SAND2016-7531C

Top-Down Nanofabrication of Donors in Silicon and Defect Centers in Diamond

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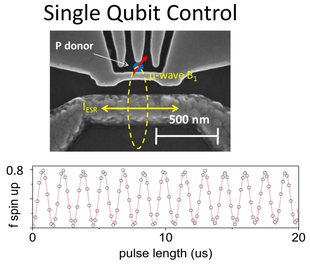
Motivation

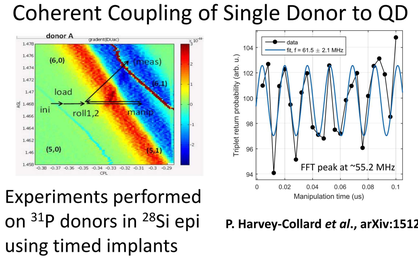
Why donors in Silicon?

- Donors in silicon have demonstrated long coherence times

Single Qubit Control



Coherent Coupling of Single Donor to QD



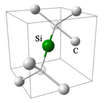
Experiments performed on ^{31}P donors in ^{28}Si epi using timed implants

P. Harvey-Collard *et al.*, arXiv:1512.01606

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

Why Color Centers in Diamond?

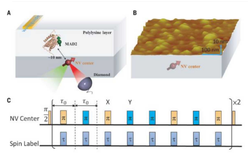
- Color centers (defects) in diamond include NV$^-$, SiV plus many more for a wide range of applications



SiV in diamond

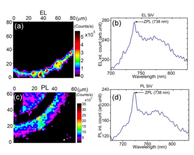
I. Aharonovich *et al.*, Rep. Prog. Phys. **74**,076501 (2011)

Single-protein spin resonance



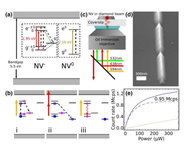
F. Shi *et al.*, Science **347**, 1135 (2015)

Electrically driven SiV



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

Readout of single NV spin



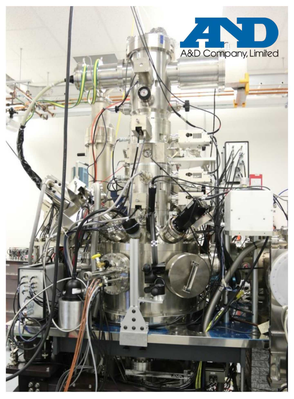
B. J. Shields *et al.*, PRL **114**,136402 (2015)

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

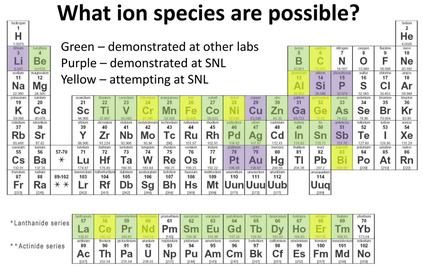
Nanoscale Top-Down Ion Implantation

nanoImplanter

- Focused ion beam system (FIB)
  - →nm beam spot size on target
- ExB Filter (Wein Filter)
  - →Multiple ion species
- Fast blanking and chopping
  - →Single ion implantation
- Direct-write lithography
  - →<35 nm targeting accuracy

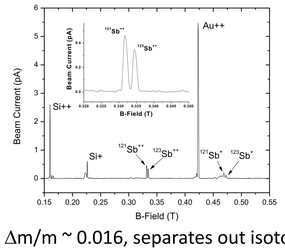


What ion species are possible?



~1/3 the periodic table are available

What mass resolution is possible?



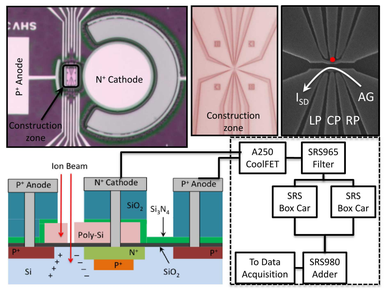
Δm/m ~ 0.016, separates out isotopes of Sb and Si in this AuSiSb source

Single Ion Implantation for Donors in Si

Single Ion Detection

We developed an integrated single ion detector in conjunction with low temperature transport devices

Integrated single ion detector with Si MOS nanostructure

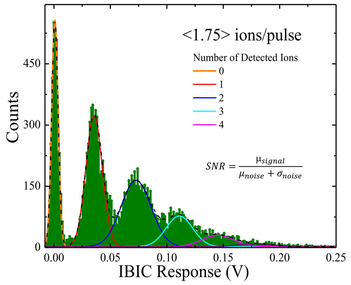


Ion Species	Energy (keV)	SiO2 Thickness	Range*(± Straggle)	SNR	Error Rate
Si	200	7 nm	273 (± 76) nm	21.2	<<1%
Sb	120	35 nm	25 (± 17.5) nm	5.2	8%
Sb	50	7 nm	25 (± 9) nm	4.4	9%
Sb	20	7 nm	11 (± 5) nm	2.5	15%

* Range measured from the SiO2/Si interface into the Si substrate

J. L. Pacheco et al., submitted to Nanotechnology

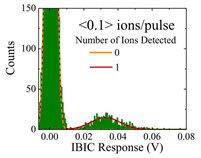
200 keV Si – Quantized Ion Detection



We find excellent agreement between the ratio of number of detected ions to Poisson probability distribution.

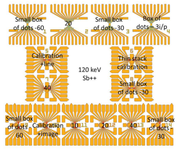
Detection down to 20 keV Sb with SNR of 2.5

Single Ion Implantation

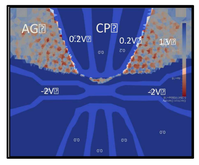


Counted Donor-SET Devices

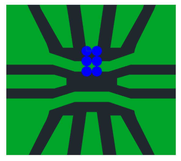
How to make counted donor devices? 120 keV Sb into a 35 nm oxide layer



Implantation plan

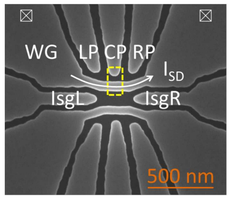


SET location (QCAD)

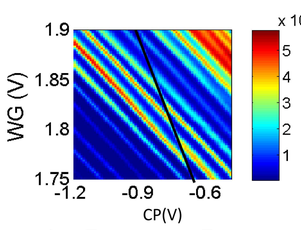


Detail of implant locations

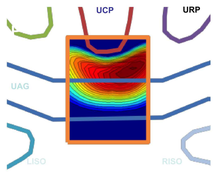
M. Singh et al., APL 108 062101 (2016)



Operation



Low Temperature Transport

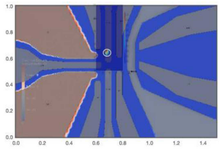


Triangulation

Counted Ion Detection and Transport in the same device

Outlook for Two Donor: D-QD-QD-D

New designs relax donor placement requirements



Use of the donor-QD coupling to reduce donor placement requirements

Work to extend this design to donor-QD-QD-donor

QCAD simulations show simultaneous electron occupation and donor ionization are possible

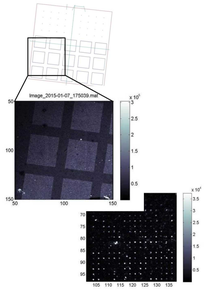
What is needed to make this?

Donor-QD (few electron) requires:
- Target depth of <10 nm
- D-QD lateral spacing of <20 nm

Difficult, but NOT impossible!

Implantation into Diamond photonics

Yield Testers

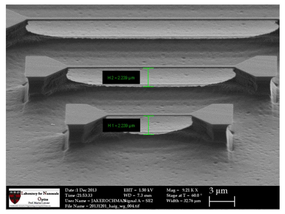


We implanted Si at a series of dose and energies into diamond substrates to form SiV color centers, yield measurement performed by the Englund group

- 10-100keV Si implants for SiV creation
- Yield ~3% at 100 keV
- Recipe for localized single color centers

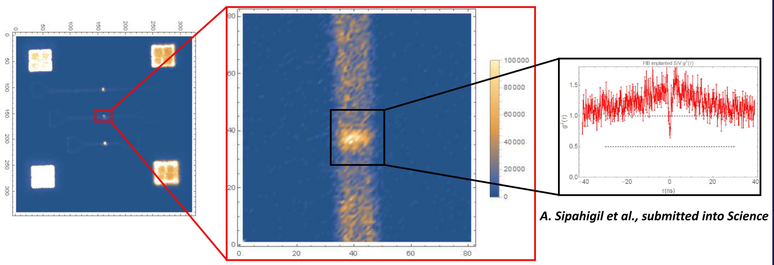
Comparison of yields under different implants
→ Towards ***deterministic*** and ***localized*** color centers

Localized Color Center Formations - Nanobeams



We locally formed SiV color centers in a series of diamond nanobeams using the SNL nanoImplanter, measurements performed by the Lukin/Loncar groups

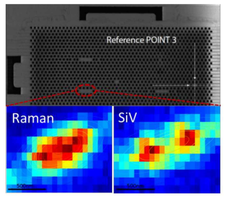
- Implanted 100 keV Si into the nanobeams forming localized SiV color centers



A. Sipahigil et al., submitted into Science

Preliminary $g^{(2)}(t)$ measurements indicate we have fabricated single SiV color centers and our collaborators have used these as a single photon switch

Test of diamond coupling - 2D Photonic Cavities

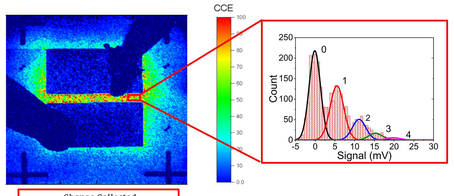


We implanted Si into a series of photonic crystals to test SiV-cavity coupling, PL and Raman measurements performed by the Englund group

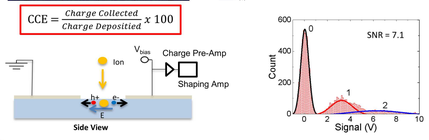
- Raman-SiV emission:
  - → ~45nm positioning accuracy

T. Schroder et al., presented at CLEO2016

Single Ion Detection in Diamond Detector



$$CCE = \frac{Charge\ Collected}{Charge\ Deposited} x\ 100$$



Demonstrated ion detection in diamond to improve yield studies:

Yield = # measured SiV / # implanted Si

Poisson Statistics

(Uncertainty in number of centers is $\sqrt{N}$)

Single Ion Detection in Diamond with SNR ~10

J. B. S. Abraham et al., submitted to Appl. Phys. Lett.

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