Superconducting Single Photon Detectors and Diamond Nanophotonics

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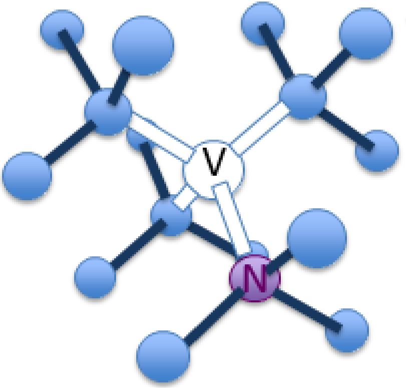
Stepping Back, Diamond and the NV^- Center [1]



- Diamond has $Fd\bar{3}m$ symmetry
- Nitrogen atom replaces a Carbon atom, and there is an adjacent vacancy
- 3 electrons from 3 Carbon atoms, 2 from the Nitrogen atom, and 1 captured electron for a total of 6
- Symmetry is deformed into C_{3v}, trigonal pyramid, where the N-V axis is deformed

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[1] Childress, Diamond Sensing Conference

The NV^- Center in Diamond as a Qubit

- Wide band-gap (5.5 eV)
- (Solid-State) Integration of electronic and optical devices on-chip
- (Solid-State) Tunable properties, fast control
- Optical access to individual electronic and nuclear spins at room temperature (637 nm transition)
- Long spin coherence times (up to .6s at 77K [1])
- Very well-studied solid-state QIP system

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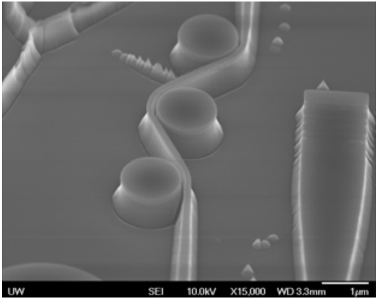
[1] Bar-Gill, doi:10.1038/ncomms2771

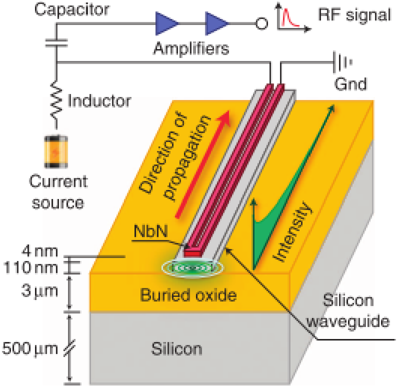
Our System, Why GaP?

- Incorporates Gallium Phosphide Waveguides/Resonators
- Wide bandgap allows optical wavelengths
- $n=3.41 > 2.41$
- GaP can be made to have a smooth surface; diamond is difficult to be made smooth
- Opto-electronic material



What is an SSPD, and how does it fit in?[1]

- Individual photons emitted by the NV^- need to be sensed
- Ideally, detector needs to be compact, fast, highly-efficient, and on-chip to avoid coupling losses
- Solution: Superconducting single photon detectors
- Over 90% efficiency in other systems, 400 ps dead time [1]
- Not yet implemented for NbN/GaP, but there are results for NbN/Diamond [2]



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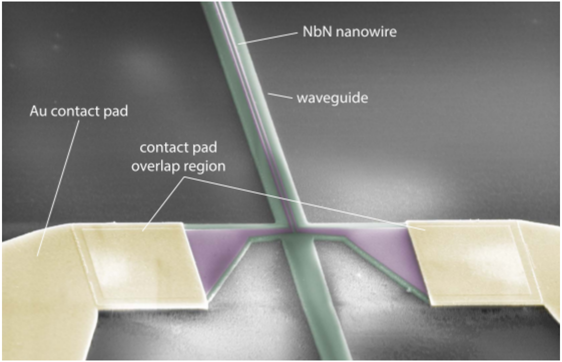
[1] Pernice, 10.1038/ncomms2307

[2] Rath, arXiv:1505.04251

How does it work?

- Detector is cooled to cryogenic temperatures
- A current is applied through contacts, and since resistance is zero there's no voltage
- A photon travels through the waveguide, and is absorbed by the detector
- The absorption event breaks/suppresses the superconductivity, and there's a voltage spike across the detector

Traveling Wave Design [1]



- Traveling wave (waveguide coupled) design maximizes the absorption rate, increasing device efficiency

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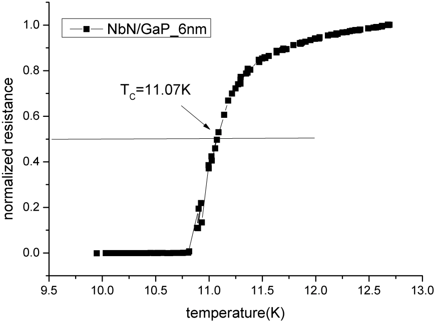
[1] Kahl, 10.1038/srep10941

Why NbN?

- Well-studied
- Partnership with Fiore Group in Eindhoven, who can produce high-quality samples



Stepping Back, History of Superconductivity

- Superconductivity first discovered by Onnes in 1911
- Phenomenological model of superconductivity described by Ginzburg Landau theory in 1950 (2003 Nobel)
- Microscopic superconductivity described by BCS theory in 1957 (1972 Nobel)
- Gor'kov showed that the two theories were connected in 1959 [1]

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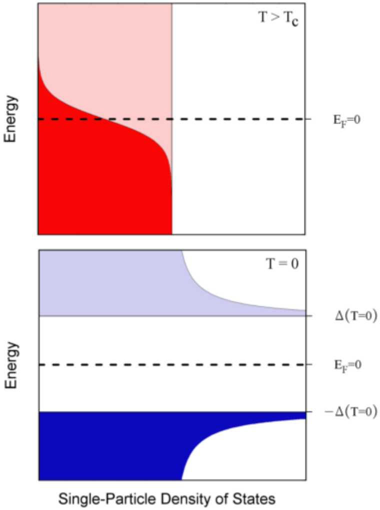
[1] Gor'kov, 0038-5646

A Little About Superconductivity [1]

- A band-gap opens up in the single-particle density of states, Δ above and below the Fermi level. 2Δ corresponds to the binding energy of the pairs.



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[1] Pracht, 10.1109/TTHZ.2013.2255047

Ginzburg Landau Theory

- The Ginzburg Landau Theory (GL) is a macroscopic description of the superconducting wave-function
- When encountering spatial inhomogeneity, GL Theory is easier to work with
- GL Theory introduces a complex order parameter, where the square is equal to the local density of superconducting electrons

$$\psi(r) = |\psi(r)| e^{i\theta(r)}, \quad |\psi(r)|^2 = n(r) \tag{1}$$

Ginzburg Landau Differential Equations

$$\alpha\psi + \beta|\psi|^2\psi + \frac{1}{2m^*}\left(\frac{\hbar}{i}\nabla - \frac{q^*}{c}\vec{A}\right)^2 \psi = 0 \tag{2}$$

$$\vec{J}_s = \frac{q^*}{m^*}|\psi|^2\left(\hbar\nabla\phi - \frac{q^*}{c}\vec{A}\right) = q^*|\psi|^2\vec{v}_s \tag{3}$$

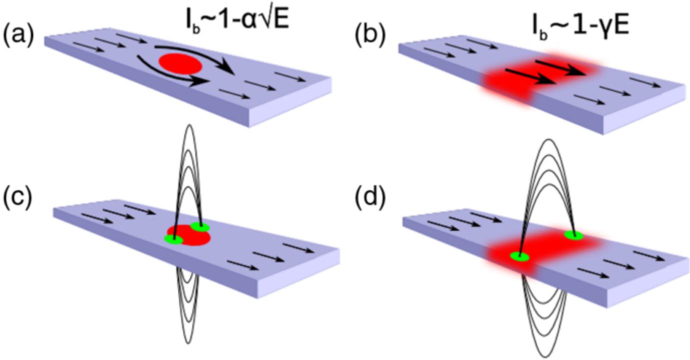
- When you remove the non-linear term in the first equation, it reduces to the Schroedinger equation with eigenvalue $-\alpha$
- The non-linear term acts like a repulsive potential of ψ on itself, spreading it out
- The quantity $\frac{-\alpha}{\beta}$ can be taken to be the value of the wave-function in the absence of surface currents and fields

Quantities of Interest in Superconductors

- Critical temperature, T_c
- Pippard's coherence length, ξ_0
- Ginzburg Landau coherence length, ξ
- Critical current, I_c
- London penetration depth, λ_L
- Electron mean-free path, l
- "Dirty" superconductor $l \ll \xi_0$
- Type-II superconductor $\kappa = \frac{\lambda_L}{\xi} > \frac{1}{\sqrt{2}}$
- NbN is type-II and "dirty"

Inherent Difficulty of Simulation

- Detection mechanism not well understood [1]



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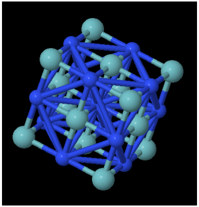
[1] Renema, 10.1103/PhysRevLett.112.117604

Open Questions

- Is the superconductivity broken in a cylindrical normal region?
- Or is the superconductivity suppressed in a more wider region?
- What role do magnetic vortices play?

Other Factors at Play

- NbN must be in $\delta - NbN$ phase for highest T_c (cubic) [1]
- Fabrication limitations – many devices likely to be broken as fabrication process is refined
- Ideally, GaP surface and NbN surface has an RMS roughness of less than half a nm, which we've achieved



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[1] Marsili, 10.1088/0953-2048/22/9/095013

What Makes a Good Detector?

- High device detection efficiency (DDE)

$$DDE = \eta_{abs} \times \eta_{reg} \tag{4}$$

- Low dark counts (Kosterlitz Thouless transition) [1]
- Low timing jitter (arrival time uncertainty)
- Low dead time (recovery time)

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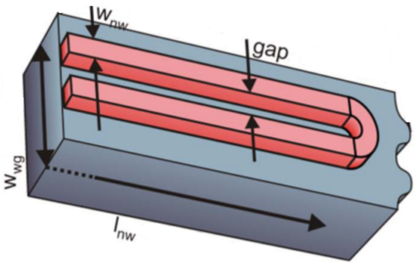
[1] Semenov, 10.1016/j.physc.2007.11.028

Geometry Constraints, Creating the Optimal Detector [1]

- Curvature of bend
- Thickness/width of the nanowire
- Fill-factor (width / distance between symmetric structures)
- Geometry of GaP waveguide



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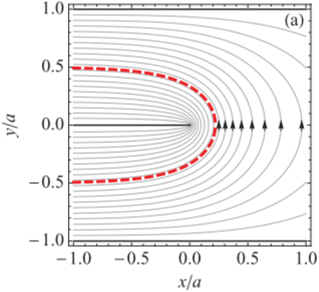
[1] Schuck, 10.1038/srep01893

Curvature of Bend [1]

- Current crowds around sharp corners, reducing the critical current
- Optimal curvature follows contour line that separates current-crowding region and current-expanding region in a gapless bend

$$y = \pm\frac{2w}{\pi}cos^{-1}\left[exp\left(\frac{x\pi}{2w}\right)\right] \tag{5}$$



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[1] Clem, 10.1103/PhysRevB.84.174510

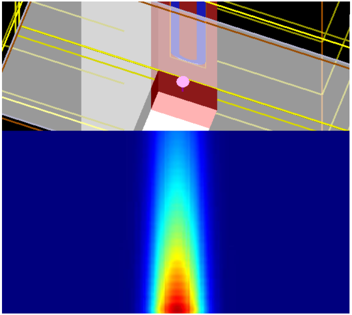
Thickness/Width

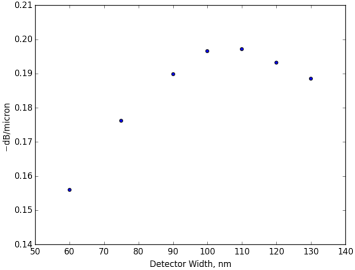
- The $\xi_{GL}(T)$ coherence length is a characteristic length scale for spatial variations in the macroscopic superconducting wave-function
- As such, to keep spatial variations (in the event of suppression/breaking of the superconductivity during photon events) uniform through the thickness, we shall keep the thickness around this value, $\xi_{GL} \approx 5nm$
- If we assume a model, we can place an upper-bound on the width associated with a wavelength cut-off, and a lower bound associated with the formation of magnetic vortices

$$30\,nm < w < 130\,nm \tag{6}$$

Simulations and Results

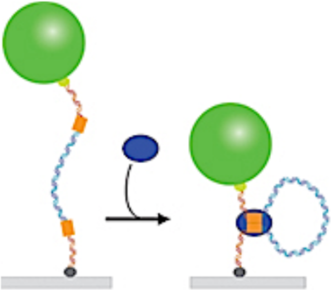
- Finishing up calculating $\eta_{abs}(w_{nw}, fill, x_{wg}, y_{wg})$
- Other approaches: double meander
- $\eta_{abs}(w_{nw}, b, c, d)$ peaks at around $w_{nw} = 110nm$
- Working on: coupling to $\eta_{reg}(w_{nw})$ to maximize DDE





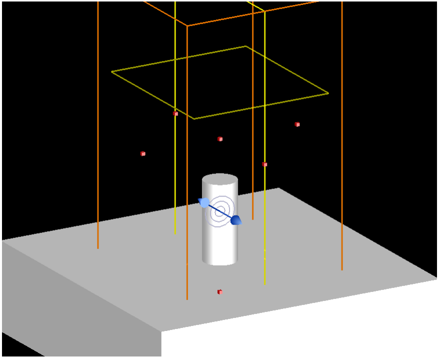
Magnetometry: Quick Overview

- Magnetic nanoparticles are tethered to diamond chip by DNA
- Motion and configuration of the DNA strand can be sensed by how the B-field of the nanoparticles affects the NV^- centers.



Problem and Solution

- Problem: too much background noise from NV^- centers that are excited around the nanoparticle, rather than those directly beneath it
- Solution: etch diamond pillars into the chip, focusing the signal



Future Work

- Start building them!

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