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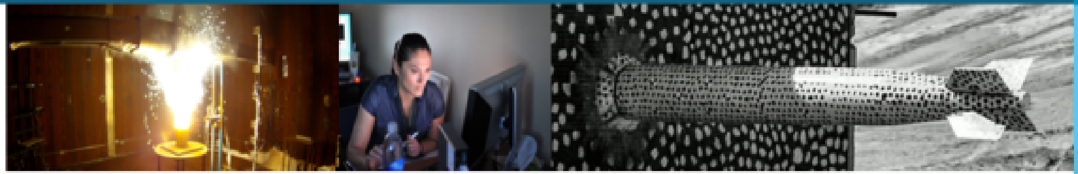
Sandia National Laboratories

THE UNIVERSITY OF NEW MEXICO

Optimization of shallow surface NV yield with Hot Implant of N-Implanted Diamond



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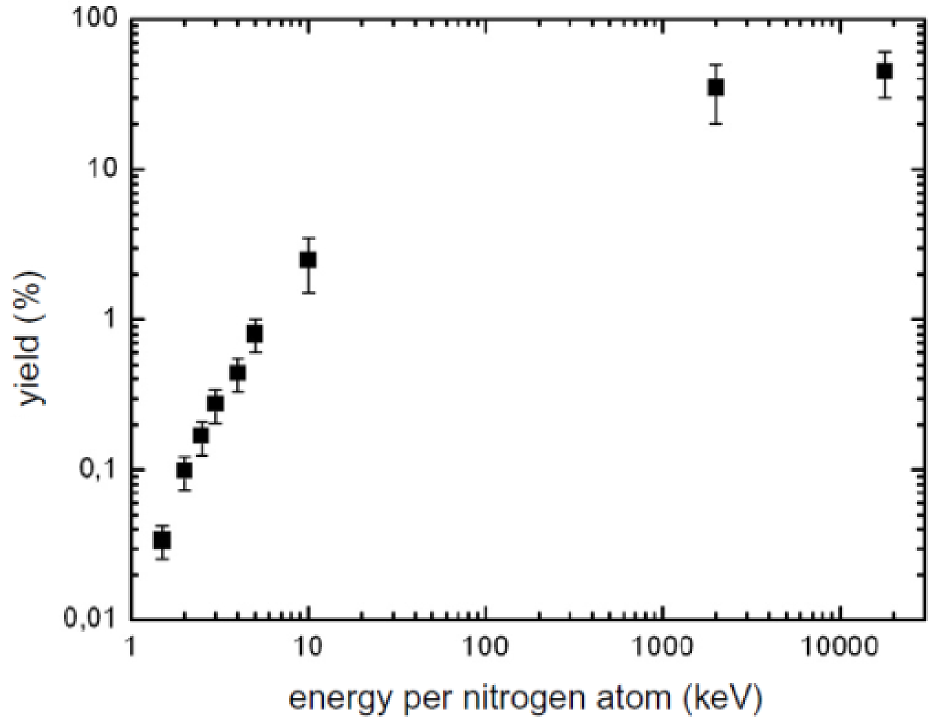
Motivation

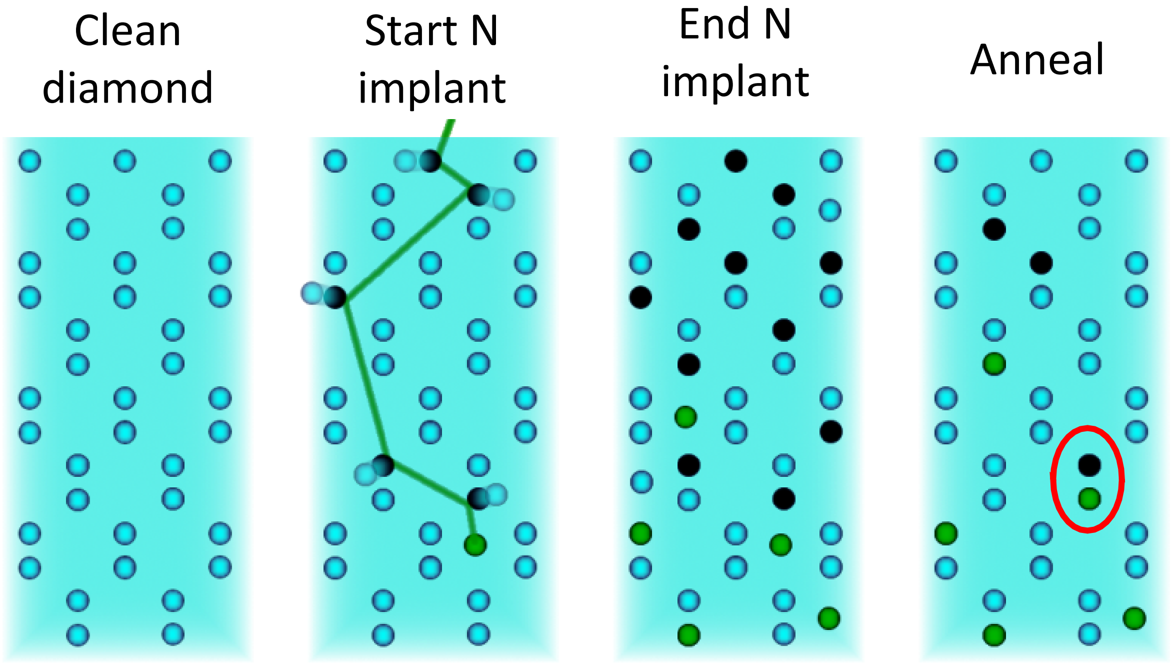
- For NV sensing, want NV layer that is **dense** and **shallow**.
- Simplest method of N-implant has diminishing NV yield for shallower implants (~1% N to NV conversion).
- Aim: Optimize and characterize NV sensitivity with dense shallow implant through hot carbon implantation.

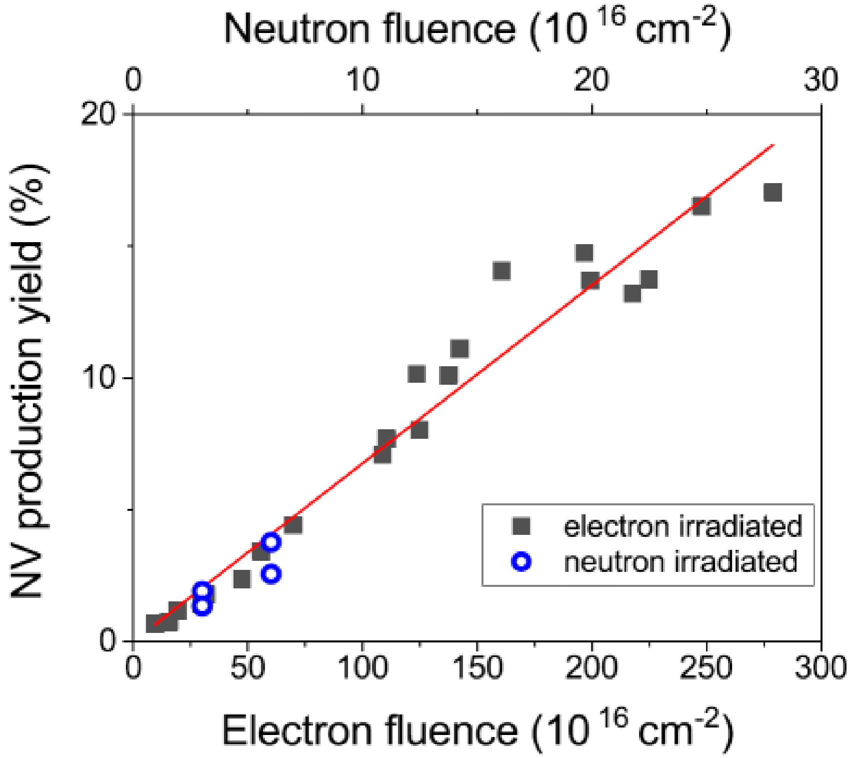


Pezzagna, S., et al. *New J. Phys.* 12.6 (2010): 065017

Adding more vacancies

- N-implantation creates N and vacancy (V) defects which form NVs in anneal.
- After NV preparation, further neutron/electron implant and anneal cycles shown to improve NV yield.



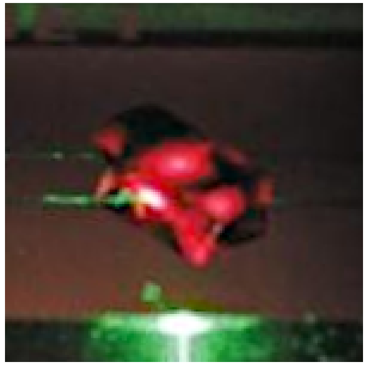


Kollarics, S., et al *Carbon* 188 (2022): 393-400.

Hot implants

- Can also implant while heating diamond (~800 C)
  - Lattice heals throughout implant – prevent graphitization
  - Vacancies mobile throughout implant – prevent divacancies
- Up to 25% photoluminescence (PL) increase with shallow hot carbon co-implantation[2]
- 45% bulk hot implant achieved with 285 h electron hot implant[1]

Lukin, Misha, KITP 2016.



Lukin, Misha, KITP 2016.

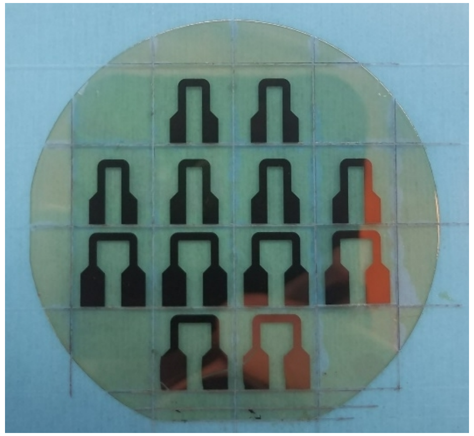
- Experimentally demonstrate:
  - Can hot carbon implants improve NV sensing properties in shallow diamonds?
  - Optimization of hot implant parameters.

[1] Kucsko, Georg, et al. *Phys. Rev. let.* 121.2 (2018): 023601.
[2] Schwartz, Julian. (2012).

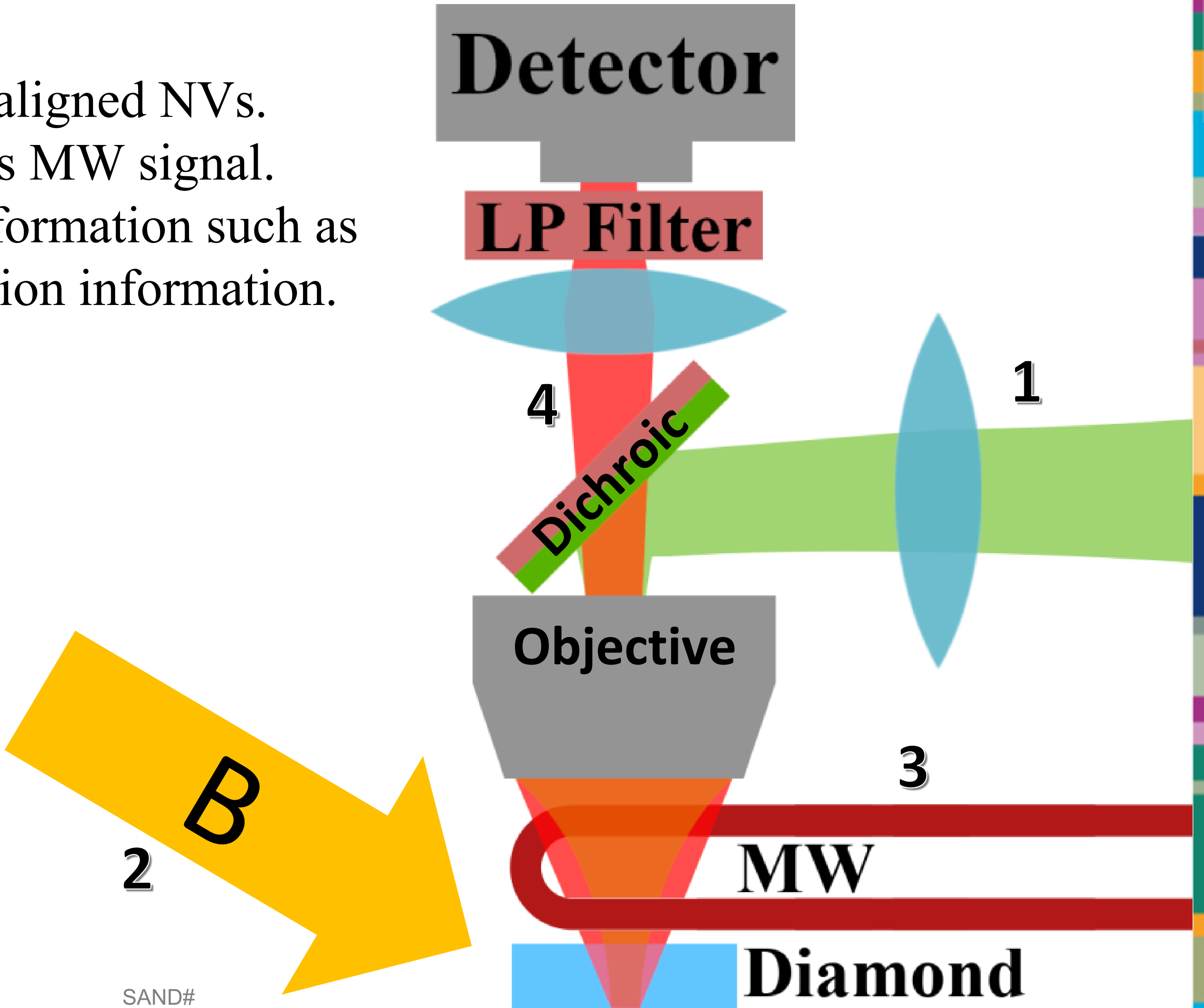
Experimental Setup

1. Green light shines on diamond.
2. External magnetic field isolates aligned NVs.
3. Copper resonator on SiC delivers MW signal.
4. Red fluorescence carries spin information such as relaxation rates and spin population information.

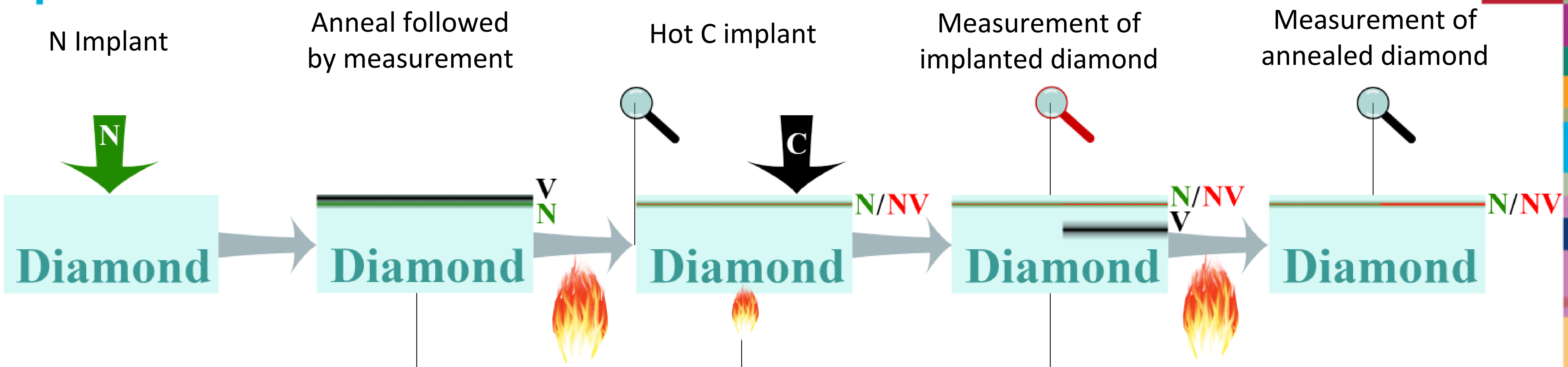
3

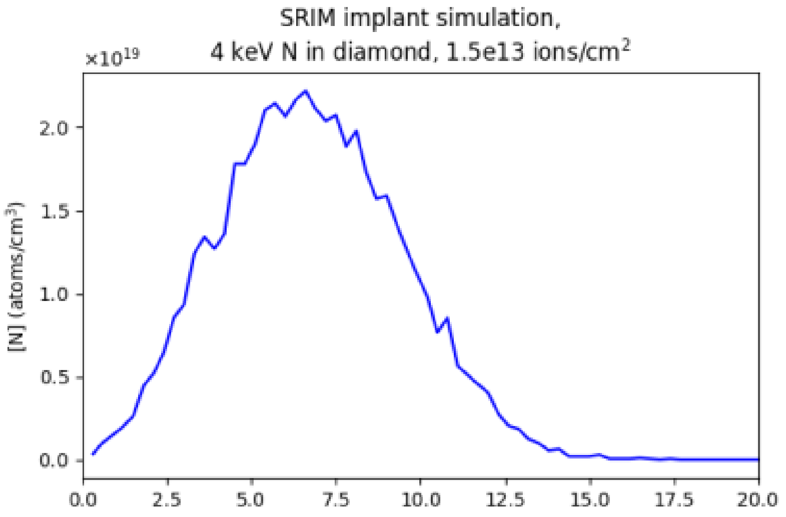


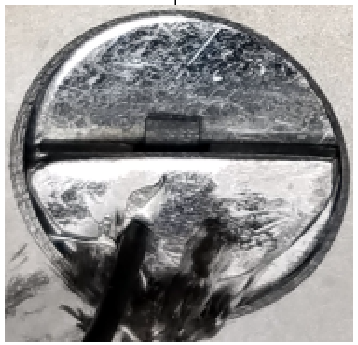
Resonator printed on SiC

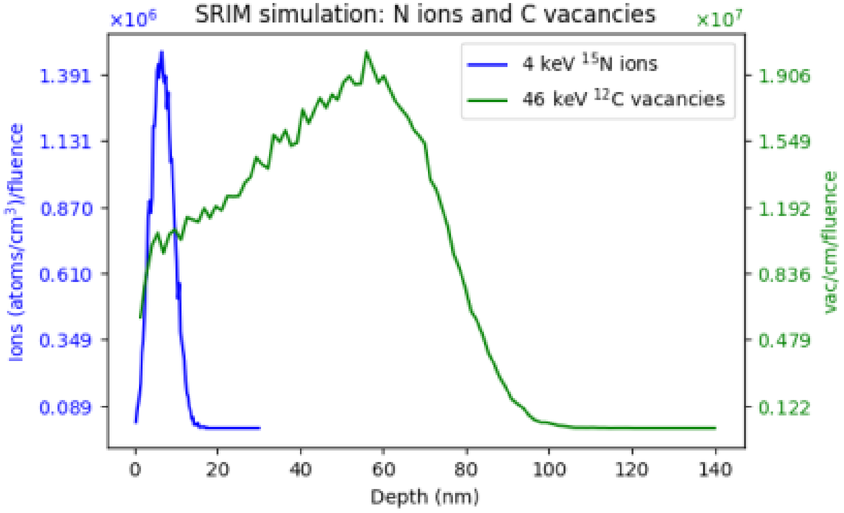


Sample preparation

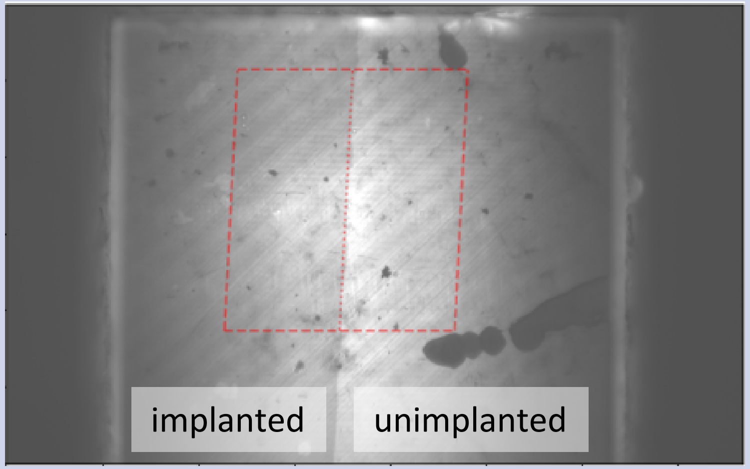
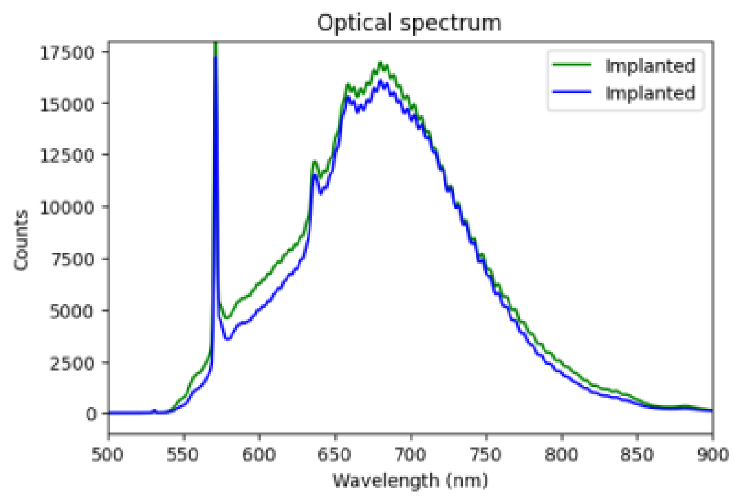
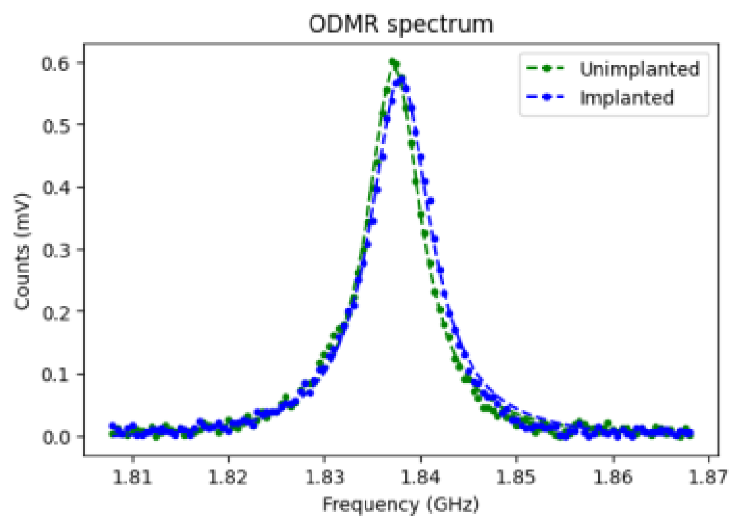




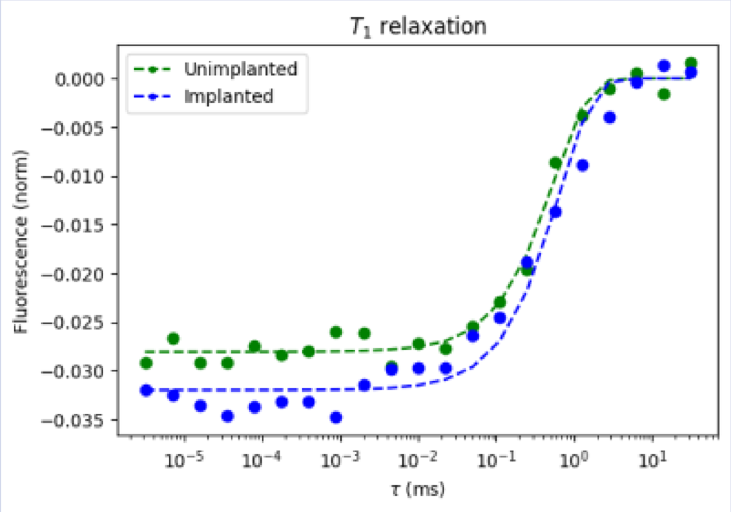
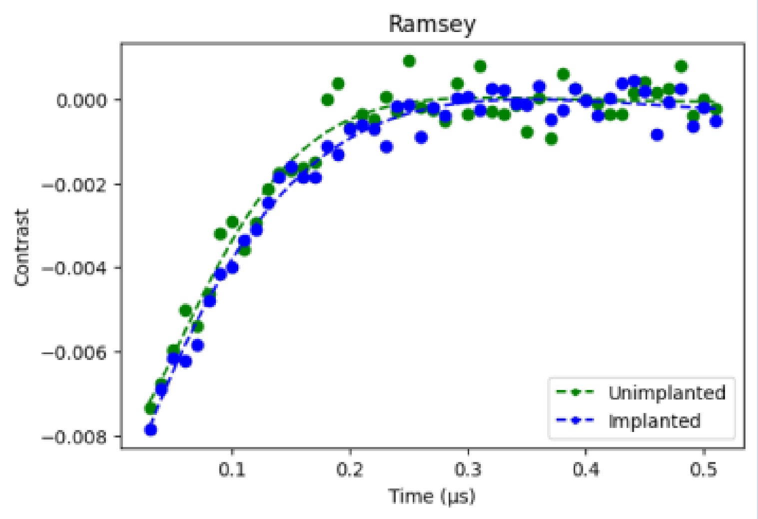
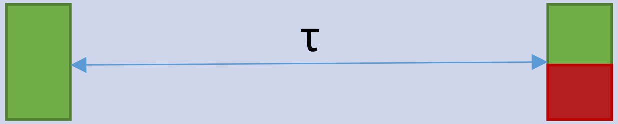
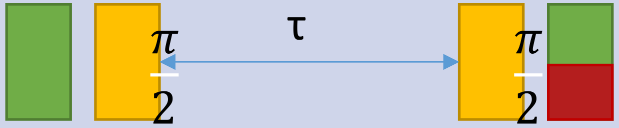




Characterization experiments

Photoluminescence map	Optical spectrum	Simultaneous PL, ODMR
		
$PL^{(I)}/PL^{(U)}$ = .86	Spectra similar	Implanted side has ~8x less contrast
Camera measurement	Spectrometer measurement	Lock-in amplifier with pulsed laser
- Comparison of (Un)Implanted PL - PL comparison across fluences - Qualitative information on $[NV^{-,0}]$	- $[NV^-]/[NV^0]$	- Measure fraction of PL due to NV^-

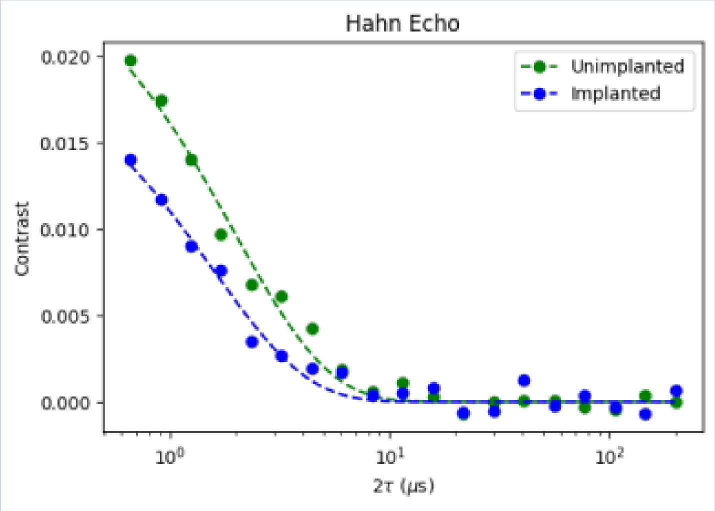
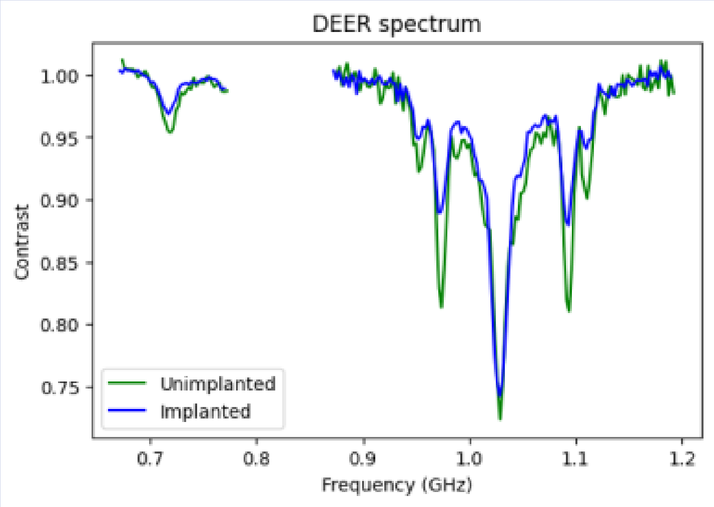
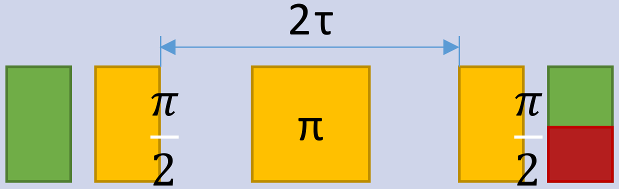
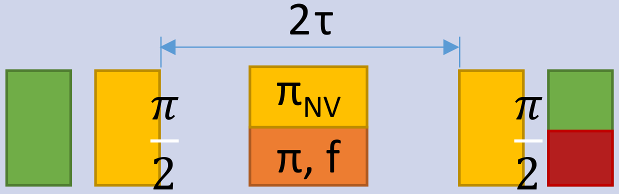
Characterization experiments (cont.)

Longitudinal relaxation T_1	Free precession time T_2^*
	
$T_1^{(U)}$ = 570 μs, $T_1^{(I)}$ = 650 μs	$T_2^{*(U)}$ = 72 ns, $T_2^{*(I)}$ = 133 ns
	
	- May yield bounds on [N][1] - Used in sensitivity calculation

Laser readout Microwave

[1]Bauch, Erik, et al. *Phys. Rev. B* 102.13 (2020): 134210.

Characterization experiments (cont.)

Spin evolution time T_2	Double electron electron resonance
	
$T_2^{(U)} = 2.86\ \mu s$, $T_2^{(I)} = 1.93\ \mu s$	*analysis in progress*
	
- May yield bounds on [N][1] - Used in sensitivity calculation	Measure of $[NV^-]$ and [N][2]

Laser | readout | Microwave 1 | Microwave 2

[1]Bauch, Erik, et al. *Phys. Rev. B* 102.13 (2020): 134210. SAND# [2]Li, Shang, et al. *Physical Review B* 104.9 (2021) : 094307.

Experimental results

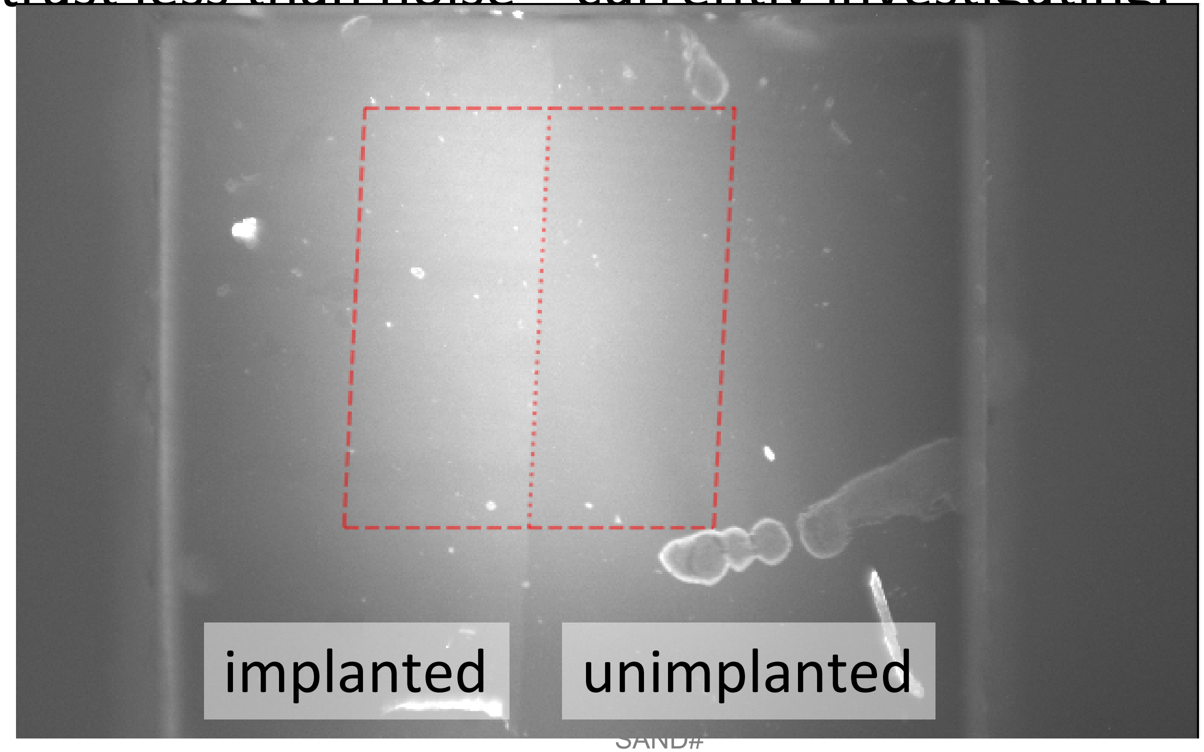
- Expect/seek better implanted PL *after anneal*
- Pre-anneal results may yield interesting results when combined with post-anneal results
  - Parasitic defects which anneal out at high temperature, or their effect on charge states[1], may be supported by a low PL ratio which increases after anneal.

Post-hot implant, pre-anneal	**Unimplanted**	**Implanted**
PL ratio, Imp./Unimp.	.86	
Optical spectra	Qualitatively similar	
ODMR FWHM (MHz)	6.9	7.7
T1 (ms)	.57	.65
T2 (μs)	2.86	1.93
T2* (ns)	72	133

[1] Deák, Peter, et al. *Physical review B* 89.7 (2014): 075203.

Experimental results (cont.)

- Measured Implanted:Unimplanted PL ratio of 1.08 after anneal
  - Even with deeper C implant, vacancy mobility may result in improved NV yield
  - Features due to thermometer melting during N-implant anneal; etching suspected in subsequent hot implant anneal.
  - Suspected etching in tube furnace anneal; annealed batch demonstrates ODMR contrast less than noise—currently investigating.



Future Directions

- Improvement in PL is promising.
- Verify PL improvement, further characterize spin properties, population densities, sensitivity.
- Optimize shallow hot implant conditions by tuning parameters – fluence, temperature, length, etc.