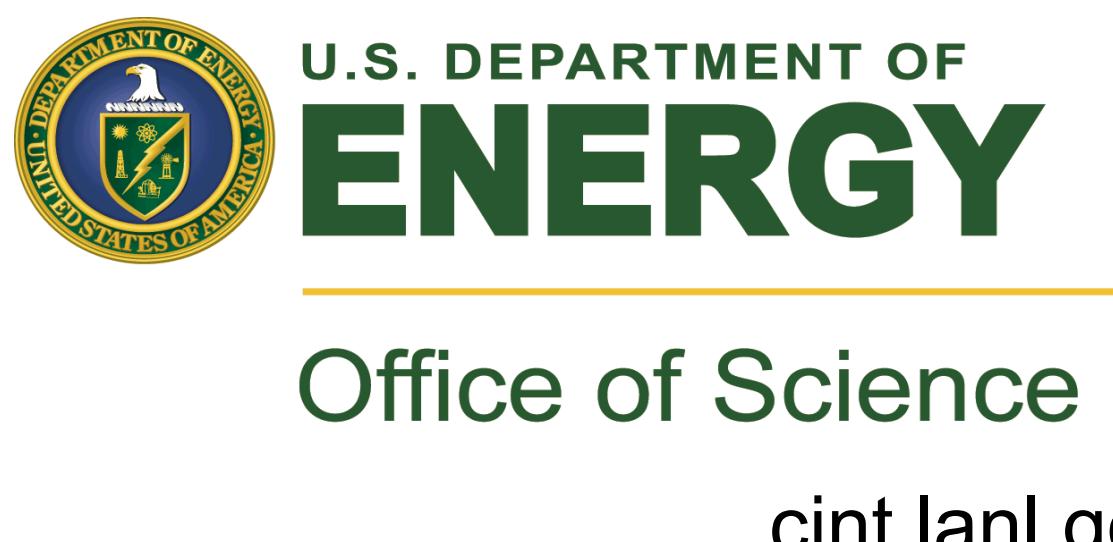




# Nanofabrication Capability of Color Centers in Diamond using Top-Down Ion Implantation

SAND2016-4265

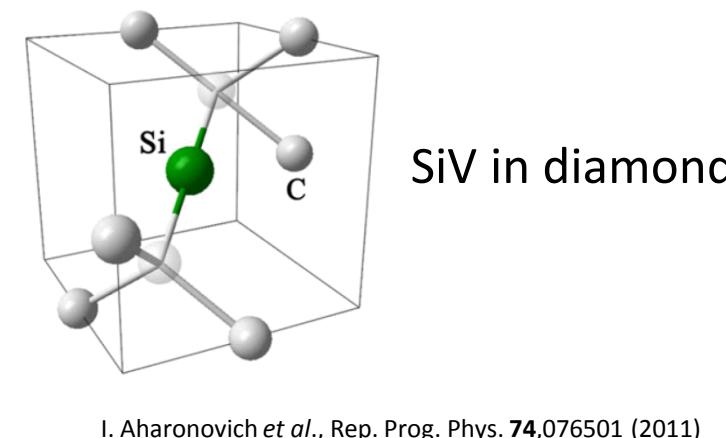
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<sup>1</sup>Sandia National Laboratories, Albuquerque, NM, <sup>2</sup>Massachusetts Institute of Technology, Cambridge MA, and <sup>3</sup>Harvard University, Cambridge MA



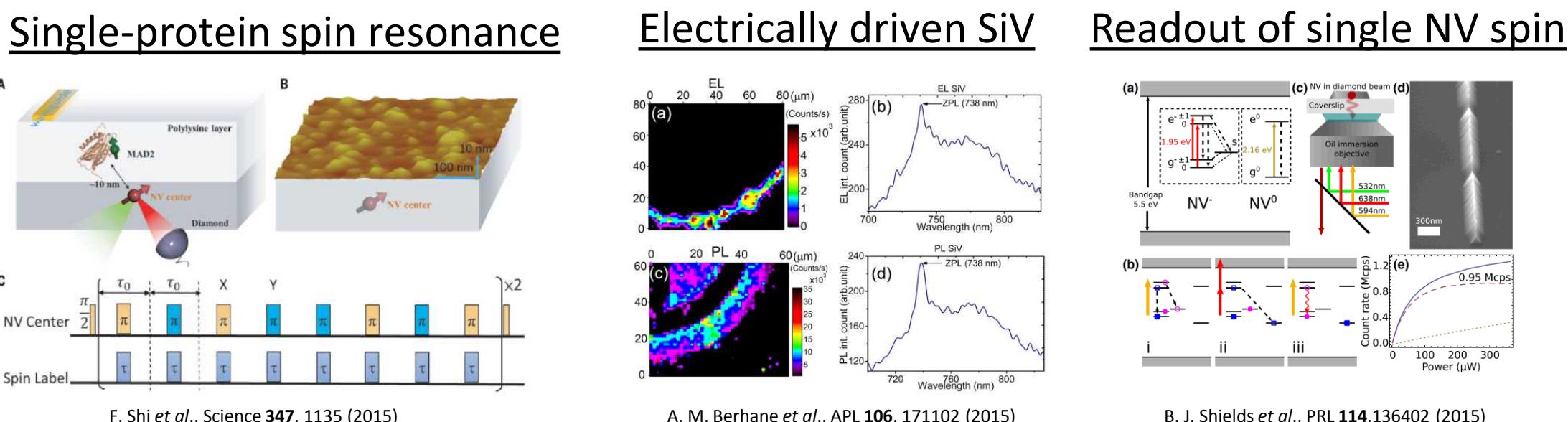
## Motivation

### Why Color Centers in Diamond?

- Color centers (defects) in diamond include NV<sup>-</sup>, SiV plus many more...



- Wide range of application from metrology to quantum computation

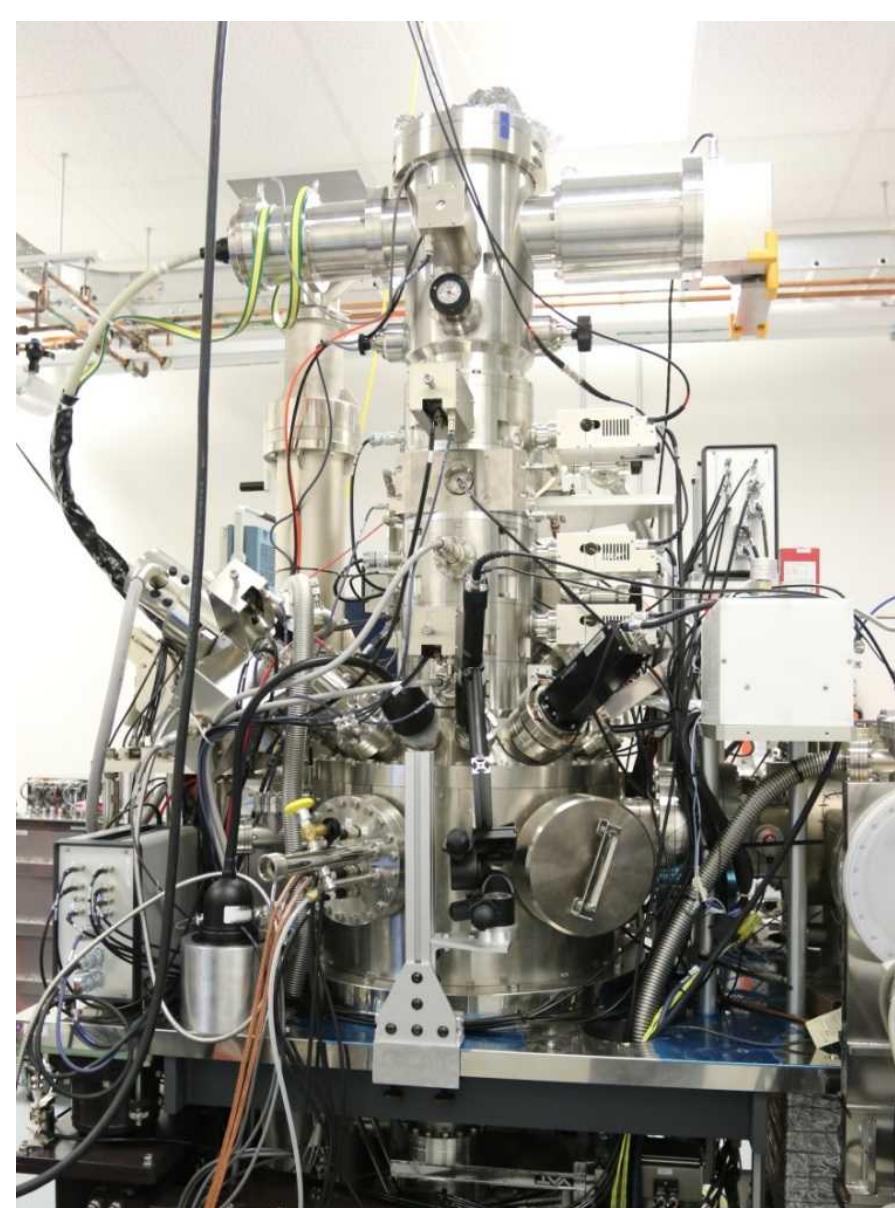


- Key question → How to produce a single color center where you want it?

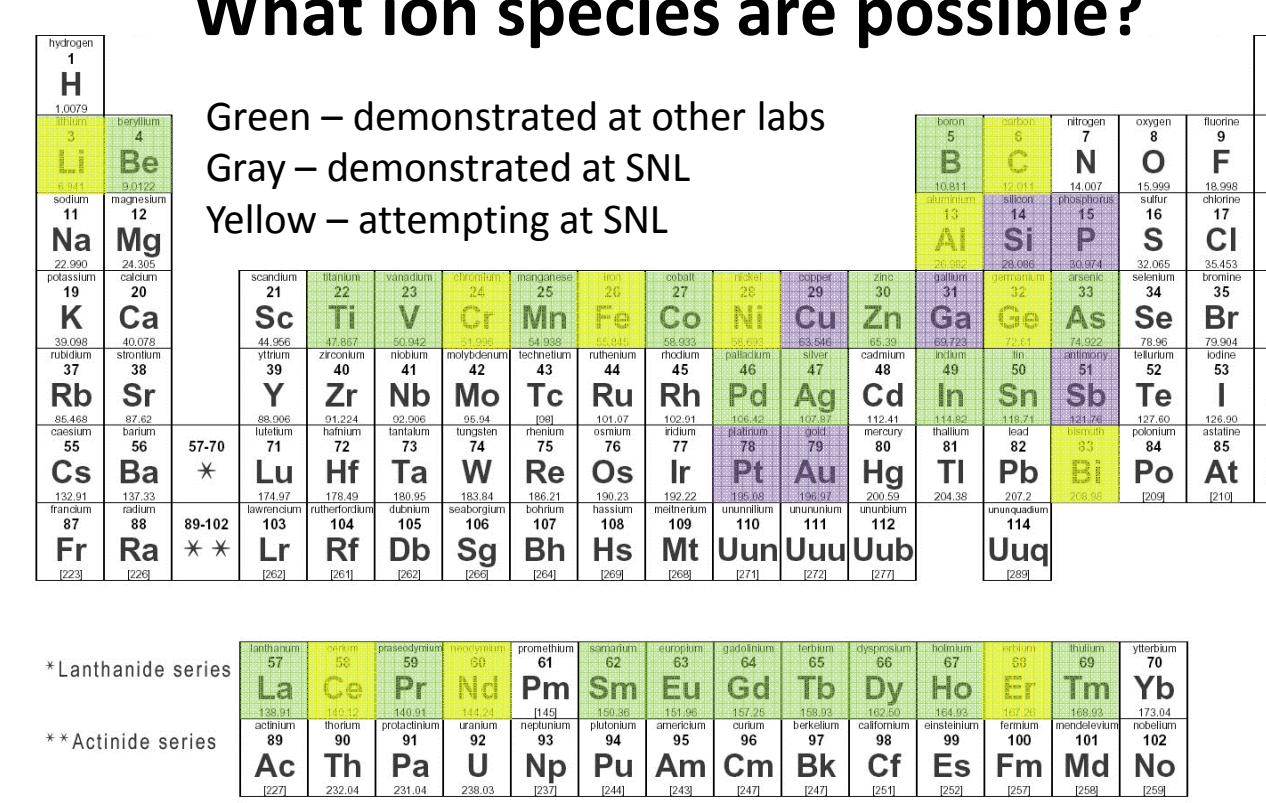
## Nanoscale Top-Down Ion Implantation

### nanolplanter

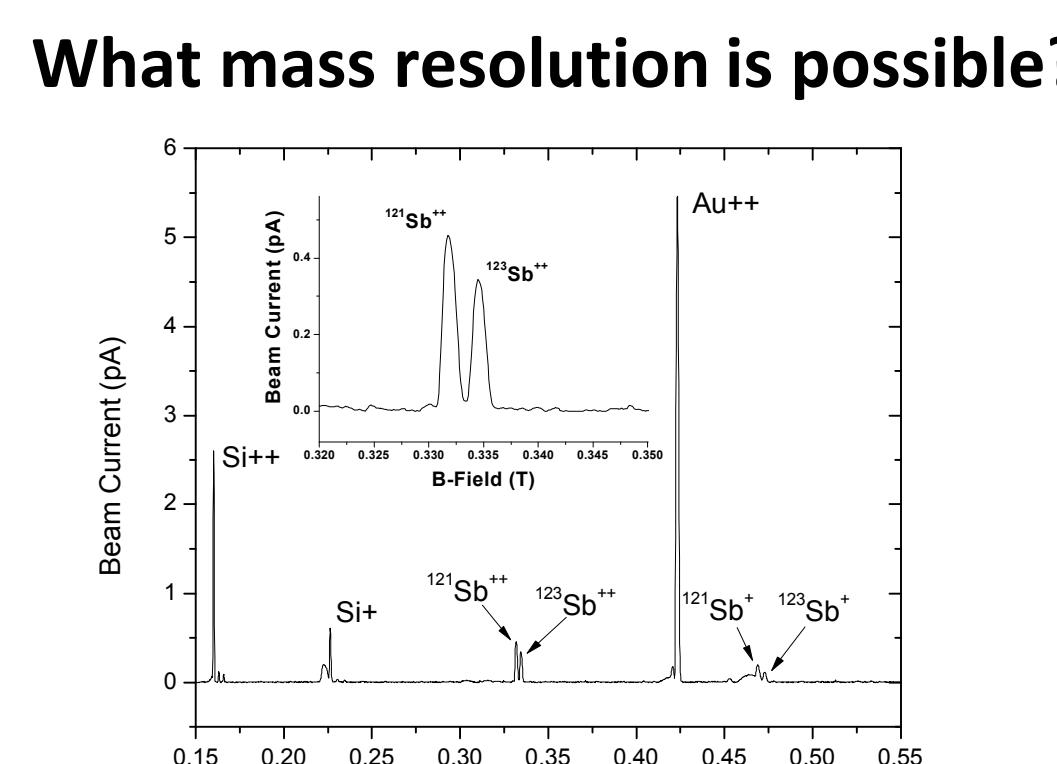
- Focused ion beam system (FIB) → nm beam spot size on target
- ExB Filter (Wein Filter) → Multiple ion species
- Fast blanking and chopping → Single ion implantation
- Direct-write lithography → nm targeting accuracy



### What ion species are possible?

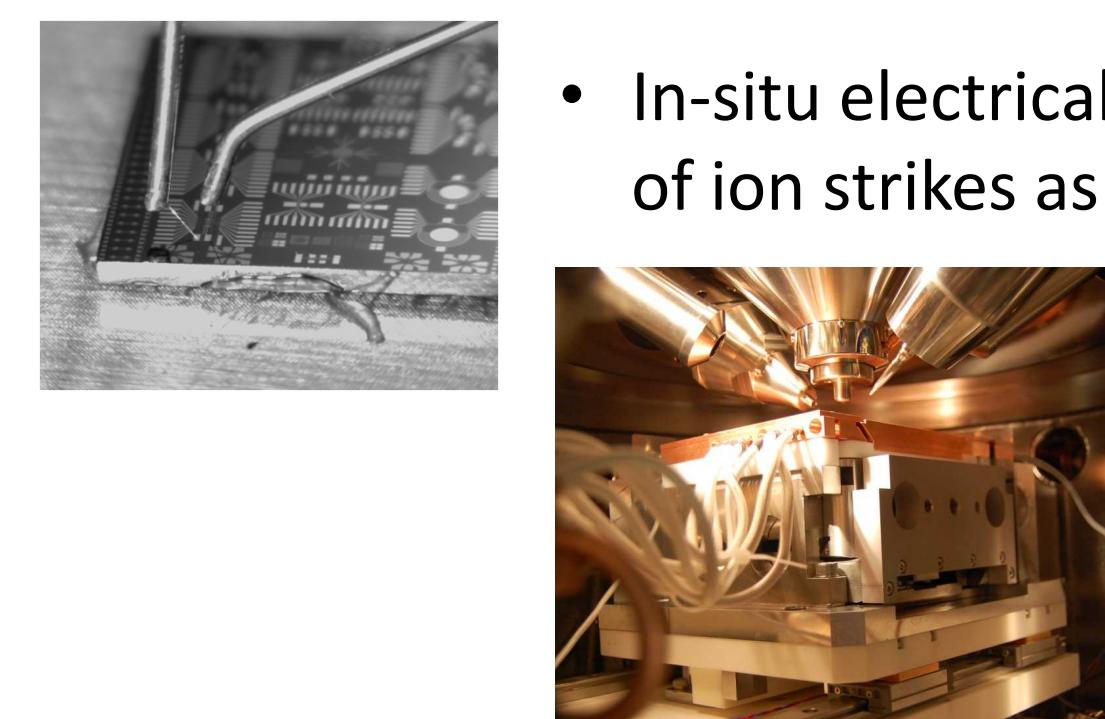


~1/3 the periodic table are available



### Direct write platform and in-situ electrical probes

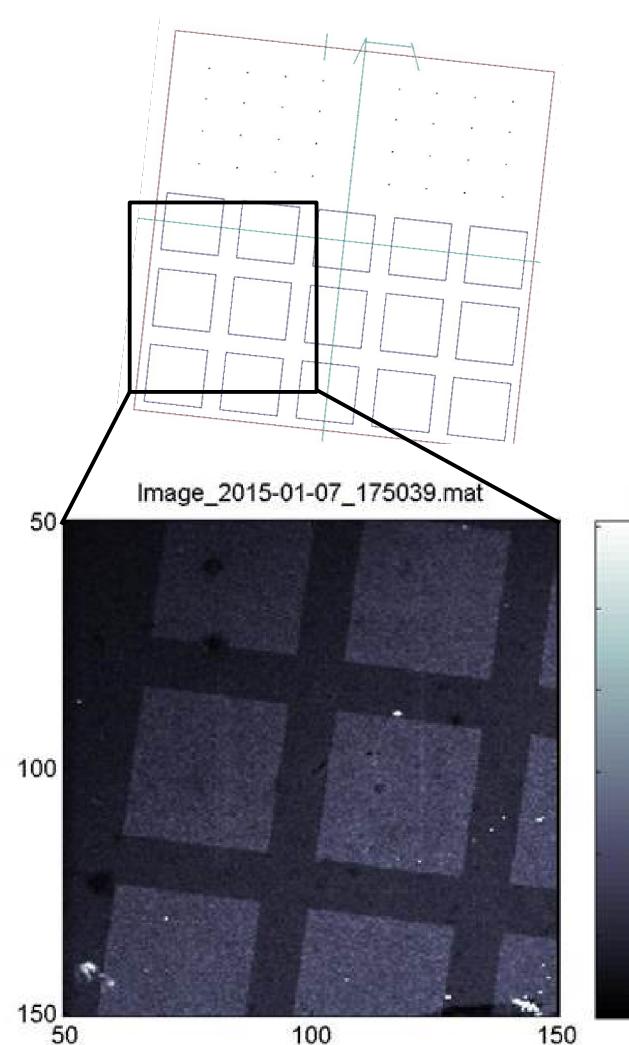
- In-situ electrical probes for measurement of ion strikes as they occur
- Low temperature stage
- Built-in lithography software (Raith ELPHY Plus) with sub-nm resolution



RAITH  
NANOFABRICATION

## Measurements on Implanted Diamond

### Yield Testers

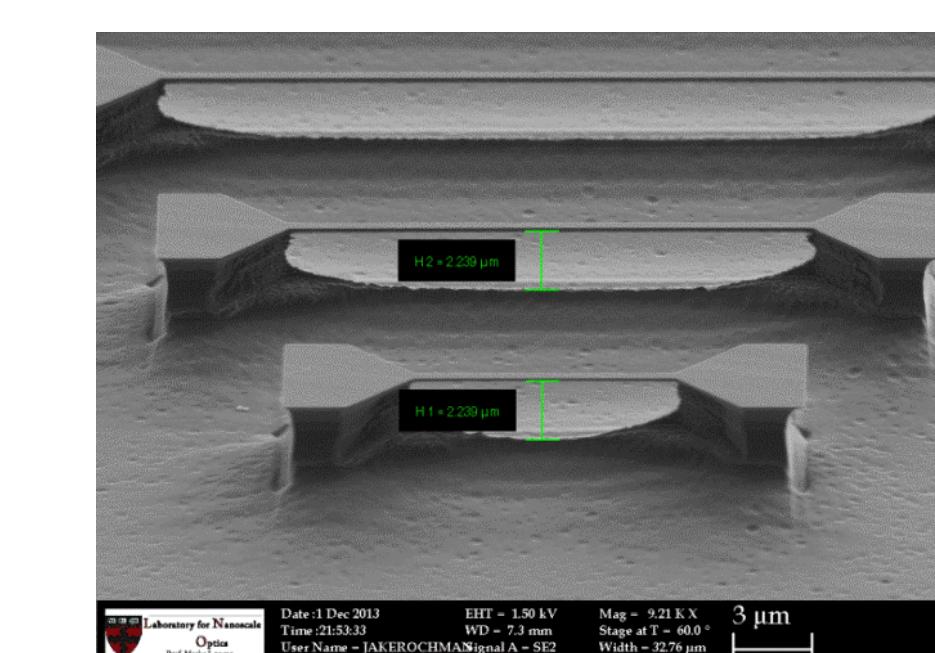


We implanted Si at a series of dose and energies into diamond substrates to form SiV color centers, yield measurement performed by the Englund group

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

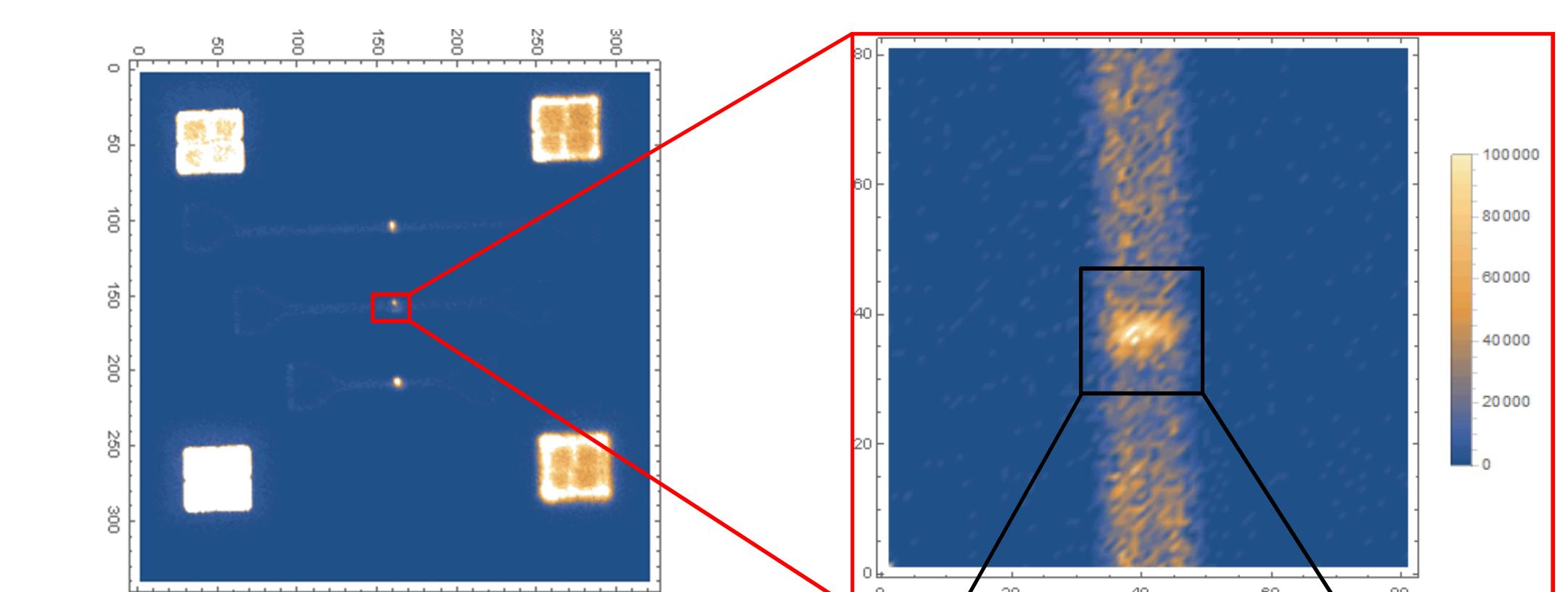
Comparison of yields under different implants  
 → Towards deterministic and localized color centers

### Localized Color Center Formations - Nanobeams



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

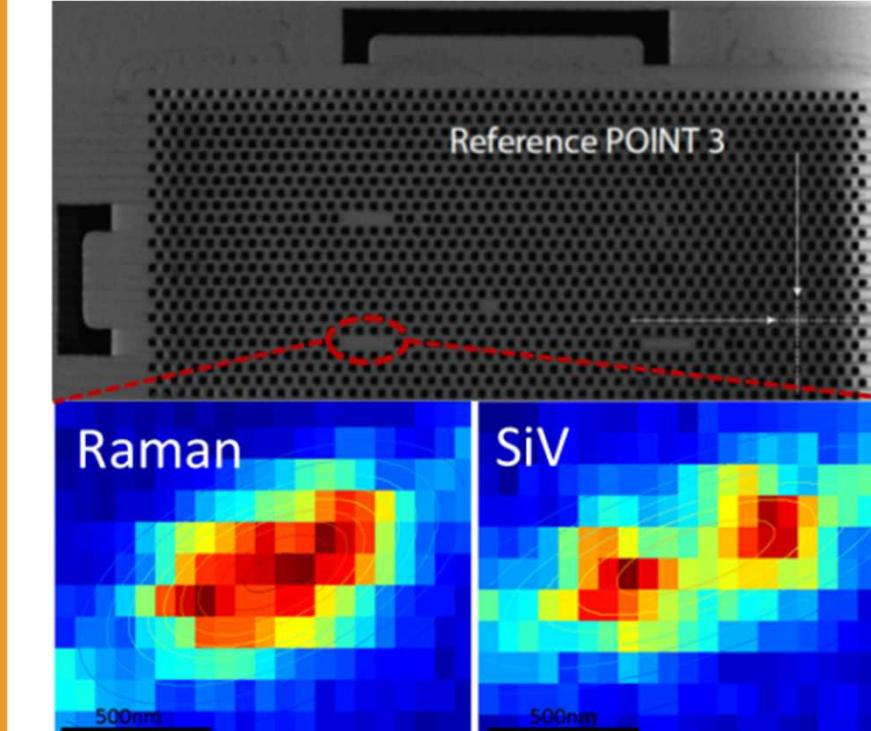
- Implanted 100 keV Si into the nanobeams forming localized SiV color centers



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

A. Sipahigil et al., Submitted into Science

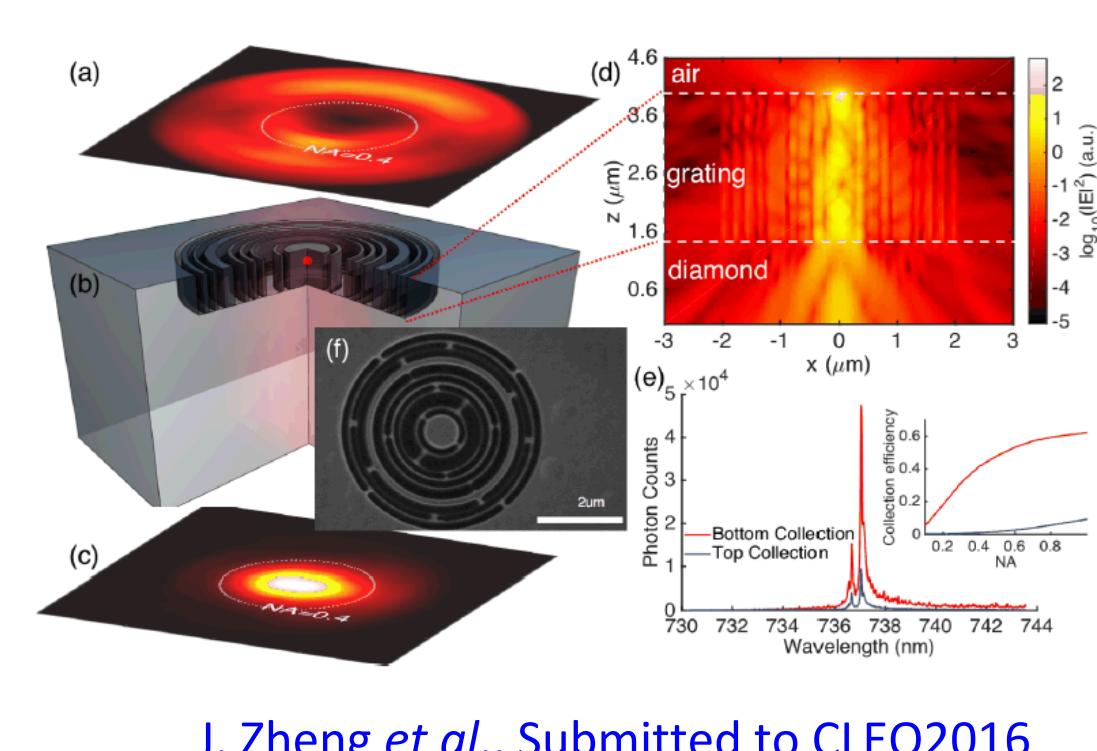
### Test of diamond coupling - 2D Photonic Cavities



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

T. Schroder et al., Submitted to CLEO2016

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



## Conclusions and Future Directions

### Color Center Formation Yields

- 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 underway to locally irradiate with light ions such as Li to test for yield improvements

### Deterministic Counted Single Ion Implantation

- Demonstrated single ion detection in diamond with a SNR of ~10
  - Beats the Poisson distribution for implanted ions, improving the understanding of the yield

See Poster by J. B. S. Abraham for more details

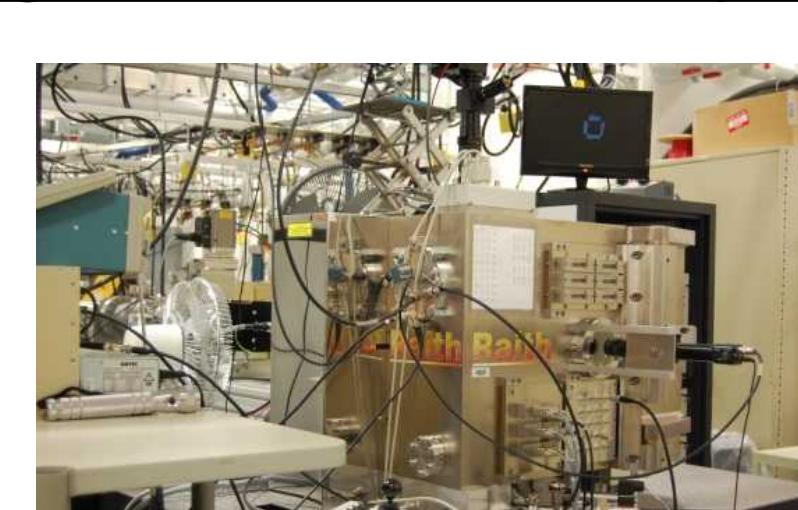
## Focused Ion Beam Capability at SNL

### MicroOne (Tandem Accelerator)



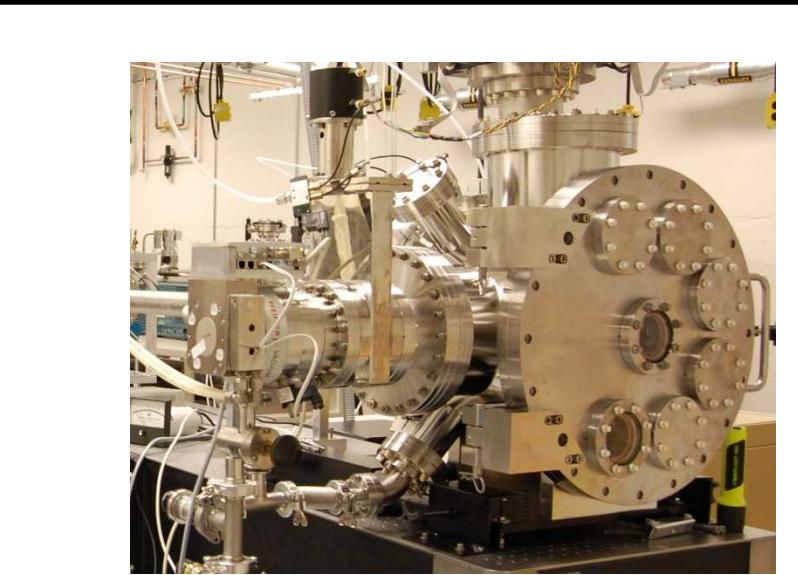
- Light to Heavy Ions – H to I
- Energy range from ~800 keV to >70 MeV
- Spot size as small as ~800 nm

### Light Ion Microbeam (Pelletron)



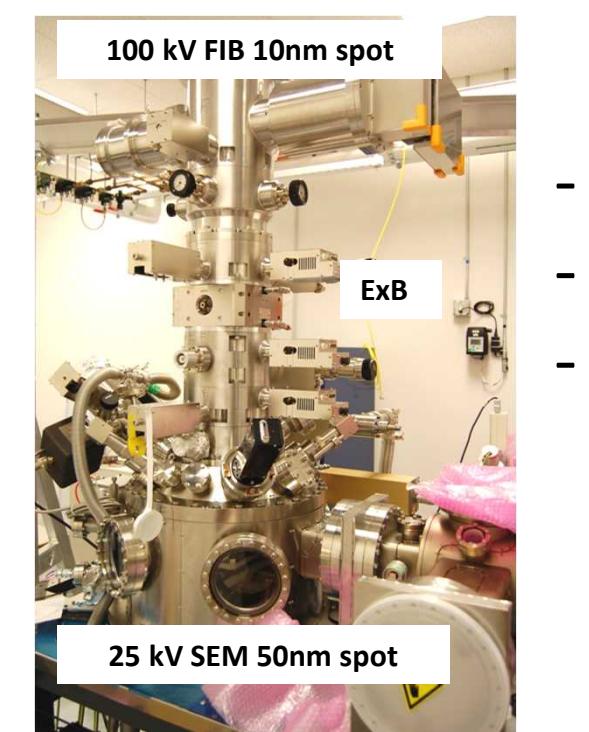
- Light Ions – H, He3, He4, N
- Energy range from ~300 keV to 3 MeV
- Spot size as small as ~150 nm

### 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

### nanolplanter



- 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