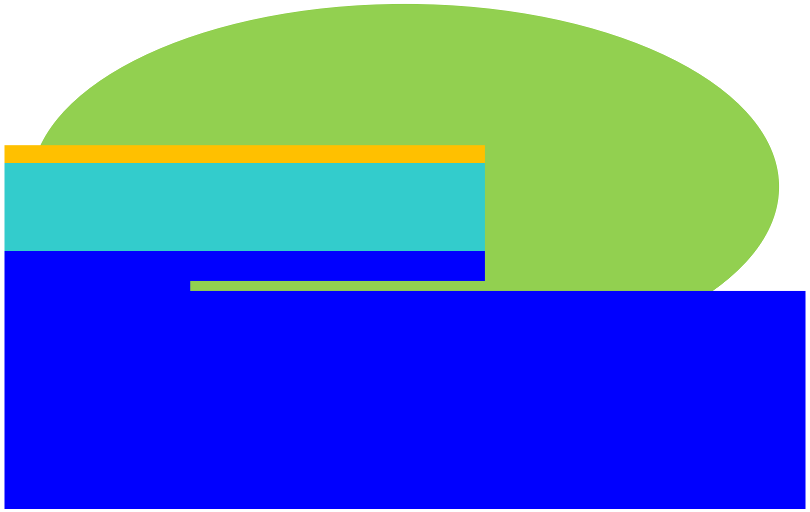
Materials Views
www.MaterialsViews.com

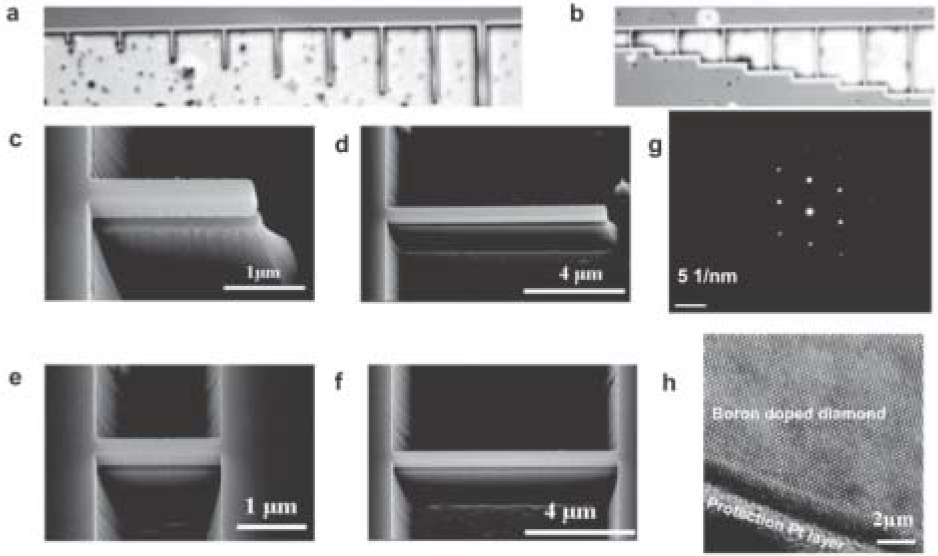
ADVANCED MATERIALS
www.advmat.de

Suspended Single-Crystal Diamond Nanowires for High-Performance Nanoelectromechanical Switches

By *Meiyong Liao,* Shunichi Hishita, Eiichiro Watanabe, Satoshi Koizumi,* and *Yasuo Koide*

Adv. Mater. **2010**, *22*, 5393–5397





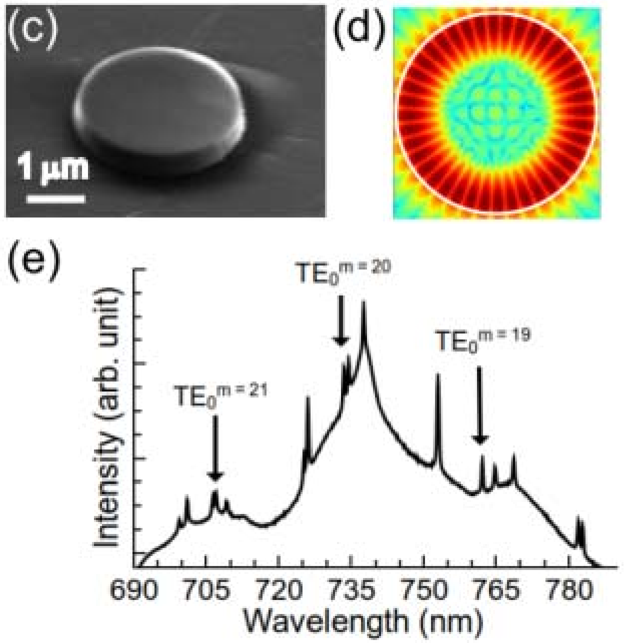
IBL in Diamond: State of the Art

Lift-off + CVD growth + RIE

Coupling of silicon-vacancy centers to a single crystal diamond cavity

Jonathan C. Lee,* Igor Aharonovich, Andrew P. Magyar, Fabian Rol, and Evelyn L. Hu

9 April 2012 / Vol. 20, No. 8 / OPTICS EXPRESS 8891



IBL in Diamond: State of the Art

Lift-off + CVD growth + RIE

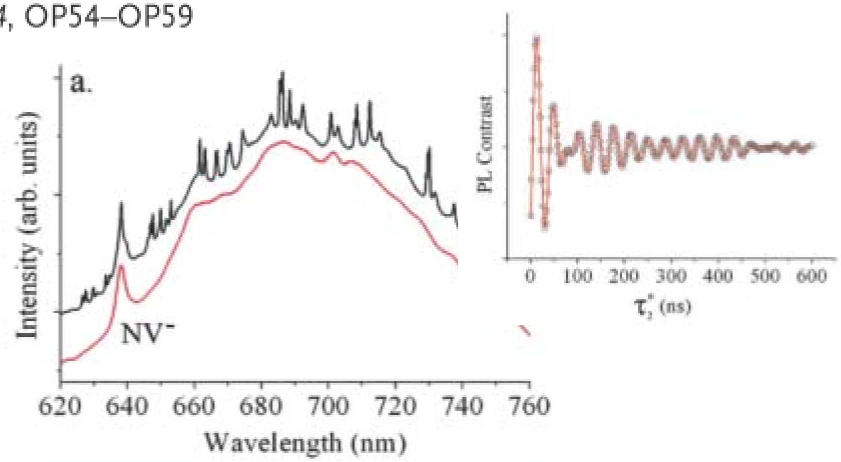
ADVANCED OPTICAL MATERIALS
www.advopticalmat.de

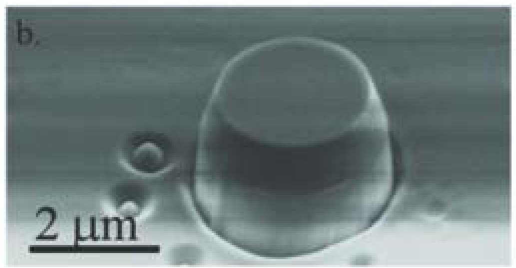
Materials Views
www.MaterialsViews.com

Homoepitaxial Growth of Single Crystal Diamond Membranes for Quantum Information Processing

Igor Aharonovich, Jonathan C. Lee, Andrew P. Magyar, Bob B. Buckley, Christopher G. Yale, David D. Awschalom, and Evelyn L. Hu*

Adv. Mater. **2012**, *24*, OP54–OP59





Outline

- Diamond
  - → Synthesis
  - → Properties
  - → Applications
- **IBL in diamond**
  - → MeV ion lithography in diamond
  - **→ keV ion beam lithography in diamond**
- Activities at the University of Torino
  - → Electrical features
  - → Optical features
  - → Microfluidics

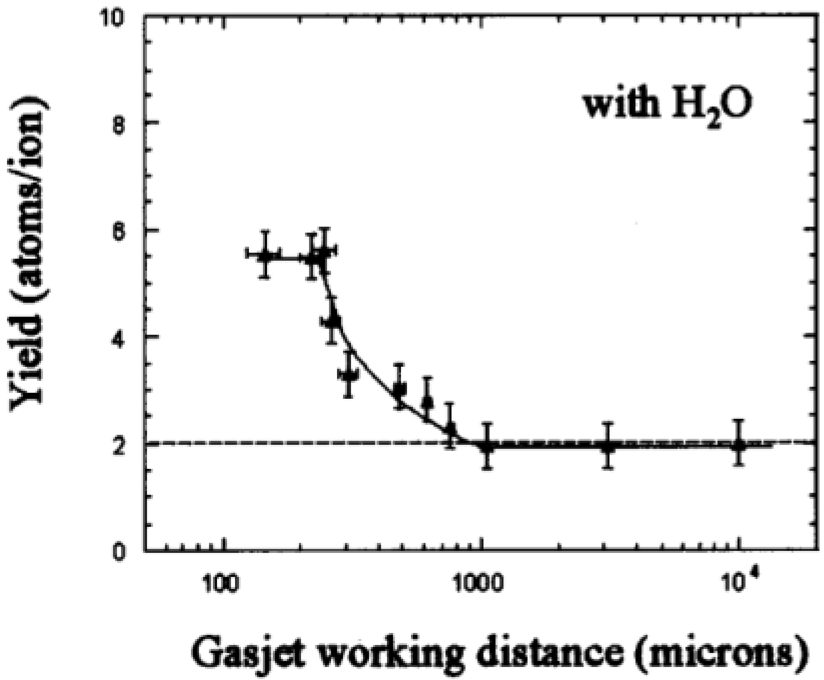
FIB in Diamond: State of the Art

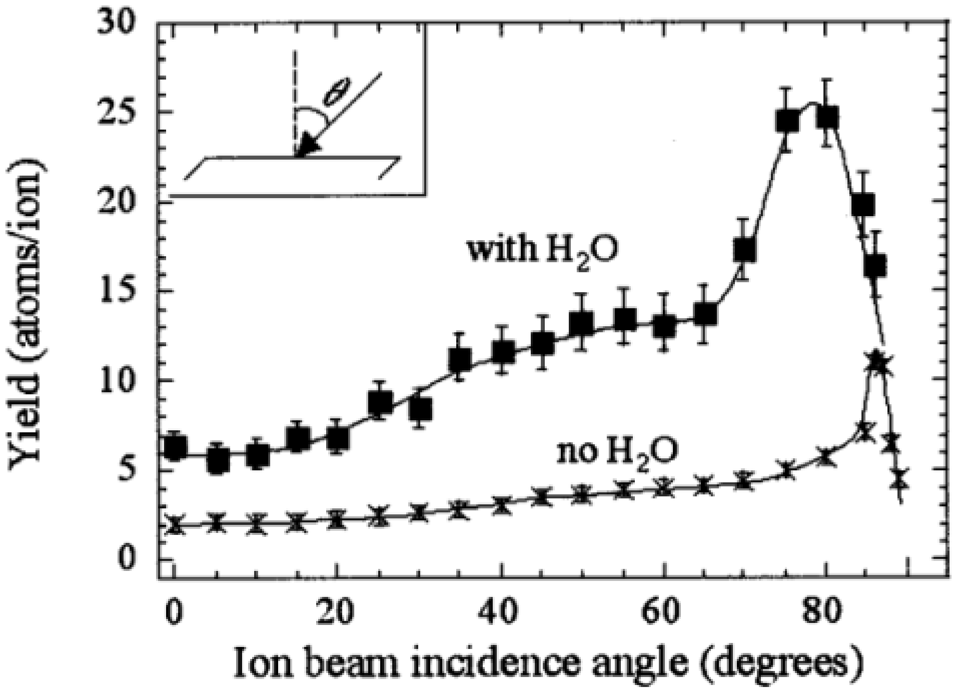
Gas-assisted milling

Focused ion beam milling of diamond: Effects of H_2O on yield, surface morphology and microstructure

D. P. Adams,[a] M. J. Vasile, T. M. Mayer, and V. C. Hodges

2334 J. Vac. Sci. Technol. B 21(6), Nov/Dec 2003





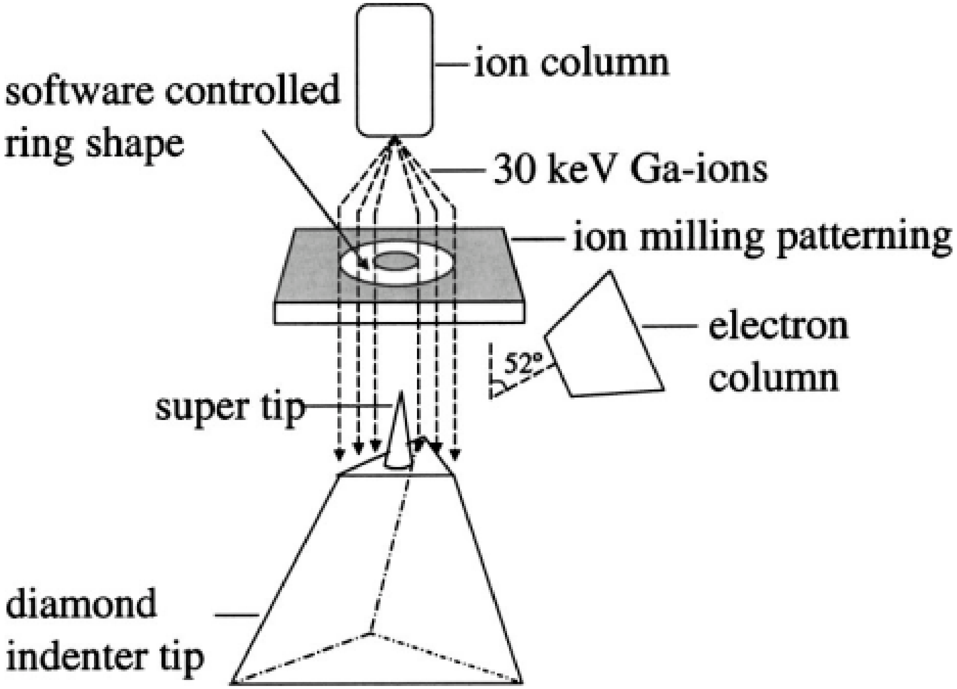
FIB in Diamond: State of the Art

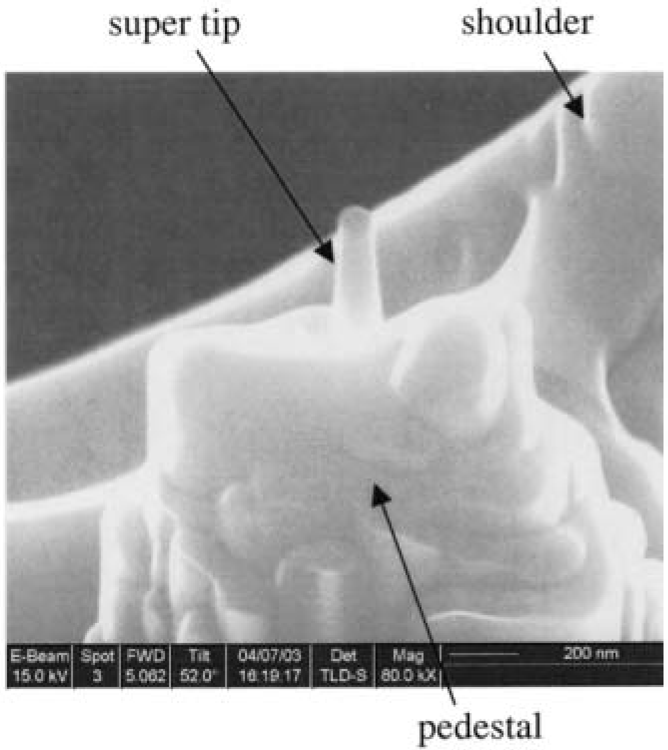
Micro & nano-indenters

Use of the focused ion beam technique to produce a sharp spherical diamond indenter for sub-10 nm nanoindentation measurements

Ning Yu and Andreas A. Polycarpou[a]

668 J. Vac. Sci. Technol. B 22(2), Mar/Apr 2004





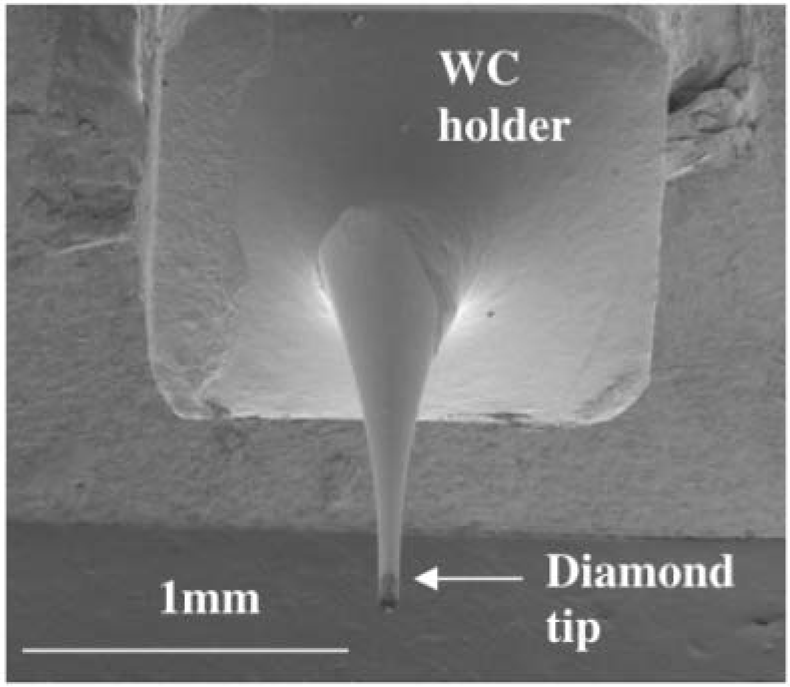
FIB in Diamond: State of the Art

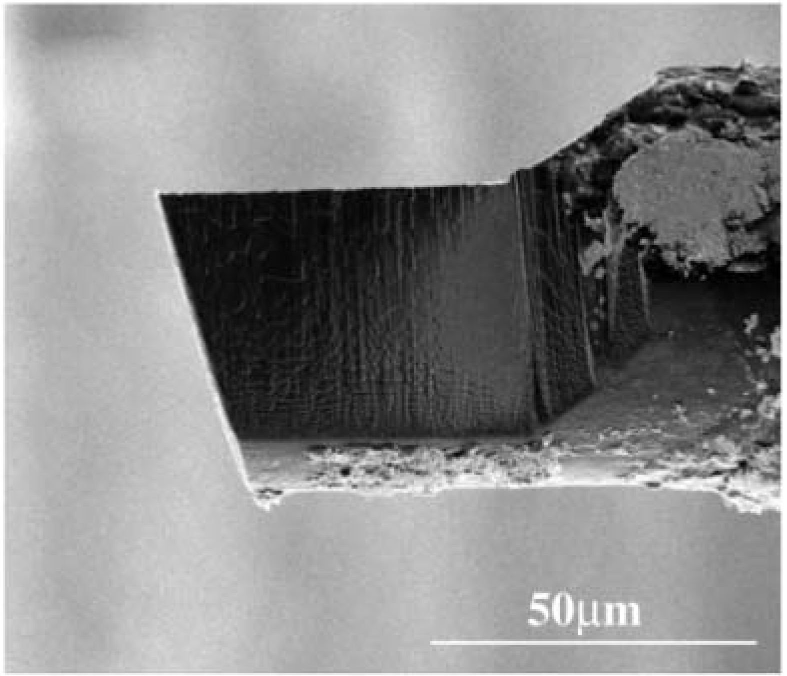
Micro- & nano-indenters

IOP Publishing — Journal of Micromechanics and Microengineering
J. Micromech. Microeng. 18 (2008) 075017 (10pp) — doi:10.1088/0960-1317/18/7/075017

Fabrication of a micro-size diamond tool using a focused ion beam

X Ding[1], G C Lim[1], C K Cheng[2], David Lee Butler[1,3], K C Shaw[1], K Liu[1] and W S Fong[1]





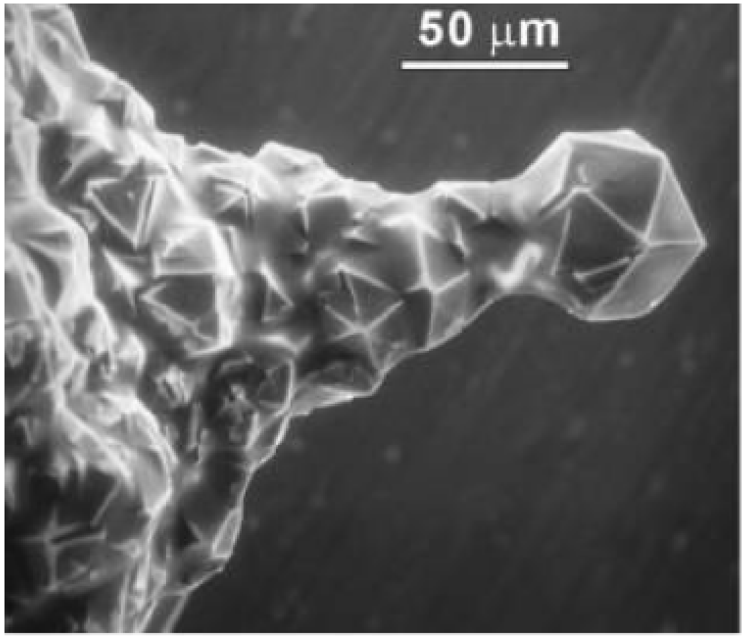
FIB in Diamond: State of the Art

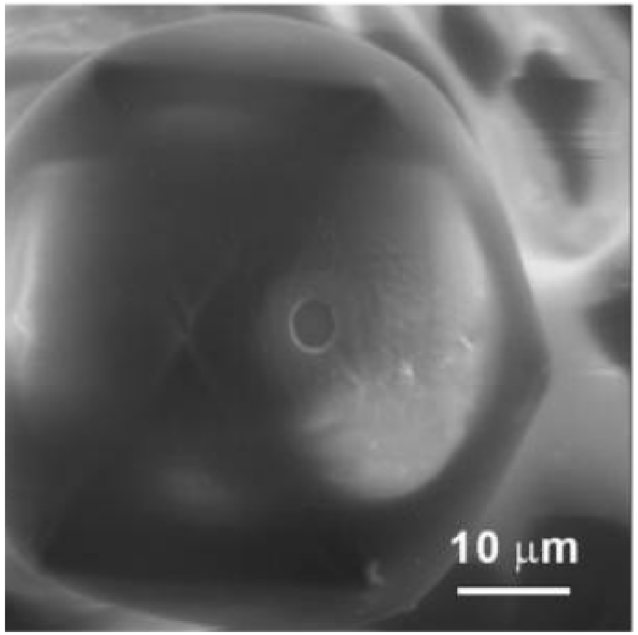
Micro-electrodes

Anal. Chem. **2009,** *81*, 5663–5670

Focused Ion Beam Fabrication of Boron-Doped Diamond Ultramicroelectrodes

Jingping Hu,[†] Katherine B. Holt,[‡] and John S. Foord[*,†]





FIB in Diamond: State of the Art

Micro-mechanical structures

Diamond & Related Materials 19 (2010) 742–747

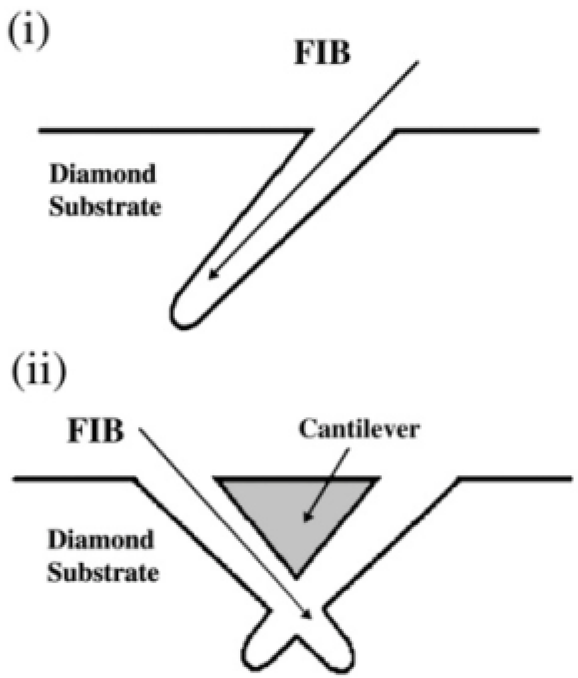
Contents lists available at ScienceDirect

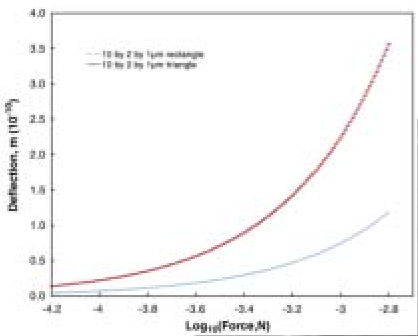
Diamond & Related Materials

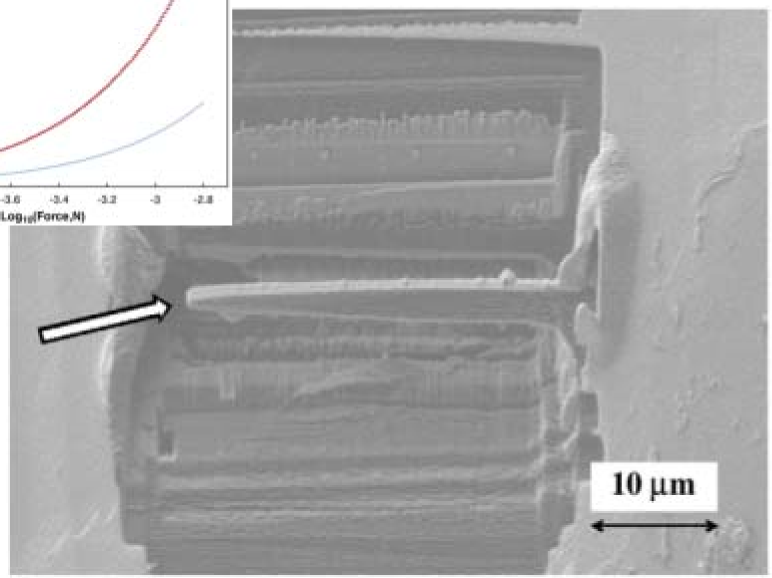
journal homepage: www.elsevier.com/locate/diamond

Fabrication and characterisation of triangle-faced single crystal diamond micro-cantilevers

Benjamin Z. Kupfer, Rezal K. Ahmad, Aiman Zainal, Richard B. Jackman *





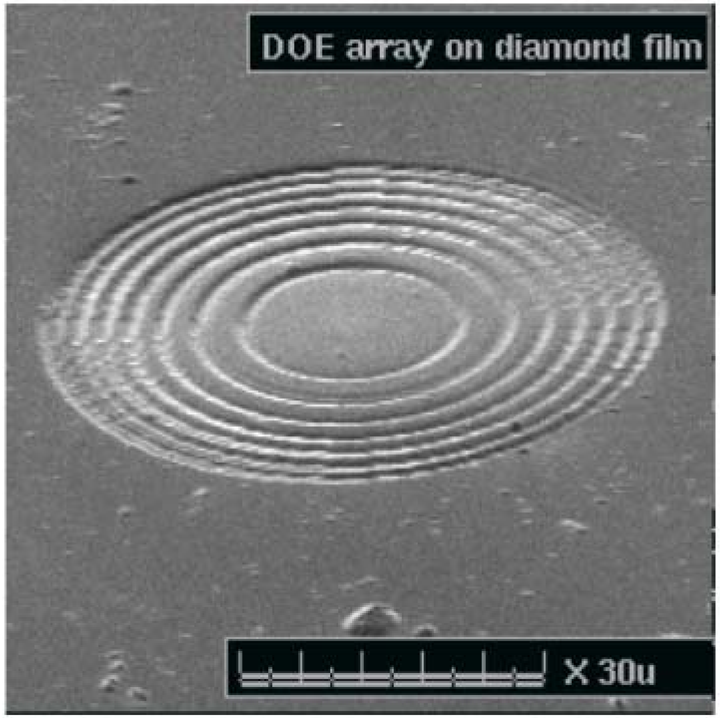


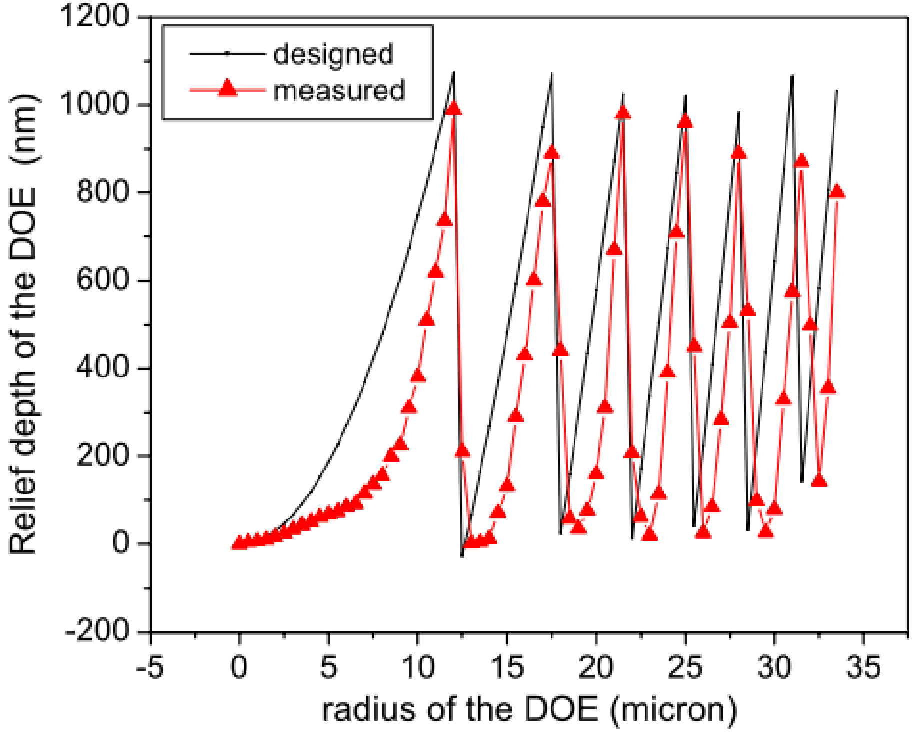
FIB in Diamond: State of the Art

Diffractive optical elements

Investigation of diffractive optical element fabricated on diamond film by use of focused ion beam direct milling

Yongqi Fu Ngoi Kok Ann Bryan Opt. Eng. **42**(8) 2214 (August 2003)





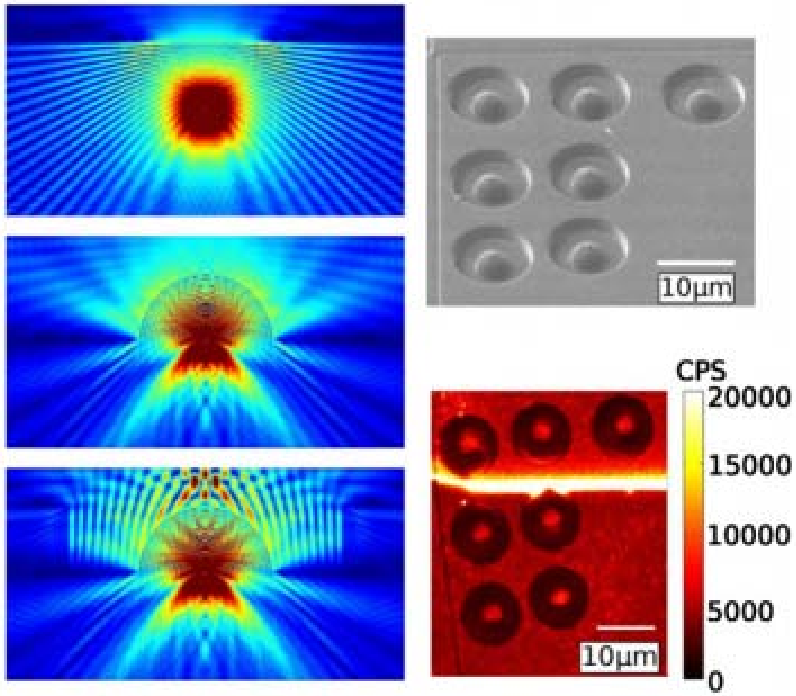
FIB in Diamond: State of the Art

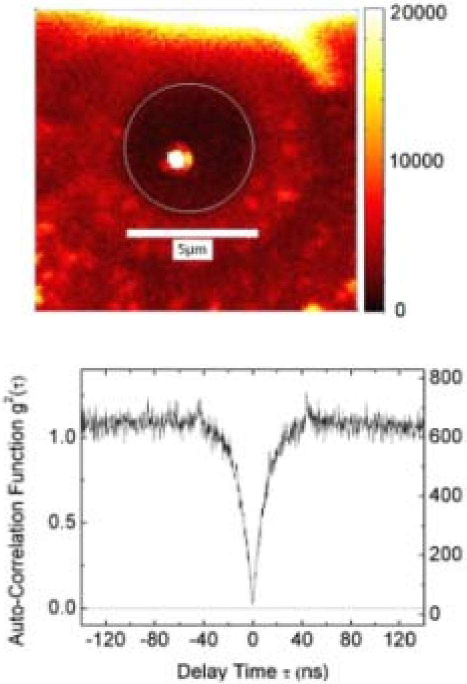
Integrated micro-optics

APPLIED PHYSICS LETTERS **97**, 241901 (2010)

Strongly enhanced photon collection from diamond defect centers under microfabricated integrated solid immersion lenses

J. P. Hadden,[a] J. P. Harrison, A. C. Stanley-Clarke, L. Marseglia, Y.-L. D. Ho, B. R. Patton, J. L. O'Brien, and J. G. Rarity





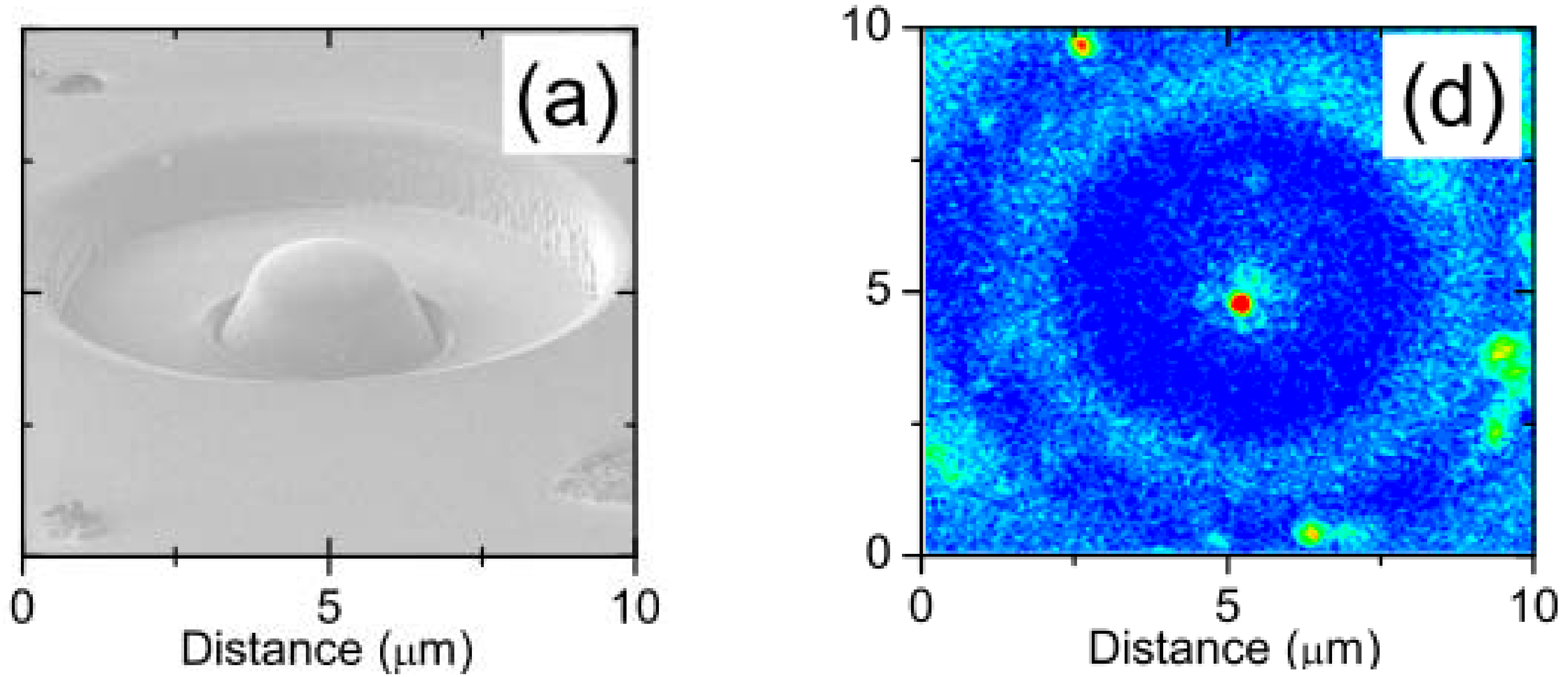
FIB in Diamond: State of the Art

Integrated micro-optics

APPLIED PHYSICS LETTERS **98**, 133107 (2011)

Nanofabricated solid immersion lenses registered to single emitters in diamond

L. Marseglia,[1,a)] J. P. Hadden,[1] A. C. Stanley-Clarke,[1] J. P. Harrison,[1] B. Patton,[1]
Y.-L. D. Ho,[1] B. Naydenov,[2] F. Jelezko,[2] J. Meijer,[3] P. R. Dolan,[4] J. M. Smith,[4] J. G. Rarity,[4]
and J. L. O'Brien



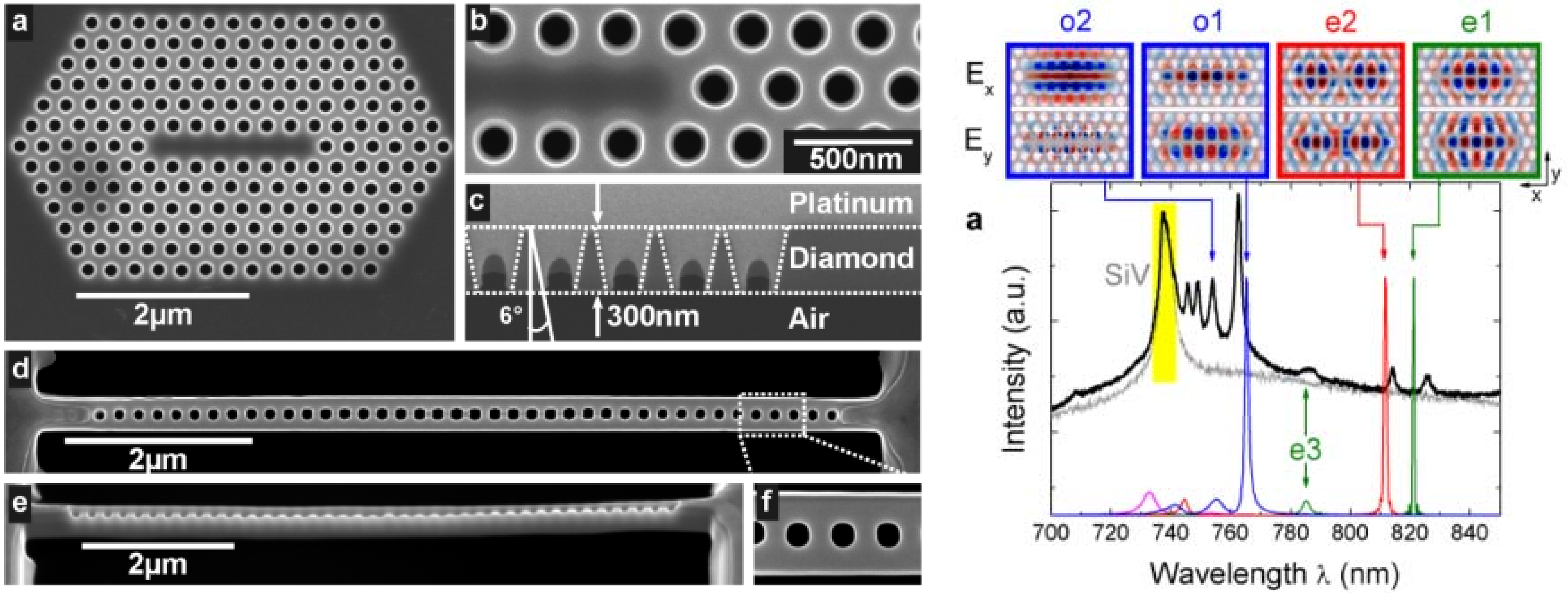
FIB in Diamond: State of the Art

Photonic structures

One- and two-dimensional photonic crystal micro-cavities in single crystal diamond

Janine Riedrich-Möller[1], Laura Kipfstuhl[1], Christian Hepp[1], Elke Neu[1], Christoph Pauly[2], Frank Mücklich[2], Armin Baur[3], Michael Wandt[3], Sandra Wolff[4], Martin Fischer[5], Stefan Gsell[5], Matthias Schreck[5], and Christoph Becher[1]*

Nature Nanotechnology 7, 69-74 (2012)



FIB in Diamond: State of the Art

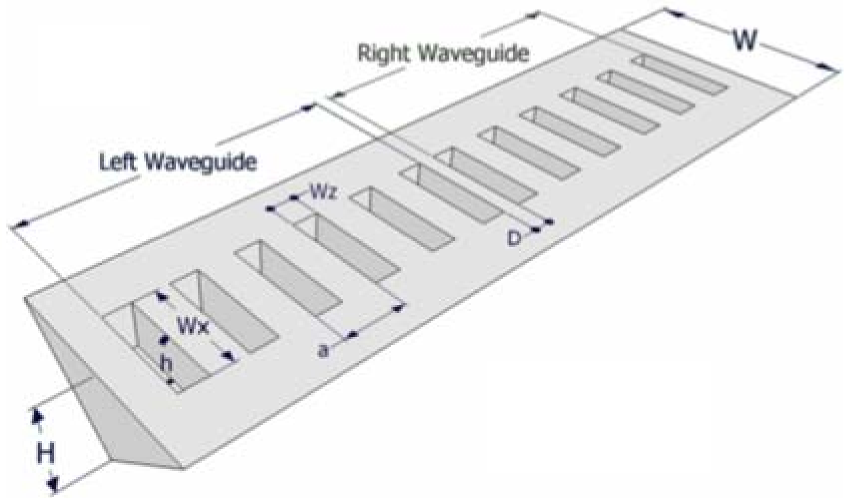
Photonic structures

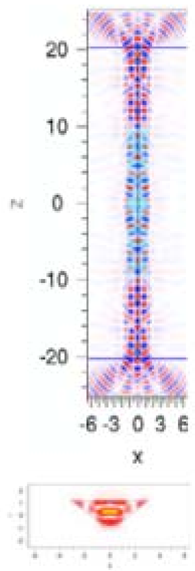
New Journal of Physics
The open-access journal for physics

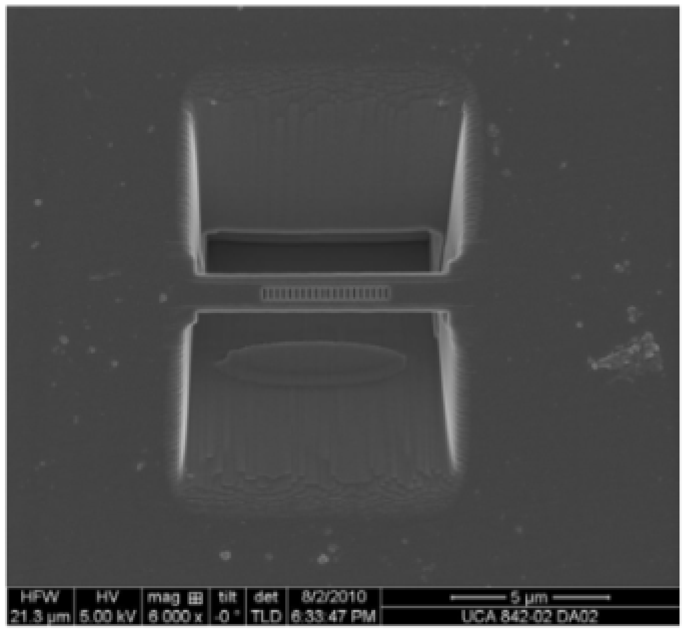
Triangular nanobeam photonic cavities in single-crystal diamond

Igal Bayn[1,3], Boris Meyler[1], Joseph Salzman[1] and Rafi Kalish[2]

New Journal of Physics **13** (2011) 025018







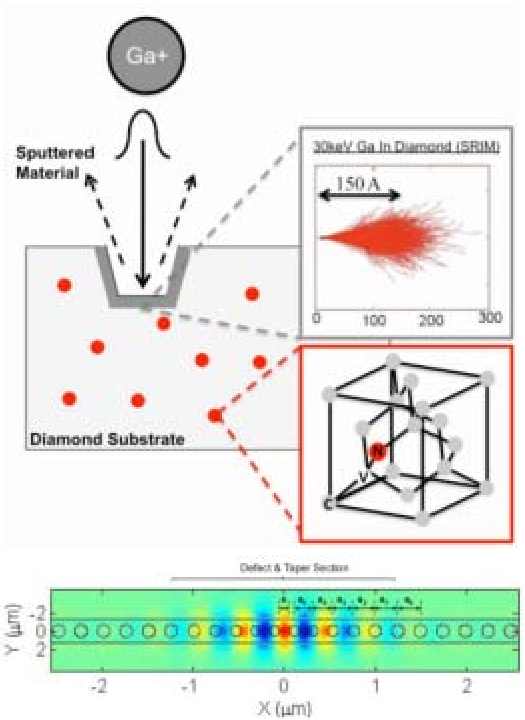
FIB in Diamond: State of the Art

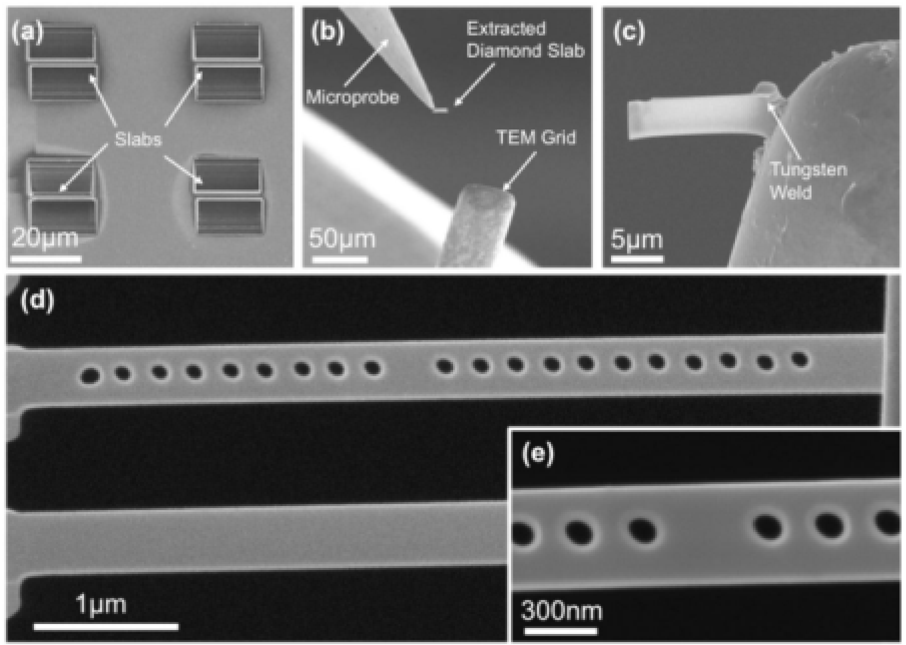
Photonic structures

Design and Focused Ion Beam Fabrication of Single Crystal Diamond Nanobeam Cavities

Thomas M. Babinec[1], Jennifer T. Choy[1], Kirsten J. M. Smith[1,2], Mughees Khan[1,3], Marko Lončar[1]

arXiv: 1008.1431





FIB in Diamond: State of the Art

Direct-write negative lithography

Diamond & Related Materials 20 (2011) 707–710

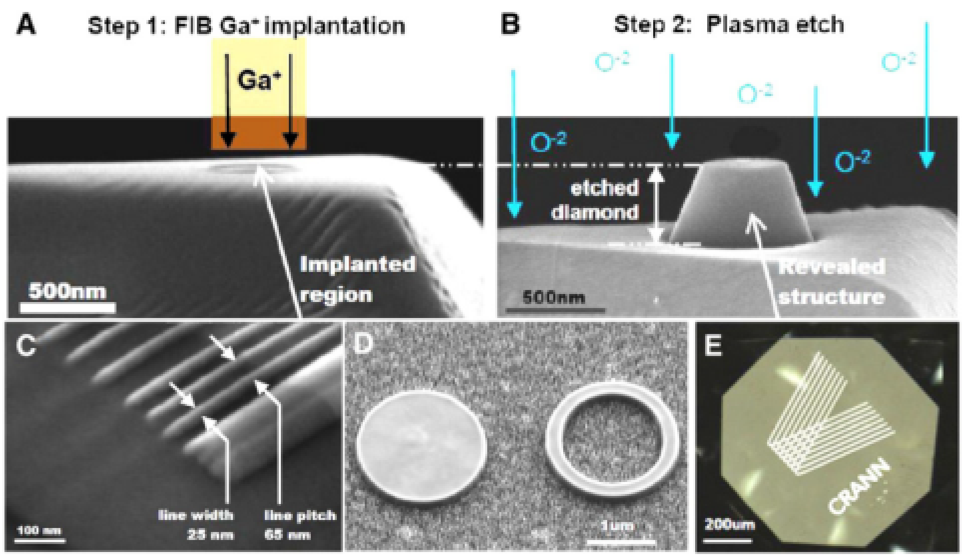
Contents lists available at ScienceDirect

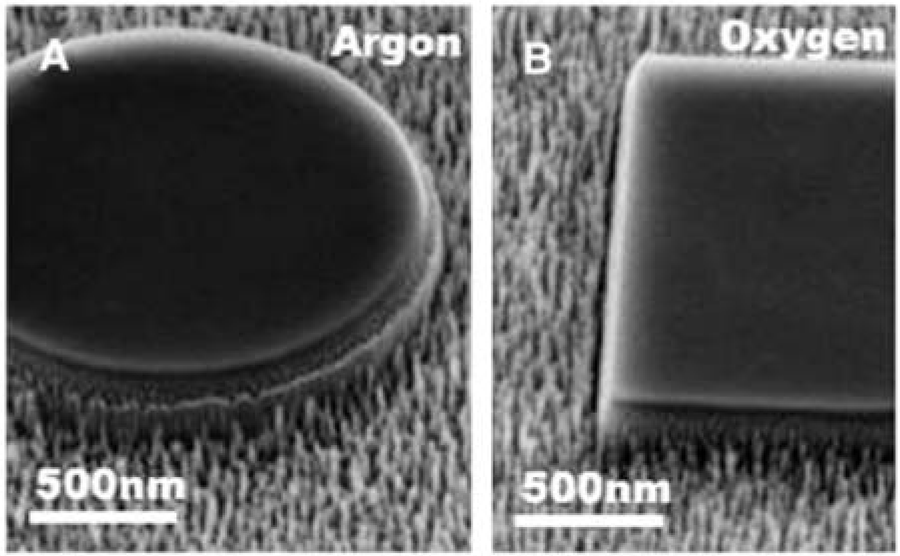
Diamond & Related Materials

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

A direct-write, resistless hard mask for rapid nanoscale patterning of diamond

Warren McKenzie [1], John Pethica, Graham Cross *



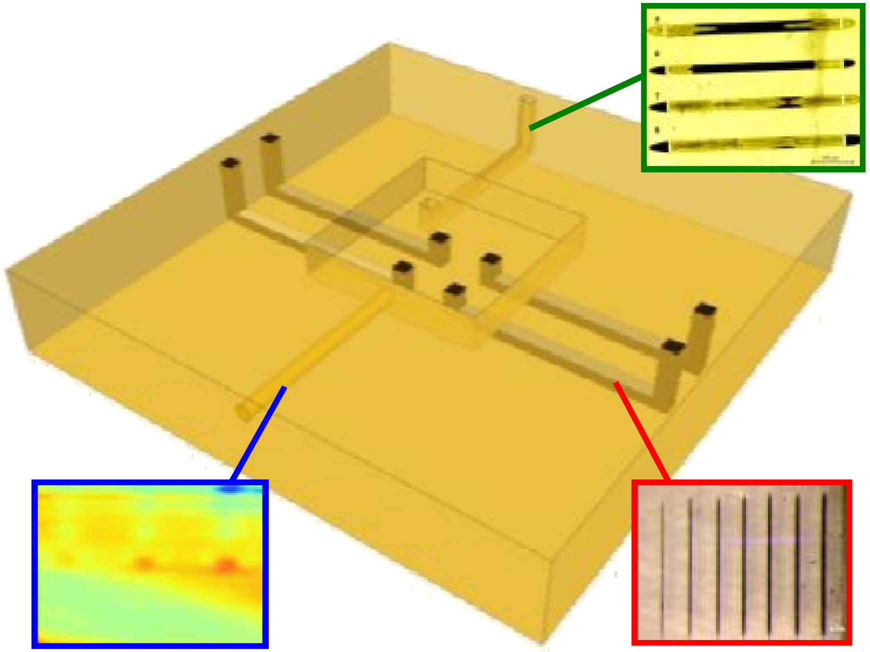


Outline

- Diamond
  - → Synthesis
  - → Properties
  - → Applications
- IBL in diamond
  - → MeV ion lithography in diamond
  - → keV ion beam lithography in diamond
- **Activities at the University of Torino**
  - → Electrical features
  - → Optical features
  - → Microfluidics

Activities at the University of Torino

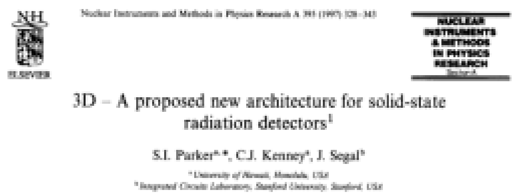
Cellular bio-sensing devices

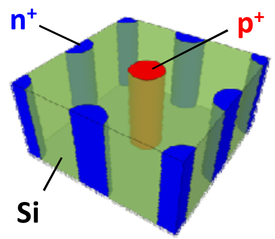


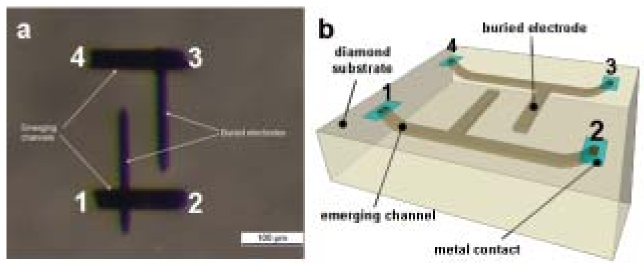
A bio-compatible and transparent diamond active substrate for interfacing with single excitable cells:

- ✓ electrical interfacing: sub-superficial micro-electrodes
- ✓ optical interfacing: integrated waveguiding structures
- ✓ chemical interfacing: microfluidic devices

Three-dimensional particle detectors

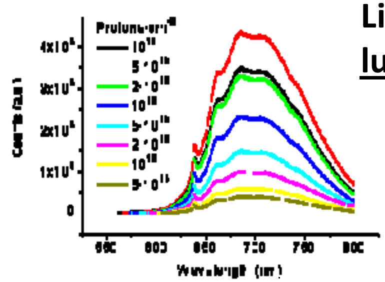






A novel geometry for induced charge collection in diamond detectors

Single photon sources



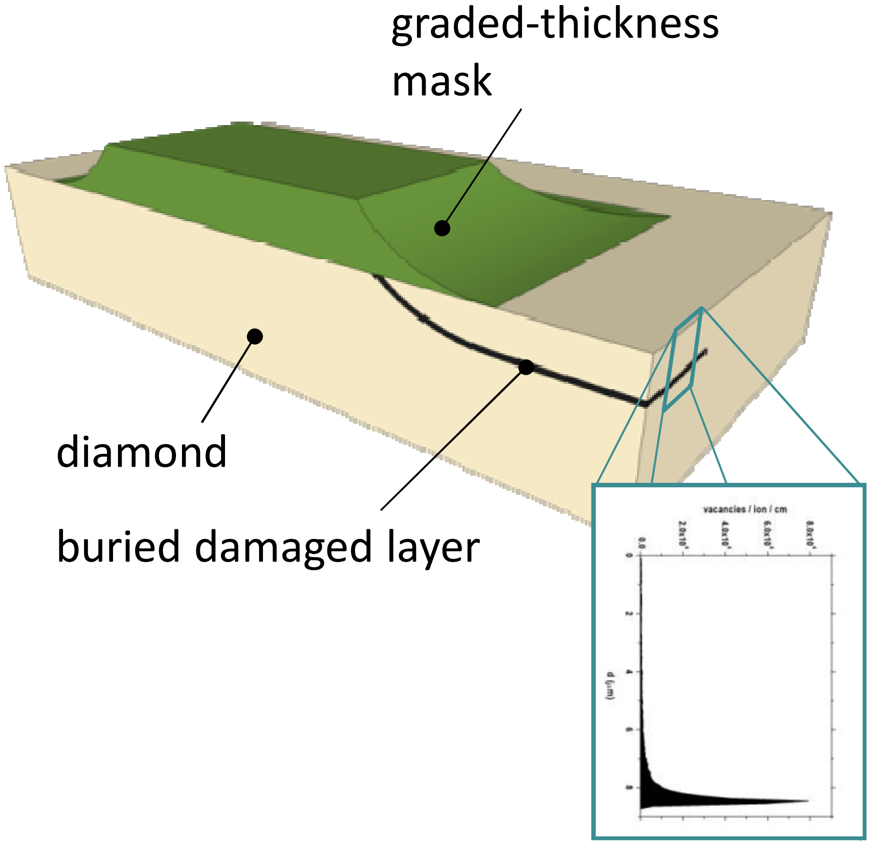
Light emitters based on luminescent centers in diamond

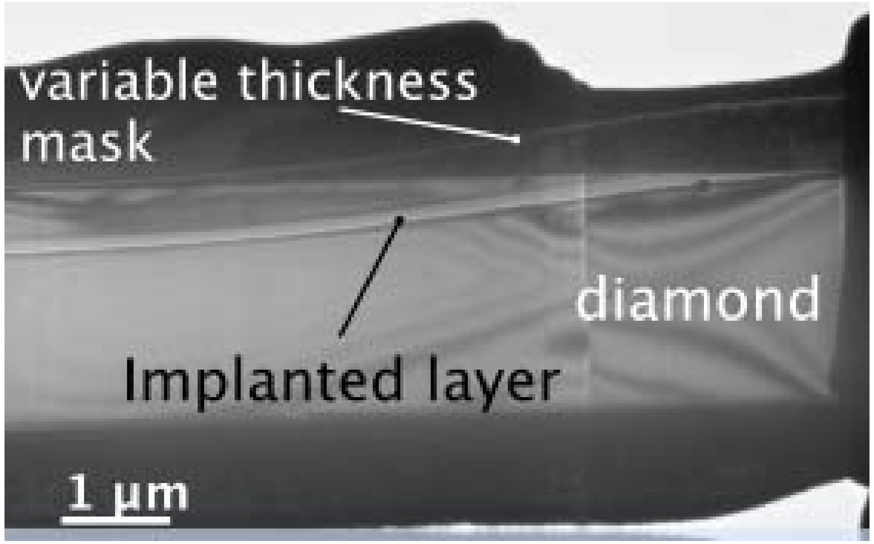
Outline

- Diamond
  - → Synthesis
  - → Properties
  - → Applications
- IBL in diamond
  - → MeV ion lithography in diamond
  - → keV ion beam lithography in diamond
- **Activities at the University of Torino**
  - → **Electrical features**
  - → Optical features
  - → Microfluidics

Electrical features

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

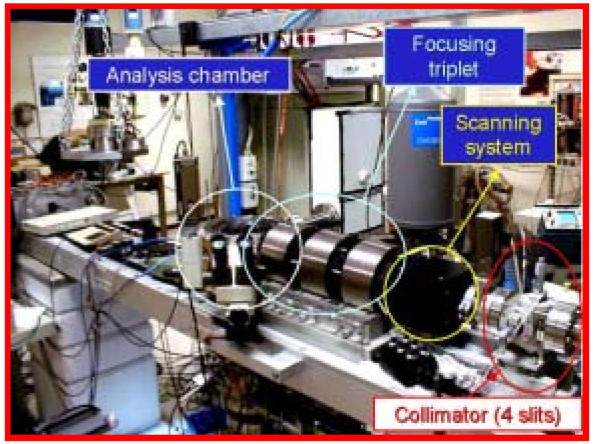




✓**definition of buried graphitic microchannels in single-crystal diamond**

Electrical features

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

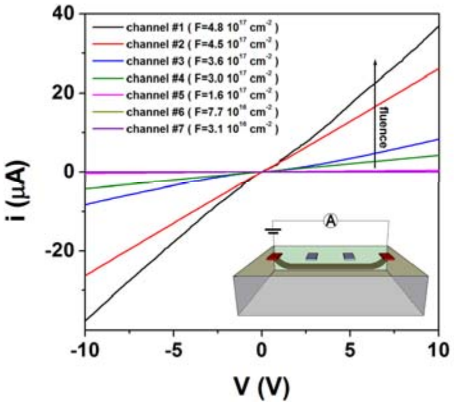


Structural TEM characterization	**Cellular bio-sensing 3D particle detectors**	**3D particle detectors**
0.5 MeV He^{+}	**1.8 MeV He^{+}**	**6 MeV C^{3+}**
F=$1\cdot10^{17}$ cm^{-2}	**F=$1\cdot10^{16}$ - $1\cdot10^{17}cm^{-2}$**	**F=$4\cdot10^{16}$ cm^{-2}**

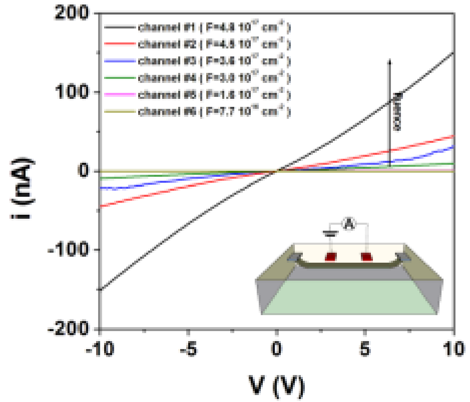
Electrical features

IV curves @ increasing fluences

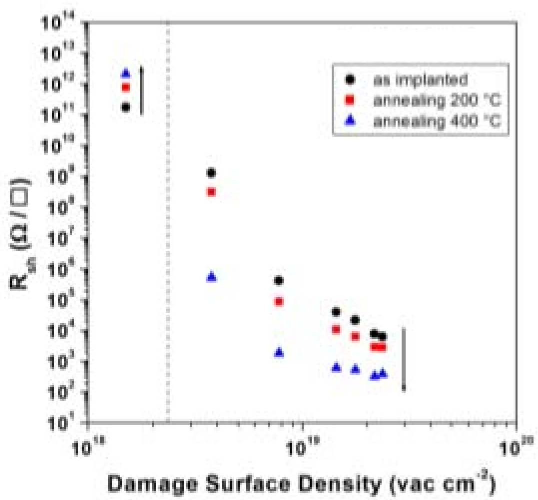
endpoints



test

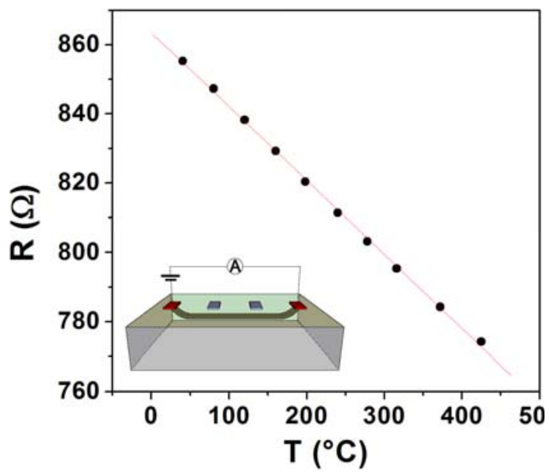


Annealing behavior

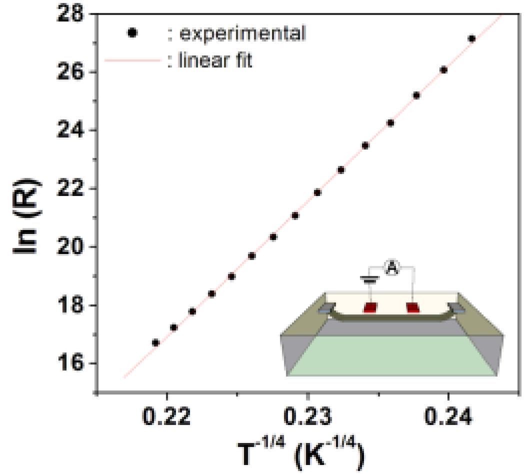


IV measurements in temperature

endpoints



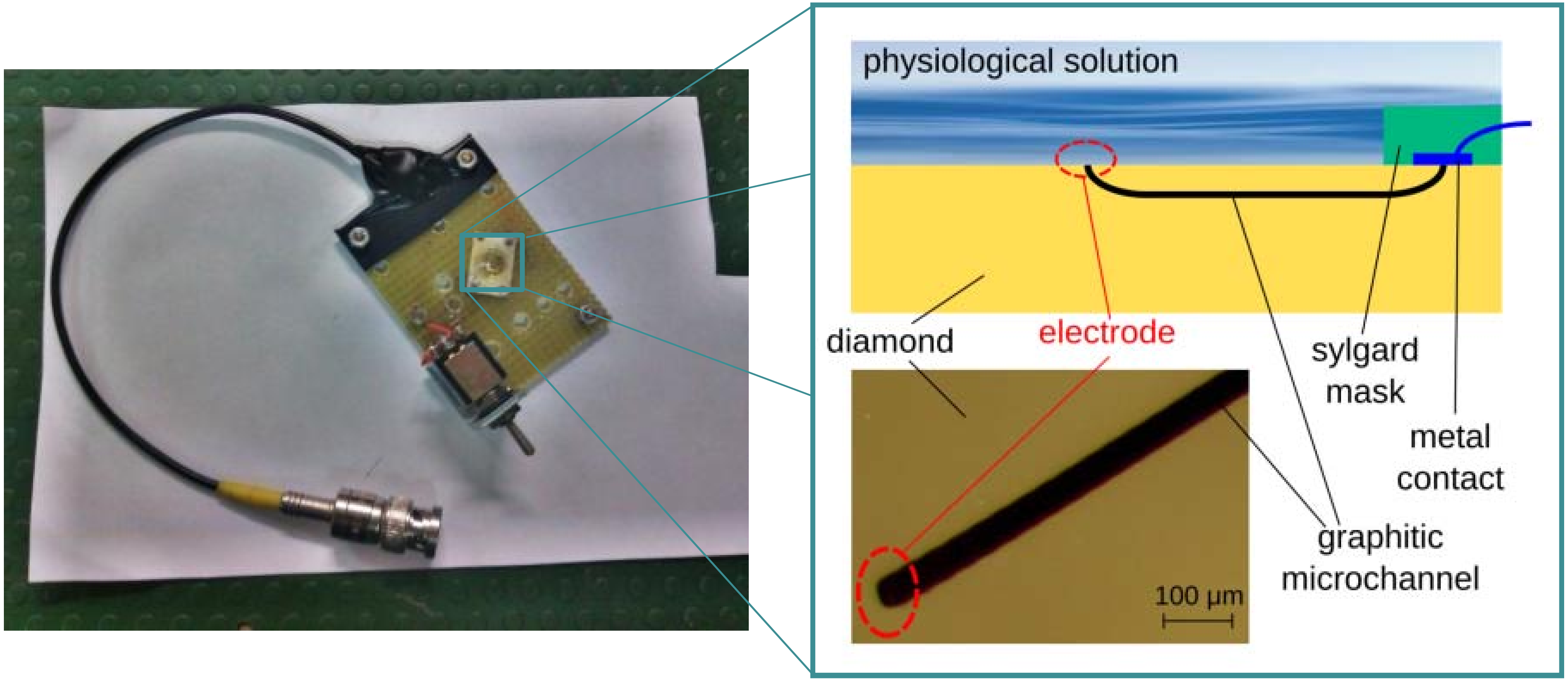
test



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

Electrical features

Amperometric detection of exocytosis activity from neuroendocrine cells

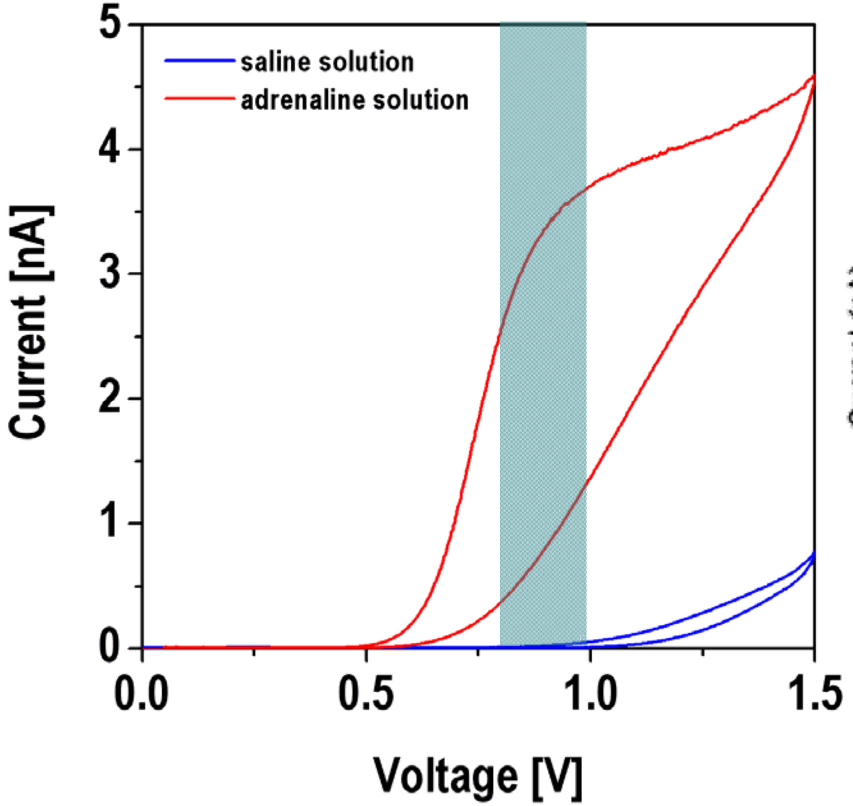


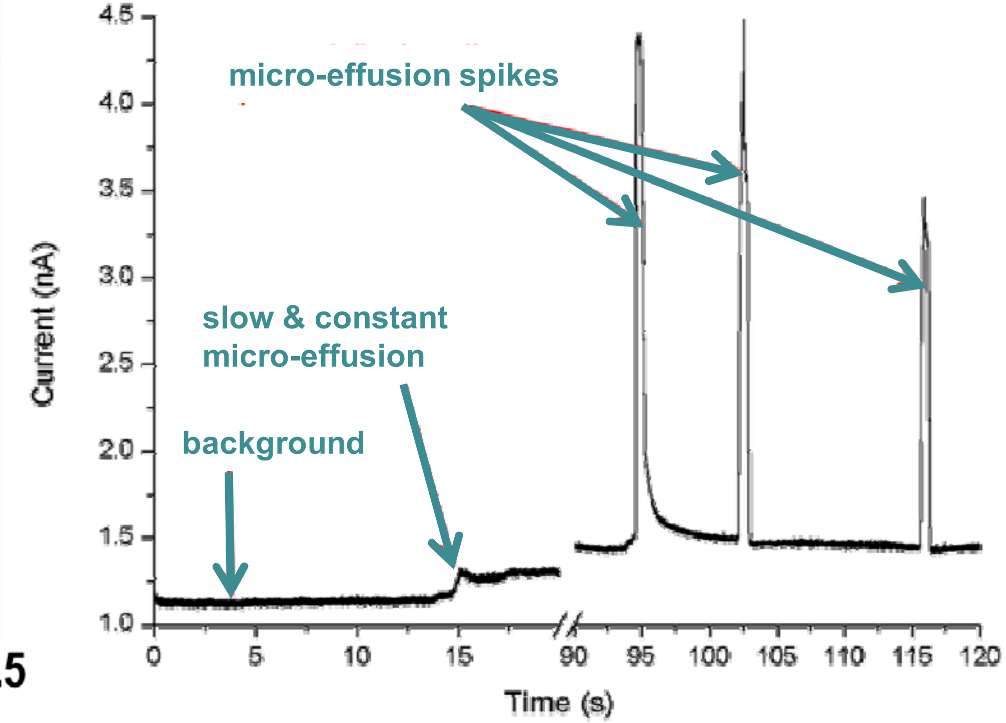
- **3×3×1.5 mm^2 type Ib single crystal diamond grown by HPHT technique**

Electrical features

Cyclic voltammetry: oidation of catecholamines (adrenaline, noradrenaline, etc.) at the biased electrode

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





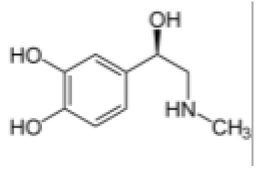
Saline solution: NaCl (128 mM), $MgCl_2$ (2 mM), glucose (10 mM), HEPES (10 mM, $CaCl_2$ (10 mM), KCl (4 mM)

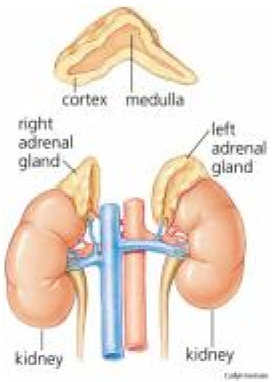
Adrenaline solution: saline solution, adrenaline (10 mM)

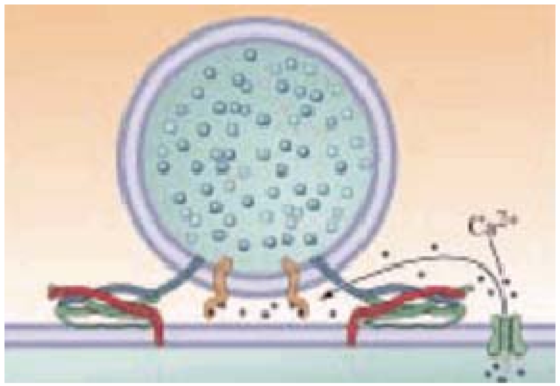
Electrical features

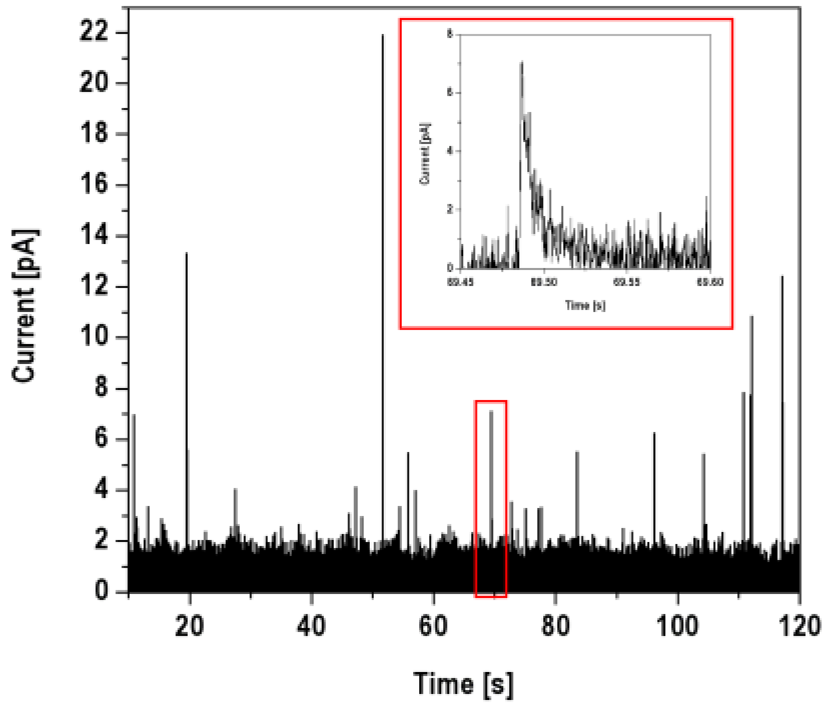
Ameprometric detection of exocytosis (*quantal release of molecules*) from chromaffin cells (*neuroendocrine cells located into the medulla part of the renal gland*): oxidation of adrenalie at the 0.8 V biased micro-electrode

Chromaffine cells: ∅ ~ 10 µm
containing 50-300 nm chromaffin granules
adrenaline concentration in the granules: 0.5 . 1 M
exocytosis: process related to synaptic transmission







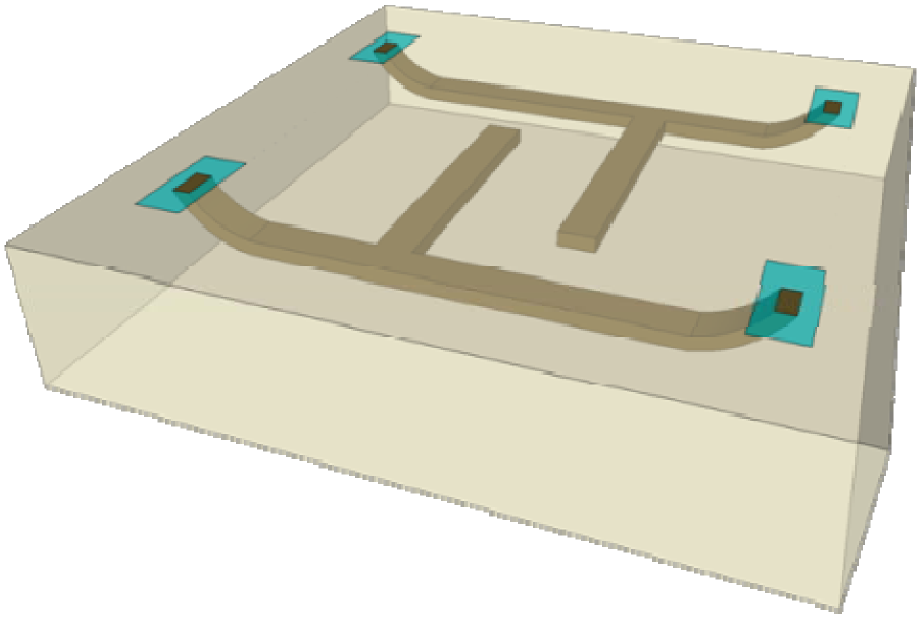


Signal detection: good performance (i.e. comparable to standard carbon fibers) in a fully miniaturized, bio-compatible and *transparent* device

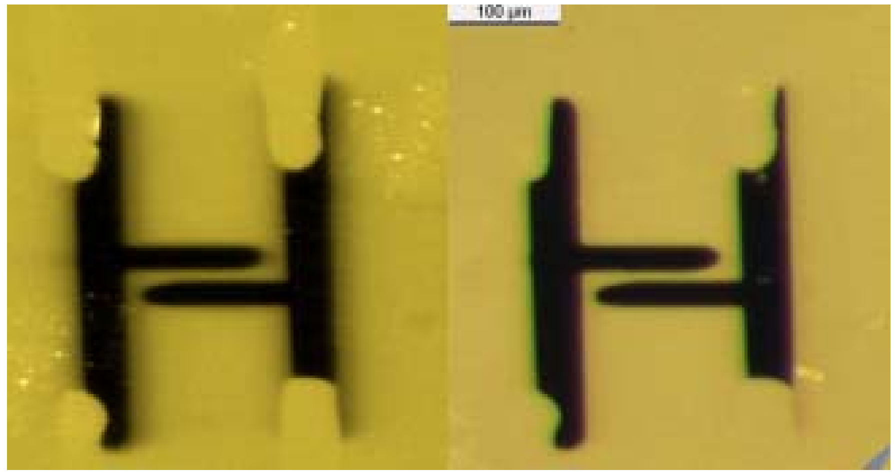
*F. Picollo et al., "*Fabrication of a Diamond-Based Cellular Biosensor by Ion Beam Lithogaphy to detect quantal exocytic events from chromaffin cells*", in preparation (2012)*

Electrical features

Buried graphitic electrodes in 3D particle detectors



before annealing ***after annealing***

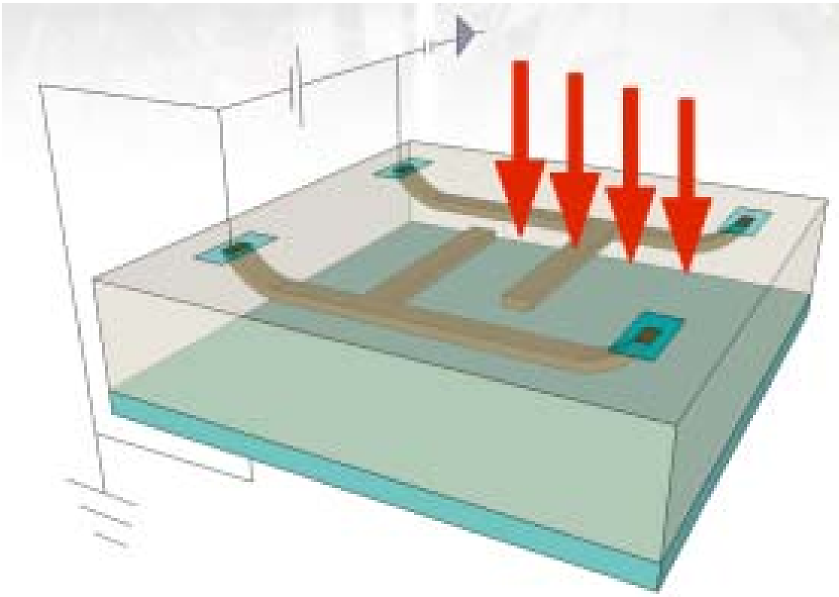


implantation @ LNL

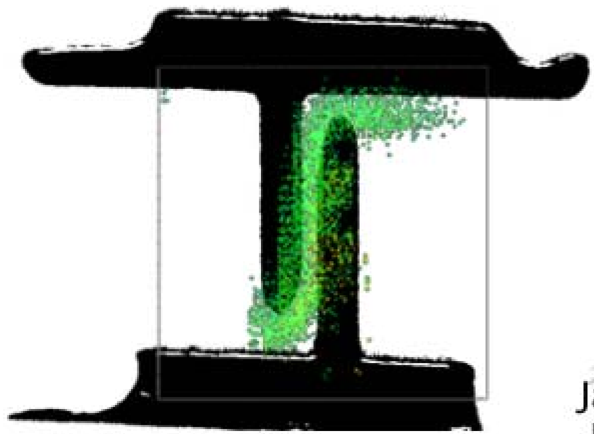
Implantation conditions: **1.8 MeV He^{+} (F = $3\cdot10^{17}$ cm^{-2}) at LNL**
6 MeV C^{3+} (F = $4\cdot10^{16}$ cm^{-2}) at RBI

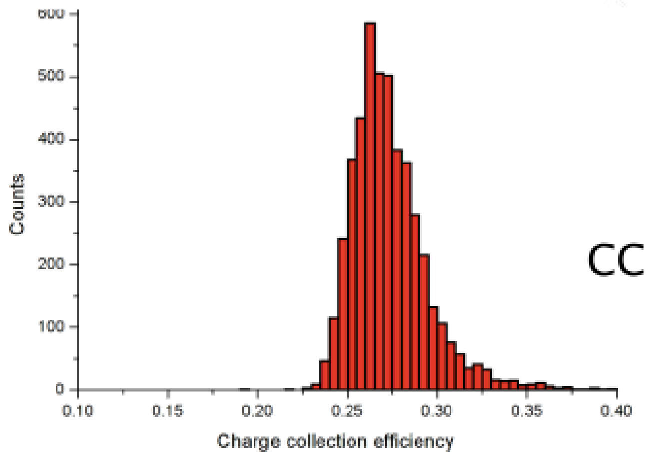
Electrical features

Charge collection characterization with
Ion Beam Induced Charge (IBIC) measurements



measurements @ LNL





IBIC probe ions: **2.0 MeV He^{+} at LNL**
2.0 MeV H^{+} at RBI

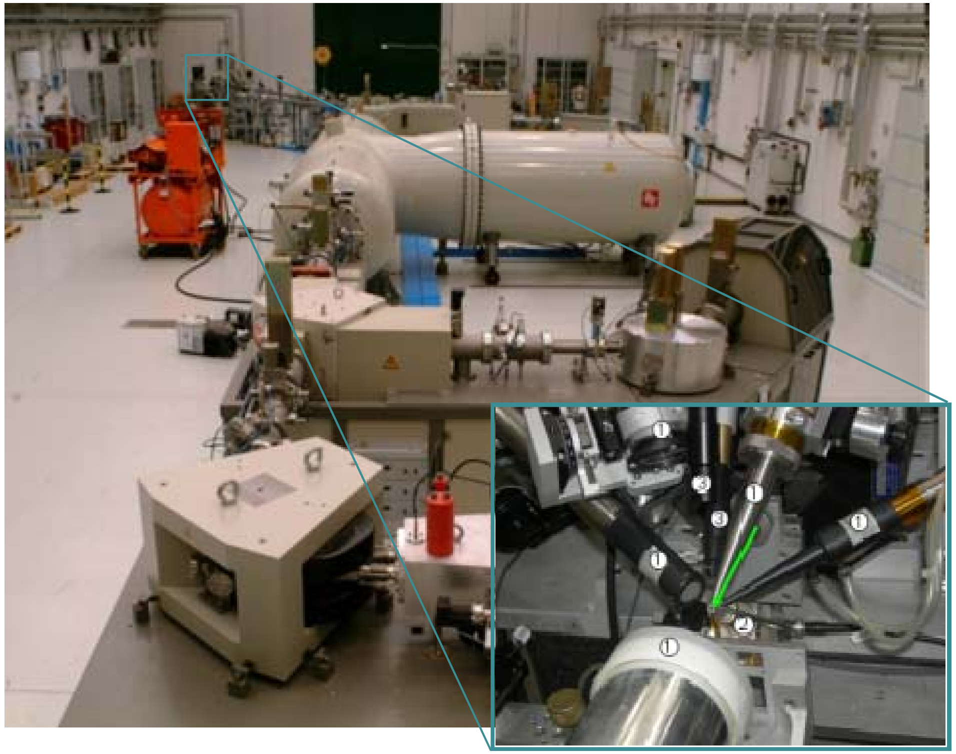
P. Olivero et al., ***Nuclear Instruments and Methods in Phys. Res. B 269****, 2340 (2011)*

Outline

- Diamond
  - → Synthesis
  - → Properties
  - → Applications
- IBL in diamond
  - → MeV ion lithography in diamond
  - → keV ion beam lithography in diamond
- **Activities at the University of Torino**
  - → Electrical features
  - **→ Optical features**
  - → Microfluidics

Optical features

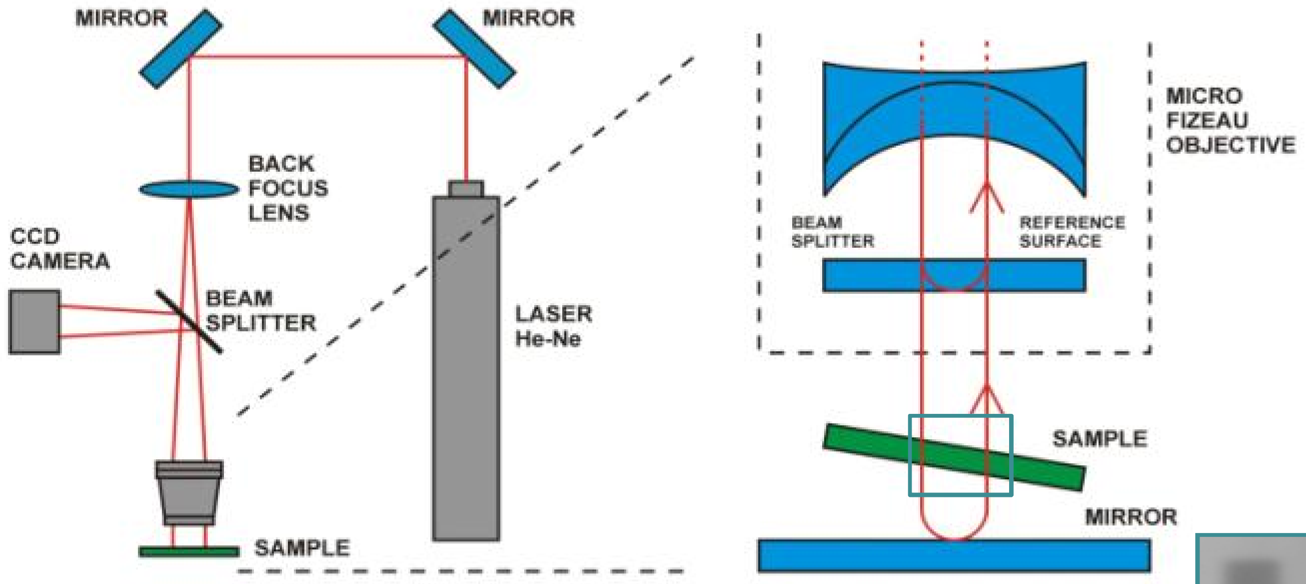
Ion implantation performed at the
LABEC external ion microbeam line



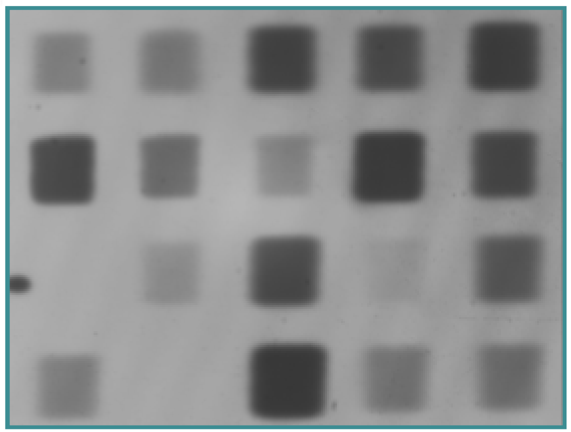
2, 3 MeV H implantation at increasing fluences (F = 10^{13} – 10^{17} cm^{-2})
over 100×100 μm^2 areas

Optical features

Laser interferometric characterization

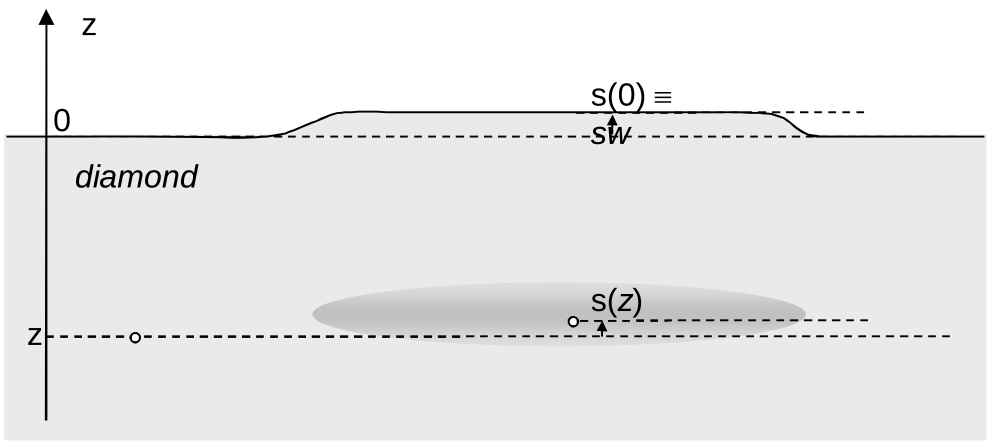


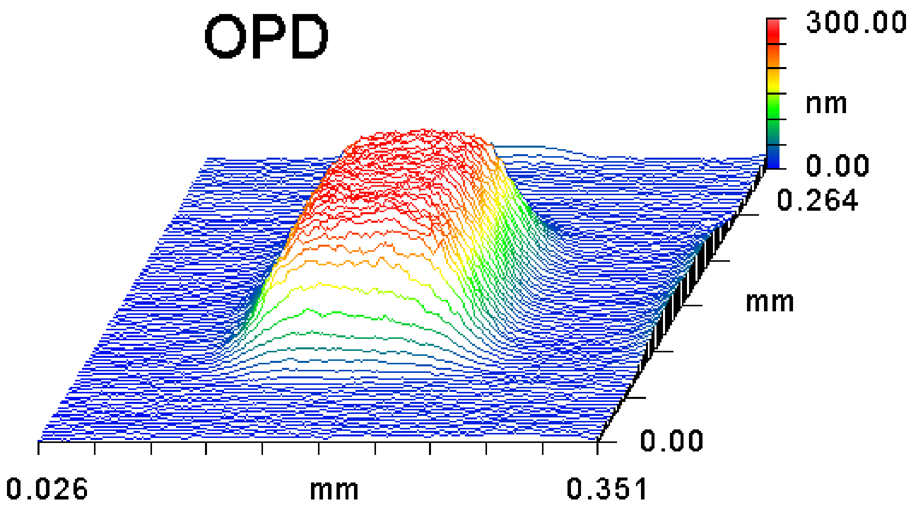
top view

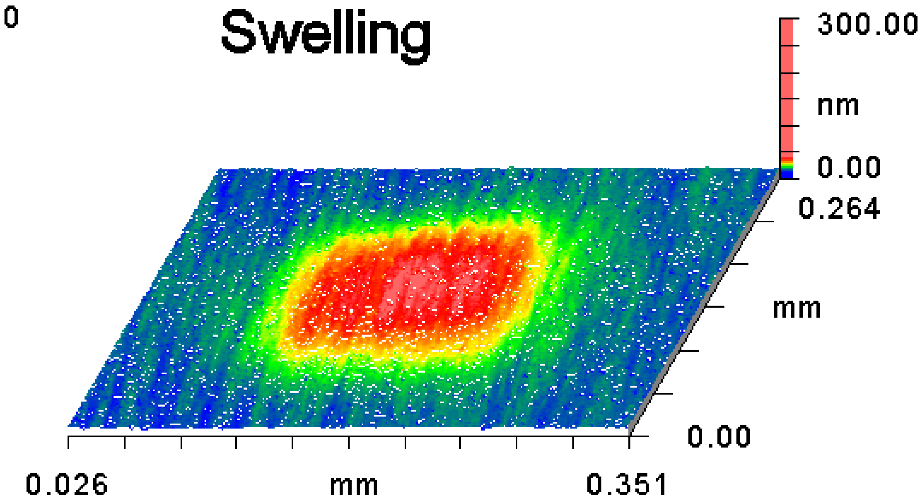


Optical features

Laser interferometric characterization

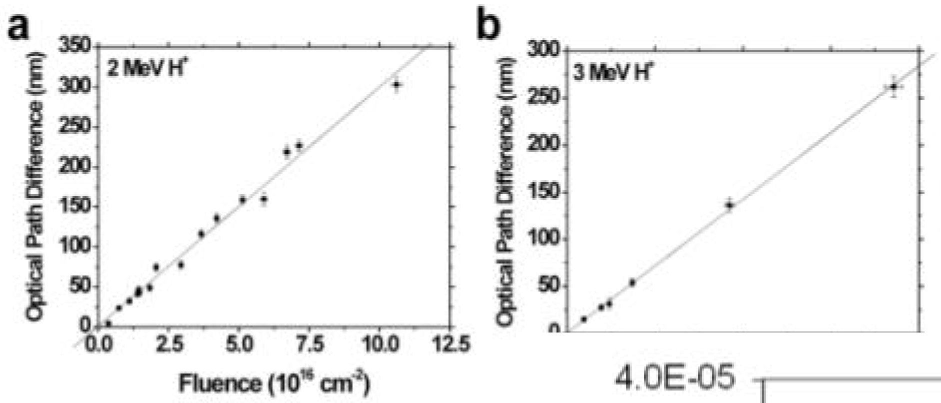


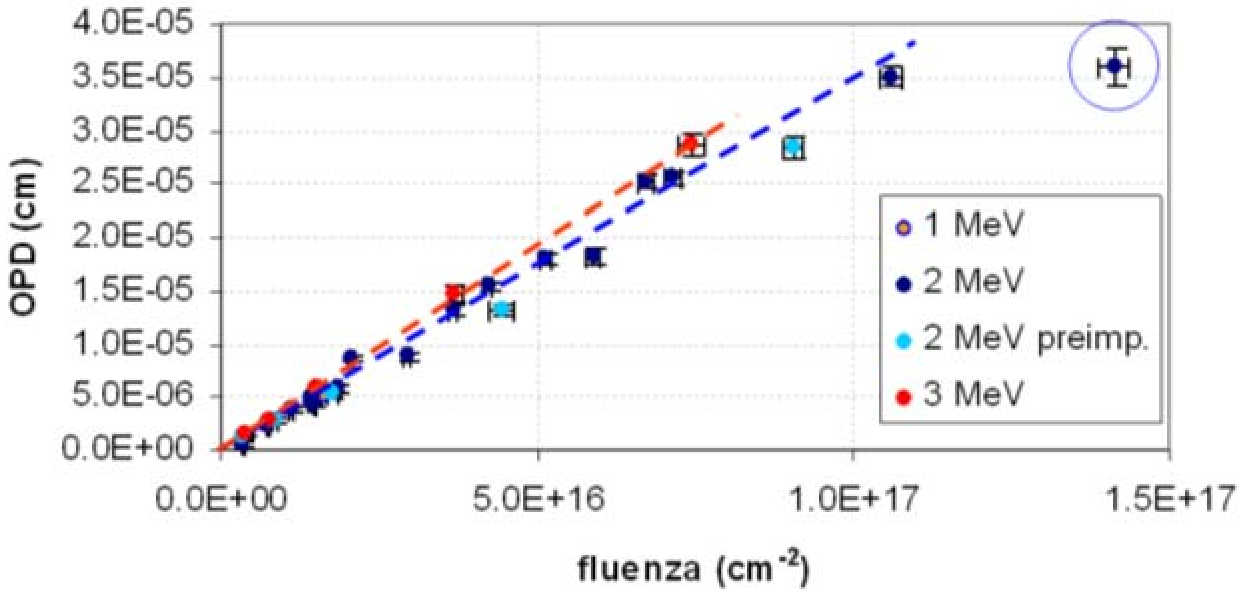




Optical features

Optical path difference (OPD) vs fluence

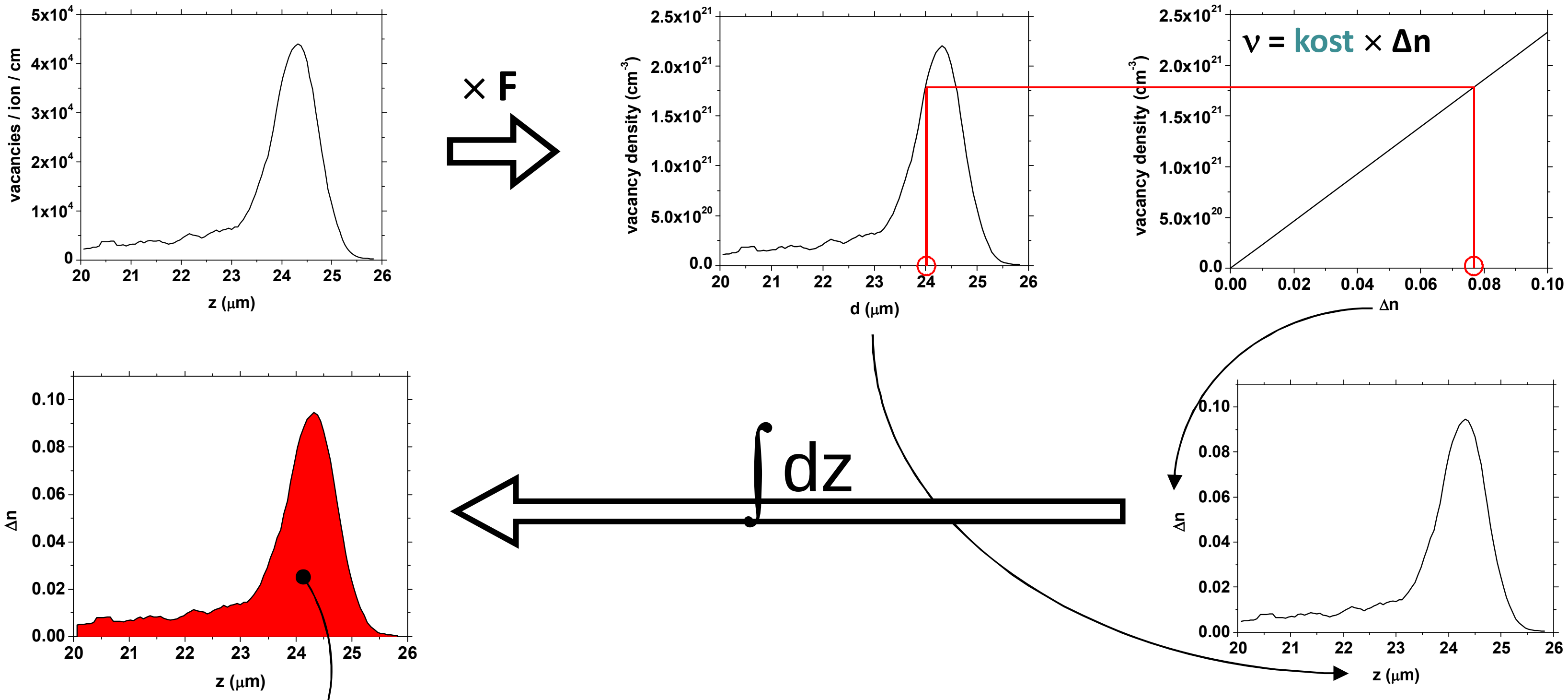


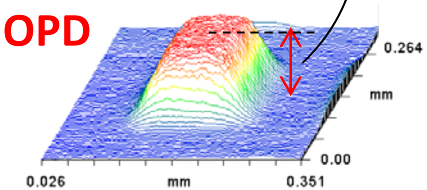


- ✓ **linear trend at low flu**
- ✓ **sub-linear trend at high fluences**
- ✓ **different trends for 2 & 3 MeV protons**

Optical features

Model: integration of the OPD along the depth direction

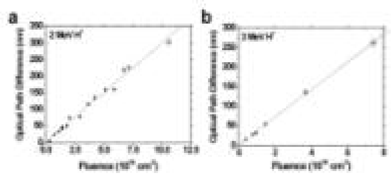




for a given value of kost: **OPD = OPD (F)**

→ linear fitting of the experimental data

$$\Delta n = (\, 4.3 \pm 0.3 \,) \cdot 10^{-23} \times \nu \; [cm^{-3}]$$



*P. Olivero et al., **Diamond and Related Materials 19**, 428 (2010)*

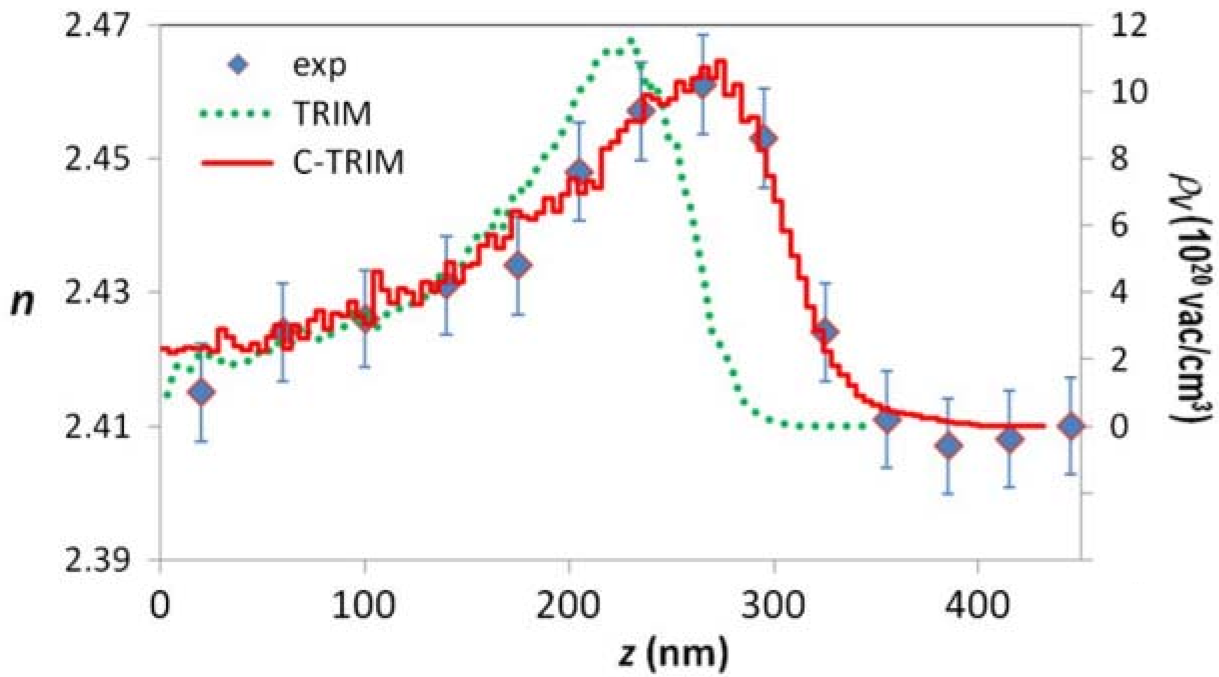
*S. Lagomarsino et al., **Optics Express 20 (17)**, 19382 (2012)*

Optical features

Ellipsometric characterization of shallow-ion-implanted diamond

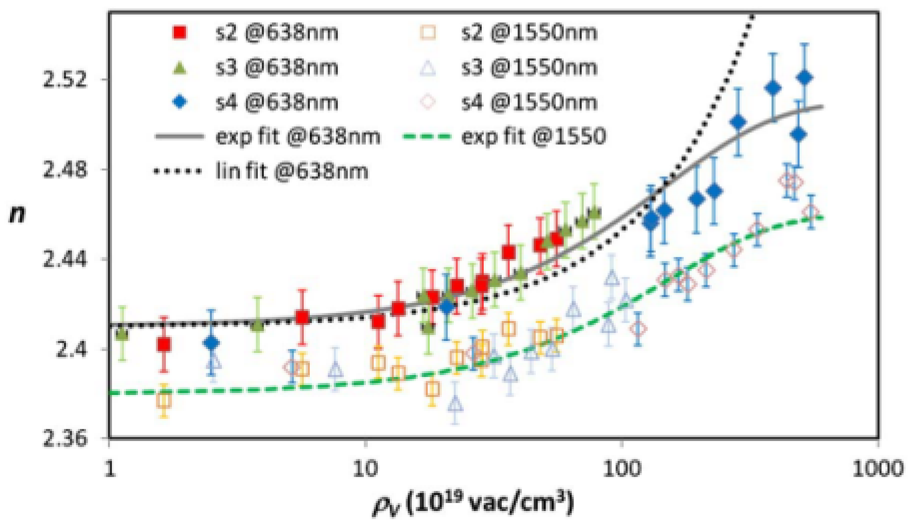
180 keV B implantation at increasing fluences (F = 10^{13} – $5\cdot10^{14}$ cm^{-2}) over the whole sample surface

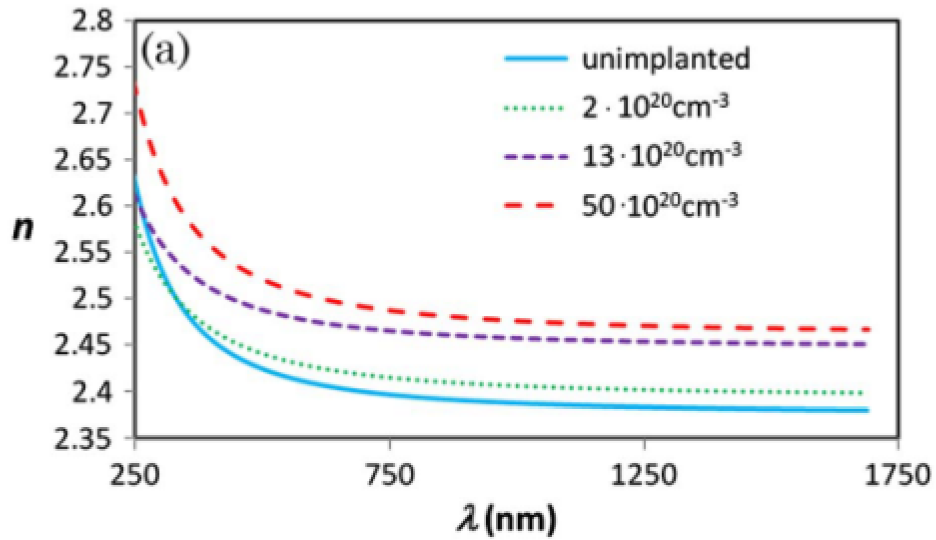
Woollam M2000-FI variable-angle spectroscopic ellissometer (246 – 1690 nm)



Optical features

Ellipsometric characterization of shallow-ion-implanted diamond





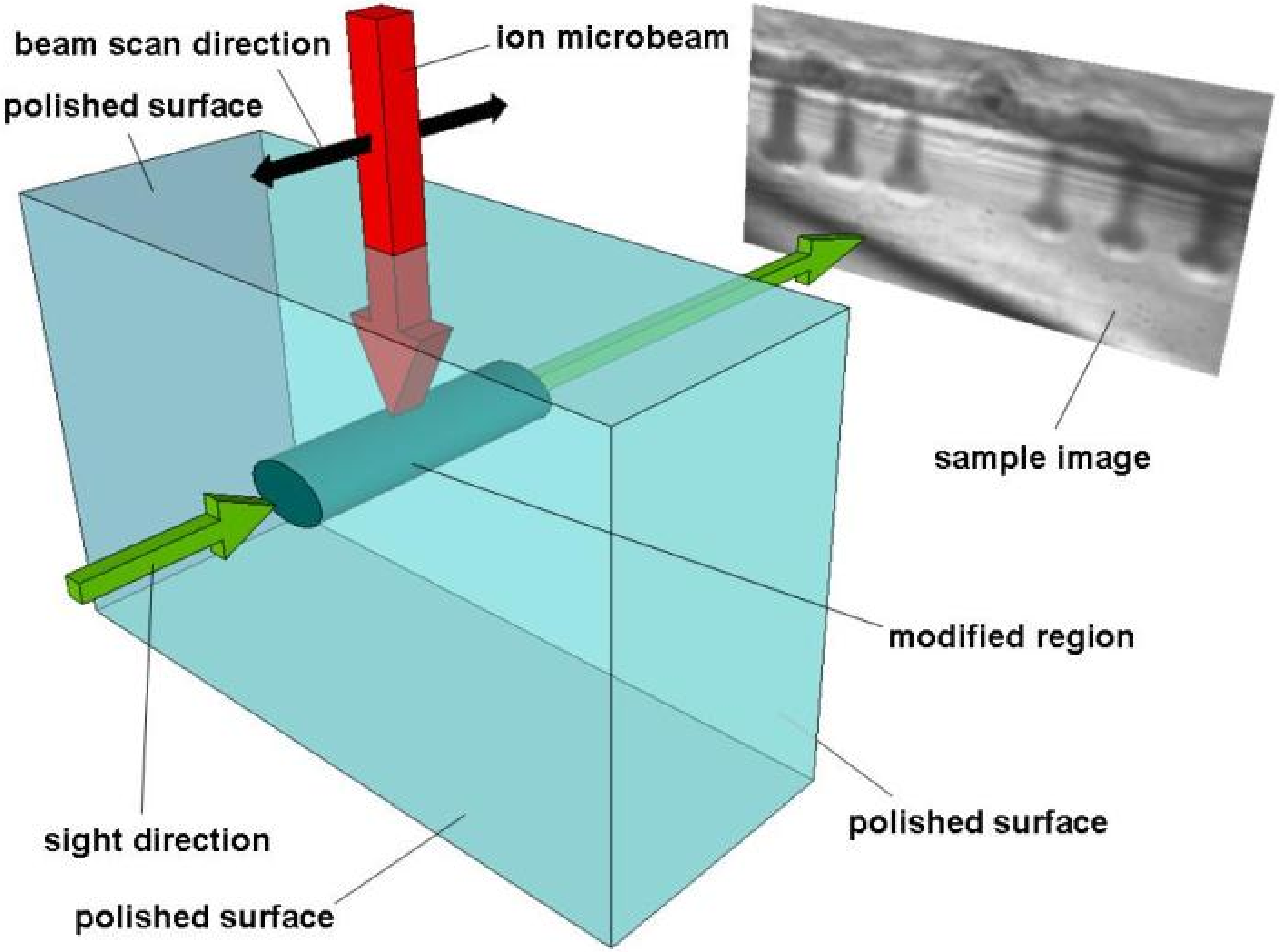
- **Linear trend at low damage levels, sub-linear trend at higher fluences**

- **Similar changes are observed over the entire spectral range under investigation**

A. Battiato et al., ***Optics Letters 37 (4)****, 671 (2012)*

Optical features

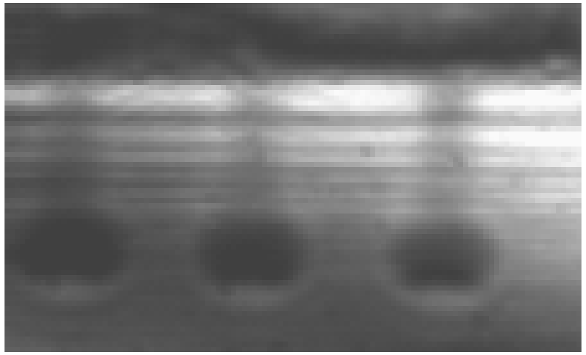
Direct writing of waveguiding structures with 5 MeV H microbeam



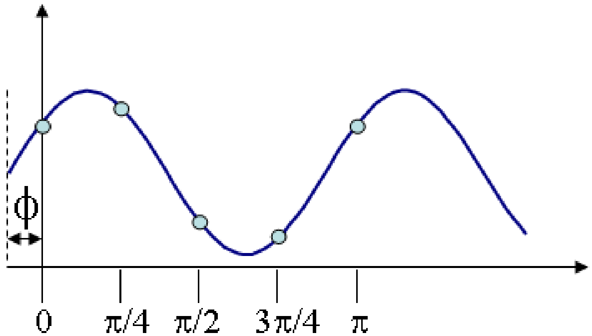
Optical features

Interferometric characterization

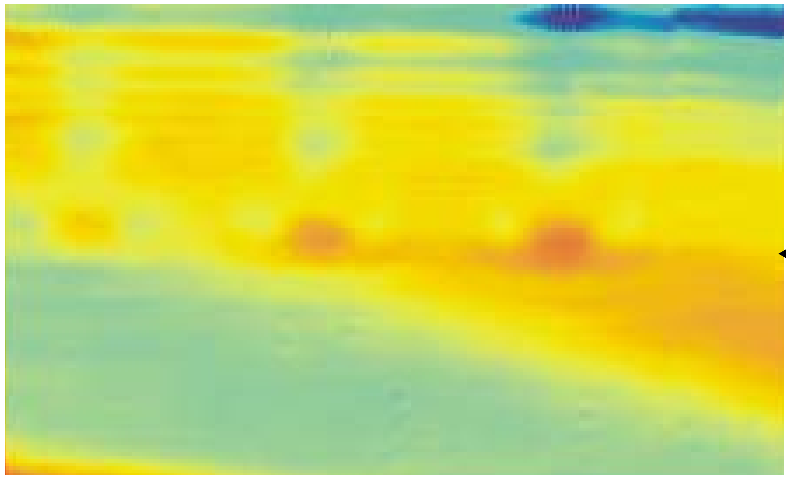
Interferometric image



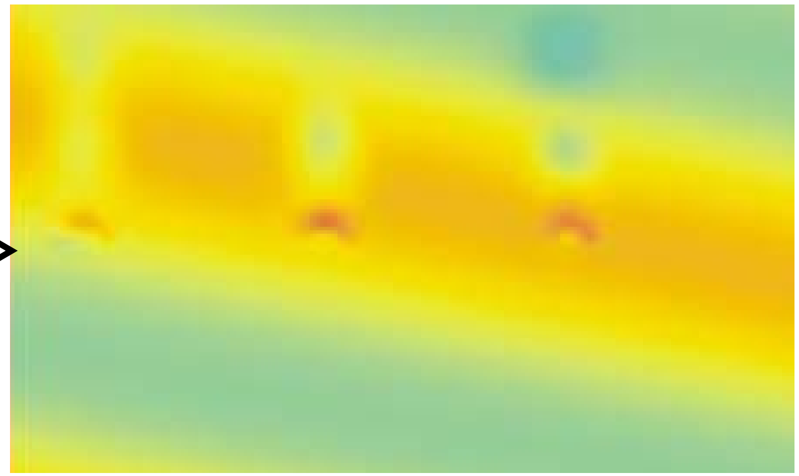
Phase shift reconstruction



Phase shift map



Finite element method



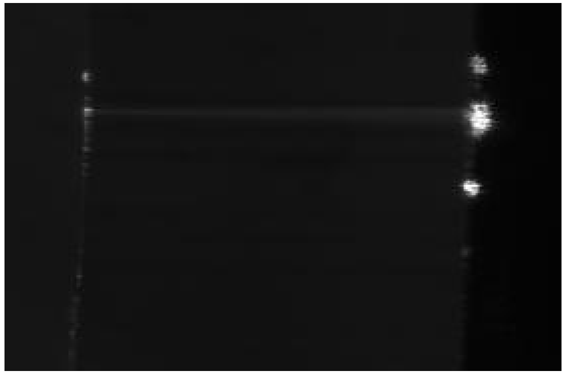
S. Lagomarsino et al., ***Physical Review Letters 105****, 233903 (2010)*

Optical features

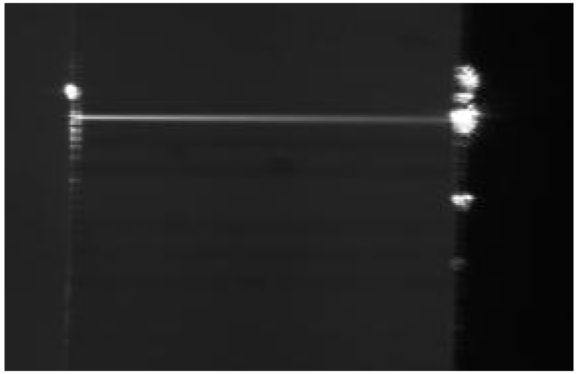
Laser-coupling characterization

λ = 532 nm, optical objectives coupled at both the input and output points

No waveguide coupling

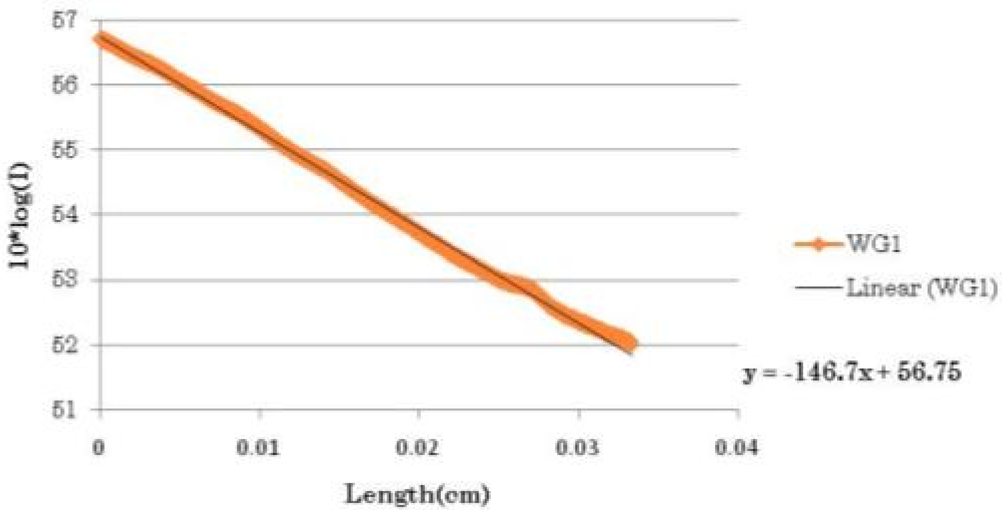


Waveguide coupling



CIBA-NUS

Strong absorption losses
(10^1 – 10^2 dB cm^{-1})



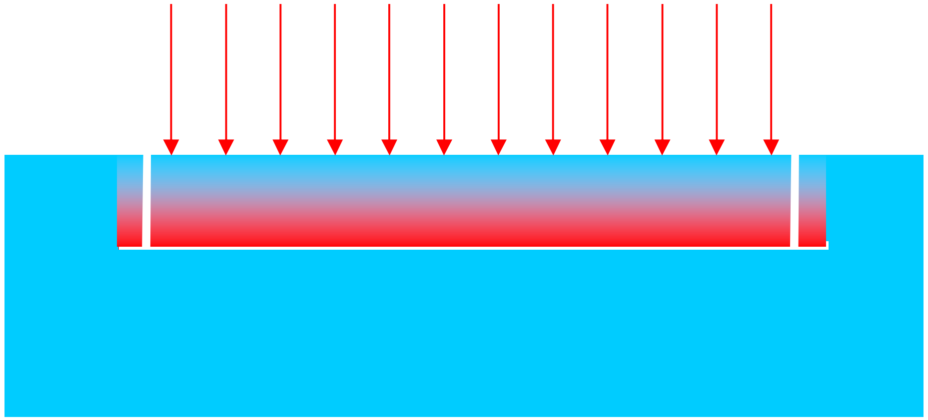
As-implanted samples: annealing can help reducing absorption losses while maintaining a suitable refractive-index contrast

Outline

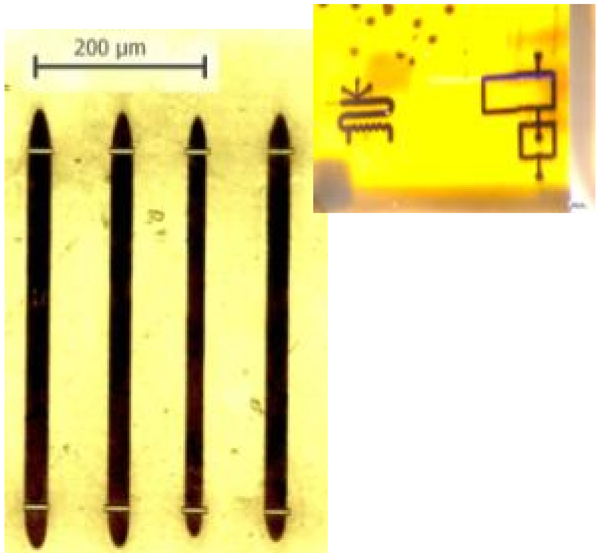
- Diamond
  - → Synthesis
  - → Properties
  - → Applications
- IBL in diamond
  - → MeV ion lithography in diamond
  - → keV ion beam lithography in diamond
- **Activities at the University of Torino**
  - → Electrical features
  - → Optical features
  - → **Microfluidics**

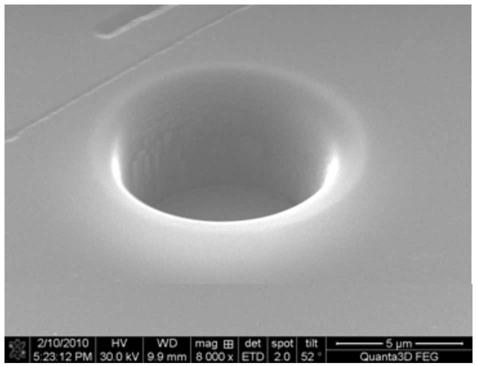
Microfluidics

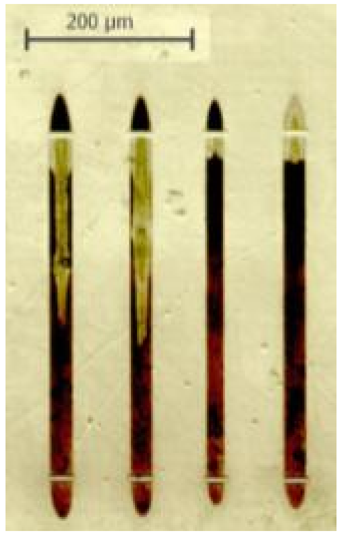
Fabrication of micro-fluidic channels



- ✓direct ion microbeam writing of buried amorphized channels
- ✓high temperature thermal annealing (1200 ÷ 1400 °C): graphitization
- ✓FIB milling of access holes
- ✓selective etching of graphite with an electrochemical process

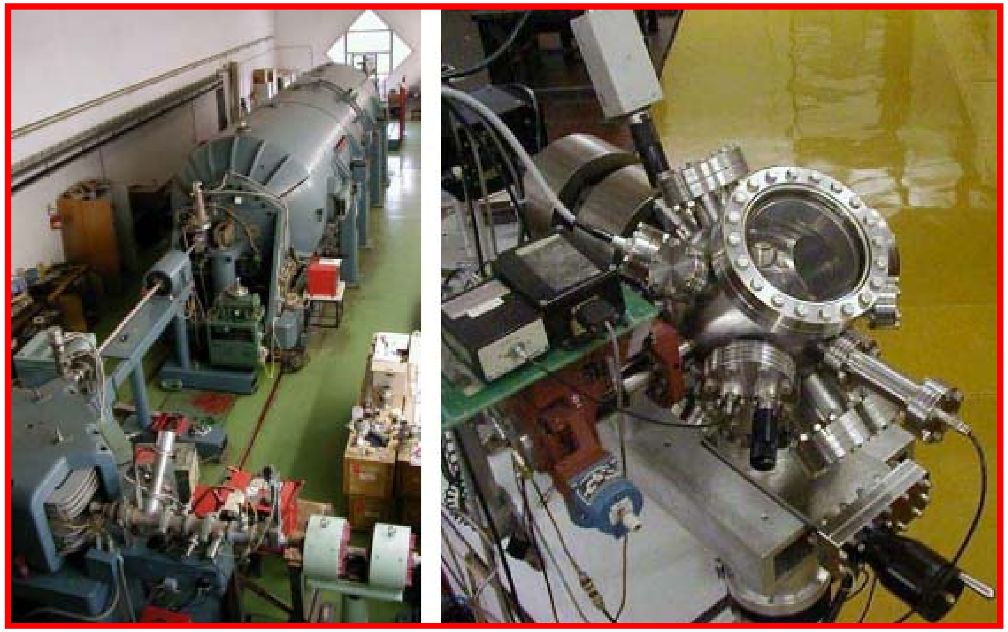




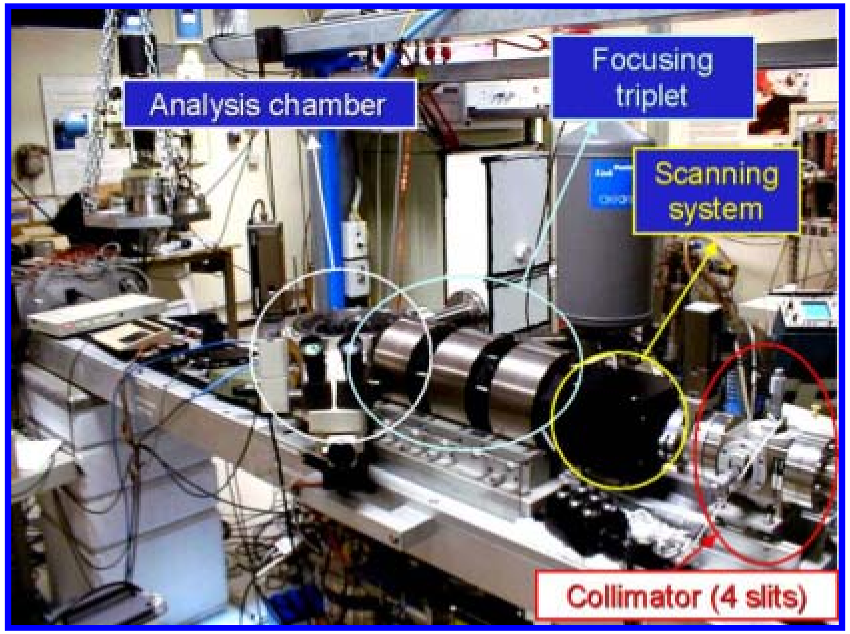


Microfluidics

Ion implantation performed at the
RBI-LIBI and LNL-AN2000 ion microbeam lines



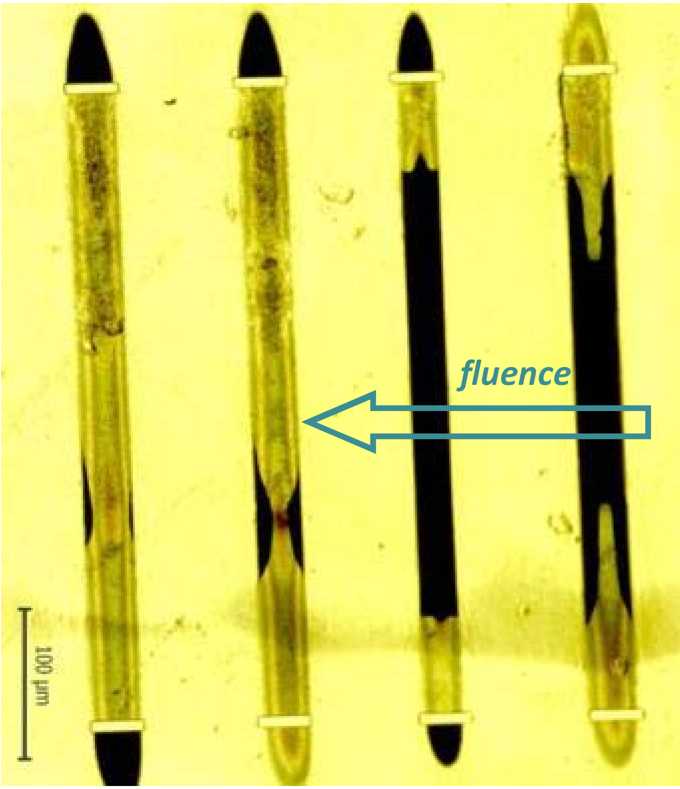
18 MeV C @ F=$2 \cdot 10^{16}$ cm^{-2}



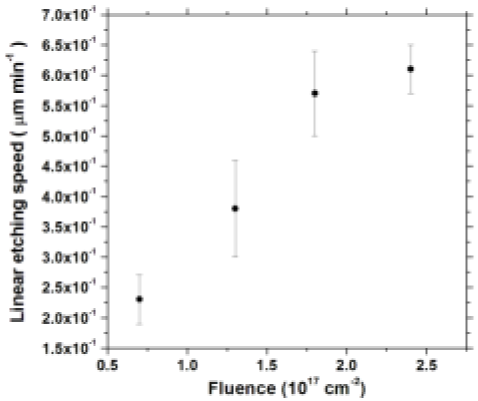
1.8 MeV He @ F=$1 \cdot 10^{17}$ cm^{-2}

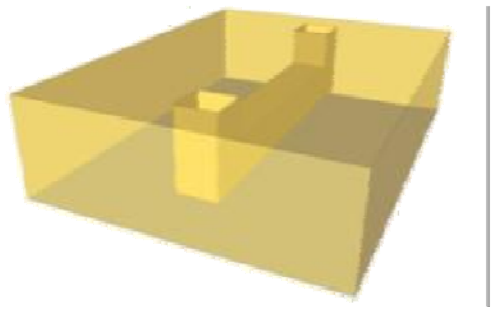
Microfluidics

Fabrication of micro-fluidic channels



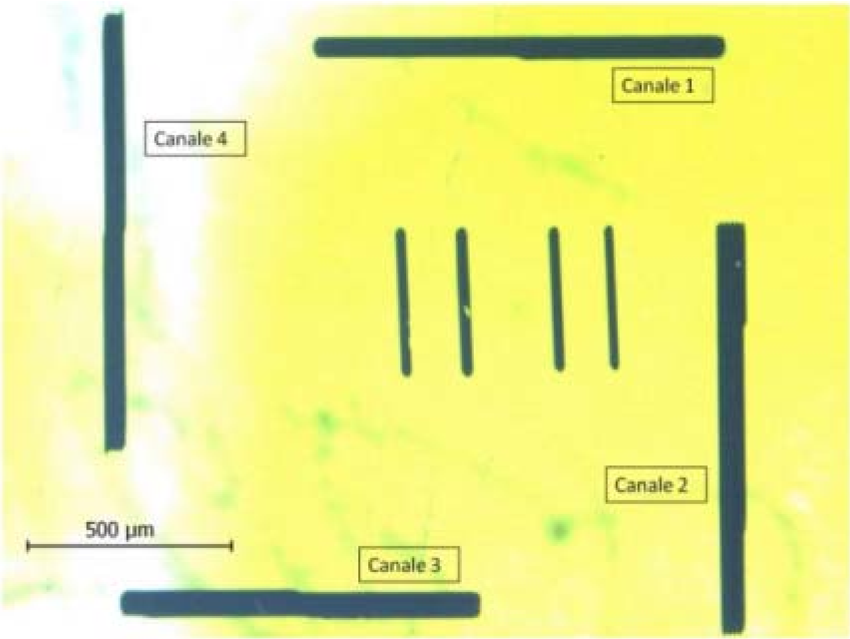
- ✓complete graphite removal from channels implanted at the highest fluence
- ✓different etching rates for channels implanted at different fluences
- ✓possibility of creating buried microfluidic channels with a monolithic approach

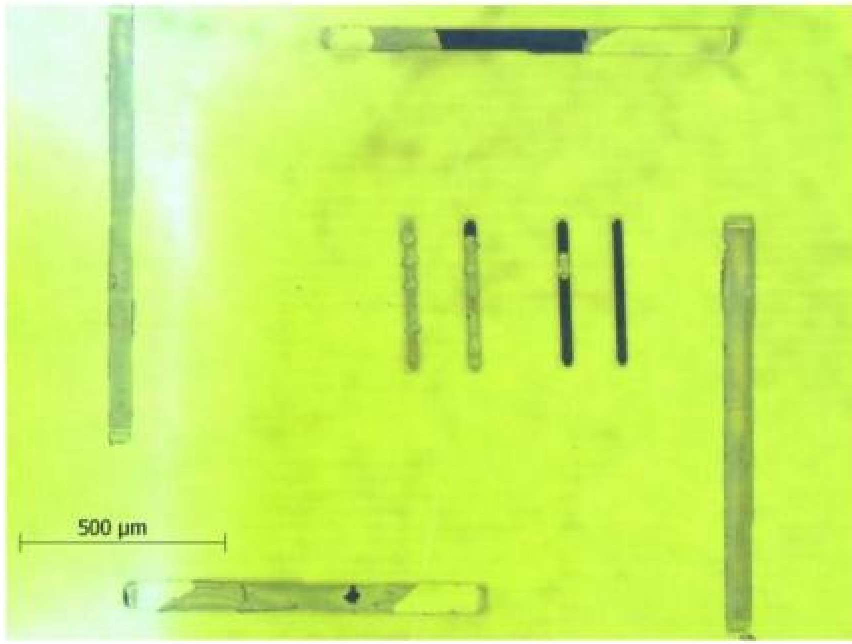




Microfluidics

mm-long microfluidic channels



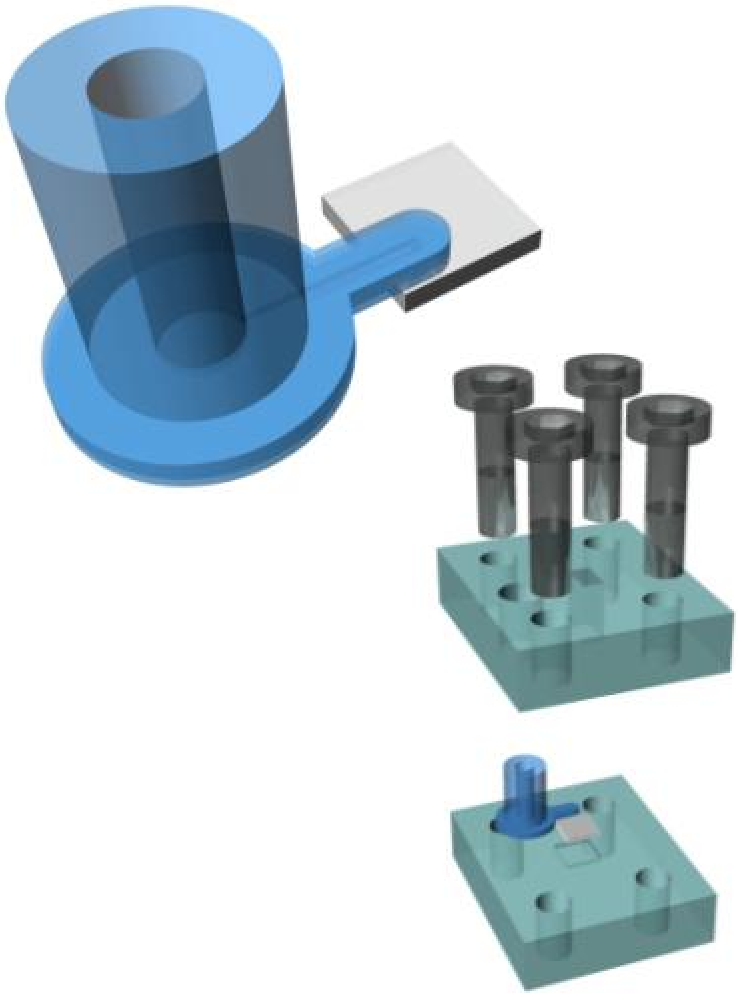


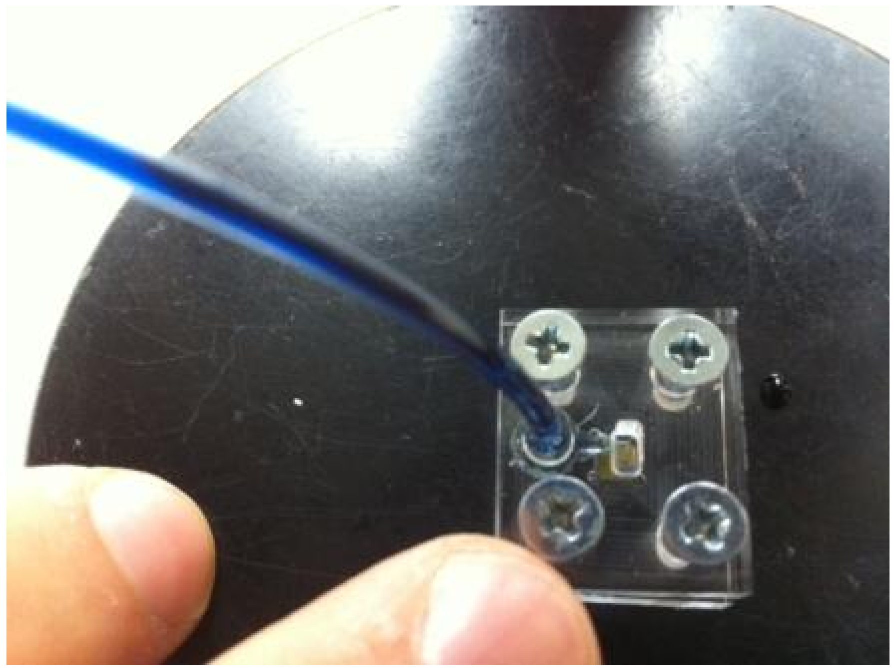
before etching

after etching

Microfluidics

liquid injection system:
mechanically clamped PDMS structure





Acknowledgments

Sample processing and characterization **University of Torino**
A. Battiato, F. Bosia, V. Carabelli, E. Carbone, J. Forneris, D. Gatto Monticone,
A. Gilardino, A. Lo Giudice, S. Gosso, D. Lovisolo, A. Marcantoni, F. Picollo, A. Re, E. Vittone

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

National Laboratories of Legnaro (INFN)
D. Ceccato, L. La Torre, V. Rigato

Ruđer Bošković Institute
V. Grilj, M. Jakšić, Ž. Pastuović, N. Skukan

LABEC laboratory (INFN)
S. Calusi, L. Giuntini, M. Massi

RUBION Laboratory
S. Pezzagna, J. Meijer

FIB microfabrication, cross-sectional TEM **MARC group, University of Melbourne**
B. Fairchild , S. Prawer, S. Rubanov

Optical / morphological characterization **National Institute of Optics**
R. Mercatelli, F. Quercioli, A. Sordini, S. Soria, M. Vannoni

Optical absorption characterization **ENEA "La Casaccia"**
A. Sytchkova

Optical modeling **Department of Energetics, University of Florence**
S. Lagomarsino, S. Sciortino

Waveguides characterization **CIBA – National University of Singapore**
A. Bettiol, V. S. Kumar

High-resolution X-ray diffraction **Department of Physics, University of Padova**
N. Argiolas, M. Bazzan

CVD diamond growth **Department of Mechanical Engineering, University of Rome Tor Vergata**
M. Marinelli, C. Verona, G. Verona-Rinati

Content sources

- www.srim.org
- www.wikipedia.org

- Australian National University
- School of Physics – University of Melbourne
- Solid State Physics Group – University of Torino
- University of Florida
- University of New South Wales
- Technion – Israel Institute of Technology