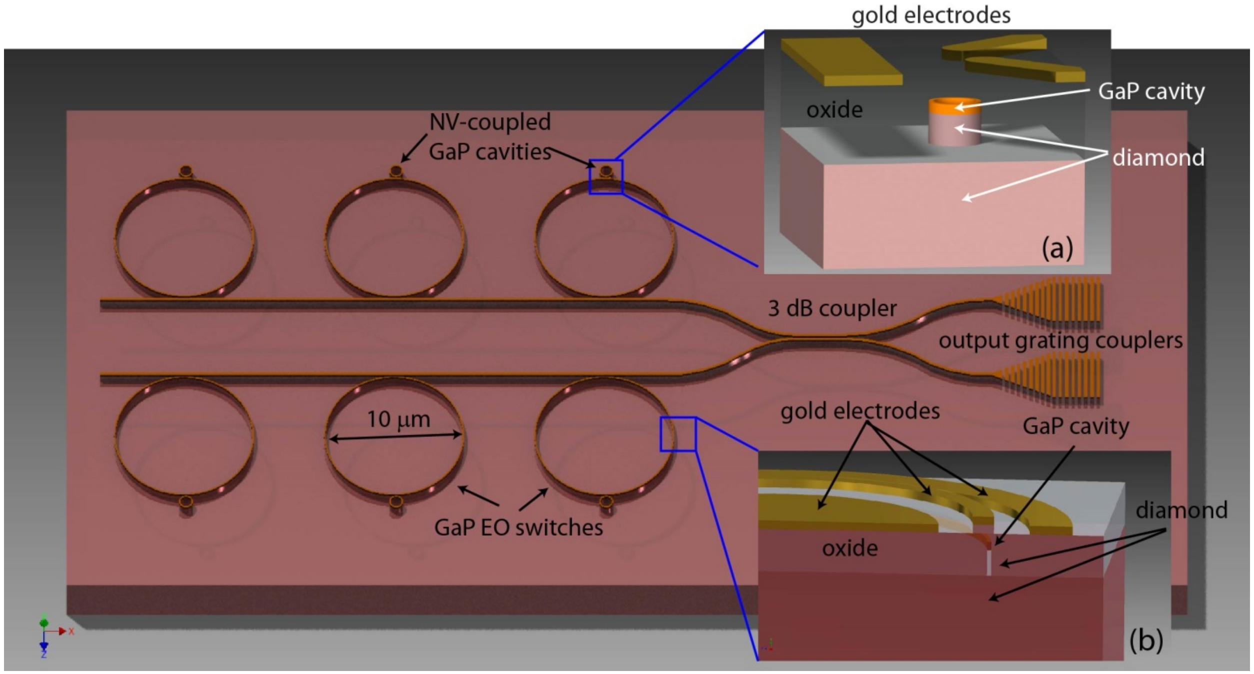
Impurities in solids for quantum information processing



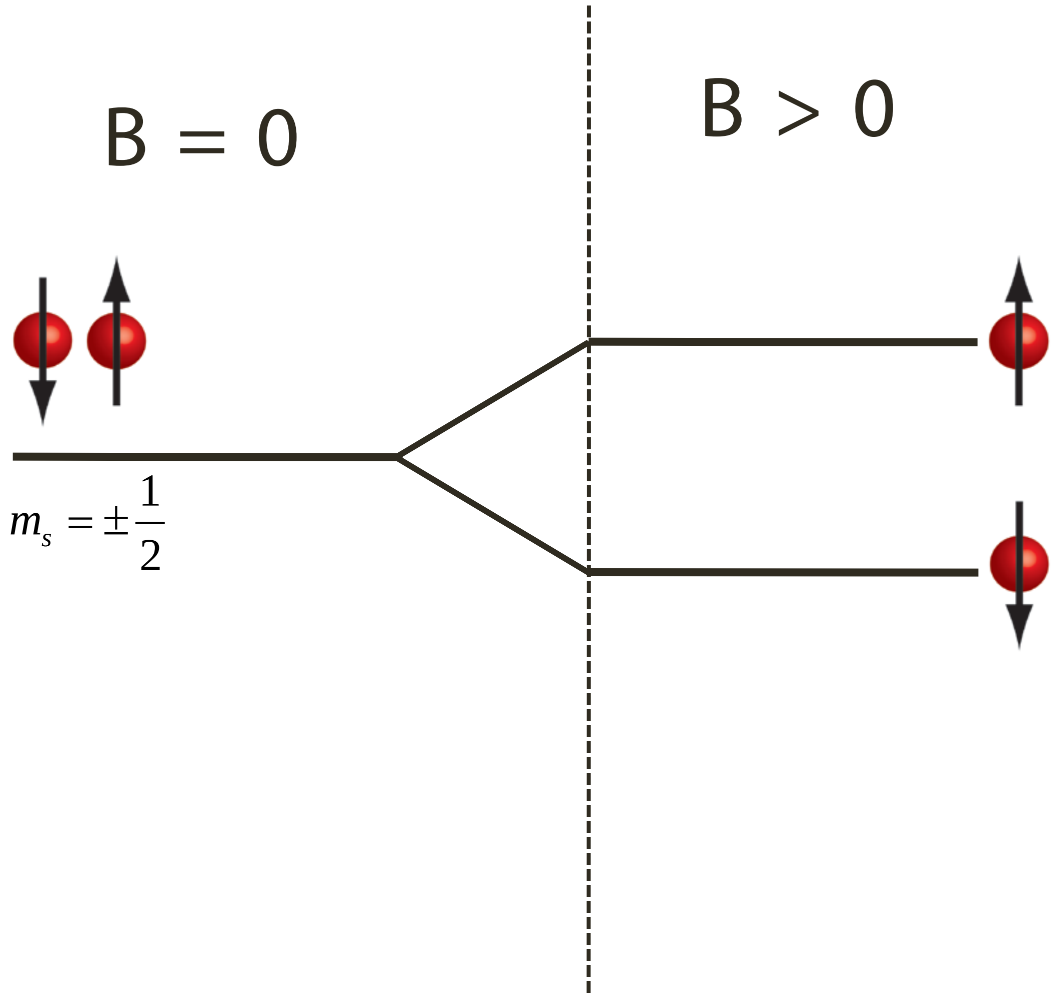
Kai-Mei Fu
Depts of Physics and Electrical Engineering, University of Washington

UW REU summer presentation
2014

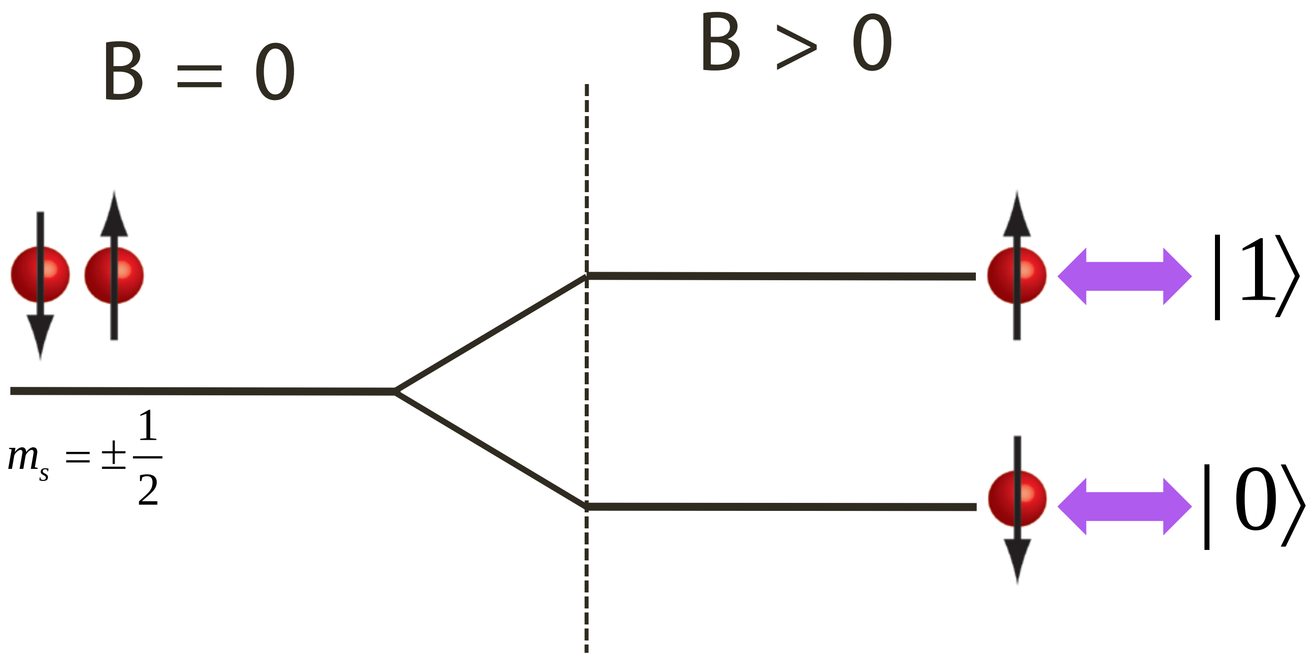
Outline

- Spin basics
- General properties of NV centers
- Toward measurement-based quantum information with the NV center

Spin ½ particle: A two-level quantum system



Application : Quantum information processing



spin `qubit'

$$|\Psi\rangle = a\,|0\rangle + b\,|1\rangle, \text{ with } |a|^2 + |b|^2 = 1$$

Why quantum information?

- Classical information bit: 0 and 1
- Quantum information qubit:

$$|\Psi\rangle = a|0\rangle + b|1\rangle$$

- Quantum 'parallelism':

$$f(|\Psi\rangle) = f(a|0\rangle + b|1\rangle)$$

$$g(|\Psi_1\rangle|\Psi_2\rangle) = \mathrm{g}((a_1|0\rangle + b_1|1\rangle)(a_2|0\rangle + b_2|1\rangle))$$

$$= g(a_1 b_1|00\rangle + a_1 b_2|01\rangle + b_1 a_2|10\rangle + b_1 b_2|11\rangle)$$

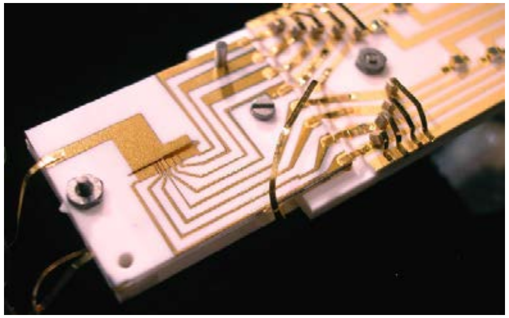
Why quantum information

- Applications:
  - Quantum algorithms
    - Factoring products of large prime numbers in polynomial time (Shor’s algorithm)
  - Simulating large quantum systems
  - Secure communication (quantum cryptography)

→ The search for a good qubit

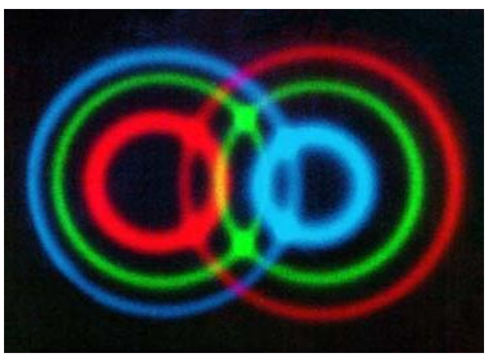
Qubit systems:

Ions and atoms



NIST, Boulder (from physicsworld.com)

Photons

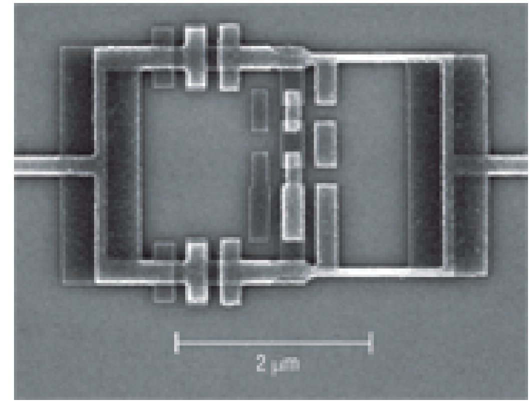


Innsbruck (from *Physical Review Lett.*)

Diamond defects

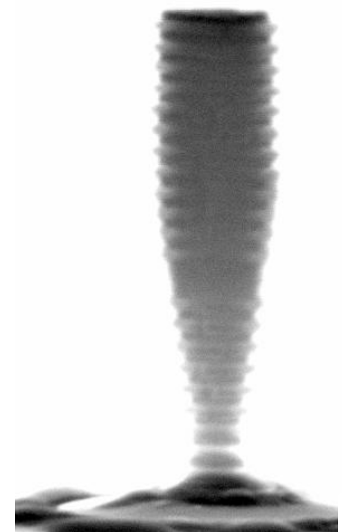
HP Labs

Superconducting qubits



Delft (from *Nature*)

Semiconductor qubits

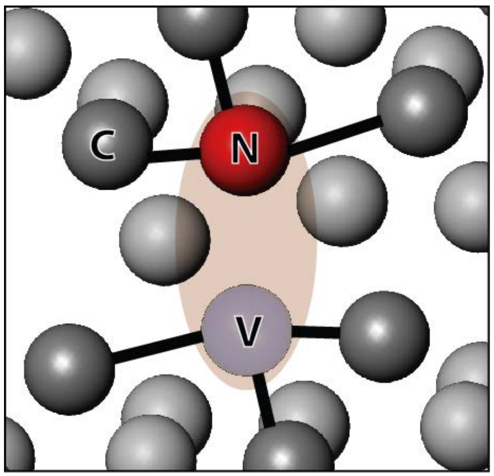


Stanford, (from *Physical Review Lett.*)

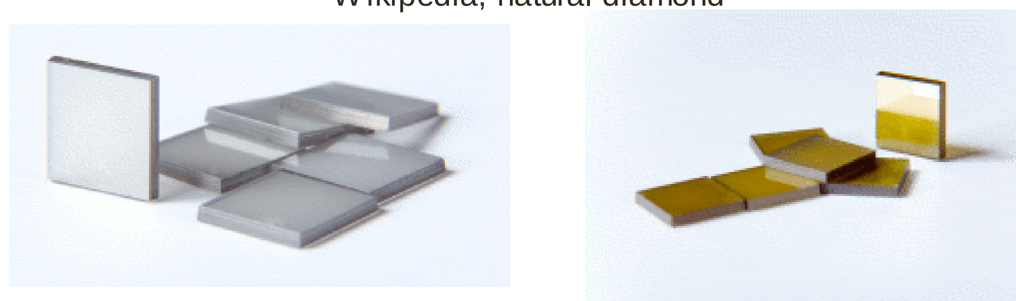
Outline

- Spin basics
- **General properties of NV centers**
- Toward measurement-based quantum information with the NV center

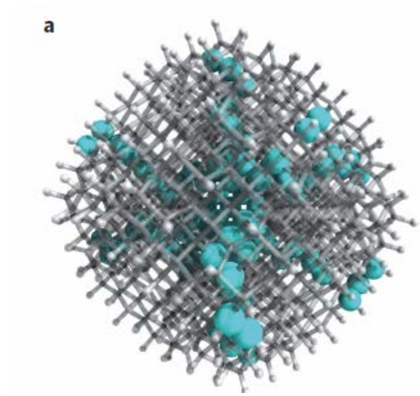
The nitrogen vacancy color center in diamond



Wikipedia, natural diamond

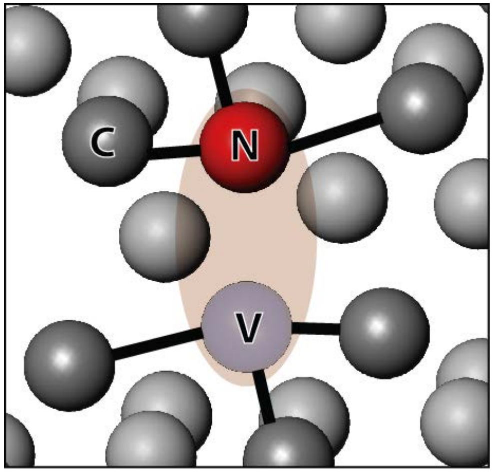


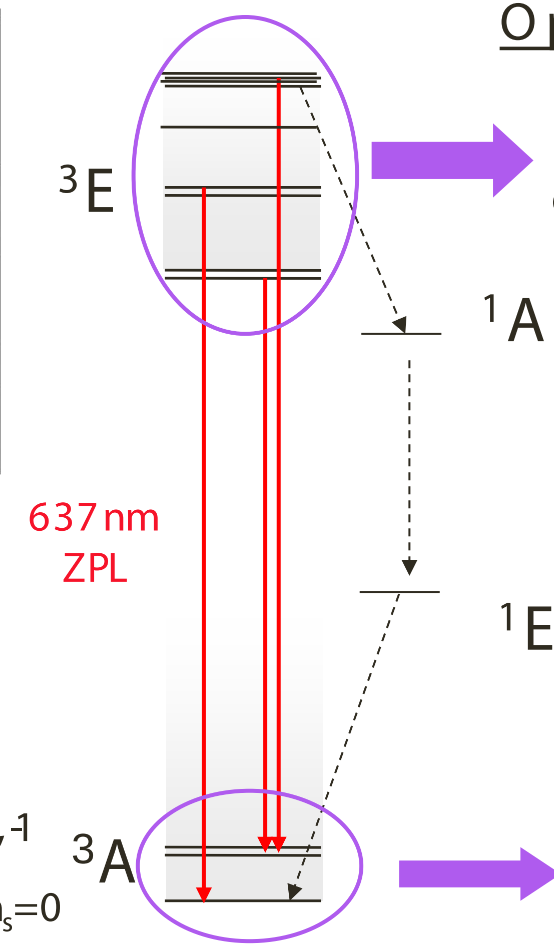
Element 6, CVD and HPHT diamond



5 nm detonation diamond nanoparticles
Bradac et al., *Nature Nanotechnology* (2010)

NV-diamond: an optically accessible, coherent solid state quantum system





Optically coupled excited states

optical spin readout for QIP

electron entanglement through photon interference

Room temperature optically detected magnetic resonance

1.8 ms coherence time[1]

qubit for QIP

nanoscale sensor

Balasubramanian *et al.* "*Nature Materials*" 8, 383 (2009) (Stuttgart)

Outline

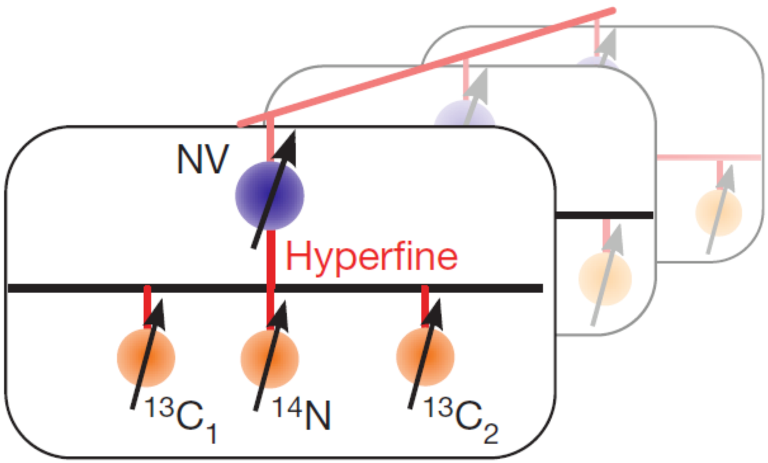
- Unique properties of NV centers
- **Toward measurement-based quantum information with the NV center**
- Optical detection of single 17 nm super-paramagnetic nanoparticles using a wide-field NV sensor array

Outline

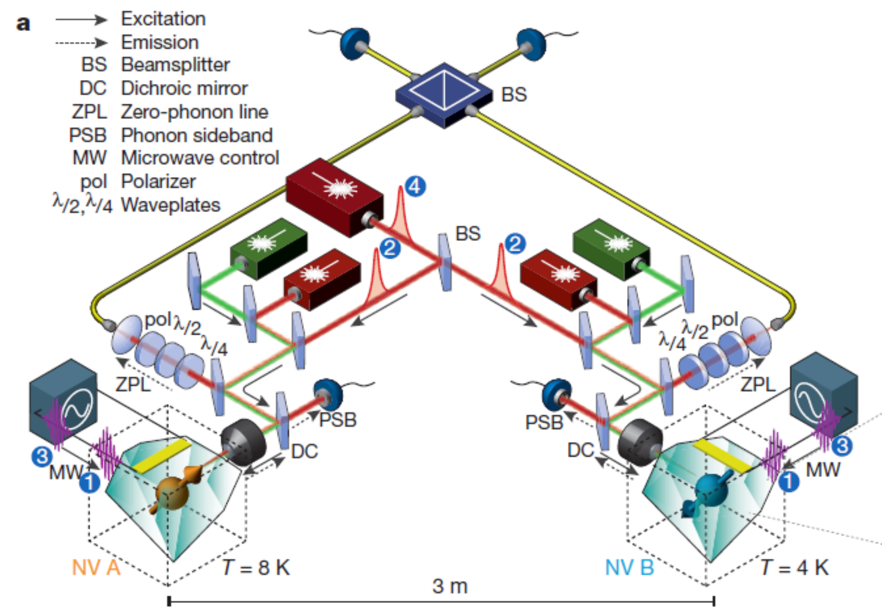
- Spin basics
- General properties of NV centers
- **Toward measurement-based quantum information with the NV center**

Quantum information with NV centers

Quantum error correction demonstrated



Stuttgart group[1]



Delft group[2]

Entanglement generated once every 10 minutes

[1]Waldherr et al. Nature 506, 204 (2014) [2]Bernian et al. Nature 497, 86 (2013)

Distributed entanglement

- Quantum repeater and long distance quantum communication*
- Cluster-state quantum computer*

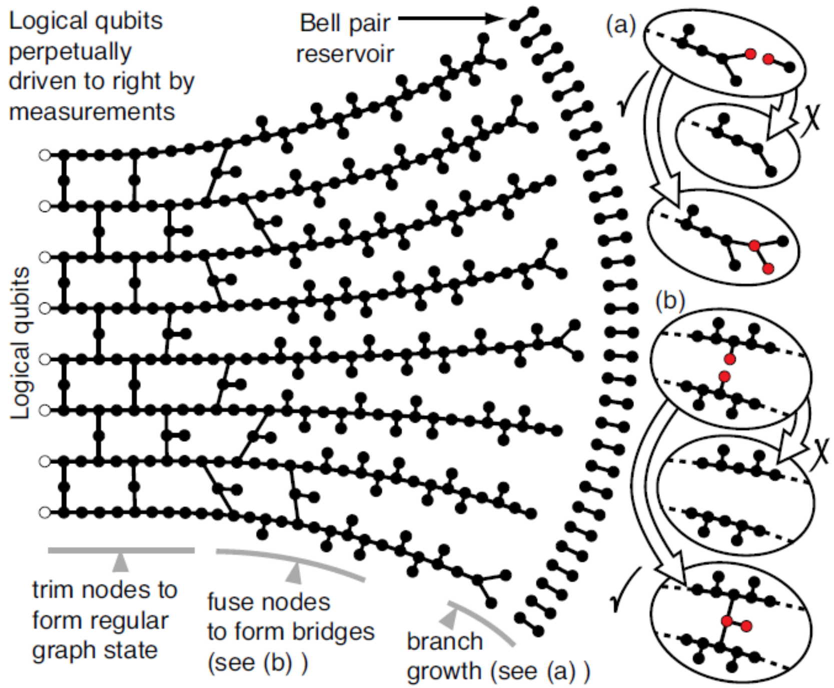


Image from Benjamin, Lovett, and Smith "Prospects for measurement-based quantum computing with solid state spins", *Laser and Photonics Reviews* 3, 556, (2009)

Graph creation:

- Initialize qubit

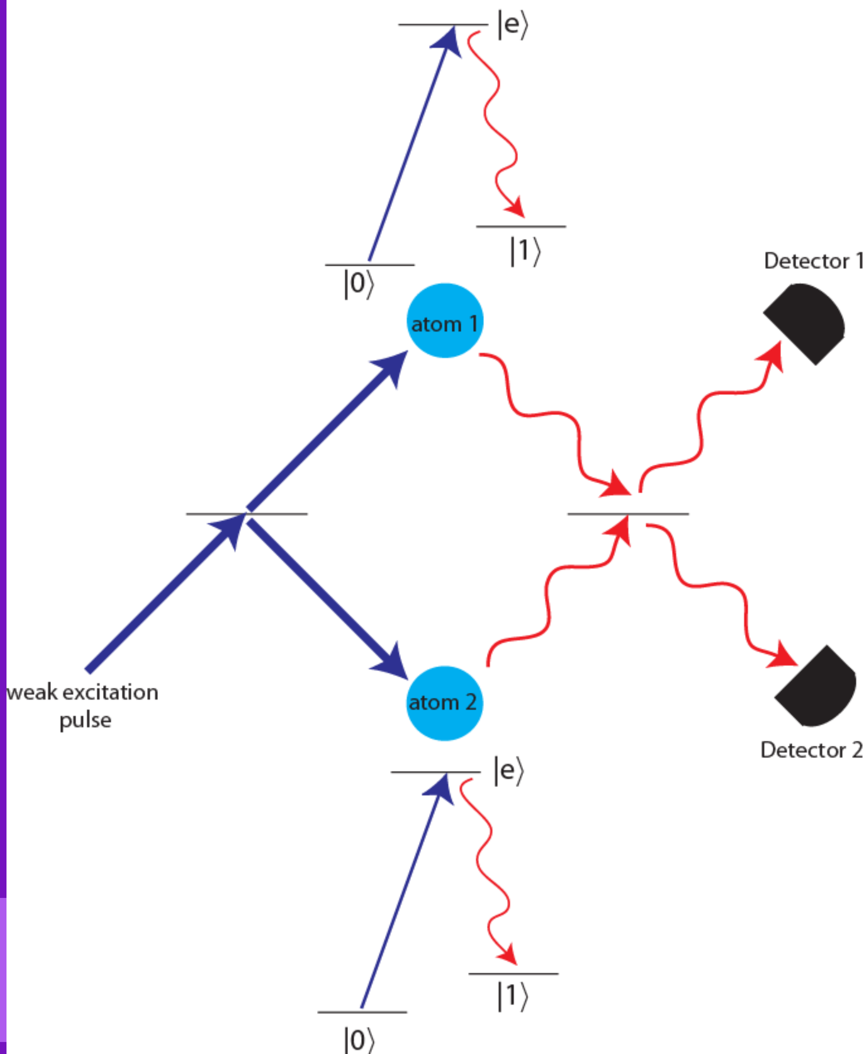
$$|+\rangle = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$$

- Perform a controlled phase gate to create edge
- 2-qubit state is

$$|G\rangle = \frac{1}{2}(|00\rangle + |01\rangle + |10\rangle - |11\rangle)$$

* Duan, Lukin, Cirac, Zoller *Nature* 414, 413, (2001), ** Raussendorf and Briegel, *PRL* 86, 5188 (2001)

Creating entanglement through measurement

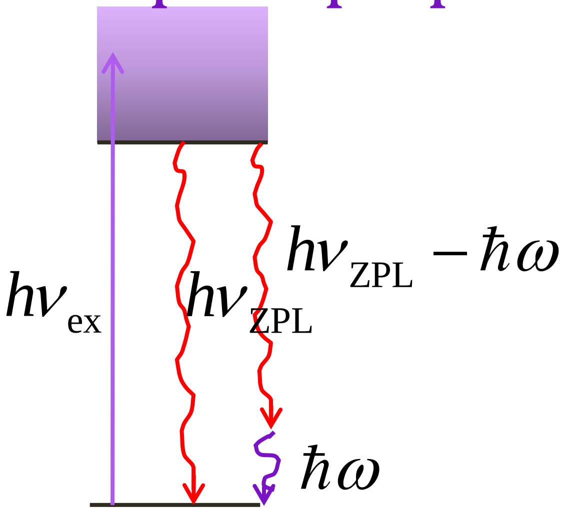


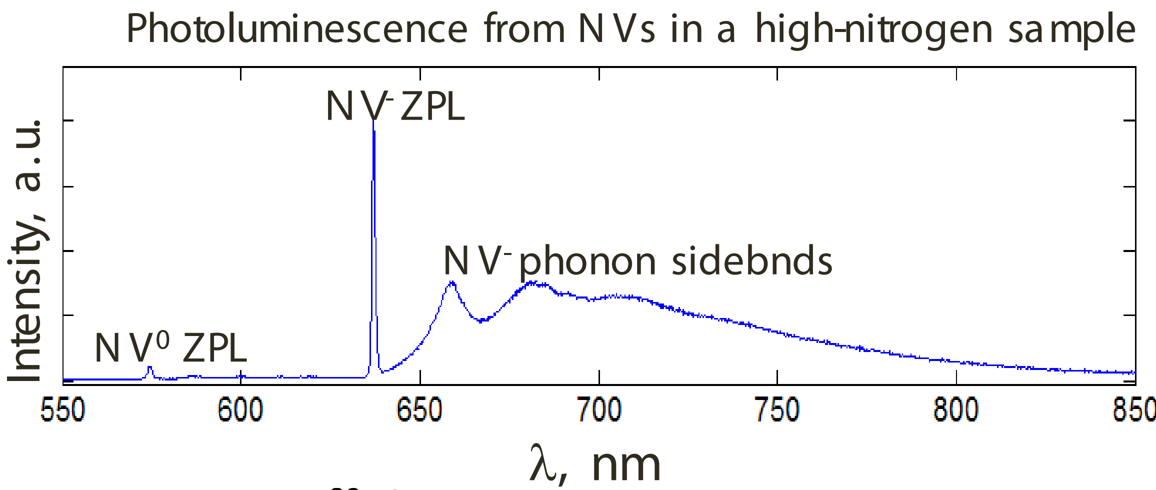
$$\Psi_i = |00\rangle$$

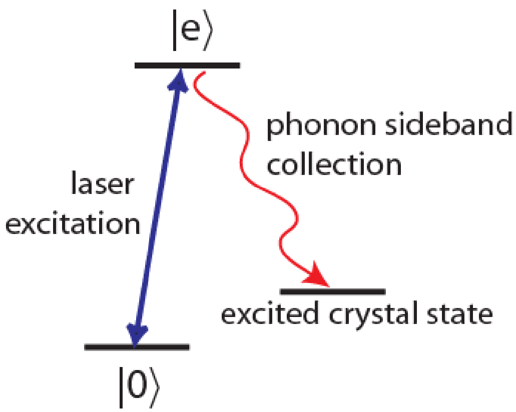
$$\Psi_f = \frac{1}{\sqrt{2}}(|01\rangle \pm |10\rangle)$$

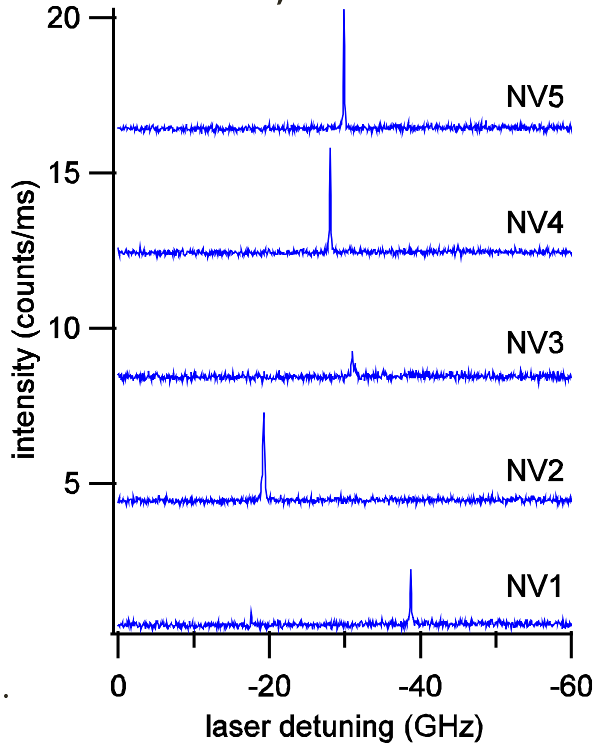
Cabrillo, Cirac, Garcia-Fernandez, Zoller, *PRA* 59, 1025 (1999), Bose, Knight, Plenio, Vedral *PRL* 83, 5158 (1999)

Entanglement success rate is so low due to NV optical properties.



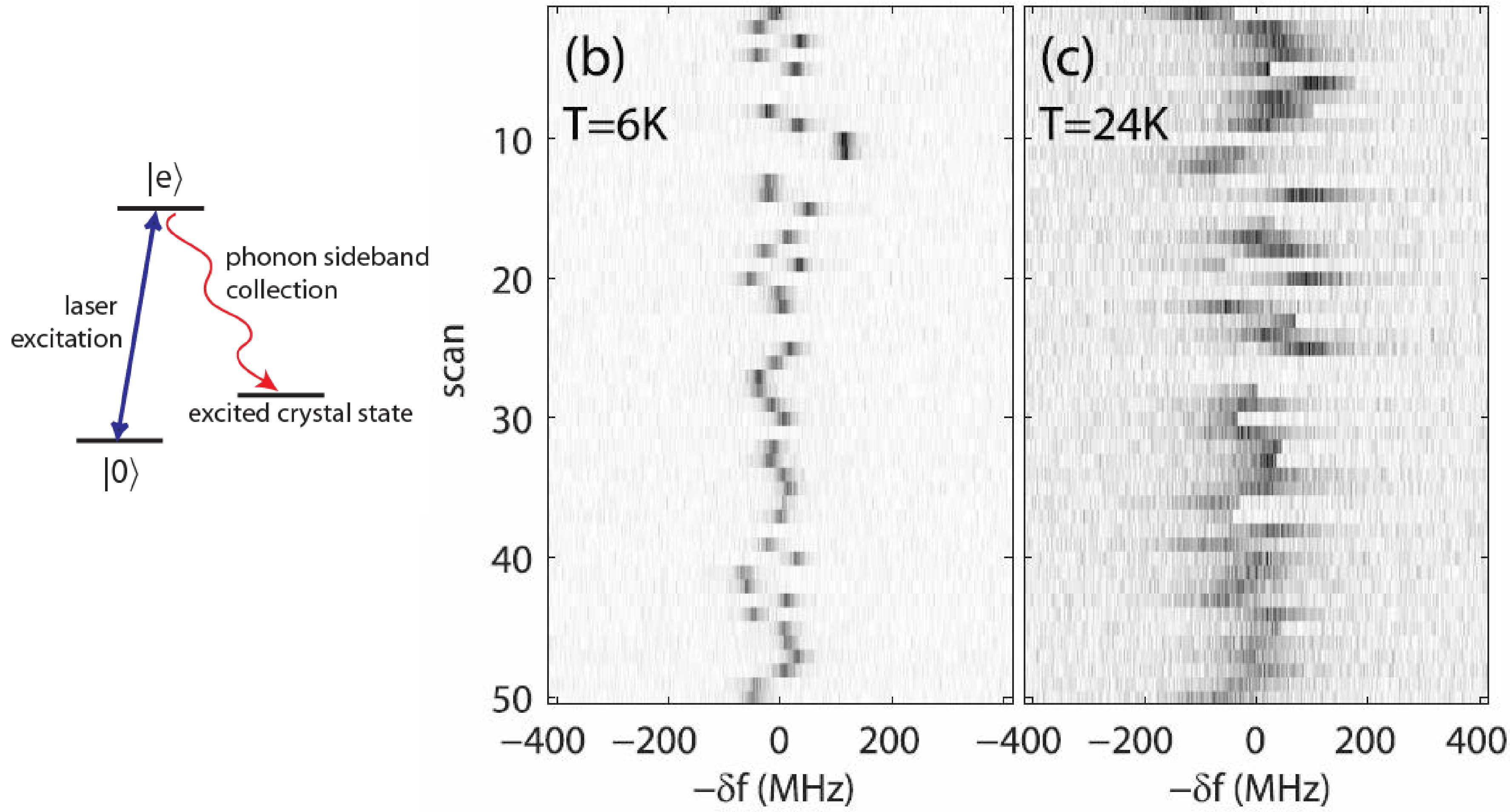






C. Santori, P. E. Barclay, K.-M. C. Fu, S. Spillane, M. Fisch, R. G. Beausoleil," Nanotechnology 21 , 274008 (2010)

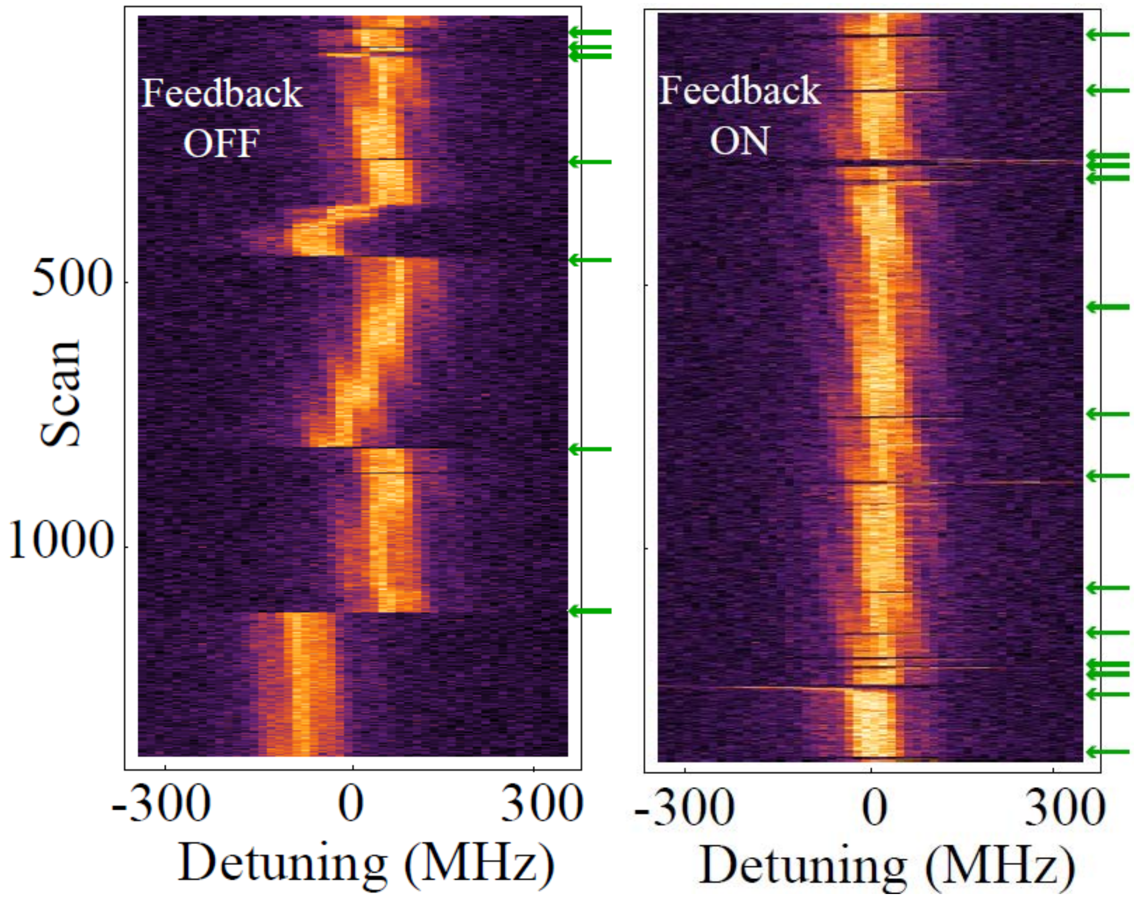
Phonon broadening and diffusion

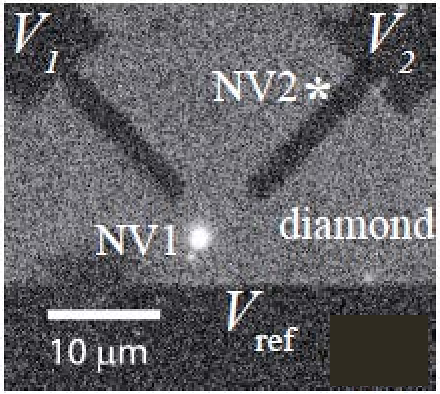


*Fu, Santori, Barclay, Rogers, Manson, Beausoleil *PRL 103*, 256404 (2009),

Real time control of optical transition frequency

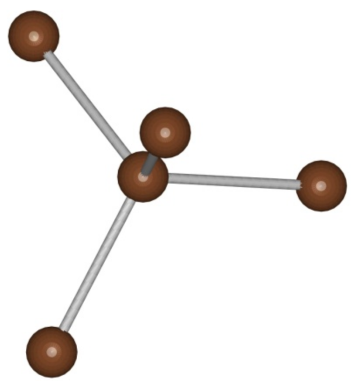
Dynamic stabilization

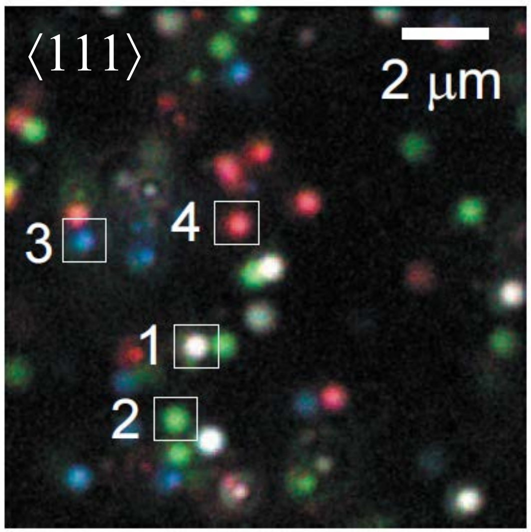


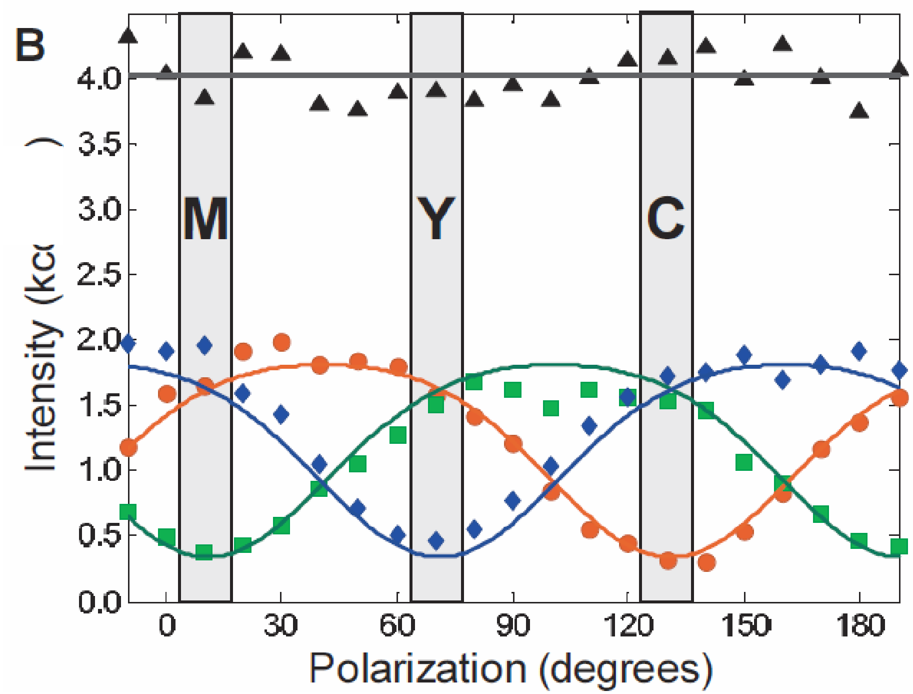


Acosta, Santori, Faraon, Huang, Fu, Stacey, Simpson, Greentree, Prawer, Beausoleil, *PRL* 108, 206401 (2012)), see also static Stark work from Stuttgart, UCSB, Harvard, Delft

Control over NV orientation

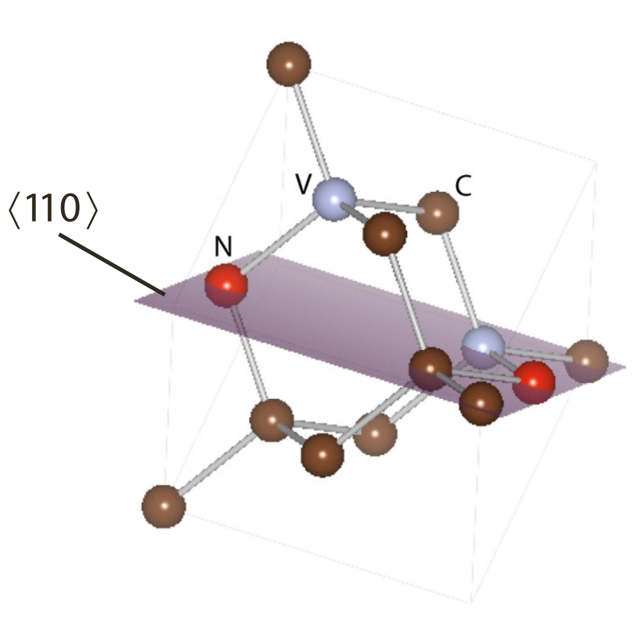






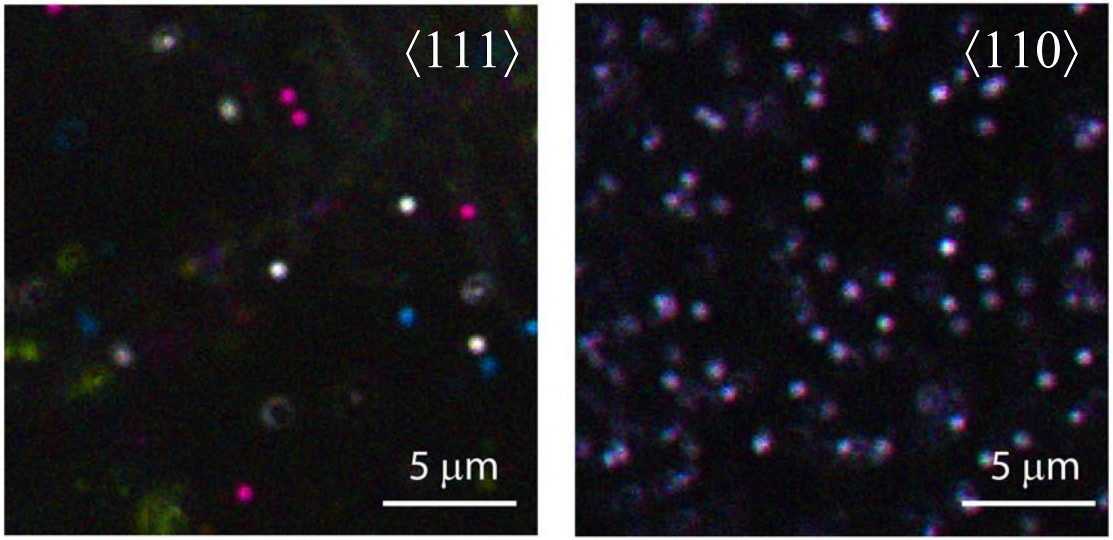
T.P. Mayer Alegre, C. Santori, G. Medeiros-Ribeiro, R.G. & Beausoleil, "Polarization-selective excitation of nitrogen vacancy centers in diamond" *Phys. Rev. B 76*, 165205 (2007) (HP Labs)

How are NVs incorporated during CVD growth?



1. Substitutional N is incorporated and vacancy diffuses to N. → 4 orientations
2. NV forms as a unit during grown. → 2 orientations

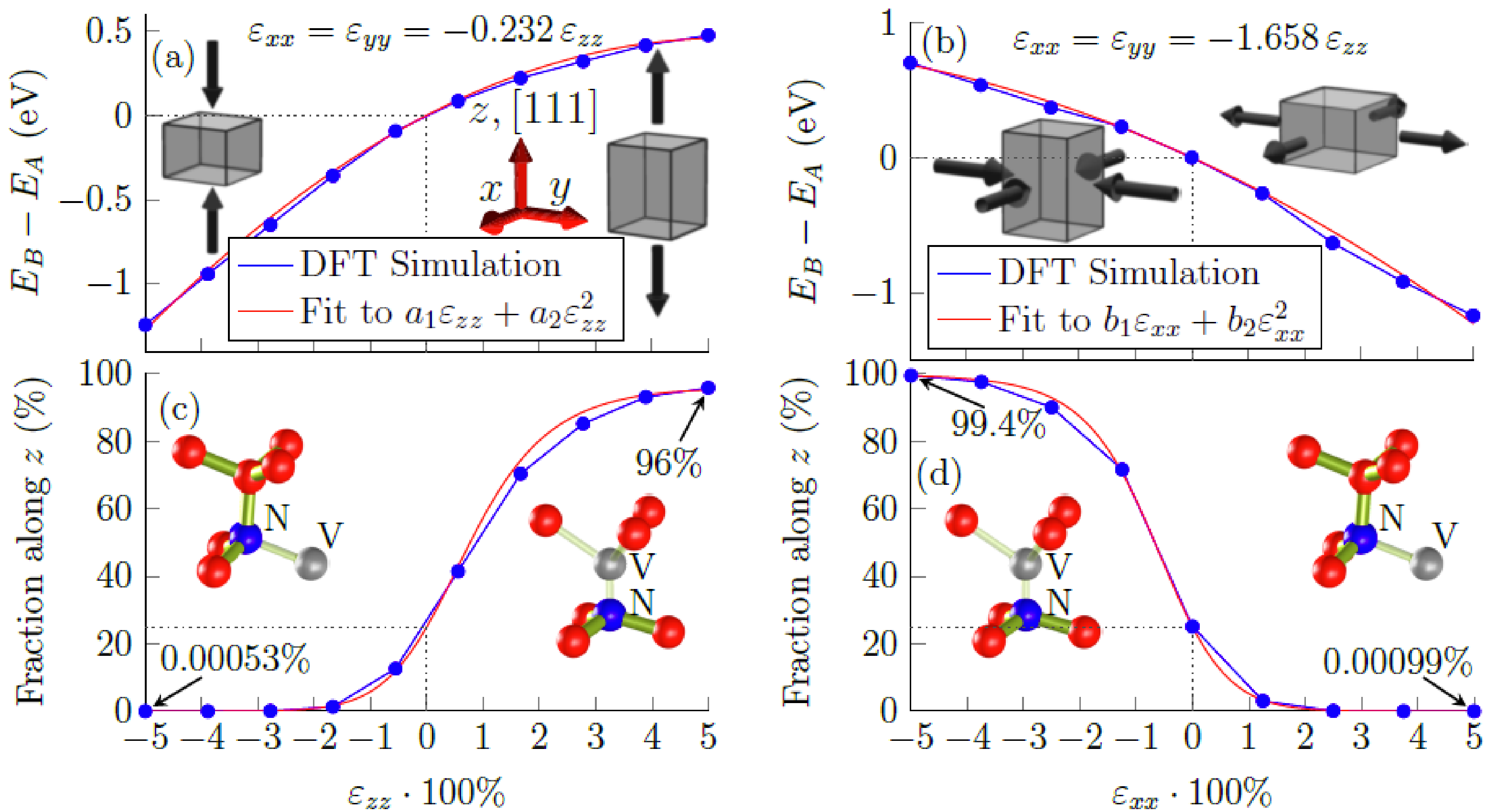
Single color observed for ⟨110 ⟩ sample



Recent Stuttgart result: 94% in a single orientation with (111) growth. (J. Michl *et al.*, 104, 102407 (2014).

A.M. Edmonds, U.F.S. D'Haenens-Johansson, R.J. Cruddace, M.E. Newton, K.-M.C. Fu, C. Santori, R.G. Beausoleil, D.J. Twitchen, M.L. Markham, "Production of nitrogen-vacancy color centers in synthetic diamond," PRB 86, 03521 (2012)

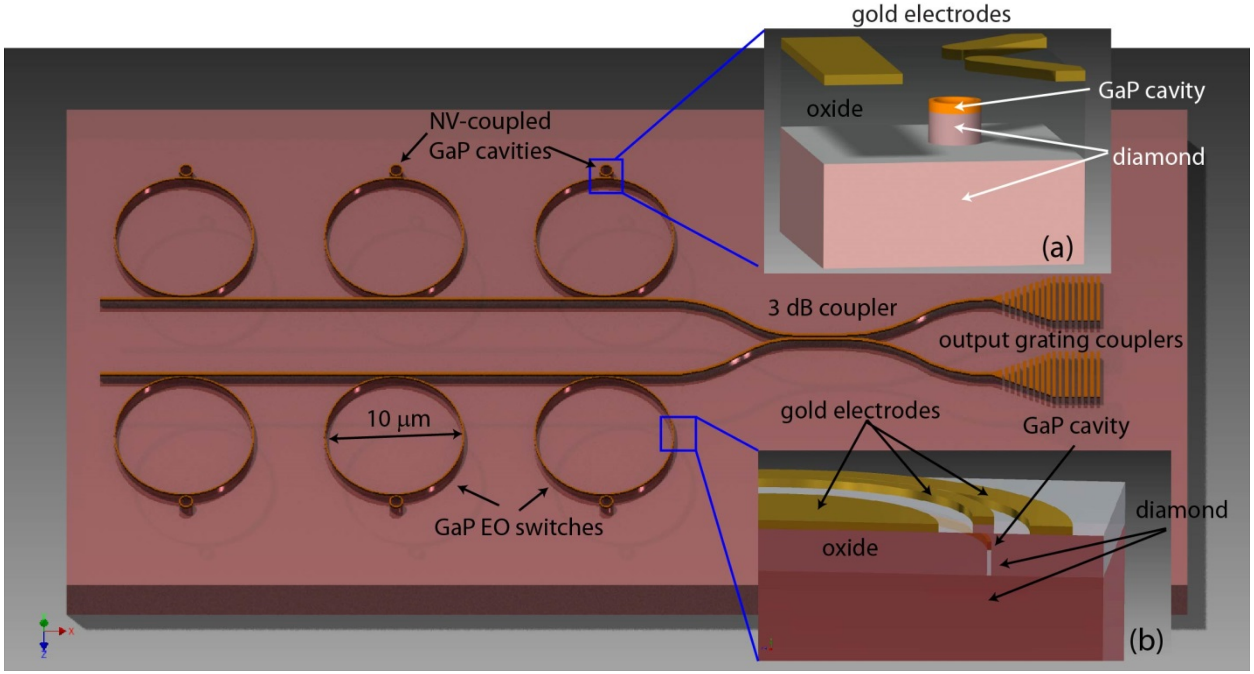
Potential simultaneous control over NV placement and orientation



T. Karin, S. Dunham, K.M.-C. Fu,

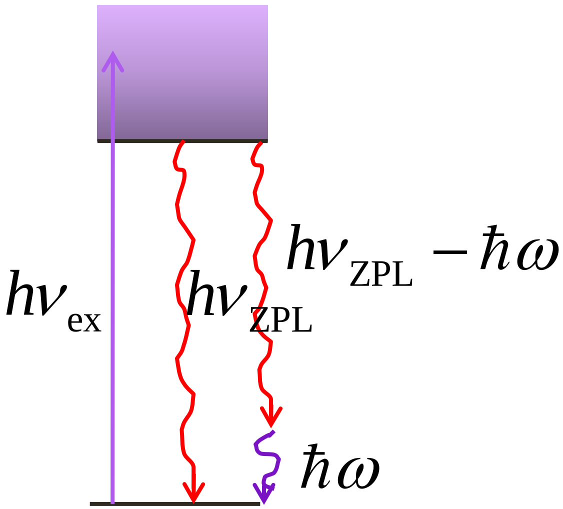
Control of optical properties are possible we will still need further improvements.

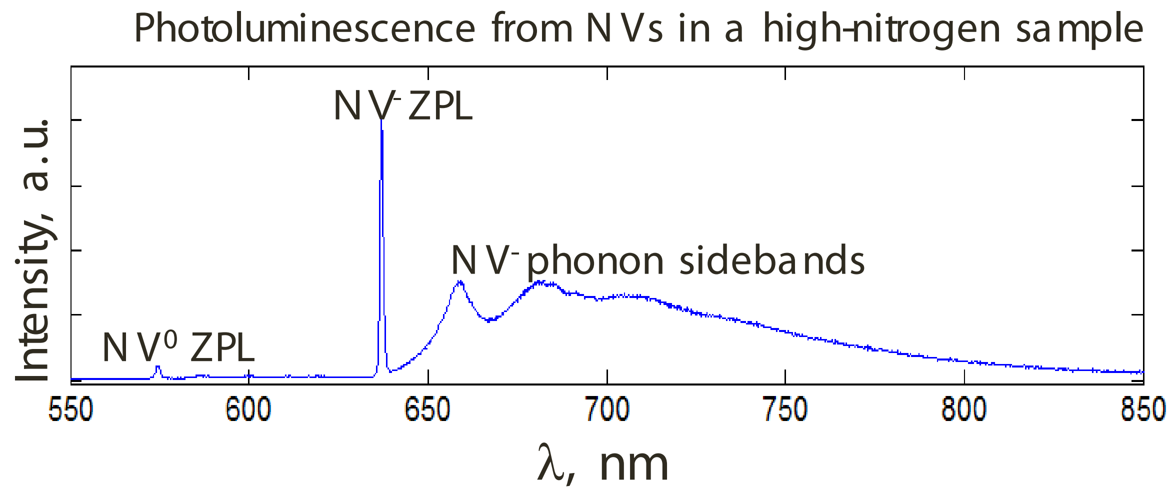
- Brokered graph states*
- Integration into optical chip

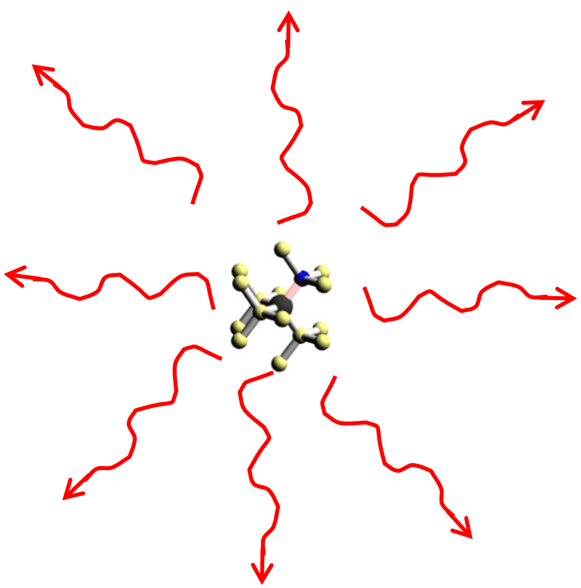


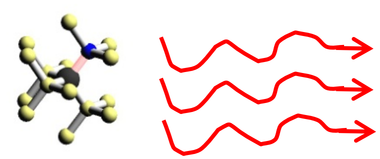
* Benjamin, Browne, Fitzsimons, Morton, *New J of Physics* 8, 141 (2006)

Goal: Collect NV⁻ zero phonon line (ZPL)

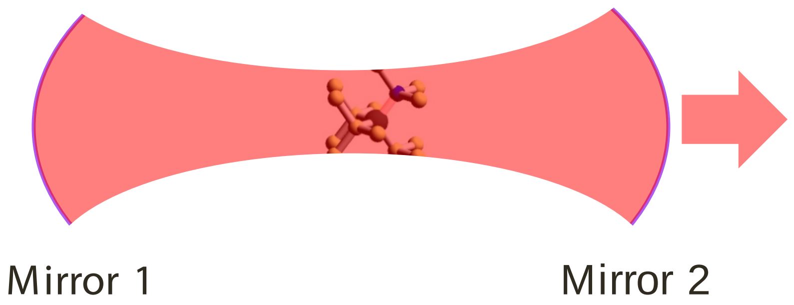








Using a cavity to control NV emission into a useful spectral and spatial mode

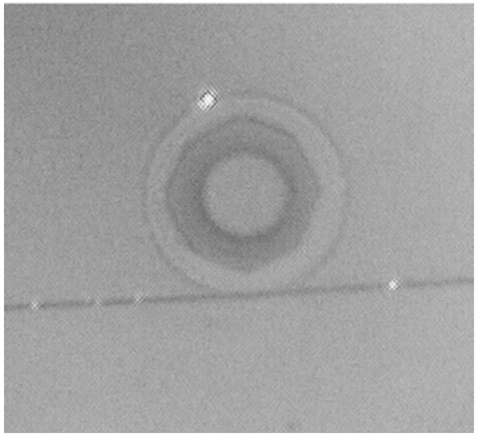


$$F_{cav} = \frac{3}{4\pi^2}\left(\frac{\lambda}{n_{cav}}\right)^3 \frac{n_{cav}}{n_D} \frac{Q}{V_{mode}} \frac{|E_{NV}|^2}{|E_{max}|^2} \frac{\vec{E}_{NV}\cdot\vec{\mu}}{\left|\vec{E}_{NV}\right|\left|\vec{\mu}\right|}$$

- Cavity is on resonance with NV
- NV is at cavity maximum
- NV polarization is aligned to cavity mode.
- High quality factor
- Small mode volume

Main geometries for optically integrated NV diamond

Nanoparticles



HP Labs[1]

Features

"Easy" cavity fabrication

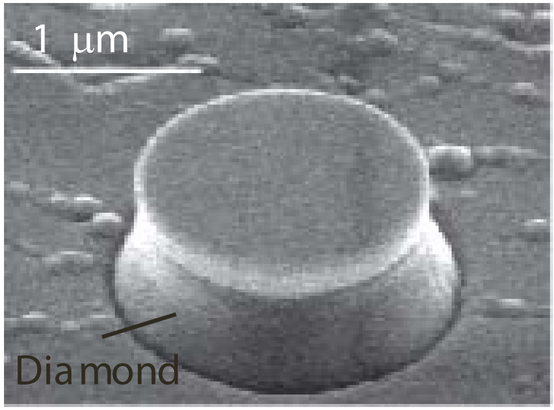
Q > 10^6 in our disks

Challenges

Poor NV optical characteristics

NV-cavity alignment

Bulk Hybrid



HP Labs[3]

Features

Better NV characteristics

Integration of EO material

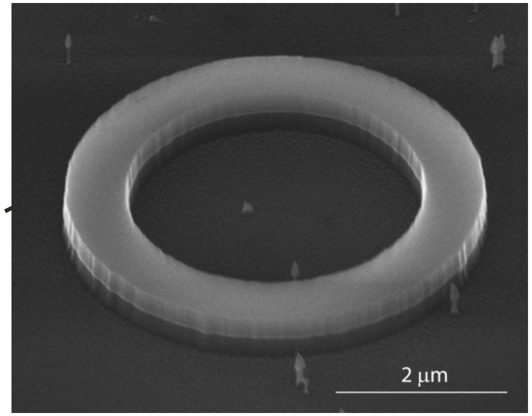
Challenges

Difficult to fabricate

Low field at NV site

Poor NV characteristics

Diamond only



HP Labs[2]

Features

Better NV characteristics

High field at NV site

Challenges

Difficult to fabricate

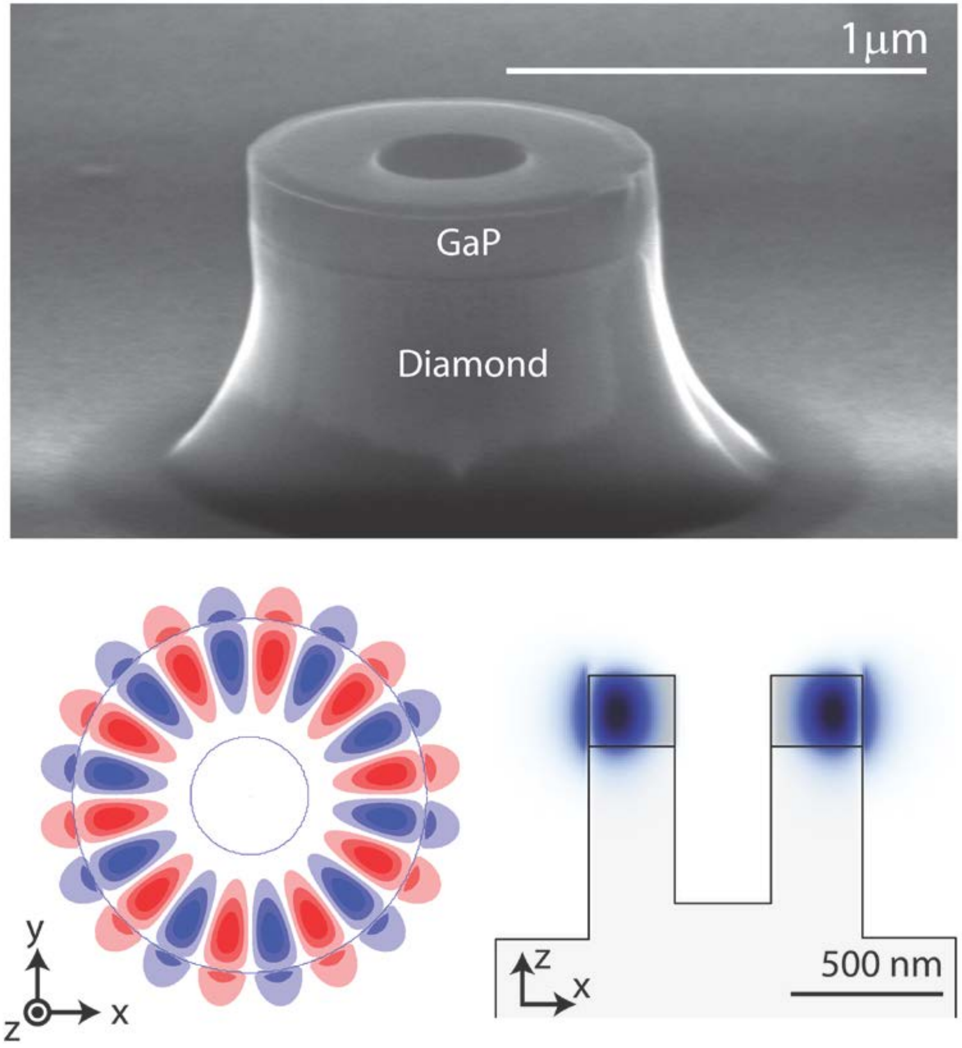
Poor NV characteristics

[1]Santori et al. *Nanotechnology*, *21*, 274008 (2010) [2]Faraon et al. *Nature* Photonics 5, 301 (2011) [3]Fu *et al.* New J. of Physics 13, 055023 (2011), Barclay *et al.*, *Physical Review* X 1, 011007(2011)

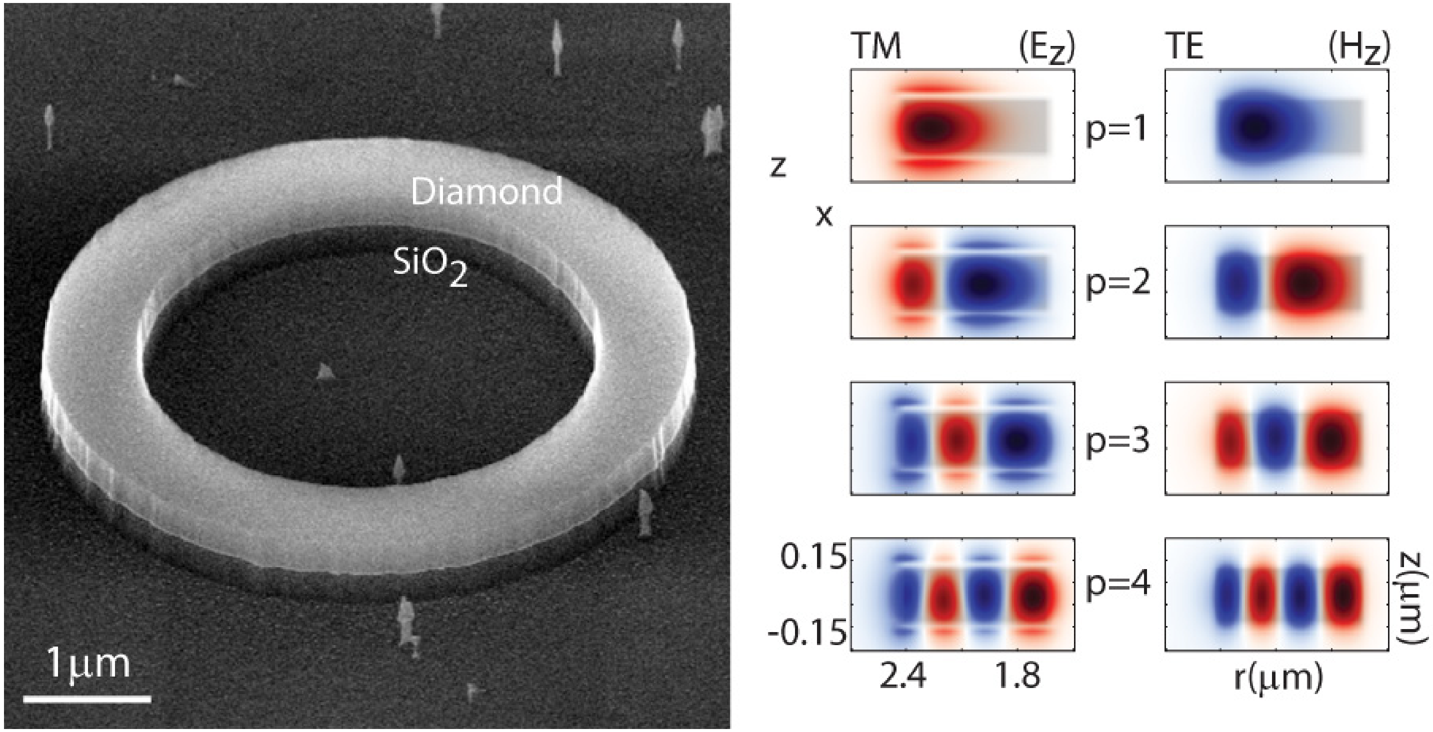
Nanoparticle-cavity work: Harvard (M. Lukin), Humbolt (O. Benson), Caltech (O. Painter)

Single-crystal diamond-cavity work: U. Oregon (H. Wang), Harvard (M. Loncar, E. Hu), Stuttgart (J. Wrachtrup), Technion (R. Kalish, J.Salzman)

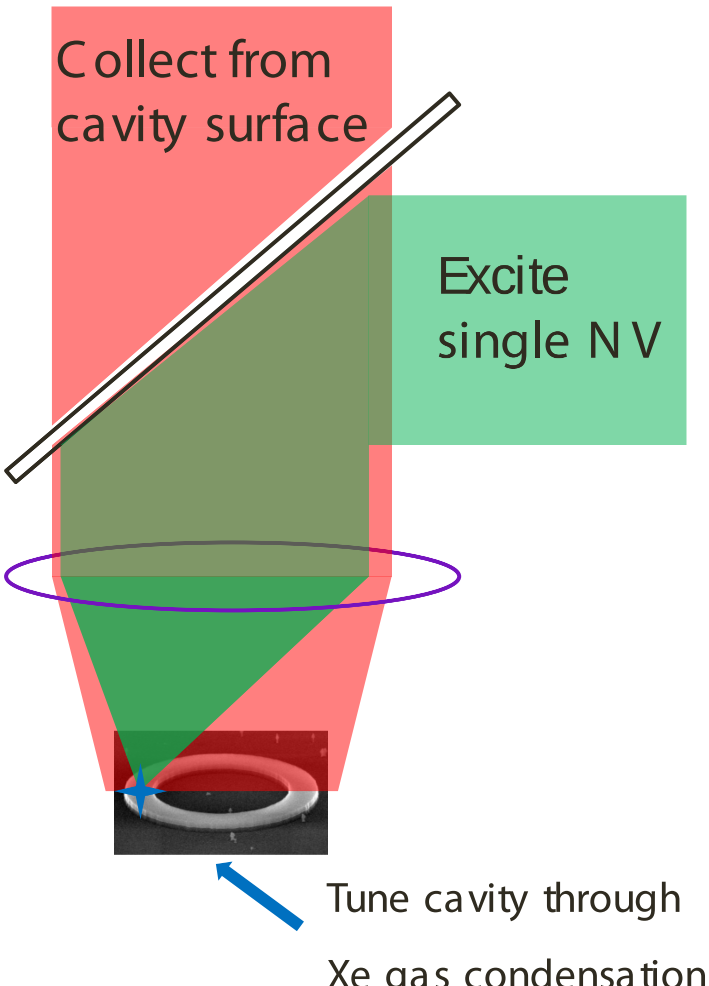
GaP-diamond ring microcavities

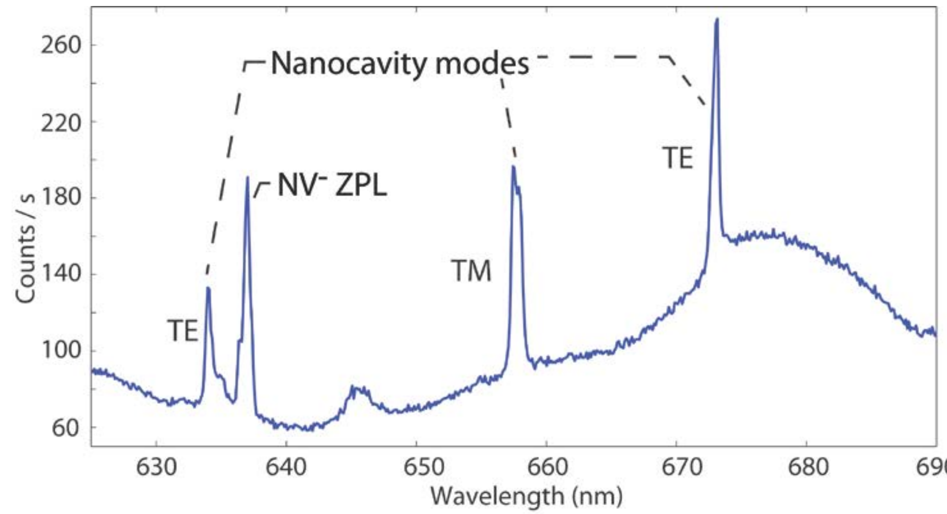


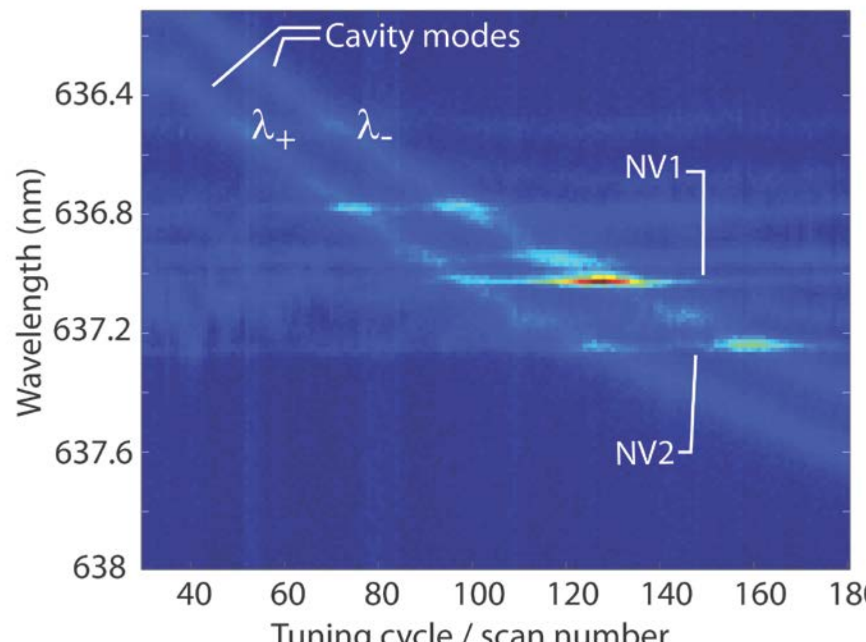
Diamond on SiO_2 microrings



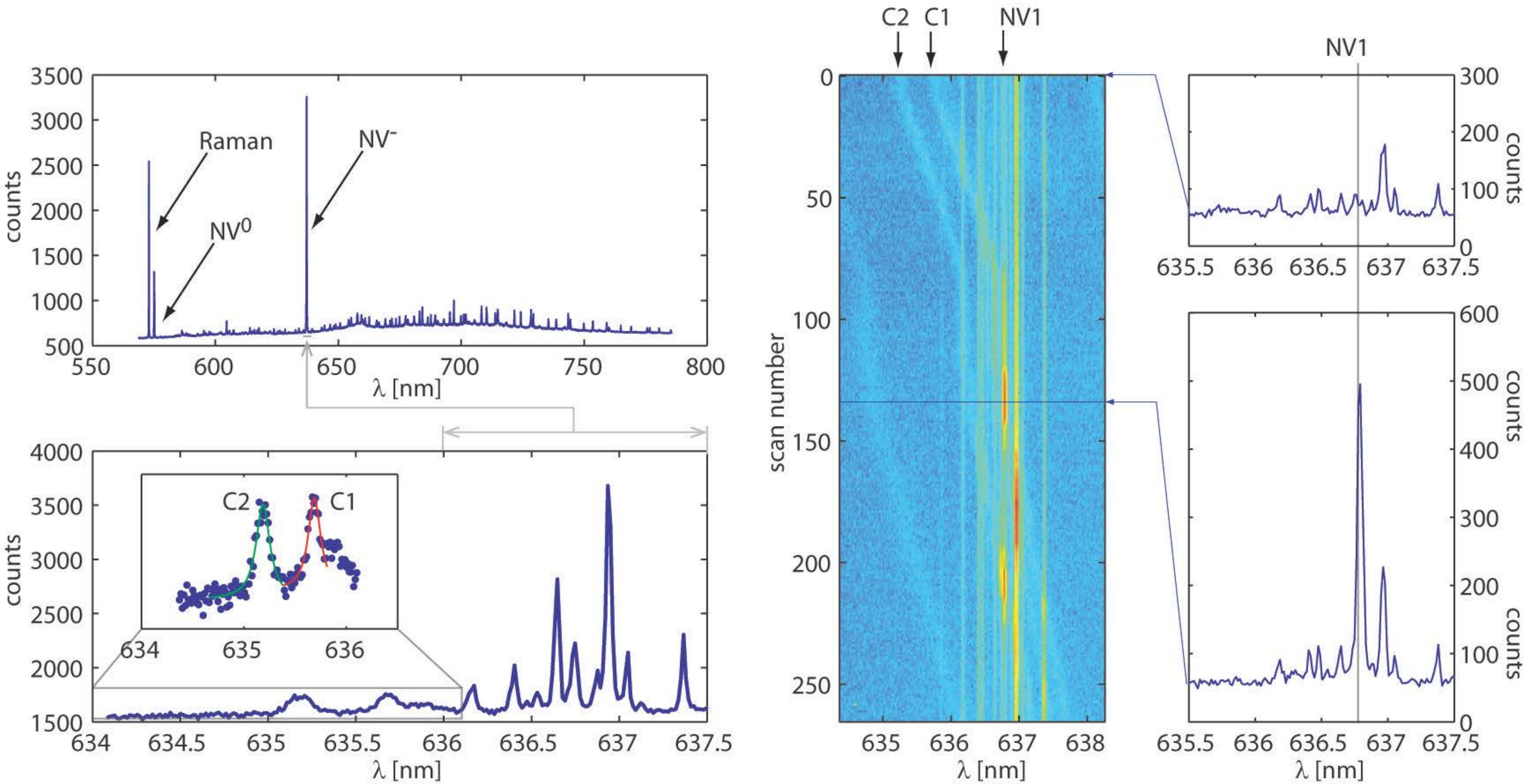
Observing cavity-NV interaction I: GaP



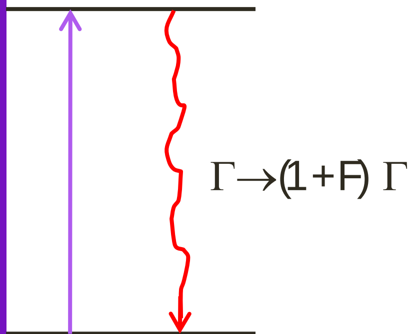




Observing cavity-NV interaction II: Diamond

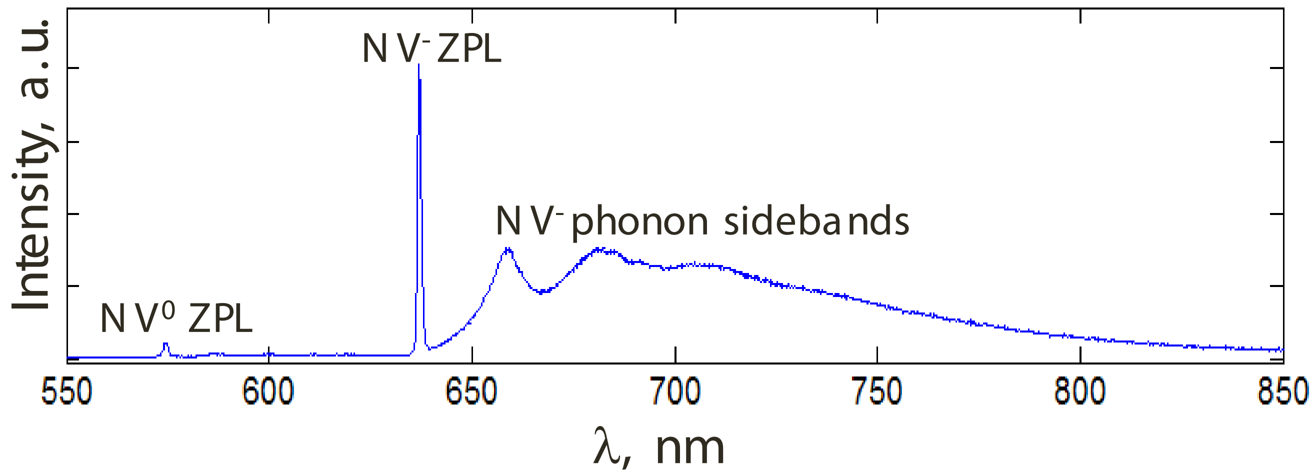


Measuring Purcell enhancement: A quantitative measurement of cavity-NV interaction



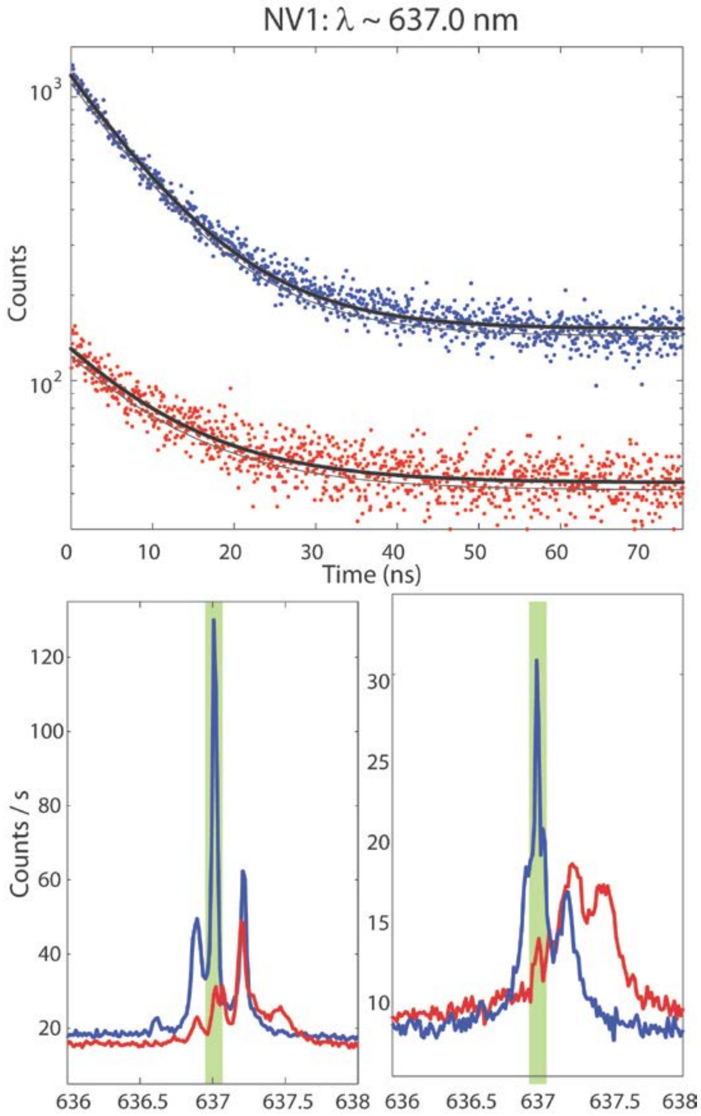
$$F_{cav} = \frac{3}{4\pi^2}\left(\frac{\lambda}{n_{cav}}\right)^3 \frac{n_{cav}}{n_D} \frac{Q}{V_{mode}} \frac{|E_{NV}|^2}{|E_{max}|^2} \frac{\vec{E}_{NV}\cdot\vec{\mu}}{|\vec{E}_{NV}||\vec{\mu}|}$$

Photoluminescence from NVs in a high-nitrogen sample



Ideal: 50% lifetime → F = 1, NV case: 50% → lifetime F = 33

GaP lifetime modification

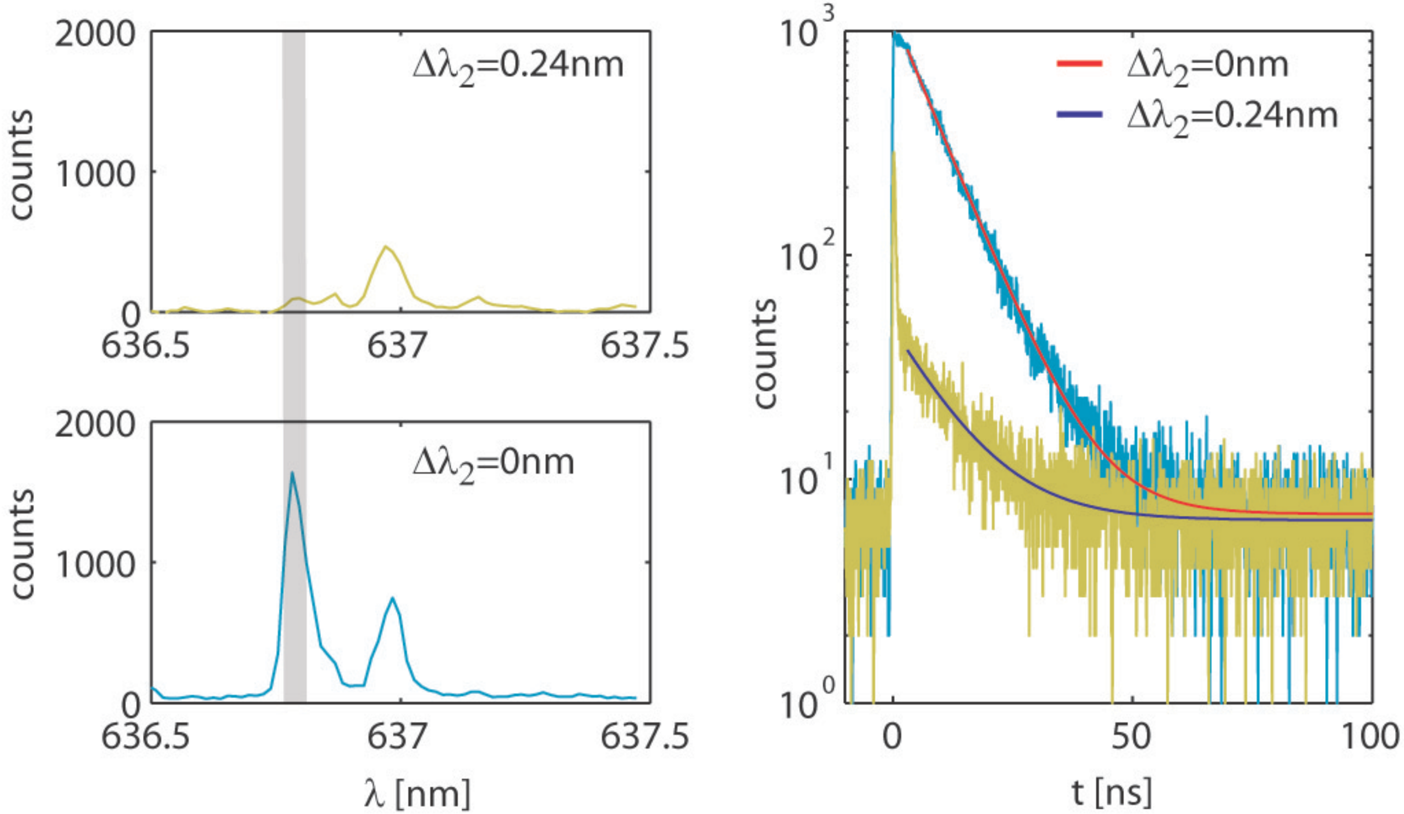


$$\Gamma = 11.6 \pm 0.3\,\text{ns} \rightarrow \Gamma = 9.7 \pm 0.1\,\text{ns}$$

$$F_{ZPL} = 6.3 \pm 1.0$$

P.E. Barclay, K.-M.C. Fu, Charles Santori, Andrei Faraon, and Raymond G. Beausoleil, *Physical Review X* 1, 011007 (2011)

Purcell factor in all-diamond cavity



$$\Gamma = 11.1\text{ns} \rightarrow \Gamma = 8.3\text{ns}$$

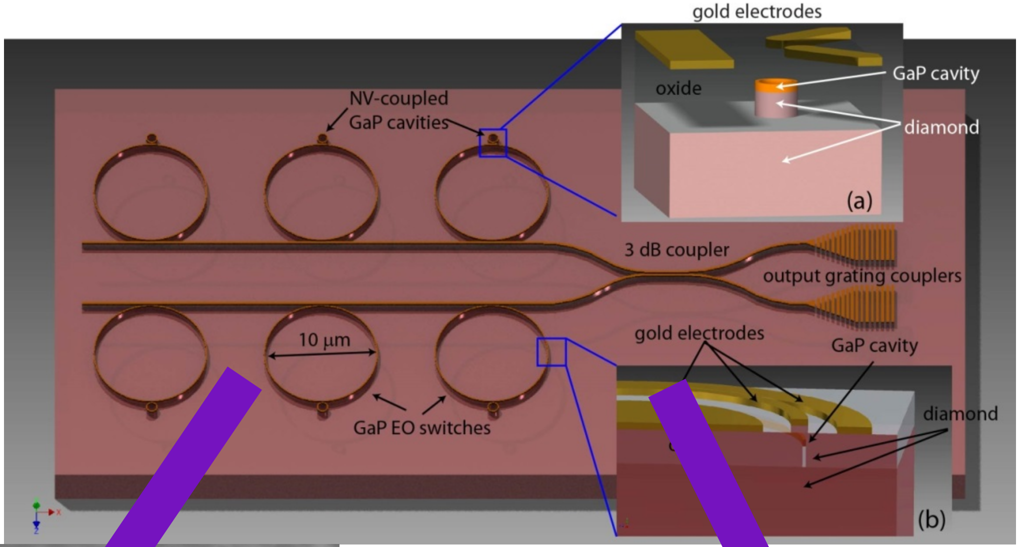
$$F_{ZPL} = 11$$

Most recent HPL result: F = 70*

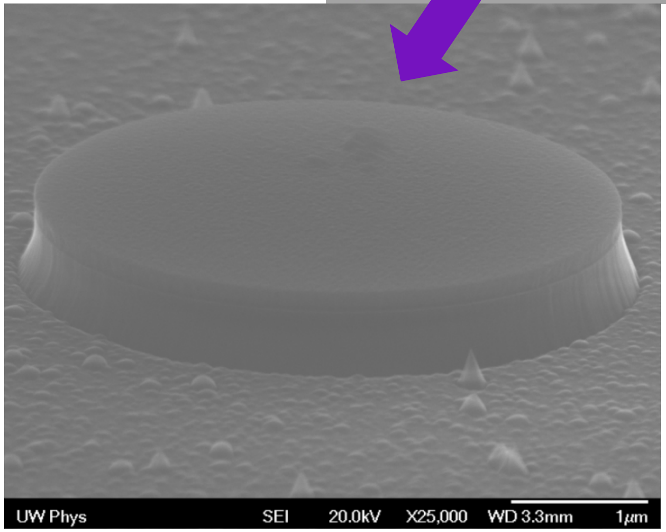
A. Faraon, P. E. Barclay, C. Santori, K.-M.C. Fu, and R. G. Beausoleil, *Nature Photonics* 5, 301 (2011)

* A. Faraon et al., Phys. Rev. Lett. **109**, 033604 (2012)

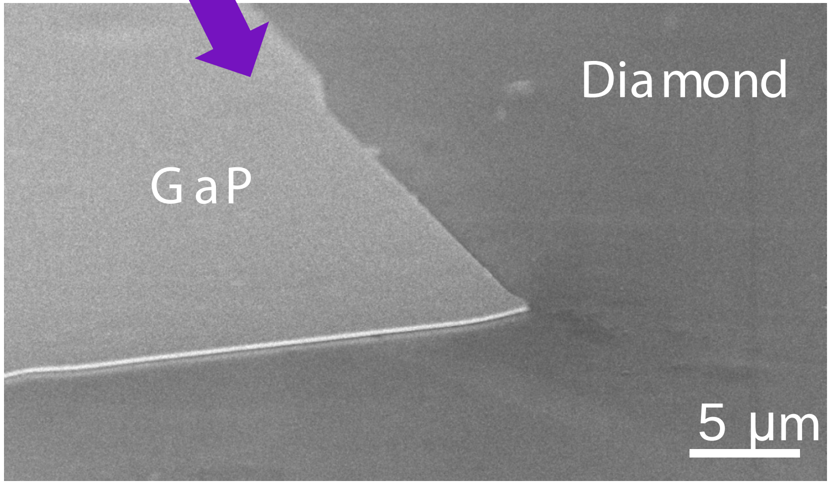
Current direction at UW: Deterministic fabrication of integrated devices in the GaP:diamond platform



Poly-GaP

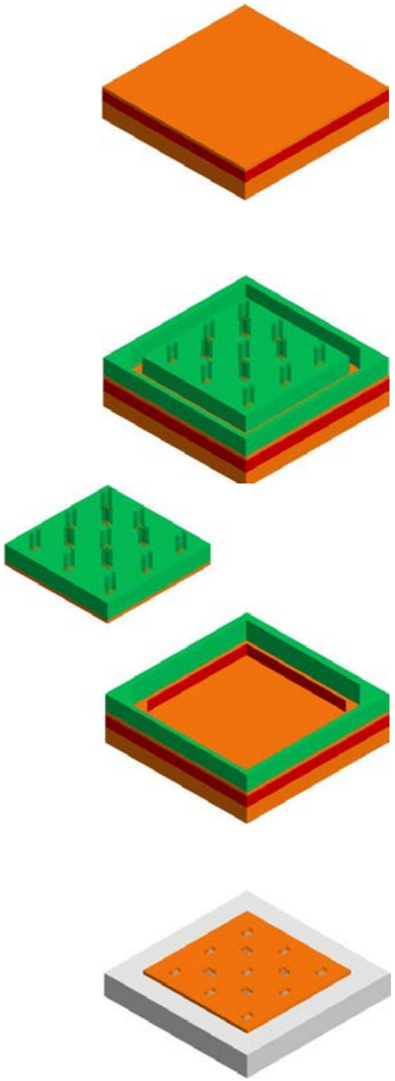


Single crystal GaP



In collaboration with Yuncheng Song and Larry Lee at Yale

Epitaxial lift-off and transfer of single-crystalline GaP

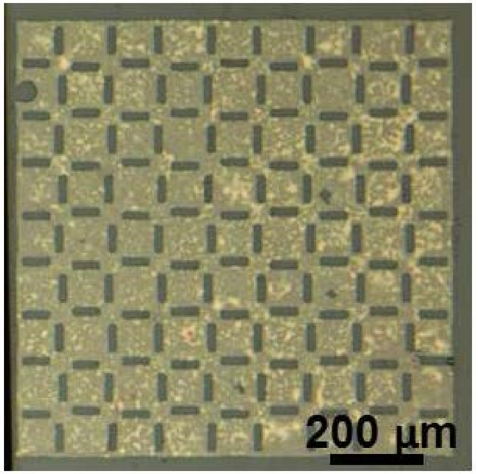


- Substrate: 200 nm GaP\800 nm AlGaP\GaP bulk

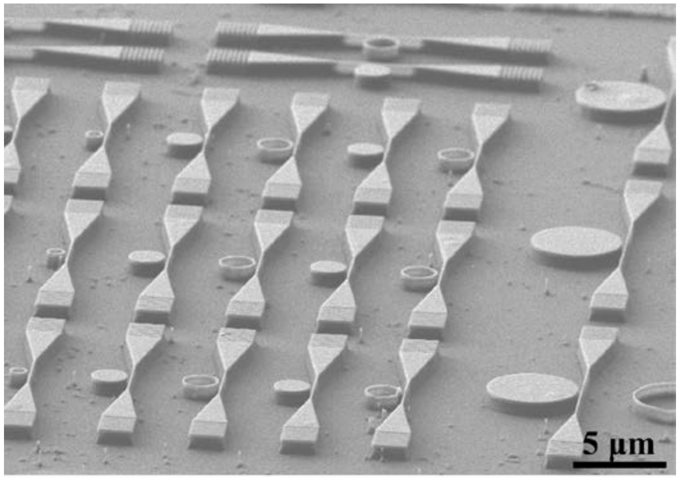
- Photoresist layer as mechanical support
- Cl_2/Ar ICP-RIE

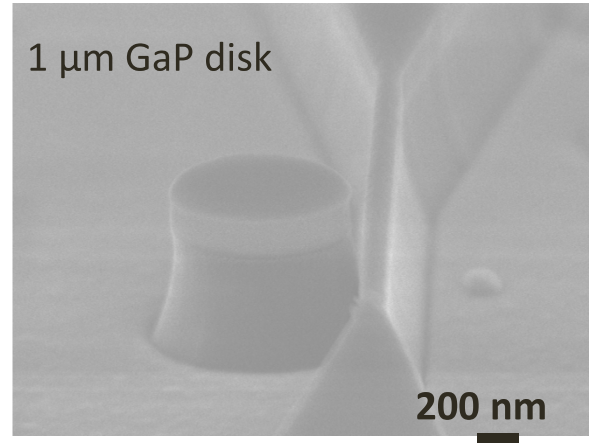
- Selective HF wet etch of AlGaP layer for GaP release

- Transfer of released layer onto diamond
- Photoresist removal

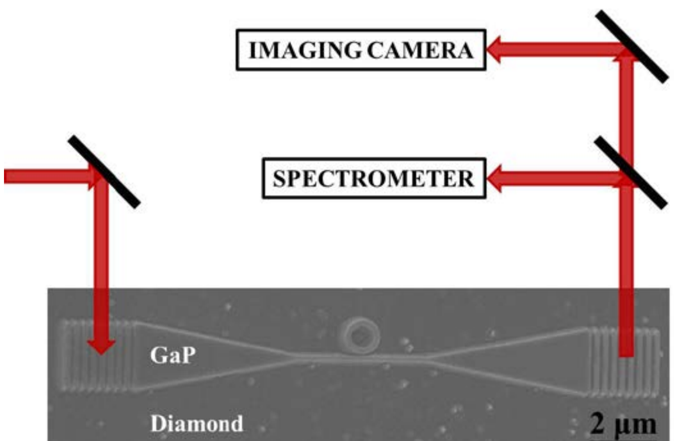


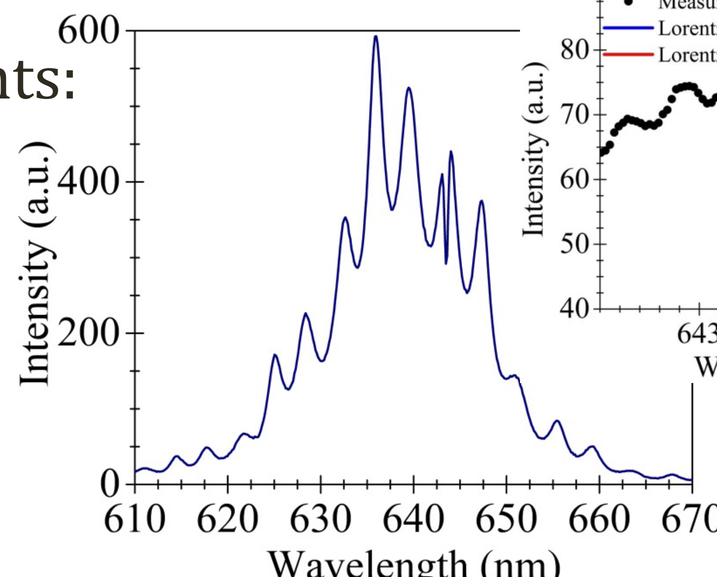
Coupled GaP resonator-waveguide structures on mechanical-grade diamond

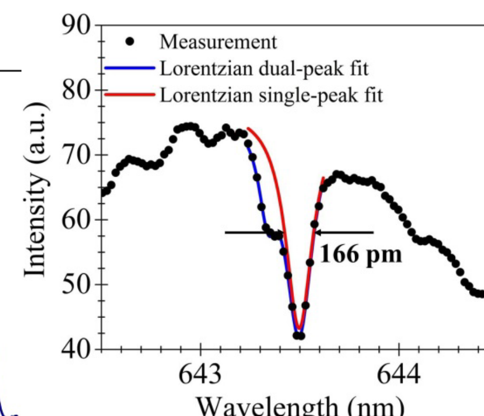




- Transmission measurements:







Q ~ 3800

N. Thomas, R.J. Barbour, Y. Song, M.L. Lee, K-M.C. Fu, Optics Express 22, 13555 (2014)

Estimated photon collection efficiency in our structures

$$\eta_{NV-WG} = \eta_{ZPL} \times \beta_{ZPL} \times \eta_{cav-WG}$$

$$\eta_{NV-WG} = \frac{\gamma_{ZPL}}{\gamma_{PSB} + \gamma_{ZPL}\left(F_{ZPL} + 1\right)} \times F_{ZPL} \times \frac{Q_i}{Q_c + Q_i}$$

18

6,000

10,000

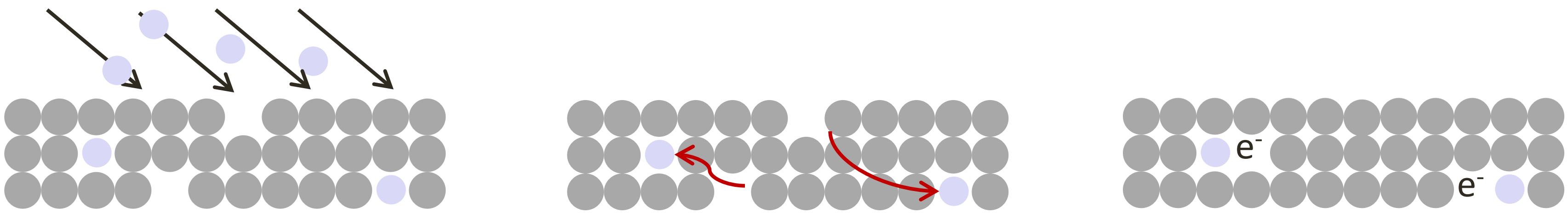
- Compare to

  free-space coupling: $\eta \approx 0.03\%$

  solid immersion lenses: $\eta \approx 0.3\%$

Creation of near-surface NV^- centers in diamond by ion implantation and annealing

Ion implantation → High-temperature anneal → Low-temperature anneal[1]



- Create vacancies
- Provide N to lattice

- Diffusion and trapping of vacancies by implanted N

- Convert NV0 → NV^-

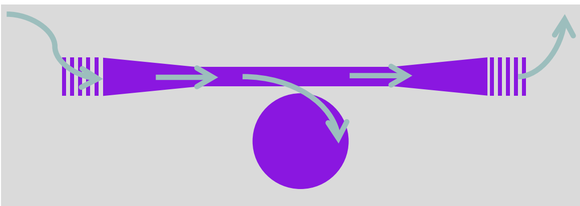
N^+ implantation, 10kV

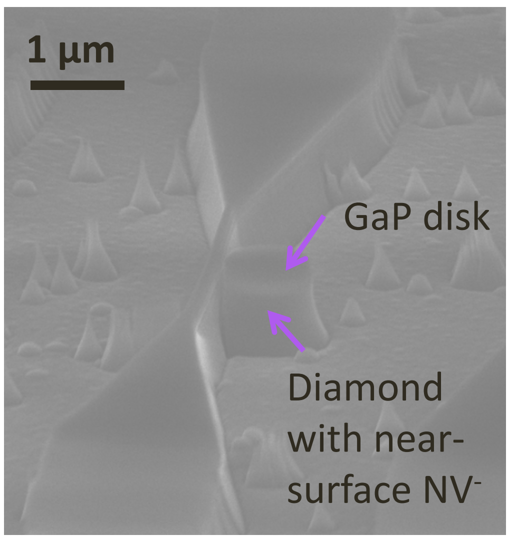
1 hour in forming gas @ 900C

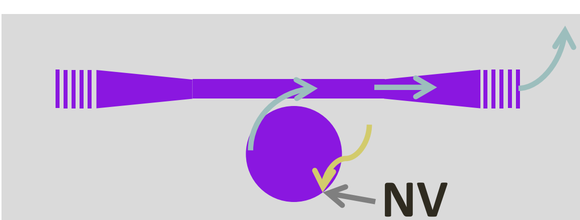
12 hours in air @ 460C

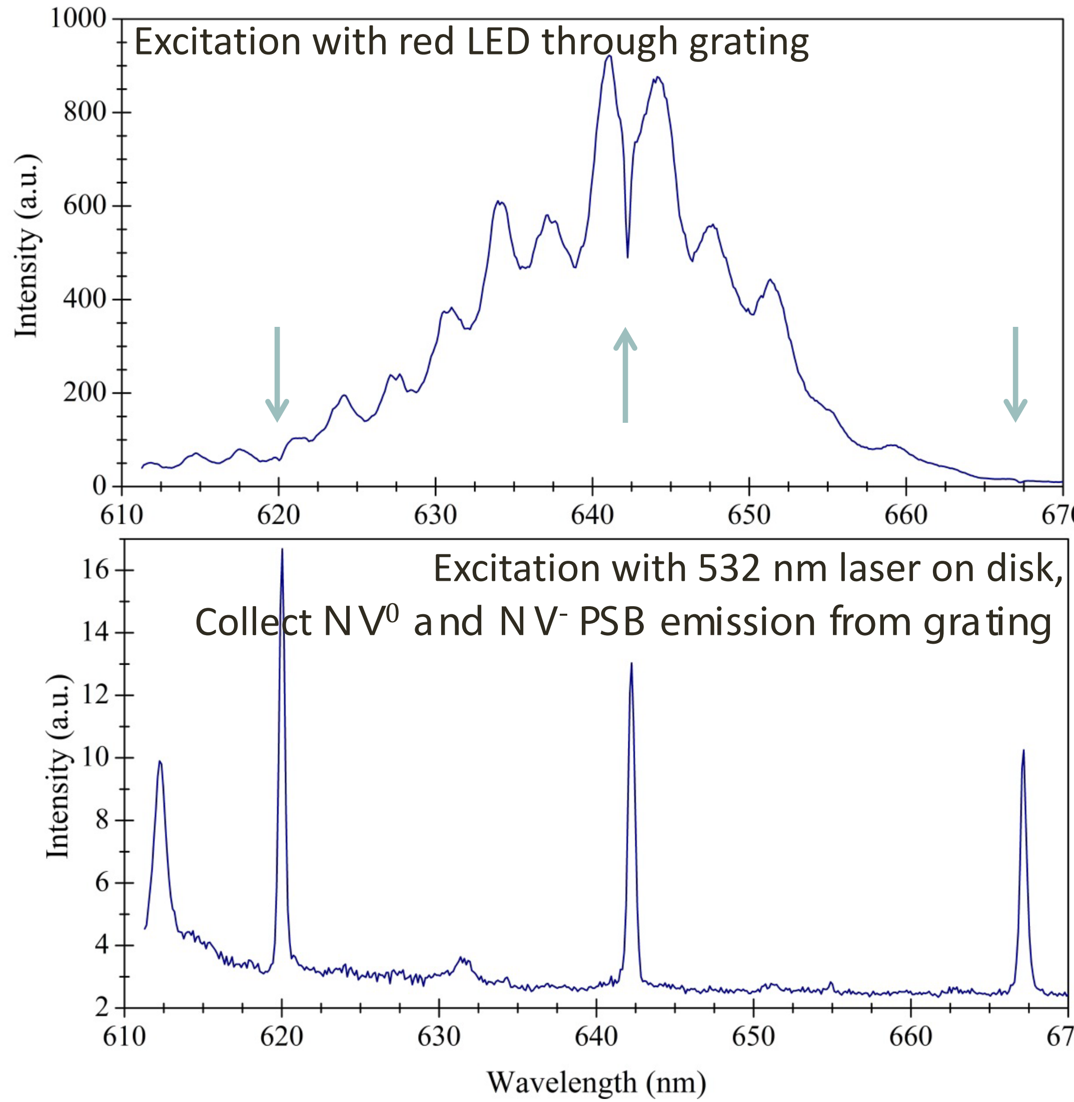
[1] K-M. C. Fu, C. Santori, P. E. Barclay, R. G. Beausoleil, Applied Physics Letters 96 , 121907 (2010)

Room temperature off-chip coupling of NV emission coupled into GaP disk resonators

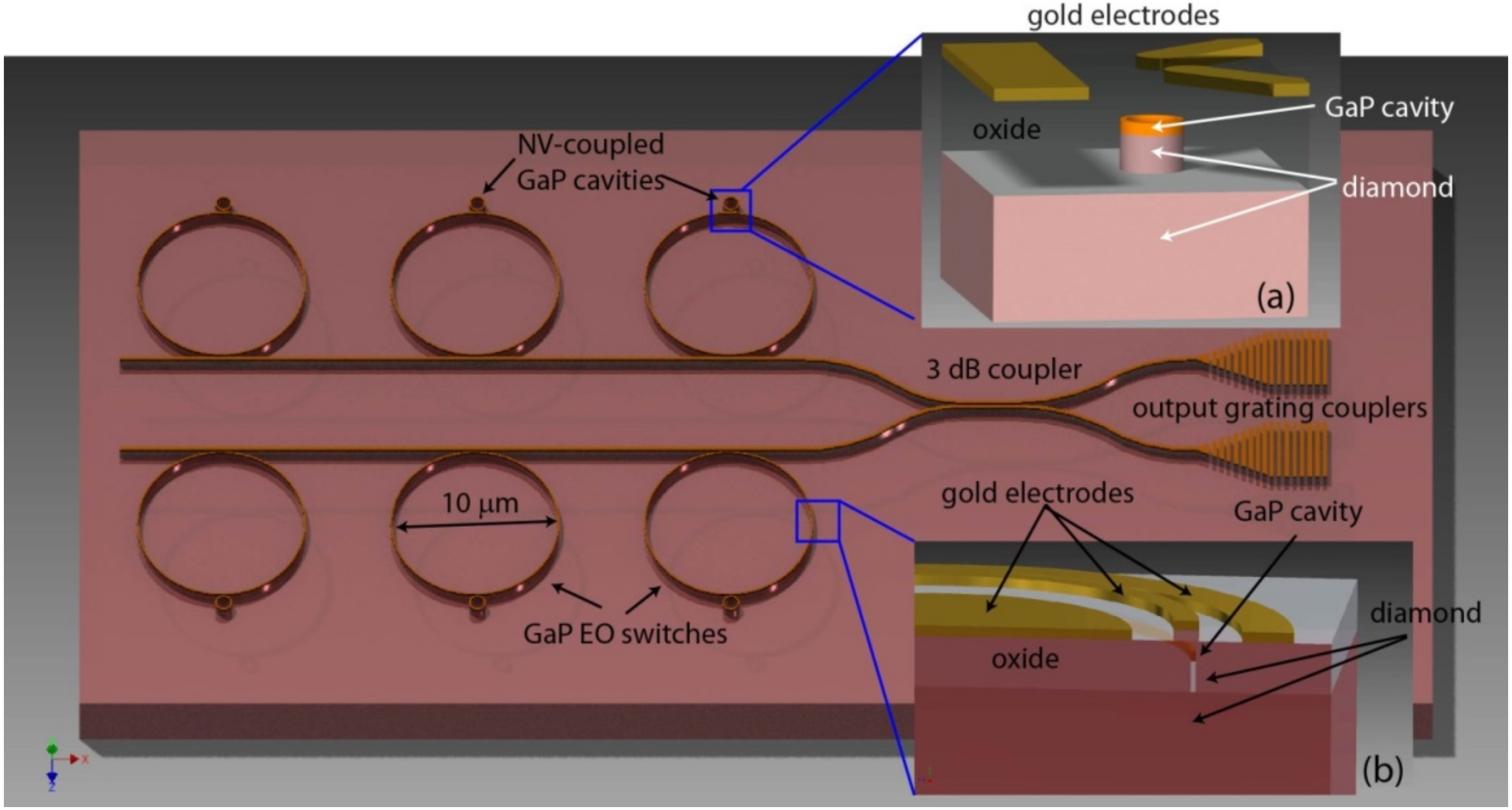








Outlook


gold electrodes
GaP cavity
oxide
diamond
(a)
NV-coupled
GaP cavities
3 dB coupler
output grating couplers
10 μm
GaP EO switches
gold electrodes
GaP cavity
diamond
oxide
(b)

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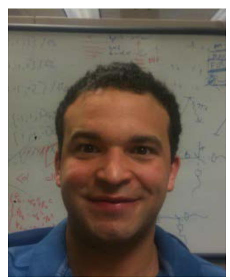
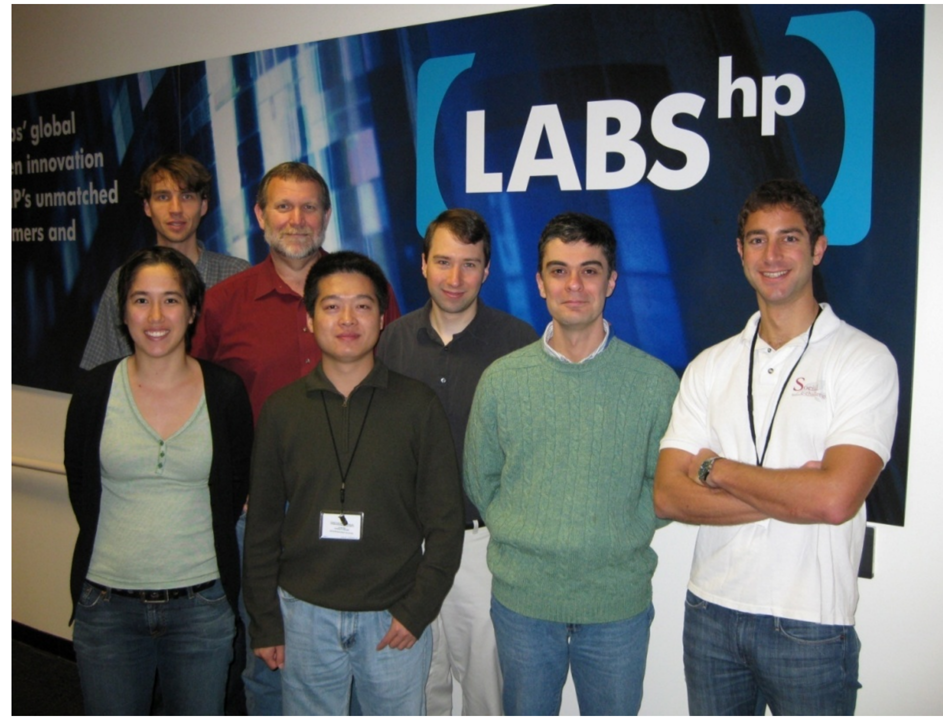
Paul Barclay (U. Calgary)





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