Engineering Quantum Defects for Quantum Network Applications

Kai-Mei Fu, University of Washington

Engineering Quantum Defects for Quantum Network Applications

Presented by:

OSA Quantum Optical Science and Technology Technical Group

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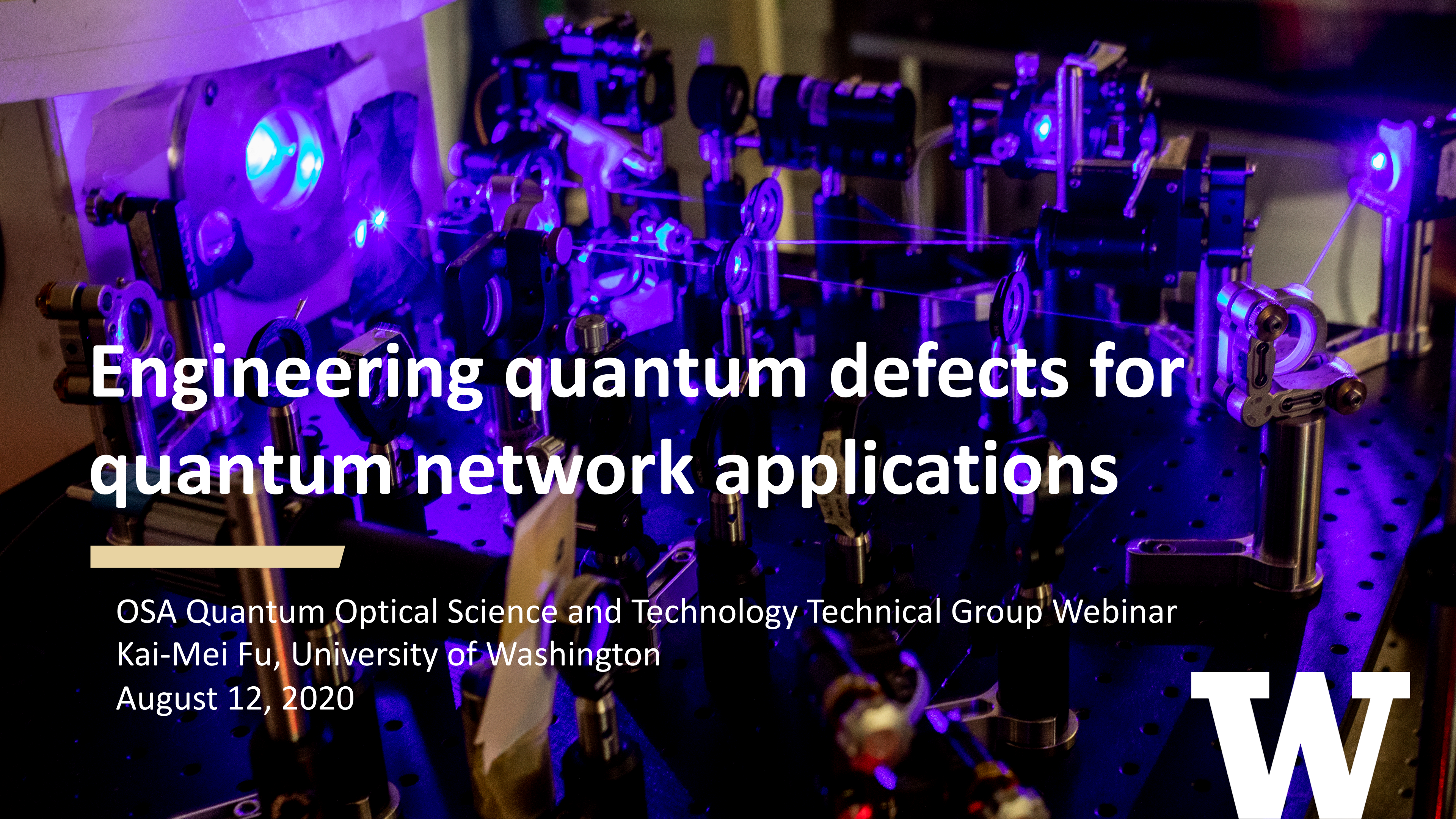
- 2427 total members worldwide
- Webpage https://www.osa.org/oq
- Webinars, technical events, networking events, etc.
- Suggestions, ideas for events, email us at OSA TGActivities/gpuentes@df.uba.ar
- Join Us for 20x20 Talks at Quantum 2.0! (submission deadline 28 August)

Welcome to the Quantum Optical Science and Technology Technical Group Webinar!



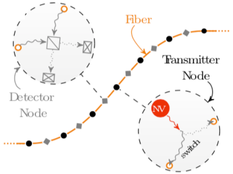
Engineering quantum defects for quantum network applications

OSA Quantum Optical Science and Technology Technical Group Webinar

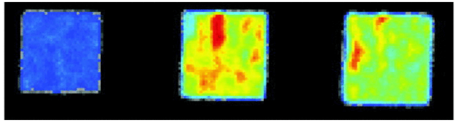
Kai-Mei Fu, University of Washington

August 12, 2020

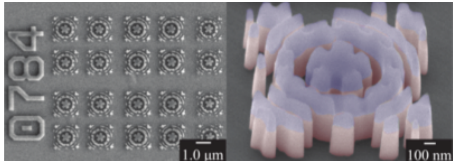
Overview of today's talk



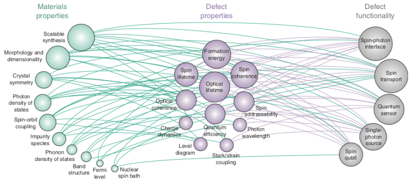
Introduction to quantum networks and defect nodes



Making and characterizing quantum defects



Integration of quantum defects into devices



Discovery and engineering of new defects

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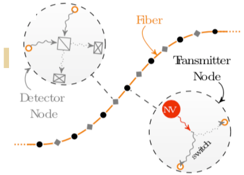
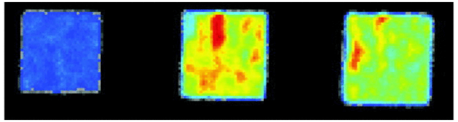
Overview of today’s talk

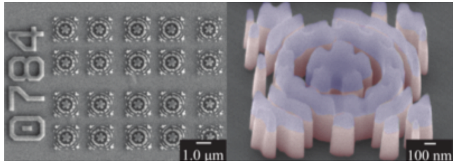


Introduction to quantum networks and defect nodes

- What is a quantum network?
- What properties do we want in a node?
- Why defects, what defects?



Making and characterizing quantum defects



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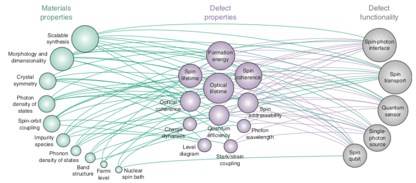

Discovery and engineering of new defects

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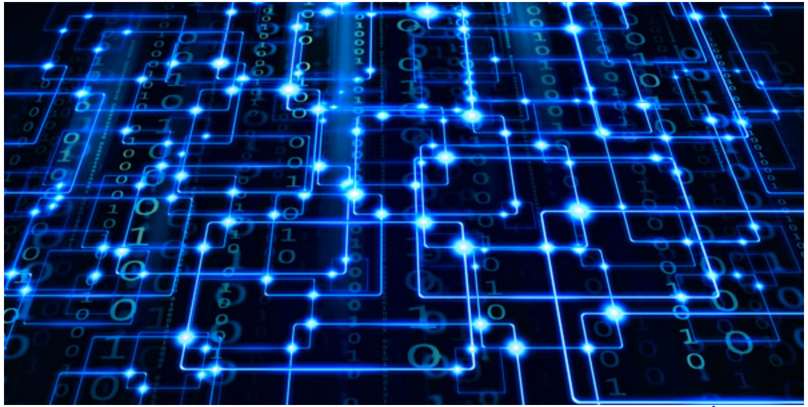
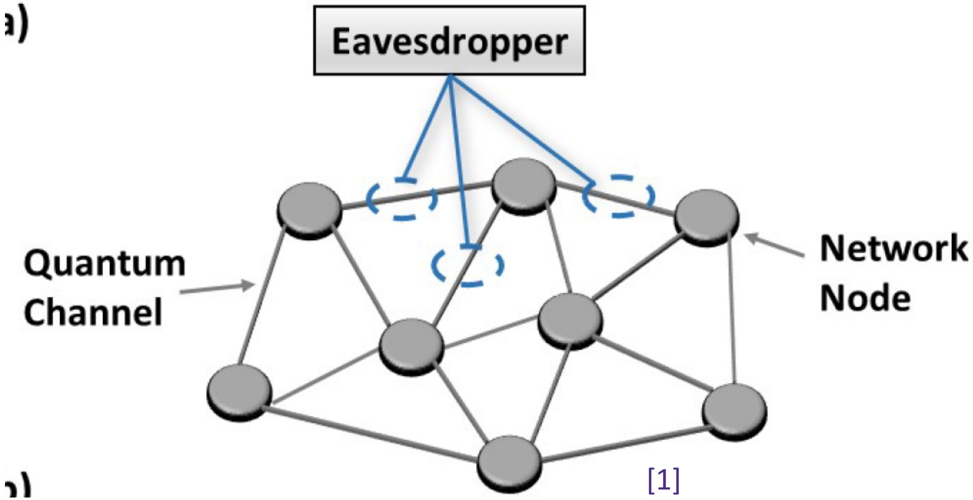
Quantum networks



quantum-networks.net

Quantum networks: nodes and edges



node:

quantum transmitter

classical receiver or **quantum memory**

qubit: *superposition of 0 and 1*

edge/channel:

direct transfer of qubits (photons) or

represents **quantum correlated states between nodes (***entanglement)*

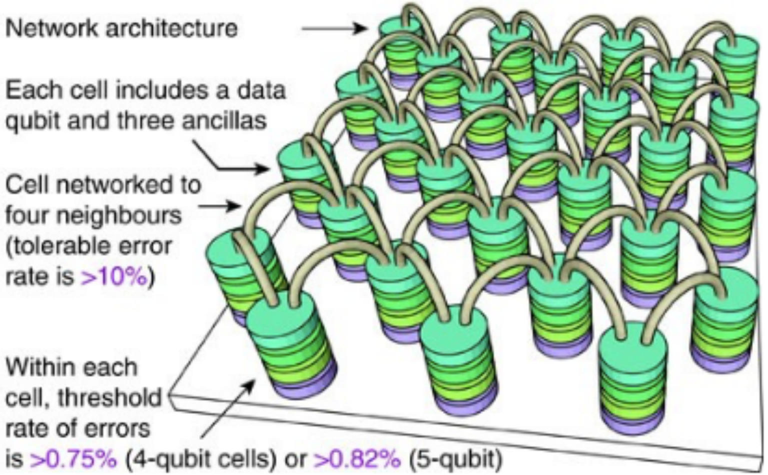
[1]"Secure quantum routing", arXiv:1607.03163

Applications for quantum networks

A quantum internet

Image credit: Ars Technica: Bob Dormon, “How the internet works”

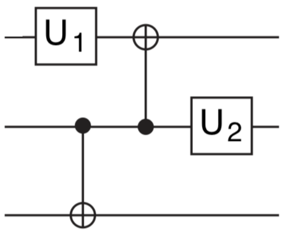
Distributed quantum computing

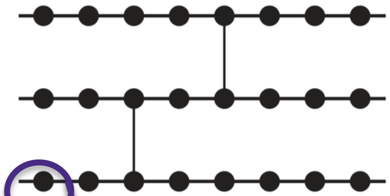


Nickerson, Li, Benjamin *Nat. Comm.* 4 1756 (2013), Oxford

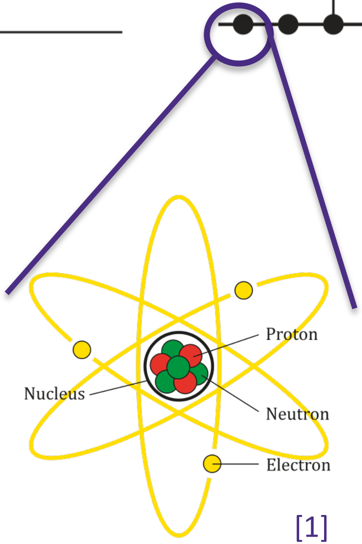
See, e.g. Wehner, Elkouss, Hanson, “Quantum internet: a vision for the road ahead” Science (2018)
Nielsen, “Cluster-state quantum computation”, Rep. on Math. Physics (2006)

Defects as quantum nodes

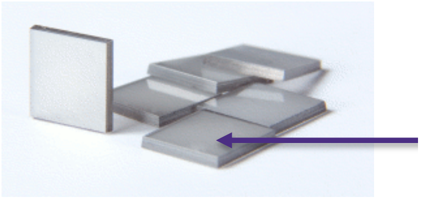




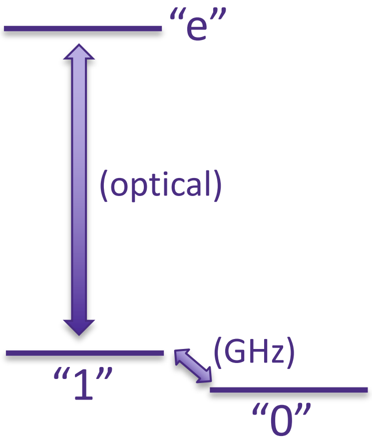
Oxford [2]

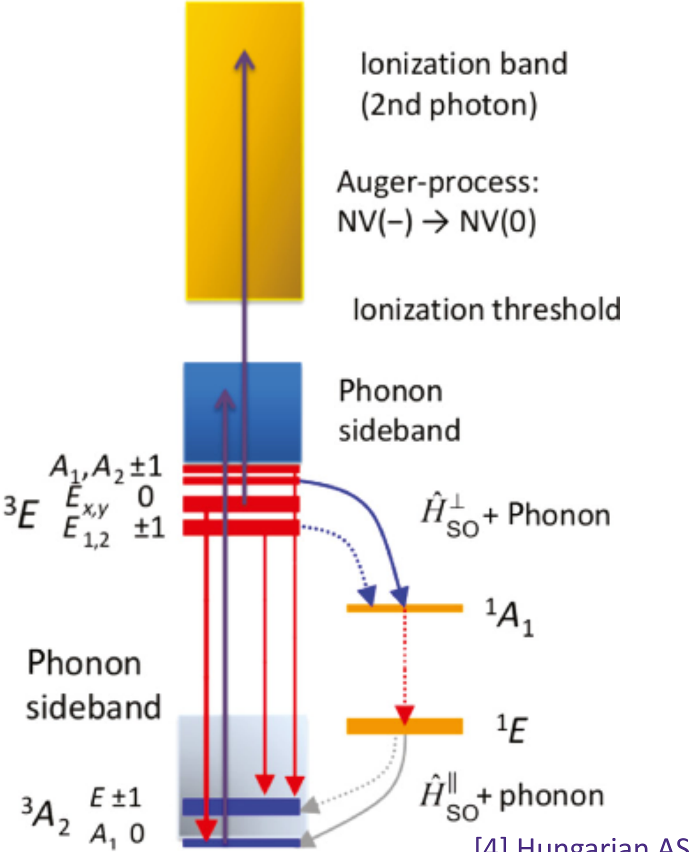


[1]



Element Six

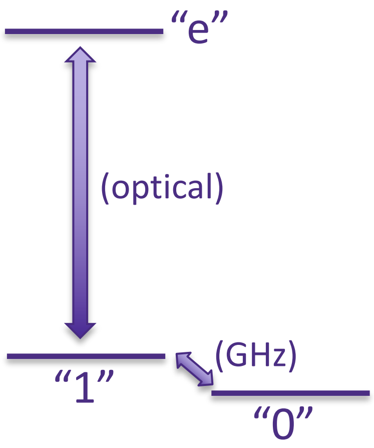




[4] Hungarian AS

[1] commons.wikimedia.org, User:AG Caesar [2] "Prospects for measurement-based quantum computing with solid state spins" *Laser & Phot. Rev.* (2009)
[3] "Quantum Defects by Design" *Nanophotonics* 2019 [4] " *Ab initio* theory of the nitrogen-vacancy center in diamond", *Nanophotonics* (2019)

Node requirements:
(1) Qubit coherence (quantum memory, T_2)



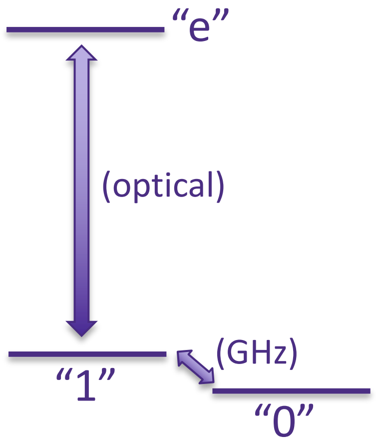
$$|\Psi\rangle = a|0\rangle + be^{i\phi}|1\rangle$$

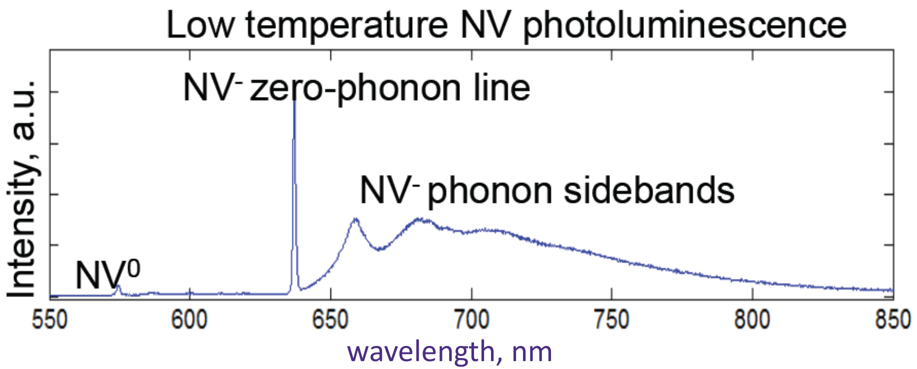
Platform	record
Trapped ion (Ba+)	10 minutes [1]
Superconducting (transmon)	0.3 ms [2]
Defect (P:Si)	39 minutes [3]

Typical times are much shorter. Defect coherence can be ps!

[1] "Single-qubit quantum memory exceeding ten-minute coherence time" *Nature* 2020, [2] "New material platform for superconducting transmon qubits with coherence times exceeding 0.3 ms" *arXiv* (2020) [3] "Room Temperature quantum bit storage exceeding 39 minutes using ionized donors in Silicon-28" *Science* 2013

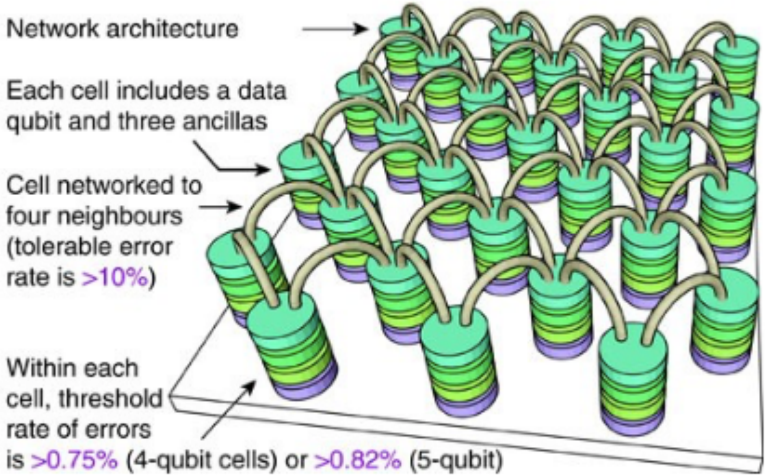
Node requirements:
(2) Stable, efficient spin-optical interface





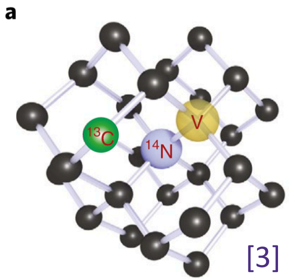
Node requirements:
(3) Multiple qubits per node with local operations

Generating edges is probabilistic:

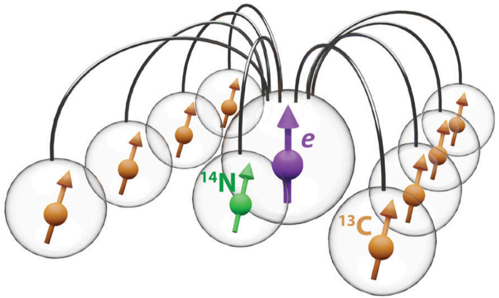


[1] Oxford

10 qubit register, NV diamond



[3]



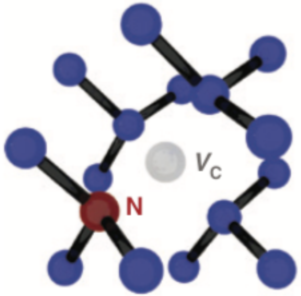
[2] Delft

Directly coupling 2 defects in a register is an outstanding challenge

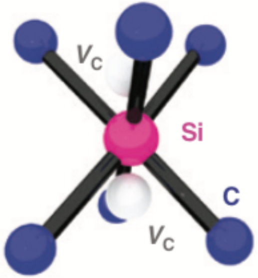
[1] “Topological quantum computing with a very noisy network and local error rates approaching one percent” *Nat. Comm.* 2013) [2] “A ten qubit solid-state spin register with quantum memory up to one minute”, PRX (2019) [3] “Quantum technologies with optically interfaced solid-state spins”, Nature Photonics (2018)

Node requirements: (4) Identical photons! (space, frequency, time, transform-limited)

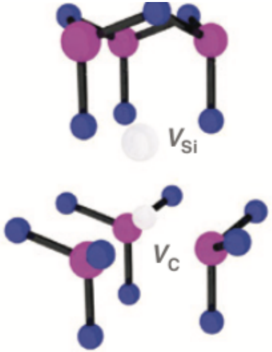
To 0th order defects are identical – this is a good starting point!:



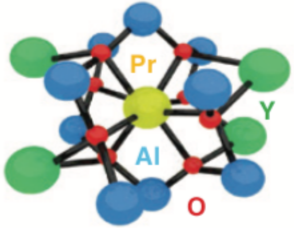
NV:diamond



SiV:diamond



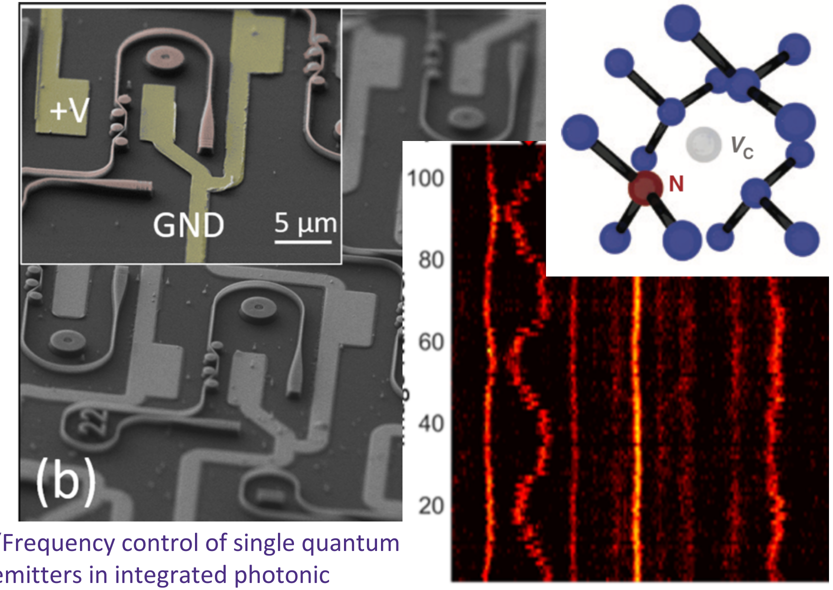
V_{Si}:SiC



Pr:YAG

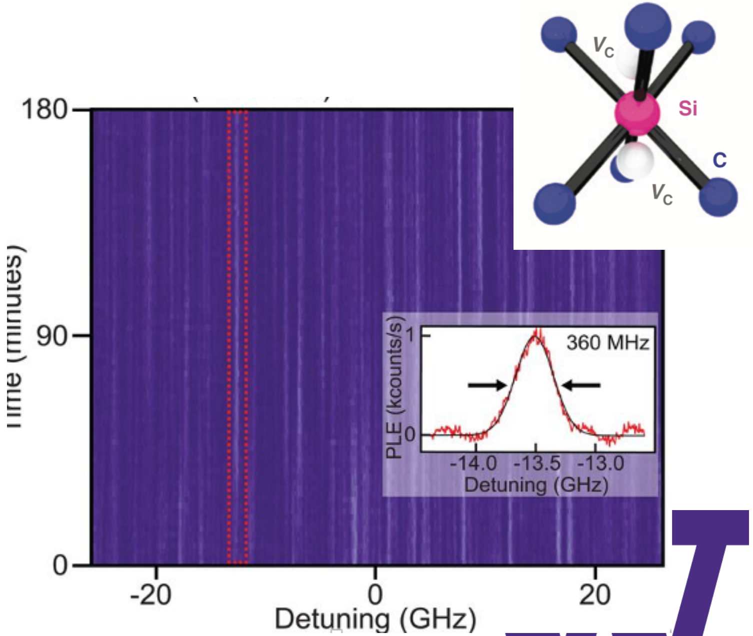
"Quantum Defects by Design" *Nanophotonics* 2019

Node requirements:
(4) Identical! But microscopic environments are different!



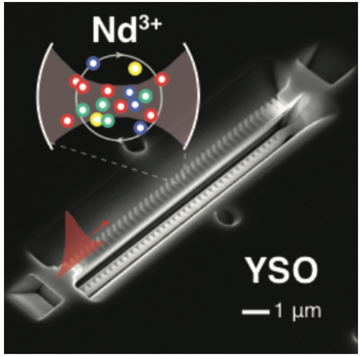
"Frequency control of single quantum emitters in integrated photonic circuits", *Nano Letters* (2018), UW

wavelength, nm

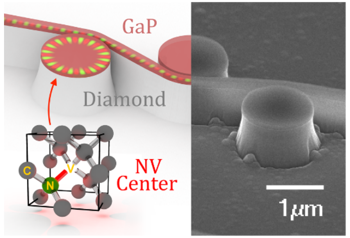


"Observation of an environmentally insensitive solid-state spin defect in diamond", *Science* (2018), Princeton

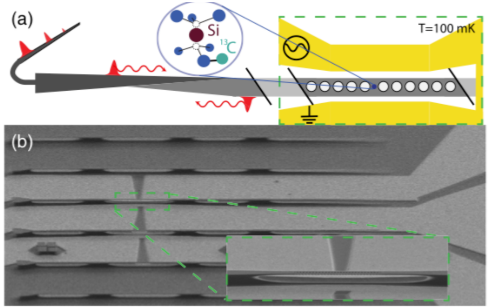
Defects are compatible with device integration
Enhanced performance and scalability



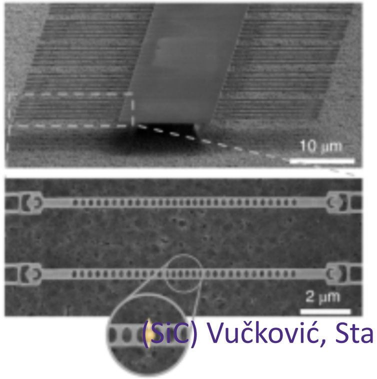
Faraon, Caltech



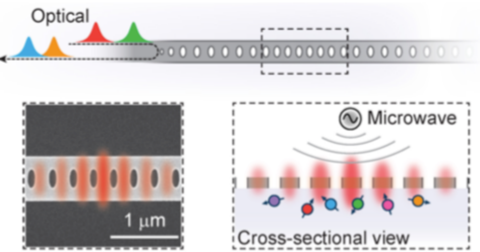
Fu, UW



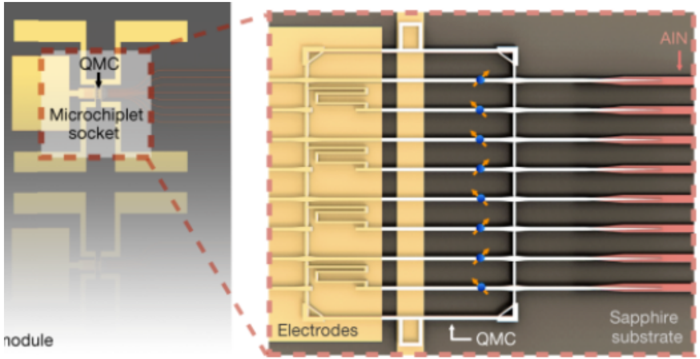
(diamond) Park, Lončar, Lukin, Harvard



(SiC) Vučković, Stanford



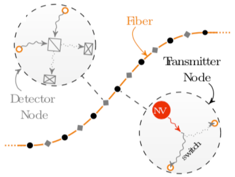
(Er:YSO) Thompson, Princeton



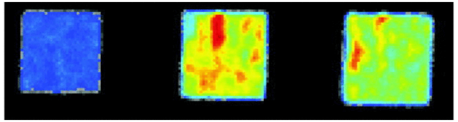
(diamond) Englund, MIT

Many, many more!

Overview of today’s talk



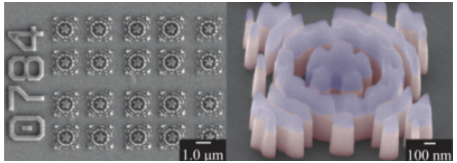
Introduction to quantum networks and defect nodes



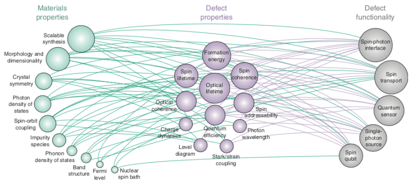
Making and characterizing quantum defects

How we make them

How we characterize them



Integration of quantum defects into devices



Discovery and engineering of new defects

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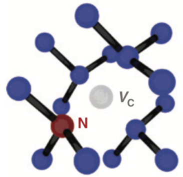
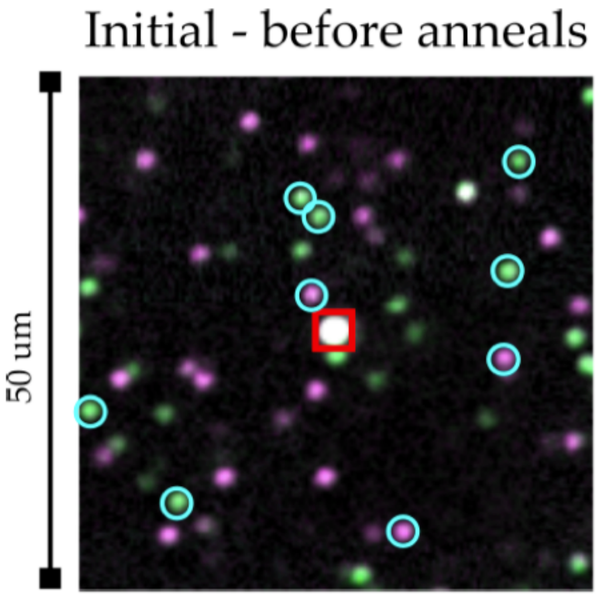
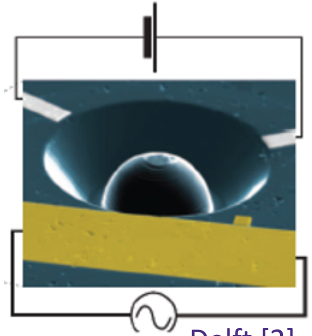
Making quantum defects
Method 1: *in situ* doping during grown (intentional or non-intentional)





Element Six CVD diamond
N < 1 ppb (suspect ~ppt)
NV ~ 4 ppq



Delft [2]

The highest quality defects, but least control

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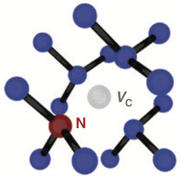
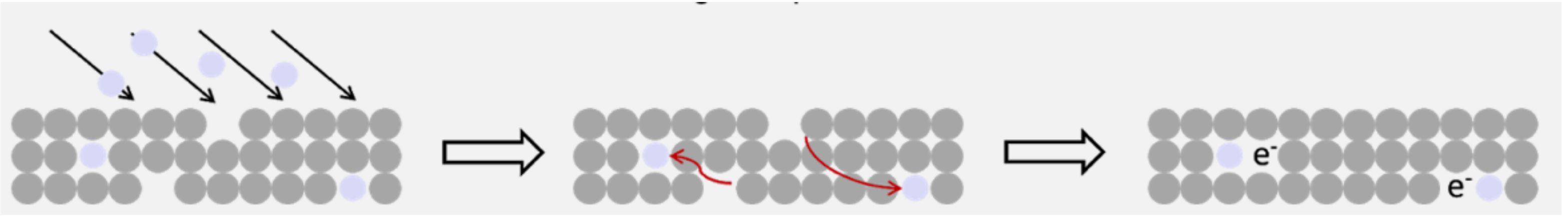
[1]"A window into NV center kinetics via repeating annealing and spatial tracking of thousands of individual NV centers" *PR Applied* (2020) [2] " Deterministic delivery of remote entanglement on a quantum network" *Nature* (2018)

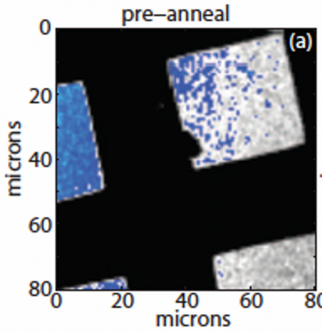
Making quantum defects
Method 2: implantation and annealing

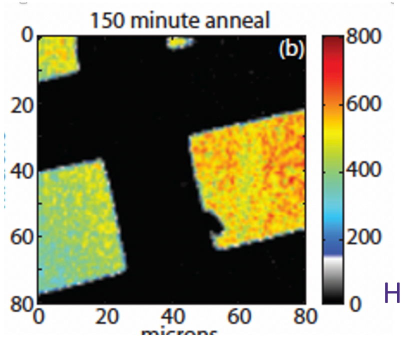


implantation | high-T vacuum anneal | 460 ℃ O_2 anneal



Control over placement, but properties are degraded.





HP, [1]

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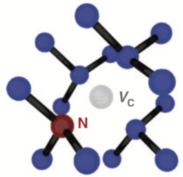
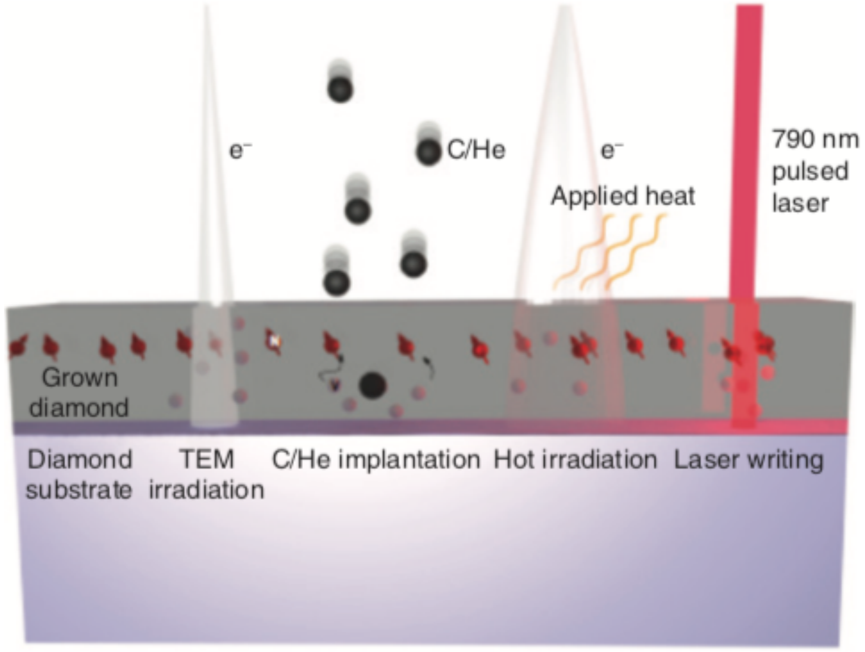
[1] “Conversion of neutral nitrogen-vacancy centers to negatively charged nitrogen vacancy centers through selective oxidation”, *APL* (2010)



Making quantum defects
Method 3: doping + X (electrons, He+, C, heat, light)



Good quantum properties
Moderate spatial control
- optical resolution
- vacancy diffusion
- doping density

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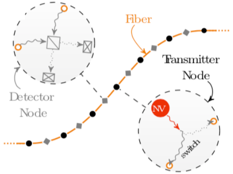
“Colour center generation in diamond for quantum technologies” *Nanophotonics* (2019)

Overview of today’s talk



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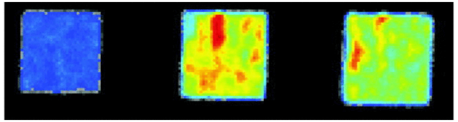

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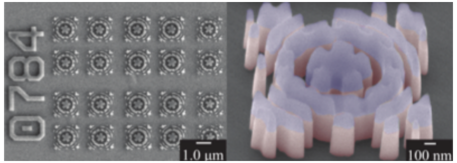

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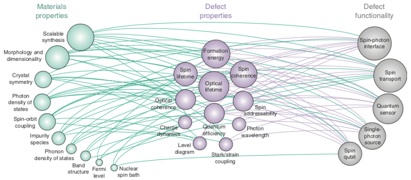

Discovery and engineering of new defects

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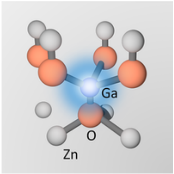
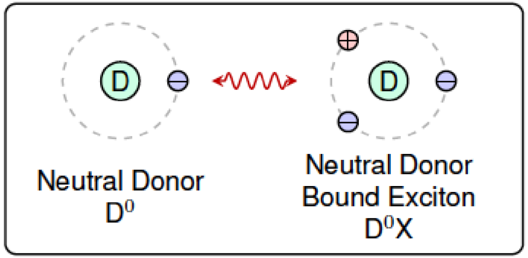
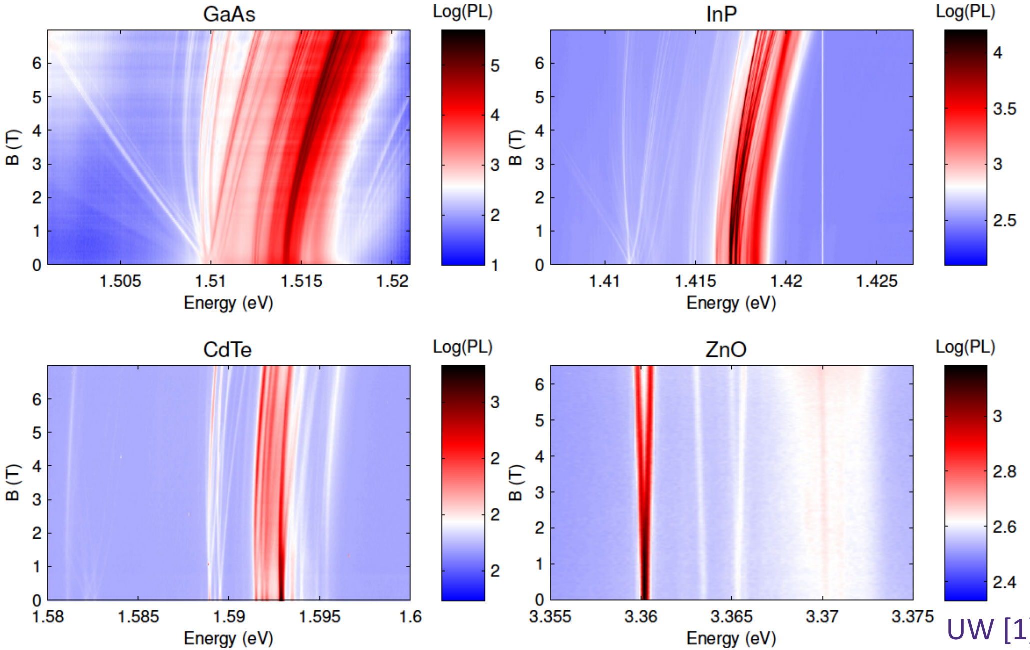
Characterizing quantum defects:
Energy level structure: Photoluminescence

(It is **really hard** to identify a new defect just from photoluminescence. Here we assume we already know something about the defect.)

donors in semiconductors
effective mass theory



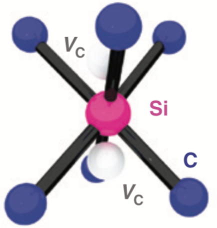


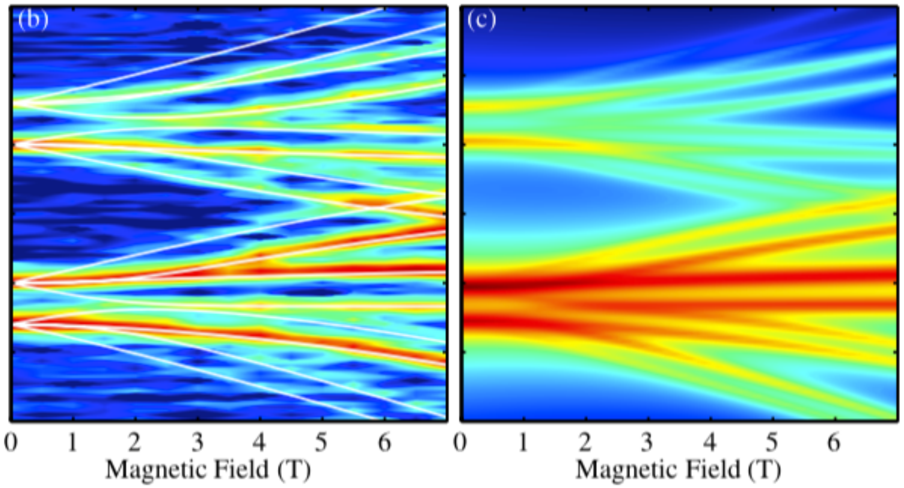


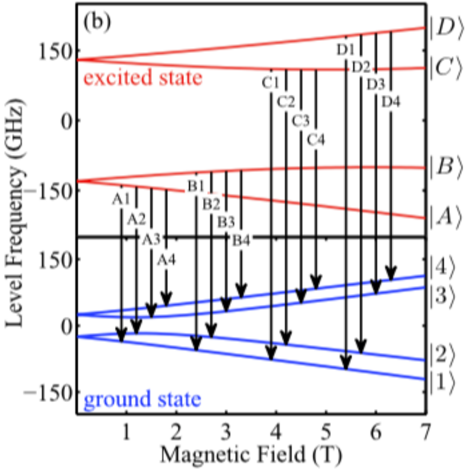
[1] “Longitudinal spin relaxation of donor-bound electrons in direct band-gap semiconductors”, *PRB* (2016) [2] “Coherence properties of shallow donor-bound electrons in ZnO”, *PR Applied* (2018)

UW [1][2]

Characterizing quantum defects:
Energy level structure: Photoluminescence







Typically, energy structure should be understood before measuring qubit properties.

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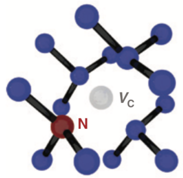
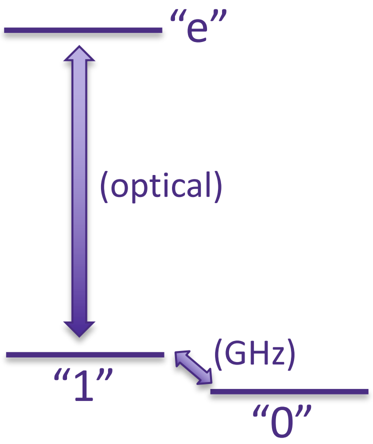
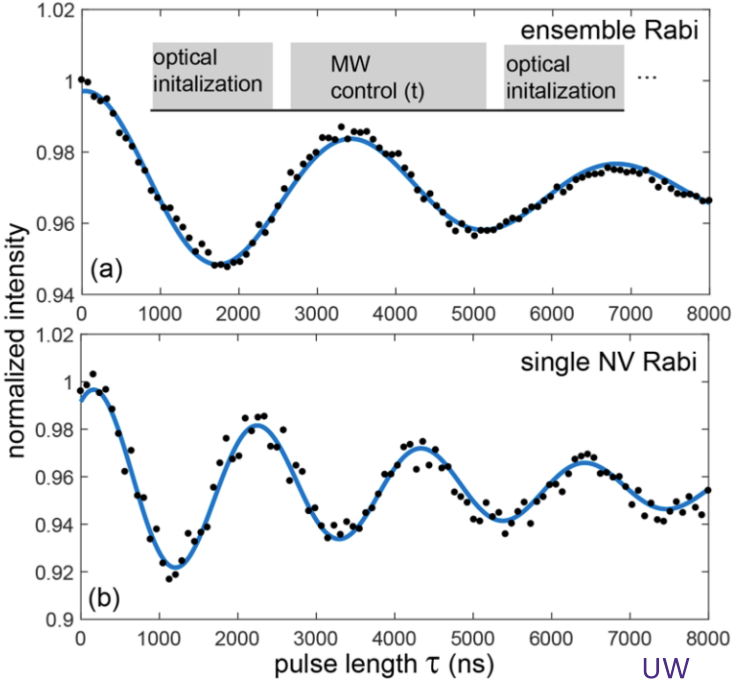
“Electronic structure of the silicon vacancy color center in diamond”, *PRL* 2014, Cambridge/ETH



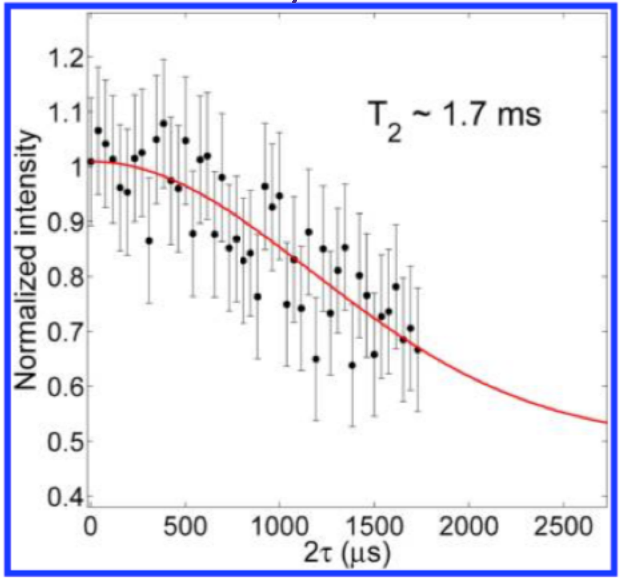
Characterizing quantum defects: Spin properties



MW driving transitions: diamond-NV



Qubit memory: Diamond-NV



HP [1]

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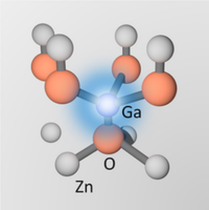
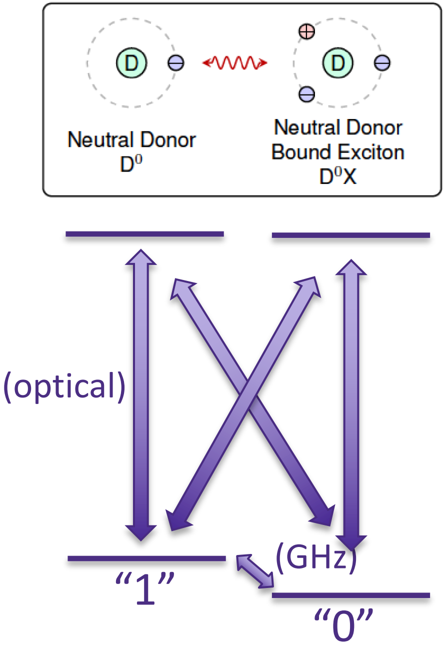
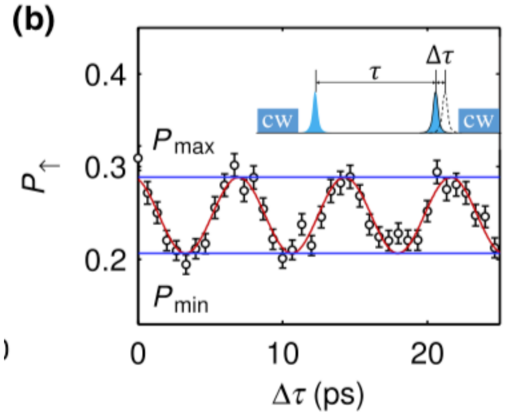
[1] “Optical and spin coherence properties of nitrogen-vacancy centers placed in a 100 nm thick isotopically purified diamond layer” *Nano Letters* (2012)

Characterizing quantum defects:
Spin properties: different spin-relaxation times

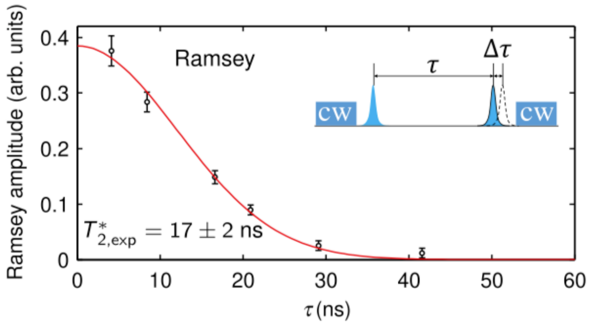




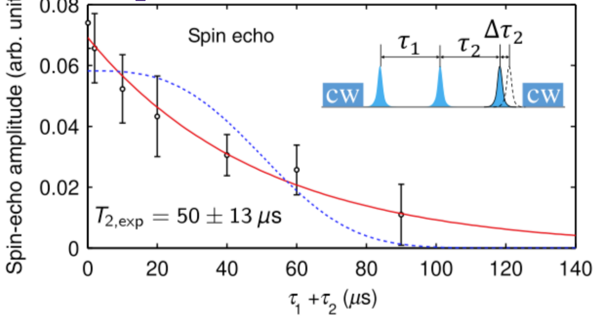
Larmor precession time



T_2^*: Ensemble dephasing time

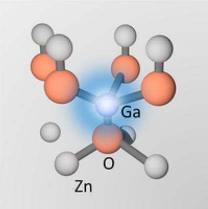


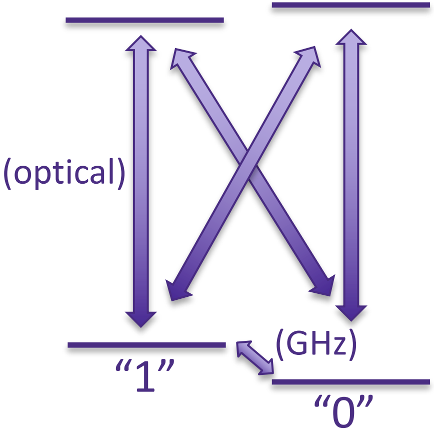
T_2: Ensemble spin echo time



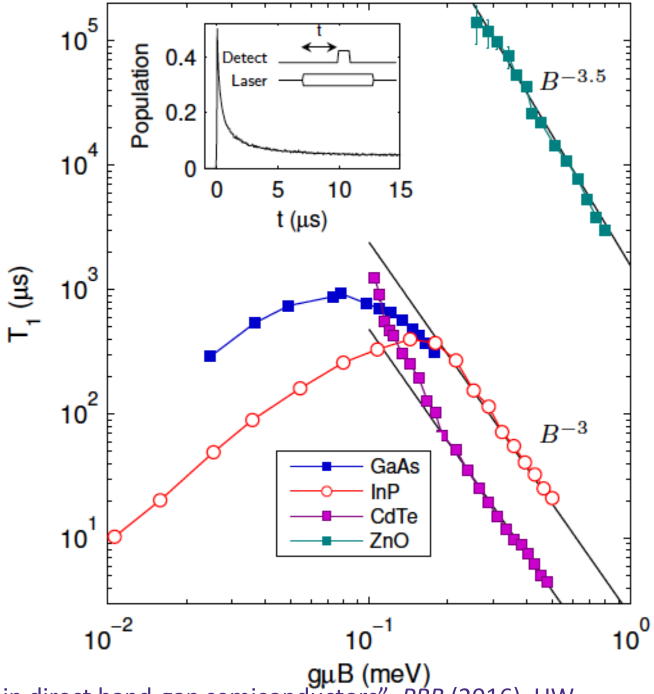
"Coherence properties of shallow donor-bound electrons in ZnO", *PR Applied* (2018), UW

Characterizing quantum defects:
Spin properties: different spin-relaxation times





T_1: "Classical" memory time



Spin precession: 10 ps

Optical emission: 1 ns

Ensemble spin T_2^*: 20 ns

Spin echo T_2: 50 μs

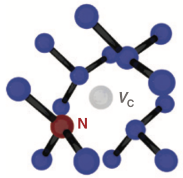
Classical memory: 500 ms

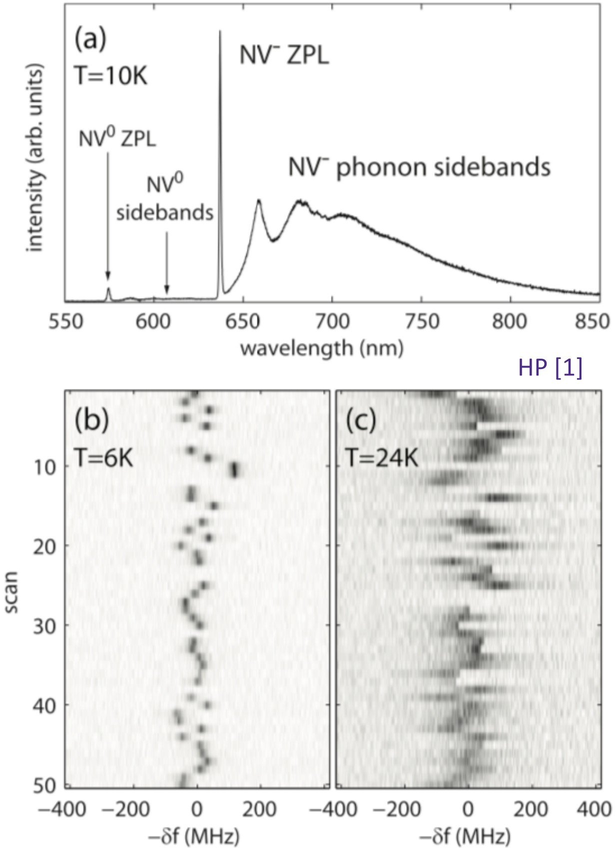
Goal: T_2 ~ 1 s

[1] "Longitudinal spin relaxation of donor-bound electrons in direct band-gap semiconductors", *PRB* (2016), UW

[2] "Coherence properties of shallow donor-bound electrons in ZnO", *PR Applied* (2018), UW

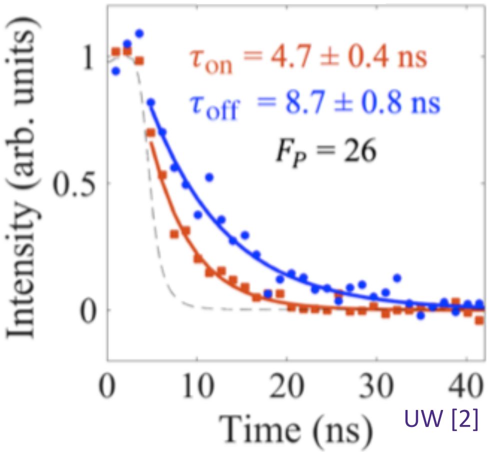
Characterizing quantum defects: Optical properties



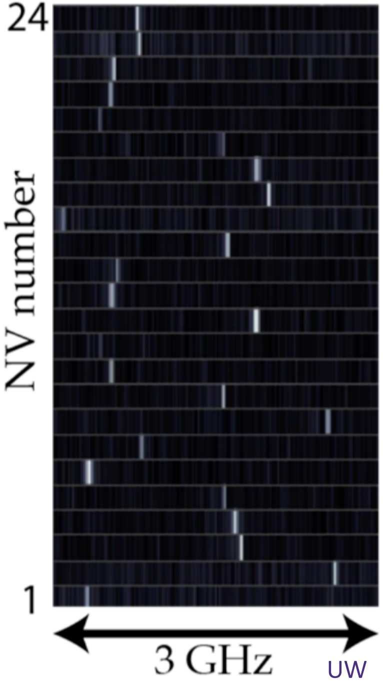


HP [1]

lifetime



UW [2]

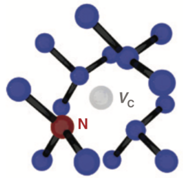


UW

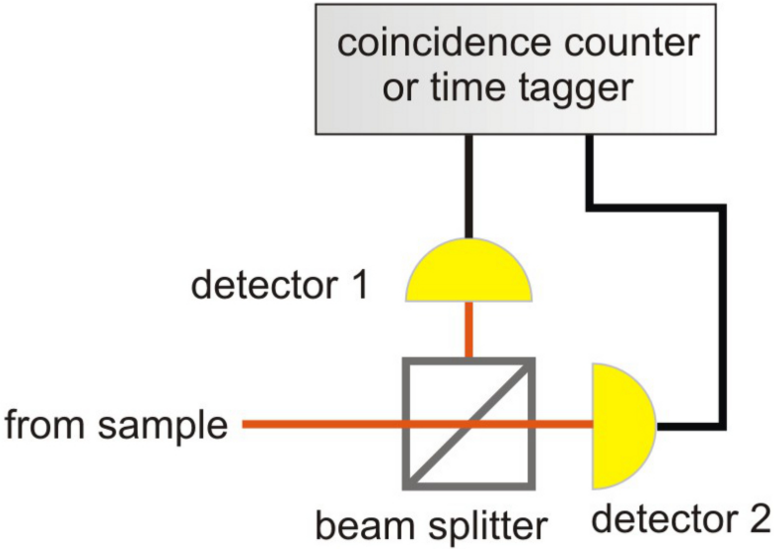
UNIVERSITY of WASHINGTON

[1]”Nanophotnics in quantum optics”, *Nanotechnoogy (2010)*

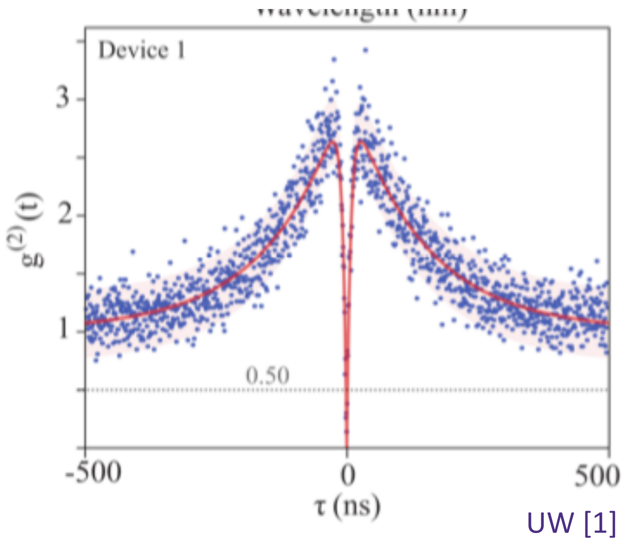
[2] “Efficient extraction of zero-phonon-line photons from single nitrogen-vacancy centers in an integrated GaP-on-diamond platorm, *PR Applied* (2016)



Check that you have a single defect



Picoquant



UW [1]

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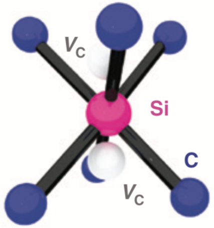
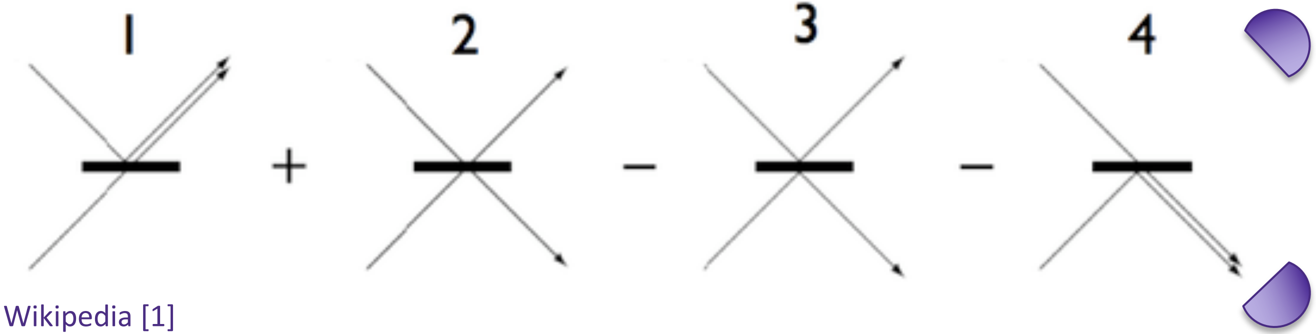
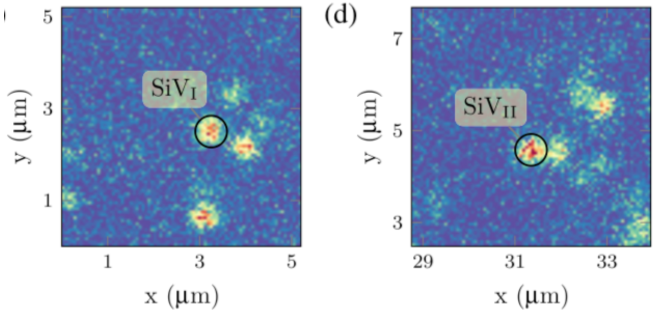
[1] "Efficient extraction of zero-phonon-line photons from single nitrogen-vacancy centers in an integrated GaP-on-diamond platorm, *PR Applied* (2016)

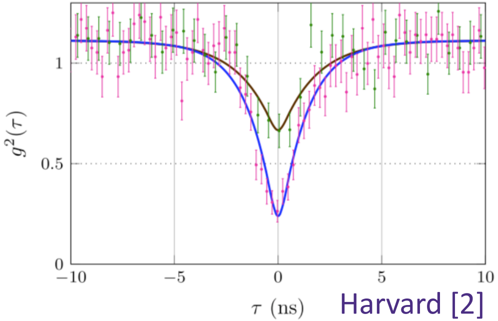


Measure photon indistinguishability



Wikipedia [1]

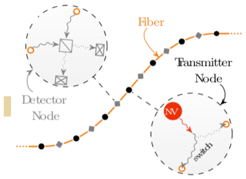




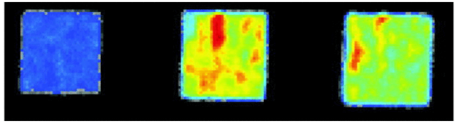
Harvard [2]

[1] QuantumCyclops, [2] "Indistinguishable photons from separated silicon-vacancy centers in diamond" *PRL* 2014

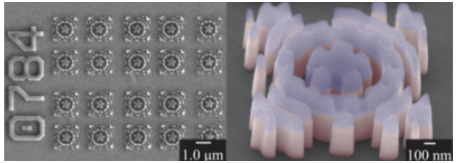
Overview of today's talk



Introduction to quantum networks and defect nodes



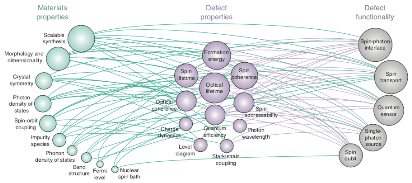
Making and characterizing quantum defects



Integration of quantum defects into devices

Nanophotonic defect-device integration

Defect degradation: potential solutions



Discovery and engineering of new defects

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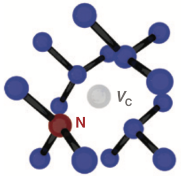
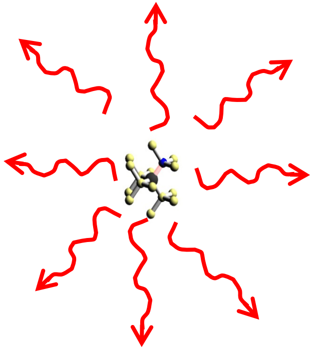
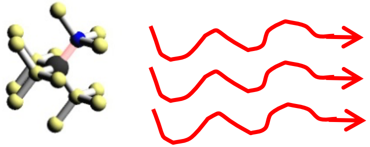
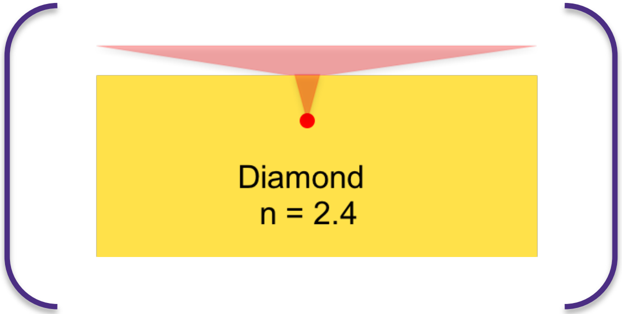


Motivation for device integration

> **Catch the photon**
> **Alter the properties of the emitter**
> Realize large networks (scalability)







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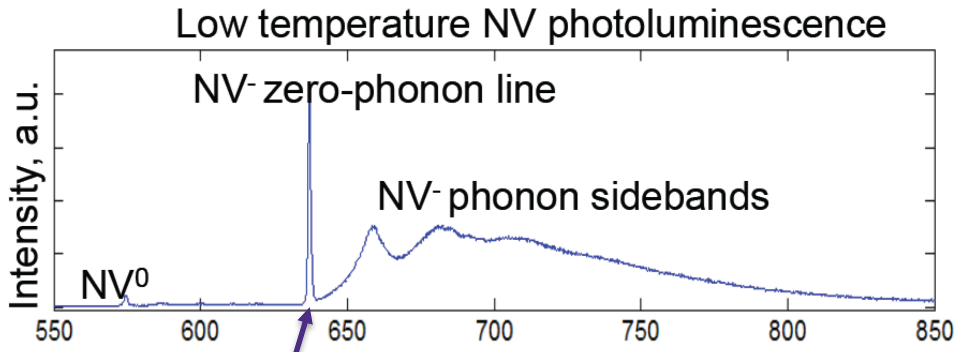
Motivation for device integration

> Catch the photon

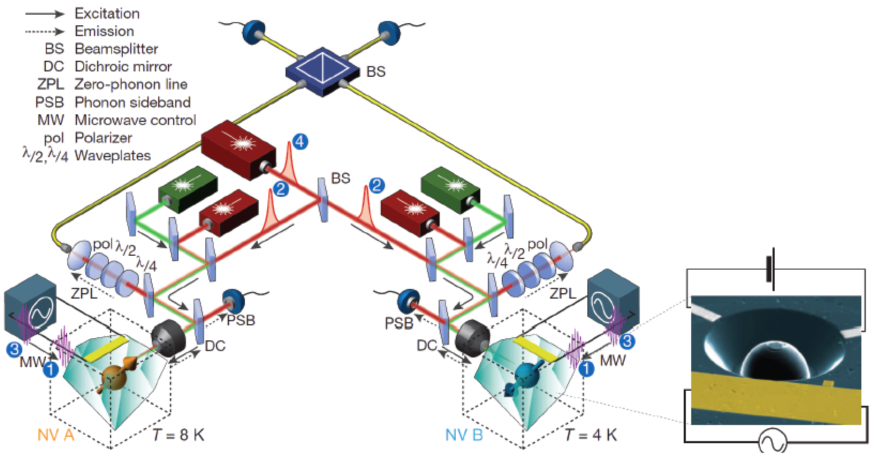
> **Alter the properties of the emitter**

> Realize large networks (scalability)

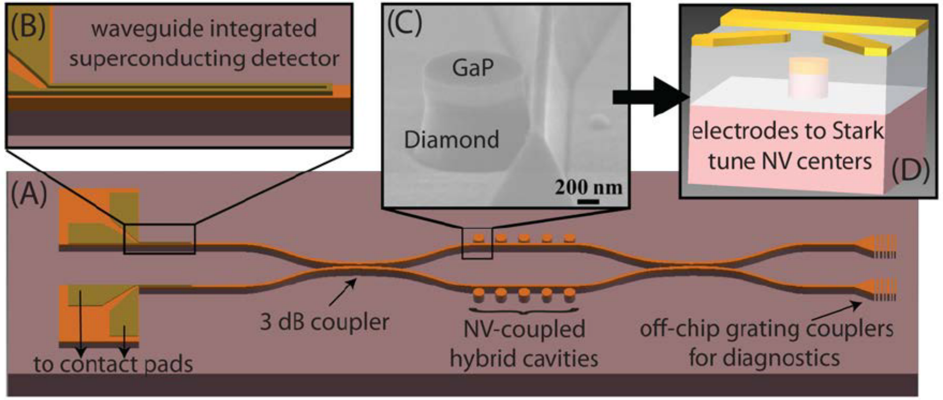


3% of emission is usable for network applications

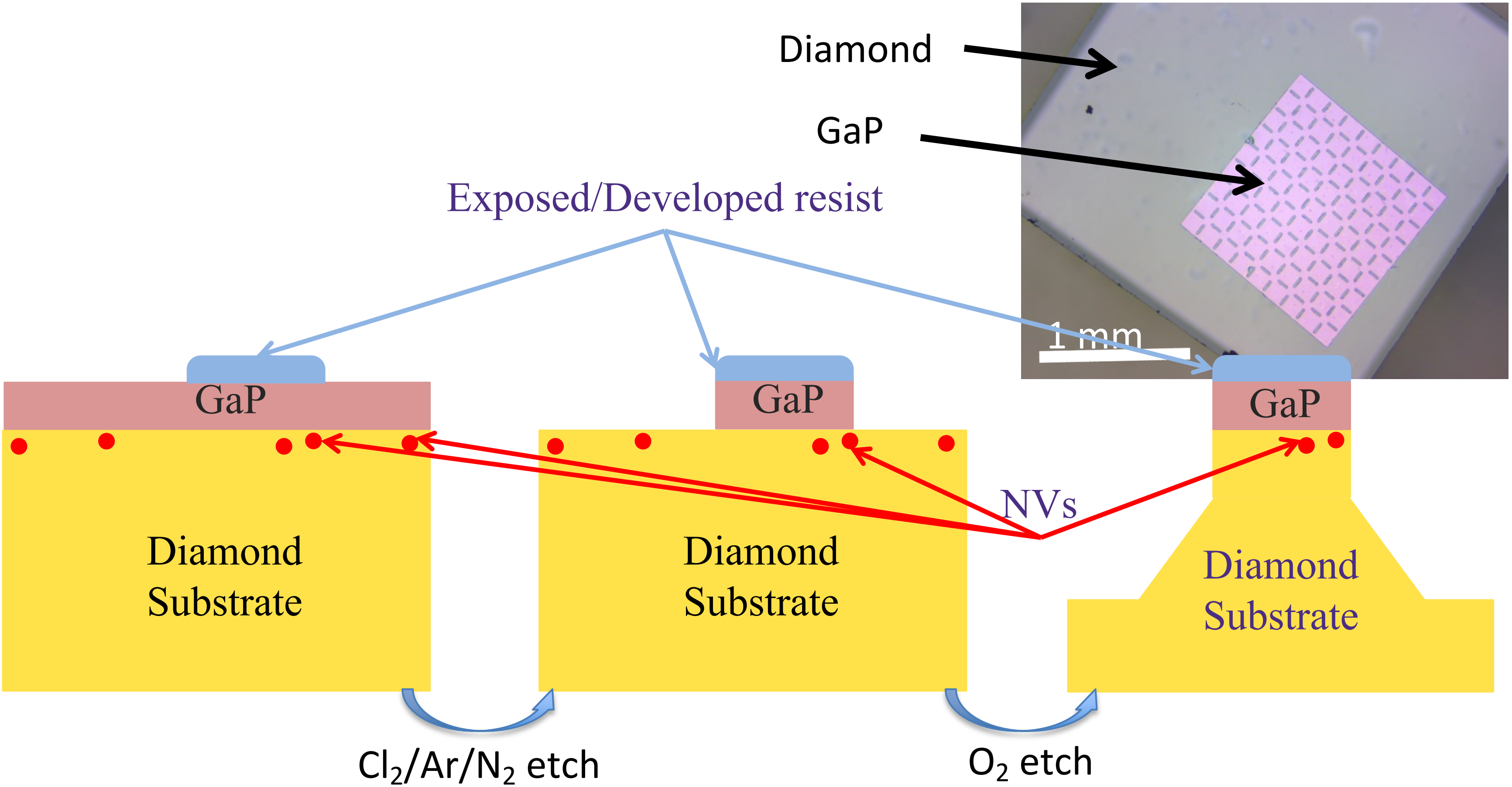
Motivation for device integration



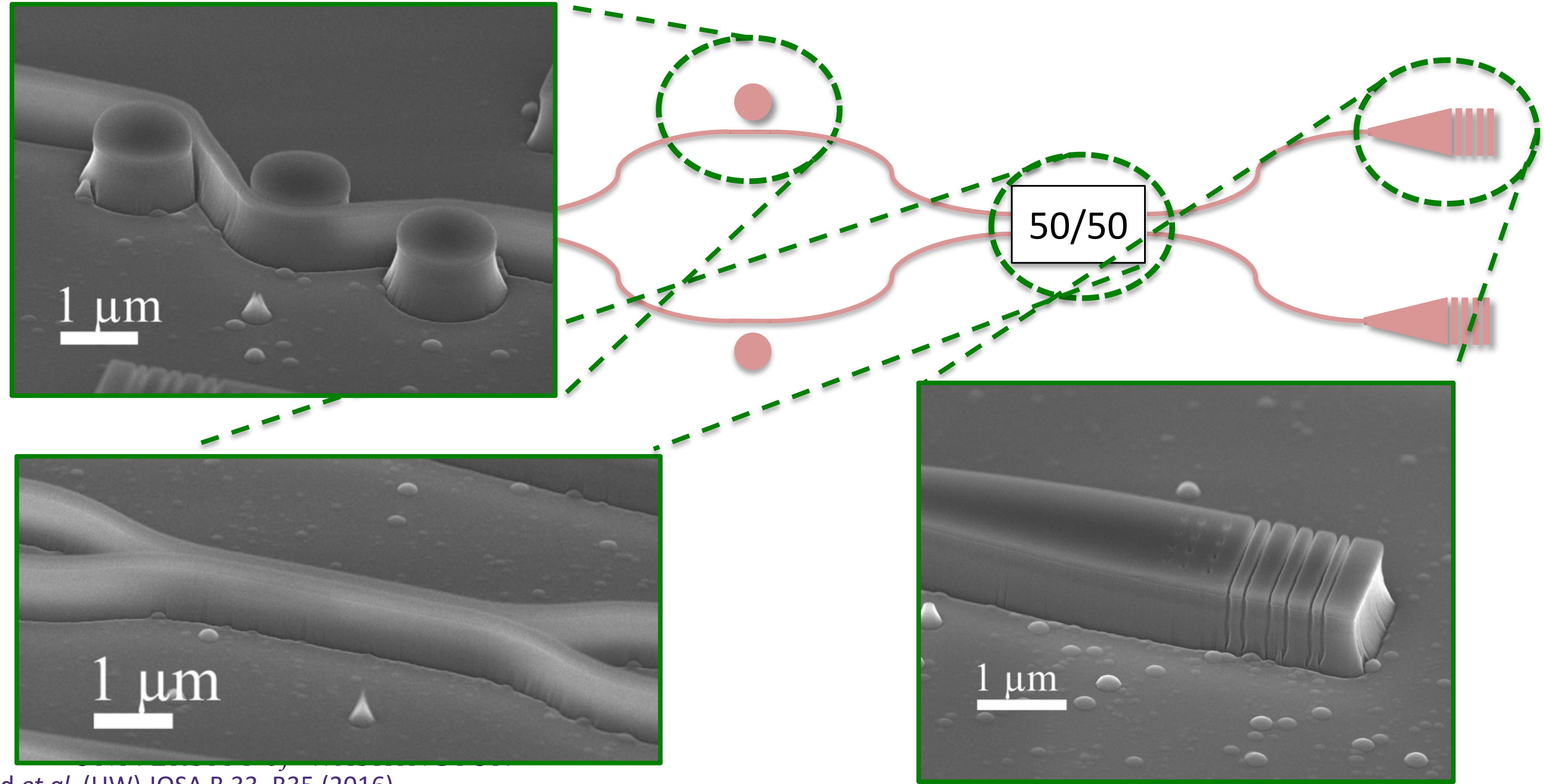
Humphreys et al. (Delft) *Nature* 558, 268 (June 2018)



Hybrid materials photonics platform

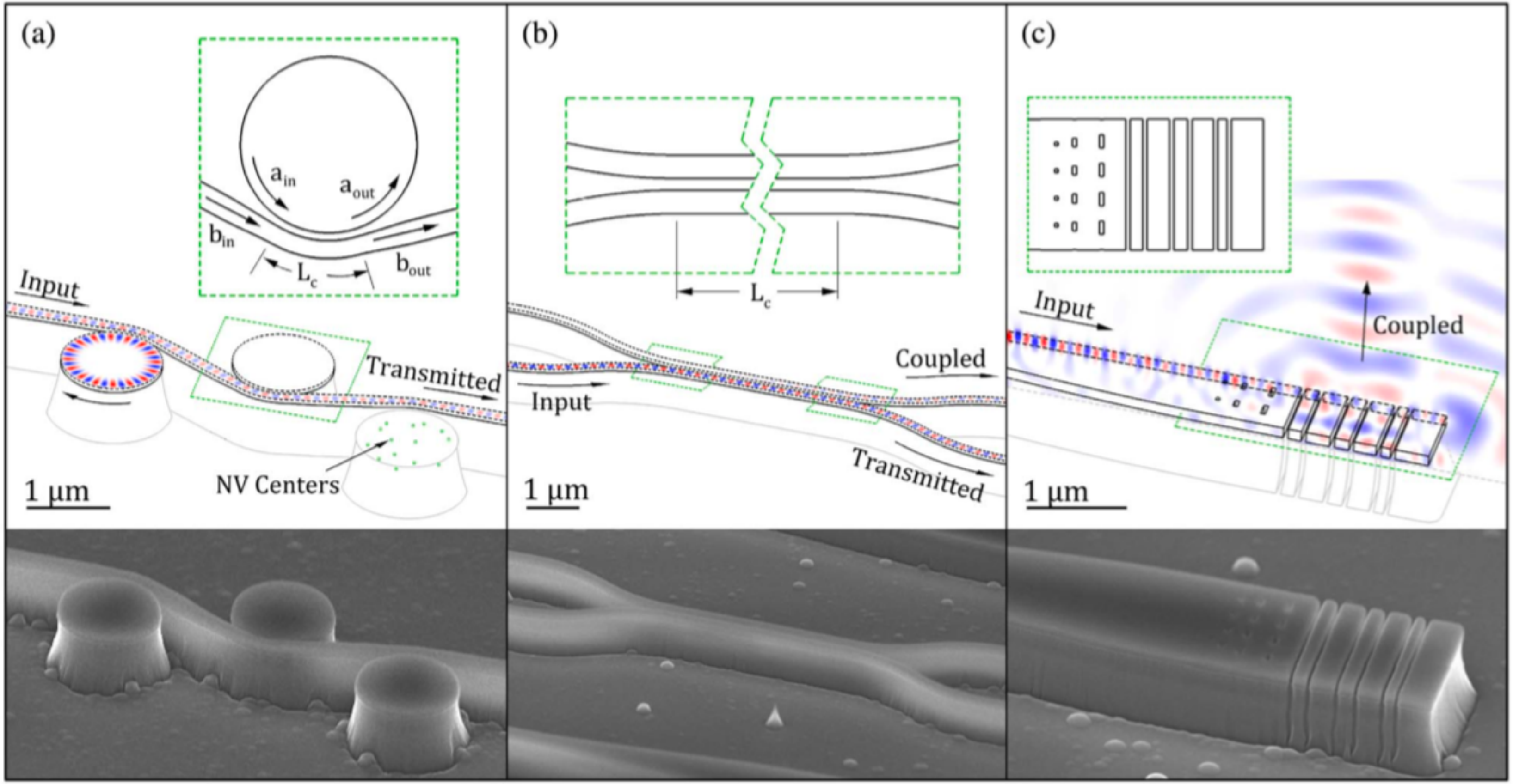


Design and fabrication of passive hybrid-material components



Gould *et al.* (UW) JOSA B 33, B35 (2016)

Design and fabrication of passive hybrid-material components



Q_i ~ 10-20k

Coupling ratio: 40-60%

Grating efficiency: 17-19%

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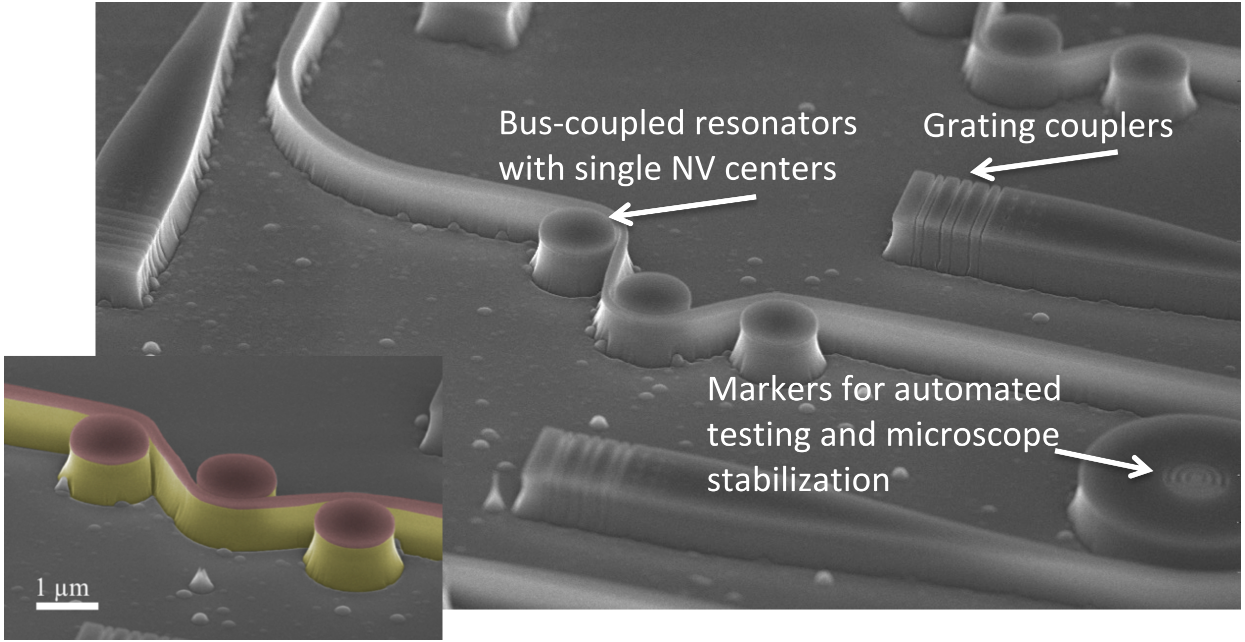
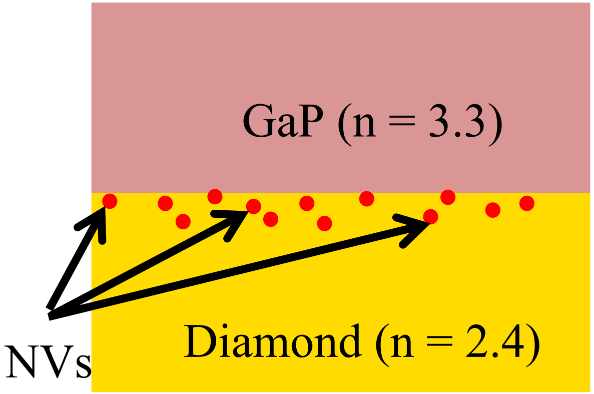
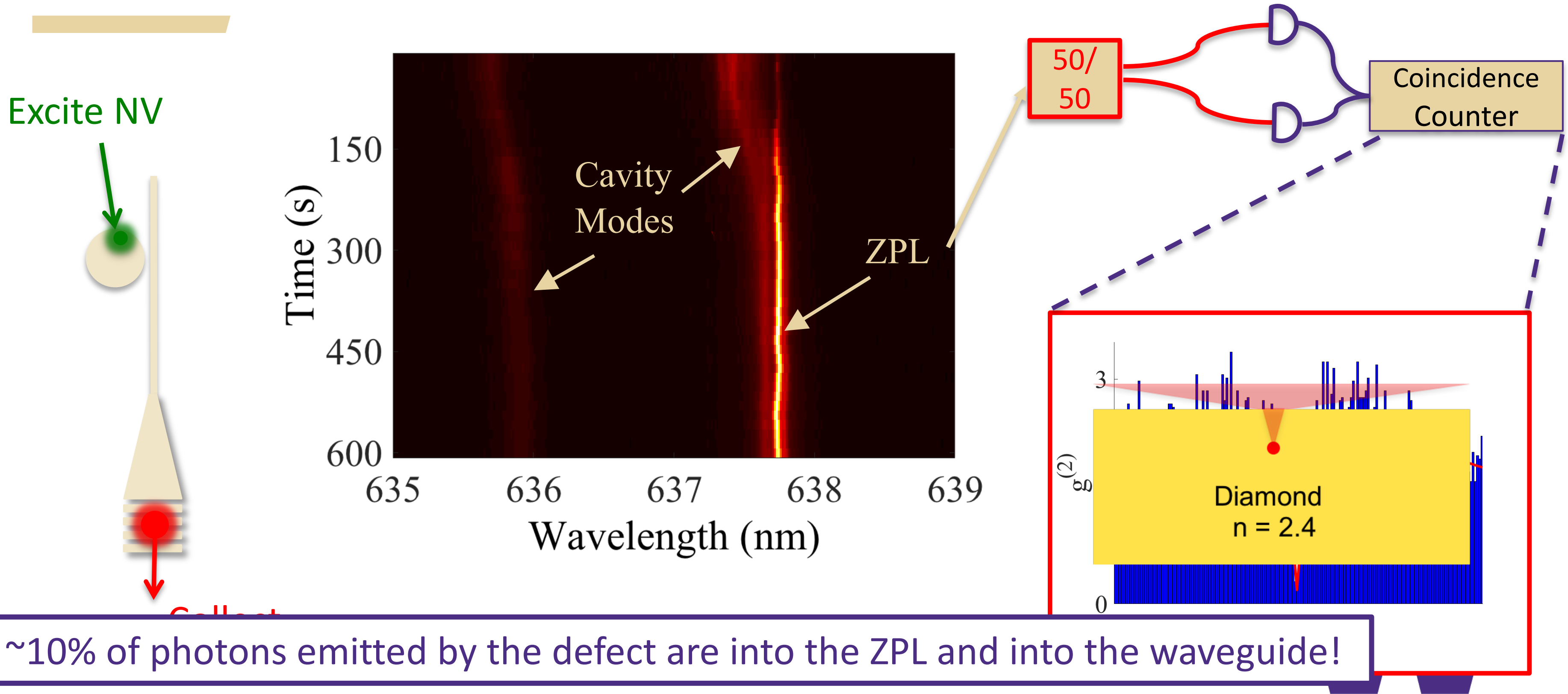
Gould *et al.* (UW) JOSA B 33, B35 (2016)

Efficient single photon collection and routing





Resonant enhancement of the zero-phonon-line emission from a single NV center

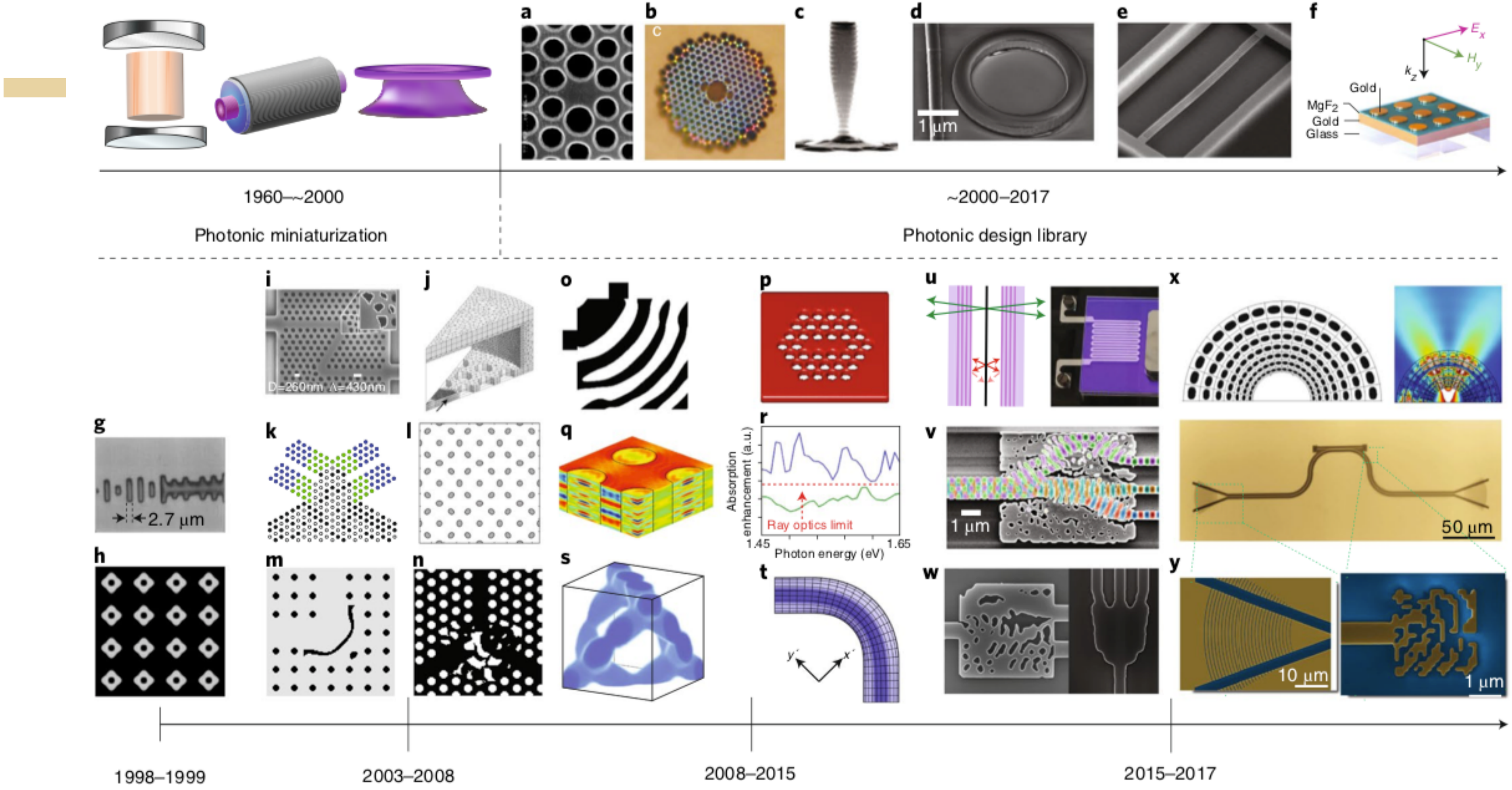


~10% of photons emitted by the defect are into the ZPL and into the waveguide!

Right now, NV centers 10-20 nm from the surface are not stable enough.

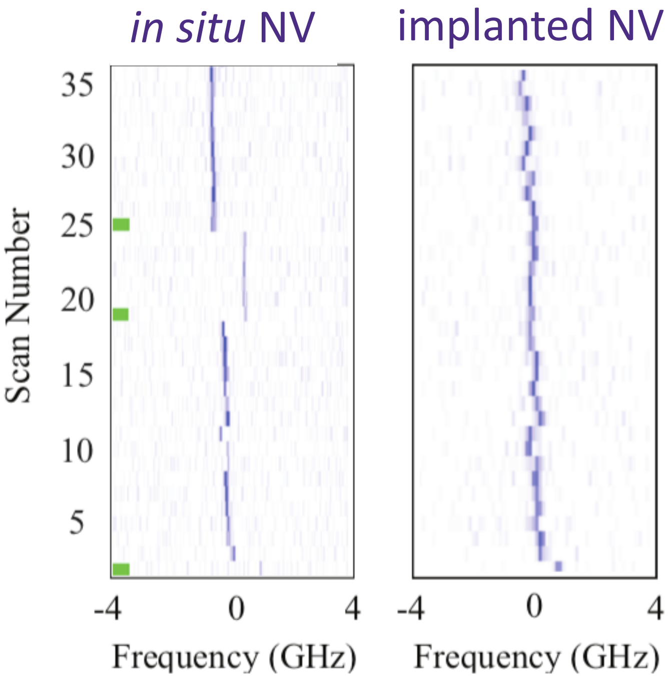
> Can we stabilize these centers further? (ongoing)
> **Can we design photonic structures for deeper centers?**
> Are there quantum defects more resilient to fabrication?

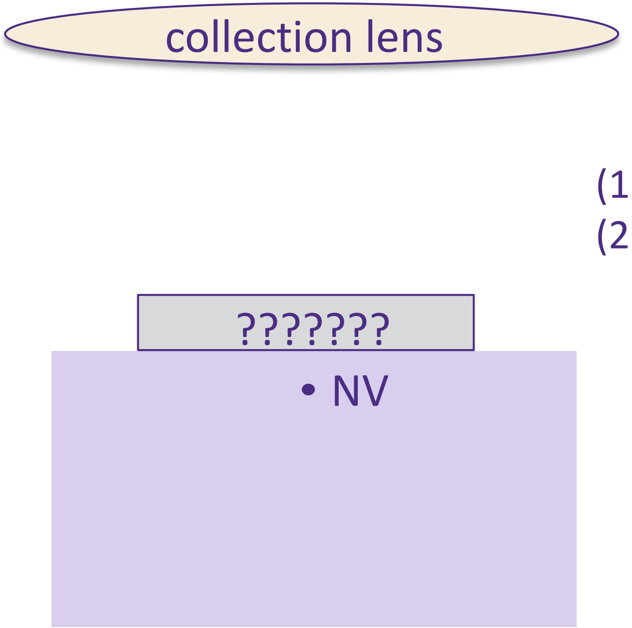
Inverse-designed photonics for light extraction



“Inverse design in nanophotonics” *Nature Photonics* (2018)

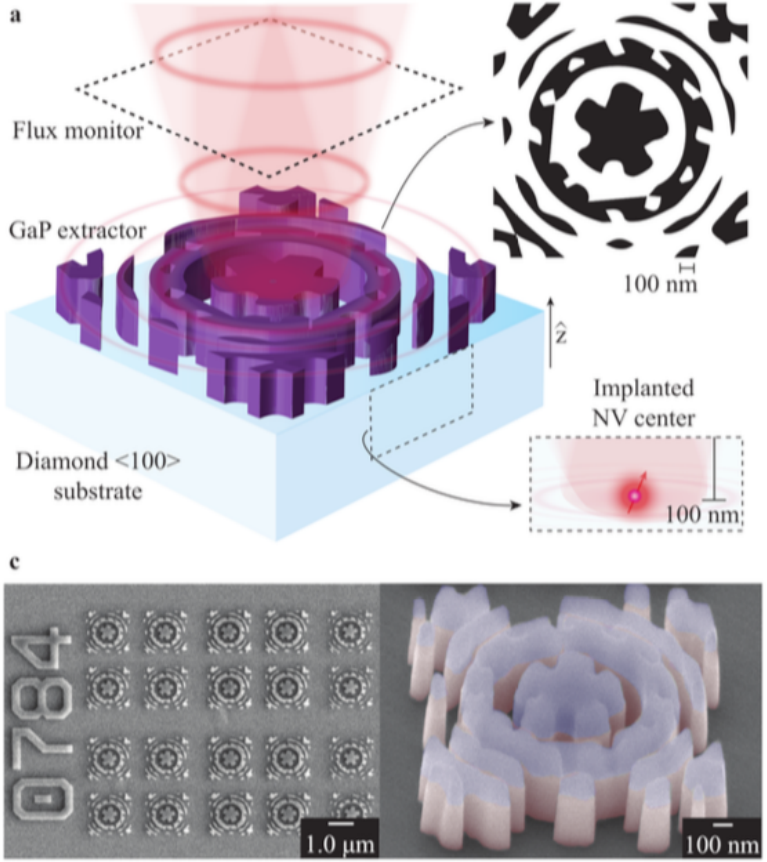
Reasonably "good" defects 100 nm from the surface formed by implantation and annealing

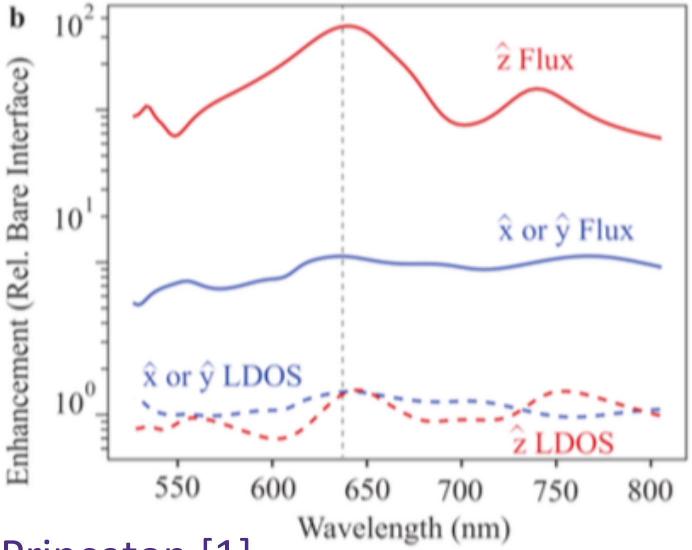




(1) Small (1.5 x 1.5 μm^2)
(2) No diamond etching

GaP-on-diamond photon extractors

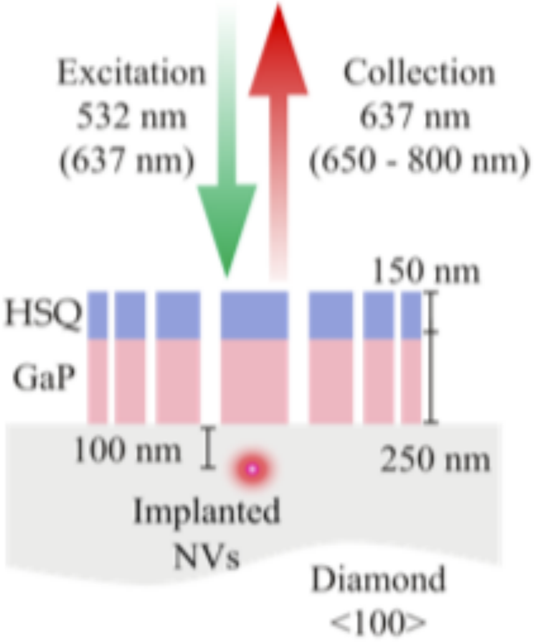


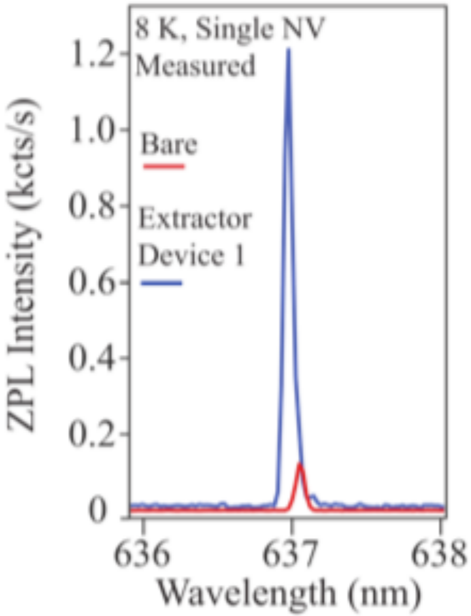


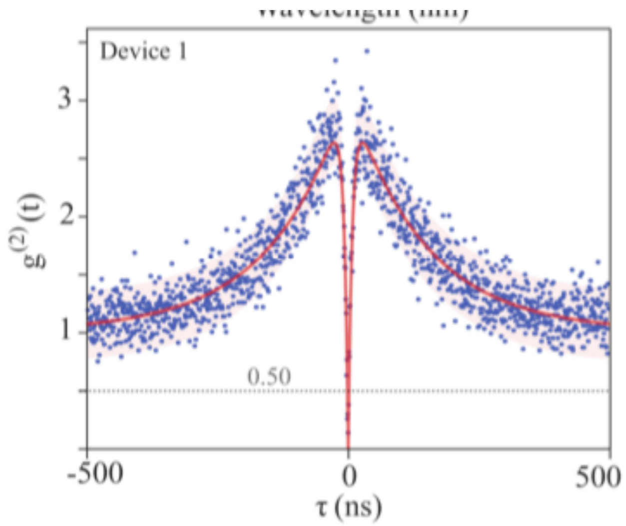
UW, Princeton [1]

[1] "Inverse-designed photon extractor for optically addressable defect qubits", arXiv (2020)

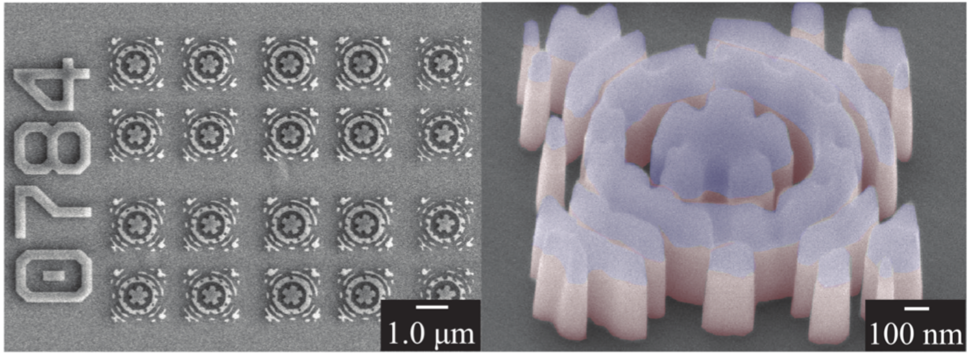
Up to 14-fold enhancement of single defect emission is observed

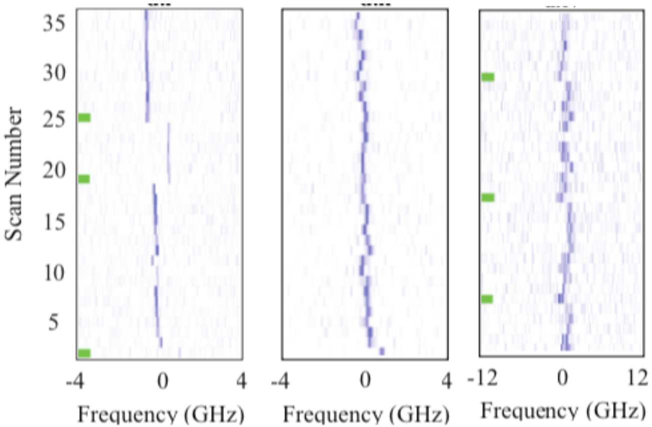






Photonics worked
Quantum defects need more work



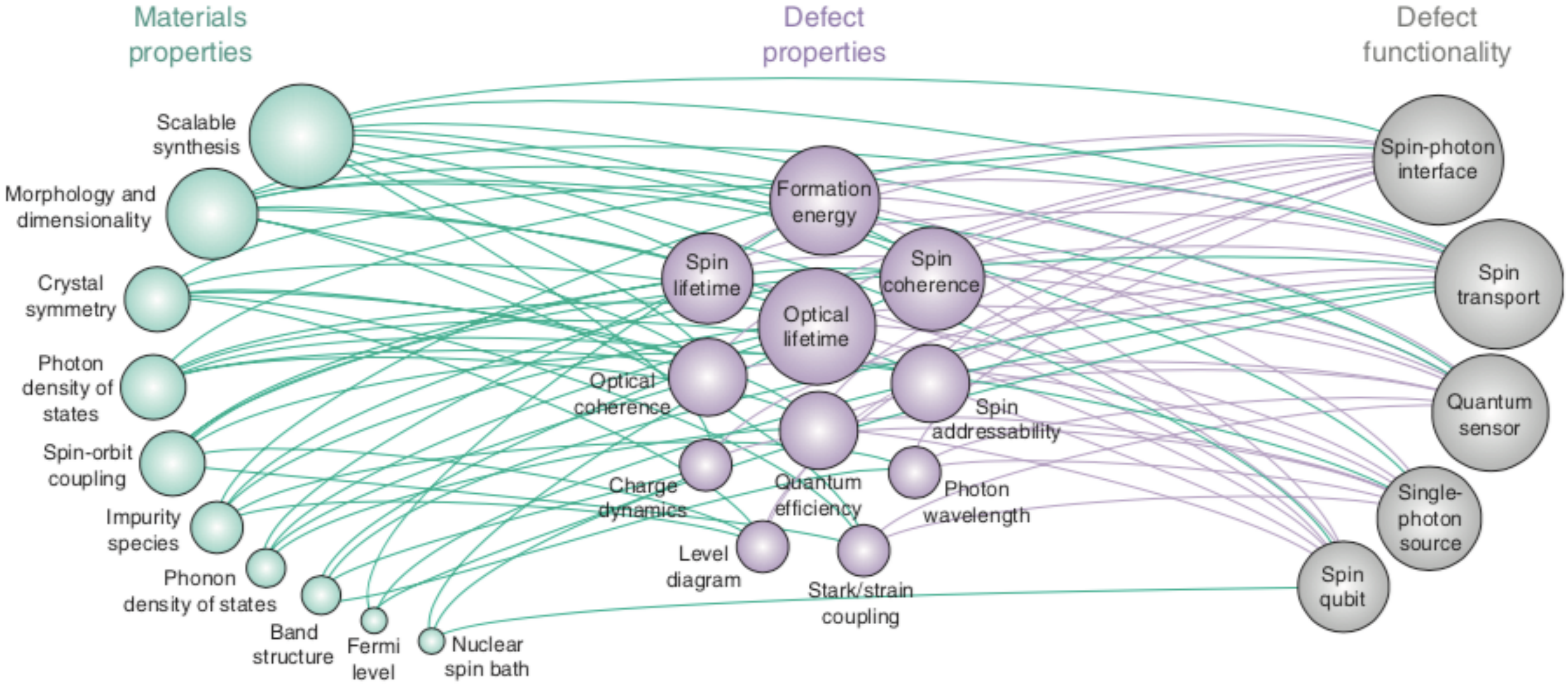


(Good qubits often make good sensors.)

Right now, NV centers 10-20 nm from the surface are not stable enough.

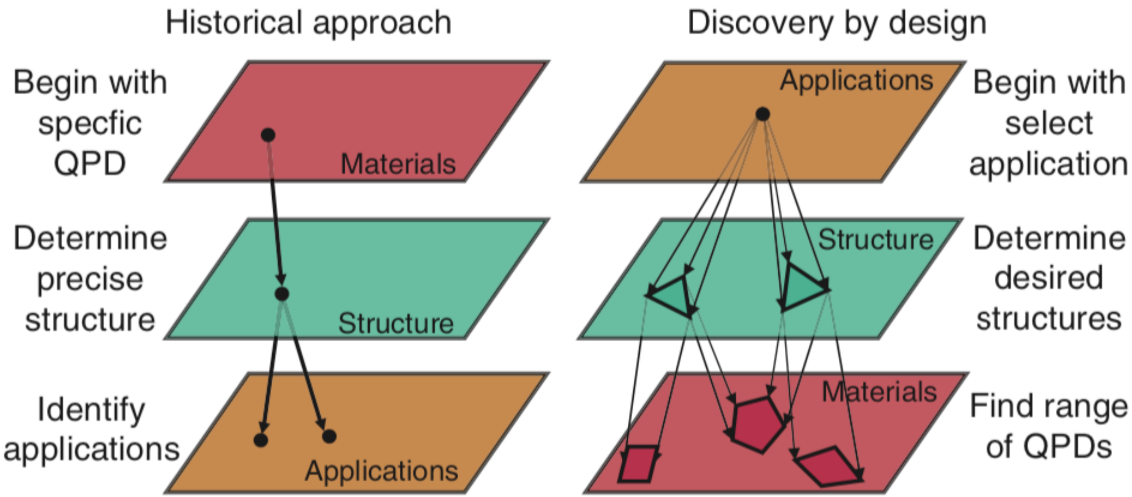
> Can we stabilize these centers further? (ongoing)
> Can we design photonic structures for deeper centers?
> **Are there quantum defects more resilient to fabrication?**
  – Yes! SiV- but ….
  – Yes! Nd:YSO, Er:YSO but..
  – Yes! …

New defects: a very large parameter space



“Quantum defects by design” *Nanophotonics* (2019)

New defects: a very large parameter space



Advancements needed:

- *ab initio* calculations
- structural imaging
- materials purity
- surface science
- quantum “screening”

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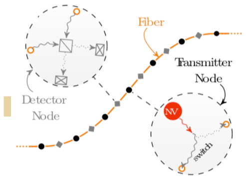
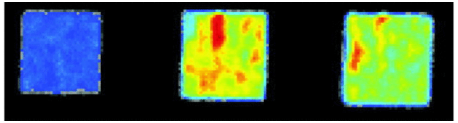
“Quantum defects by design” *Nanophotonics* (2019)

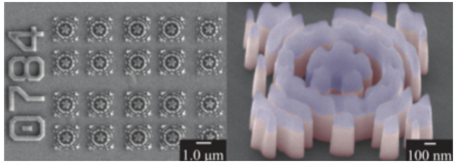
Summary of today's talk



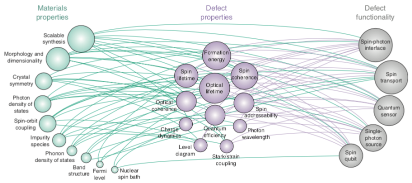
Defects may be the ideal hardware platform for realizing quantum networks



For quantum network applications, there are stringent requirements on both the spin and optical properties



Defects-based technologies can leverage concurrent advances in integrated photonics



There is no perfect defect for each application …

– but there might be.

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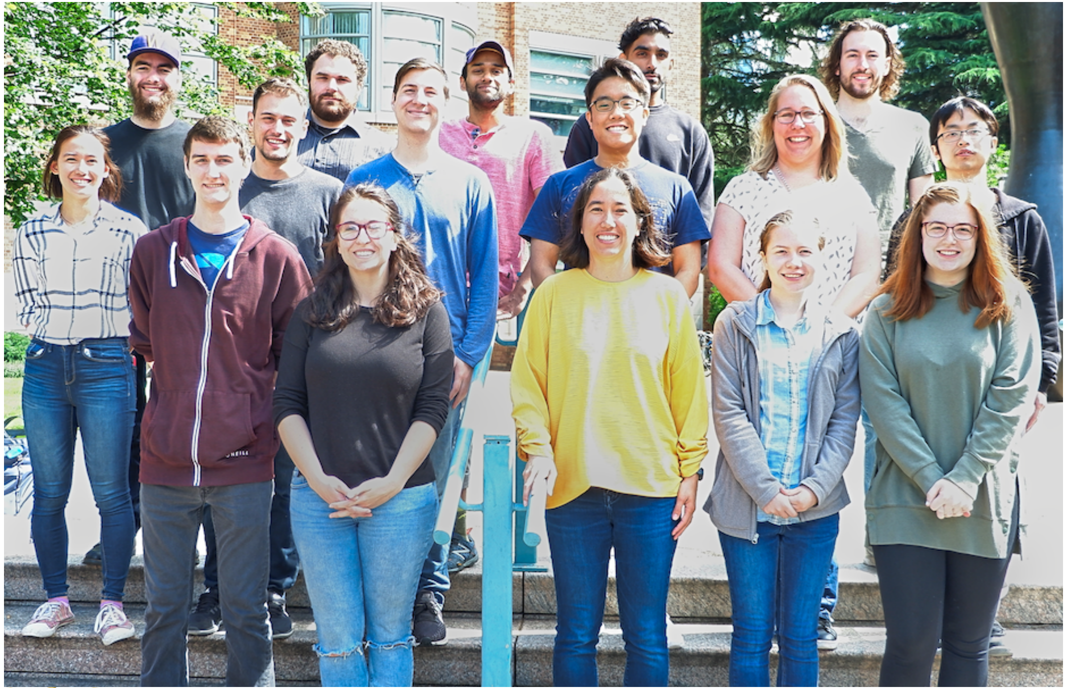
Acknowledgements



Summer 2019

NSF

ARO MURI AIQM
AB-INITIO QUANTUM MATERIALS

UW MEM·C

National Nanotechnology Coordinated Infrastructure
(Washington Nanofabrication Facility)

Diamond Photonics

*Mike Gould, PhD
*Emma Schmidgall, posdoc
Srivatsa Chakravarthi, grad
Christian Pederson, grad
Alan Logan, grad
Zeeshawn Kazi, grad

Semiconductor Spins

Xiayu Linpeng, grad
Maria Viitaniemi, grad
Vasileios Naouris, grad

Collaborators:

Colin Stanley, Glasgow (GaAs growth)
Satoru Seto, Ishikawa (CdTe growth)
Simon Watkins, Simon Fraser (InP, ZnO growth
Y. Kozuka, NIMS (ZnO growth)
Fariba Hatami, Humboldt (GaP growth)
M.Kawasaki, U. Tokyo (ZnO growth)
Mikhail Durnev, Ioffe (theory)
Mikhael Glazov, Ioffe (theory)
Alejandro Rodriguez, Princeton (theory)

*graduated/departed

Questions? (One day, please come and visit us!)