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Optical spin readout of acceptor-bound excitons in germanium

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Sandia National Labs

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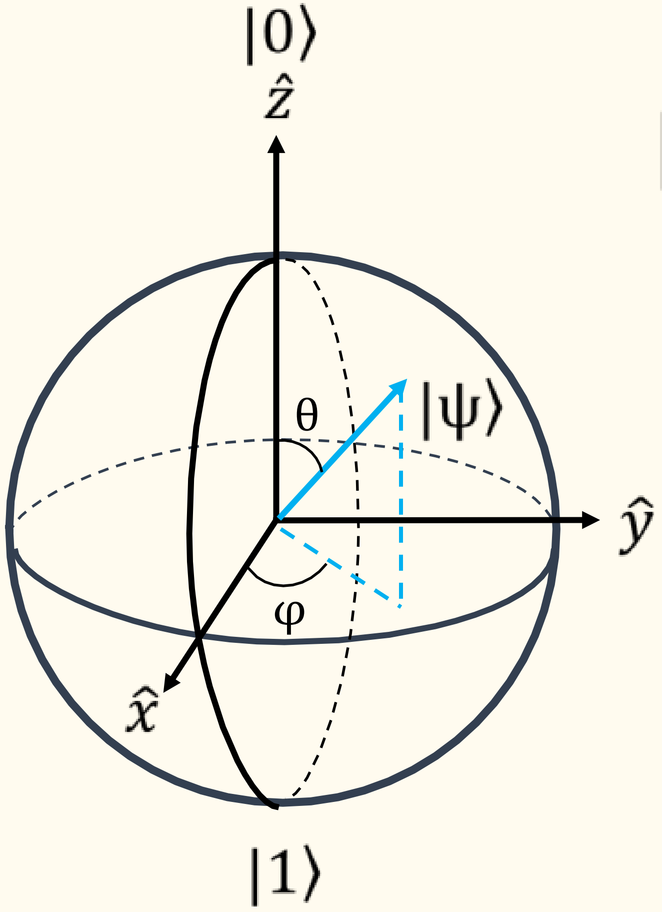
Overview

- **Nuclear spins as qubits**
- Optimizing Ga-doped Ge
- Device implementation and experiment
- Spin-selective optical readout of resonant excitons
- (Other projects/interests)

From classical to quantum

0

1

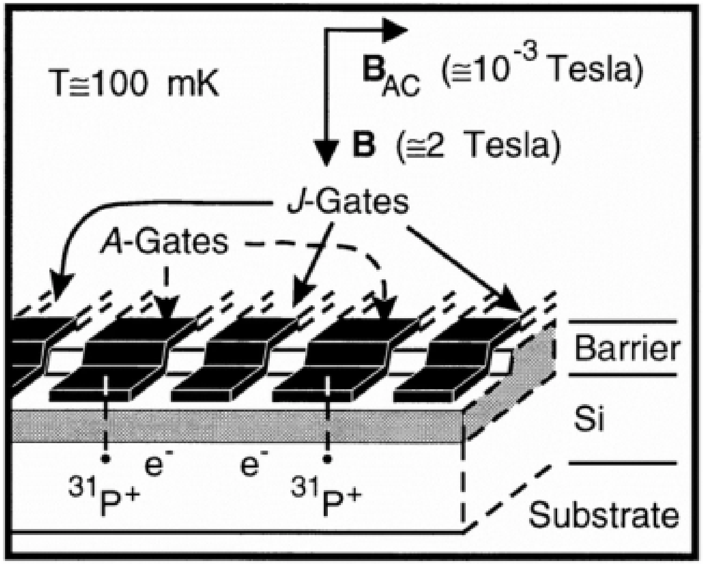


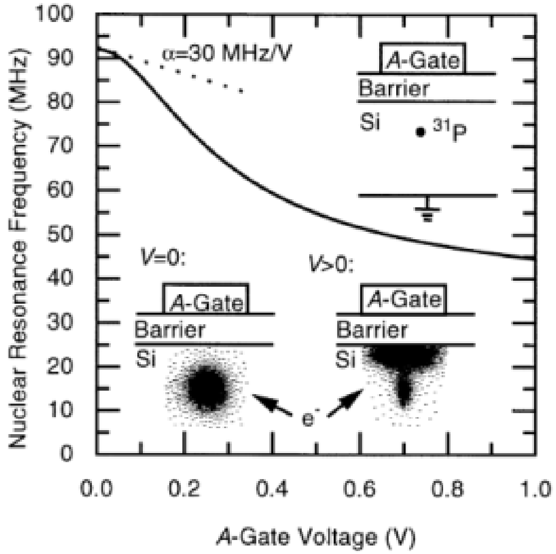
$$|\psi\rangle = \cos\frac{\theta}{2}|0\rangle + e^{i\varphi}\sin\frac{\theta}{2}|1\rangle$$

Challenges:

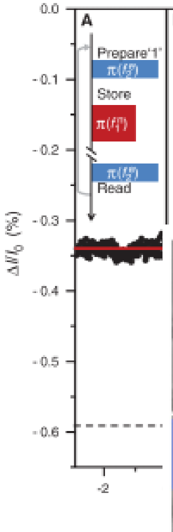
- ❑ Coherence and stability of a quantum state
- ❑ Large scale (~10^6) with low error (~10^{-4}~10^{-6})

Nuclear spin detection in Phosphorus-doped Silicon

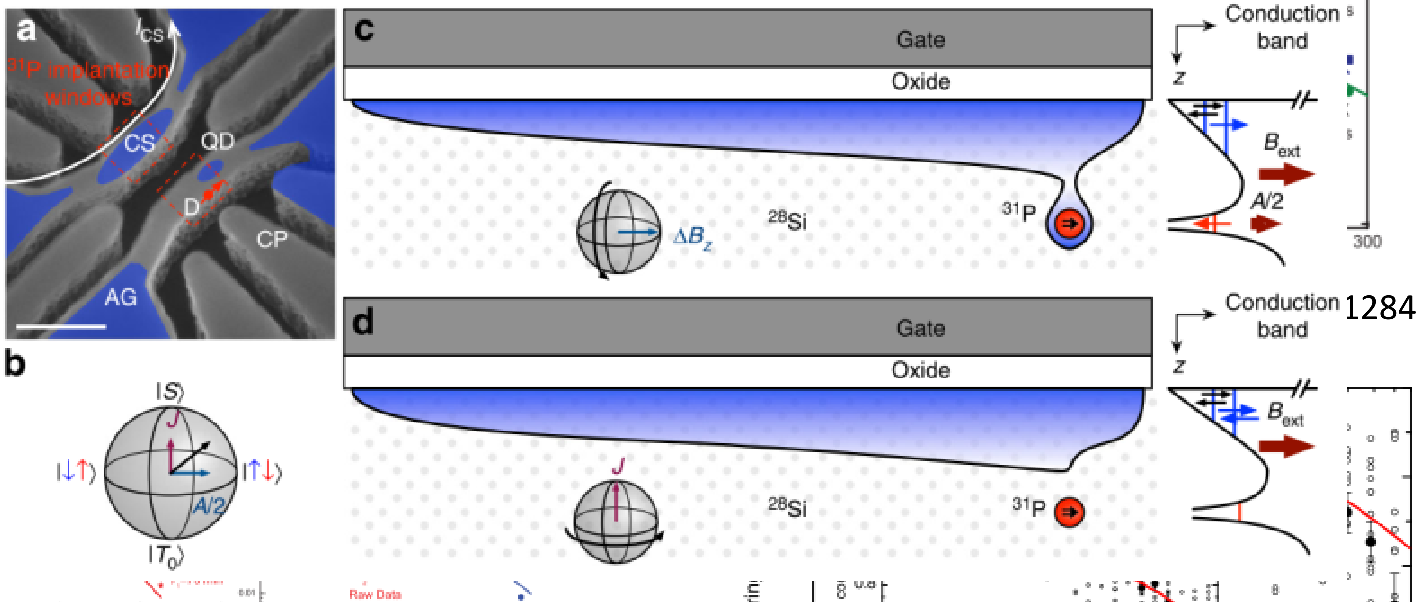




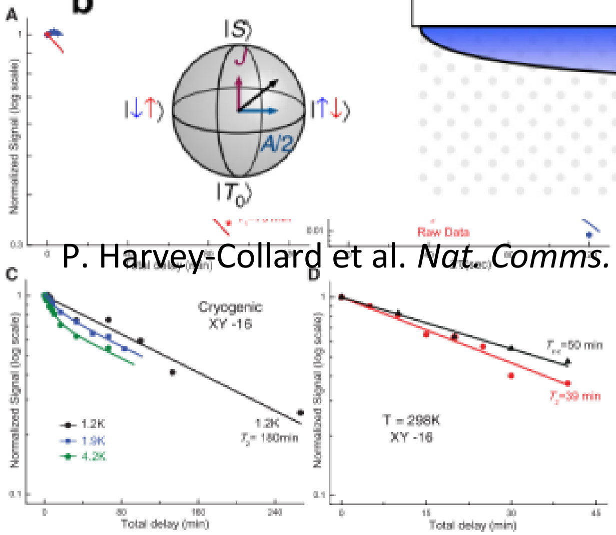
B. Kane *Nature* 393 (1998) 133-137



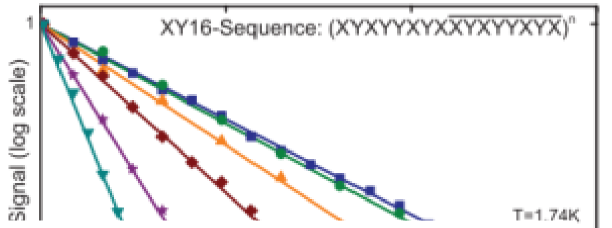
D. McCa

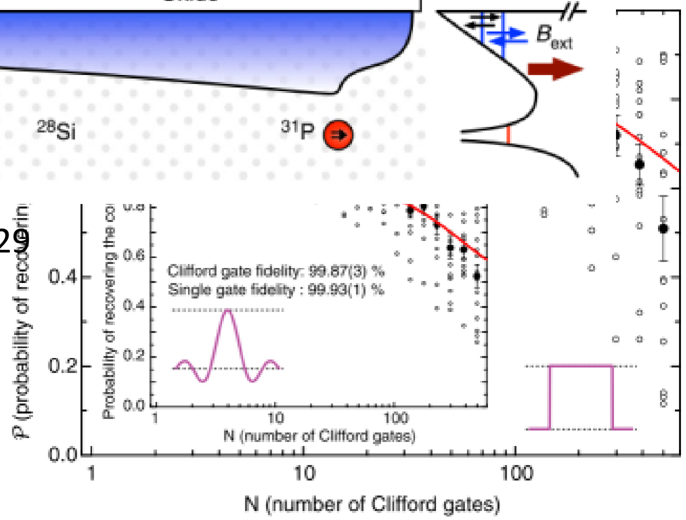


P. Harvey-Collard et al. *Nat. Comms.* 8 (2017) 1029



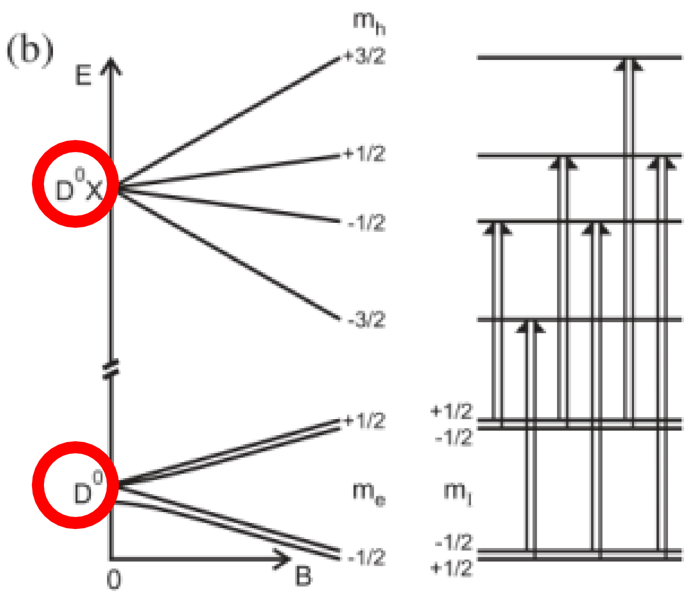
K. Saeedi et al. *Science* 342 (2013) 830-833



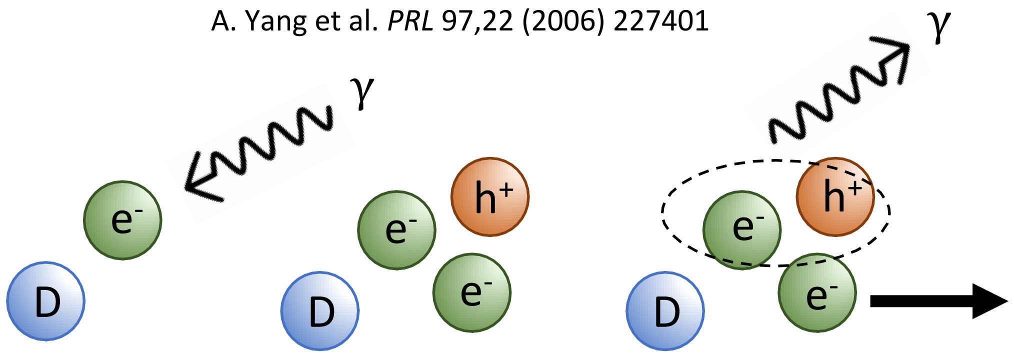


J. Muhonen et al. *J. Phys. Cond. Mat.* 27 (2015) 154205

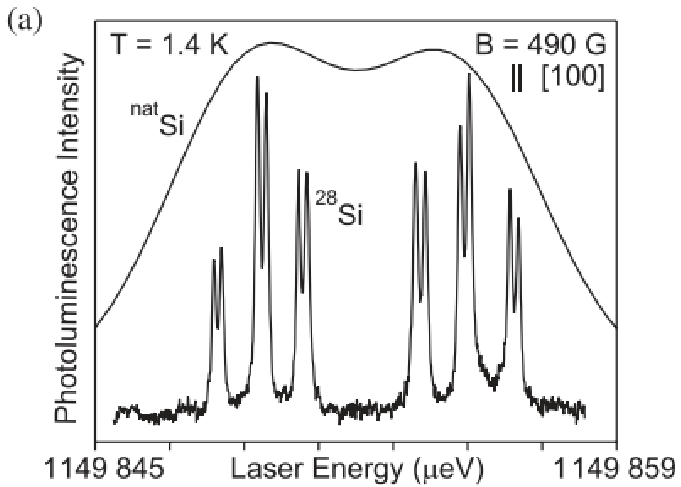
Optical spin readout in P-doped Si

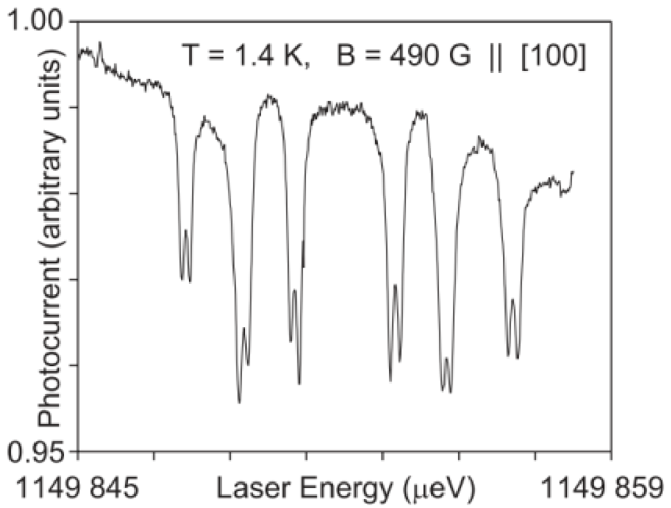


A. Yang et al. *PRL* 97,22 (2006) 227401

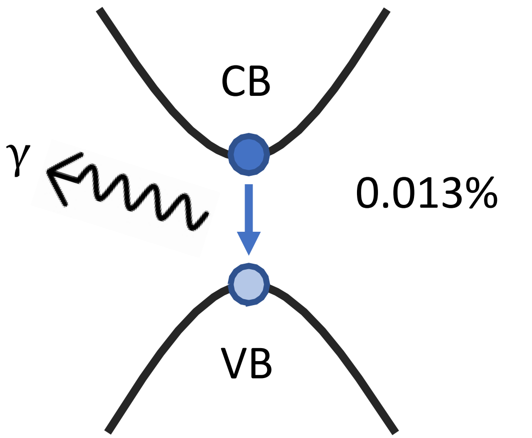


1. D^0 2. D^0X 3. $D^+ + e^-$

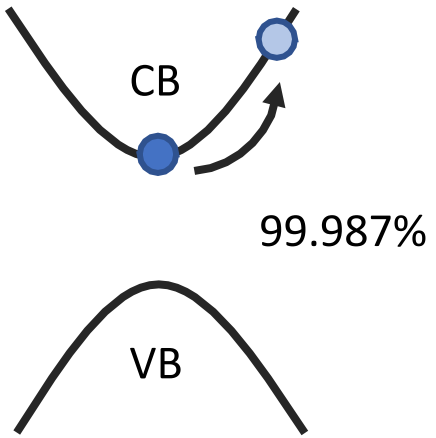




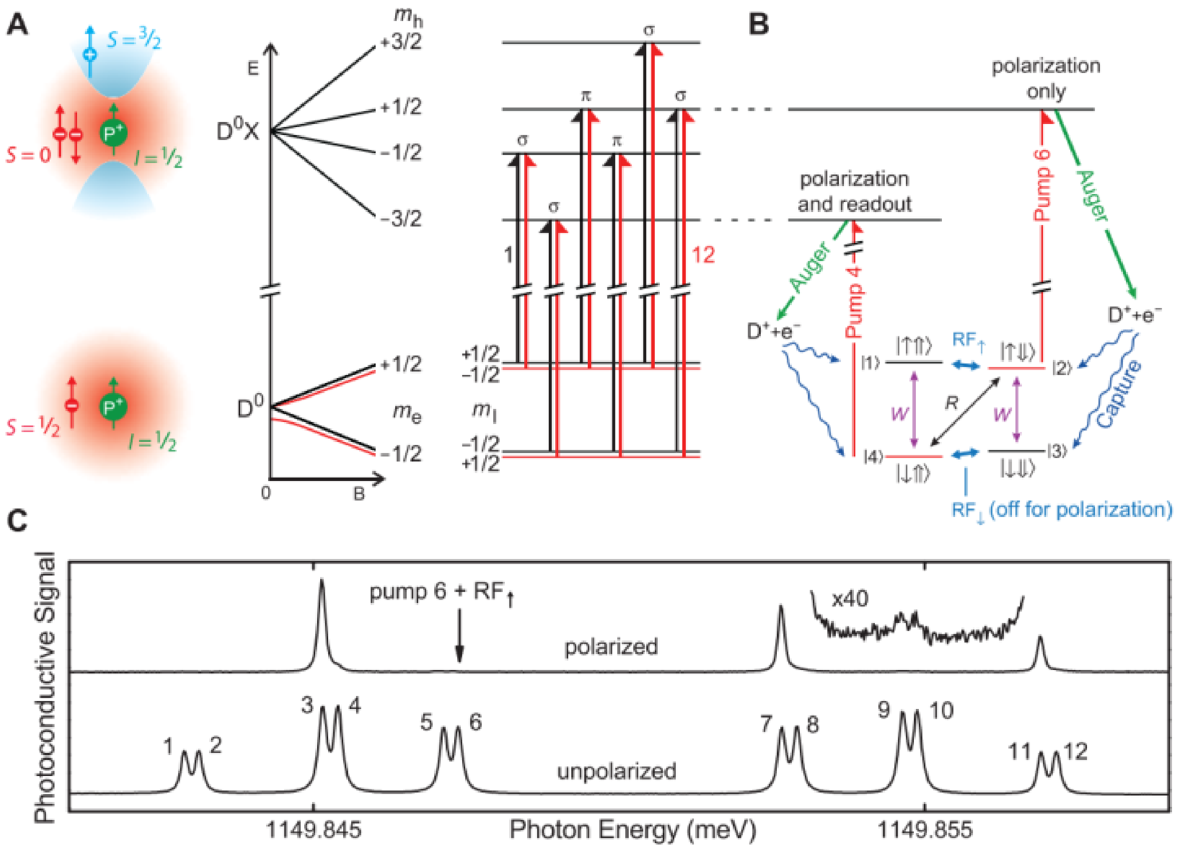
Radiative recombination



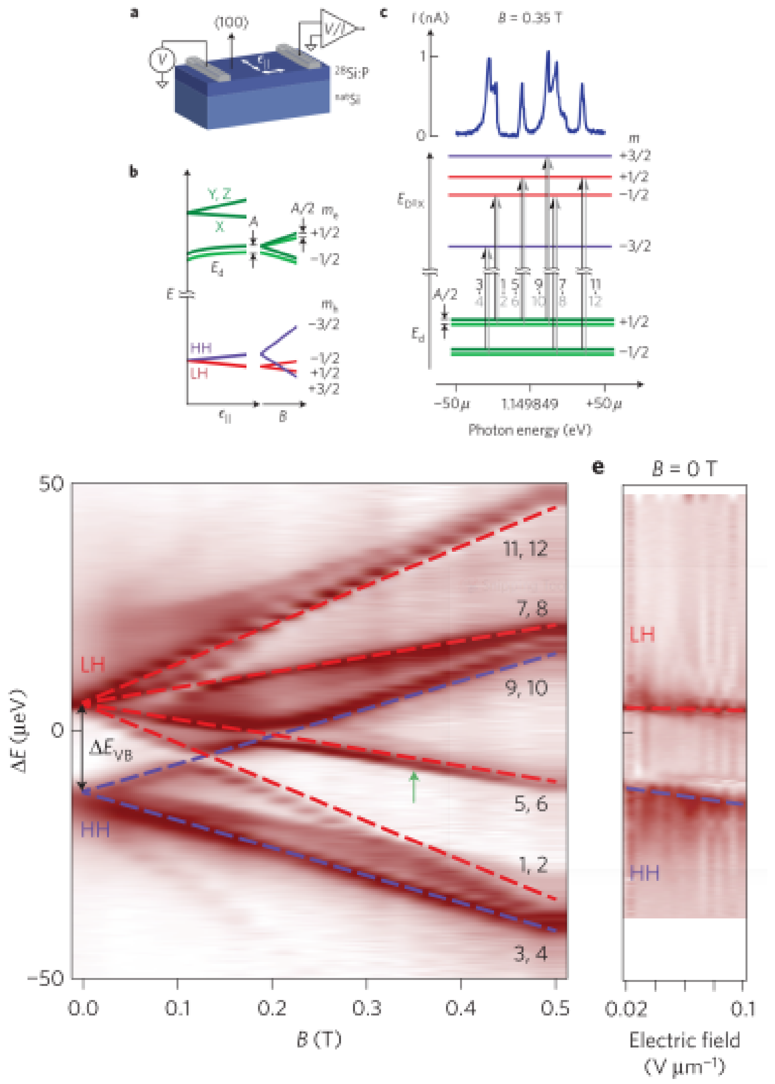
Dominant non-radiative Auger recombination



Selective optical polarization addresses spin qubits



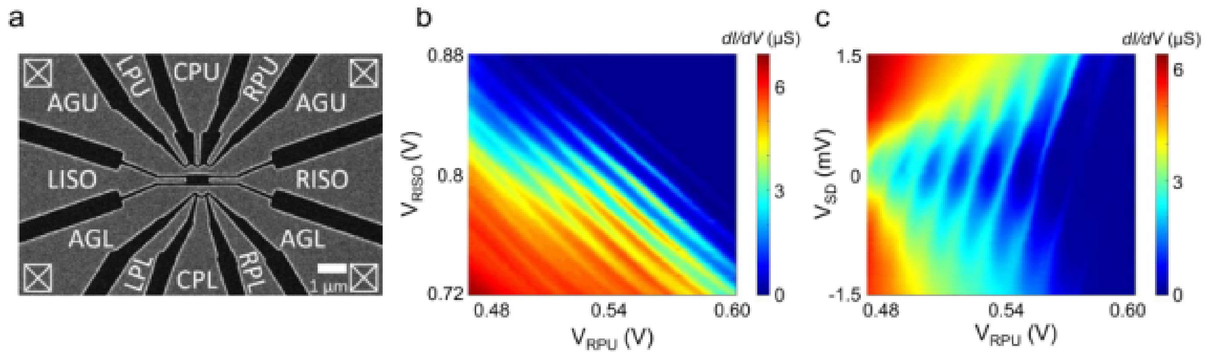
M. Steger et al. *Science* 336 (2012) 1280-1284



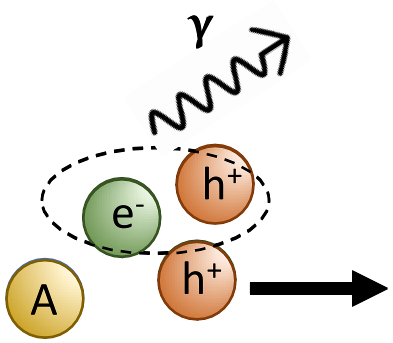
C. C. Lo et al. *Nature Mat.* 14 (2015) 490-494

Holes in germanium host advantageous properties to Si

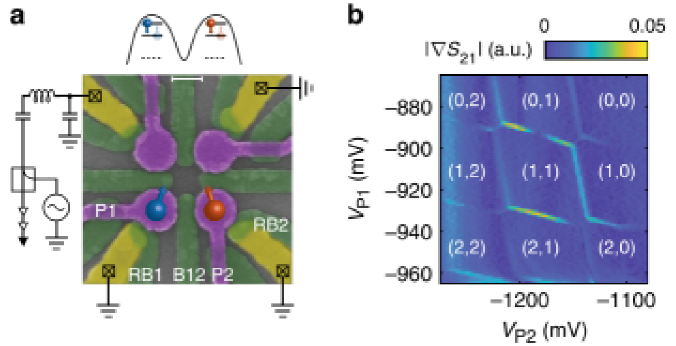
- ✓ High mobility (~10^6 $cm^2/V\,s$)
- ✓ Large spin-orbit coupling (~2.1 meV)
- ✓ Tunable g-factor
- ✓ Scalability



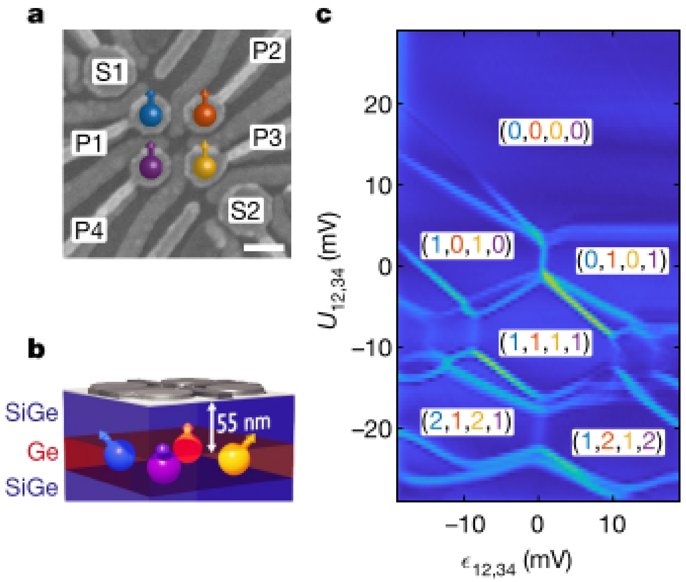
W. Hardy et al, *Nanotech.* 30 (2019) 215202



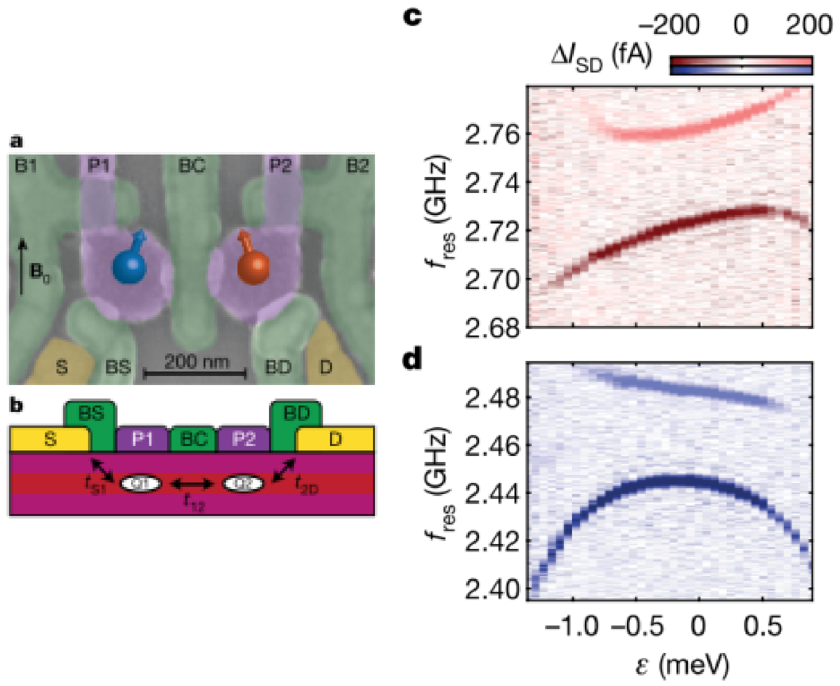
3. $D^+ + h^+$



N. Hendrickx et al, *Nat. Comms* 11 (2020) 3478



N. Hendrickx et al, *Nature* 591 (2021) 580-585



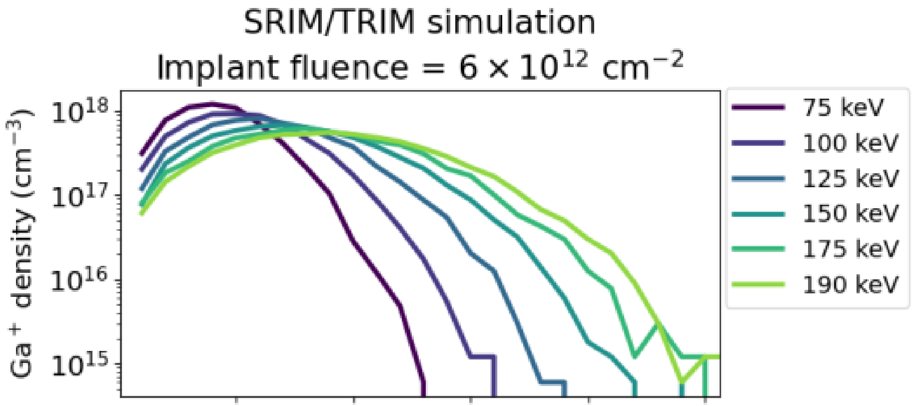
N. Hendrickx et al, *Nature* 577 (2020) 487-491

Overview

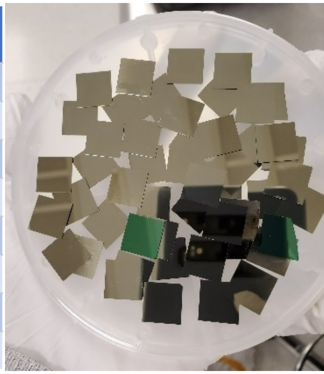
- Nuclear spins as qubits
- **Optimizing Ga-doped Ge**
- Device implementation and experiment
- Spin-selective optical readout of resonant excitons
- (Other projects/interests)

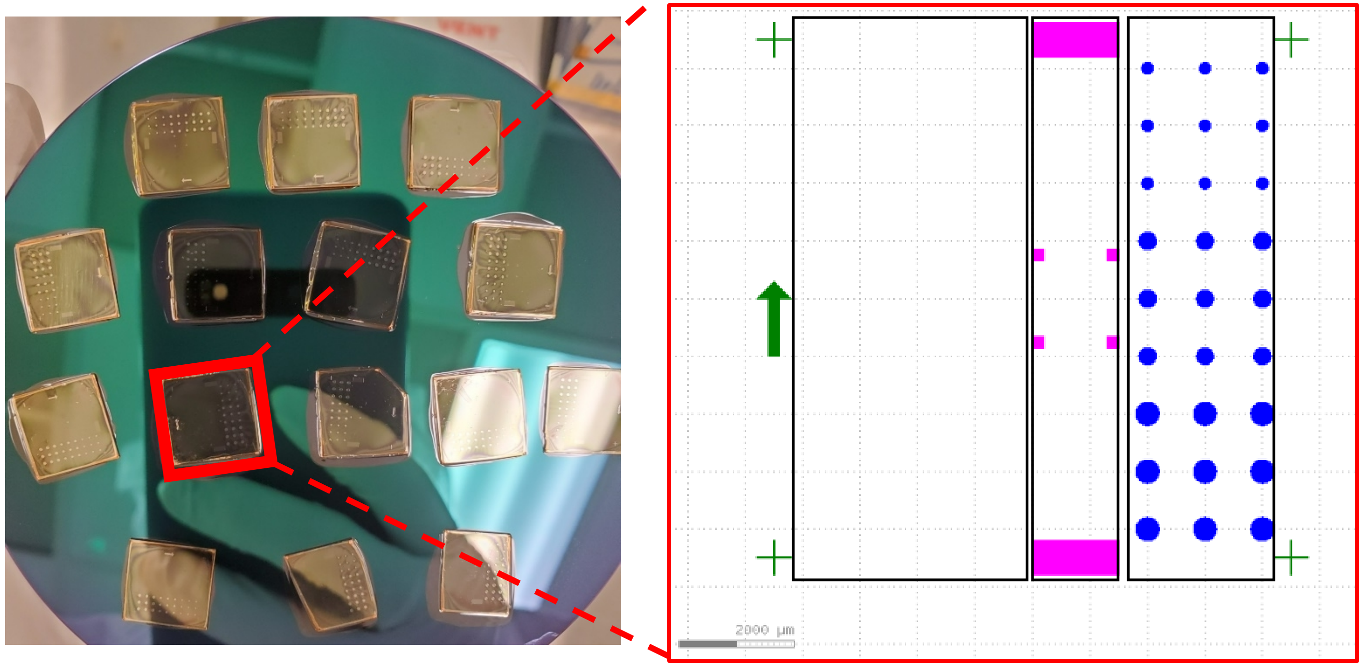
Implanting Ga into Ge to serve as acceptor

- ✓ Broad, well-distributed profile (implant energy)
- ✓ Sufficient carrier density (dopant density)
- ✓ Sufficient carrier activation (anneal temperature)



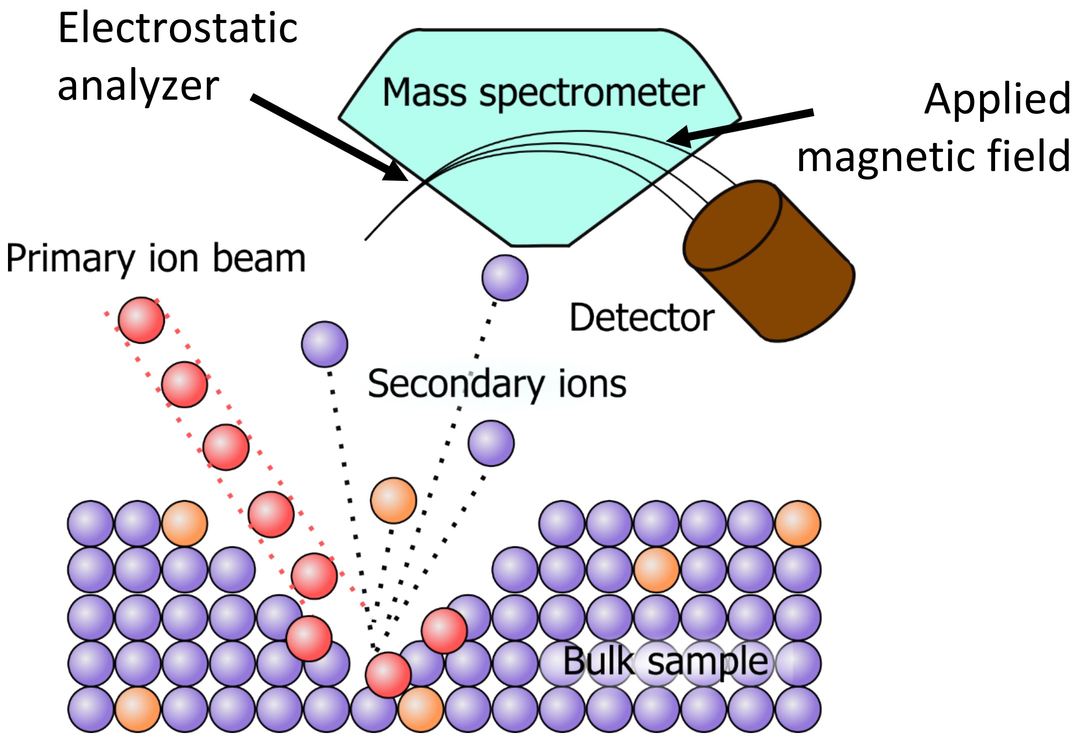
	0 implant	6E10 /cm^2	2E11 /cm^2	6E11 /cm^2	2E12 /cm^2	6E12 /cm^2
500 C	Ge146	Ge220	Ge162	Ge212	Ge178	Ge186
550 C	Ge147	Ge155	Ge213	Ge215	Ge179	Ge187
600 C	Ge148	Ge156	Ge219	Ge172	Ge180	Ge217
650 C	Ge149	Ge157	Ge214	Ge173	Ge210	Ge189
700 C	Ge150	Ge158	Ge196	Ge197	Ge216	Ge218
750 C	Ge151	Ge198	Ge167	Ge199	Ge183	Ge191
800 C	Ge152	Ge160	Ge168	Ge176	Ge184	Ge192
850 C	Ge153	Ge202	Ge169	Ge177	Ge185	Ge193





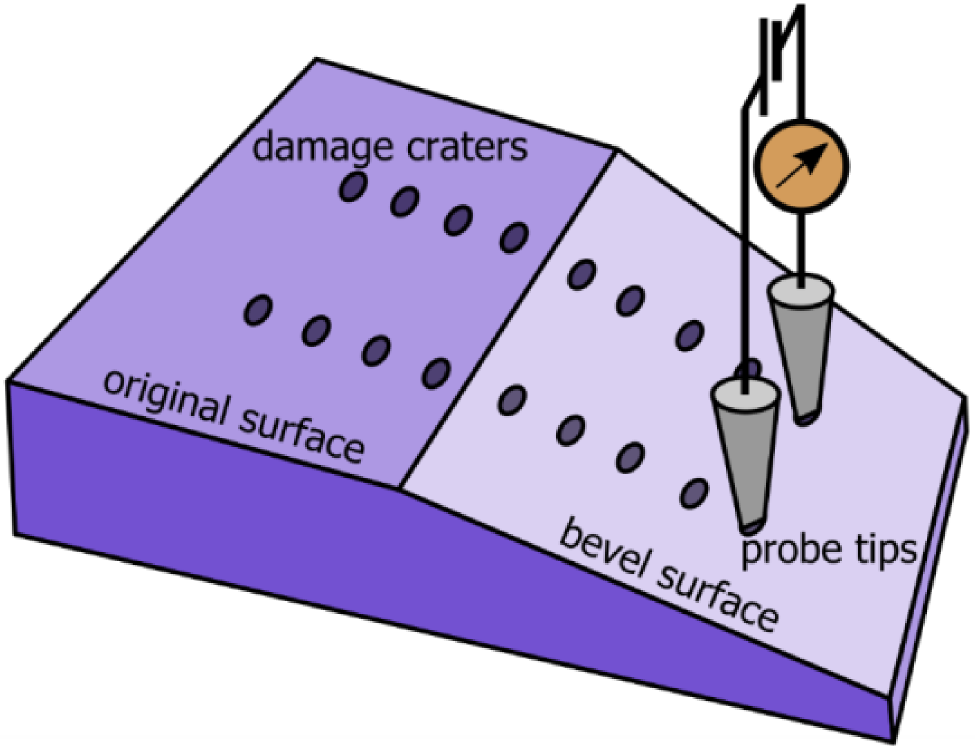
Secondary ion mass spectrometry (SIMS) and spreading resistance profiling (SRP) analysis

SIMS



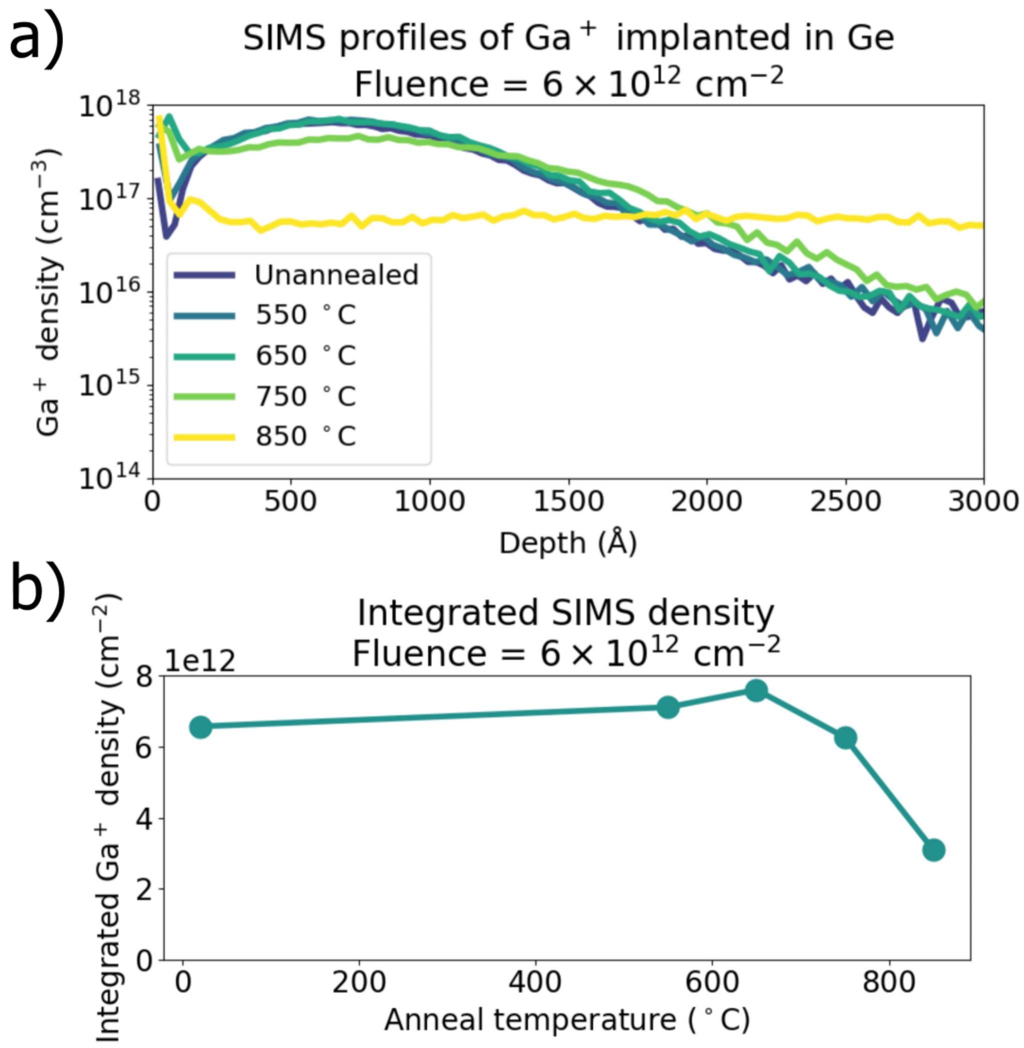
Discriminates concentration of ionic species

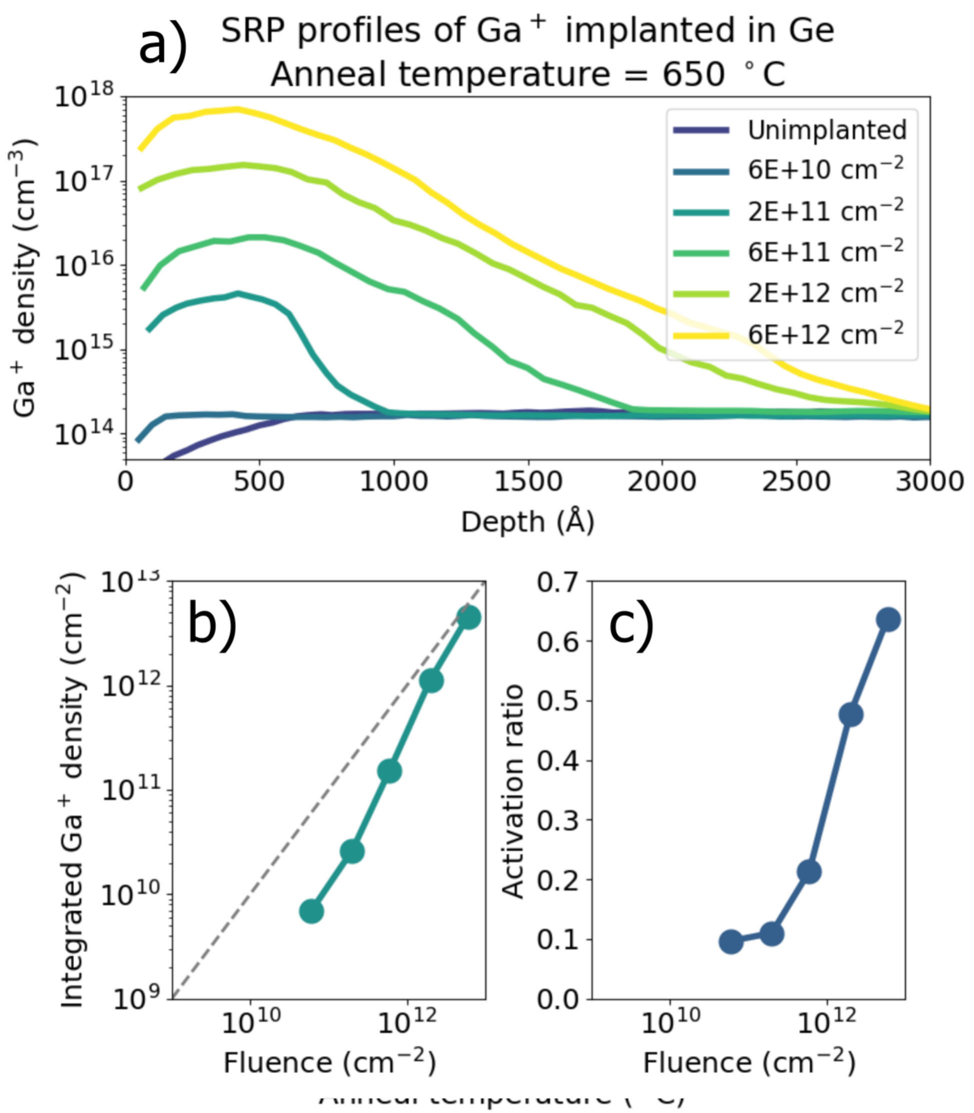
SRP



Total charge carrier density

Implanted ion activation decreases for T > 650 °C and increases with fluence





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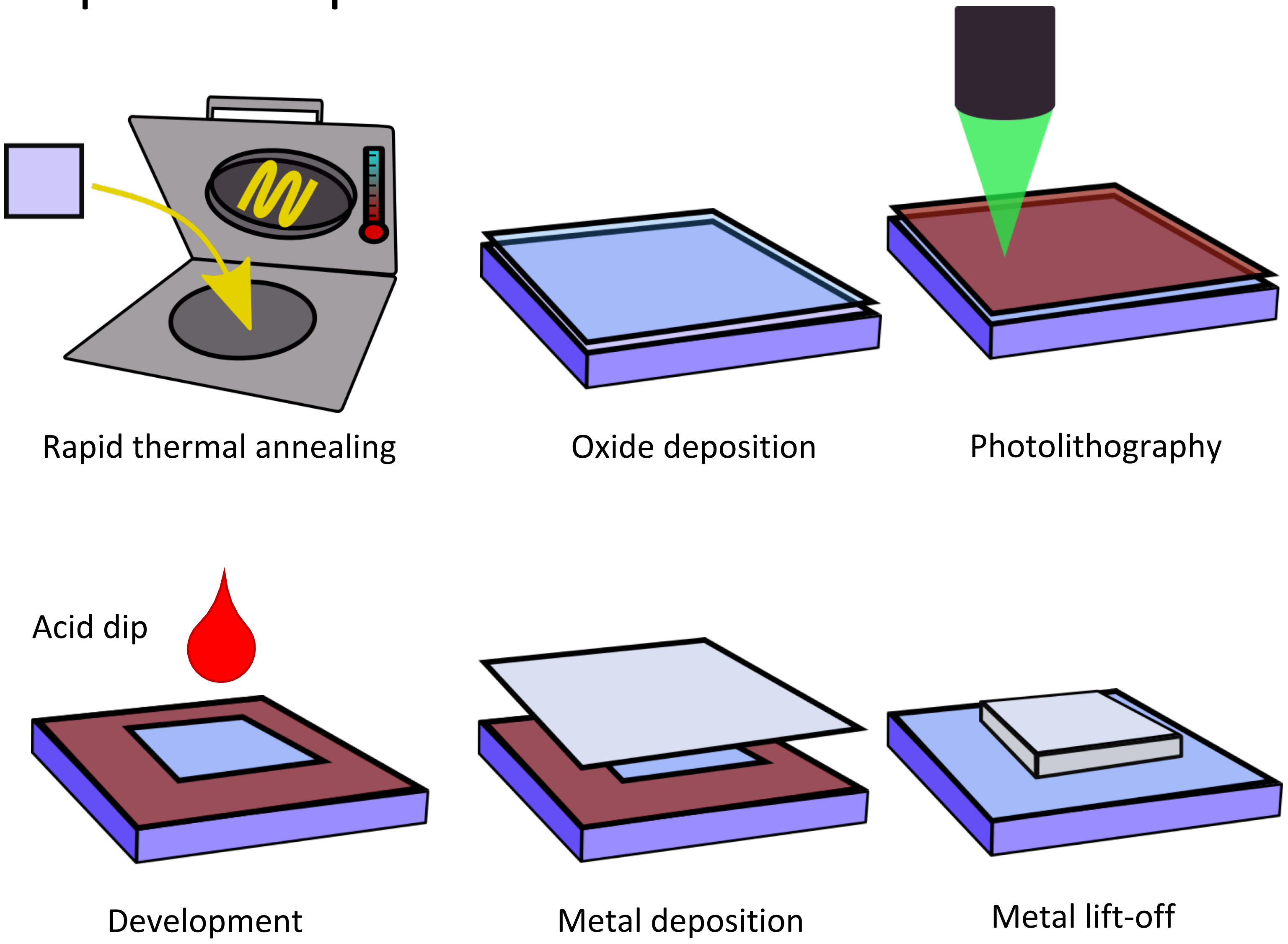
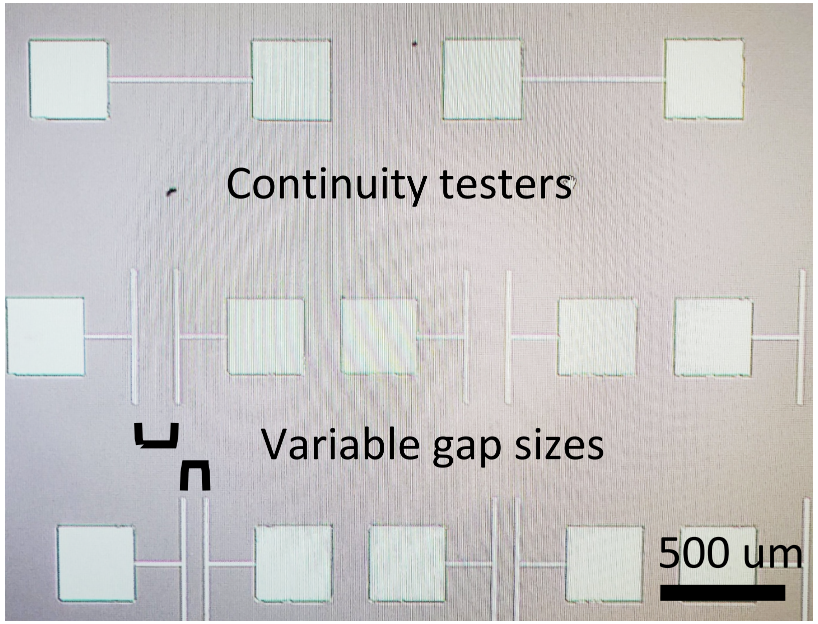
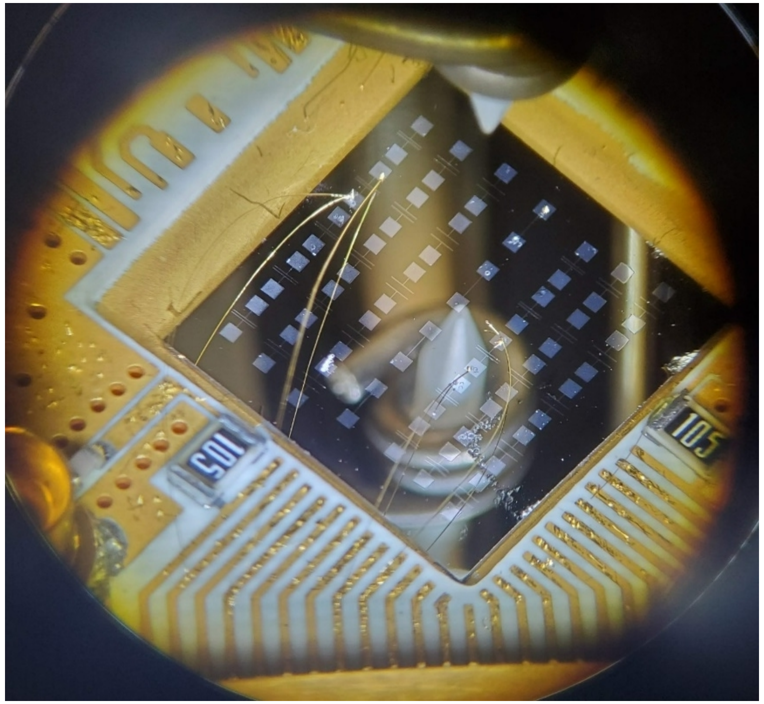
- (Other projects/interests)

Optical spin readout cleanroom device fabrication



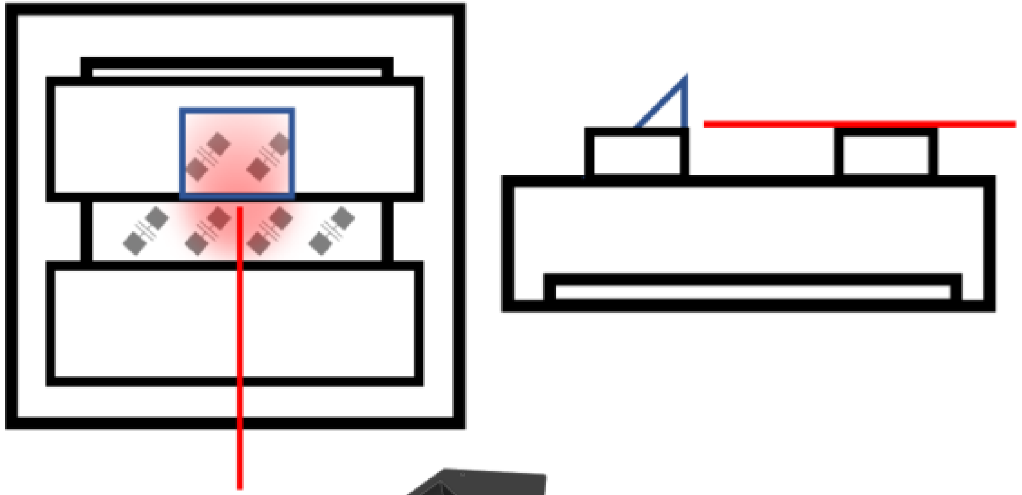


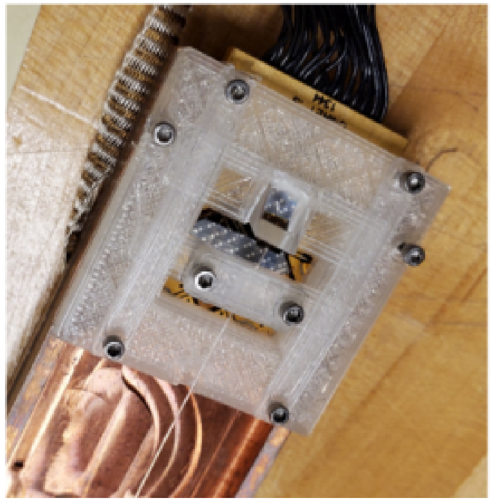
Devices selected on basis of photoresponse

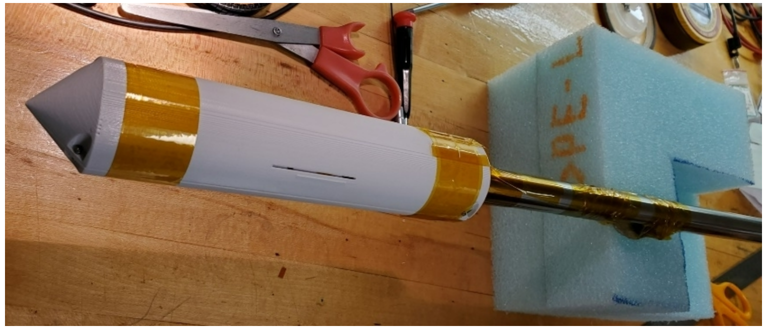


Wire bonding

Mounted device and fiber

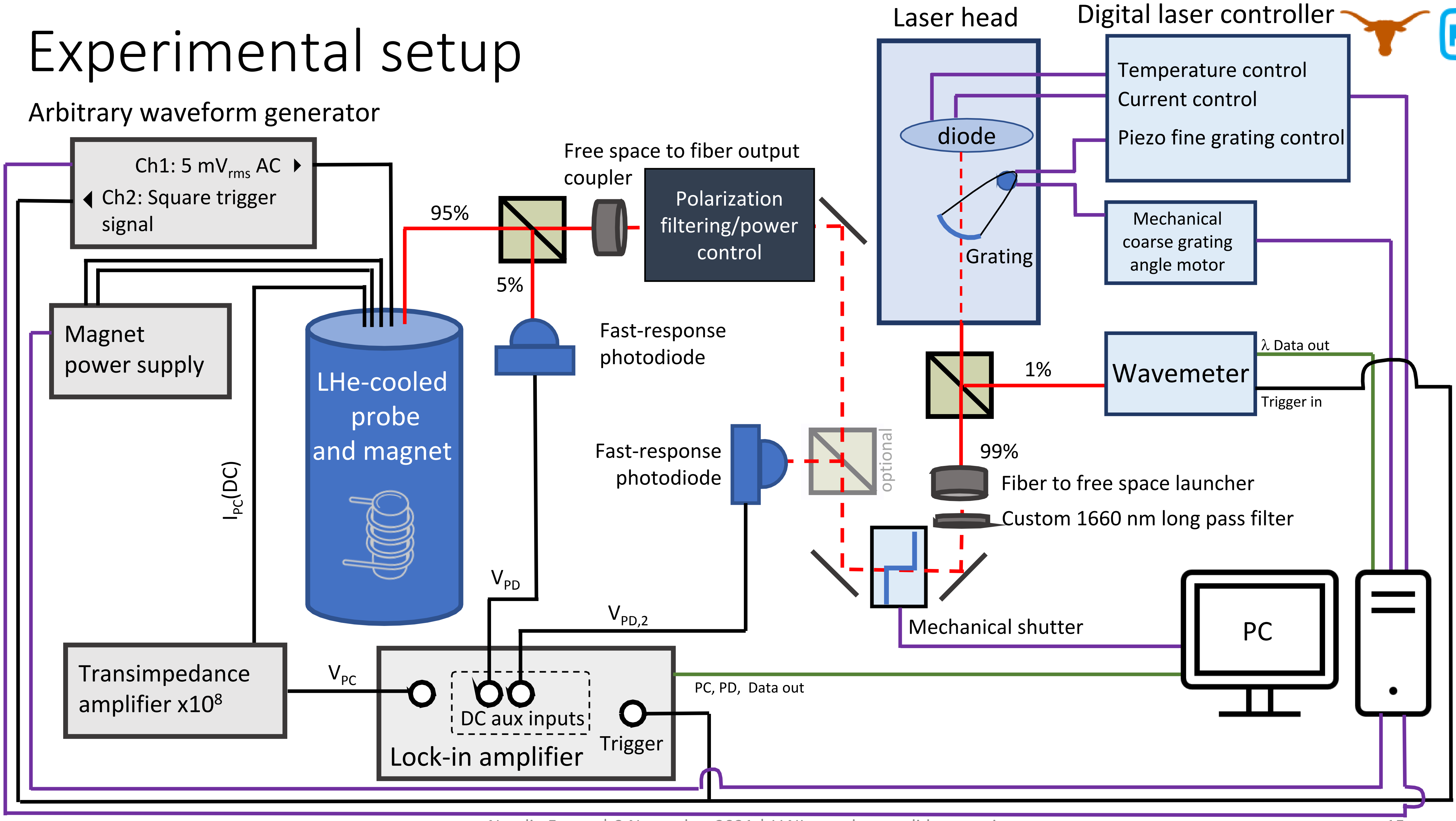




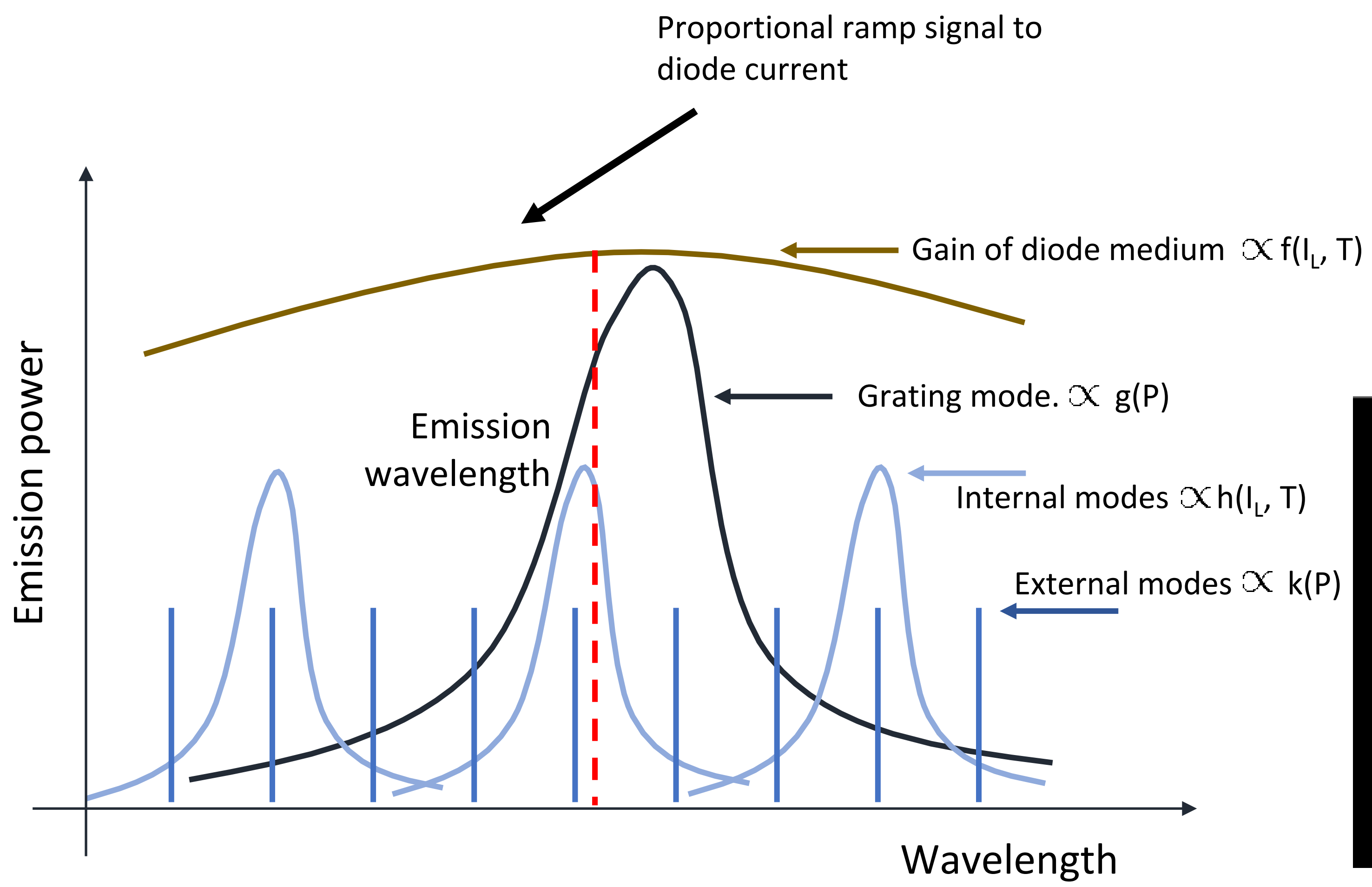


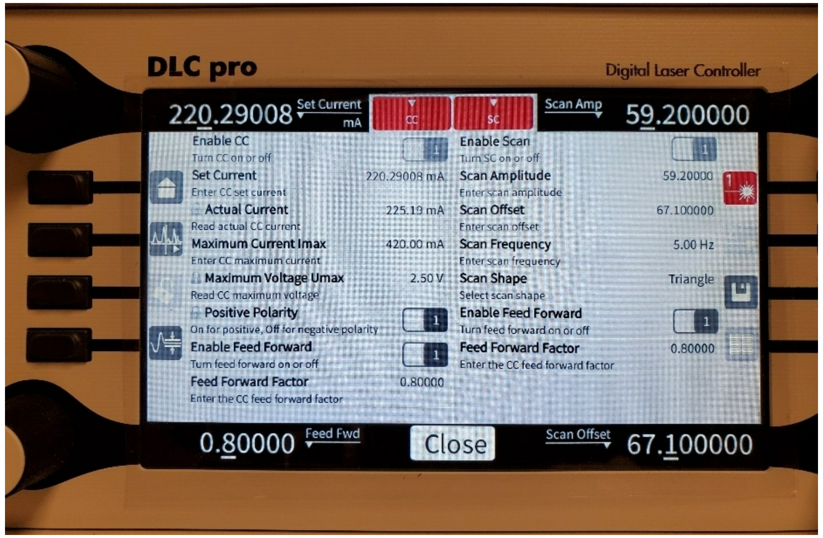
3D printed shell encasing

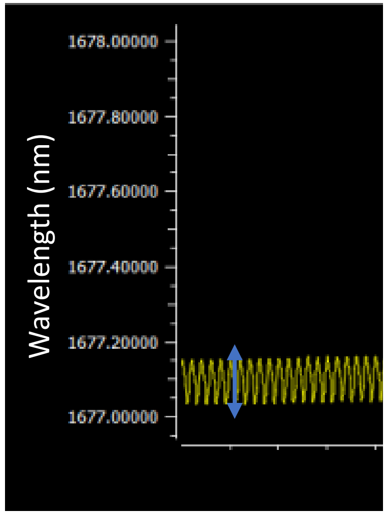
Experimental setup



Digital laser control of emission wavelength

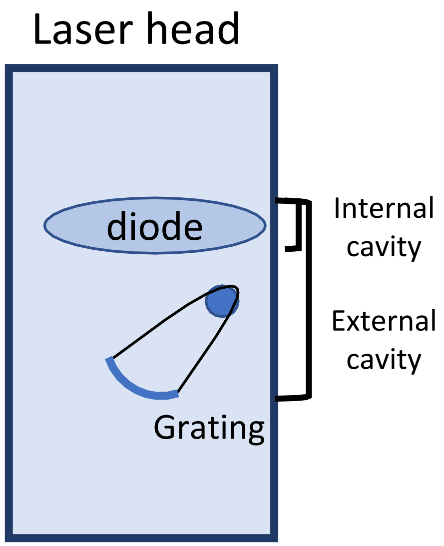




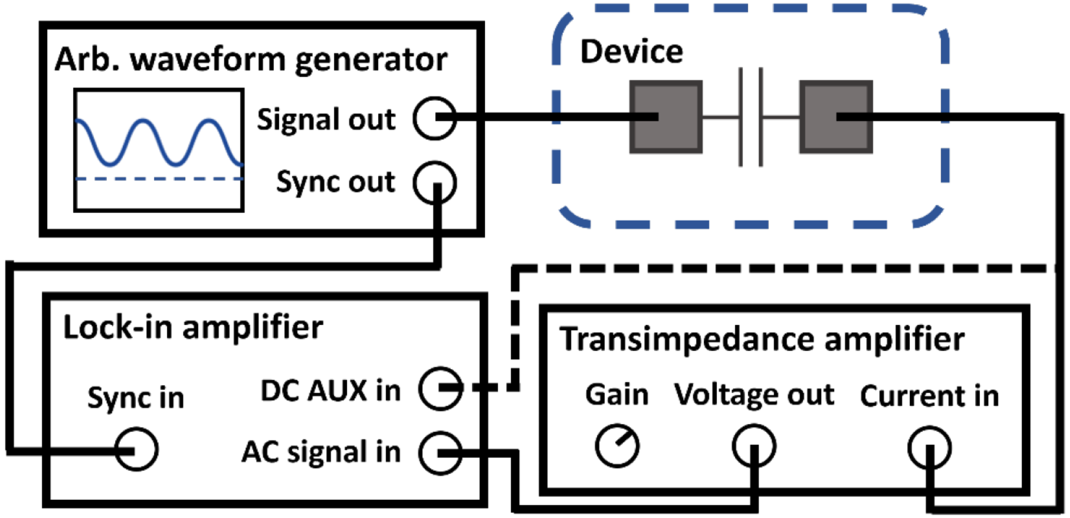


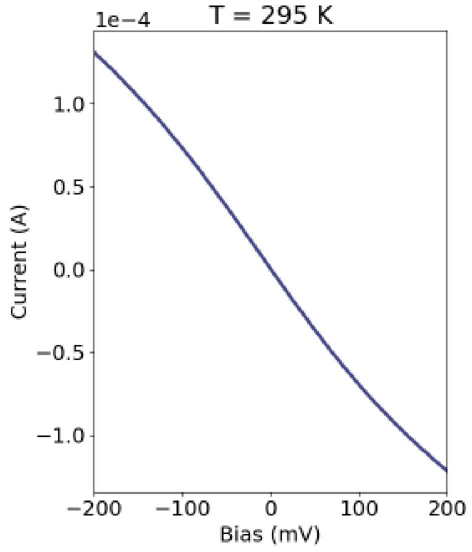
Piezo voltage ramp

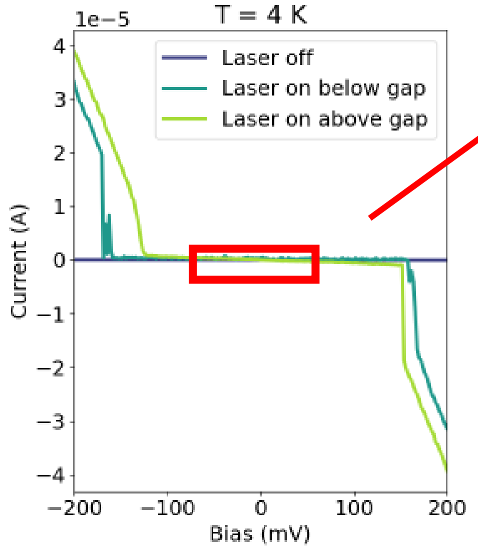
Gr

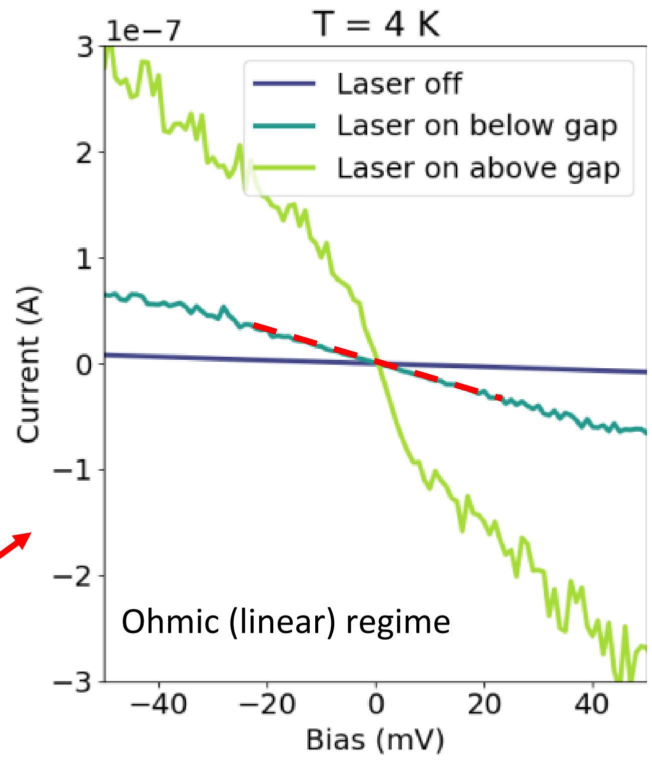


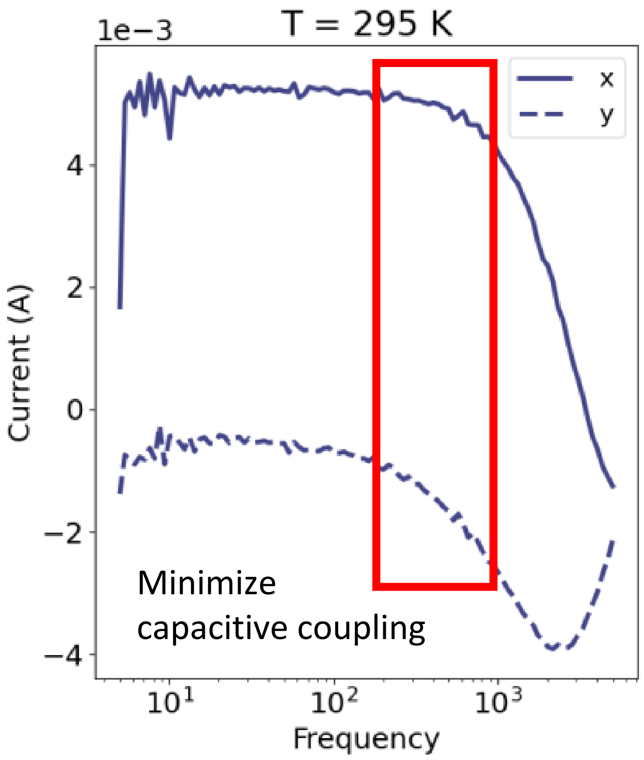
Initial device characterization











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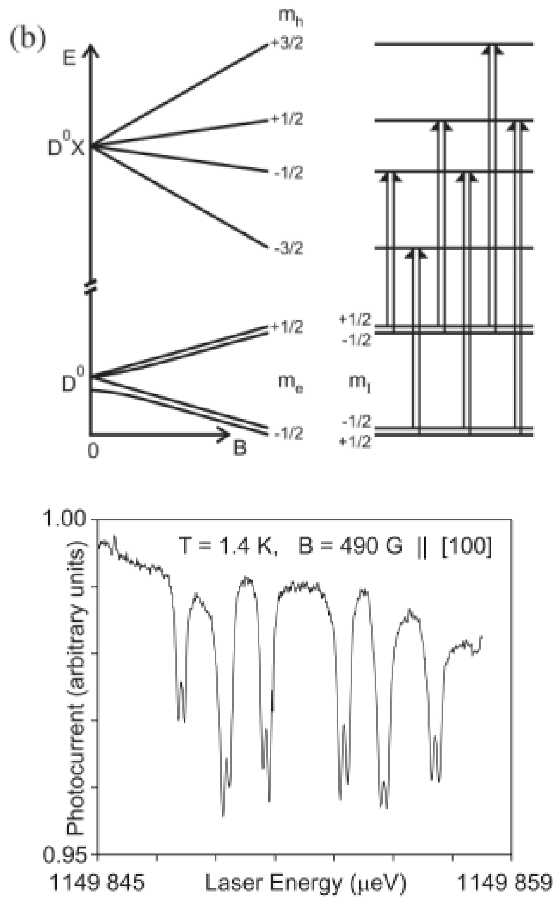
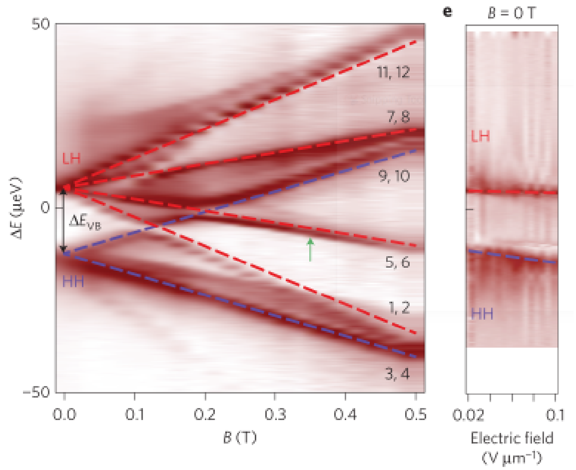
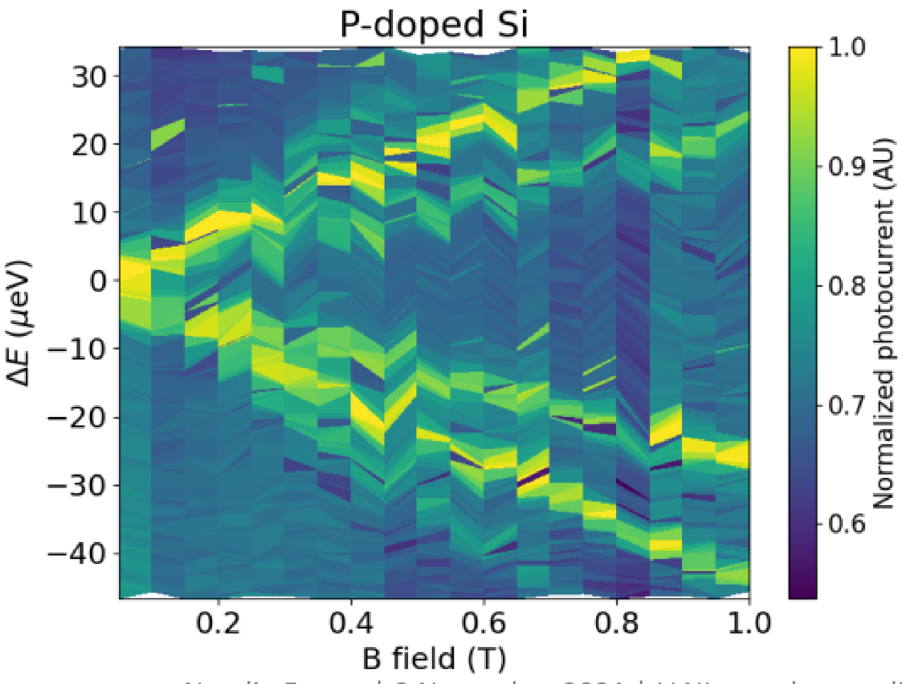
Reproducing results on P-doped Si



A. Yang et al. *PRL* 97,22 (2006) 227401



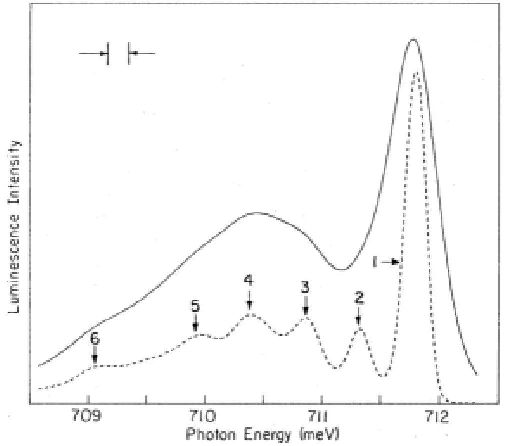
C. C. Lo et al. *Nature Mat.* 14 (2015) 490-494



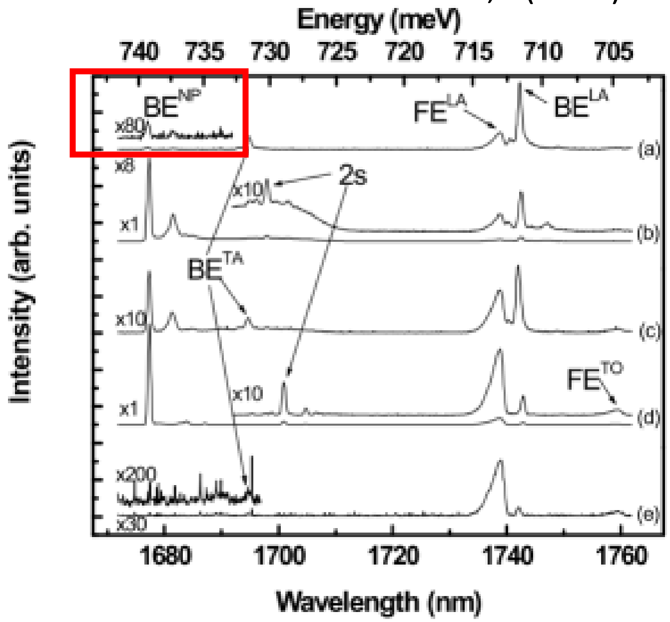
D^0X formation (scanning)

D^0 neutralization

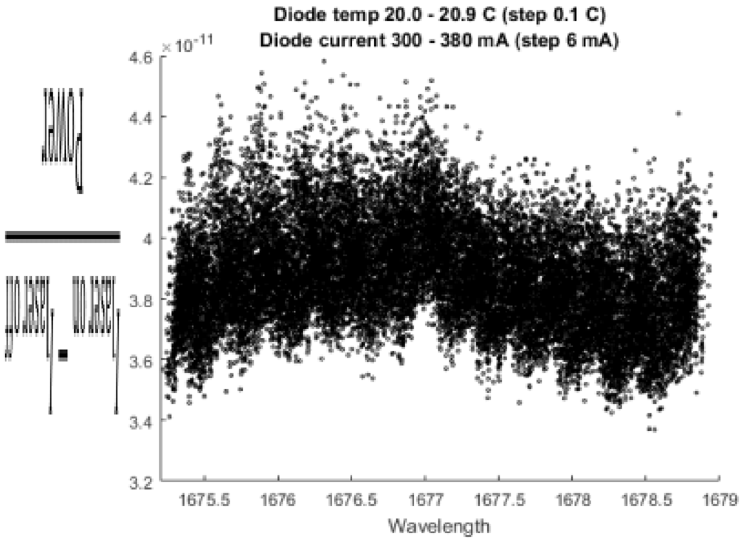
Measurement of acceptor-bound exciton transition in Ga-doped Ge



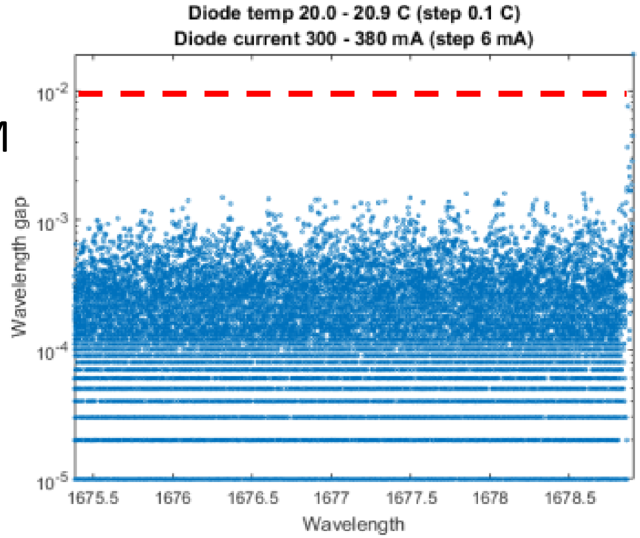
G. Held et al. *Solid State Comm.* 47,6 (1983) 459-462

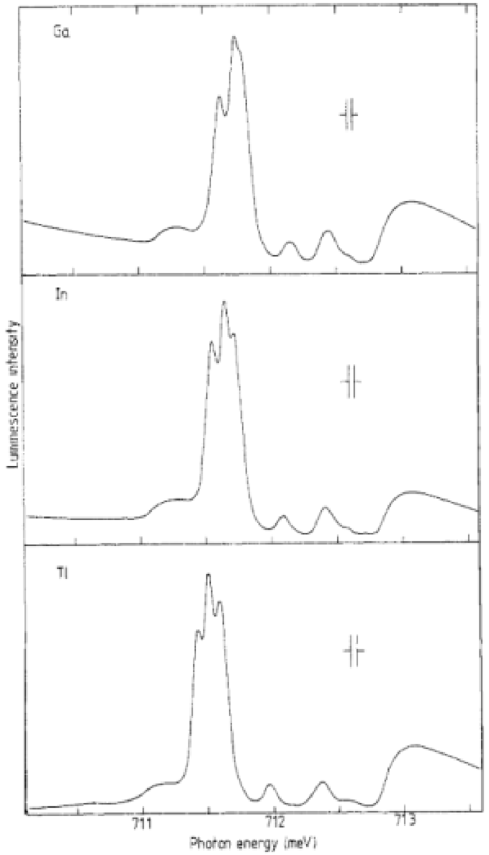


M. Allardt et al. *Solid State Phen.* 178-179 (2011) 289-294



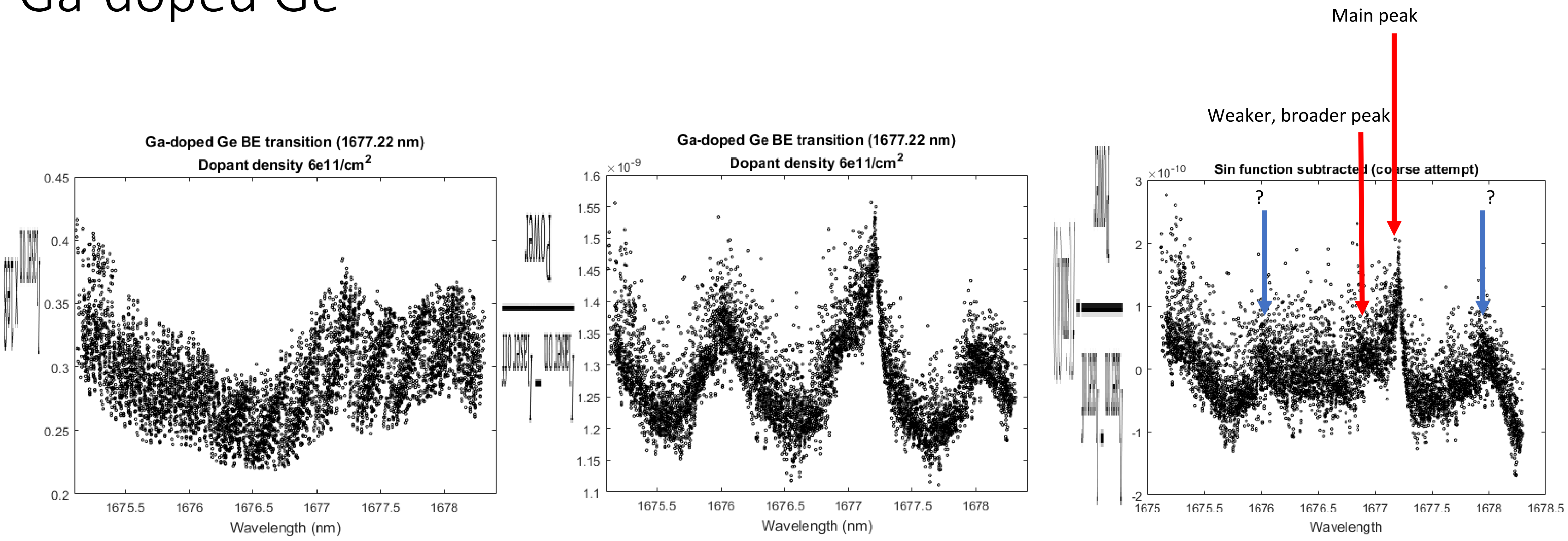
Target FWHM





E. Lightowlers and Z. Chiechanowska
J. Phys. C 14, 23 (1981) L719-L724

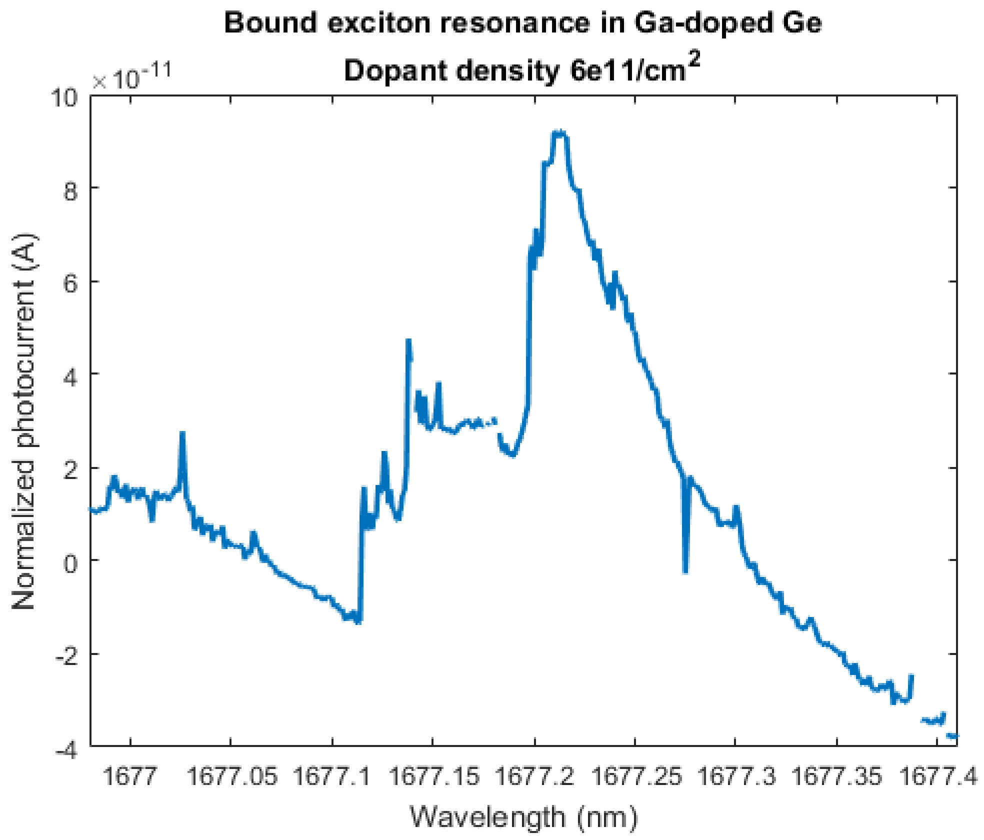
Measurement of acceptor-bound exciton transition in Ga-doped Ge

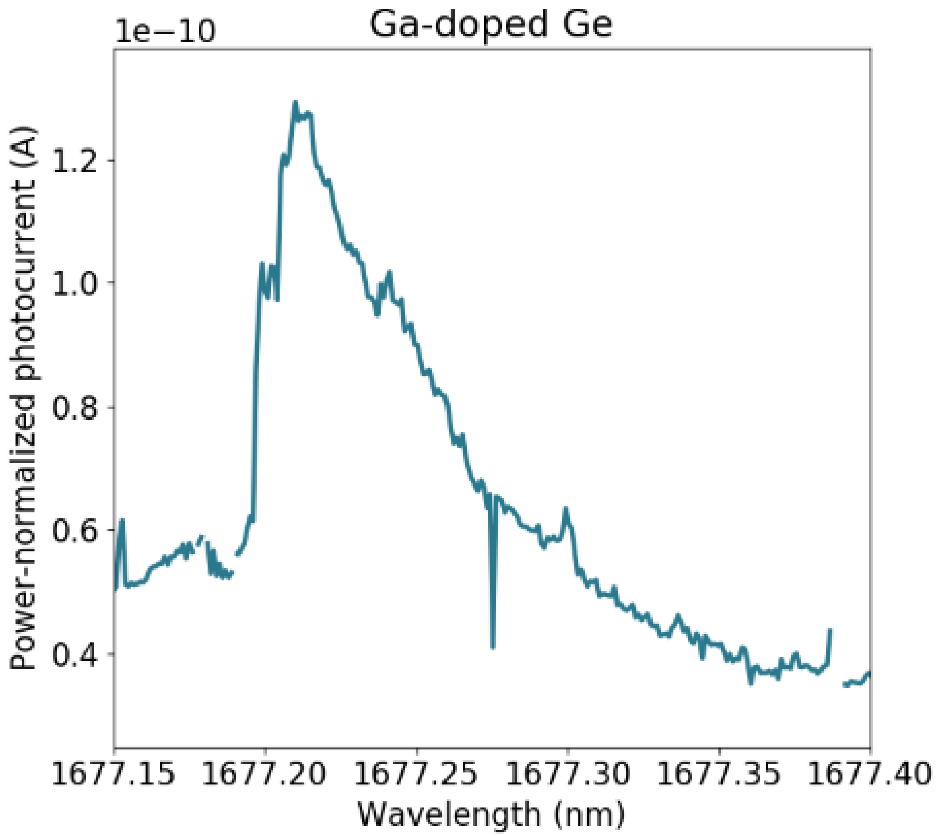


Signal refinement

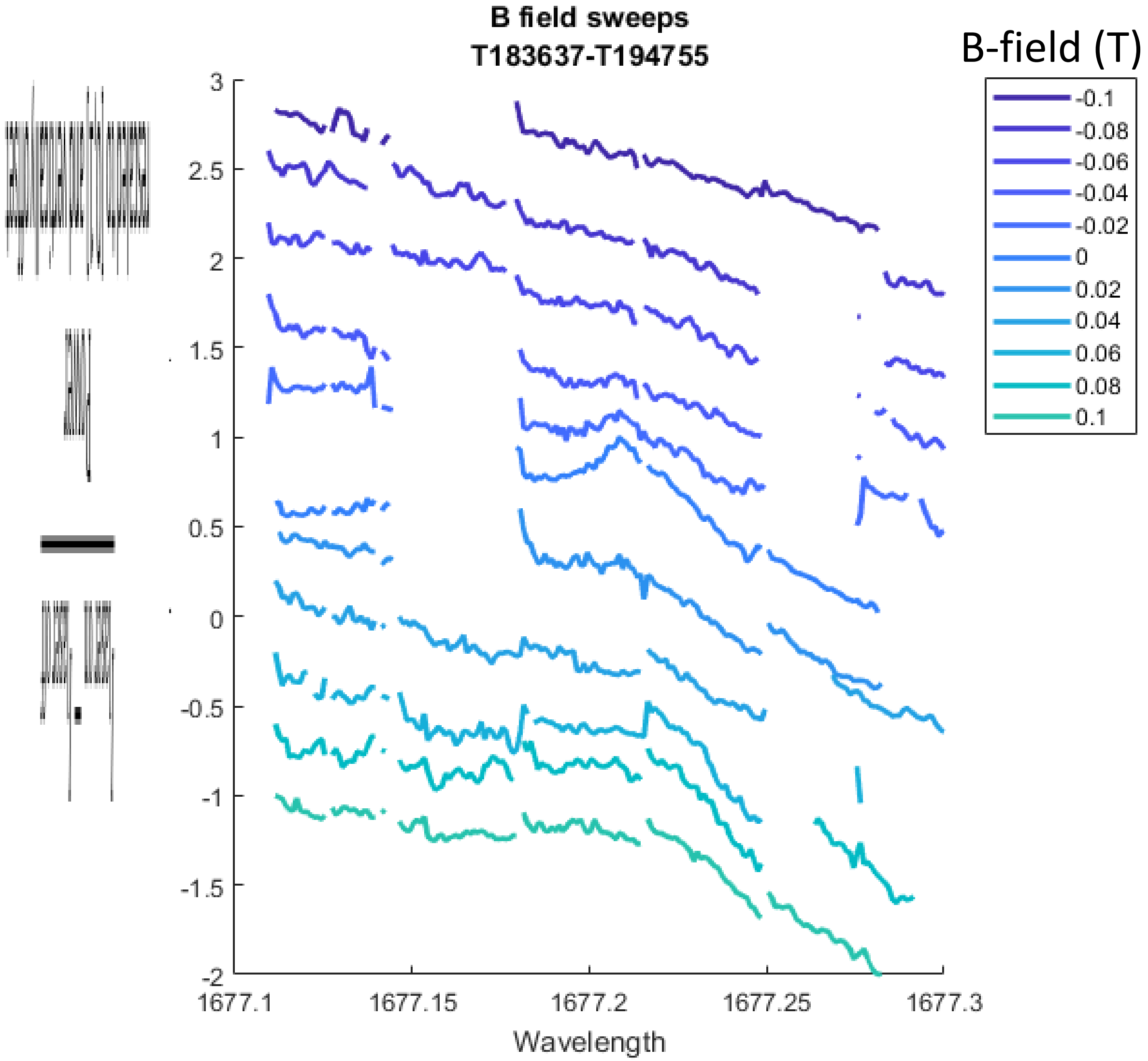
Measurement of acceptor-bound exciton transition in Ga-doped Ge

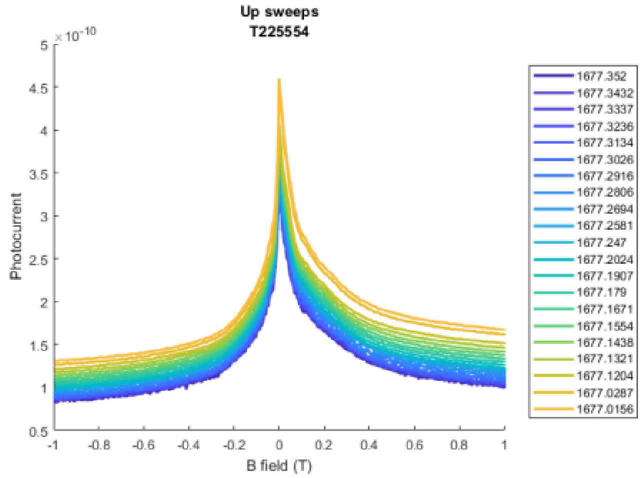
Fast scanning method for line refinement

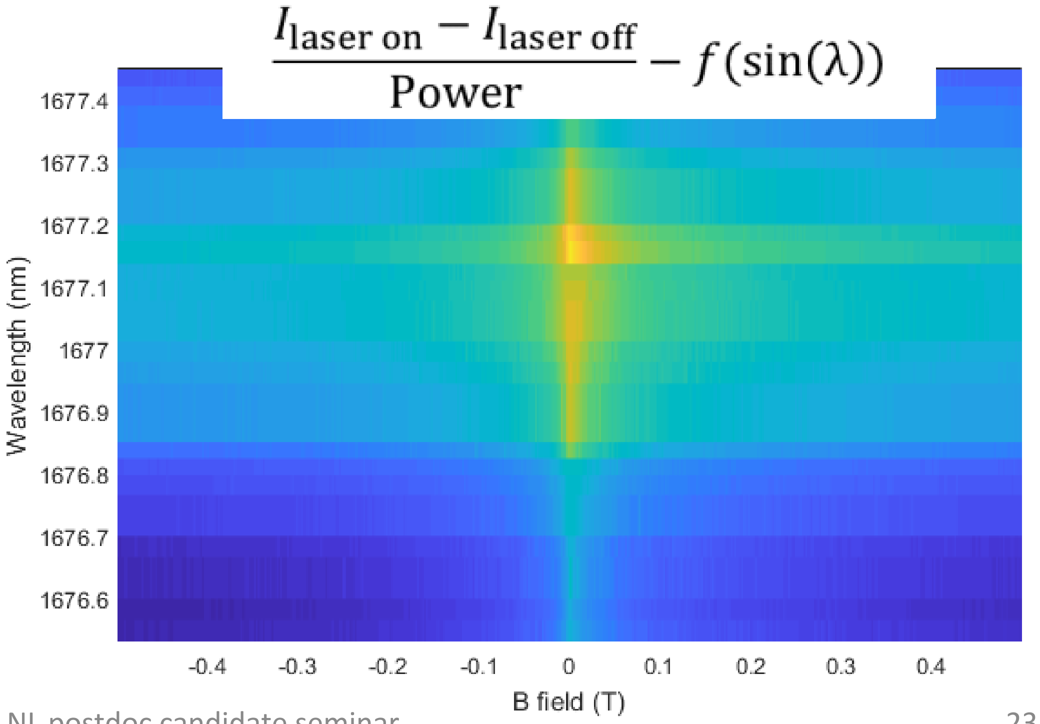




Magnetospectroscopy lifts degeneracy of neutral acceptor-exciton states

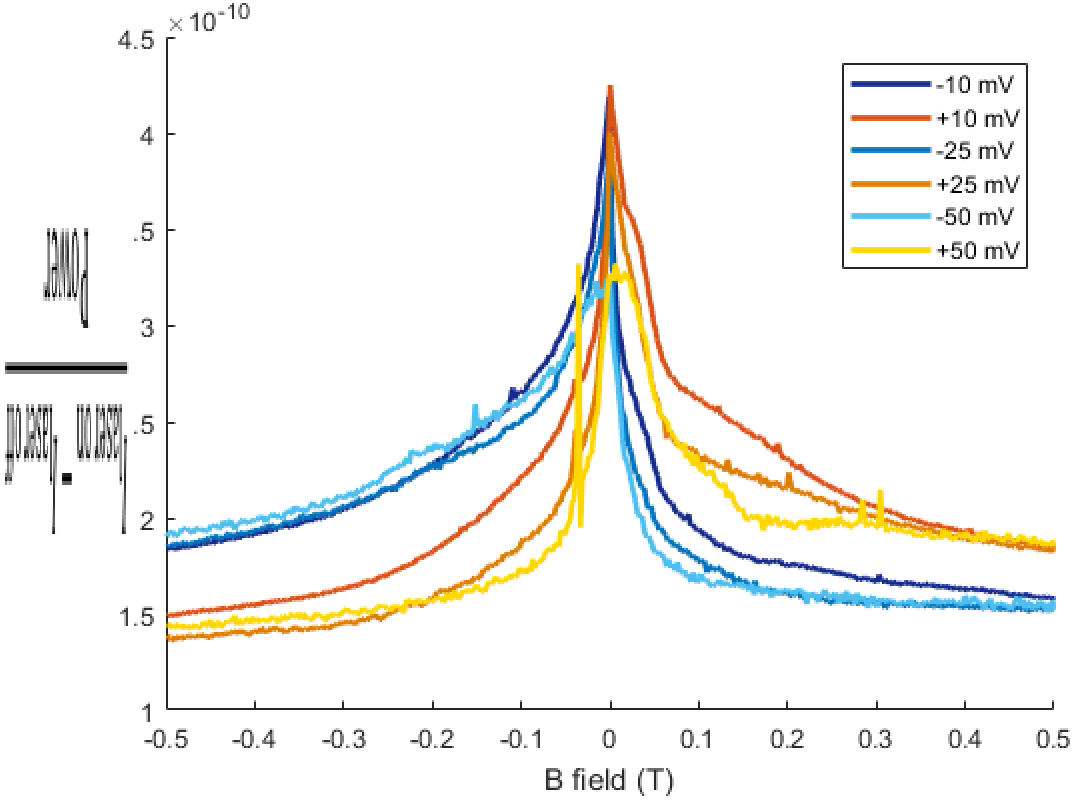


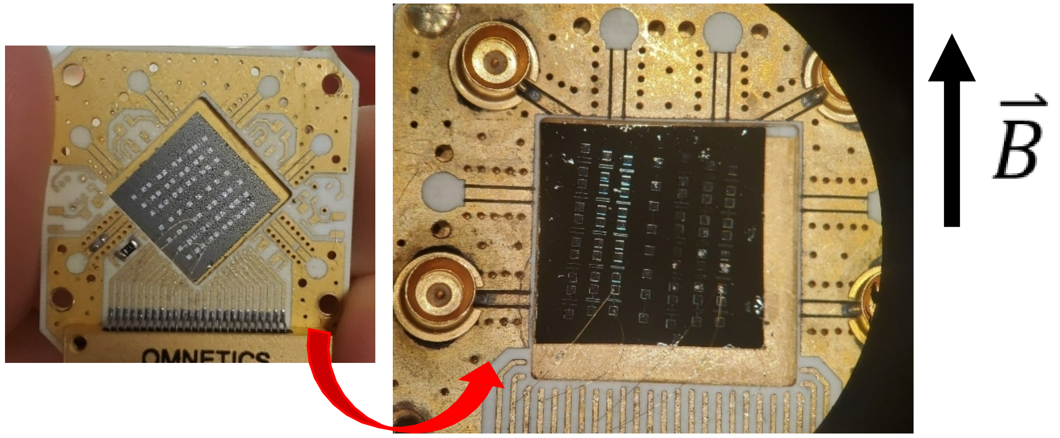


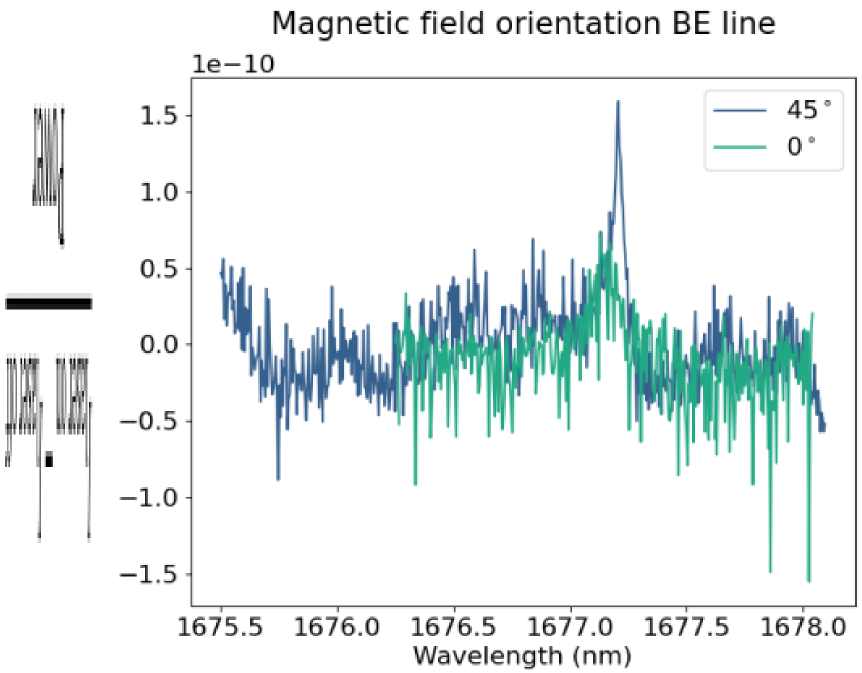


Challenges with magnetospectroscopy in germanium

- Smaller g-factor
- Many transitions near same energy







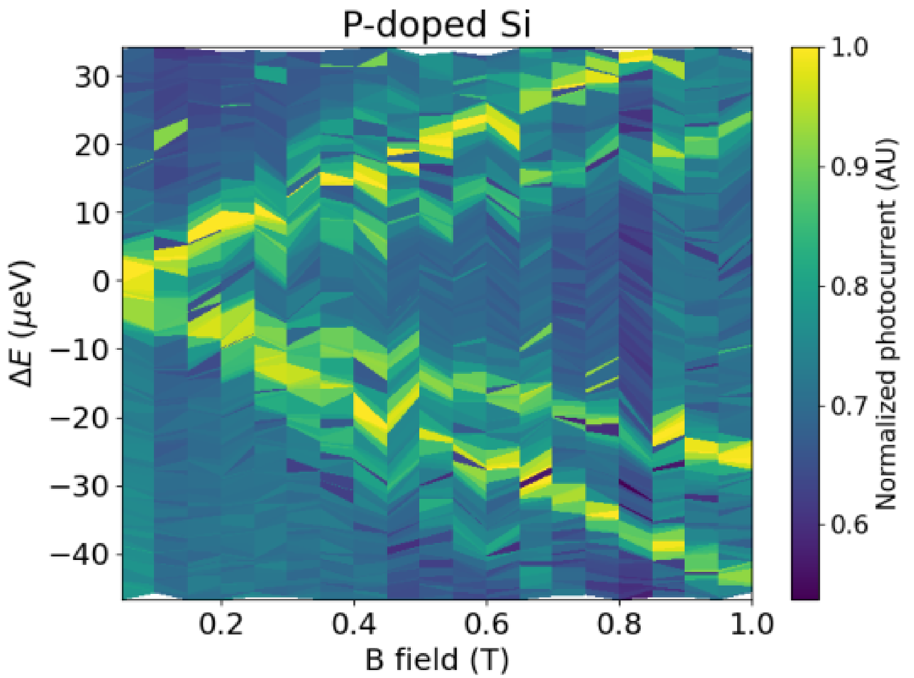
Summary

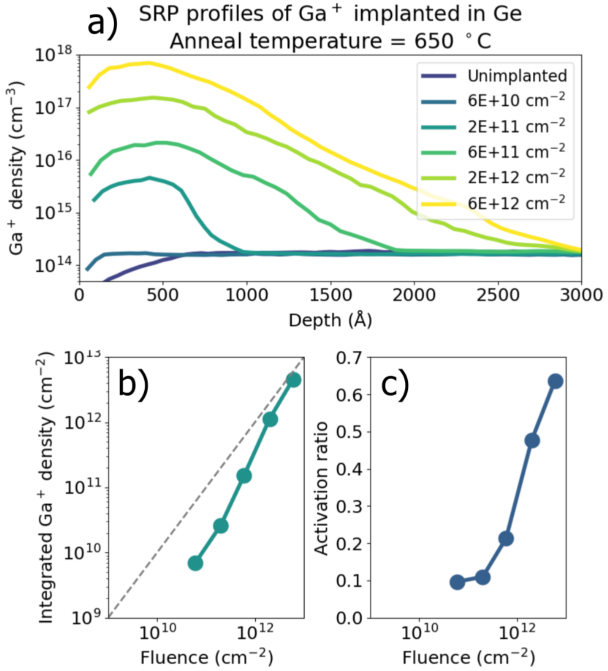
✓ Quantified dopant activation in implanted Ge

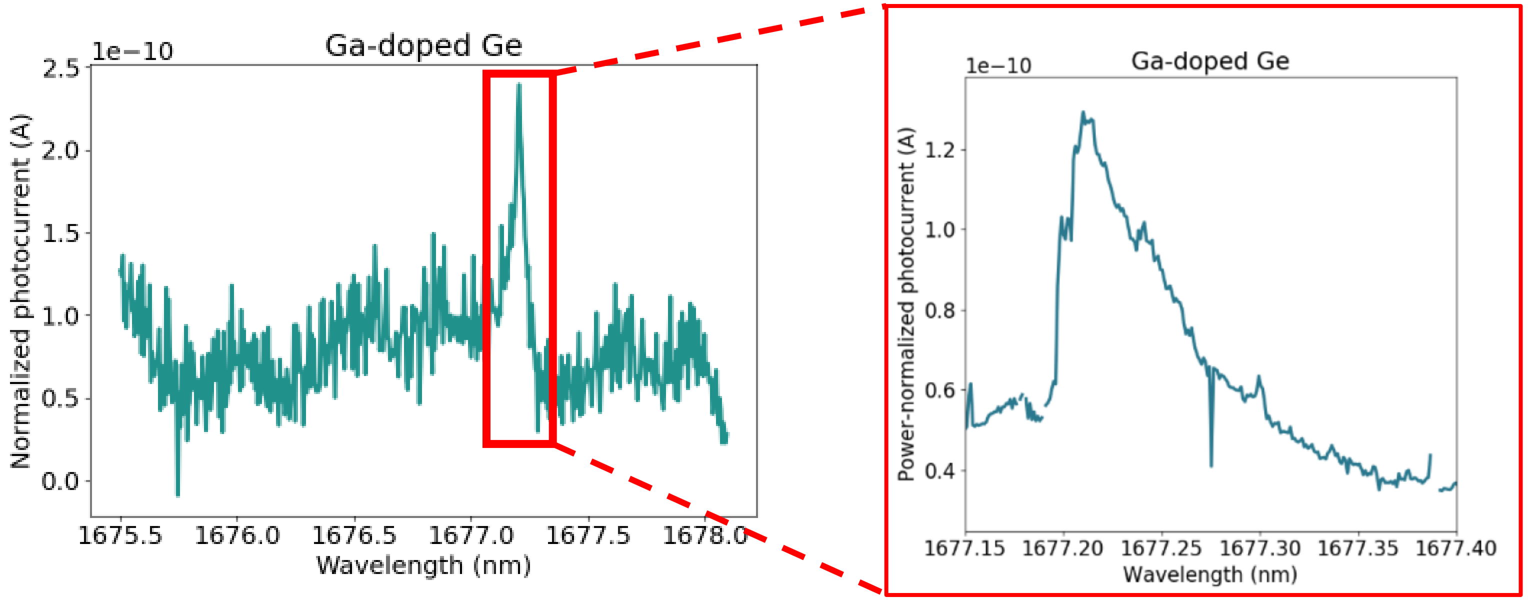
✓ Reproduced P-doped Si bound exciton Zeeman spectrum

✓ Measured Ga-doped Ge bound exciton transition

❑ Looking forward: improvements to SNR to resolve weak Ge Zeeman spectrum





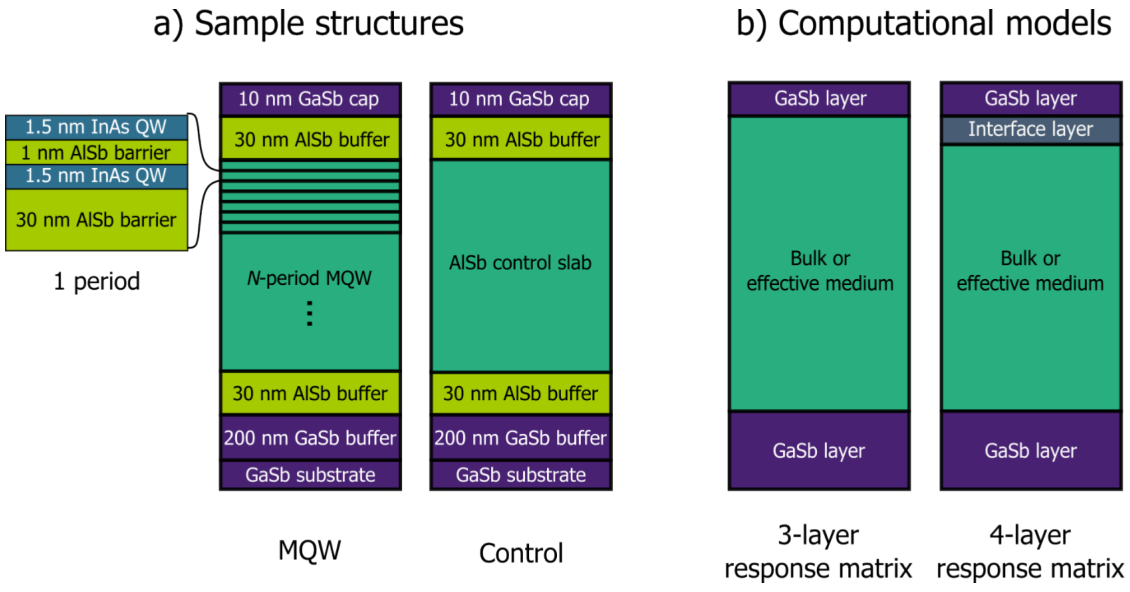


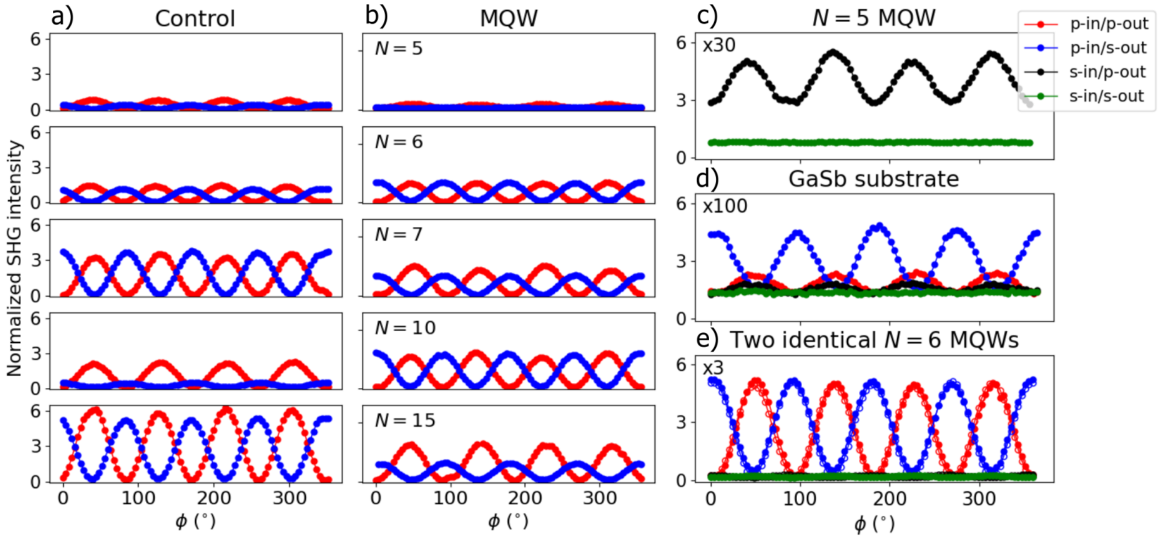
N. D. Foster et al, *in preparation*

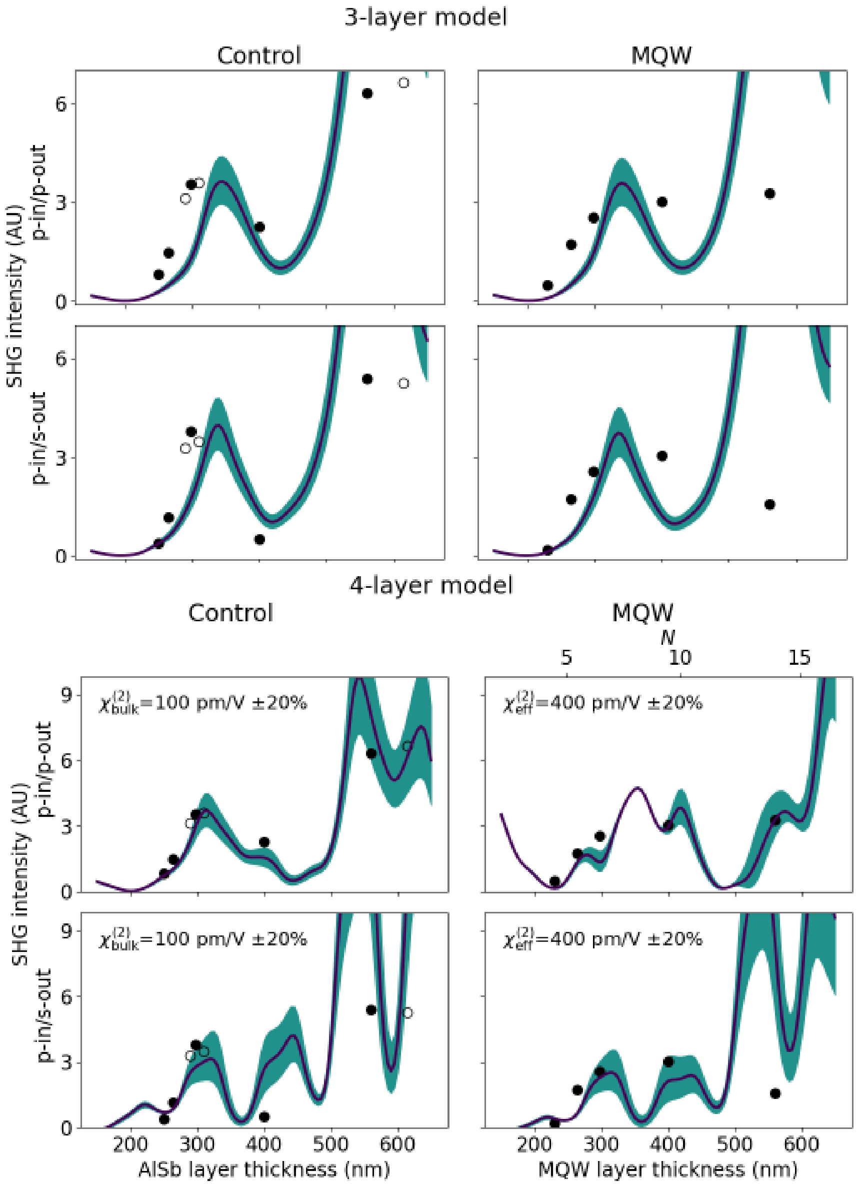
Overview

- Nuclear spins as qubits
- Optimizing Ga-doped Ge
- Device implementation and experiment
- Spin-selective optical readout of resonant excitons
- **(Other projects/interests)**

Measurement of $\chi^{(2)}$ in III-V semiconductor QWs

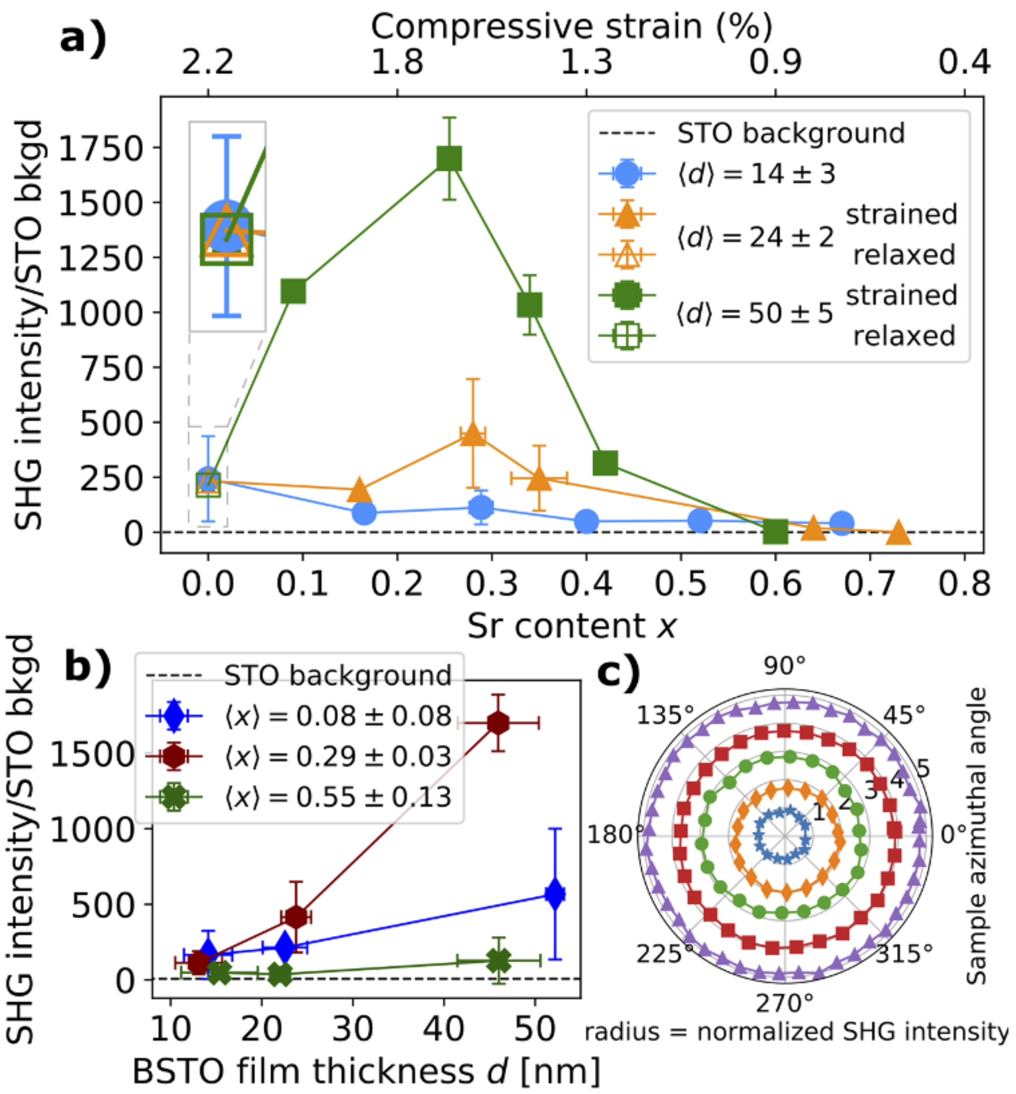


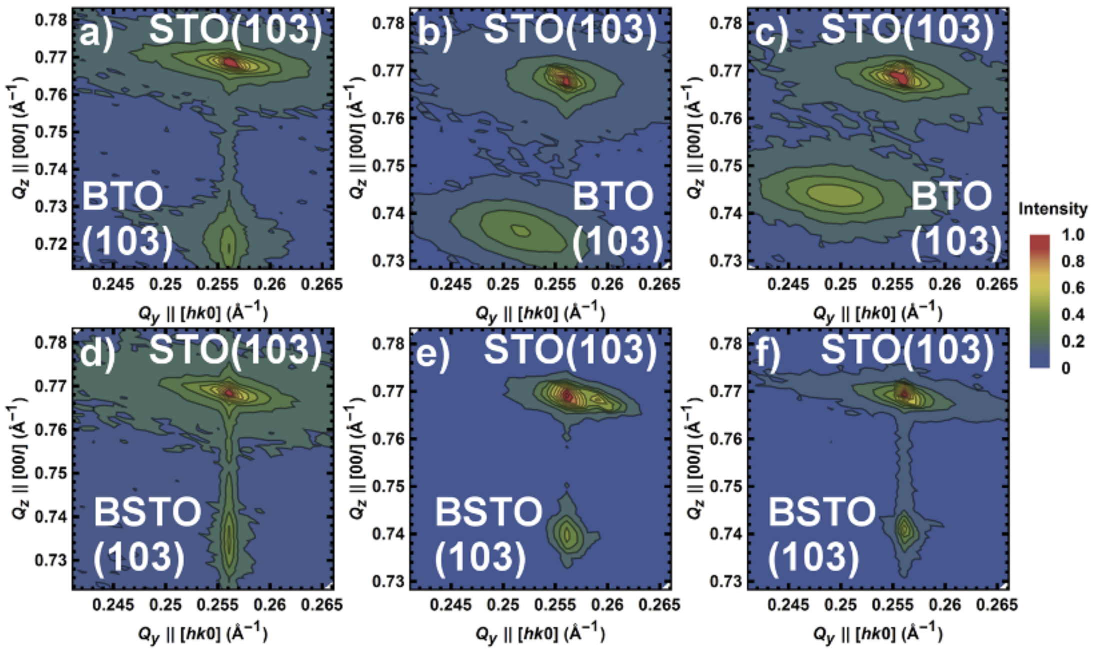


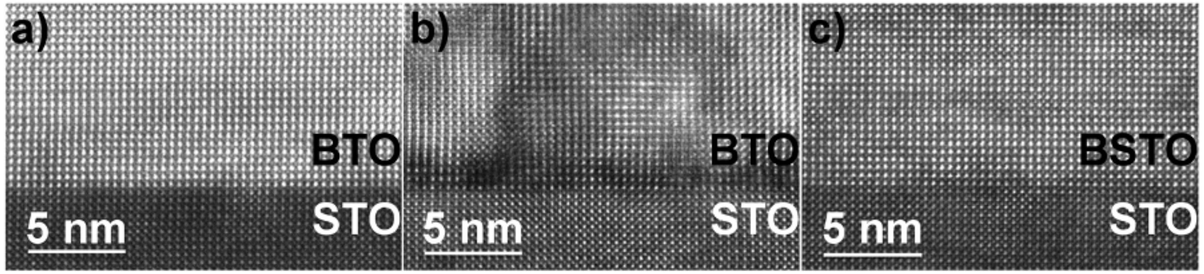


N. D. Foster et al, *in preparation*

Strain dependence of $\chi^{(2)}$ in thin film $Ba_xSr_{1-x}TiO_3$

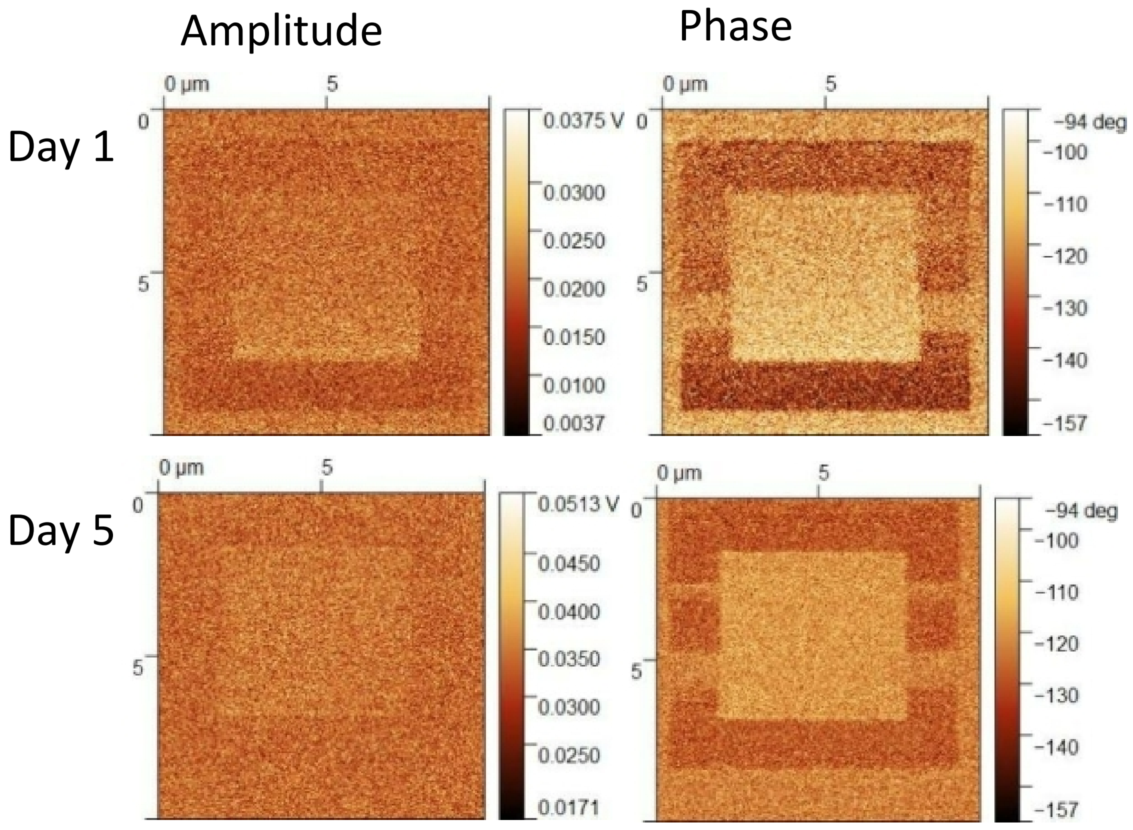




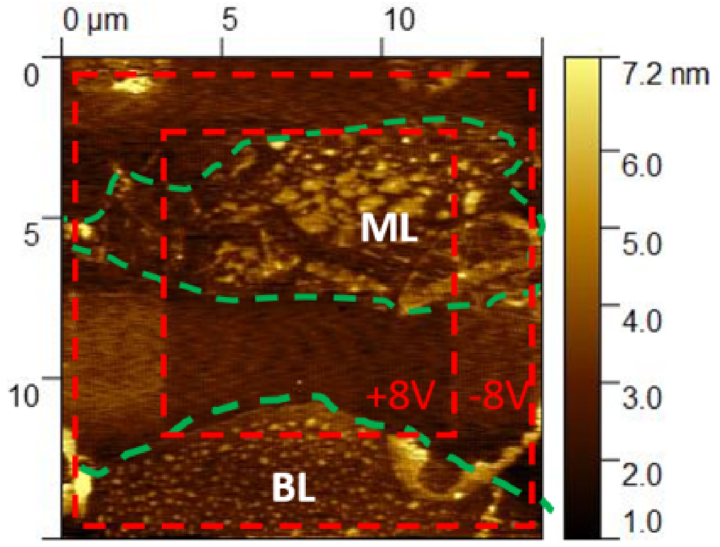


N. D. Foster et al, *AIP Advances* 9 (2019) 025312

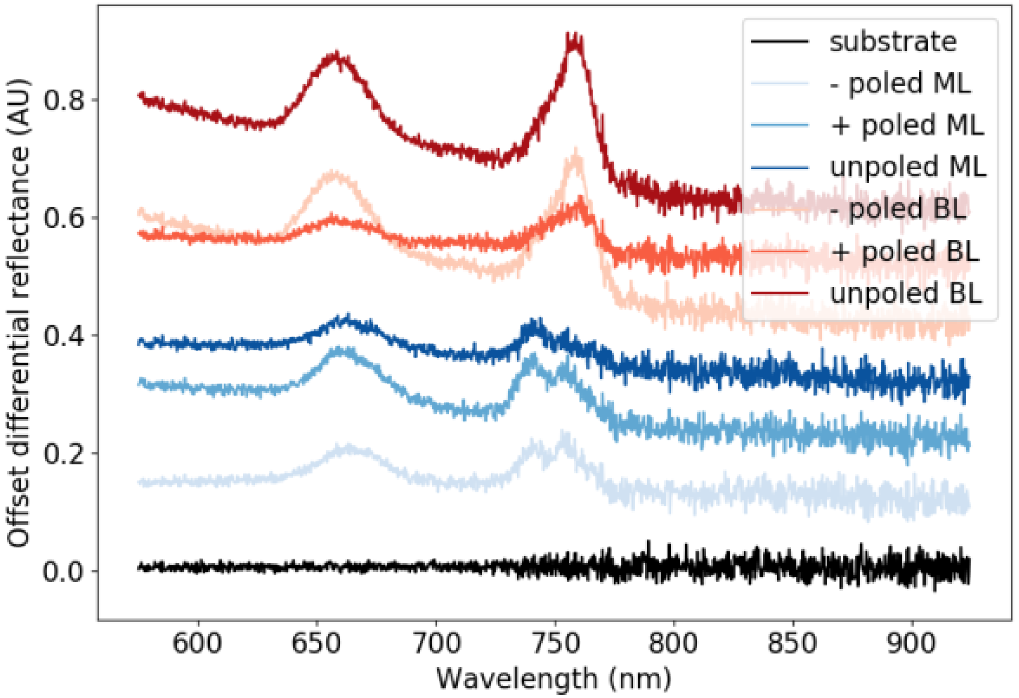
Ferroelectric proximity effect on excitonic properties of TMDs



Piezo-force microscopy (PFM) reveals longevity of nonvolatile ferroelectric domains in PZT

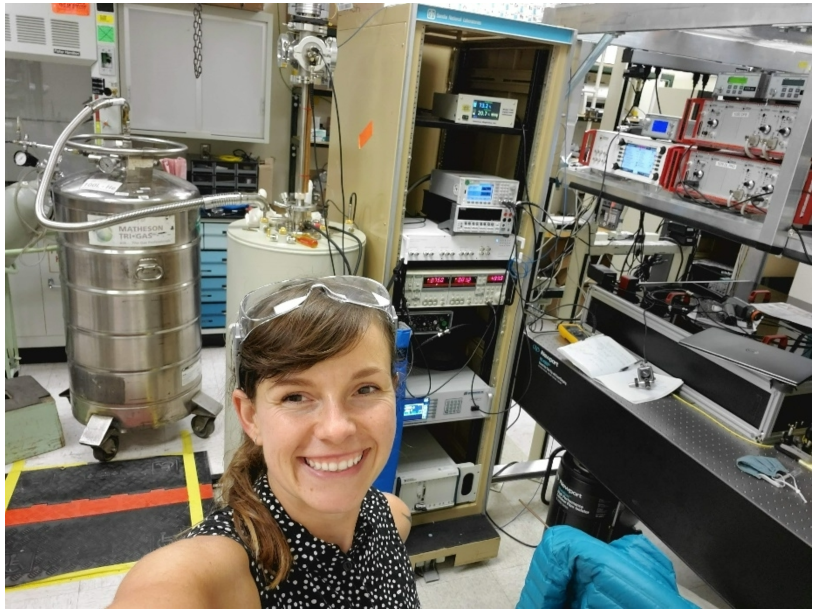


Poled $MoSe_2$ on PZT



Unpublished data

Acknowledgments



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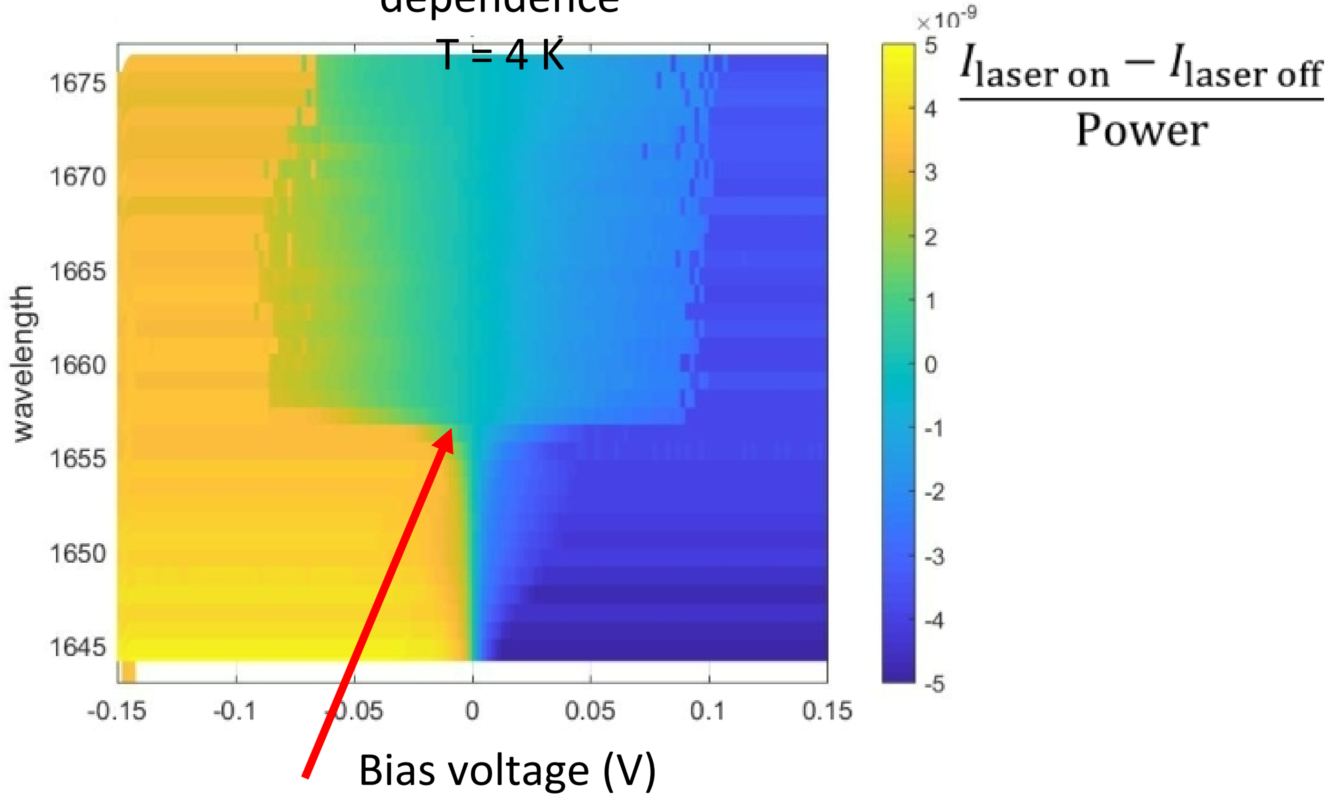
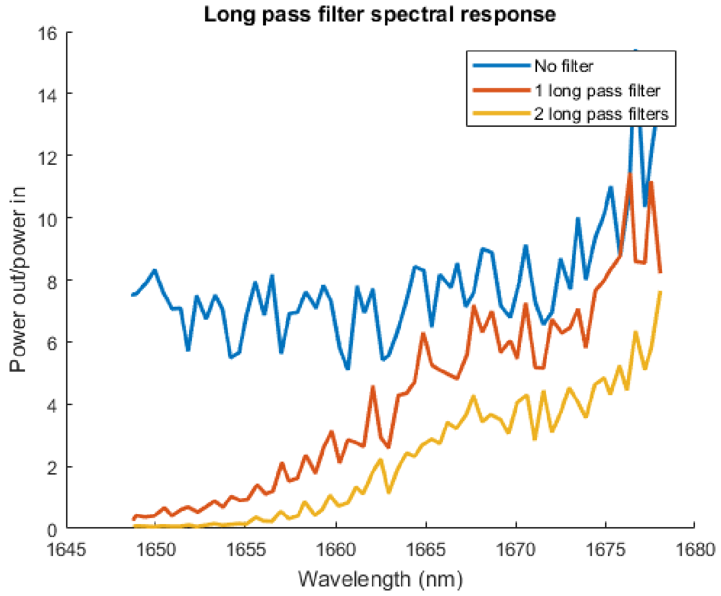
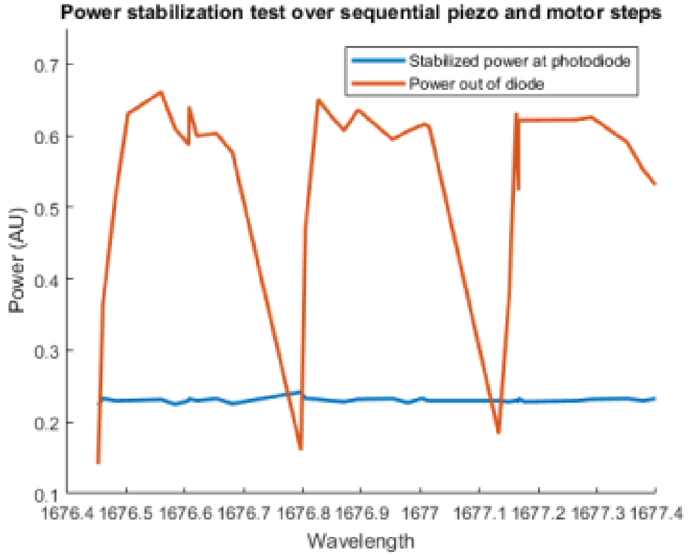
Supplementary

DC I-V wavelength dependence
T = 4 K

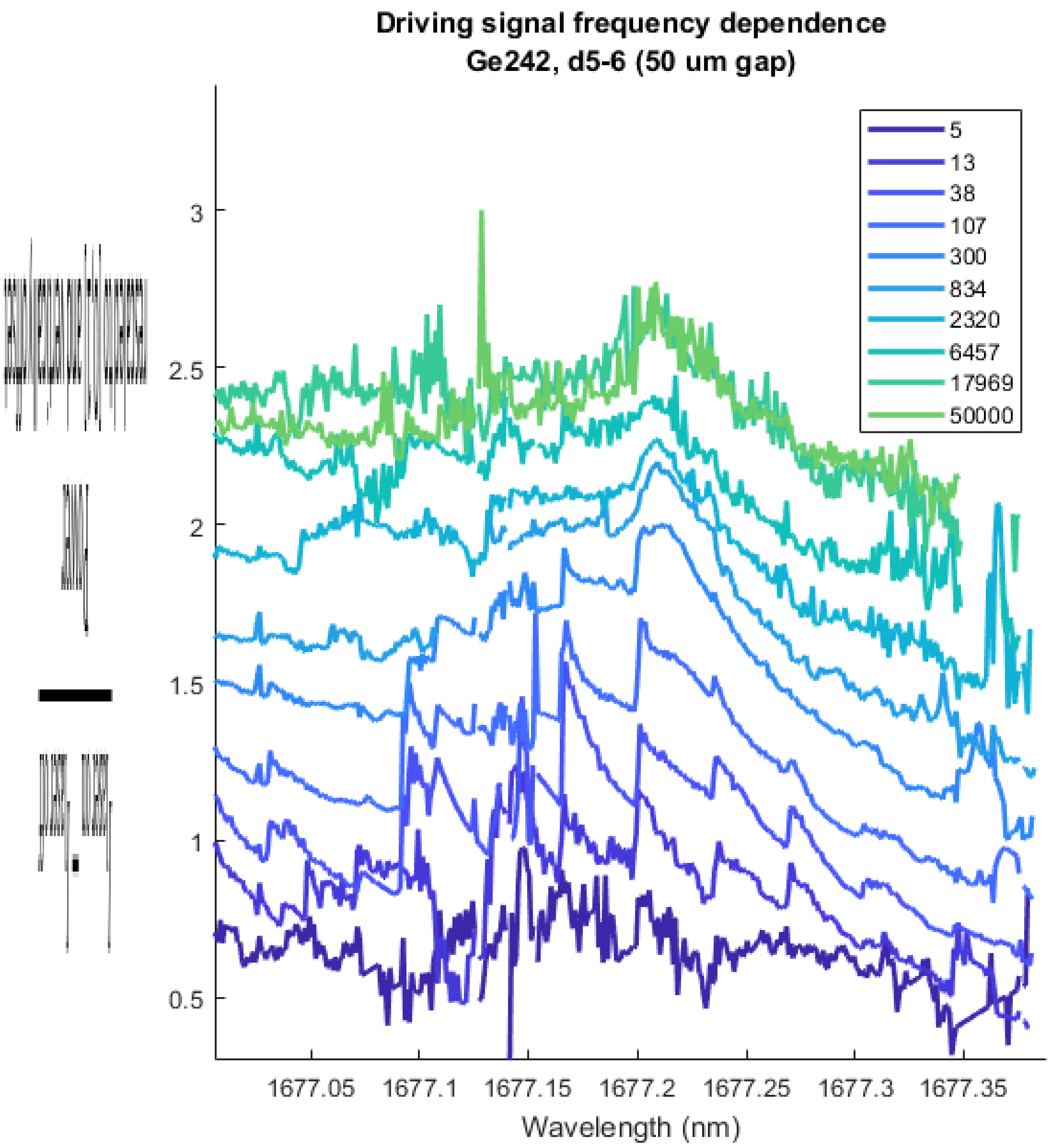


More carriers available when above-gap light neutralizes excitons





Supplementary



Driving signal frequency (Hz)