Yield Improvement of SiV⁻ Color Centers in Diamond *via* Silicon/Carbon Sequential Implantation

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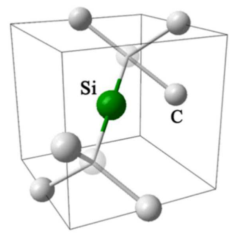
Motivation

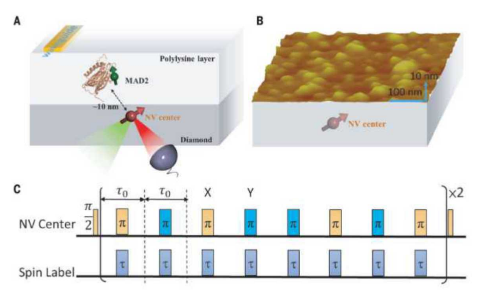
Why Color Centers in Diamond?

- Color centers (defects) in diamond include NV⁻, SiV plus many more…
- Wide range of application from metrology to quantum computation



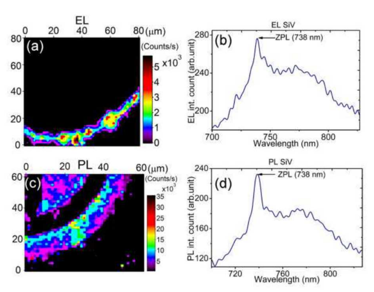
I. Aharonovich *et al.*, Rep. Prog. Phys. **74**,076501 (2011)

Single-protein spin resonance



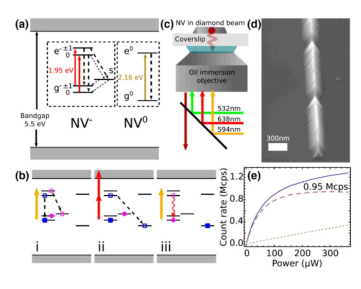
F. Shi *et al.*, Science **347**, 1135 (2015)

Electrically driven SiV



A. M. Berhane *et al.*, APL **106**, 171102 (2015)

Readout of single NV spin



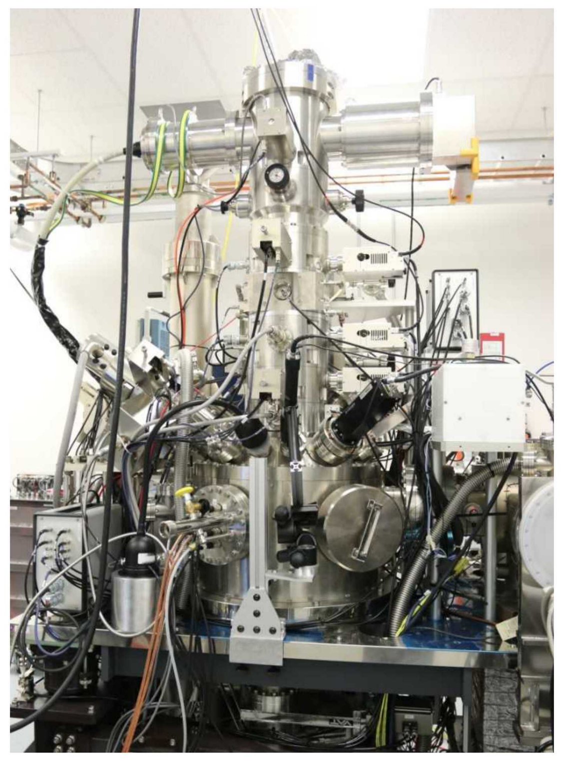
B. J. Shields *et al.*, PRL **114**,136402 (2015)

- Key question → How to produce a ***single*** color center ***where*** you want it?

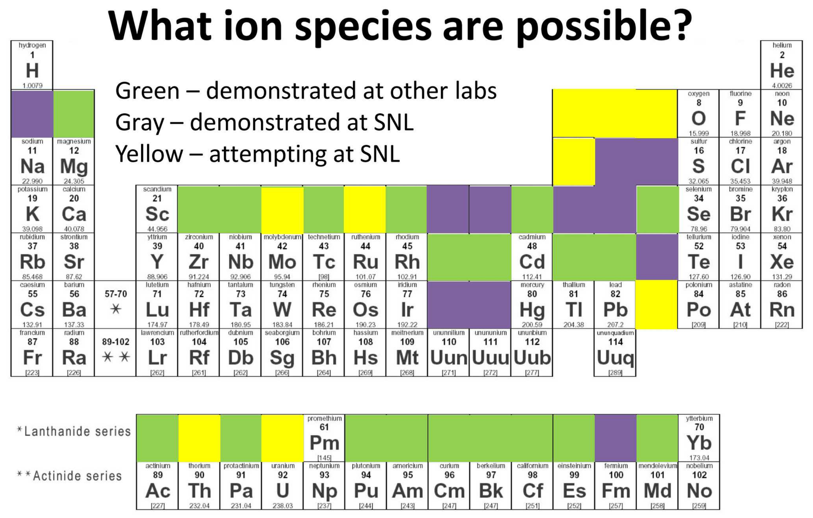
Nanoscale Top-Down Ion Implantation

nanoImplanter

- Focused ion beam system (FIB)
  →nm beam spot size on target
- ExB Filter (Wien Filter)
  →Multiple ion species
- Fast blanking and chopping
  →Single ion implantation
- Direct-write lithography
  →nm targeting accuracy

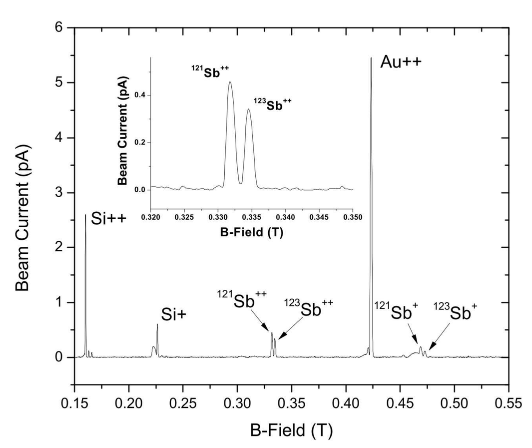


What ion species are possible?



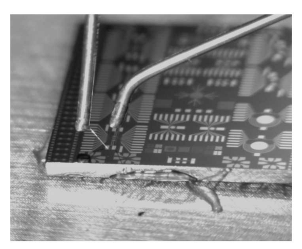
~1/3 the periodic table are available

What mass resolution is possible?

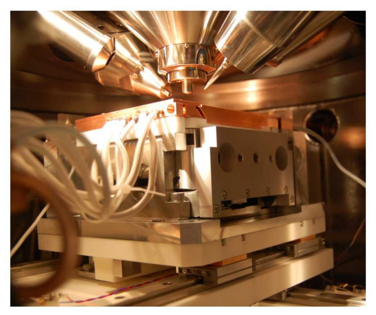


Δm/m ~ 0.016, separates out isotopes of Sb and Si in this AuSiSb source

Direct write platform and in-situ electrical probes



- In-situ electrical probes for measurement of ion strikes as they occur



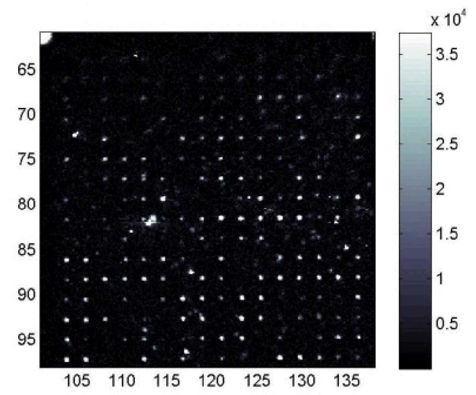
- Low temperature stage
- Built-in lithography software (Raith ELPHY Plus) with sub-nm resolution

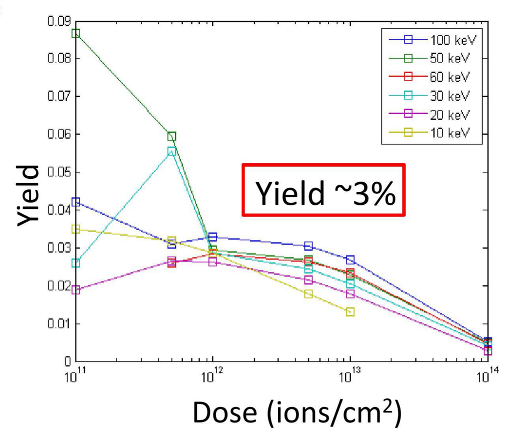
RAITH NANOFABRICATION

SiV Yield – How to improve?

Yield Testers

Yield = # measured SiV / # implanted Si





- 10-100keV Si implants for SiV creation
- Yield ~3% at 100 keV

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

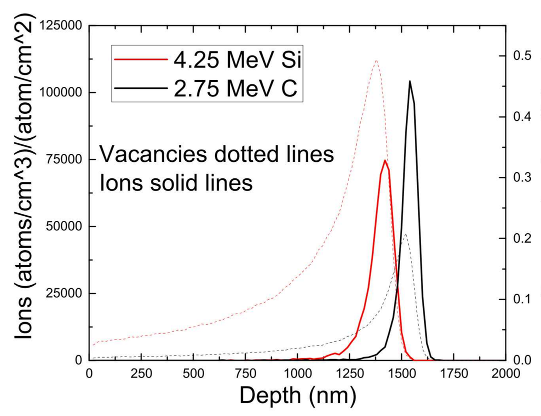
How to Improve the Yield of the SiV centers?

What is limiting the yield? Vacancies, charge state of the defect?

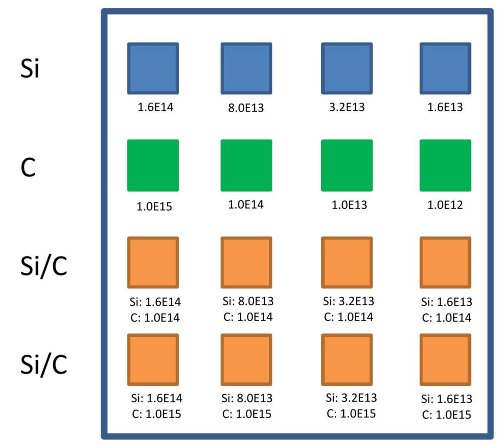
Yield →
- Electrical Charge State Control
- Localized Band Bending via Boron Doping
- Sequential Implantation to create excess vacancies

Sequential Si and C Implantation – mm sized areas

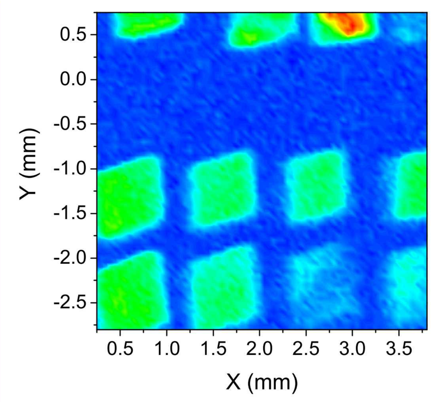
SRIM Simulations

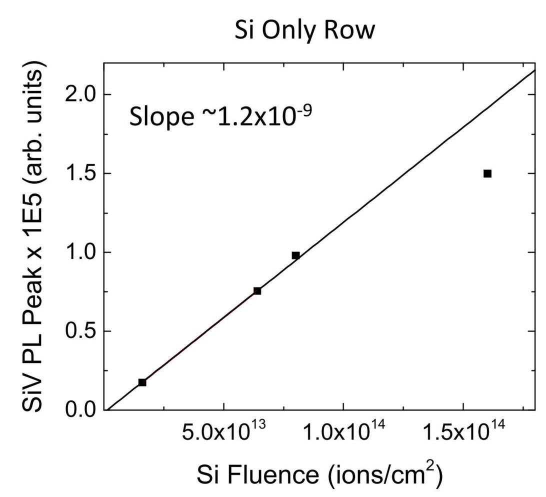


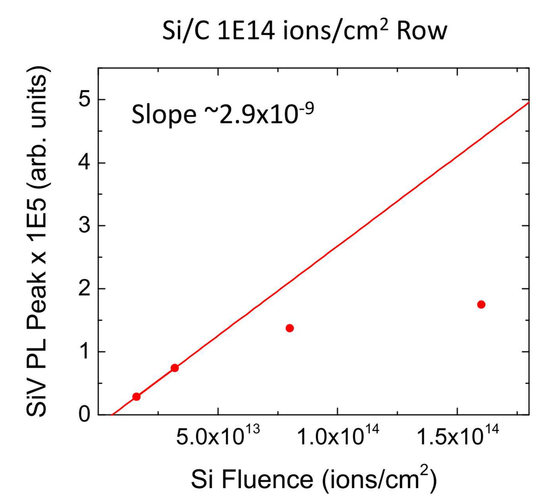
Experimental Layout



PL Signal

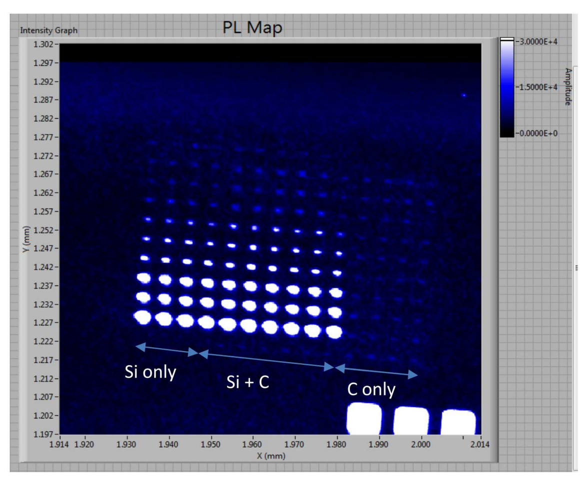


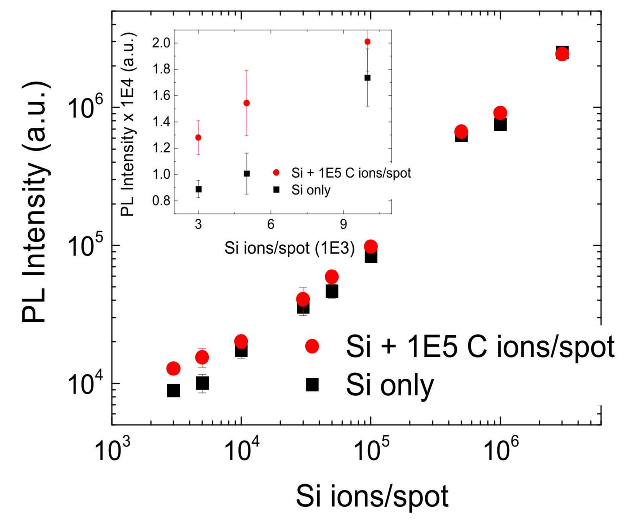




Results →First SNL demonstration of improved yield with 2.4x increase using sequential implantation of Si/C on Tandem

Sequential Si and C Implantation – μm sized areas



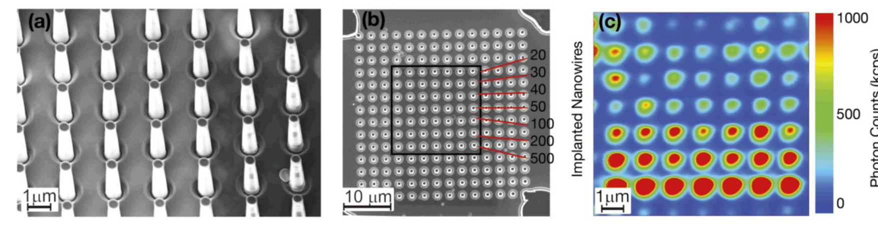


Results → 1.4x improvement in SiV yield with C implantation

Conclusions and Future Directions

Nanoscale Top-down Ion Implantation

- Demonstrated focused ion beam implantation for application in single atom devices.



L. Marseglia, *et al.*, *Optics Express* (2018)

SiV Formation Yield

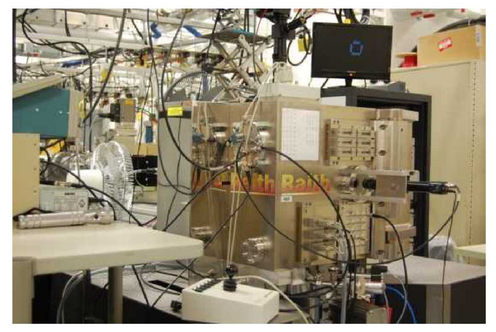
- Yield needs to be understood and/or improved as a function of color center type and implantation depth
  →Demonstrated a technique to extract yield numbers
- Yield can be improved for a given depth with pre-irradiation to damage the localized areas (excess vacancies)
  →Experiments demonstrate up to 2.4x improvement with sequential carbon implantation. C source development underway for the nanoImplanter.

Focused Ion Beam Capability at SNL

MicroOne (Tandem Accelerator)

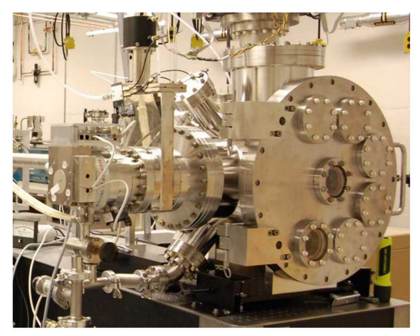
- Light to Heavy Ions – H to I
- Energy range from ~800 keV to >70 MeV
- Spot size as small as ~800 nm

Light Ion Microbeam (Pelletron)



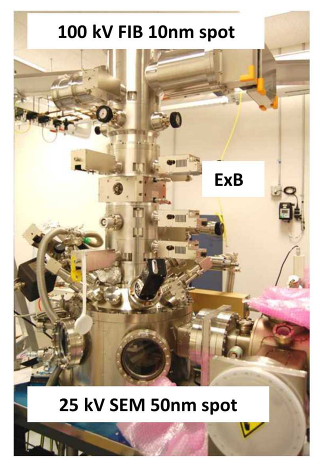
- Light Ions – H, He3, He4, N
- Energy range from ~300 keV to 3 MeV
- Spot size as small as ~150 nm

NanoBeamLine (HVEE Implanter)



- Light to Heavy Ions – H to Xe
- Energy range from ~10 keV to 350 keV
- Spot size as small as ~800 nm

nanoImplanter



- Liquid Metal Ion Sources – Au, Si, Sb, P, Li, etc…
- Energy range from 10 keV to 200 keV
- Spot size as small as ~10 nm

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