GaP-on-Diamond Integrated Photonics Platform for Measurement-Based Quantum Networks

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Motivation

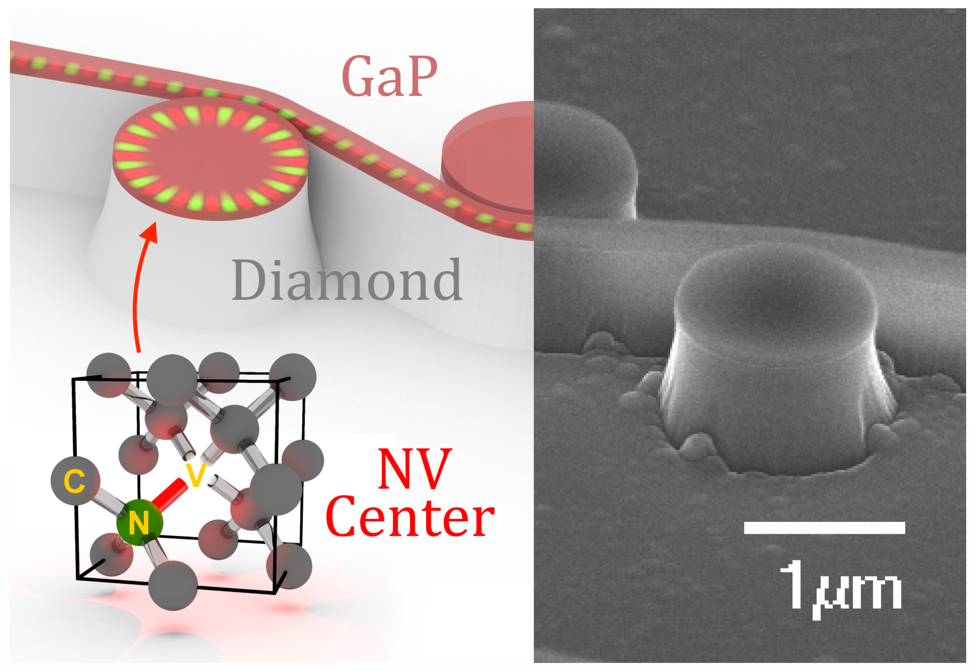
Solid-state defects are promising qubit candidates for distributed quantum computation. The Nitrogen-vacancy (NV) center in diamond is particularly attractive due to:

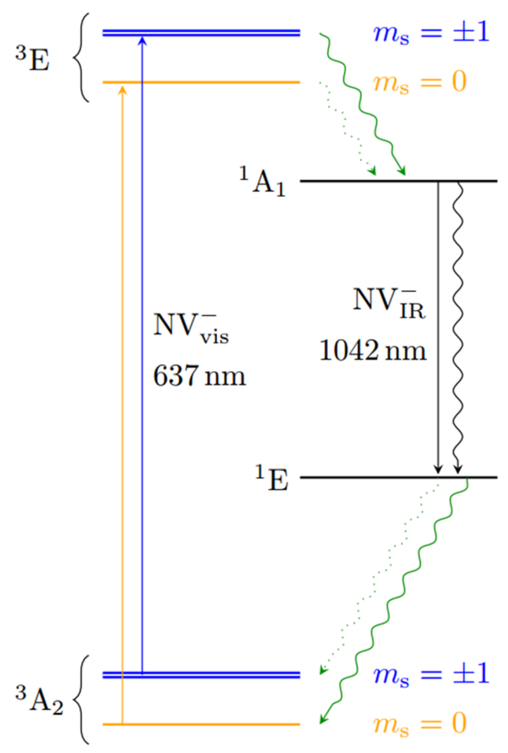
- Long electron spin-coherence time
- Optical initialization and readout of electron spin
- Access to multiple nuclear spins

Why Gallium Phosphide (GaP) ?

- Higher index than diamond for photonics
- Ultra smooth surface for nanowire detectors

We demonstrate the fabrication and operation of individual components in the platform and provide a clear roadmap for their integration.





Niobium nitride superconducting nanowire detectors

The NV photons are evanescently coupled to the nanowire detectors patterned over waveguides.

- 8nm thick, 60-90nm wide and 20/40 um long
- Critical temperature ~14K, operated at 4.2K
- High quantum efficiency (~94% shown)
- Low dark count rate (< 1 Hz)
- Low timing jitter (< 50 ps)

Essential for:

- On chip $g^{(2)}$ measurement
- On chip Hong-Ou-Mandel measurement
- Efficient NV entanglement generation

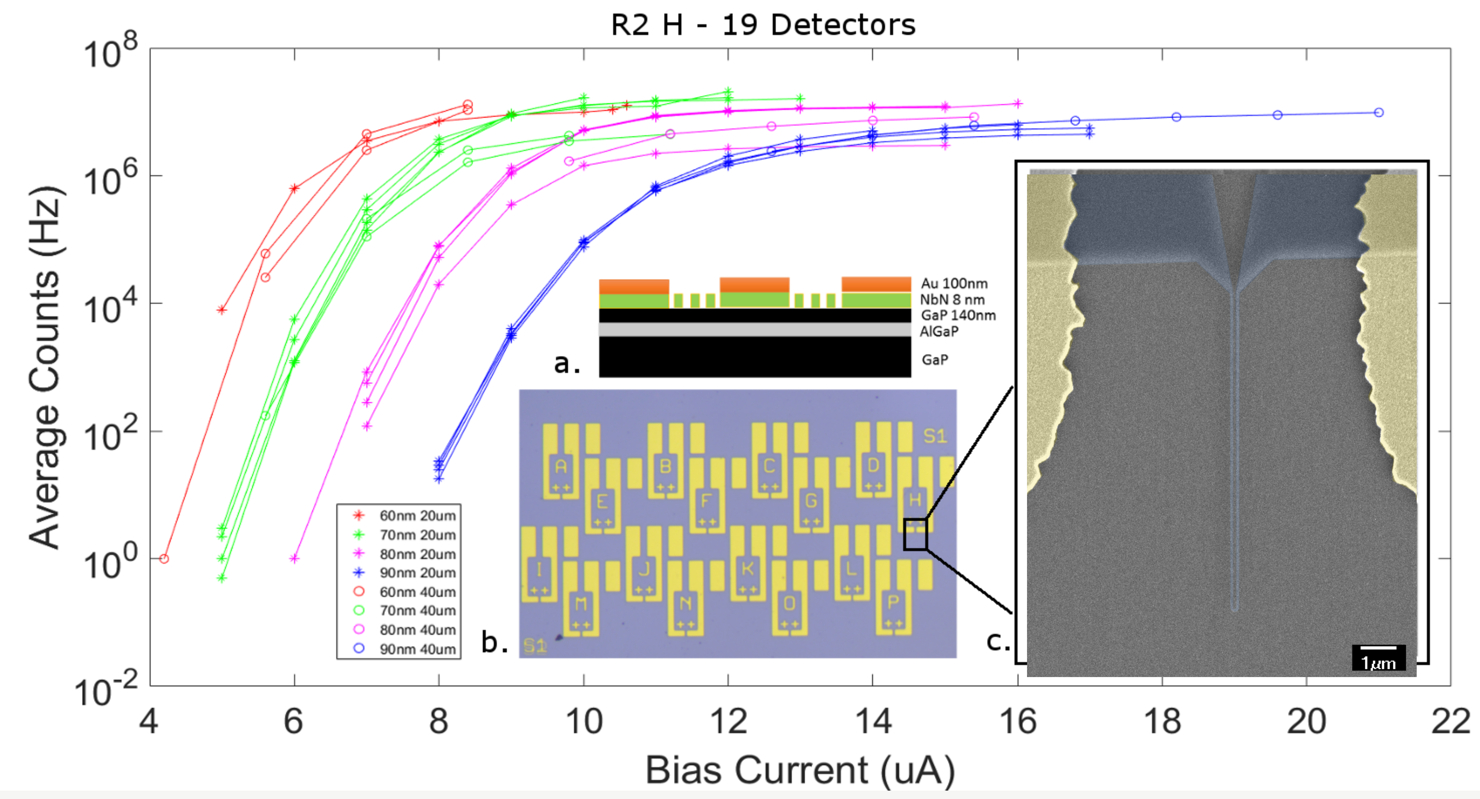


Figure: Count rates for 19 detectors vs bias current (All data taken at 4.2 K). Inset: SEM of nanowire (false color blue-NbN)

Photon extraction from NV centers

Integrated photonics provides a solution for two challenges inherent to NV centers in diamond: **[1]**

1. High refractive index of diamond limits free-space collection efficiency
   - Photonic components patterned on 125nm GaP membrane on Diamond substrate [n_{GaP} (3.3) > $n_{Diamond}$ (2.4)]
   - Near surface NV centers (10 to 20nm deep) efficiently coupled to 150nm wide single-mode ridge waveguides

2. Phonon interactions result in only 3% photon emission at desired zero-phonon line (ZPL) transition
   - Purcell Enhancement of ZPL emission by resonant micro-disk cavities (shown Purcell factor of 26, lifetime reduced from 8.7 to 4.7ns)

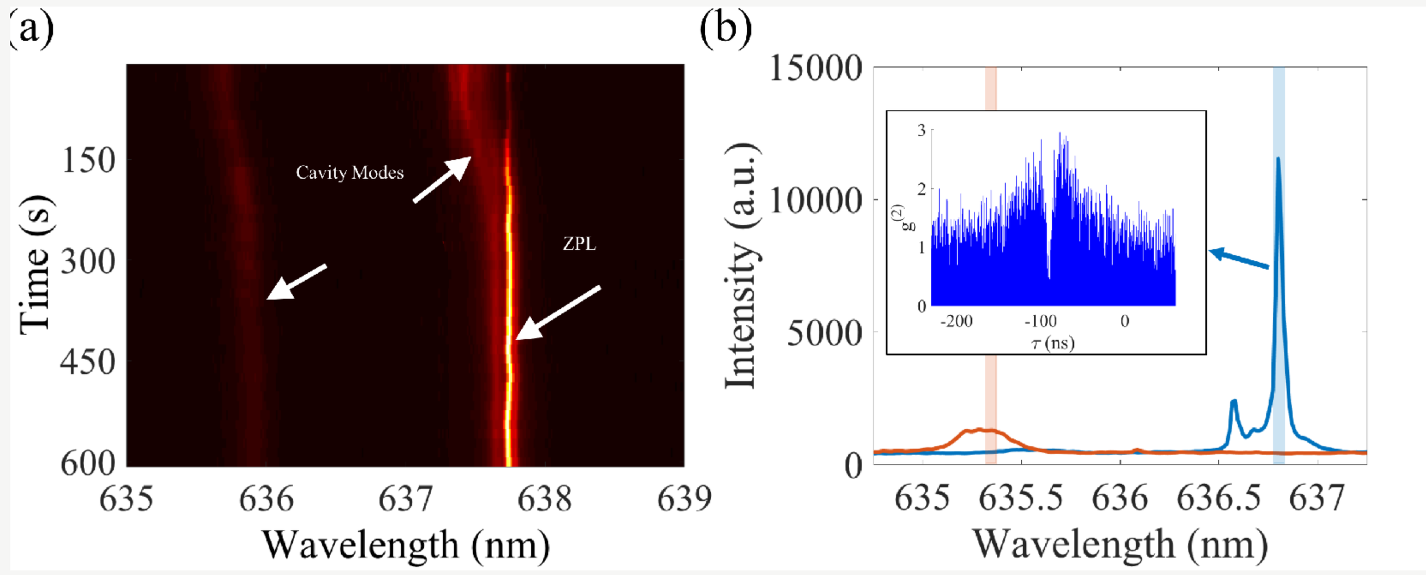
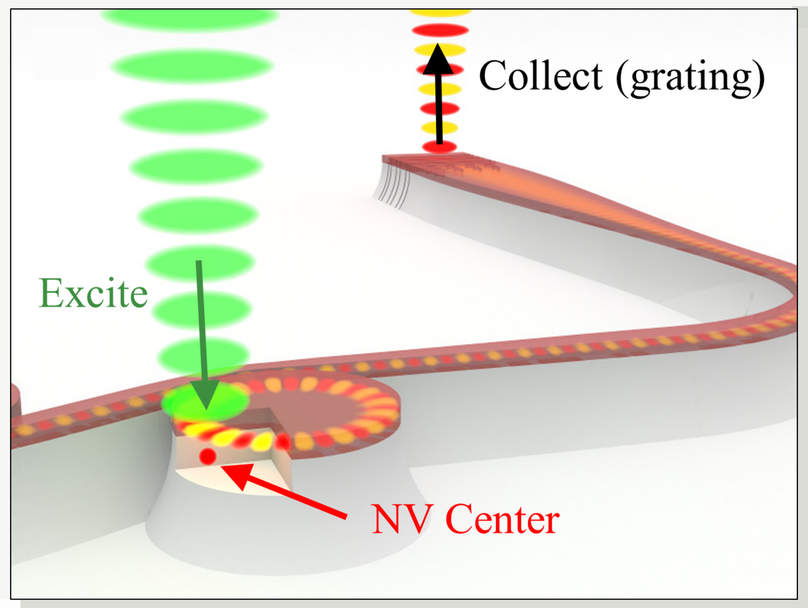
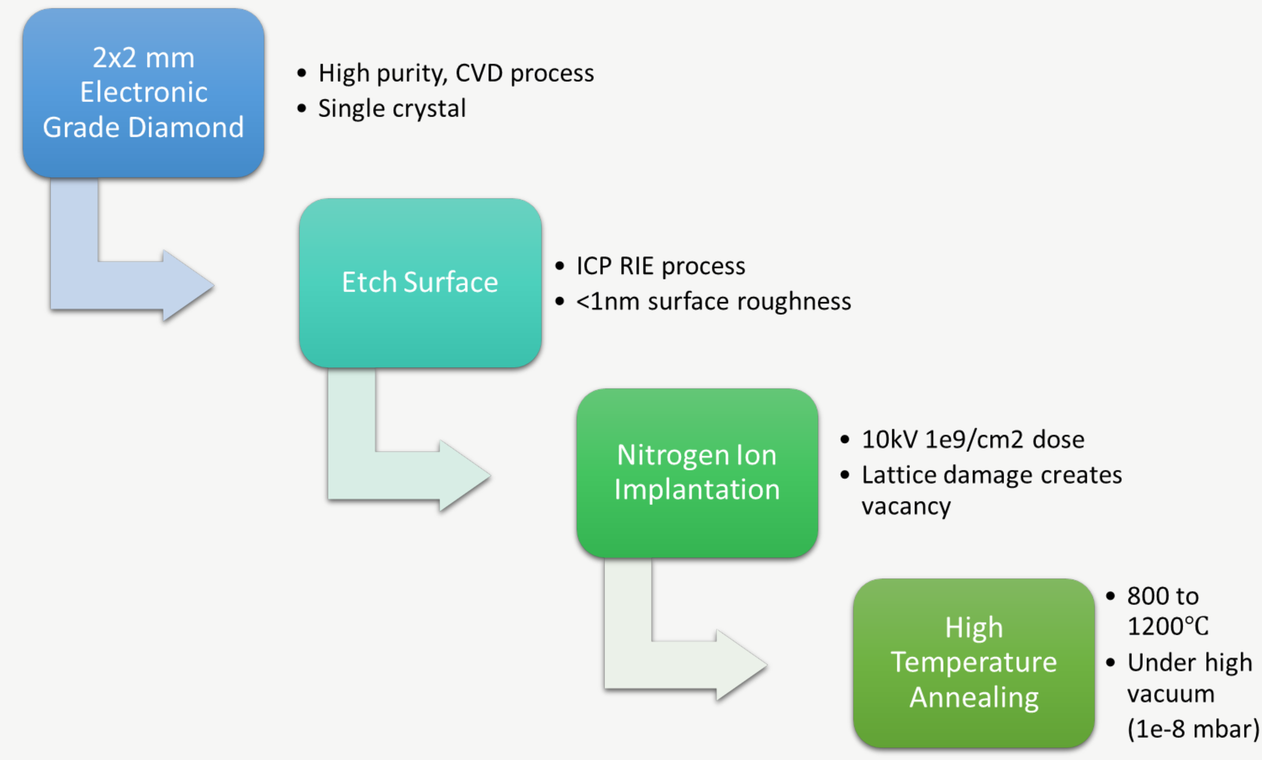


Figure: a) Tuning of cavity modes onto the NV ZPL with Xenon gas, and subsequent enhancement of ZPL (at 8K). b) Plot showing ZPL and G2 measurement. Below - illustration of excitation and collection of NV photons on test devices.



Creating NV centers in diamond



1 NV FORMATION

UNIVERSITY of WASHINGTON

All fabrication performed at the Washington Nanofabrication Facility, University of Washington, an NSF NNCI node. This material is based upon work supported by the National Science Foundation under Grant No. (1640986, 1506473) and the DARPA QUINESS Program.

2 NV PHOTON

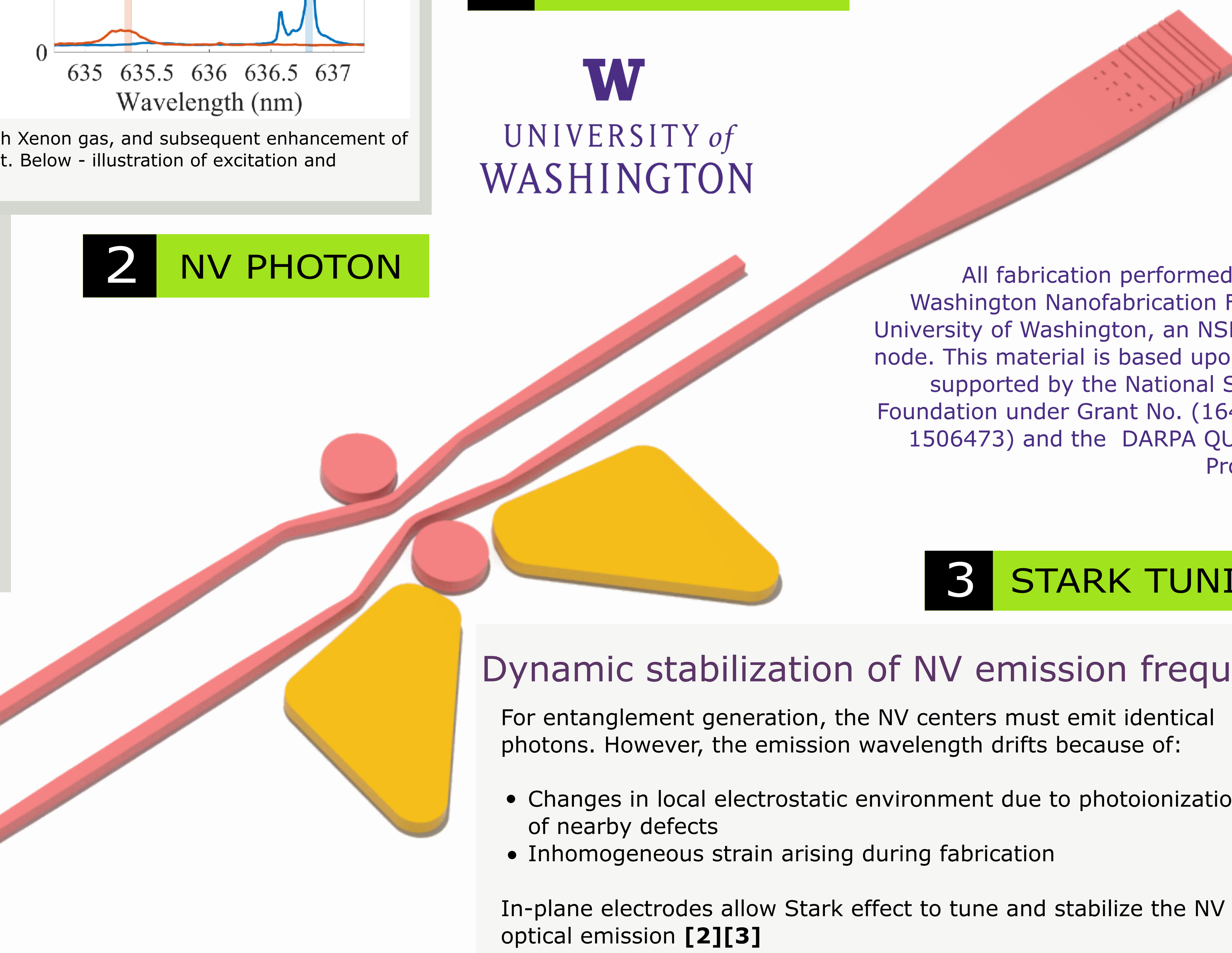


Figure: A NV entanglement generation unit consisting of two resonant disks (with NV directly below), directional coupler, stark tuning electrodes, grating couplers and superconducting detectors.

3 STARK TUNING

Dynamic stabilization of NV emission frequency

For entanglement generation, the NV centers must emit identical photons. However, the emission wavelength drifts because of:

- Changes in local electrostatic environment due to photoionization of nearby defects
- Inhomogeneous strain arising during fabrication

In-plane electrodes allow Stark effect to tune and stabilize the NV optical emission **[2][3]**

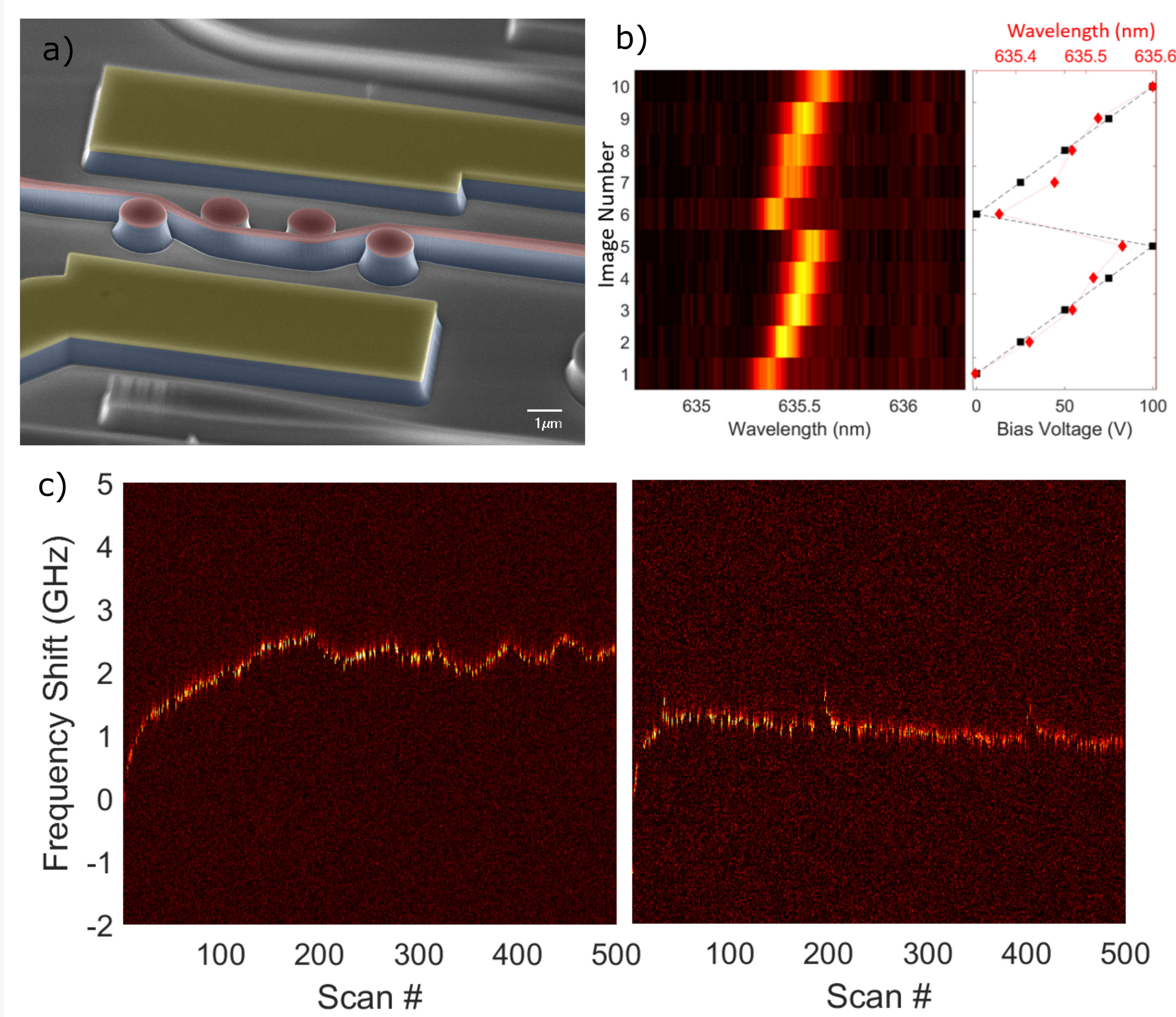


Figure: a) SEM image of stark tuning devices (false color showing gold, GaP and diamond; gold, red, blue). b) NV emission wavelength shift with increasing electrode voltage. c) Stabilization of emission by voltage feedback control.

4 PASSIVES

Passive photonic components

We fabricated and characterized large number of photonic components to optimize design and establish fabrication tolerances **[4]**

- Grating couplers (average efficiency ~17%)
- Directional couplers (different coupling ratios)
- Waveguides loops (loss estimation)
- Y-junctions

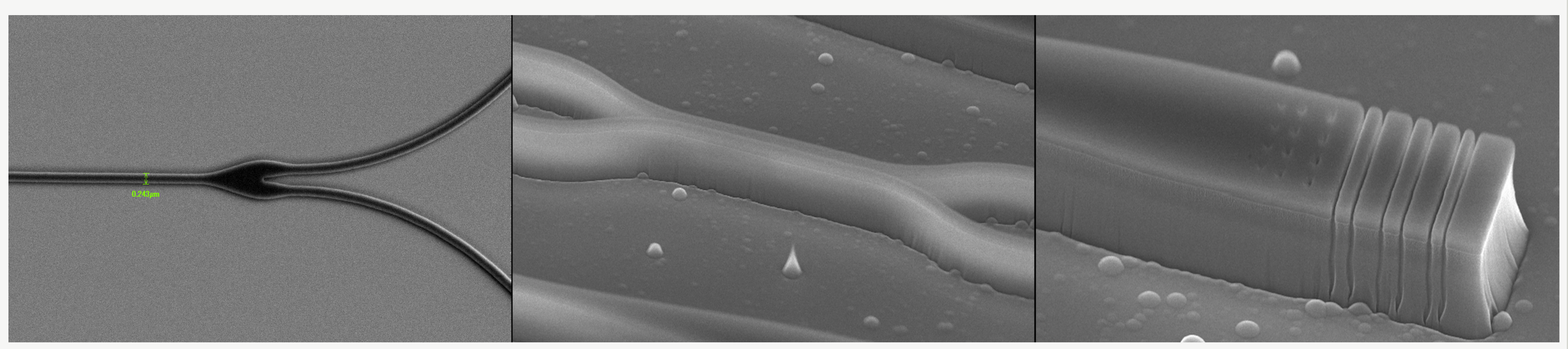


Figure: SEM images of passive components; Y-junction, directional coupler and grating coupler.

5 DETECTION

References:

1. M. Gould et al. "Efficient Extraction of Zero-Phonon-Line Photons from Single Nitrogen-Vacancy Centers in an Integrated GaP-on-Diamond Platform." Phys. Rev. Applied 6, 011001 (2016).

2. V. M. Acosta et al. "Dynamic Stabilization of the Optical Resonances of Single Nitrogen-Vacancy Centers in Diamond." Phys. Rev. Lett. 108, 206401 (2012)

3. E. R. Schmidgall et al. "Frequency Control of Single Quantum Emitters in Integrated Photonic Circuits." Nano Letters 18, 1175 (2018)

4. M. Gould et al. "Large-scale GaP-on-diamond integrated photonics platform for NV center-based quantum information." JOSA B 33.3 (2016): B35-B42.