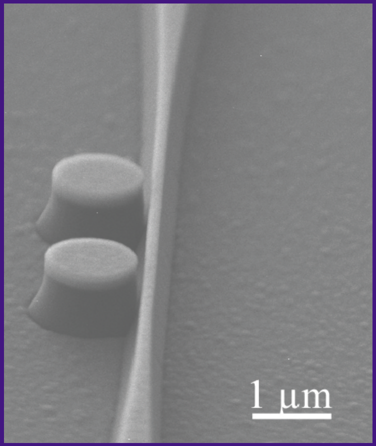
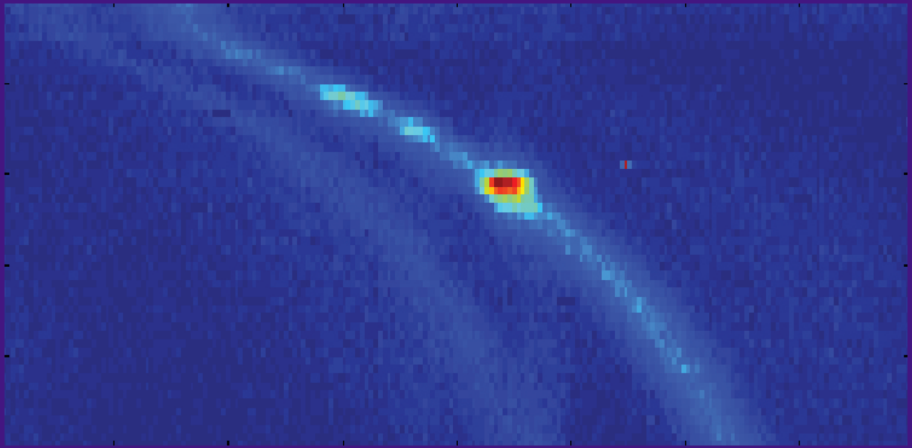
Nitrogen-vacancy centers in diamond for quantum information and sensing applications



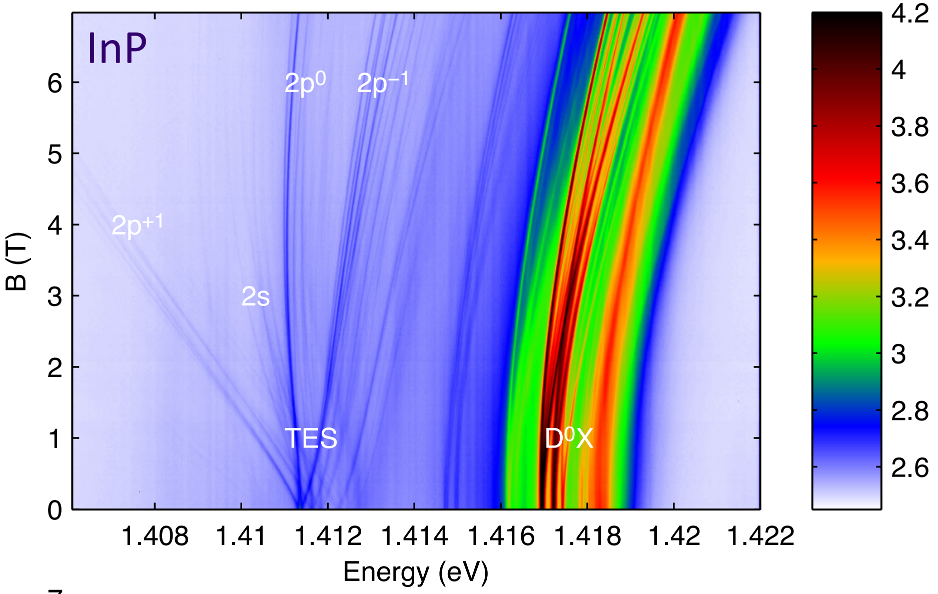


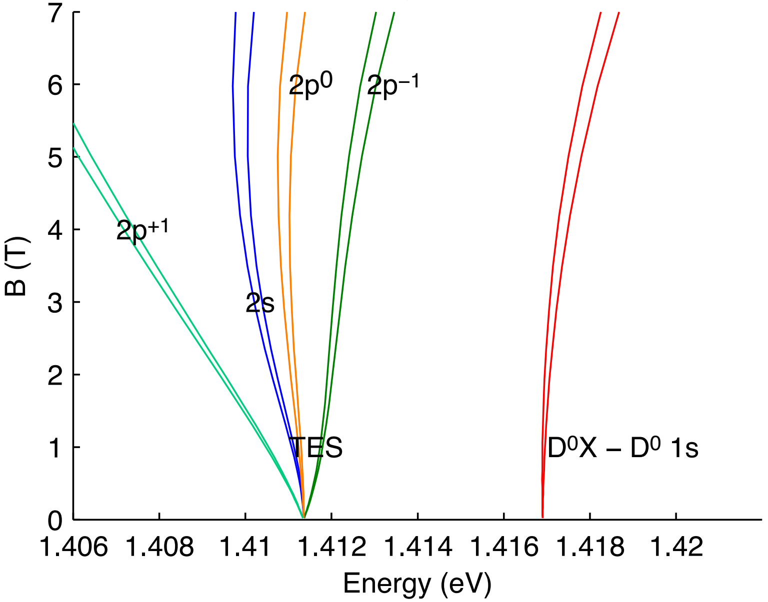
Kai-Mei Fu

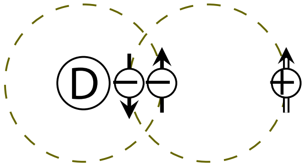
UW physics REU seminar
July 13, 2015

UNIVERSITY *of* WASHINGTON

Defect physics: Atomic-like physics in a solid state matrix

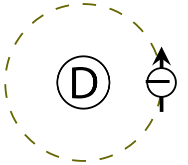






Donor Bound Exciton

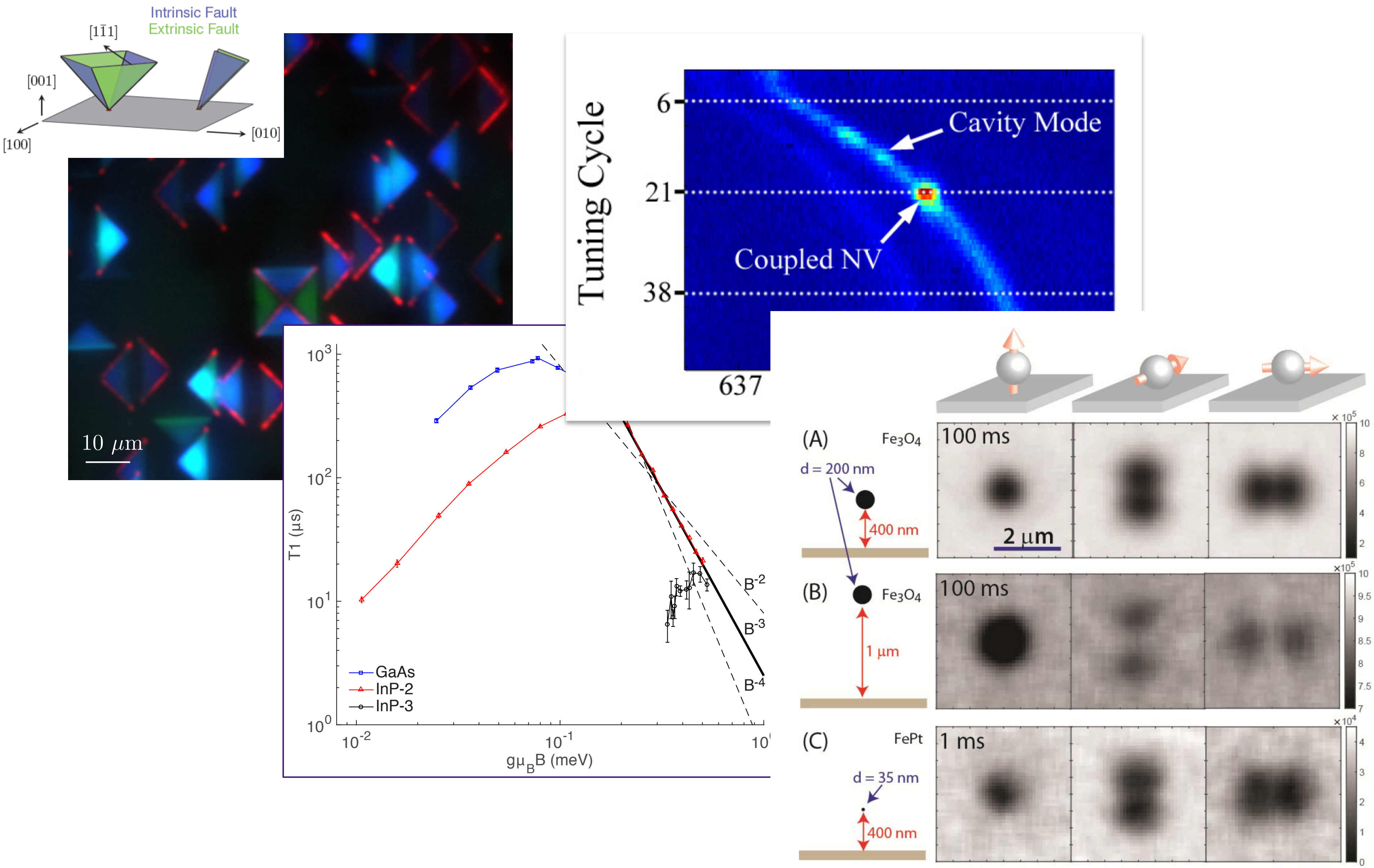
D^{0}X



Neutral Donor

D^0

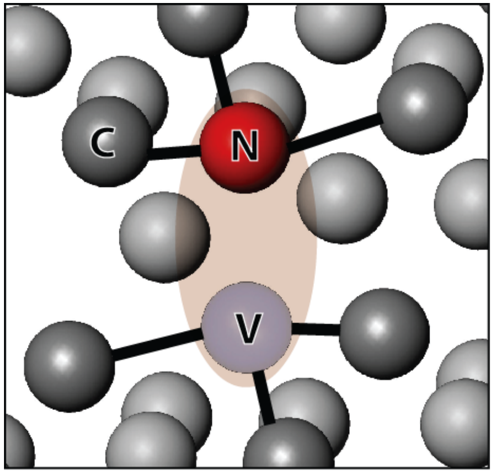
From fundamental to applied



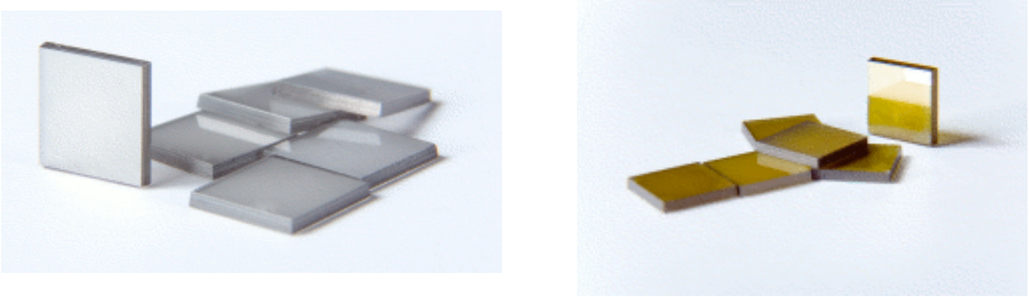
Outline

- Overview of the nitrogen-vacancy center in diamond
- Toward scalable entanglement generation in diamond

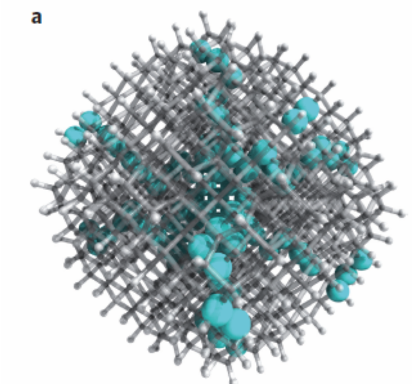
The nitrogen vacancy color center in diamond



Wikipedia, natural diamond

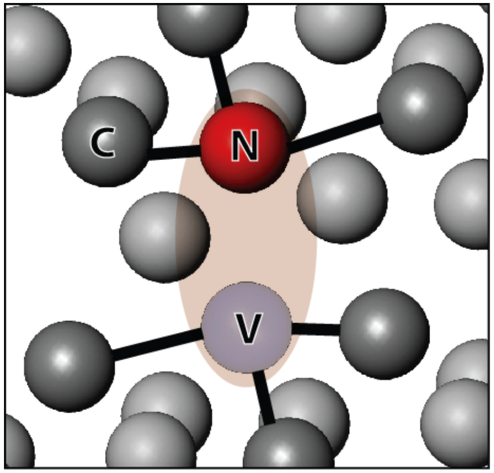


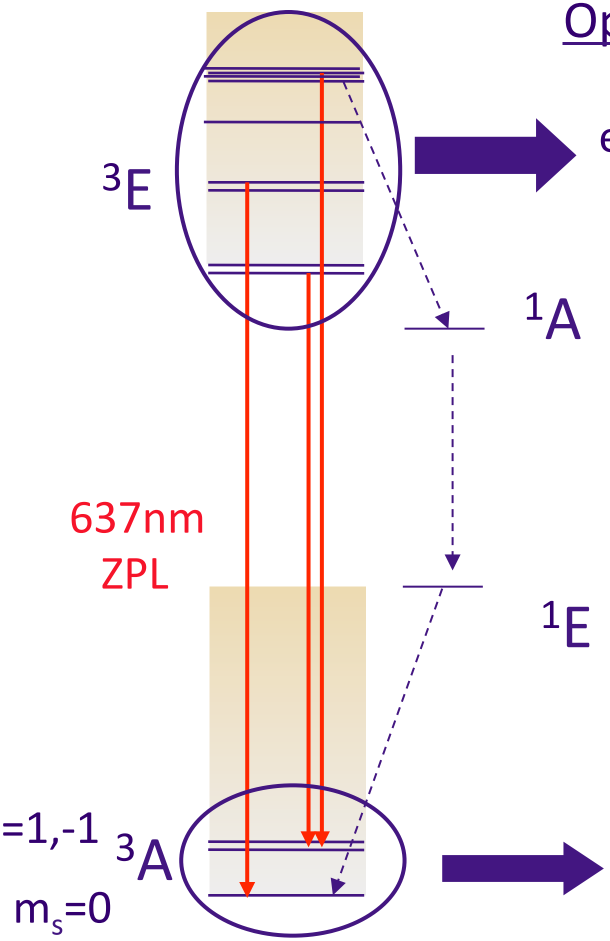
Element 6, CVD and HPHT diamond



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)

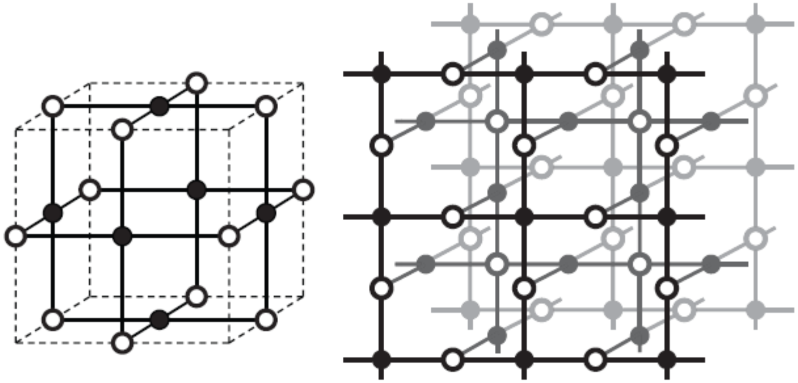
Outline

- Overview of the nitrogen-vacancy center in diamond
- **Toward scalable entanglement generation in diamond**
  - **Motivation for diamond**
  - Defect engineering
  - Coupling to optical devices
- Wide-field optical imaging of magnetic fields using diamond

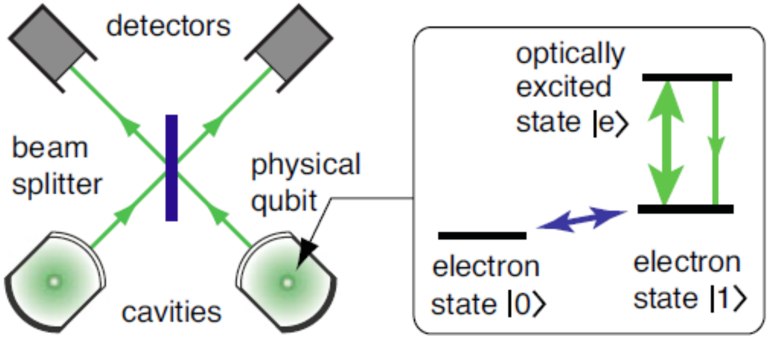
Motivation: distributed quantum computing

Strong, 2-body interactions are difficult to control and implement, perhaps impossible for large quantum systems

Qubit network + single qubit operations/ measurement is a universal quantum computer[1]



Protocols exist to build network even in the presence of extreme losses[2]



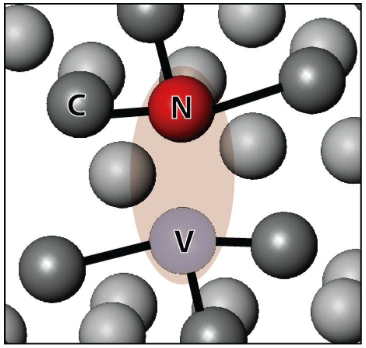
Figures from SC Benjamin, BW Lovett, JM Smith, Laser and Photonics Review 3, 556 (2009), Y Li and SC Benjamin NJP 14, 093008 (2012)

[1] R Raussendorf, J Harrington, K Goyal, NJP 9, 199 (2007), SD Barrett and P Kok, PRA 71, 060310 R (2005)

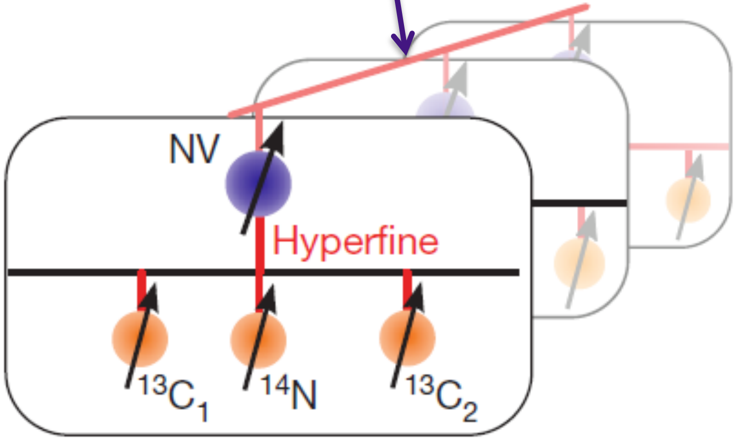
Motivation for physical platform: NV center

Atoms: nature's quintessential quantum particle

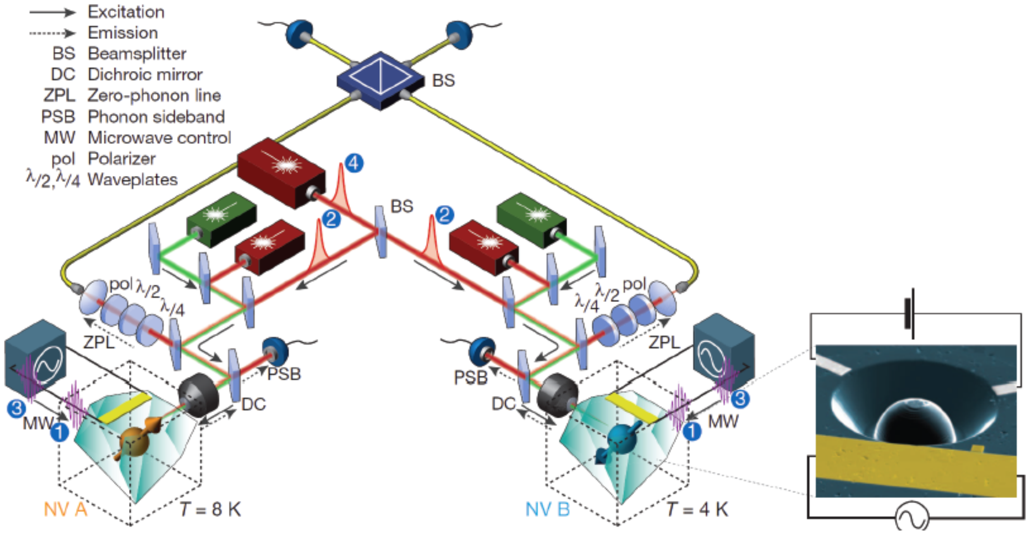
Solid-state: a platform for scalability



photonic interconnect?



Quantum registers: Stuttgart group[1]

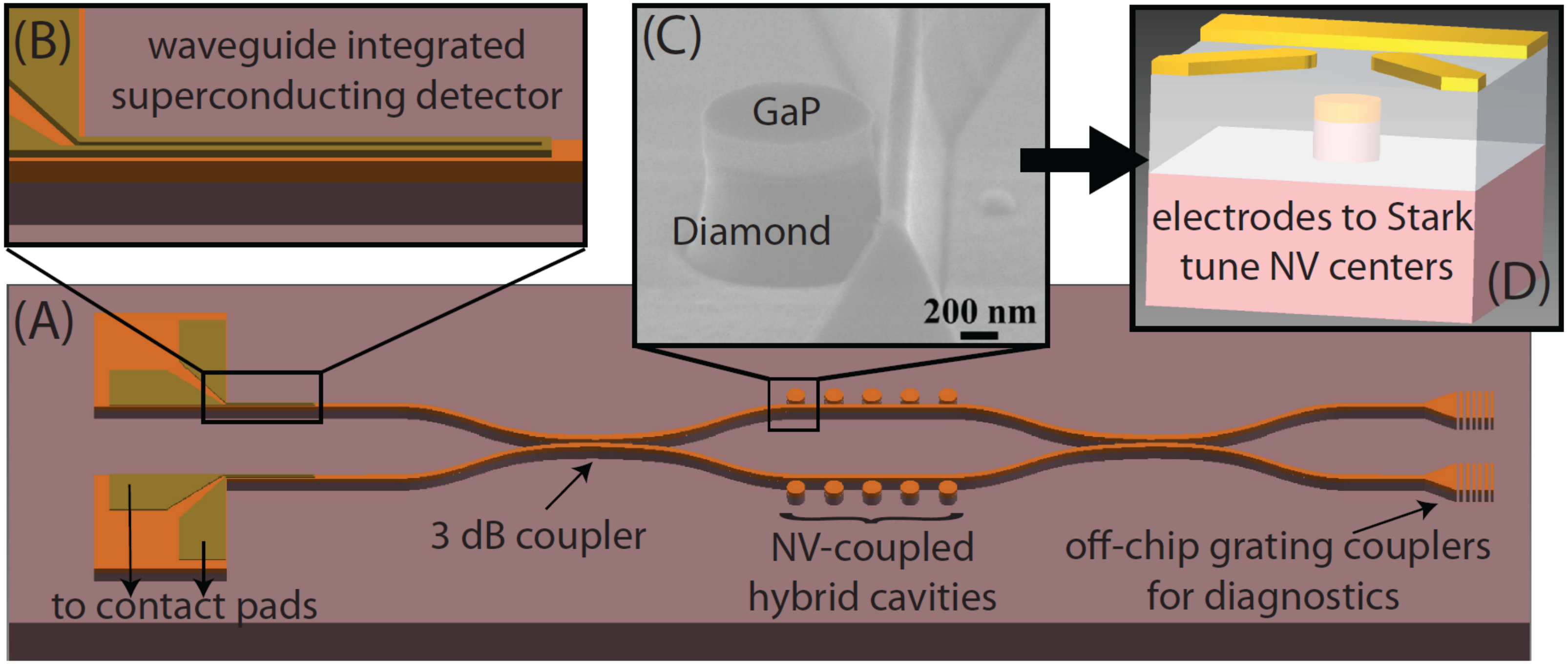


Free space interconnect: Delft group[2]

0.01 Hz, ~0.87 fidelity

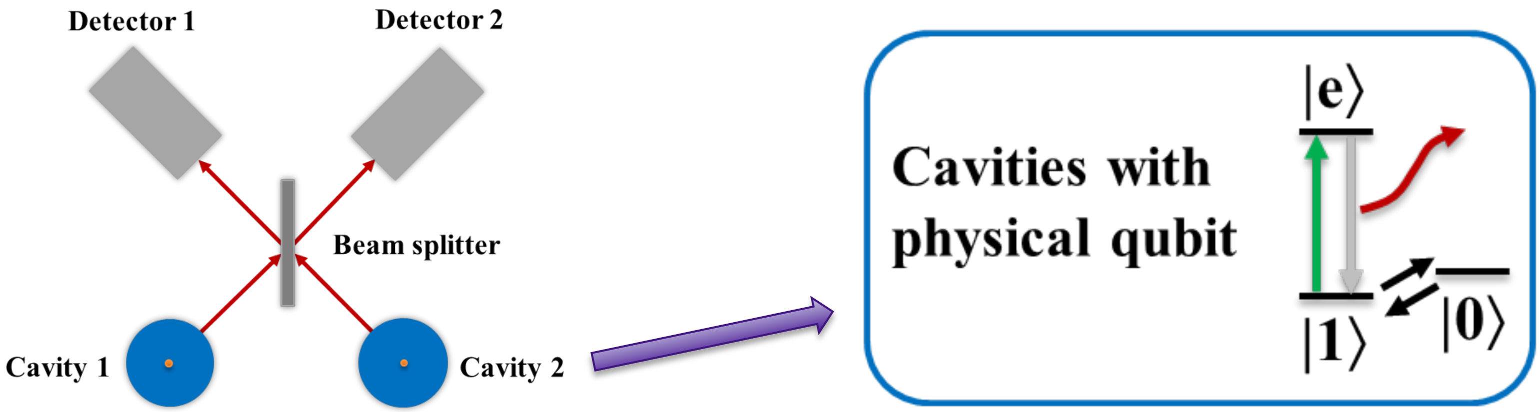
[1] Waldherr et al. Nature 506, 204 (2014) [2] Bernian et al. Nature 497, 86 (2013)

Goal: move as much as possible onto a chip to realize practical entanglement rates



Why is entanglement generation so slow in current experimental demonstrations?

How remote entanglement is generated



Prepare superposition state: $\frac{1}{\sqrt{2}}(|0\rangle + |1\rangle) \otimes \frac{1}{\sqrt{2}}|(|0\rangle + |1\rangle)$

After optical excitation: $\frac{1}{\sqrt{2}}(|0\rangle + |e\rangle) \otimes \frac{1}{\sqrt{2}}|(|0\rangle + |e\rangle)$

$$\frac{1}{2}(|00\rangle + |0e\rangle + |e0\rangle + |ee\rangle)$$

After detection of single photon: $\frac{1}{\sqrt{2}}(|01\rangle \pm |10\rangle)$

Figures from S. C. Benjamin et al., Laser Photon. Rev. 3 (2009), Scheme from SD Barrett and P Kok, PRA 71, 060310 R (2005)

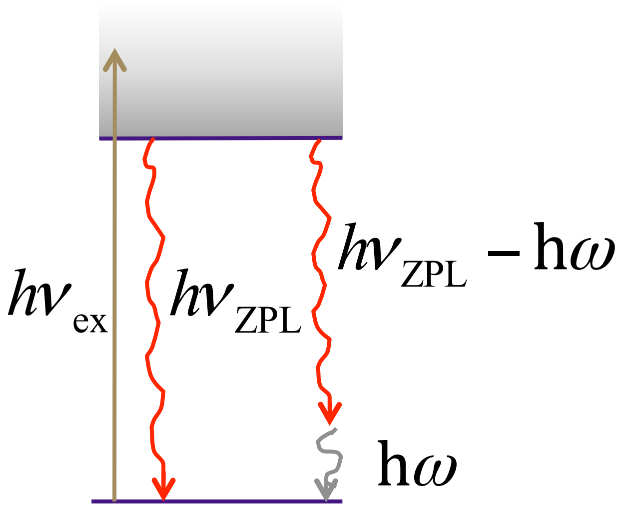
Requirements for entanglement generation

- The properties of the two photons must be identical
- The photons must be detected
  - Protocol scales as square of detection efficiency
- Ground state coherence time must be long compared to entanglement generation procedure.

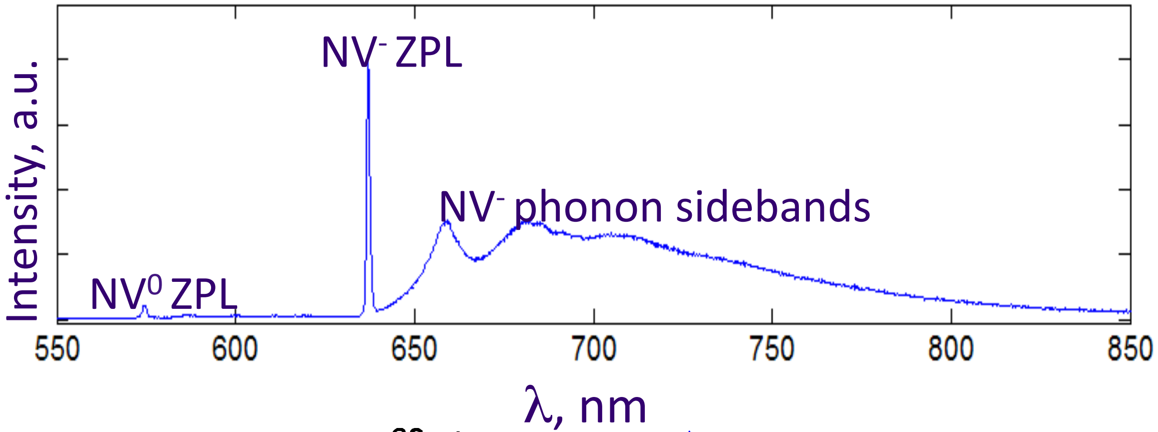
Outline

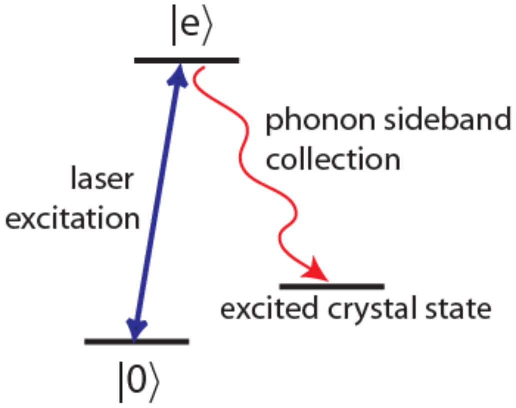
- Overview of the nitrogen-vacancy center in diamond
- **Toward scalable entanglement generation in diamond**
  - Motivation for diamond
  - **Defect engineering (toward identical photons)**
  - Coupling to optical devices (toward efficient detection)
- Wide-field optical imaging of magnetic fields using diamond

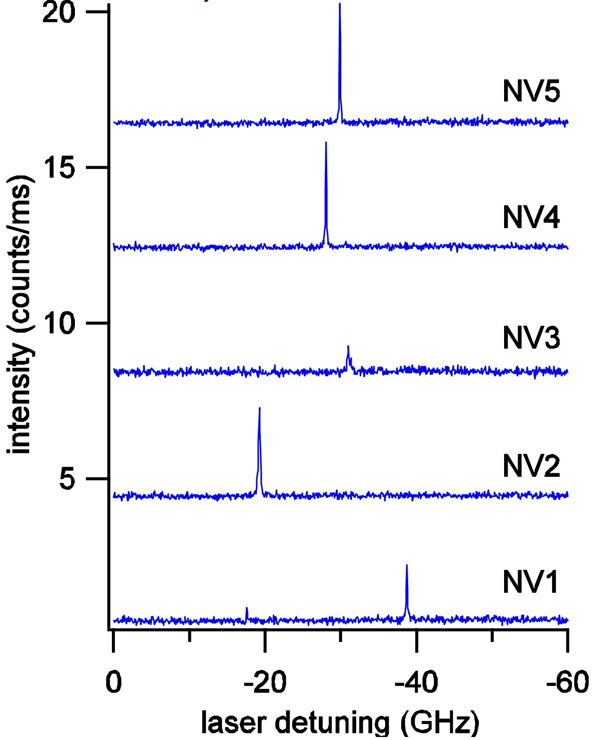
Photons emitted from NV centers are not identical



Photoluminescence from NVs in a high-nitrogen sample

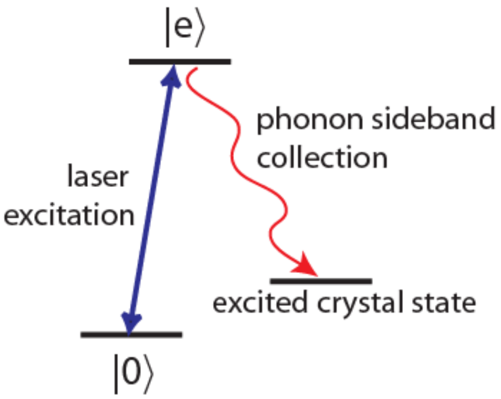


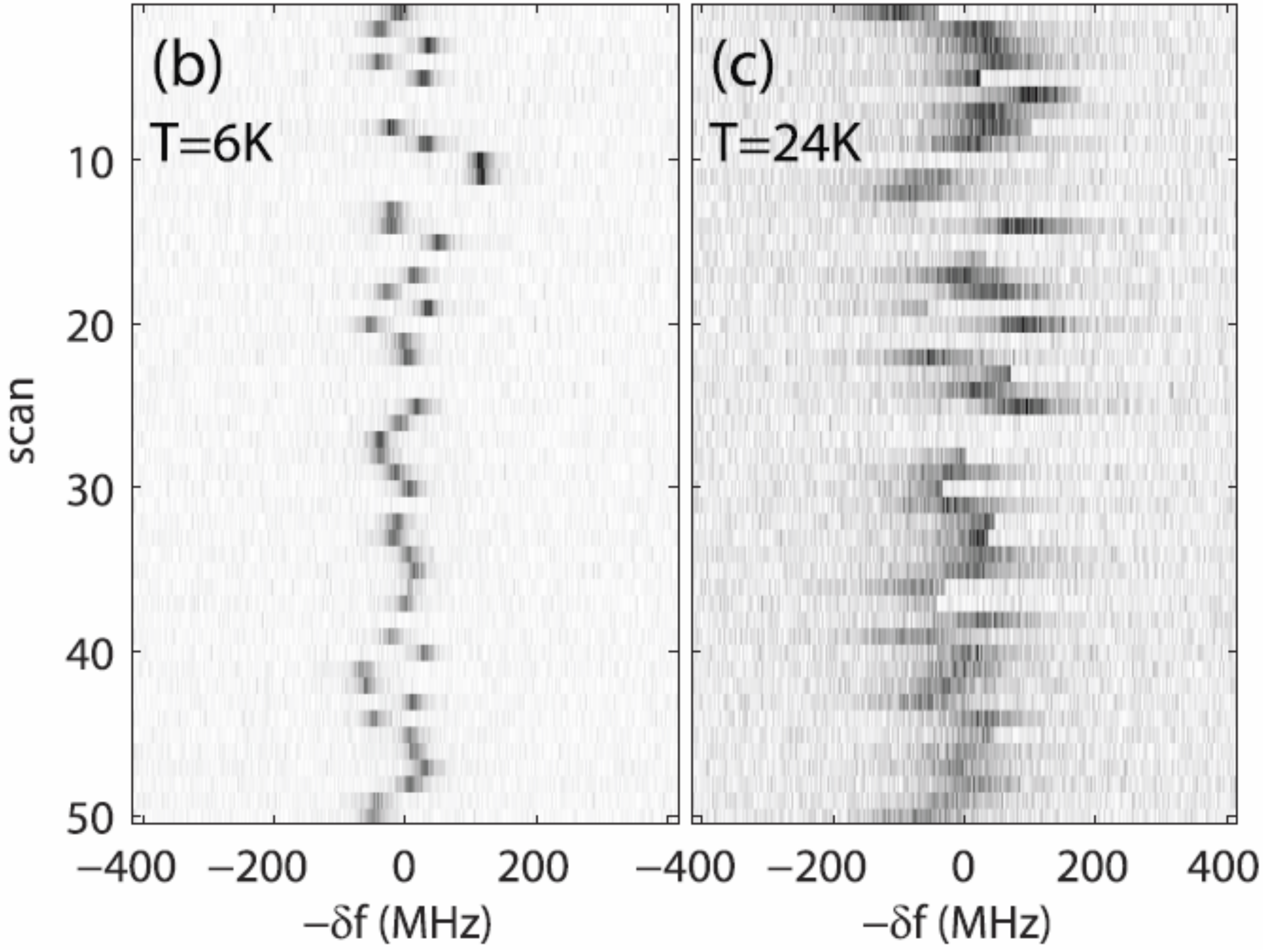




C. Santori, P. E. Barclay, K.-M. C. Fu, S. Spillane, M. Fisch, R. G. Beausoleil, Nanotechnology 21 , 274008 (2010)

Phonon broadening and diffusion





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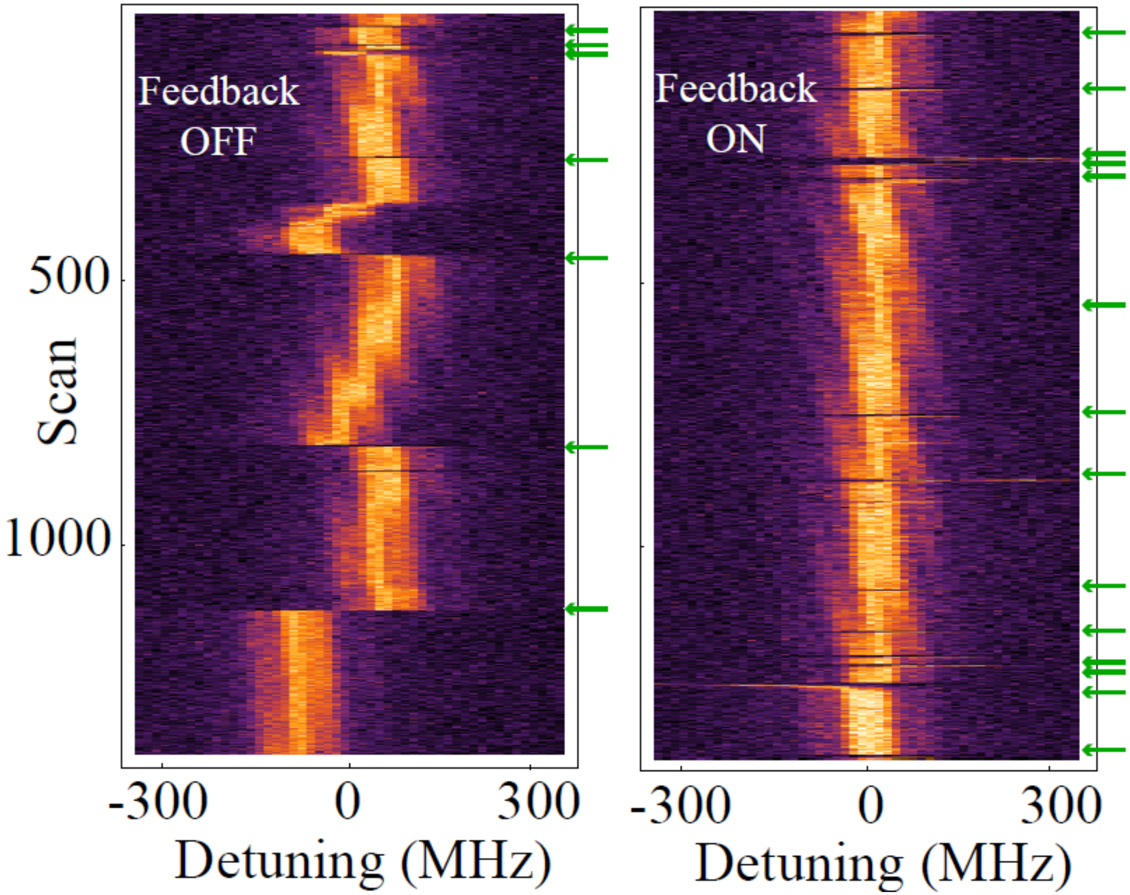
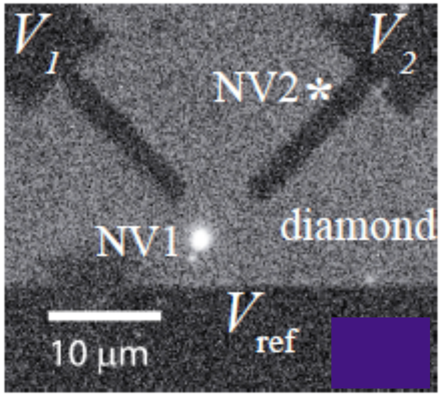
*Fu, Santori, Barclay, Rogers, Manson, Beausoleil *PRL 103*, 256404 (2009),

Real time control of optical transition frequency

Dynamic stabilization



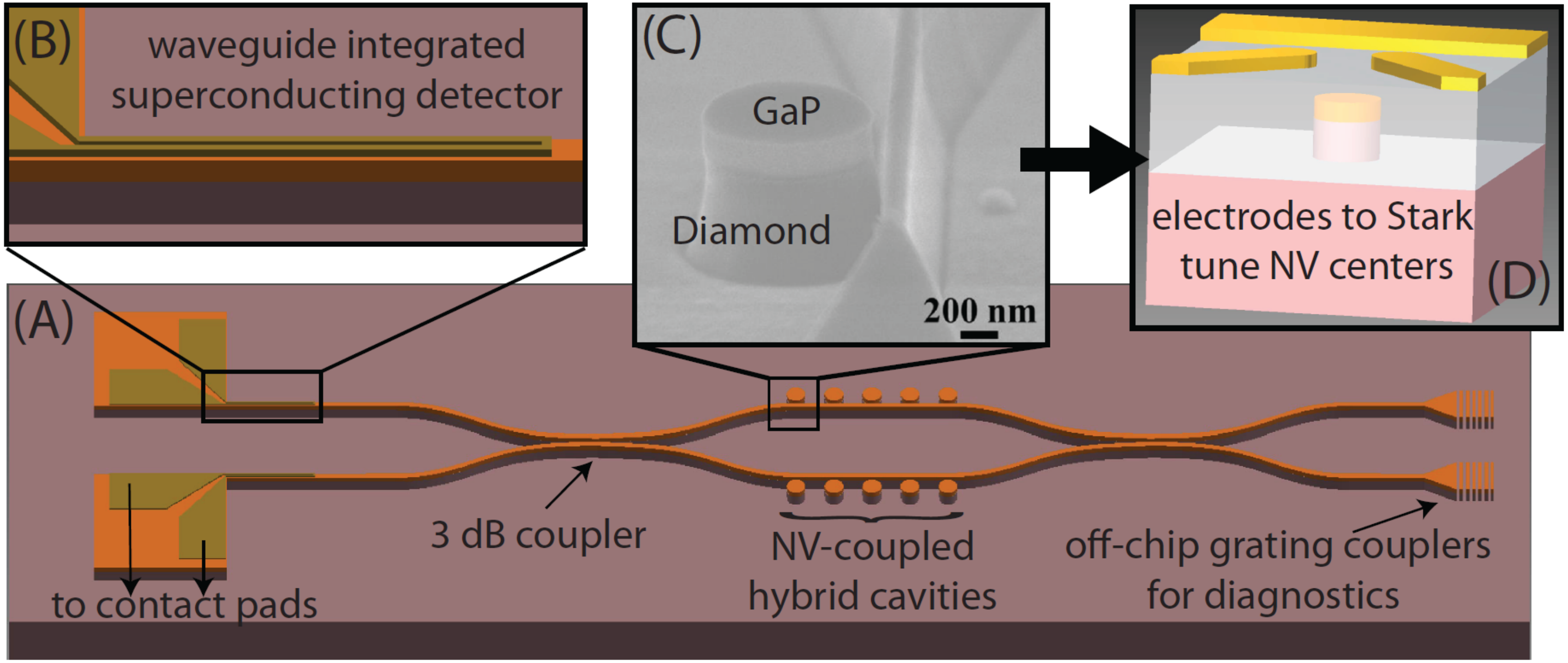


Acosta, Santori, Faraon, Huang, Fu, Stacey, Simpson, Greentree, Prawer, Beausoleil, *PRL* 108, 206401 (2012)), see also static Stark work from Stuttgart, UCSB, Harvard, Delft

Outline

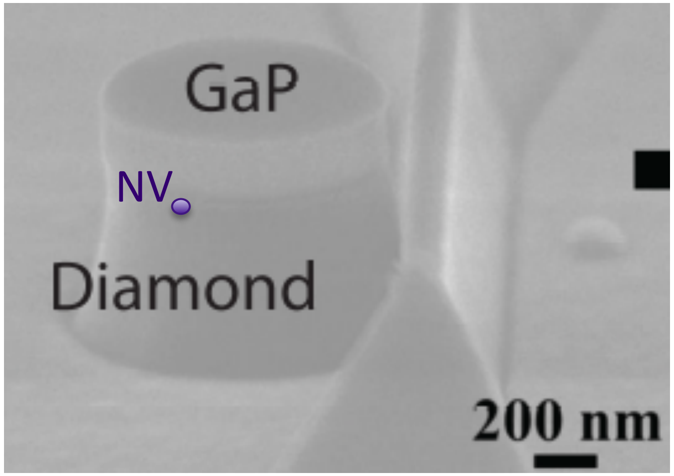
- Overview of the nitrogen-vacancy center in diamond
- **Toward scalable entanglement generation in diamond**
  - Motivation for diamond
  - Defect engineering (orientation, placement, etc.)
  - **Coupling to optical devices**
- Wide-field optical imaging of magnetic fields using diamond

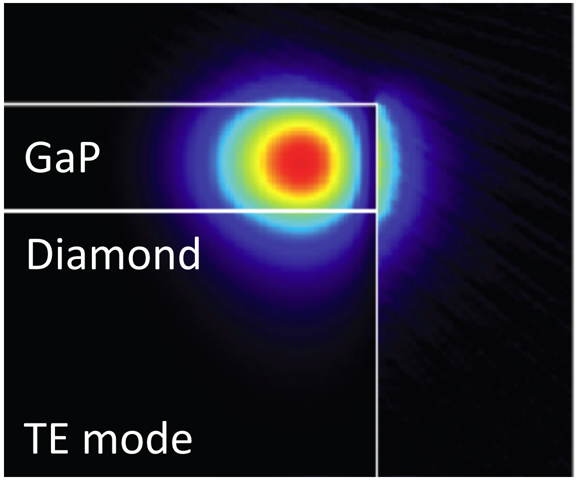
Requirements for the photonics platform

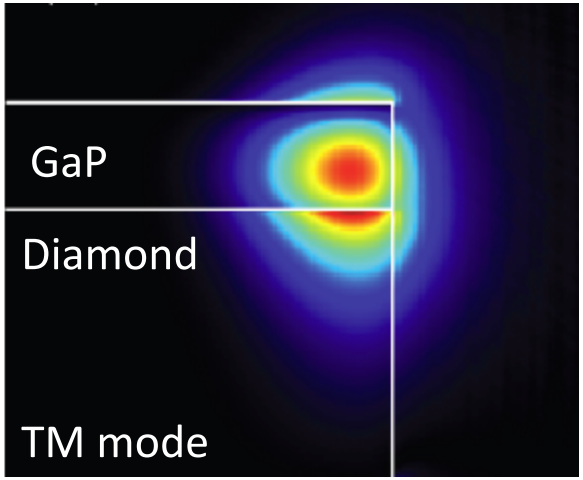


- **Scalable**
- Actively route the photon on-chip
- Detect the photon with an on-chip detector
- Collect the zero-phonon line photon from the NV center into an on-chip waveguide.

Our system: GaP on diamond





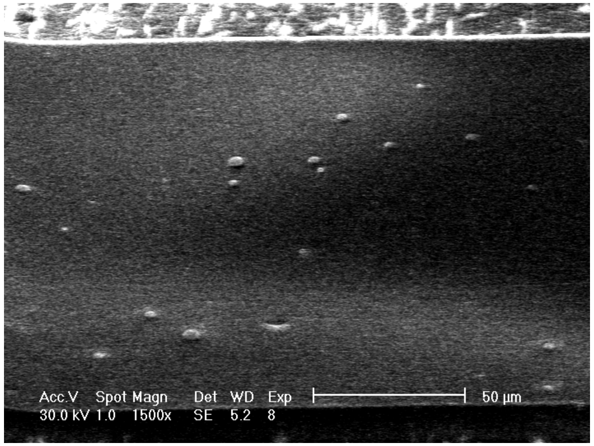


Refractive index of GaP is greater than that of diamond: $n_{GaP} = 3.3$, $n_d = 2.4$

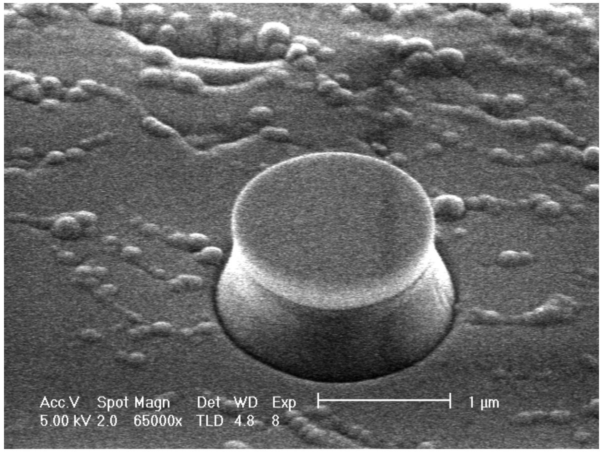
GaP is transparent at NV ZPL wavelength: 637 nm

Scalable GaP/diamond platform

At HP[1]

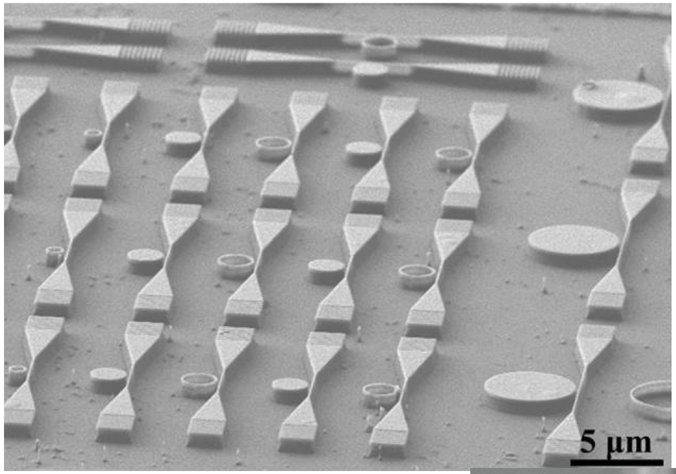


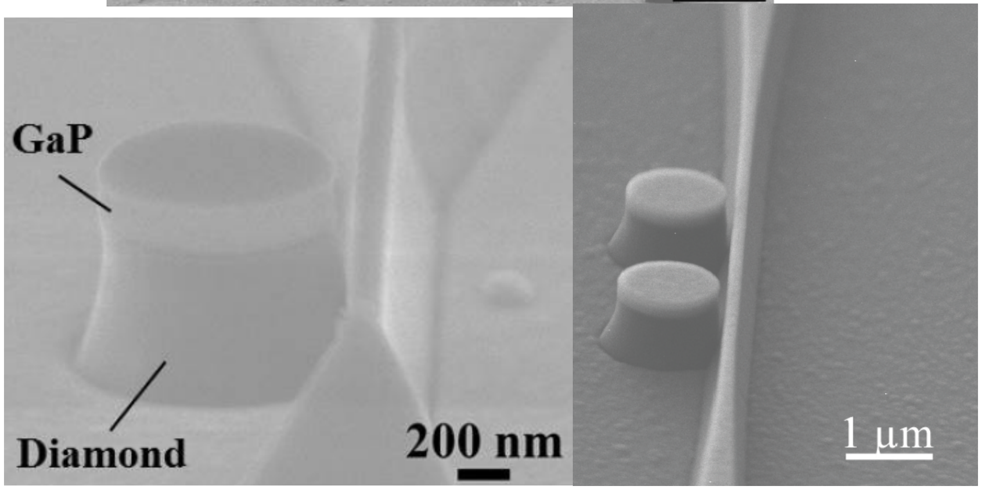
Randomly placed cavities



6x Purcell enhancement observed.

At UW[2]



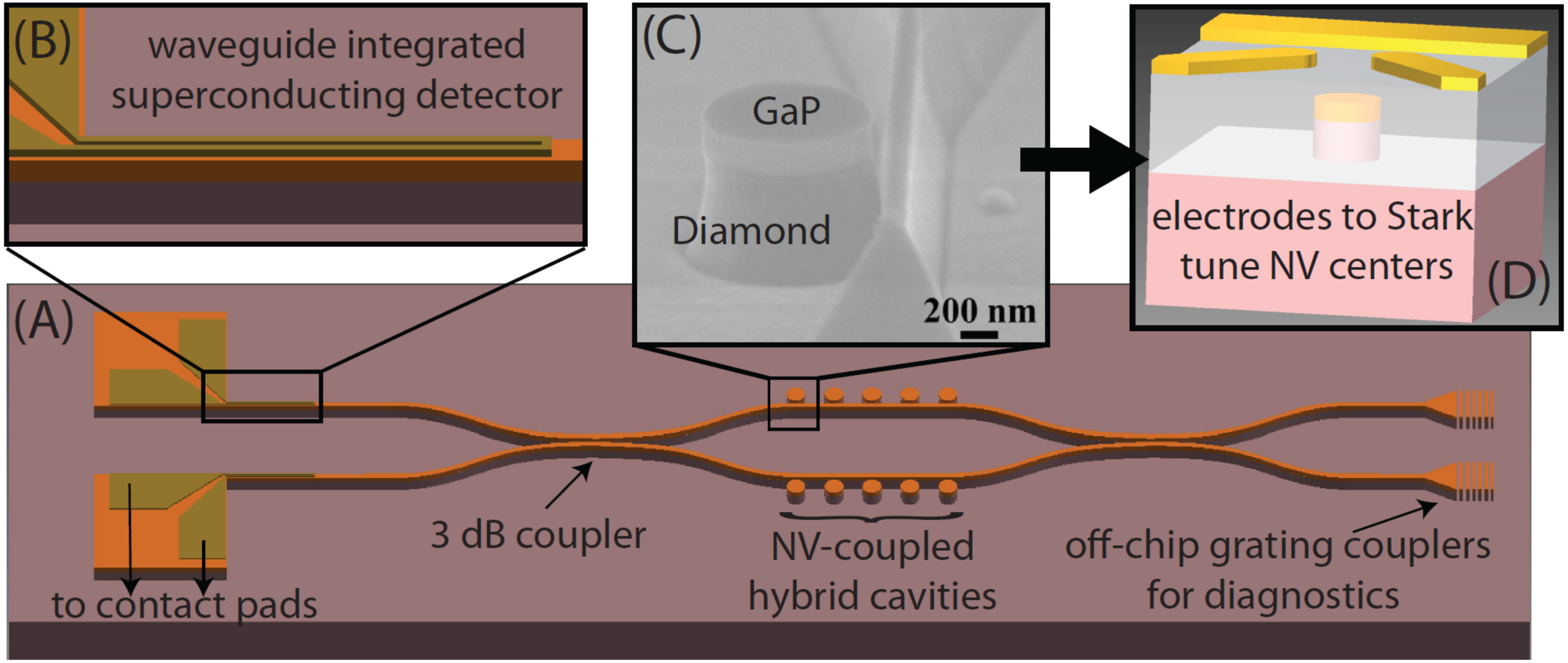


Theoretical performance: 40% collection efficiency

[1] P. Barlay, K.-M.C. Fu, C. Santori, A. Faraon, R.G. Beausoleil, *PRX* 1, 011007 (2011)

[2] N. Thomas, R.J. Barbour, Y. song, M.L.Lee, K.-M.C.Fu, *Optics Express* 22, 13555 (2014)

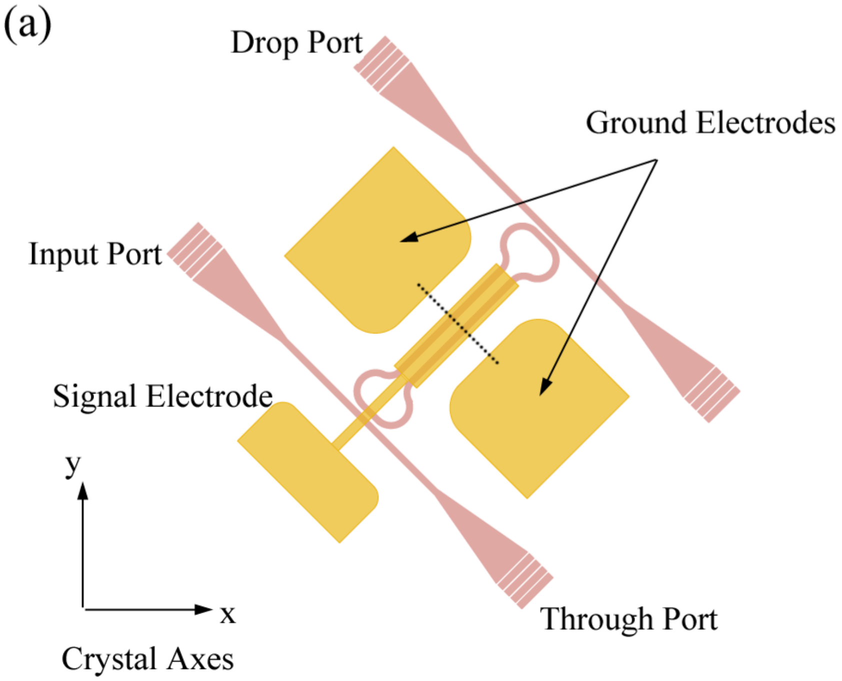
Requirements for the photonics platform

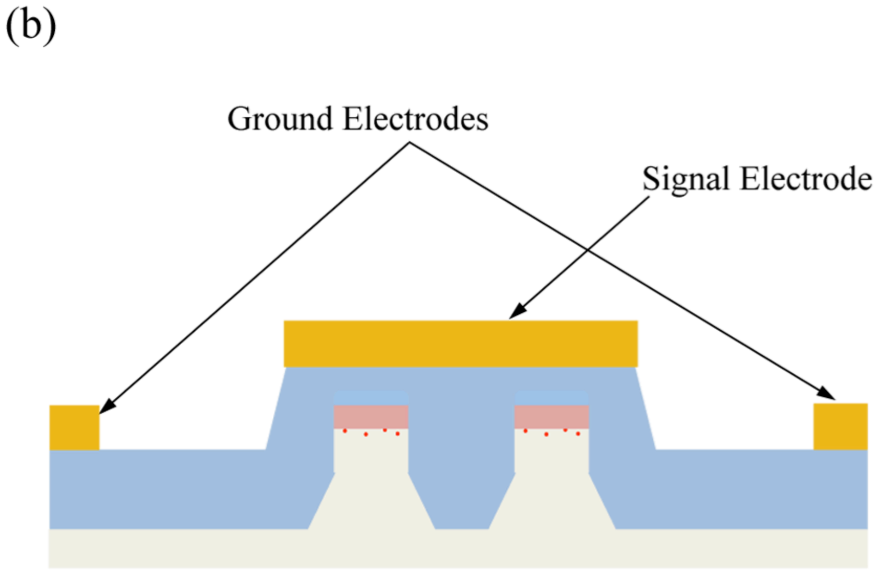


- > Scalable
- > **Actively route the photon on-chip.**
- > **Detect the photon with an on-chip detector**.
- > Collect the zero-phonon line photon from the NV center into an on-chip waveguide.

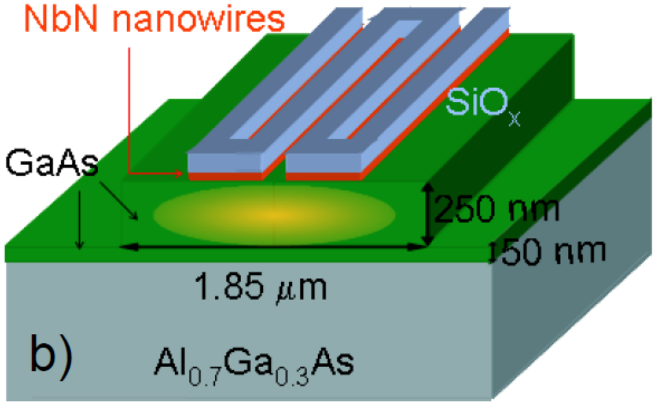
Promising for active devices: GaP exhibits linear electro-optic effect

- Platform has inherently low device yield → need switch
- GaP is an electro-optic material: r_{41} = 1 pm/V:
  - Should allow tuning of resonators on the order of 100 GHz, NV linewidth < 100 MHz

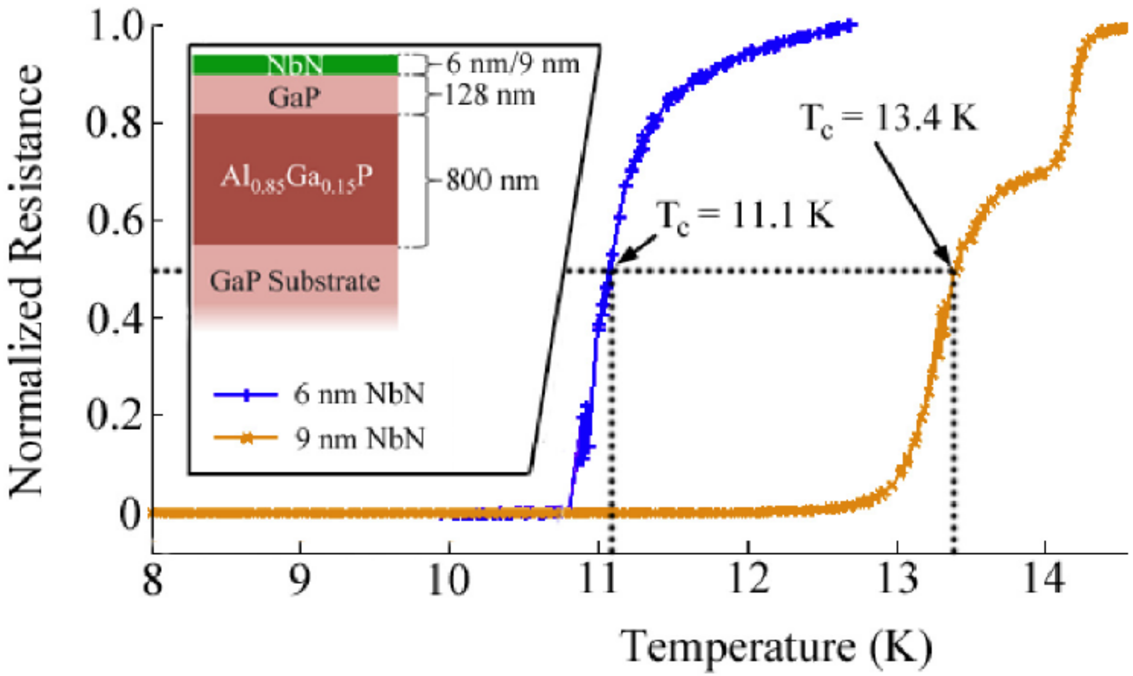




Promising for on-chip detectors: MBE GaP surface is smooth enough

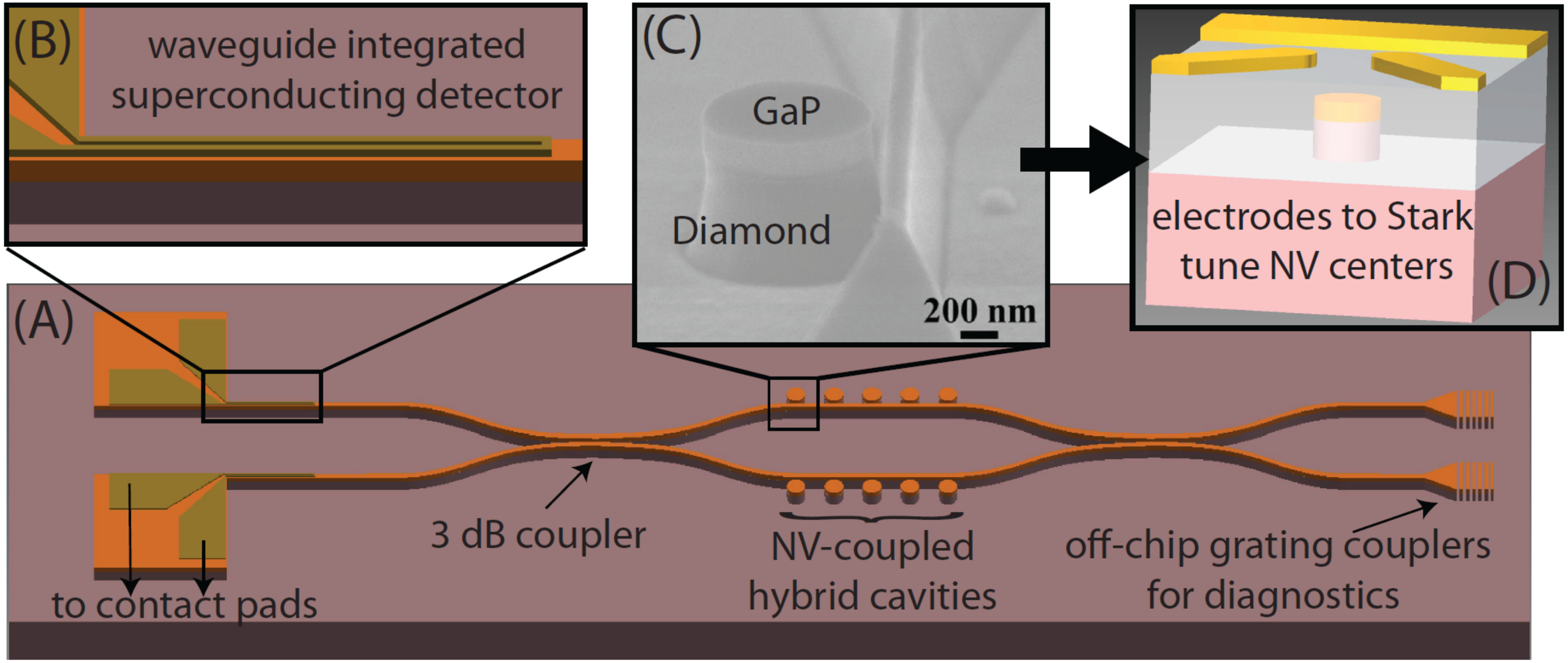


Collaborator Andrea Fiore’s GaAs devices (Eindhoven)



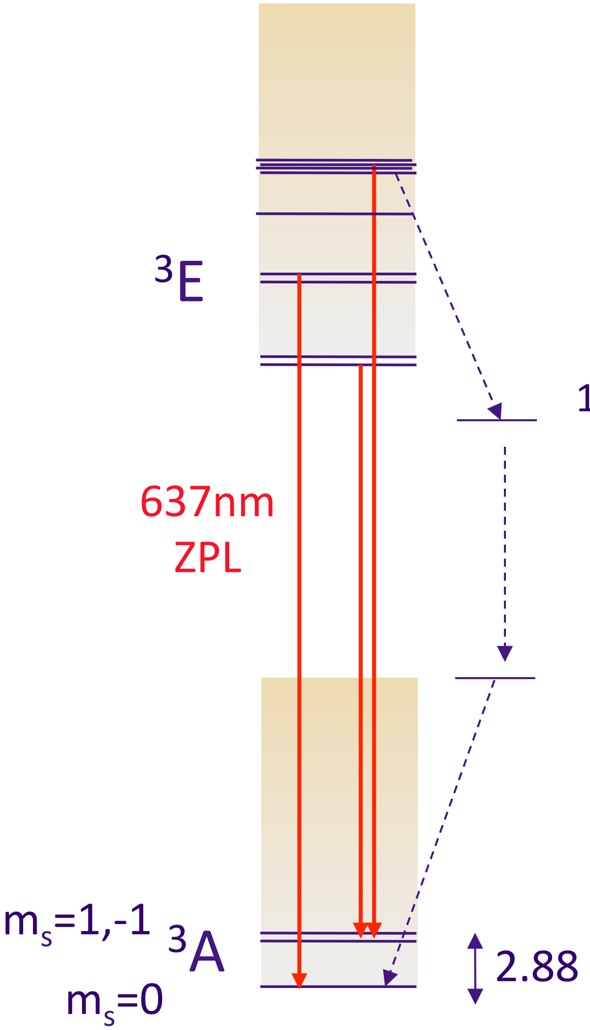
Sprengers *et al.Applied Physics Letters* 99, 18110 (2011)

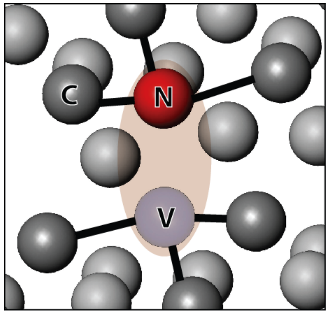
Requirements for the photonics platform

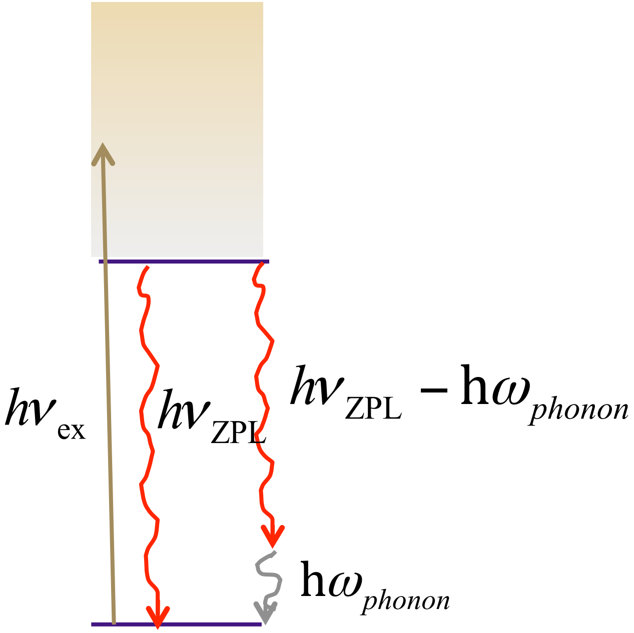


- > Scalable
- > Actively route the photon on-chip.
- > Detect the photon with an on-chip detector.
- > **Collect the zero-phonon line photon from the NV center into an on-chip waveguide.**

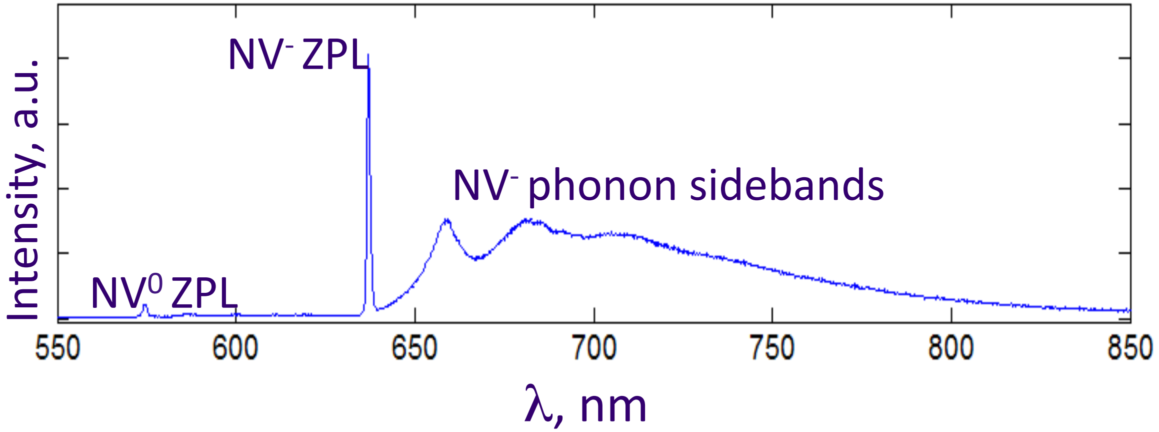
Enhance and collect zero phonon line from NV centers



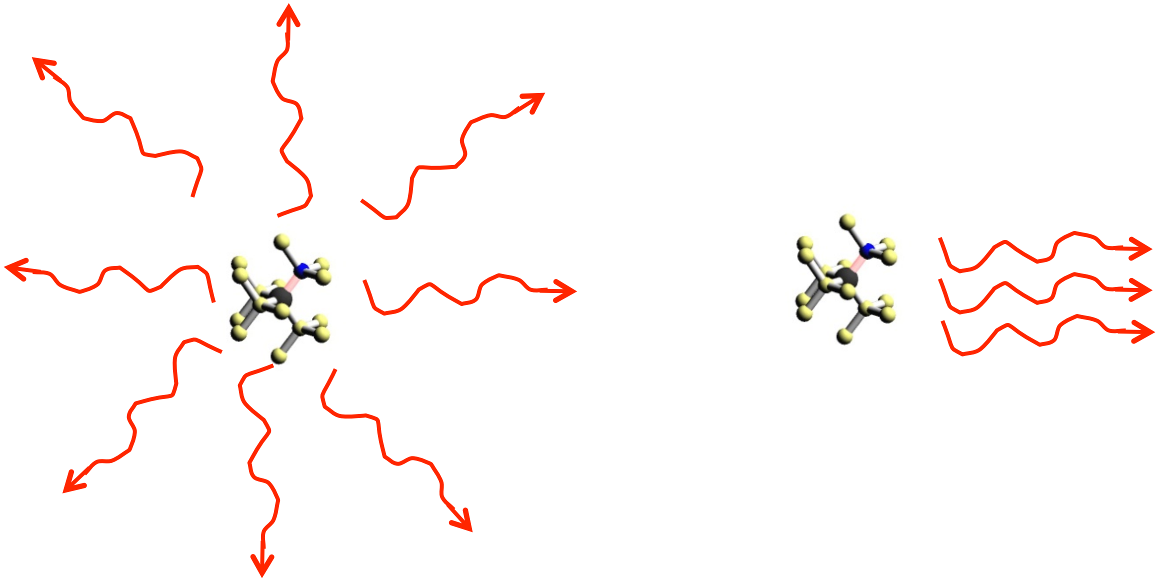




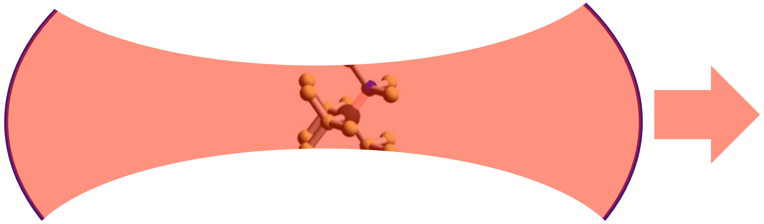
Low temperature NV photoluminescence



Enhance and **collect** zero phonon line from NV centers



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



Mirror 1

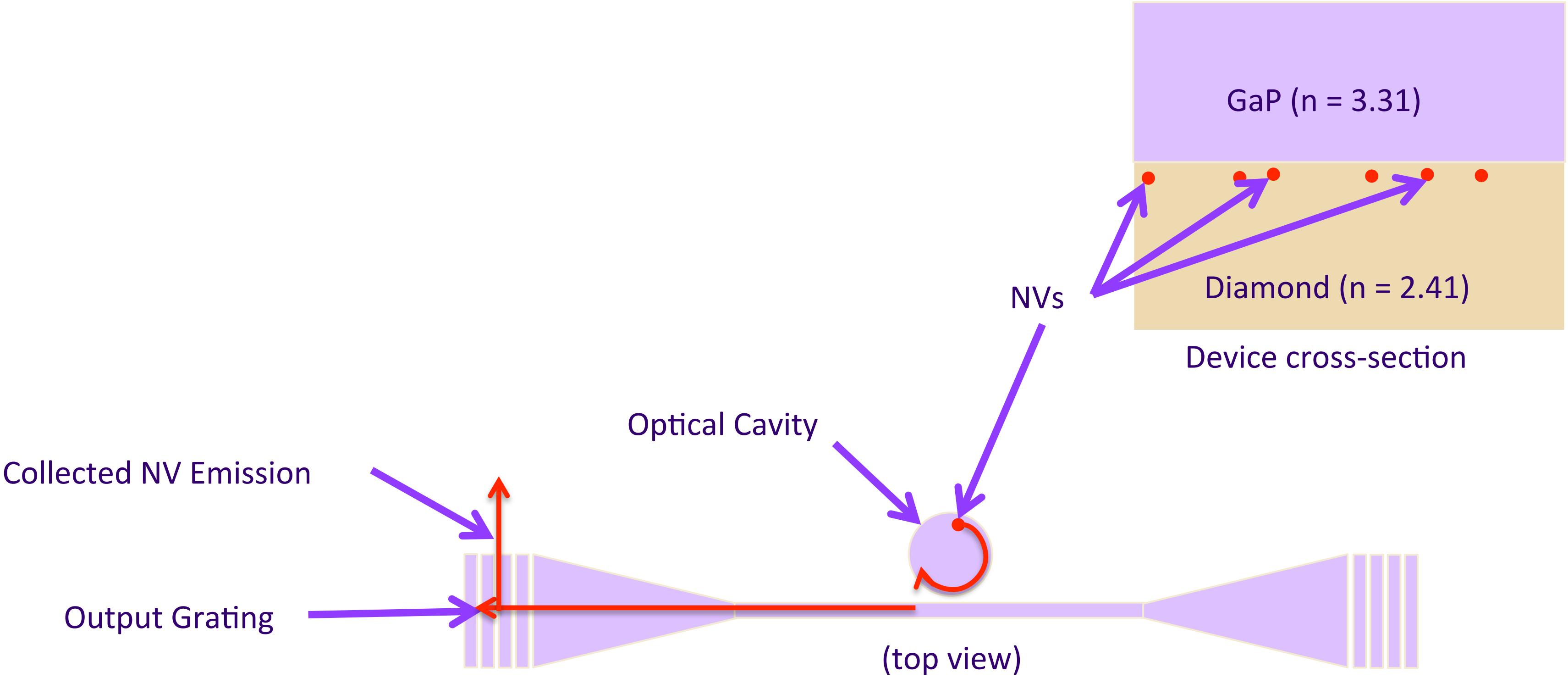
Mirror 2

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

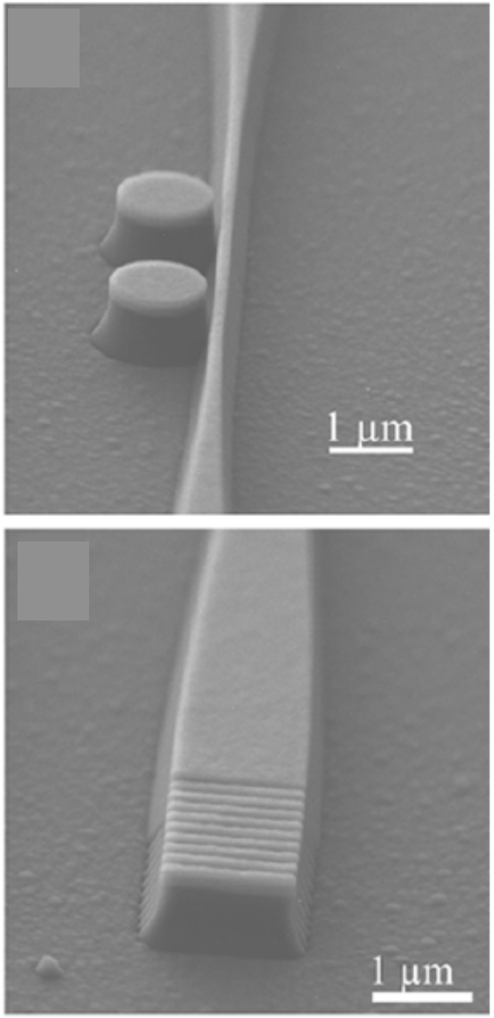
- Cavity is on resonance with NV
- NV is at cavity maximum
- NV electric dipole is aligned to cavity mode.
- High quality factor
- Small mode volume

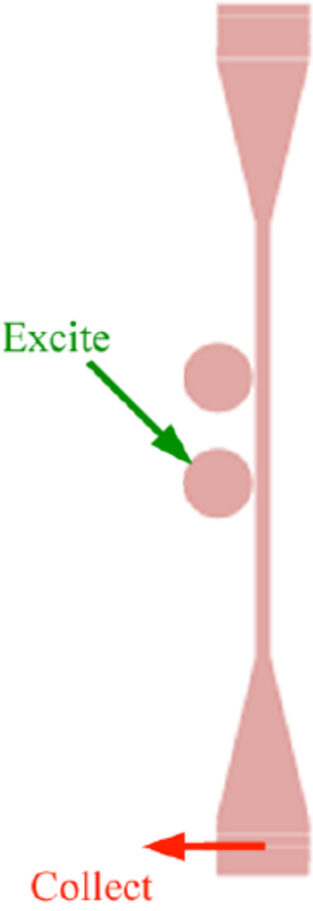
Purcell, 1946

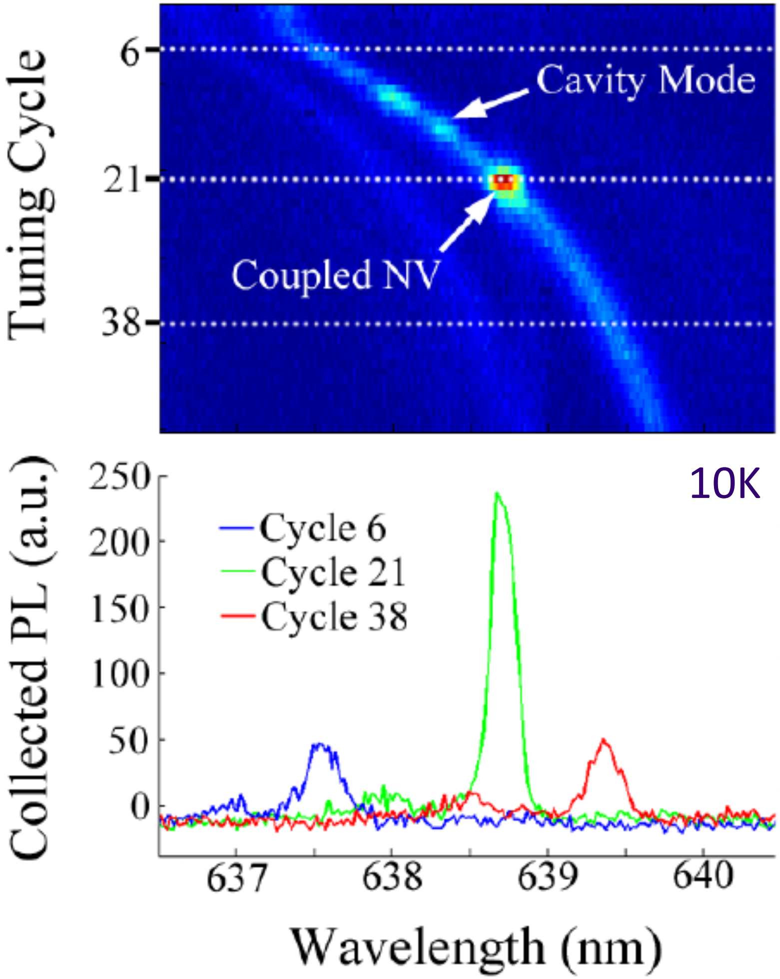
GaP/diamond hybrid devices



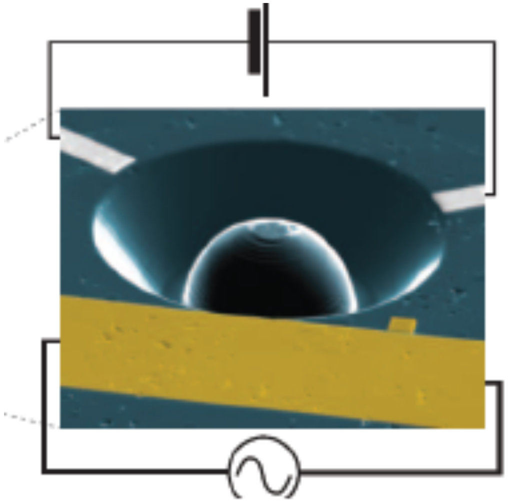
Observation of ZPL emission from grating

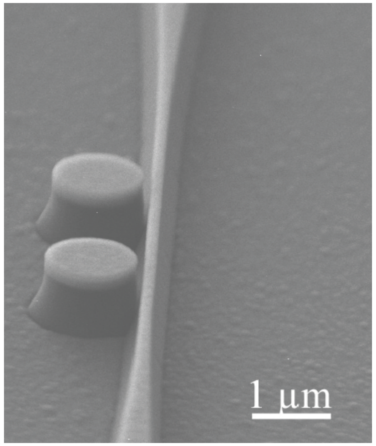






Comparison to free space coupling





740,000 total cts/s detected
3% ZPL
22,000 ZPL cts/s

↓

Achieved entanglement generation rate: 0.01 Hz
(Delft group, Science 345, 532 2014)

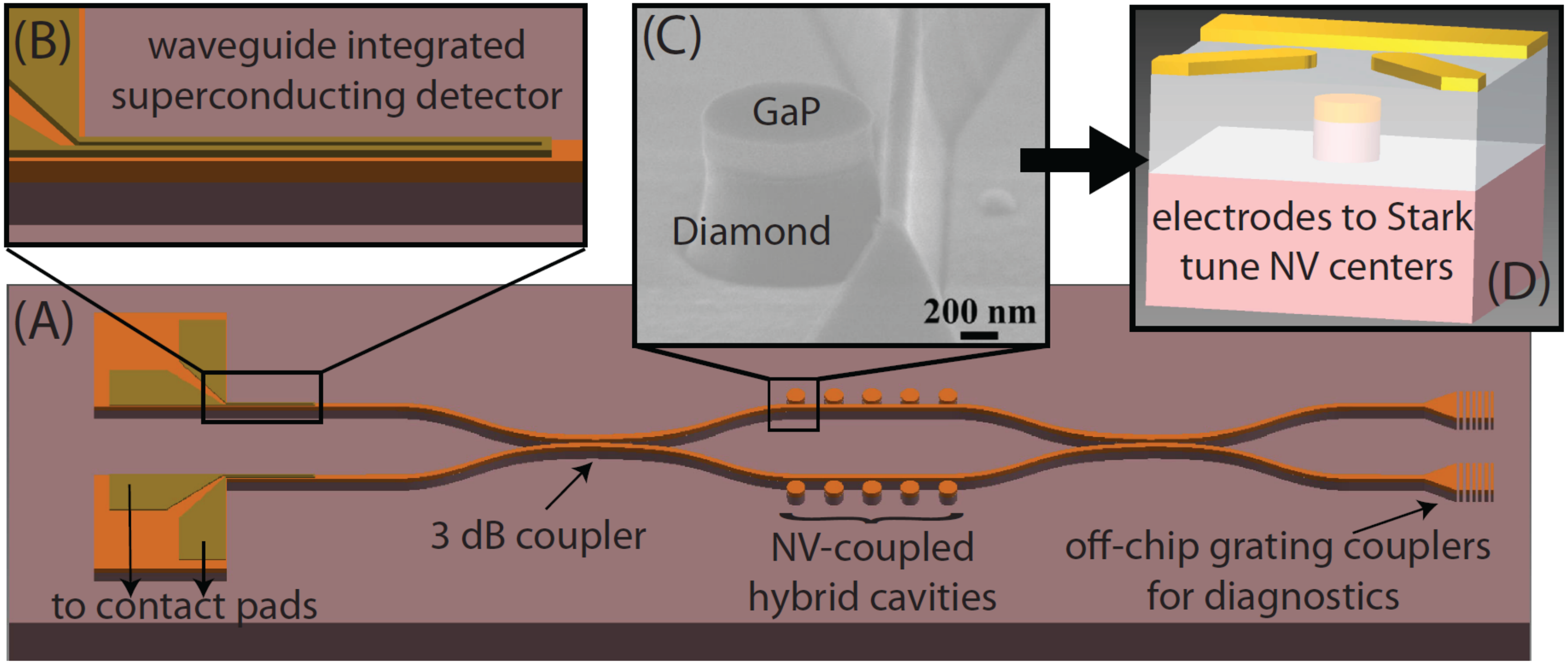
400 ZPL cts/s detected
1% grating efficiency
40,000+ ZPL cts/s in the waveguide

↓ Minor fabrication improvements
10×

400,000+ ZPL cts/s in the waveguide

7/20 tested devices show enhanced NV emission

GaP/Diamond platform for on-chip entanglement



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