NV Formation through Repeated Annealing

Emma Hunt

INT REU, University of Washington
Kai-Mei Fu, Optics and Spintronics Group

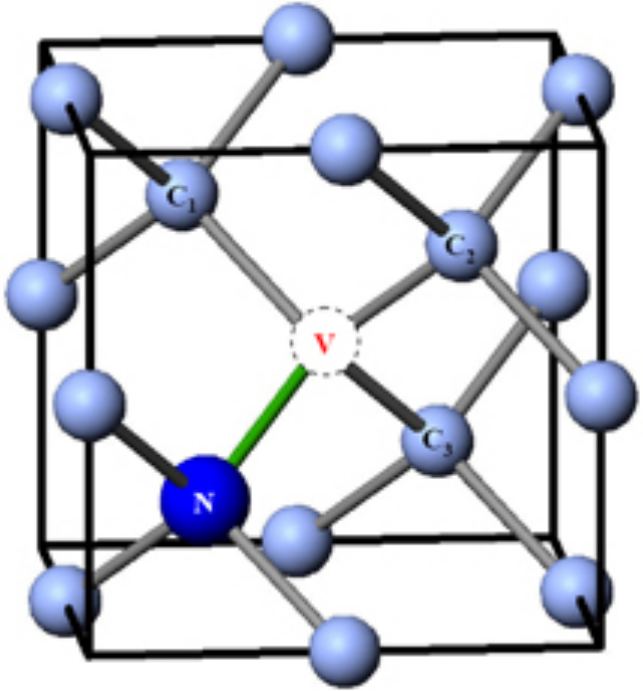
August 15, 2018

Nitrogen-Vacancy Center

- Point defect in diamond
- Substitutional nitrogen with adjacent vacancy
- Optically accessible spin states

Applications

- Quantum sensing
- Quantum information



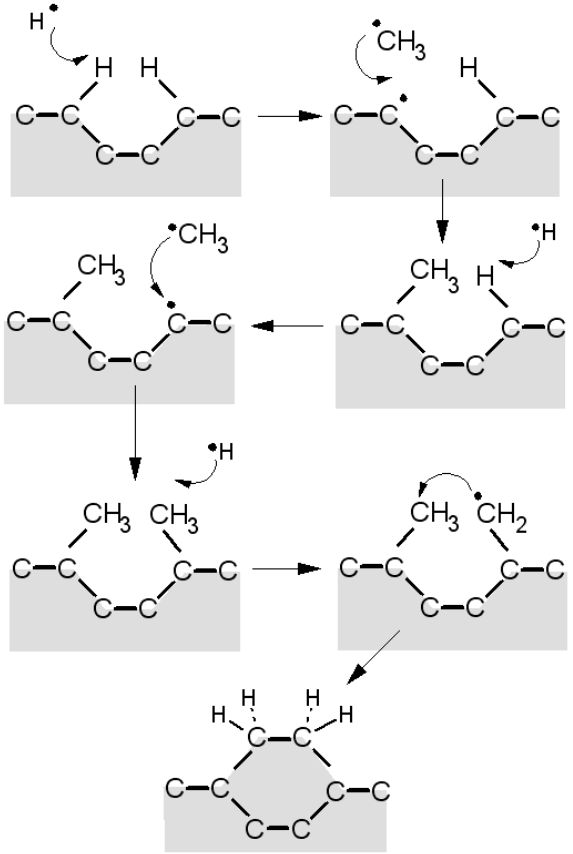
Awschalom Group: Quantum Computing with Defects, University of Chicago

Incorporating nitrogen into diamond

- Grown-in
- Irradiation

Our sample:

- Single crystal diamond
- Grown in substitutional nitrogen
- Chemical vapor deposition (CVD)
- High purity (nitrogen is <0.5 ppb)
- Low vacancy concentration

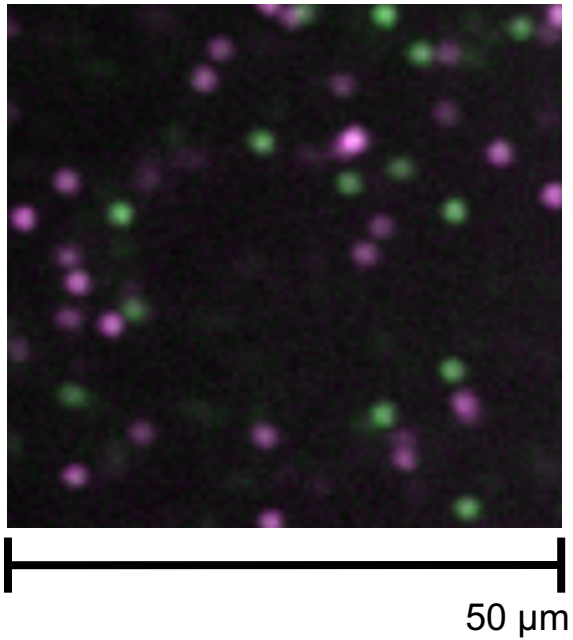


CVD Diamond Group, University of Bristol

Imaging

- Confocal scanning
- Excite NV- with 532 nm green laser
- Collect 637 nm light with SPCM

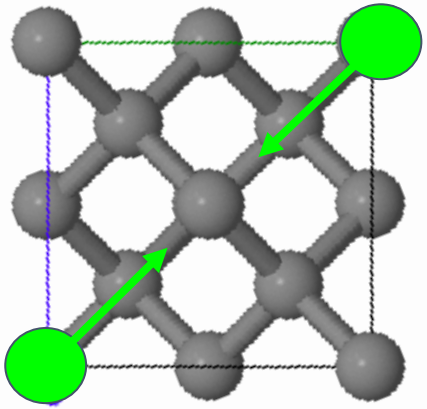
2000x2000x500 μm^3
diamond sample

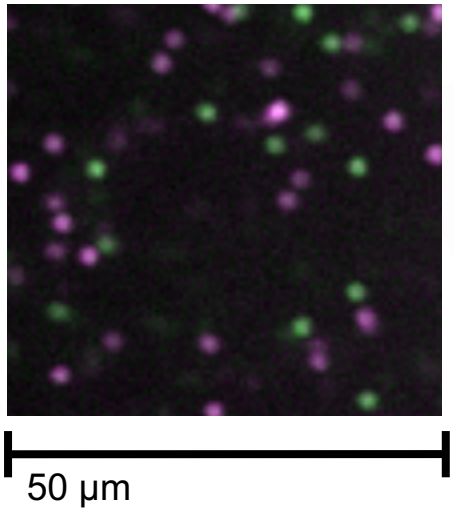


NV Orientations

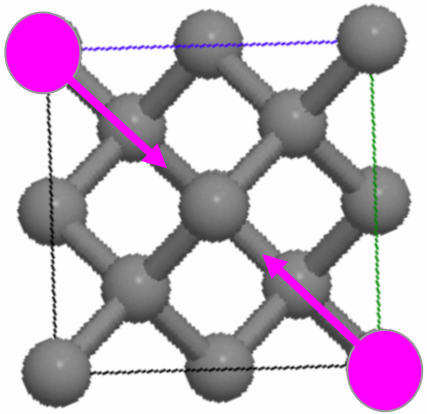
- 8 possible orientations, 2 distinguishable in our setup
- Intensity = dot product of laser polarization axis with NV orientation axis
- 90º between the two orientations

O1 orientation:





O2 orientation:

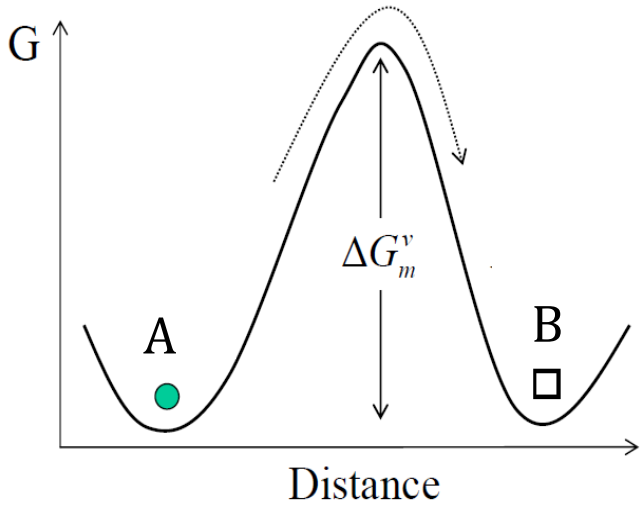


http://lampx.tugraz.at/~hadley/ss1/crystalstructure/structures/diamond/diamond.php

Annealing

Anneal = heat slowly, hold temp, cool slowly

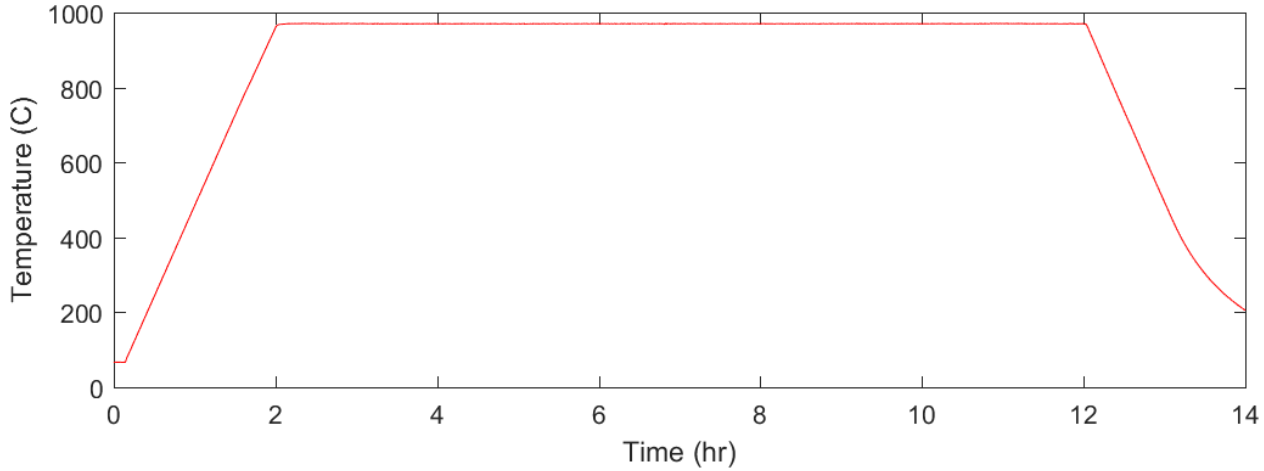
- Adds energy to the lattice
  - Creates new species
  - Mobilizes species



University of Virginia: Defects and Microstructure in Materials, Leonid Zhigilei

Possible Benefits of Annealing

- Control orientation of NVs (with strain?)
- Control density of NVs without damaging the lattice
- Increase NV density?



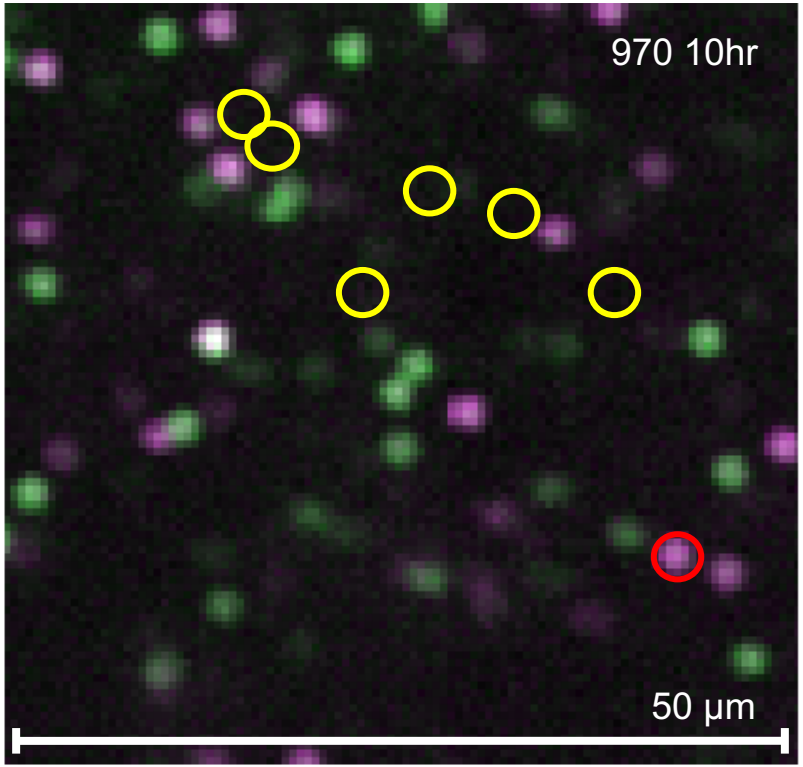
Anneals

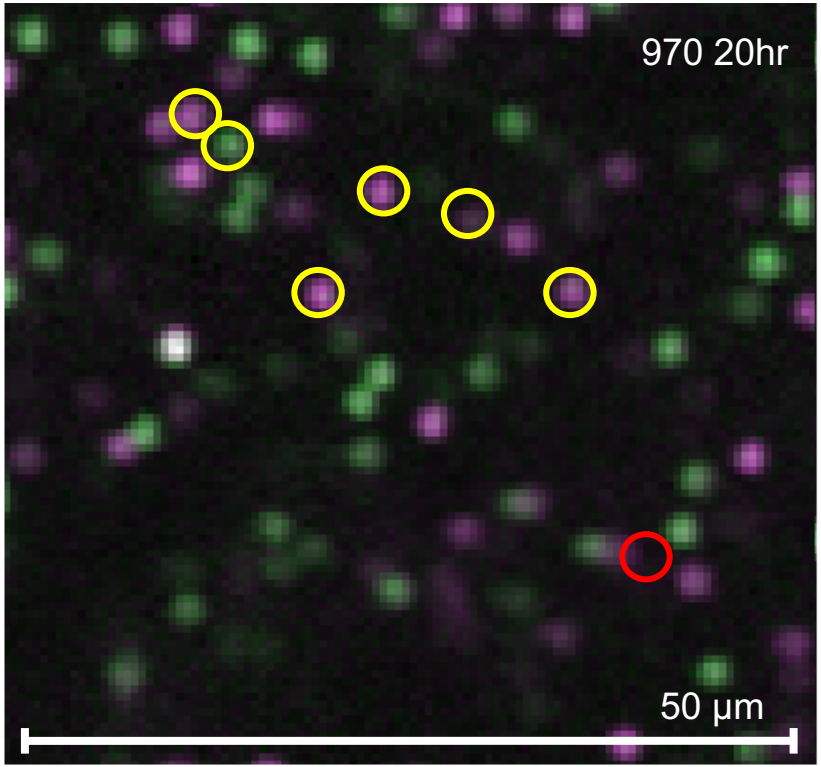
Temperature (ºC)	Time (hrs)
800	2
800	10
950	10
960	10
960	10
970	2
970	10
970	20
980	2

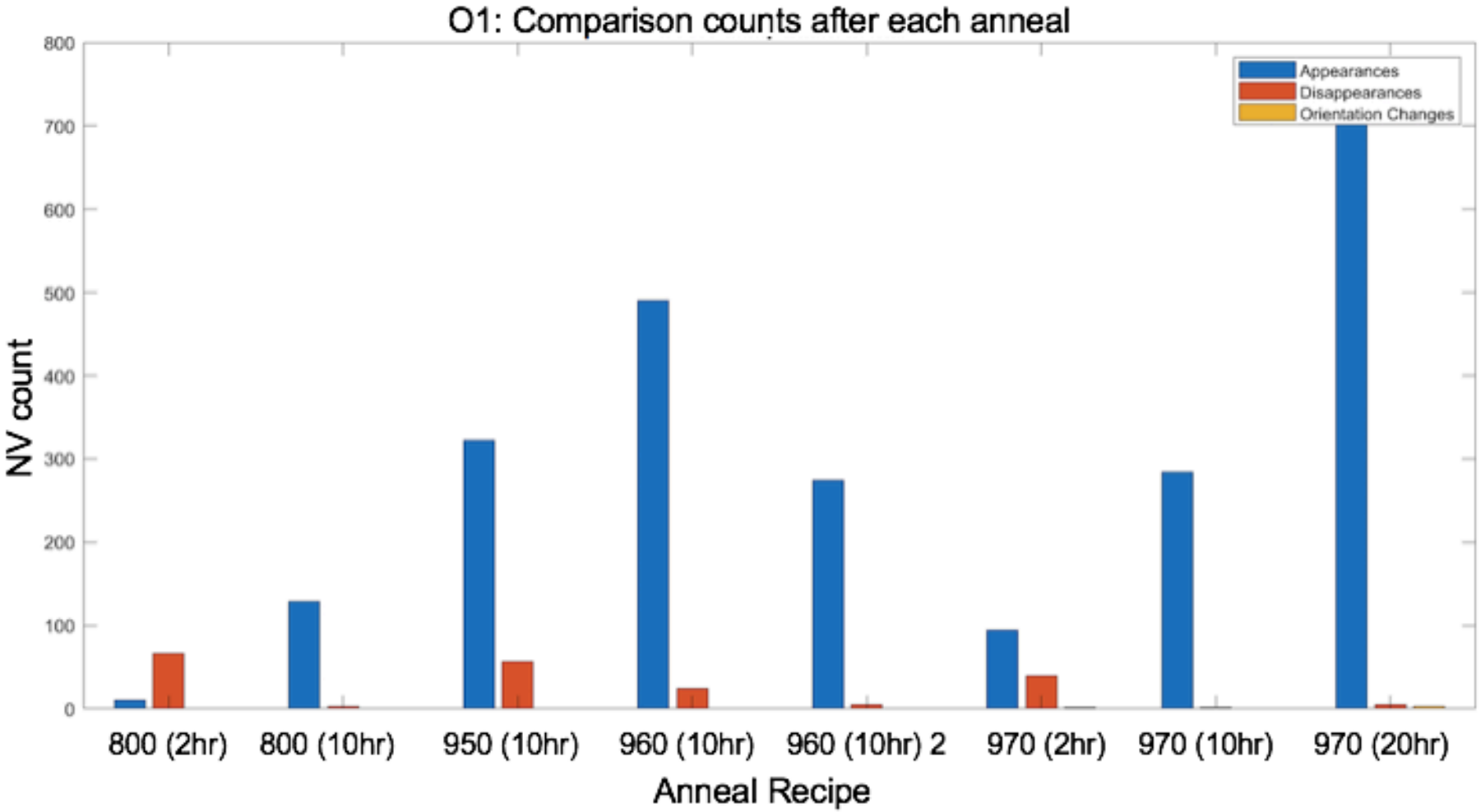
Large Scan Methods

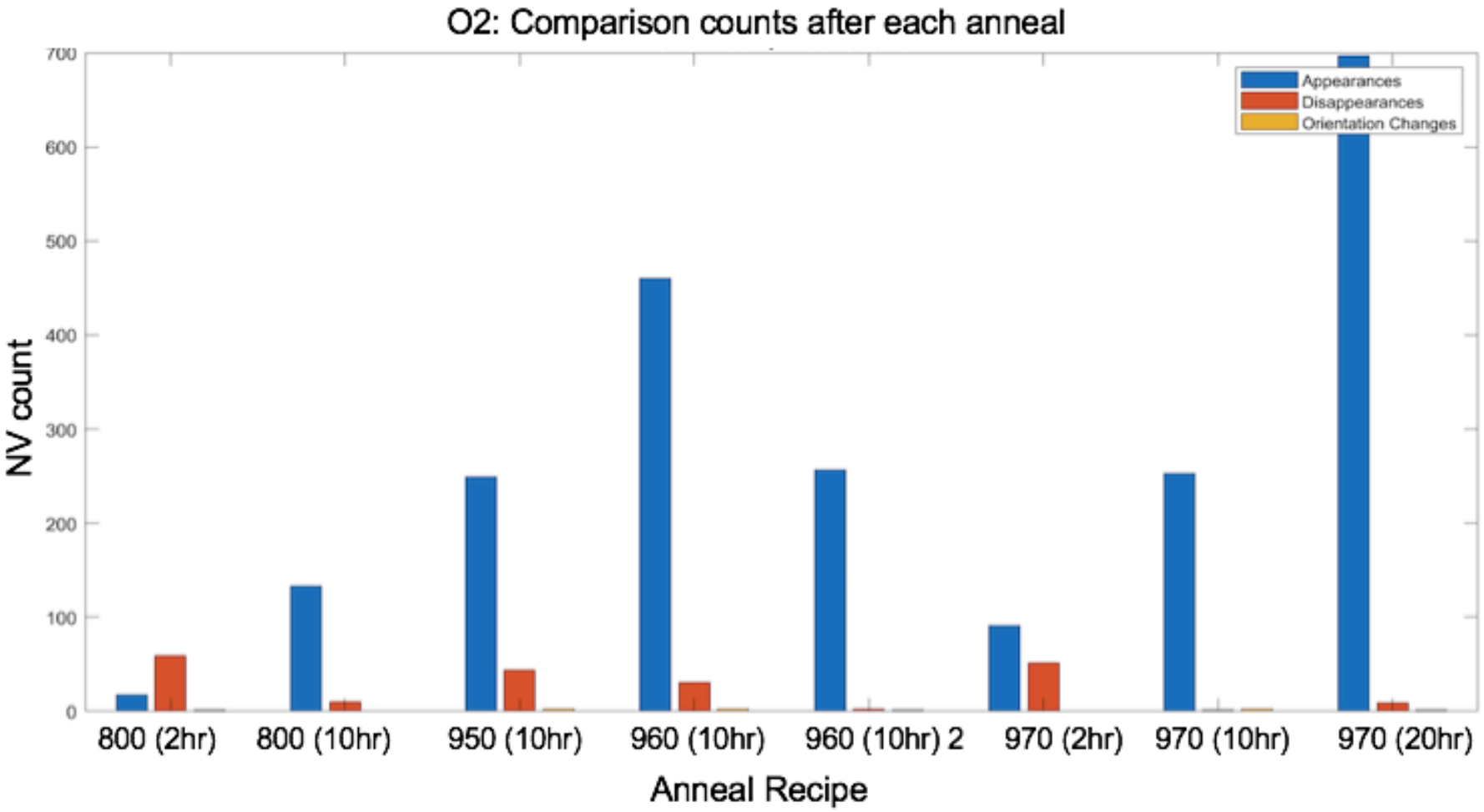
- total area: 350 µm^2
- scan takes about 18 hours
- 240 µm depth (from top surface)
- 81 50x50 µm^2 small piezo scans stitched together (162 total)
- Used a larger stage to move between small scans
- Compared sequential large scans
- Tallied appearances, disappearances, possible reorientations

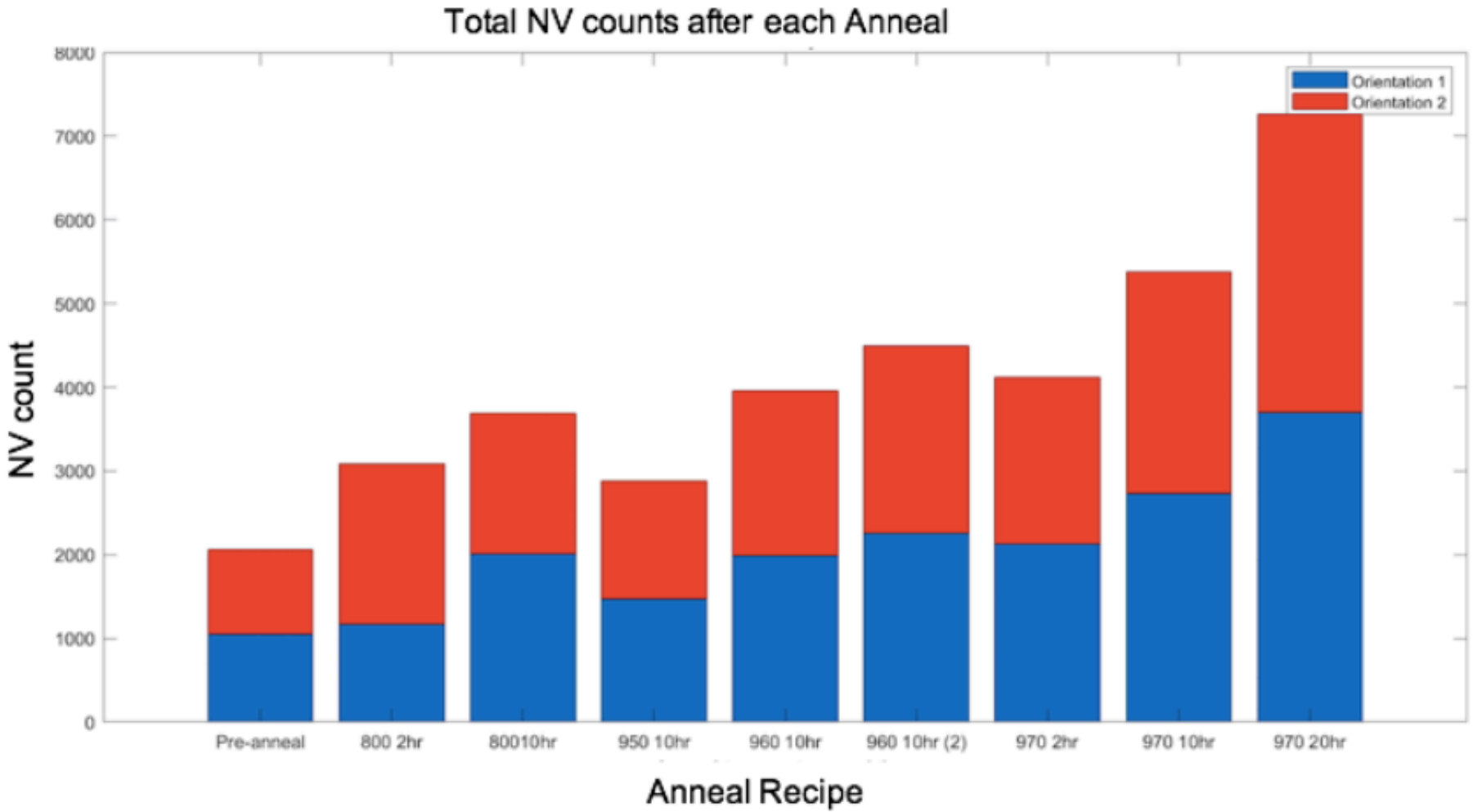
Large Scan Data: Comparisons





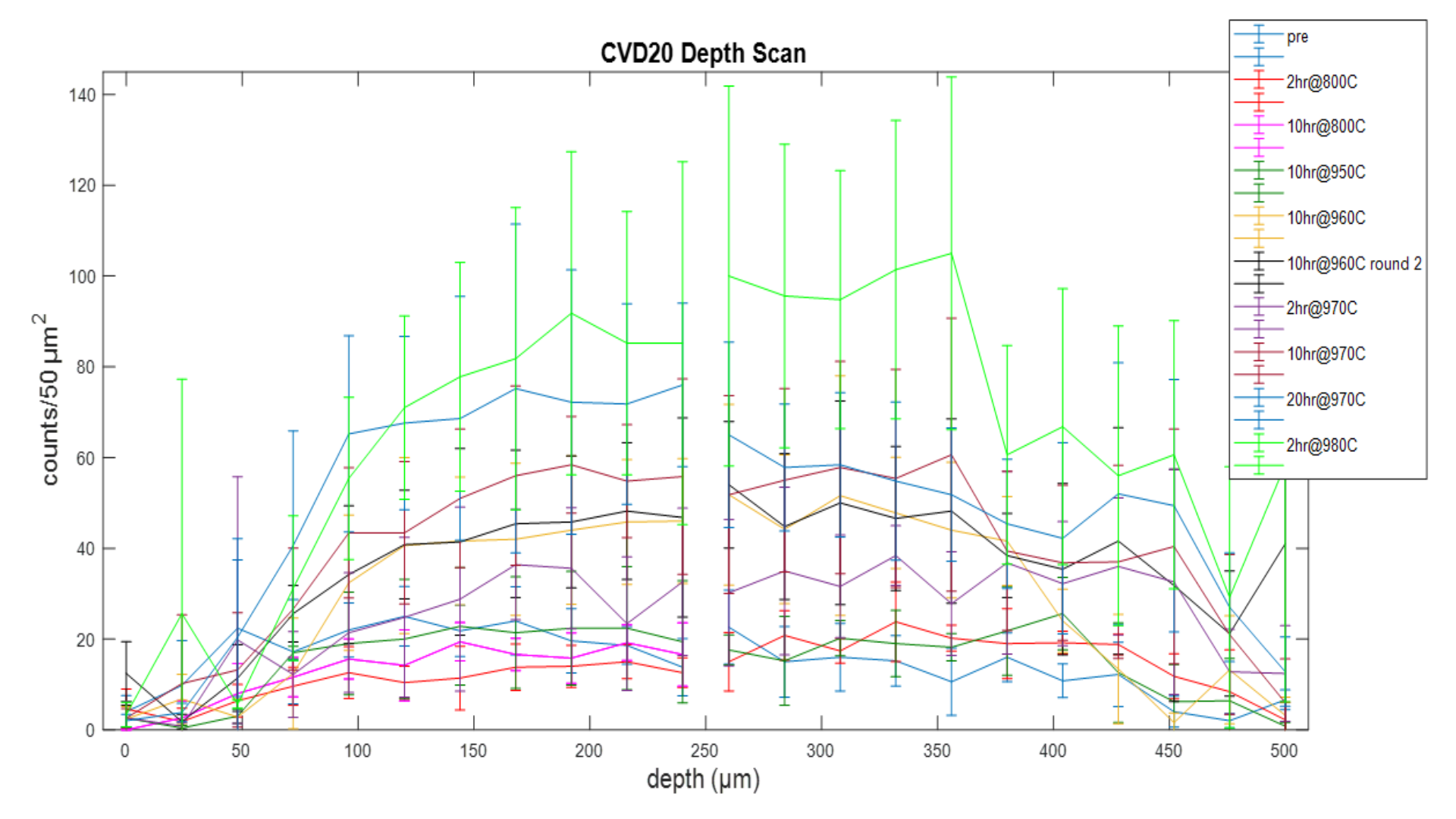

O1: Comparison counts after each anneal
Appearances
Disappearances
Orientation Changes
NV count
800
700
600
500
400
300
200
100
0
800 (2hr)
800 (10hr)
950 (10hr)
960 (10hr)
960 (10hr) 2
970 (2hr)
970 (10hr)
970 (20hr)
Anneal Recipe

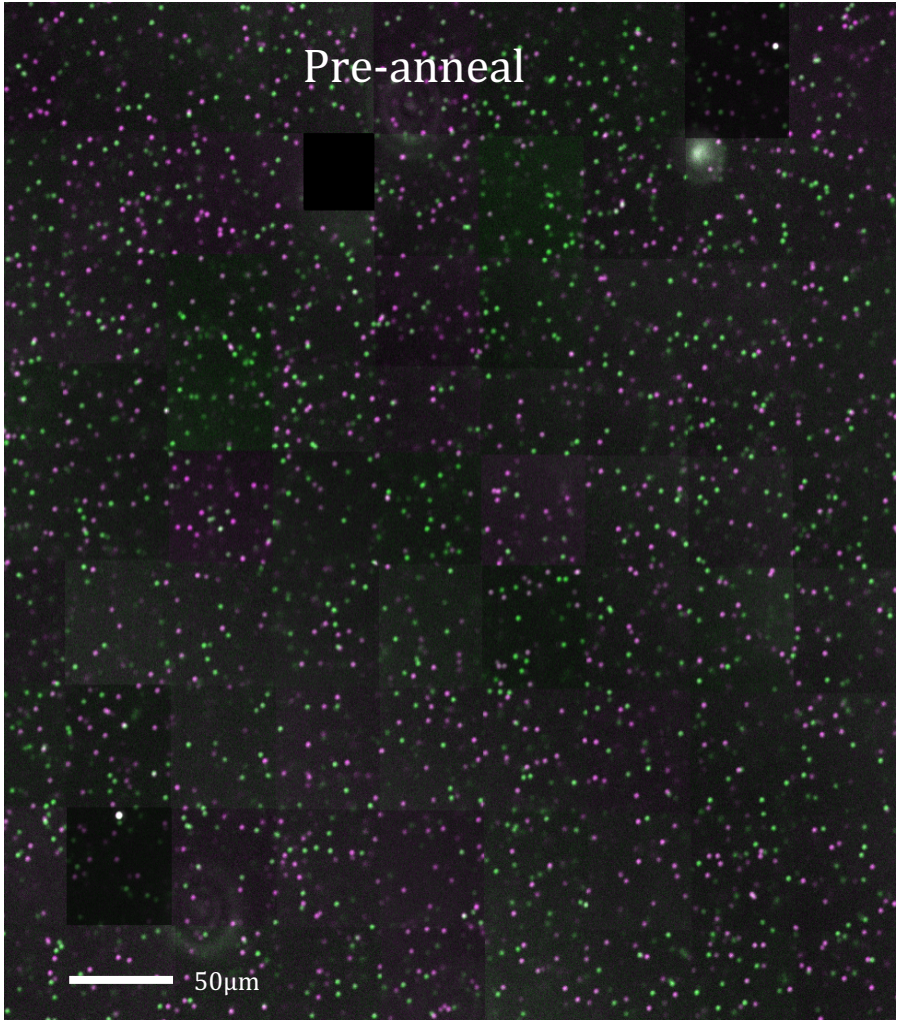

O2: Comparison counts after each anneal
Appearances
Disappearances
Orientation Changes
NV count
0
100
200
300
400
500
600
700
800 (2hr)
800 (10hr)
950 (10hr)
960 (10hr)
960 (10hr) 2
970 (2hr)
970 (10hr)
970 (20hr)
Anneal Recipe

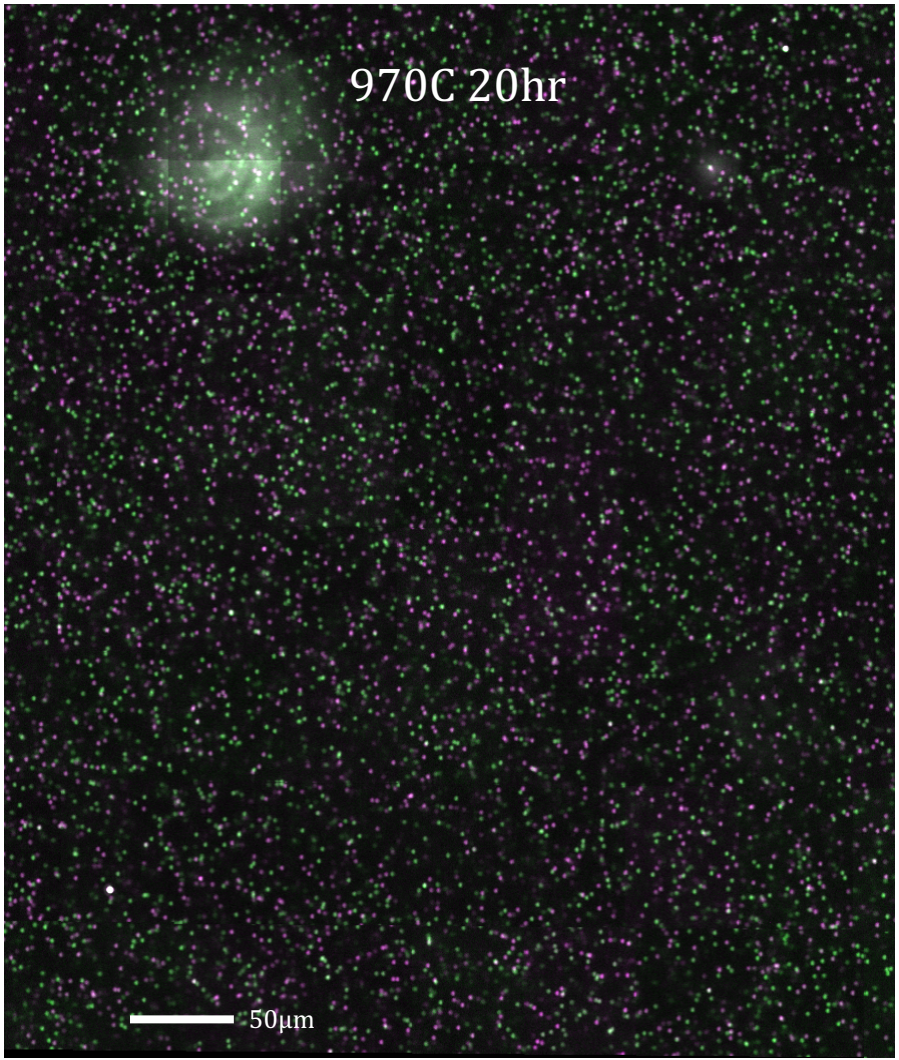

Total NV counts after each Anneal
NV count
Anneal Recipe
Orientation 1
Orientation 2
0
1000
2000
3000
4000
5000
6000
7000
8000
Pre-anneal
800 2hr
80010hr
950 10hr
960 10hr
960 10hr (2)
970 2hr
970 10hr
970 20hr

Depth Scan Methods

- Five different 50x50 μm^2 areas averaged per depth
- 11 depths: from 0 μm (surface) to 100 μm (max range of objective) every 10 μm
- Two separate depth scans for both surfaces


CVD20 Depth Scan
counts/50 µm^2
depth (µm)
0
20
40
60
80
100
120
140
0
50
100
150
200
250
300
350
400
450
500
pre
2hr@800C
10hr@800C
10hr@950C
10hr@960C
10hr@960C round 2
2hr@970C
10hr@970C
20hr@970C
2hr@980C


Pre-anneal
50μm


970C 20hr
50μm

Why we should not see a major increase in NV-

- Relatively low vacancy and nitrogen concentration
  - low probability of finding each other
- Other possible defects stable up to high temperatures
  - NVH (>1600C)
  - Nitrogen aggregates
  - Vacancy aggregates

Theories

- NV0 turning into NV-
  - Via high energy photons (4)
- Presence of some other defect (Nickel, Boron, etc.)

Future Work

- more data: more anneals with more samples
- scan for other defects: NV0, etc.
- Is repeated annealing a viable way to increase NV concentration in diamond?

References

(1) Deák, Peter, et al. "Formation of NV centers in diamond: A theoretical study based on calculated transitions and migration of nitrogen and vacancy related defects." *Physical Review B*89.7 (2014): 075203.

(2) Pinto, H., et al. "On the diffusion of NV defects in diamond." *physica status solidi (a)* 209.9 (2012): 1765-1768.

(3) Mainwood, Alison. "Nitrogen and nitrogen-vacancy complexes and their formation in diamond." *Physical Review B* 49.12 (1994): 7934.

(4) Khan, R. U. A., et al. "Colour-causing defects and their related optoelectronic transitions in single crystal CVD diamond." *Journal of Physics: Condensed Matter* 25.27 (2013): 275801.

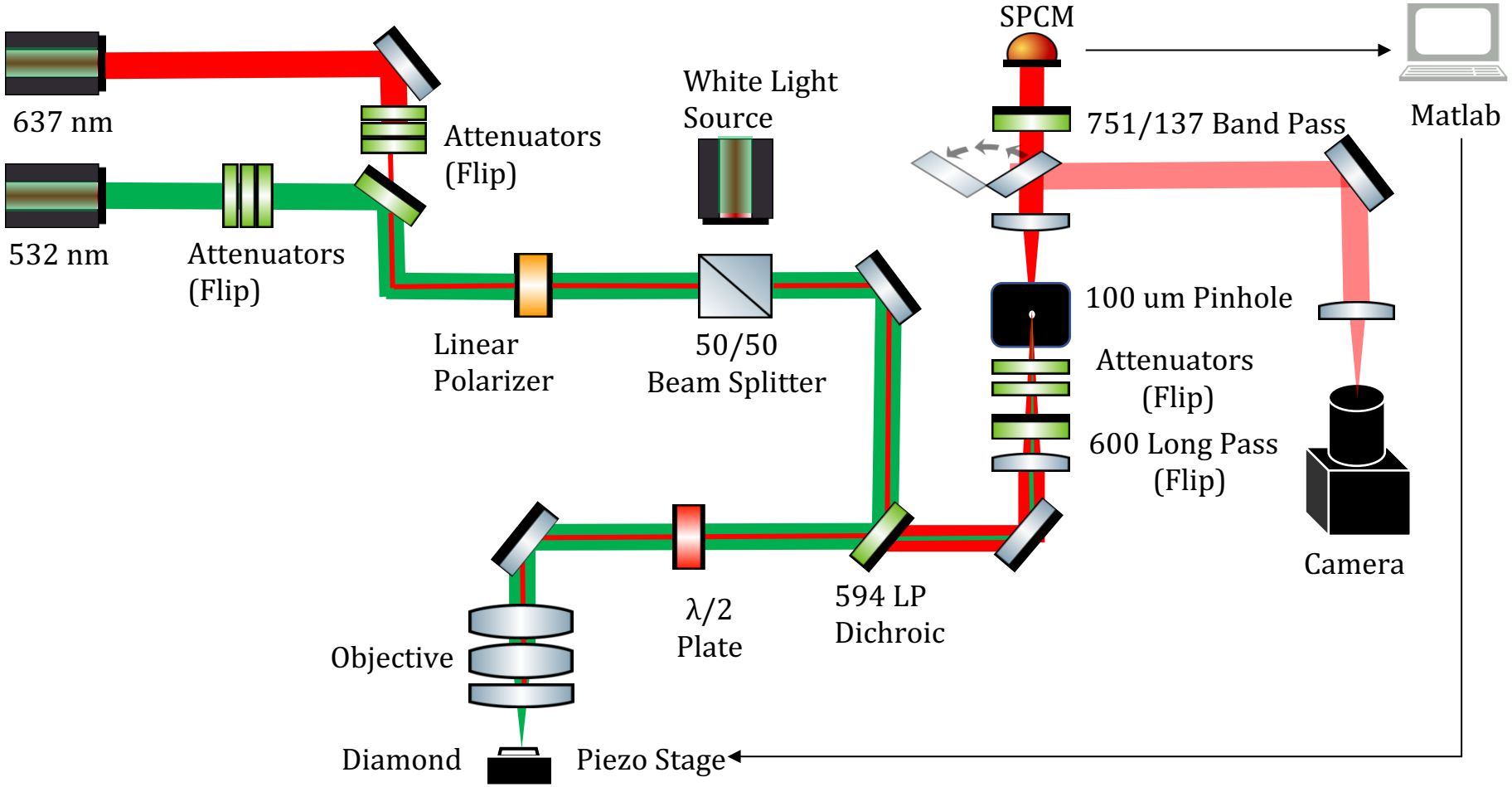
(5) Karin, Todd, Scott Dunham, and Kai-Mei Fu. "Alignment of the diamond nitrogen vacancy center by strain engineering." *Applied Physics Letters* 105.5 (2014): 053106.

Processes during Anneal

Temperature (ºC)	Process	Energy (eV)	Max Stable Temp (ºC)
T > 600	$C_I + V \rightarrow \varnothing$		
T < 800	$N_I + N_s \rightarrow N_2$		
	$N_I + V \rightarrow NV?$		
	N_I mobile		650
	V^0 mobile	$+2.3 \pm .3$	
T > 800	$N_s + V^0 \rightarrow (NV-) + h$	+5.8	1700
	$N_2 + V^0 \rightarrow N_2V$	+5.65	2200
	$2V \rightarrow V_2$	+4.2	1100
	$N_s + VH \rightarrow NVH$	+2.3	1600

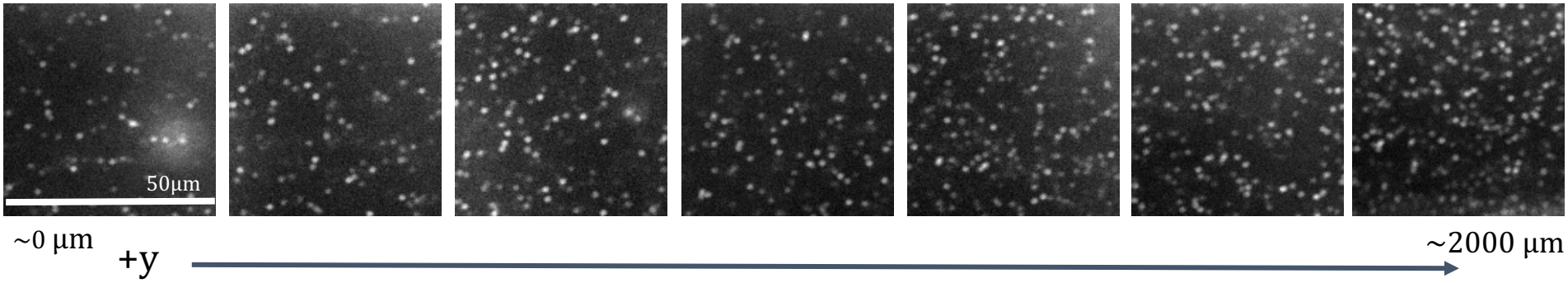
Theories

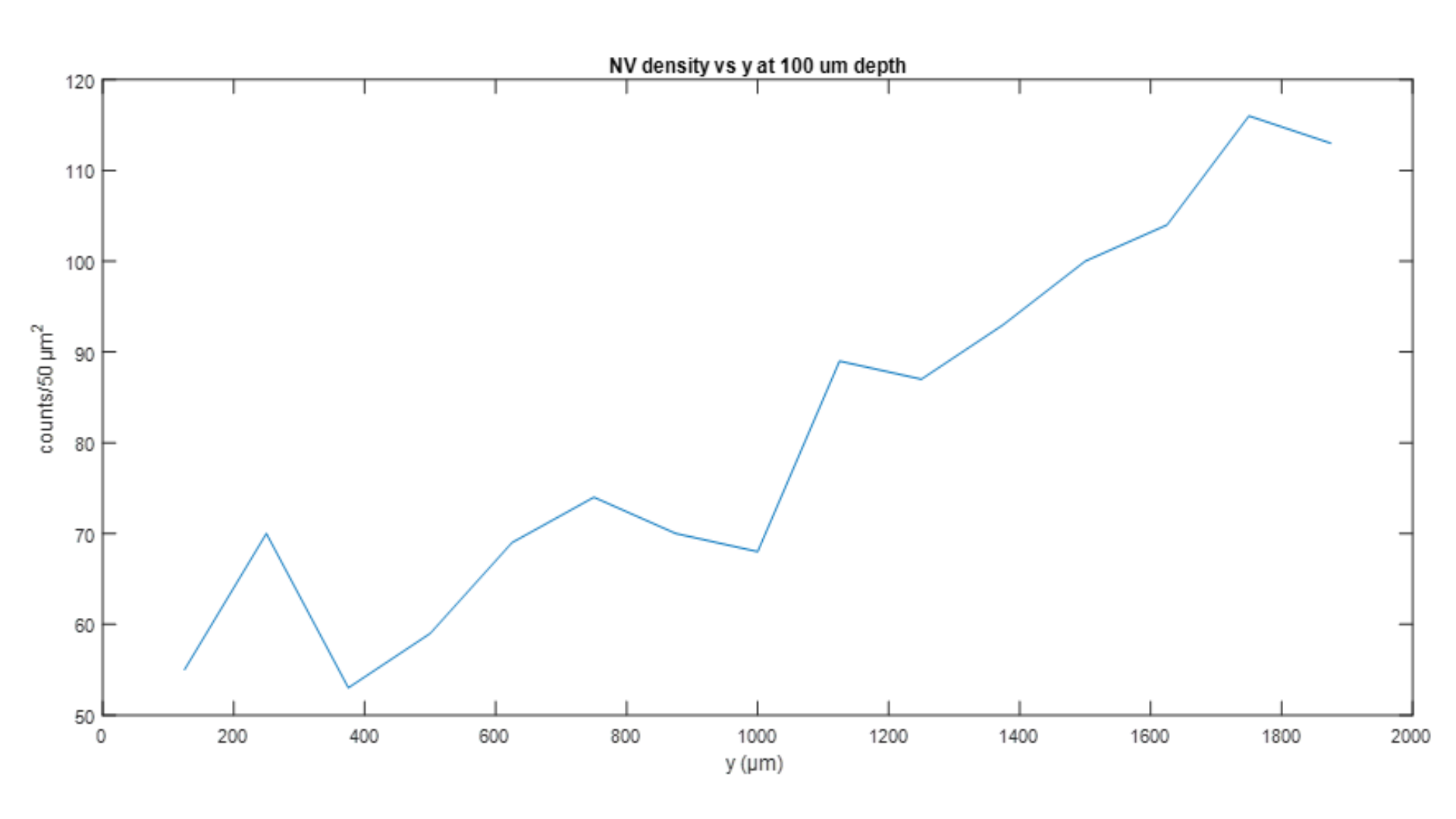
- NV forming via N + V (vacancy migrating to nitrogen)
  - Unlikely due to range of V migration, low vacancy concentration
  - Self-limiting (2)
- Hydrogen breaking away from NV
  - NVH stable up to 1600C (1)
- NV0 turning into NV-
  - Via high energy photons (4)
- Presence of some other defect (Nickel, Boron, etc.)


637 nm
532 nm
Attenuators
(Flip)
Attenuators
(Flip)
White Light
Source
Linear
Polarizer
50/50
Beam Splitter
SPCM
751/137 Band Pass
Matlab
100 um Pinhole
Attenuators
(Flip)
600 Long Pass
(Flip)
Camera
λ/2
Plate
594 LP
Dichroic
Objective
Diamond
Piezo Stage

Issues

- Red laser optimization
- Image stitching/overlaying
- Nonuniform NV- distribution




NV density vs y at 100 um depth
120
110
100
90
80
70
60
50
counts/50 µm^2
0
200
400
600
800
1000
1200
1400
1600
1800
2000
y (µm)