Accelerators and Ion Beams for Quantum Technologies

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Accel'22 - International Conference on Accelerators for Research and Sustainable Development: From Good Practices Towards Socioeconomic Impact (Friday 27 May 2022)

Outline

- First and second quantum revolutions
- Ion implantation – past, present and future
- Straggling and energy considerations
- Poisson versus deterministic implantation
- Counting ions
- Accelerators/implanters for quantum applications
- Examples: Quantum applications
  - Qubits and colour centres

Acknowledgements

IAEA
International Atomic Energy Agency
Atoms for Peace and Development

CRP No: F11020 - Ion Beam Induced Spatio-Temporal Structural Evolution of Materials: Accelerators for a New Technology Era

Ministry of Education
SINGAPORE

MOE Tier 2 grant: Colour centre engineering in wide band-gap semiconductor membranes using ion implantation

3 The first and second quantum revolutions

10.1098/rsta.2003.1227

THE ROYAL SOCIETY

Quantum technology: the second quantum revolution

By Jonathan P. Dowling[1] and Gerard J. Milburn[2]

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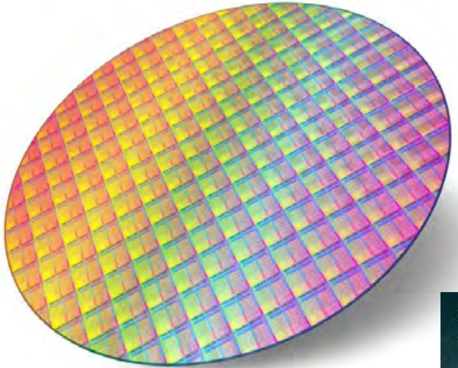
Published online 20 June 2003

We are currently in the midst of a *second quantum revolution*. The first quantum revolution gave us new rules that govern physical reality. The second quantum revolution will take these rules and use them to develop new technologies. In this review we discuss the principles upon which quantum technology is based and the tools required to develop it. We discuss a number of examples of research programs that could deliver quantum technologies in coming decades including: quantum information technology, quantum electromechanical systems, coherent quantum electronics, quantum optics and coherent matter technology.



www.semiconductors.org

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Ion implantation past, present and future

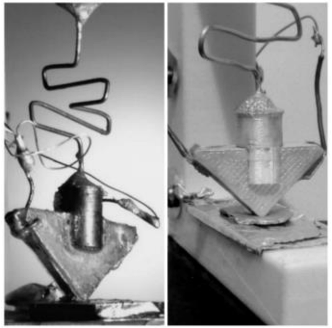
William Shockley (Bell Labs) – Oct. 28, 1954 patent

- Implantation doping – ion bombardment with group III or V ions to change the conductivity.
- Depth of the implanted doping is controlled by energy.
- Heating the irradiated semiconductor to "repair radiation damage" (400 °C) at least a factor 2 too low !

1956 Nobel Prize (Physics)

"for their researches on semiconductors and their discovery of the transistor effect"

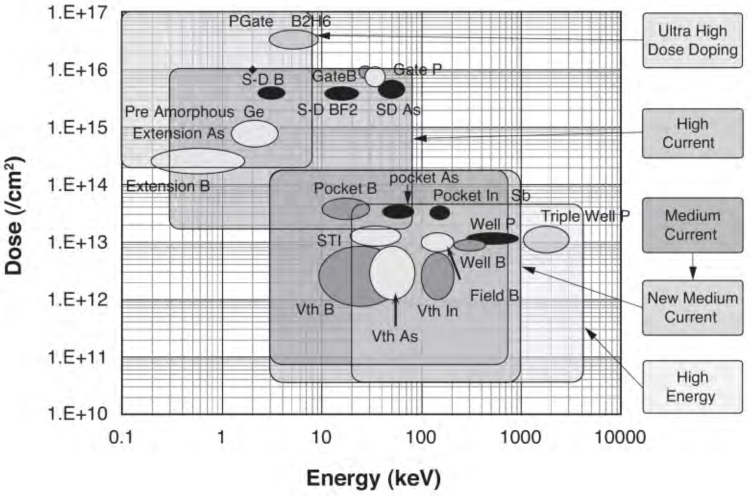
John Bardeen, William Shockley and Walter Brattain at Bell Labs, 1948



Ion implantation past, present and future

Implanters in industry

In this process example, 11 or the 59 processing steps involve ion implantation. B, P, As etc – implantation.



https://www.ulvac.co.jp/

SEI TECHNICAL REVIEW · NUMBER 73 · OCTOBER 2011

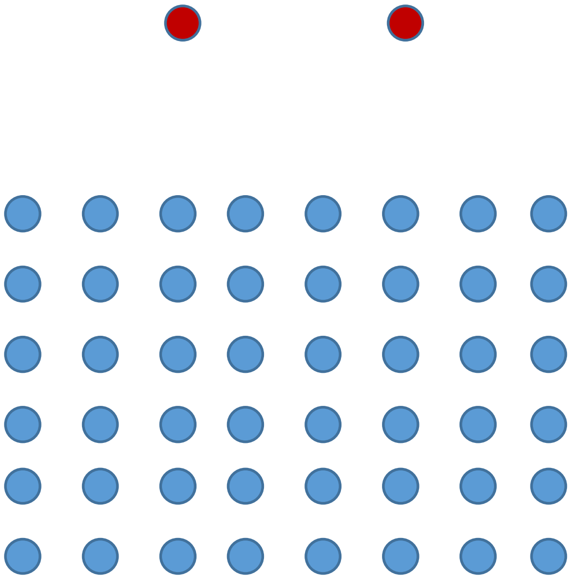
Table 1. Ion Implantation Process Step

No.	Process for double well CMOS		Current CMOSFET (1999 -)	
(Well formation)				
1	High resistivity n-type Si wafer		10Ω - cm	
(Field Oxide Layer formation)				
2	Field SiO_2 layer	Thermal Oxidation	SiO_2 under layer for LOCOS	
3	Si_3N_4 layer	CVD		
4	Resist Coating			
5	Photo Etching	Mask 1	To implant below p-field oxide layer	
6	Dry Etching (Si_3N_4)			
7	Resist Removal		P channel resist stripping	
8	Resist Coating			
9	Photo Etching	Mask 2	To implant below n-field oxide layer	
10	Dry Etching (Si_3N_4)			
11	Field Oxidation	Steam Oxidation		
(Gate formation)				
12	Si_3N_4 - SiO_2 Underlayer removal		for LOCOS formation	
13	Dumas or HCl Oxidation		Gate Layer formation	
14	Resist Coating			
15	Photo Etching	Mask 3	To implant n-channel	
16	B Implantation	300 ~ 1000keV, 1E13	N-channel well formation & channel stopper	HE
17	B or In Implantation	40 ~ 100keV, 1E12	N-channel punch-through stopper	M
18	B Implantation	20 ~ 50keV, 1E12	N-channel Vth control	M
19	Resist stripping			
20	Resist Coating			
21	Photo Etching	Mask 4	To implant p-channel	
19	P Implantation	600 ~ 3000keV, 1E13	P-channel well formation & channel stopper	HE
22	P or Sb Implantation	80 ~ 150keV, 1E12	N-channel punch-through stopper	M
23	P Implantation	40 ~ 100keV, 1E12	N-channel Vth control	M
24	Resist stripping			
(p-channel Source Drain formation)				
25	Poli-Si Film formation	SiH_4 ThermalCVD	for gate electrode formation	
26	Resist Coating			
27	Photo Etching	Mask 5	for p-channel gate electrode formation	
28	Dry Etching (Poli-Si)	CF_3 gas	P-gate formation	
29	B Implantation	1 – 10keV, 2E14	P-channel extension & p-gate doping	LE
30	SiO_2 Film formation	CVD		
31	Side Wall formation	RIE		
32	Post Treat.			
33	B or BF_2 Implantaion	10 – 50keV, 2E15	P-channel source drain implant	H
34	Resist stripping			
(n-channel Source Drain Formation)				
35	Resist Coating			
36	Photo Etching	Mask 6	for n-channel gate electrode formation	
37	Dry Etching (Poli-Si)	CF_3 gas		
38	P Implantaion	5 ~ 30keV, 2E14	N-channel extension & n-gate doping	LE
39	SiO_2 Film formation	CVD		
40	Side Wall formation	RIE		
41	Post Treat.			
42	As Implantaion	20 – 50keV, 5E15	N-channel source drain implant + gate implant	H
43	RTA	1000°C	S/D activation	
44	Side Wall process with HF	HF		
45	Co + TiN Film formation			
46	Saliside RTA #1 step			
47	TiN Removal	Sulfate Cleaning		
48	Saliside RTA #2 step			
(Electrode formation)				
49	PSG-CVD Film formation	P Glass Film	Interlayer dielectric formation	
50	Reflow	1000°C	Surface planarization for wiring	
51	Resist Coating			
52	Photo Etching	Mask 7	Source drain contact formation	
53	Dry Etching (PSG)			
54	As Implant for Contact	30 - 50keV, 5E15/cm²	Reduction of contact resistance	H
55	Si added Al Sputtering	Si, 1 – 3%	To avoid alloy pit	
56	Resist Coating			
57	Photo Etching	Mask 8	Source drain wiring	
58	Dry Etching (Al)	BCl_3 Gas		
59	H_2 Anneal	400 – 600°C	To improve Si-SiO_2 interface, To stabilize of S/D contact	

Photo Etching Process 8 cycles HE : 2 step M : 4 step H ; 5 step (LE : 2 step)

Ion implantation past, present and future

Implantation of single ions



The challenges !

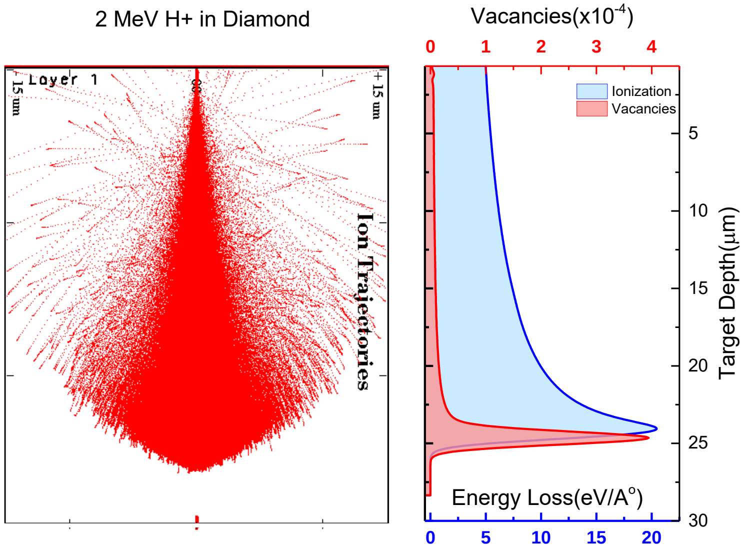
How can we implant single ions deterministically ?

How precisely can we position the ions ?

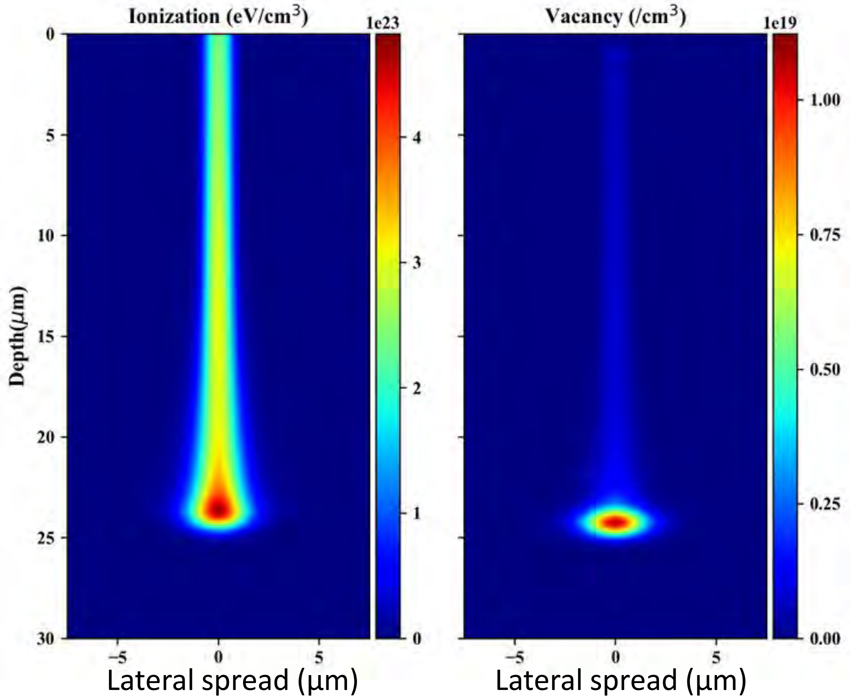
How do we know that an ion has been implanted ?

How do we “activate” the implanted ion (Yield)?

Straggling and energy considerations

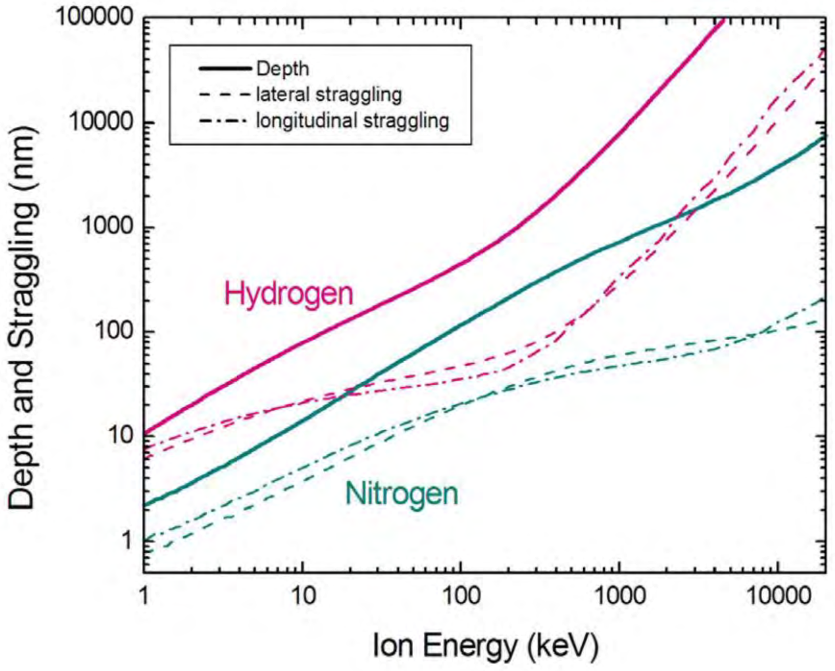


SRIM simulation (www.srim.org)



Beam: 2 MeV protons, Range: 25 μm, Displacement energy: 45 eV, Density : 3.52 g/cm^3

Straggling and energy considerations



Ion Implantation, Edited by Mark Goorsky, Published by InTech 2012, page 4

Straggling and energy considerations

Matrix : Donor	Bohr orbit diameter (nm)	Energy for 20 nm depth (keV)	Lateral straggling (nm)	Number of e–h pairs per impact
C(diamond) : N	—	15	6.3	710
Si : P	2.44	12	8.5	1400
Si : As	1.96	20	5.7	2100
Si : Sb	2.64	22	4.8	2250
Si : Bi	1.94	28	3.7	3100

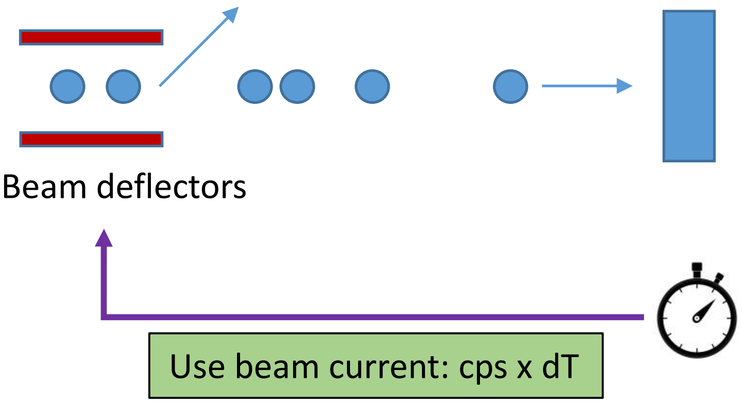
Depth precision — Lateral precision — Detection

Kane computer architecture: 20 nm depth, 20 nm spacing

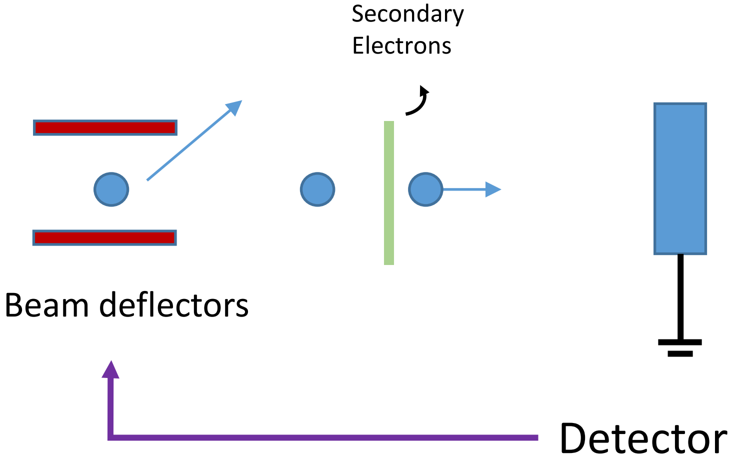
J. Phys.: Condens. Matter **27** (2015) 154204

Poisson versus deterministic

Ions emerging from an ion source arrive at the target at random time intervals (Poisson statistics).



Deterministic – Control over single ions using detection (eg SE or the sample as a detector)

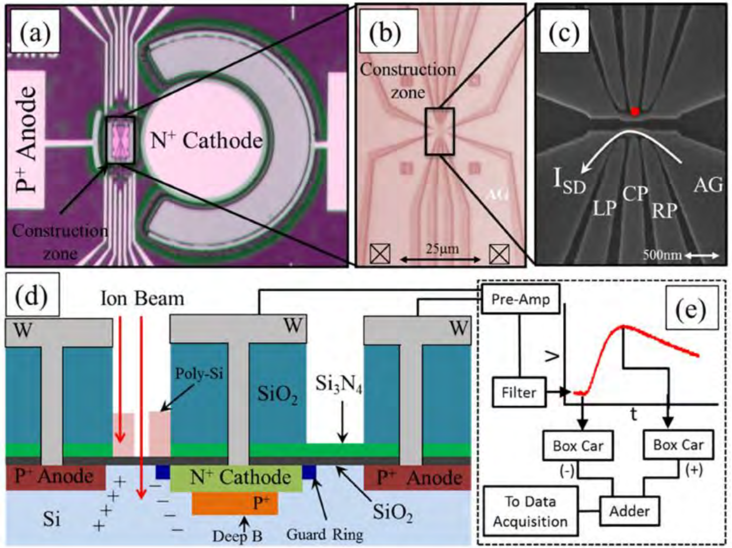


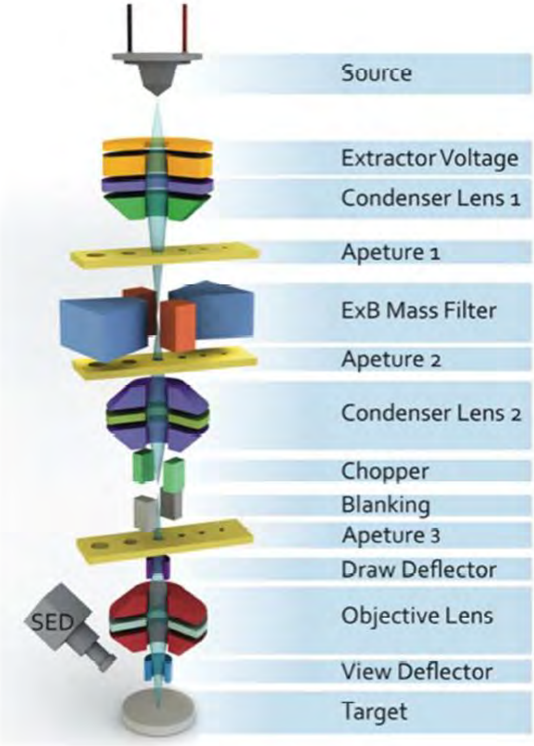
Counting ions

REVIEW OF SCIENTIFIC INSTRUMENTS **88**, 123301 (2017)

Ion implantation for deterministic single atom devices

J. L. Pacheco, M. Singh, D. L. Perry, J. R. Wendt, G. Ten Eyck, R. P. Manginell, T. Pluym, D. R. Luhman, M. P. Lilly, M. S. Carroll, and E. Bielejec
Sandia National Laboratories, Albuquerque, New Mexico 87185, USA





Accelerators/implanters for quantum applications

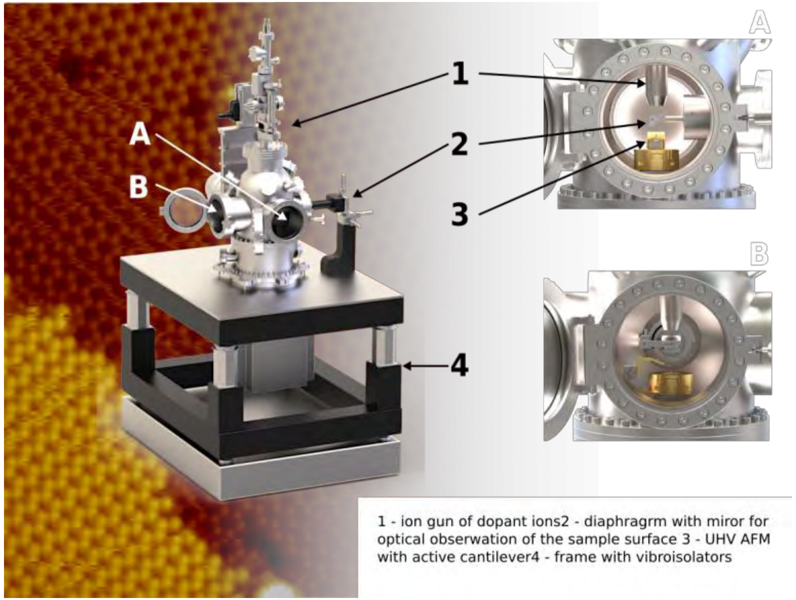
Q-one system

Existing systems

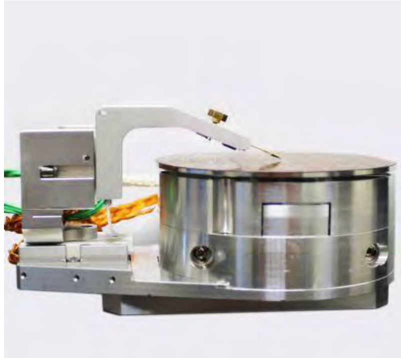
- Surrey
- Manchester

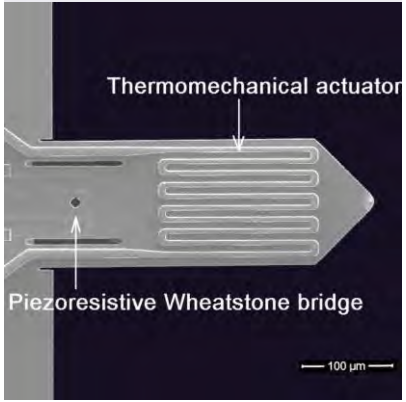
Nano aperture techniques

nano analytik



1 - ion gun of dopant ions2 - diaphragrm with miror for optical obserwation of the sample surface 3 - UHV AFM with active cantilever4 - frame with vibroisolators



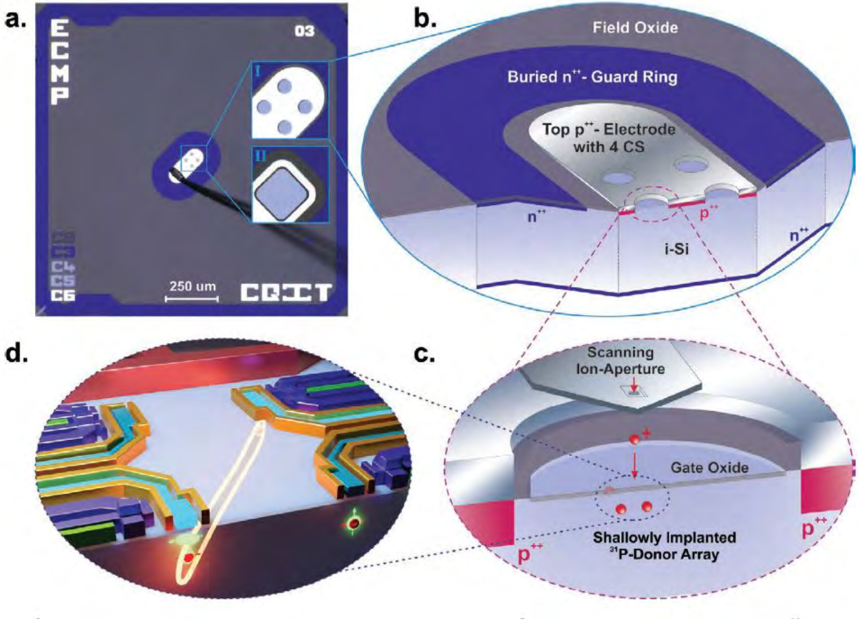


Systems

- LBL
- Leipzig
- Uni. Of Melbourne

Quantum applications - Qubits

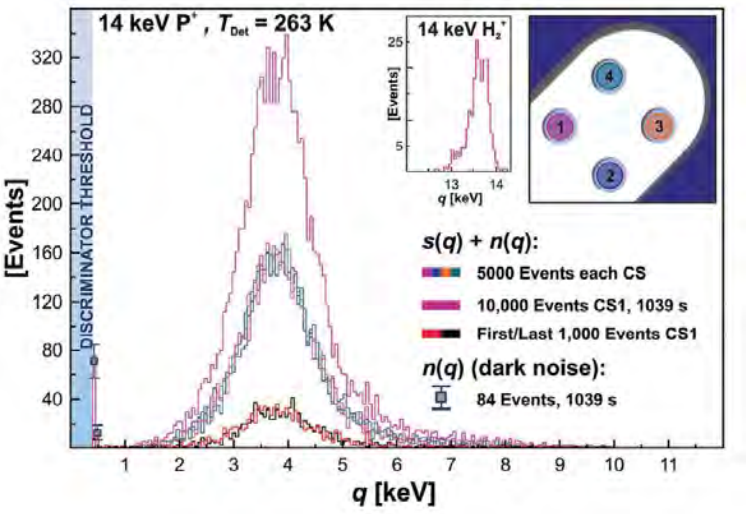
Adv. Mater. **2022**, *34*, 2103235



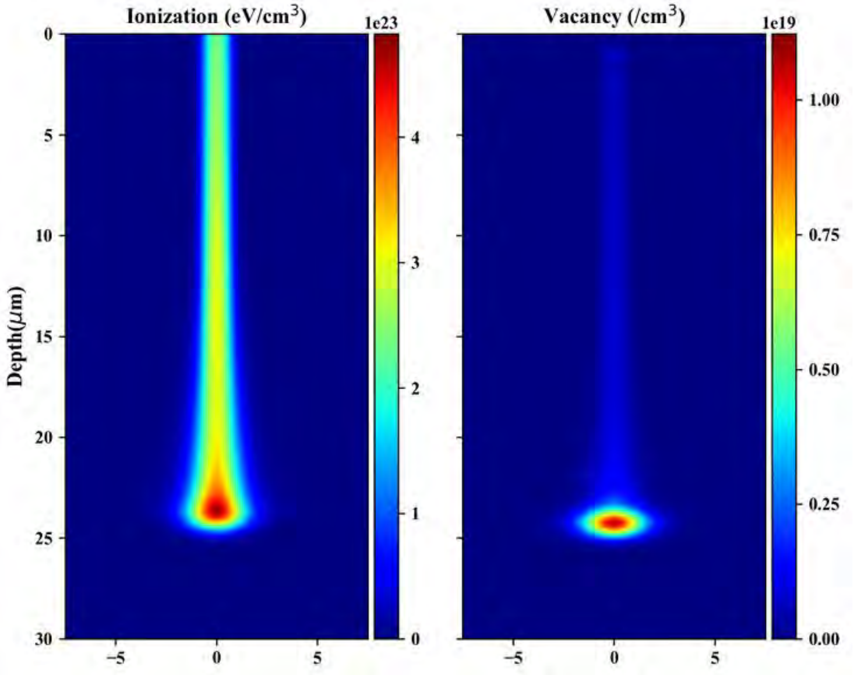
RESEARCH ARTICLE
ADVANCED MATERIALS
www.advmat.de

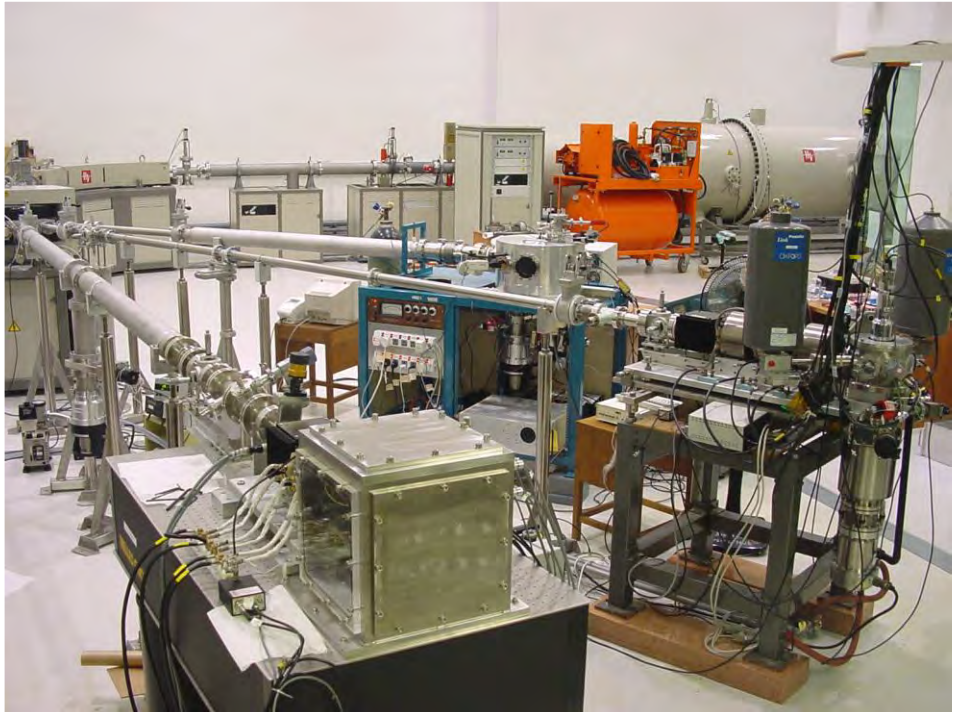
Deterministic Shallow Dopant Implantation in Silicon with Detection Confidence Upper-Bound to 99.85% by Ion–Solid Interactions

Alexander M. Jakob, Simon G. Robson, Vivien Schmitt, Vincent Mourik, Matthias Posselt, Daniel Spemann, Brett C. Johnson, Hannes R. Firgau, Edwin Mayes, Jeffrey C. McCallum, Andrea Morello, and David N. Jamieson*

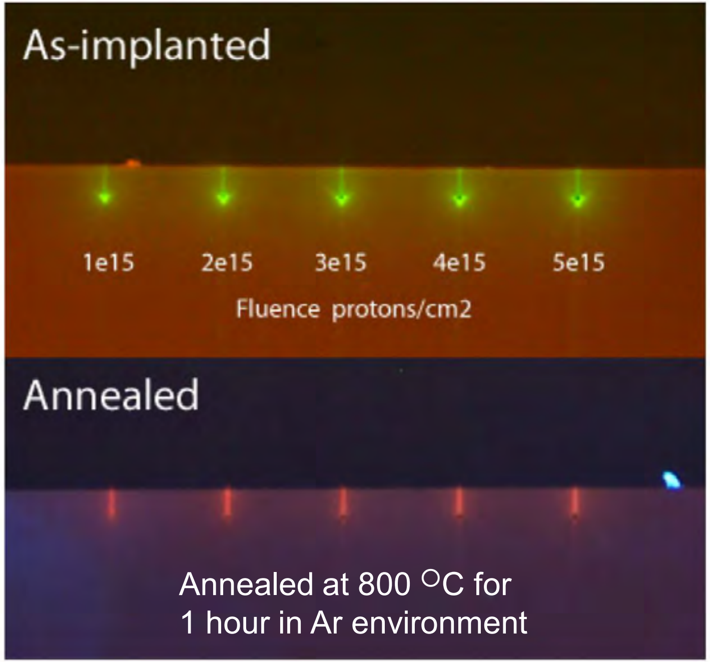


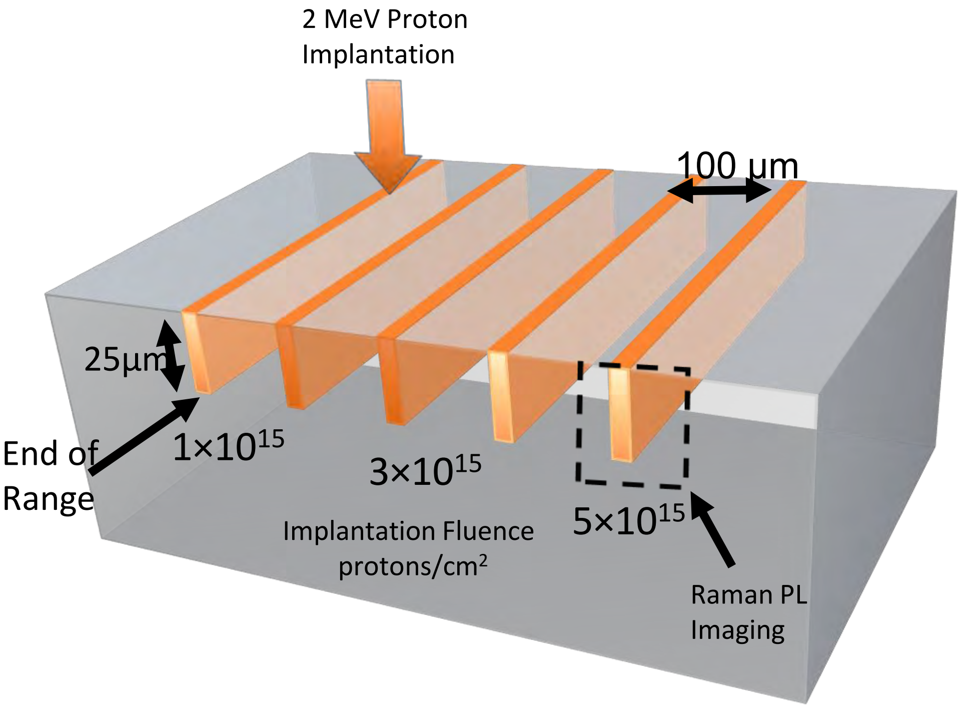
What about MeV accelerators ?





Colour Centre Engineering in Diamond





Diamond sample: Type IIa optical grade single crystal CVD

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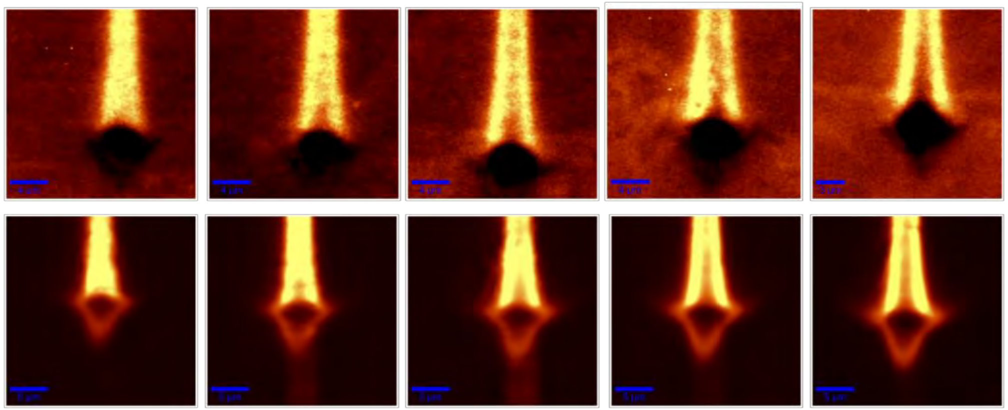
Hyperspectral imaging

NV^0 center – 1430 cm^{-1} (575 nm) (Raman excitation wavelength 532nm)



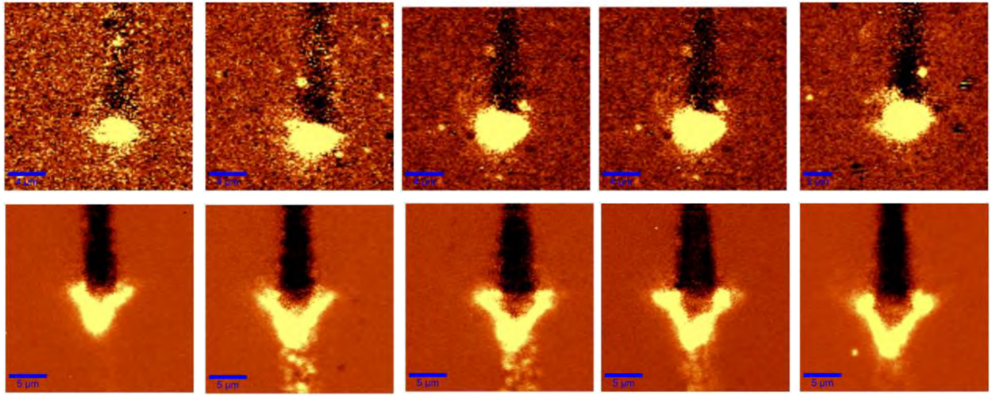
As implanted

Annealed

1e15 2e15 3e15 4e15 5e15

Fluence – protons/cm^2

EOR defects
540 – 560 nm

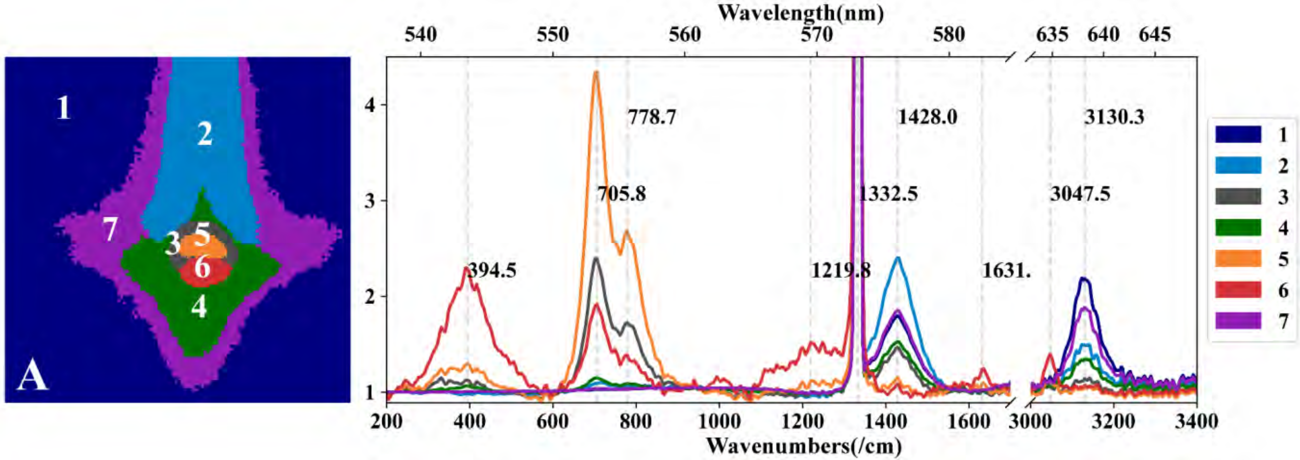


As implanted

Annealed

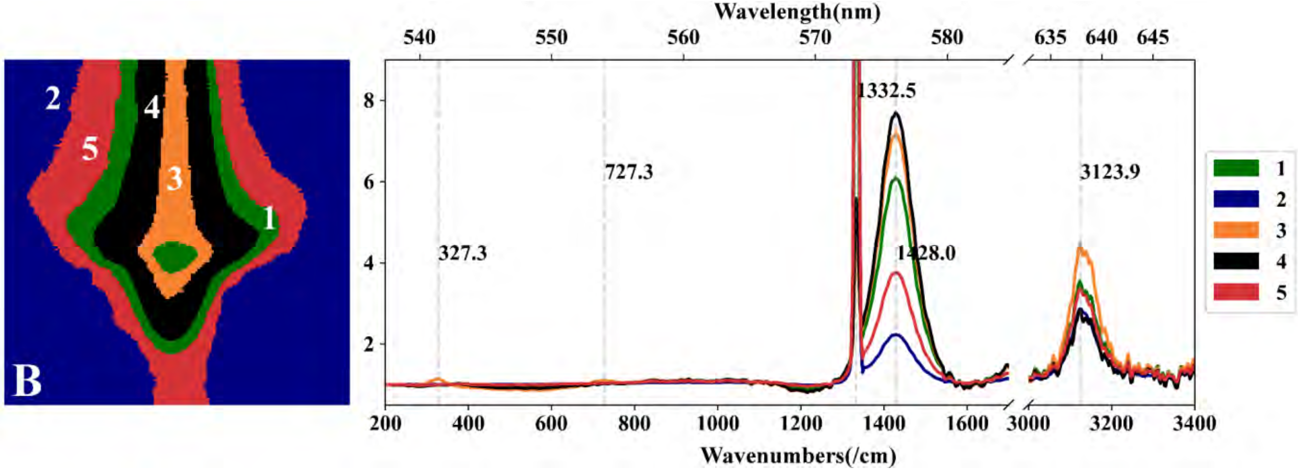
Raman (532 nm)

As implanted



Fluence 5 $\times 10^{15}$

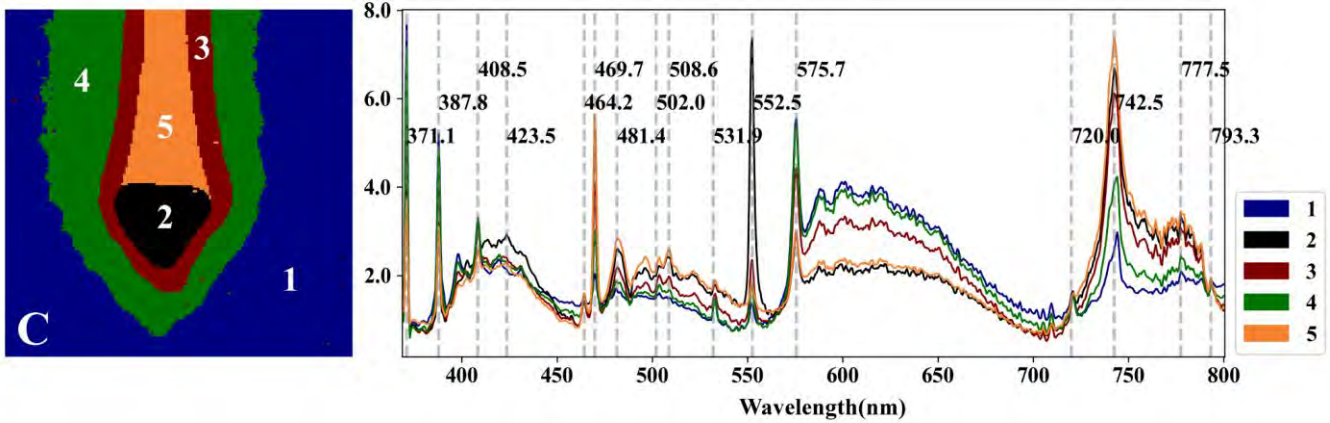
Annealed at 800 ℃



PL (355 nm)

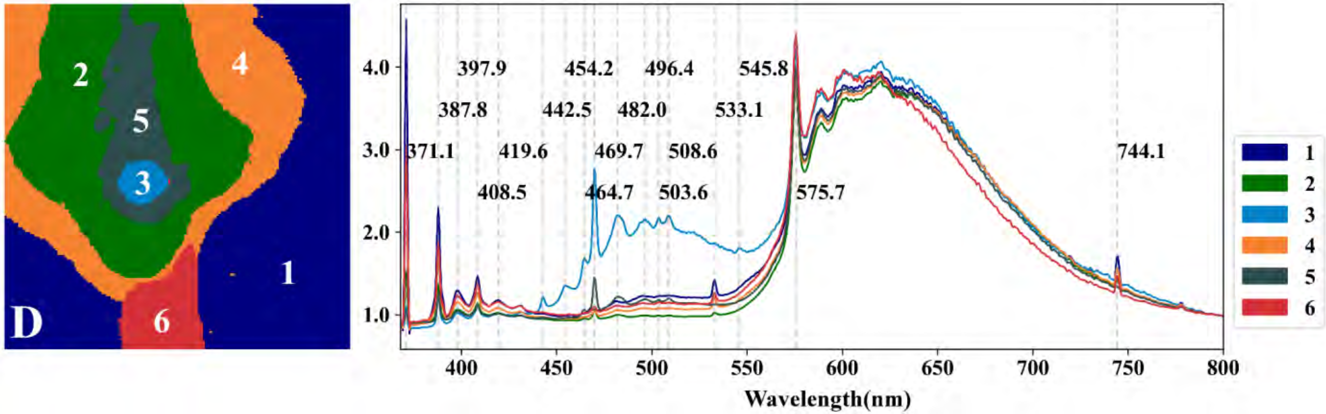
As implanted

Fluence 5 ×10[15]

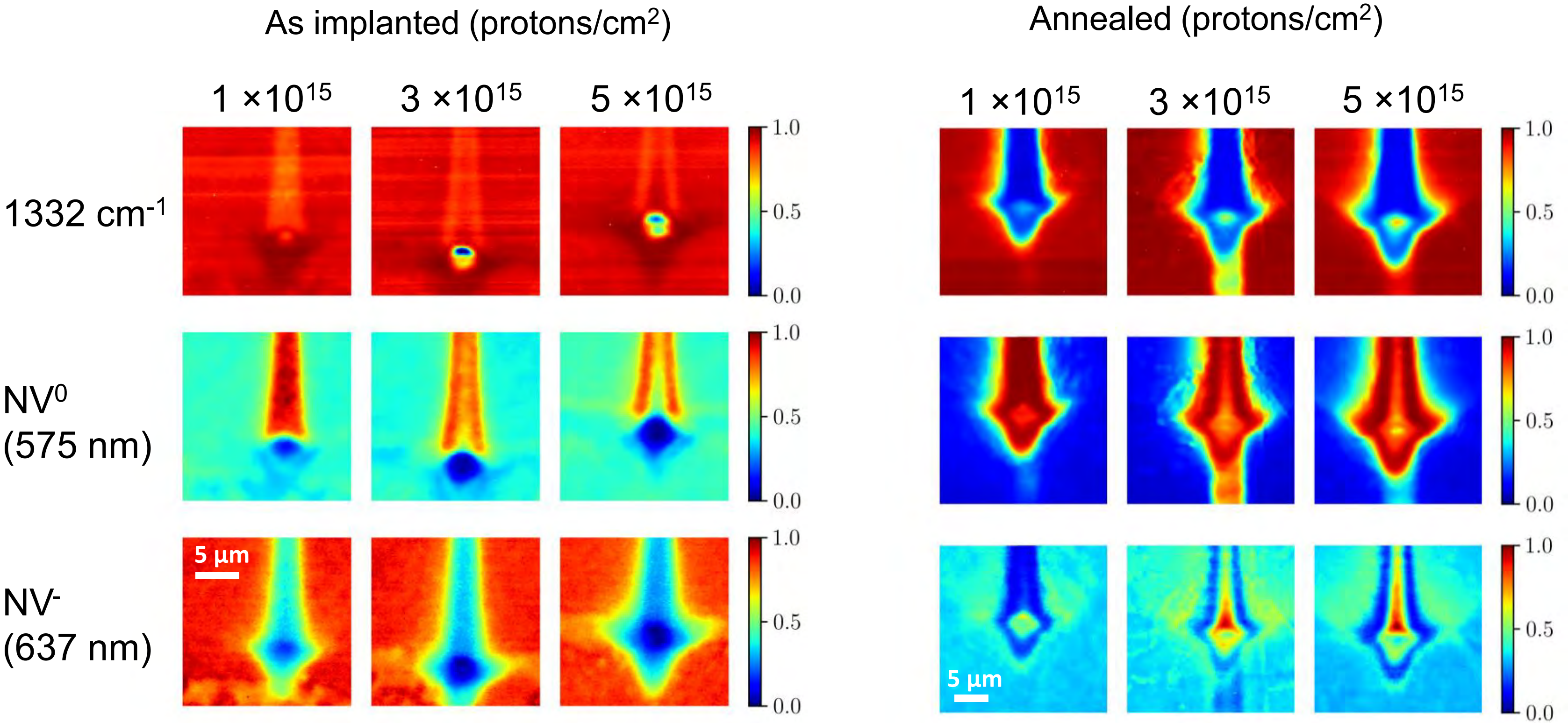


Annealed at

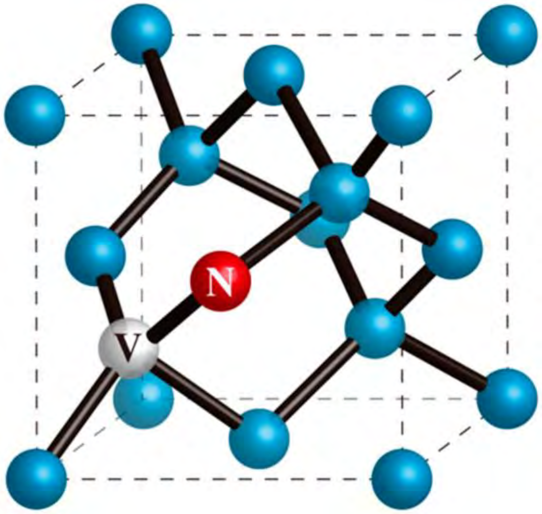
800 °C



NV centres

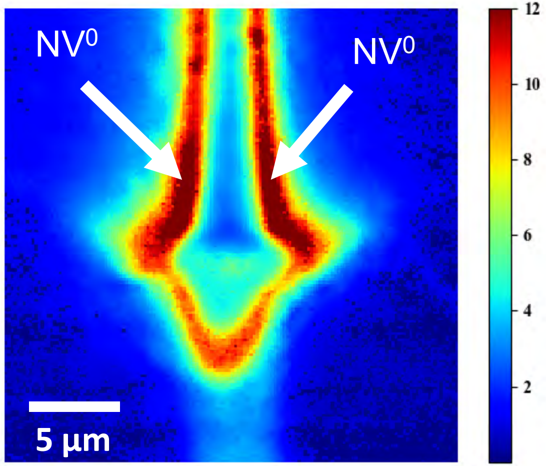

As implanted (protons/cm2)
Annealed (protons/cm2)
1 ×1015
3 ×1015
5 ×1015
1 ×1015
3 ×1015
5 ×1015
1332 cm-1
NV0
(575 nm)
NV-
(637 nm)
5 µm
5 µm
1.0
0.5
0.0

Conversion from NV^- to NV^0

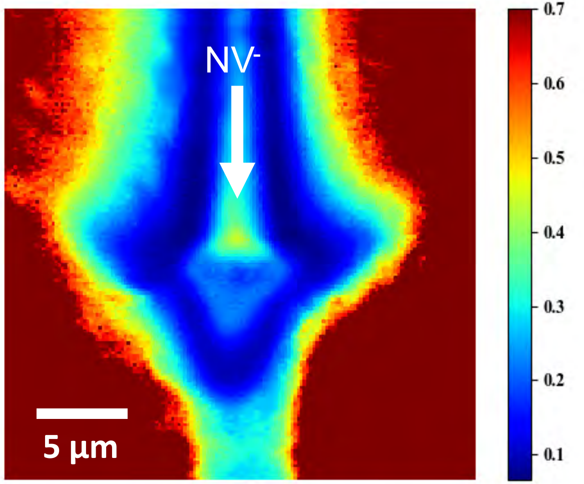


The NV centre
in diamond

After annealing Fluence 5 $\times 10^{15}$



$$\frac{NV^0}{NV^-}$$

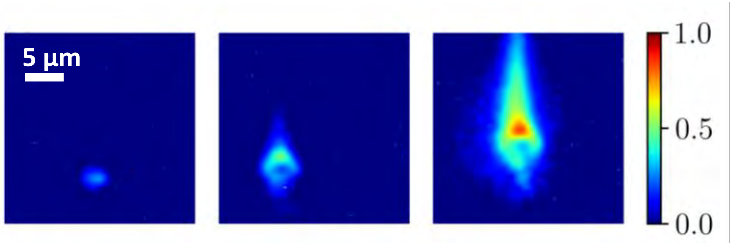


$$\frac{NV^-}{NV^0}$$

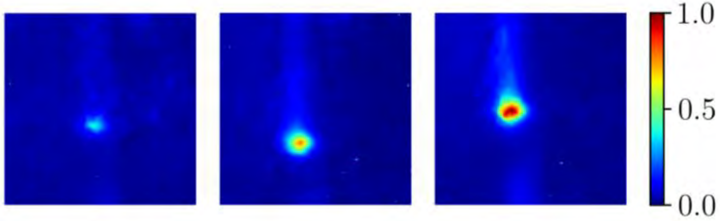
Enhancement in NV^0 at the edge of implantation
NV^- concentrated in central (ionization region)

Radiation induced damage centres

TR12 centre 469 nm (Isolated split self-interstitial)

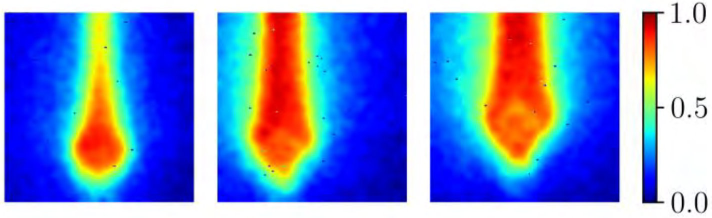


1×10^{15} 3×10^{15} 5×10^{15}



1×10^{15} 3×10^{15} 5×10^{15}

GR 1 centre 741 nm (Isolated vacancy)



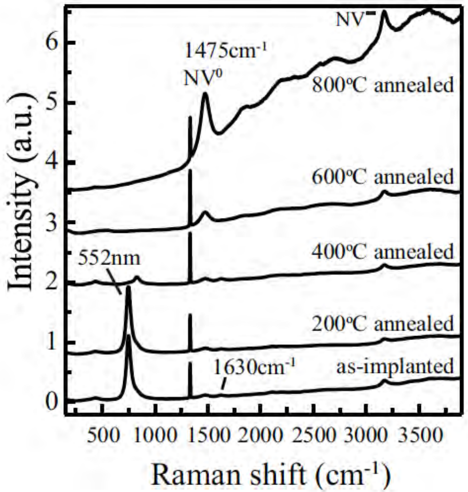
1×10^{15} 3×10^{15} 5×10^{15}

Anneals out at 800 ℃

Defect centres at the EOR

As implanted

- Both 543 nm, 552 nm anneal out by 800 ℃
- 543 nm corresponds to peak in vacancies (Bragg peak, complex defects)
- 552 nm is upper part of the EOR (Carbon rich, interstitial?)



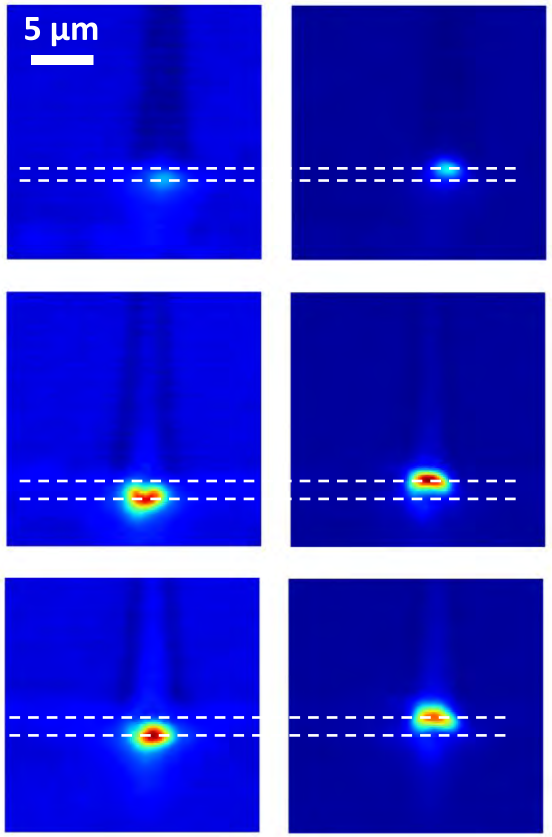
543 nm

552 nm

1×10^{15}

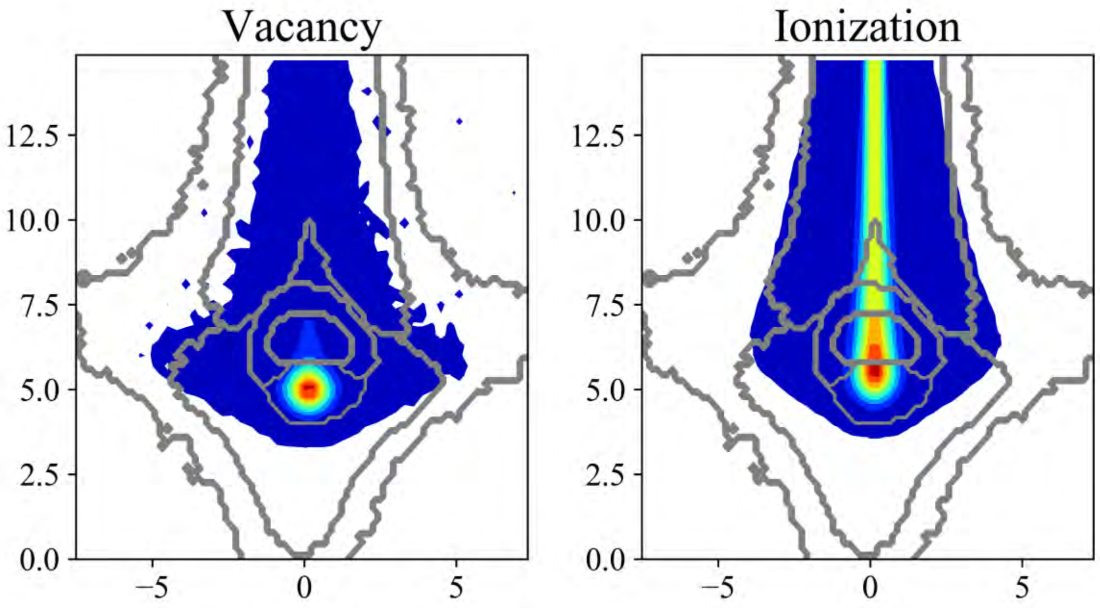
3×10^{15}

5×10^{15}



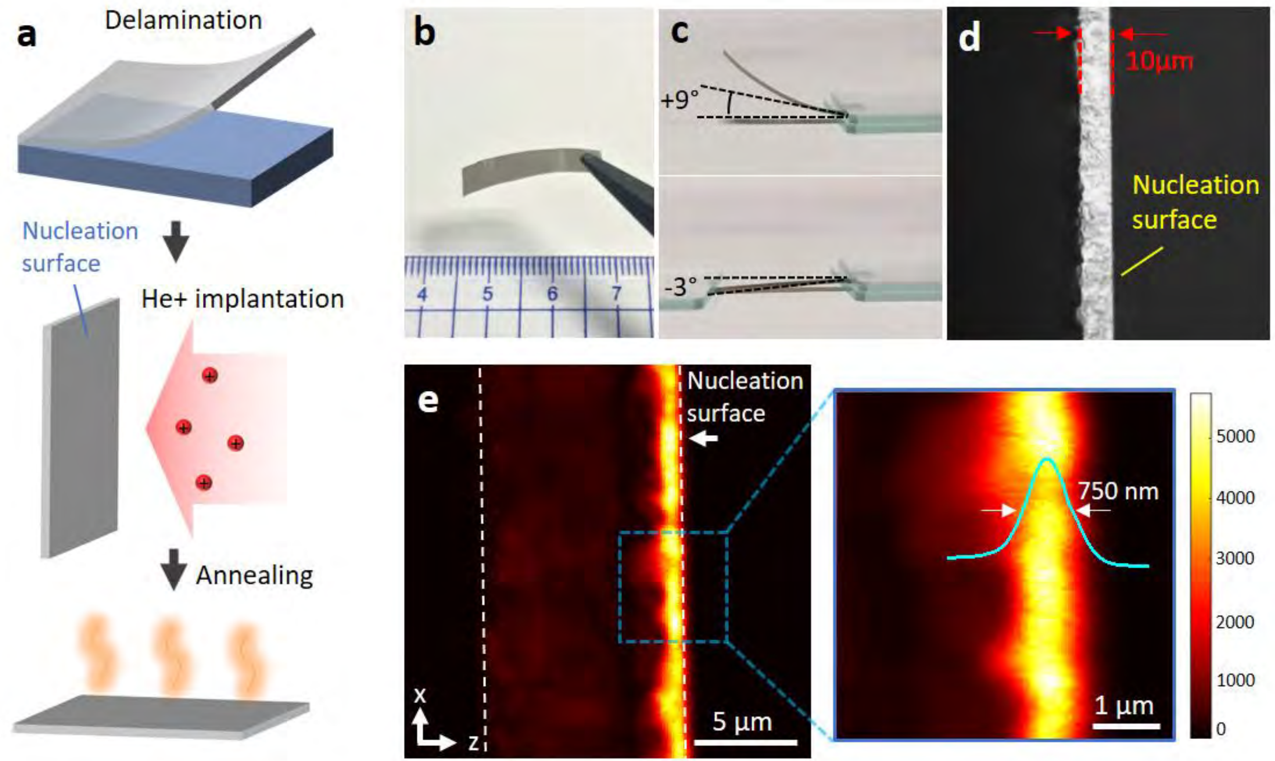
Comparison with SRIM simulation

As implanted
Fluence: 5×10^{15} protons/cm^2

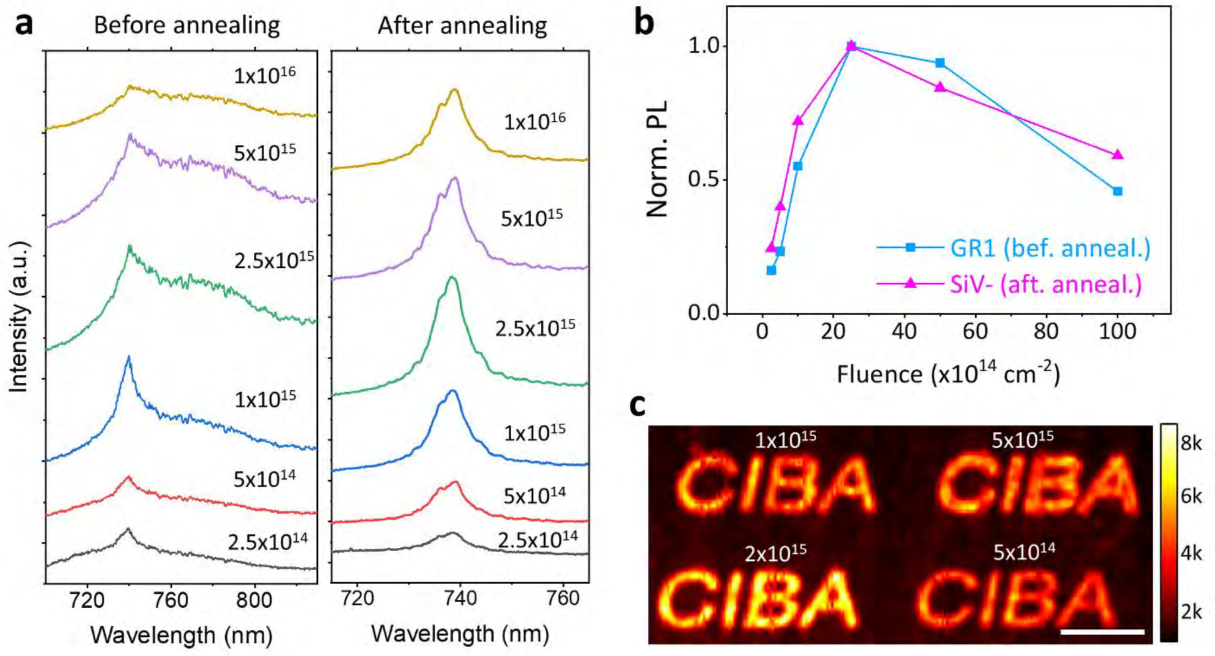


As-implanted Raman cluster map is overlaid on top of the vacancy and ionization densities from SRIM simulation.

Colour centres in diamond (SiV)



Colour centres in diamond (SiV)



Other colour centres in diamond

Table 1 Photophysical properties of the group IV defects.

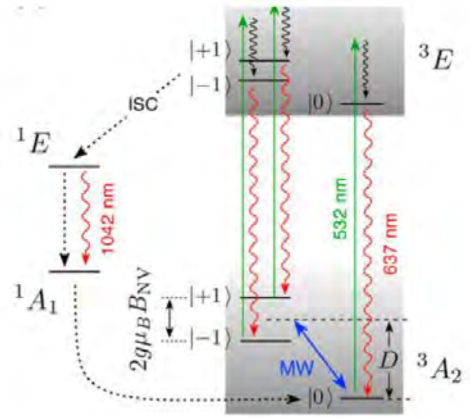
	ZPL	FHWM at RT	Excited state Lifetime	Ground-state splitting	Spin-lattice relaxation T_1	Transverse relaxation time T_2
SiV^-	738 nm	0.7–5 nm [ref. [16]]	1.0–2.4 ns [ref. [16]]	~50 GHz [ref. [36]]	>1 s, at 100 mK [ref. [36]]	T_2 ~13 ms, at 100 mK [ref. [36]]
GeV^-	602 nm	~5 nm [ref. [29]]	1.4–5.5 ns [ref. [29]]	~170 GHz [ref. [37]]	25 μs, at 2 K [ref. [37]]	T_2^* ~20 ns [ref. [37]]
SnV^-	620 nm	~6 nm [ref. [32]]	~6 ns [ref. [33]]	~850 GHz [ref. [32]]	~60 μs [ref. [38]]	Unknown
PbV^-	520 nm, 552 nm	~7 nm [ref. [34,35]]	>3 ns [ref. [34]]	5.7 THz, at 520 nm 4.2 THz, at 552 nm [ref. [34]]	Unknown	Unknown

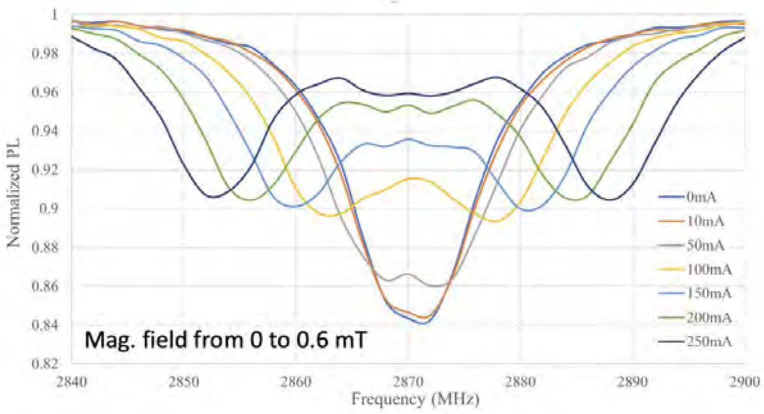
For detailed discussion and references, see main text

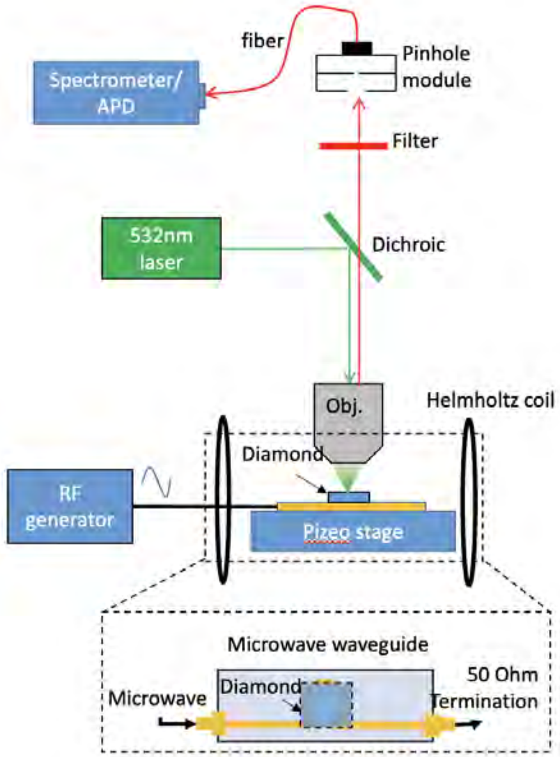
NATURE COMMUNICATIONS | https://doi.org/10.1038/s41467-019-13332-w

Optically detected magnetic resonance (ODMR)

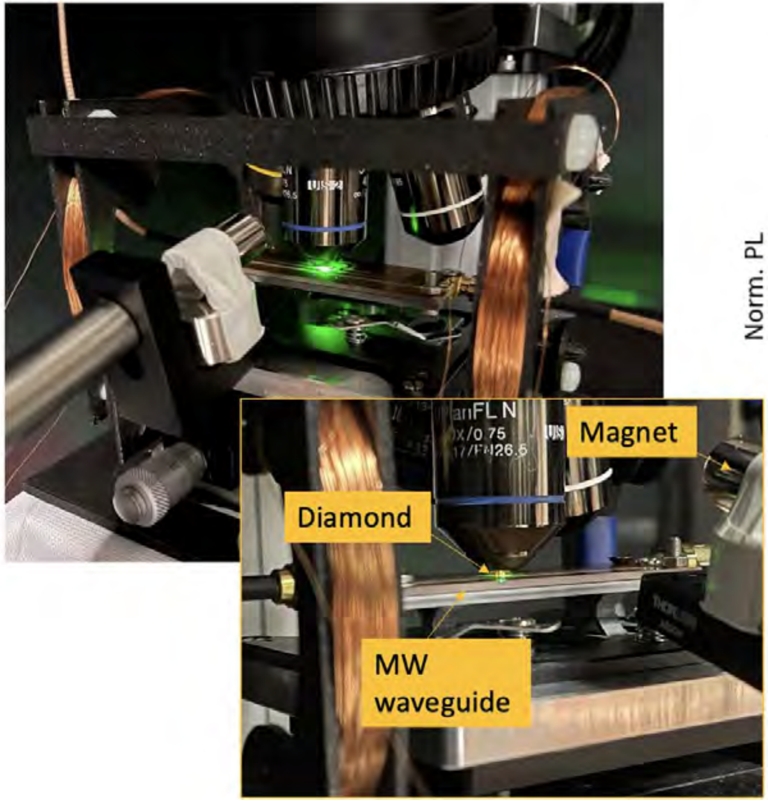
NV- centre

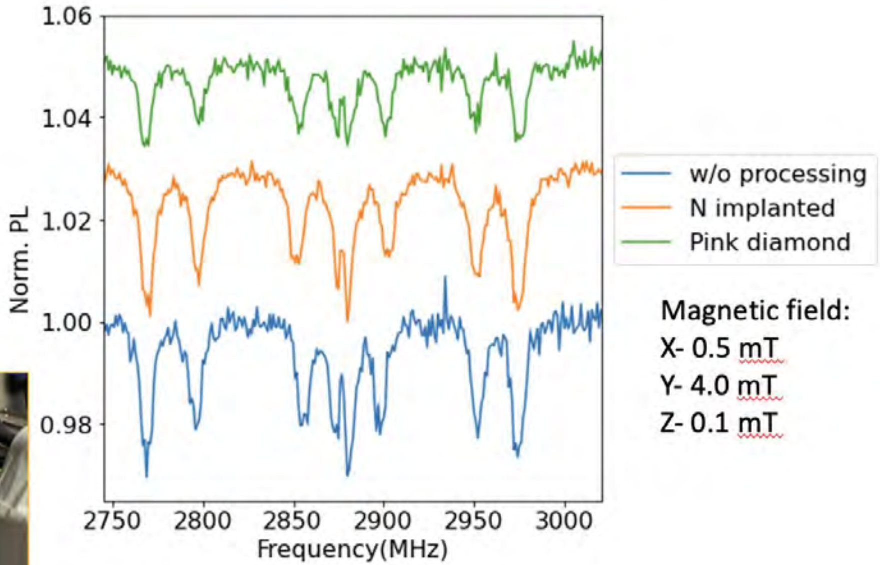






Optically detected magnetic resonance (ODMR)

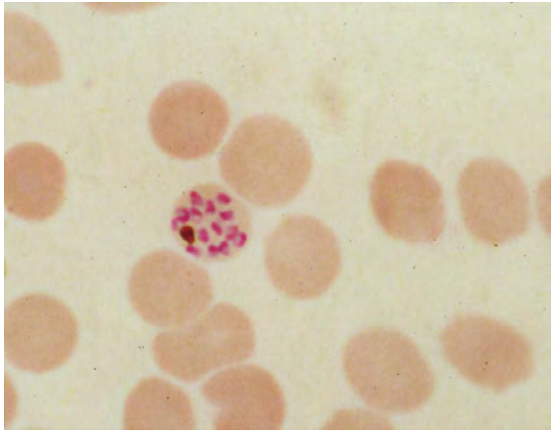




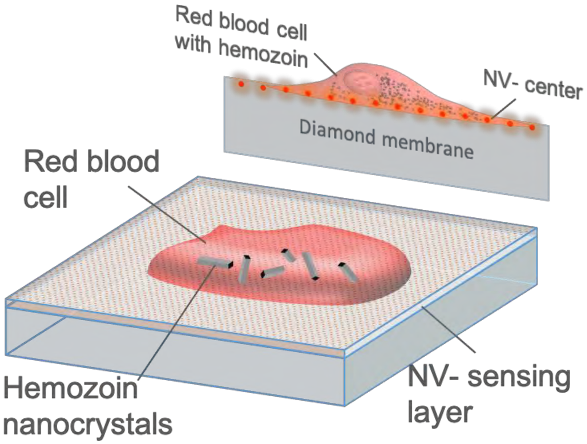
Magnetic field:
X- 0.5 mT
Y- 4.0 mT
Z- 0.1 mT

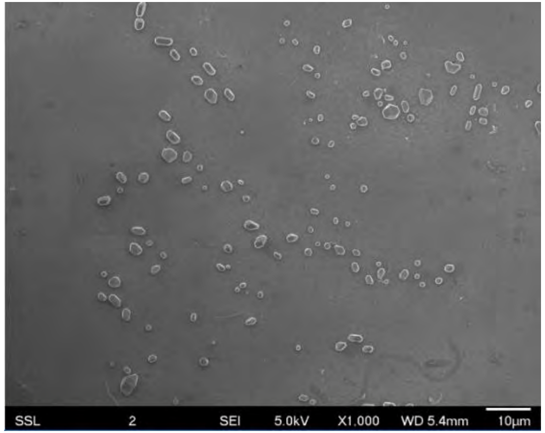
Quantum Sensing

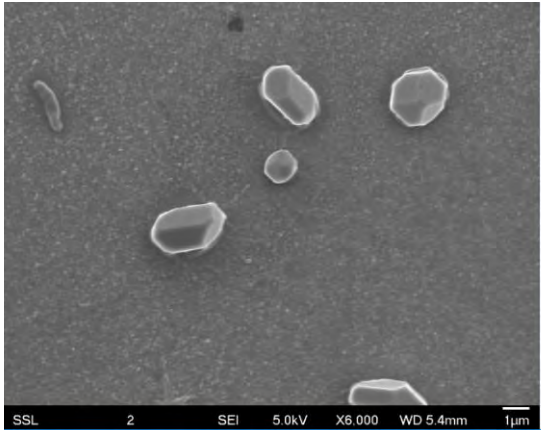
Detecting Hemozoin crystals in Malaria infected blood cells



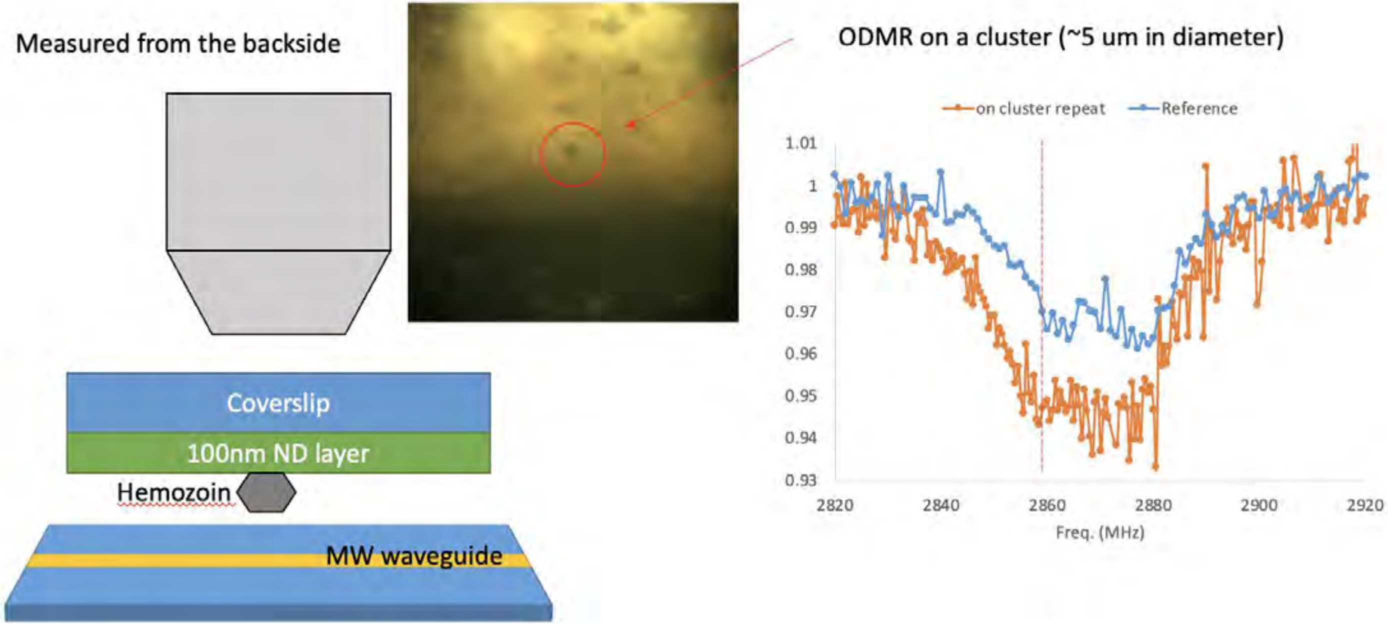
NV sensing for hemozoin







Quantum Sensing of hemozoin



Conclusion

- Ion beams and accelerators have an important role to play in future quantum technologies.
- The are still many challenges associated with achieving “true” deterministic doping.
- Applications include, but are not limited to, Qbits for solid state quantum computing, single photo sources for quantum communications and quantum sensing.

Thank-you