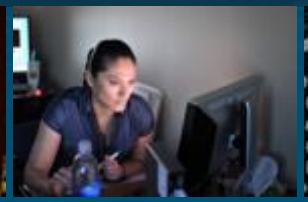
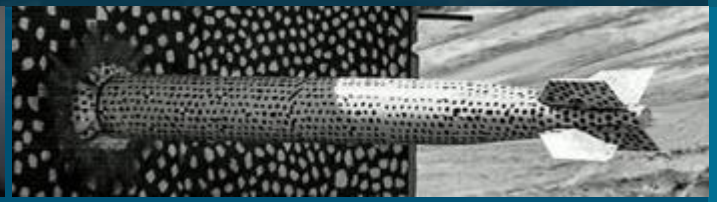
This paper describes objective technical results and analysis. Any subjective views or opinions that might be expressed in the paper do not necessarily represent the views of the U.S. Department of Energy or the United States Government.

SAND2021-3000C

Sandia National Laboratories

Measurement of the out-of-plane g-factor in strained Ge/SiGe using single-hole quantum dots





Presented by

Andrew J. Miller[1]

Mitchell Brickson[1], Will J. Hardy[1], Chia-You Liu[2], Jium-Yun Li[2], Andrew D. Baczewski[1], Michael P. Lilly[3], Tzu-Ming Lu[3], Dwight R. Luhman[1]

[1] Sandia National Laboratories

[2] National Taiwan University

[3] Sandia National Laboratories, Center for Integrated Nanotechnologies

This work was supported by the Laboratory Directed Research and Development Program at Sandia National Laboratories and was performed, in part, at the Center for Integrated Nanotechnologies, a U.S. DOE, Office of Basic Energy Sciences user facility.

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Strained-germanium/SiGe quantum dots

Several advantages of this material, compared to electron-based quantum dots:

- Large spin-orbit coupling allows for electrical control of qubits
- Atomic *p*-orbital character suppresses hyperfine induced decoherence
- Strain separates the heavy-and light-hole subbands, and the heavy-holes are expected to show a dramatic *g*-factor anisotropy between in- and out-of-plane magnetic fields

g-factor anisotropy in strained-Ge

	Theory	Ballistic holes, 1D channel[1]	Kondo effect, 2D systems[2]	Few-hole qubit[3]
In-plane	≈ 0	0.76 - 1	0.3(1)	0.2 - 0.3
Out-of-plane	21.2	10.4 - 15.0	5.5(10)	?
$g_\perp/g_\parallel$		~20	~20	?

- Calculation of $g_\perp$ using Luttinger parameters[1]

$$\kappa = 3.41, \qquad q = 0.06$$

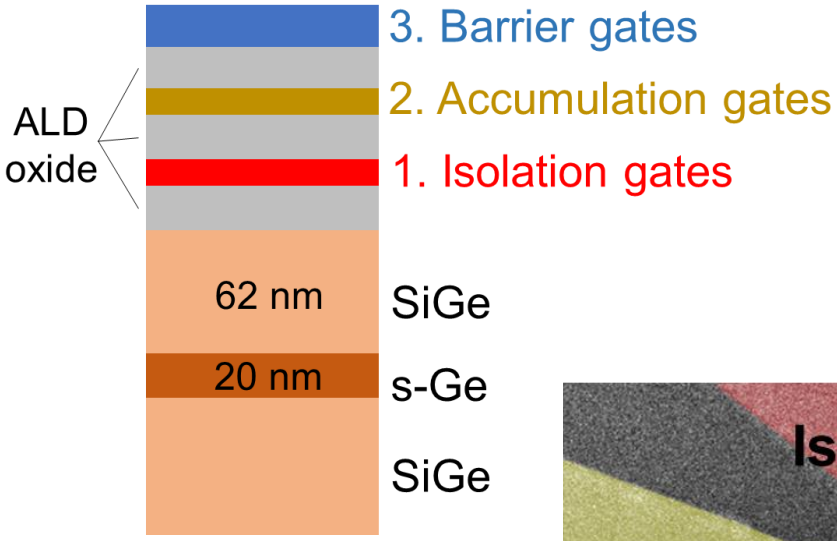
$$g_\perp = 6\kappa + \frac{27q}{2} = 21.27$$

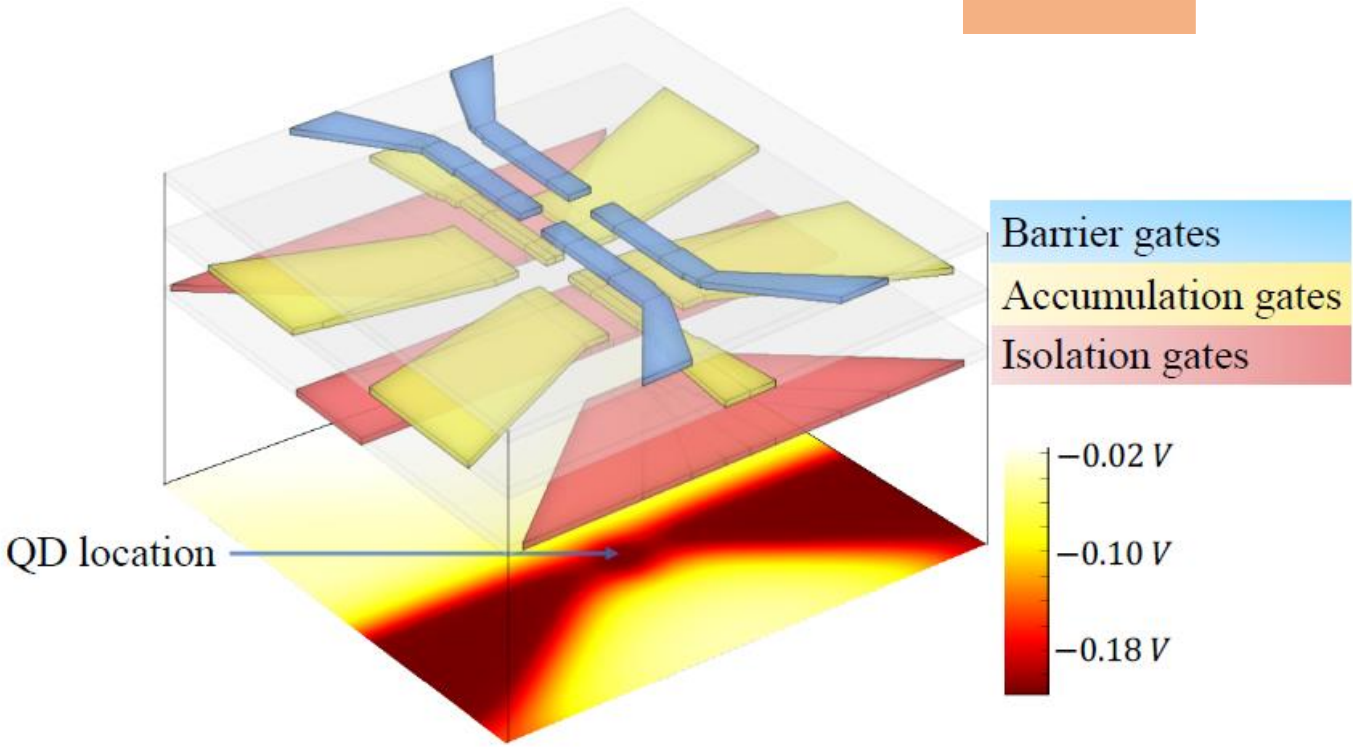
[1] R. Mizokuchi et al. Nano Letters, *18*, 4861-4865, 2018. https://doi.org/10.1021/acs.nanolett.8b01457

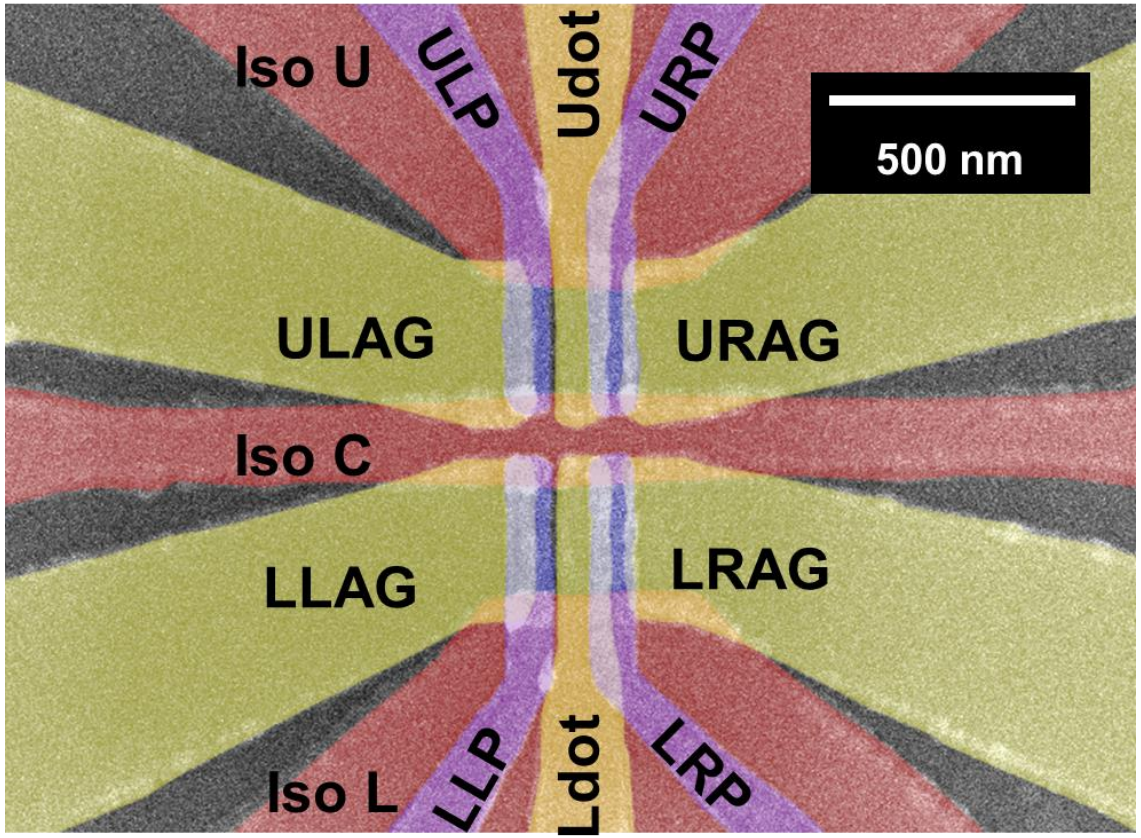
[2] A. Hofmann et al. arXiv, 1910.05841, 2019. https://arxiv.org/abs/1910.05841

[3] N.W. Hendrickx, et al. Nat. Comms. *11*, 3478, 2020. https://doi.org/10.1038/s41467-020-17211-7

Device design

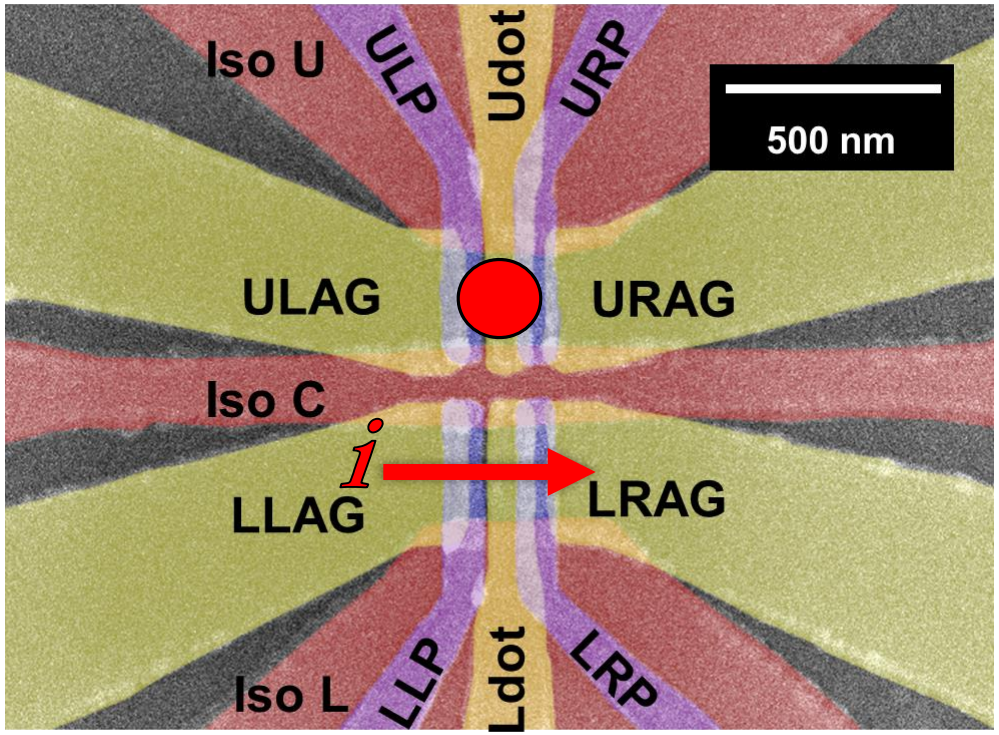


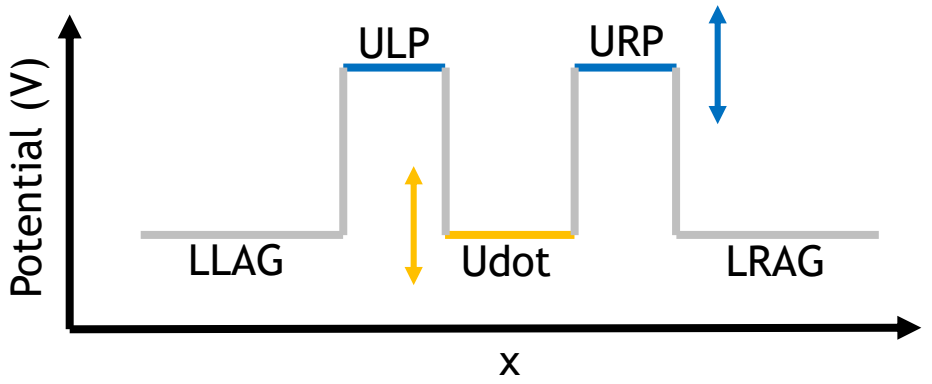


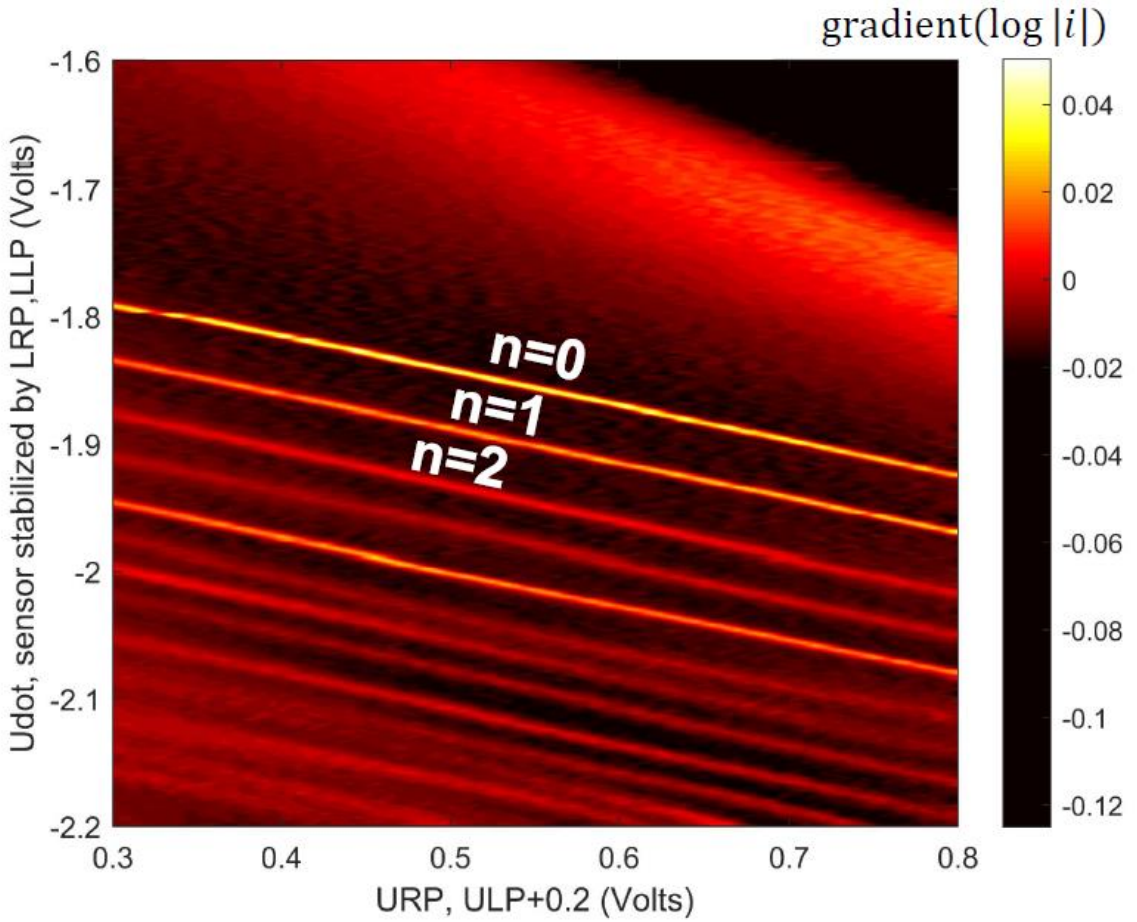


Device tuning

- Quantum dot formed in the upper channel and tuned to the single-hole regime
- Transport through lower channel is used as a charge sensor

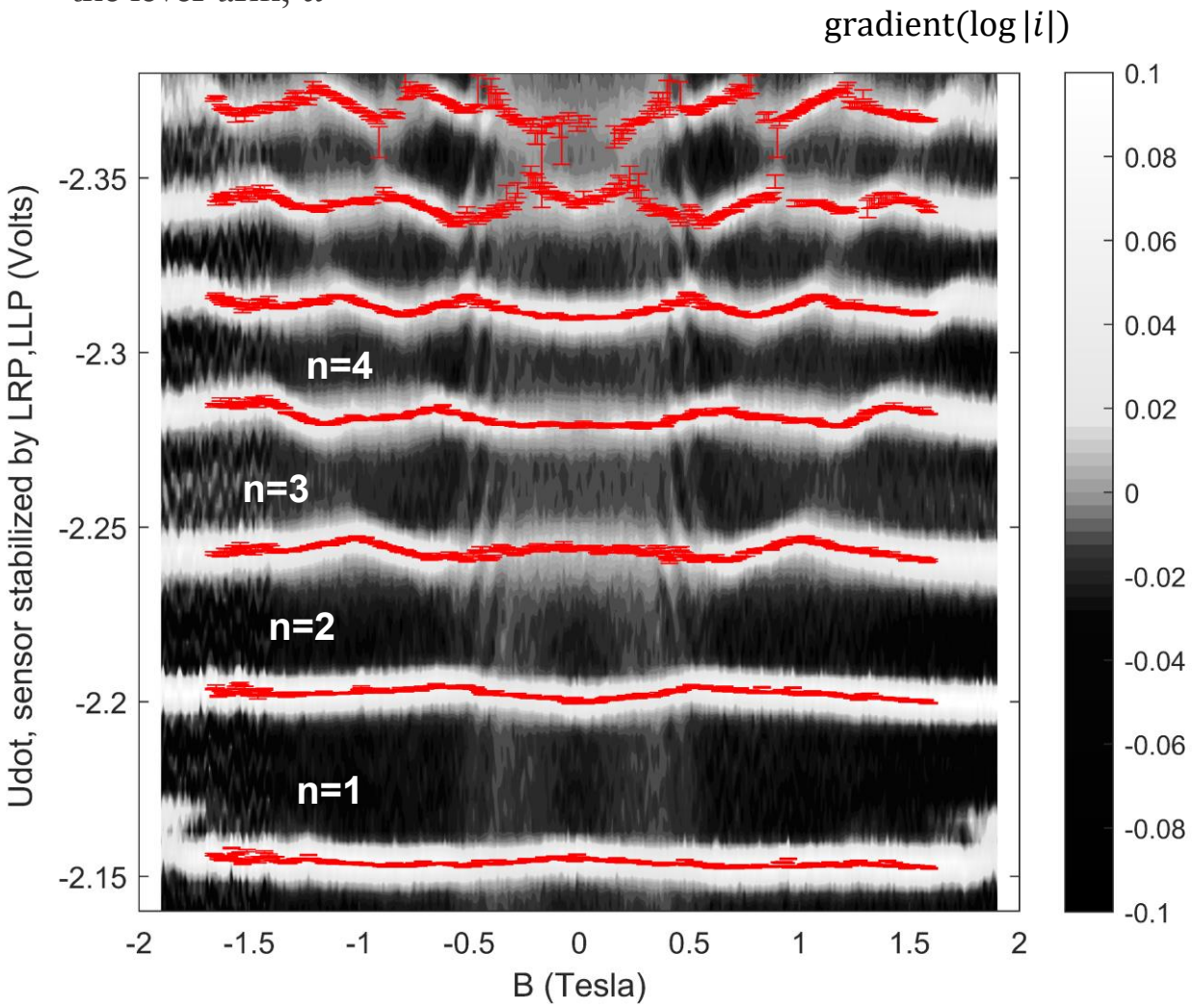


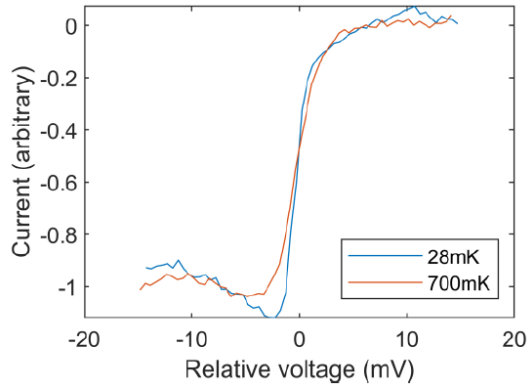




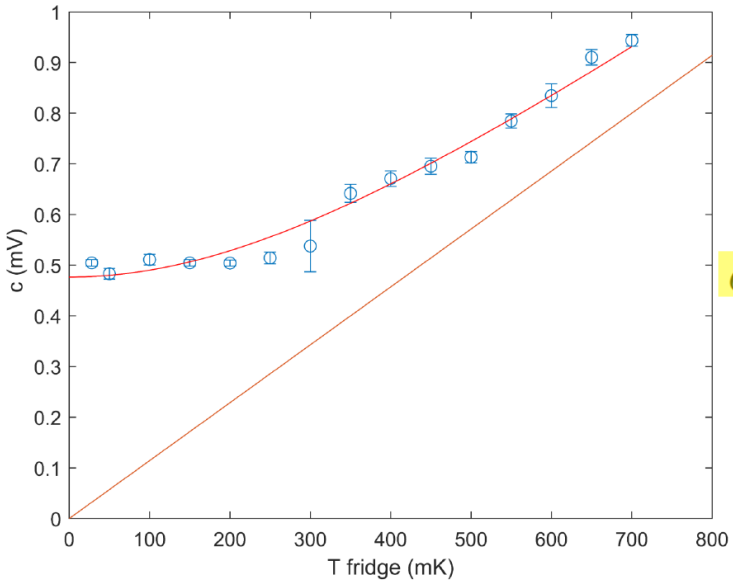
Magnetospectroscopy

- Ten scans like this one on the left were taken, charge sensing lines have been fit using gaussians shown in red
- On the right, an analysis of the thermal broadening was used to determine the base temperature of the holes, as well as the lever-arm, α





$$I = \frac{a}{(1 + \exp\left[(V - b)/c\right])} + d$$

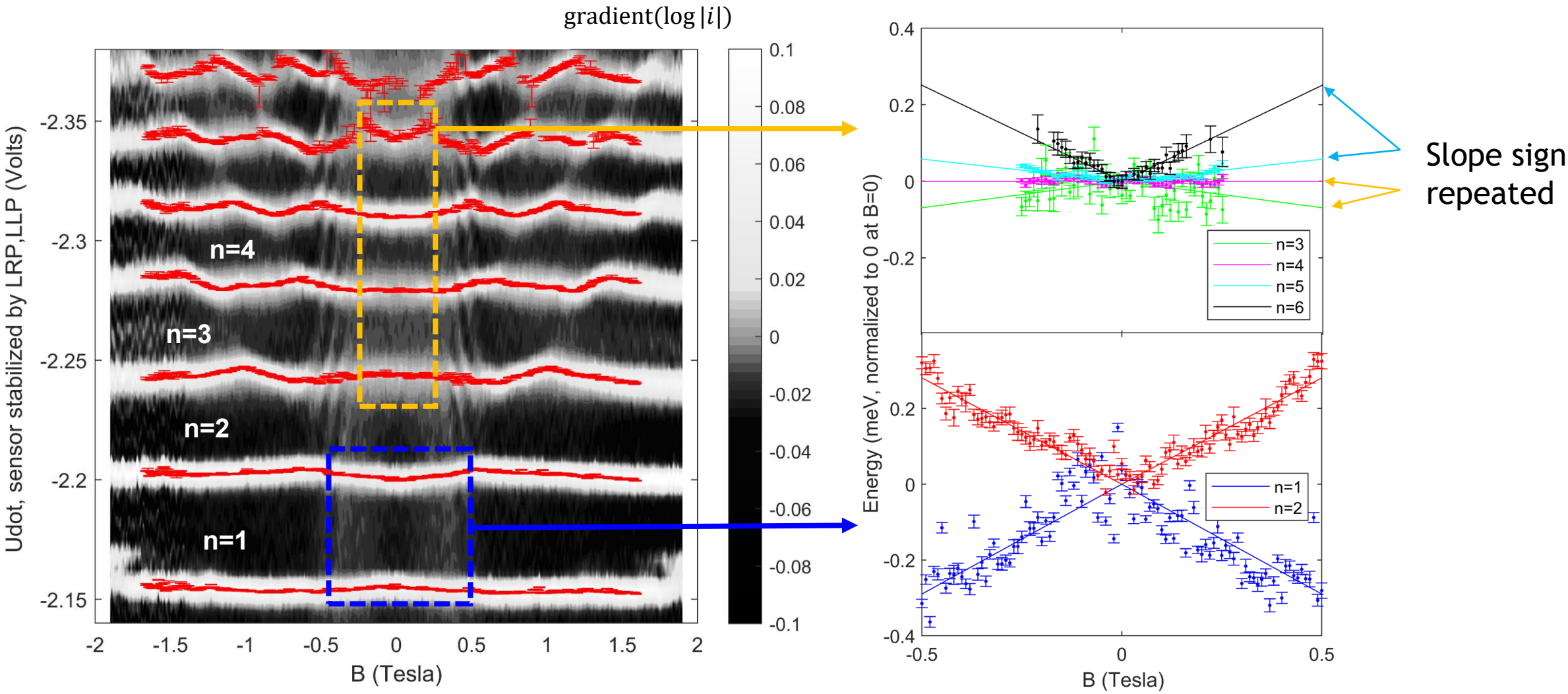


$$c = \frac{k_B}{\alpha}\sqrt{T_0^2 + T_{\text{bath}}^2}$$

$$\alpha = 75.4(35)\text{meVV}^{-1}$$

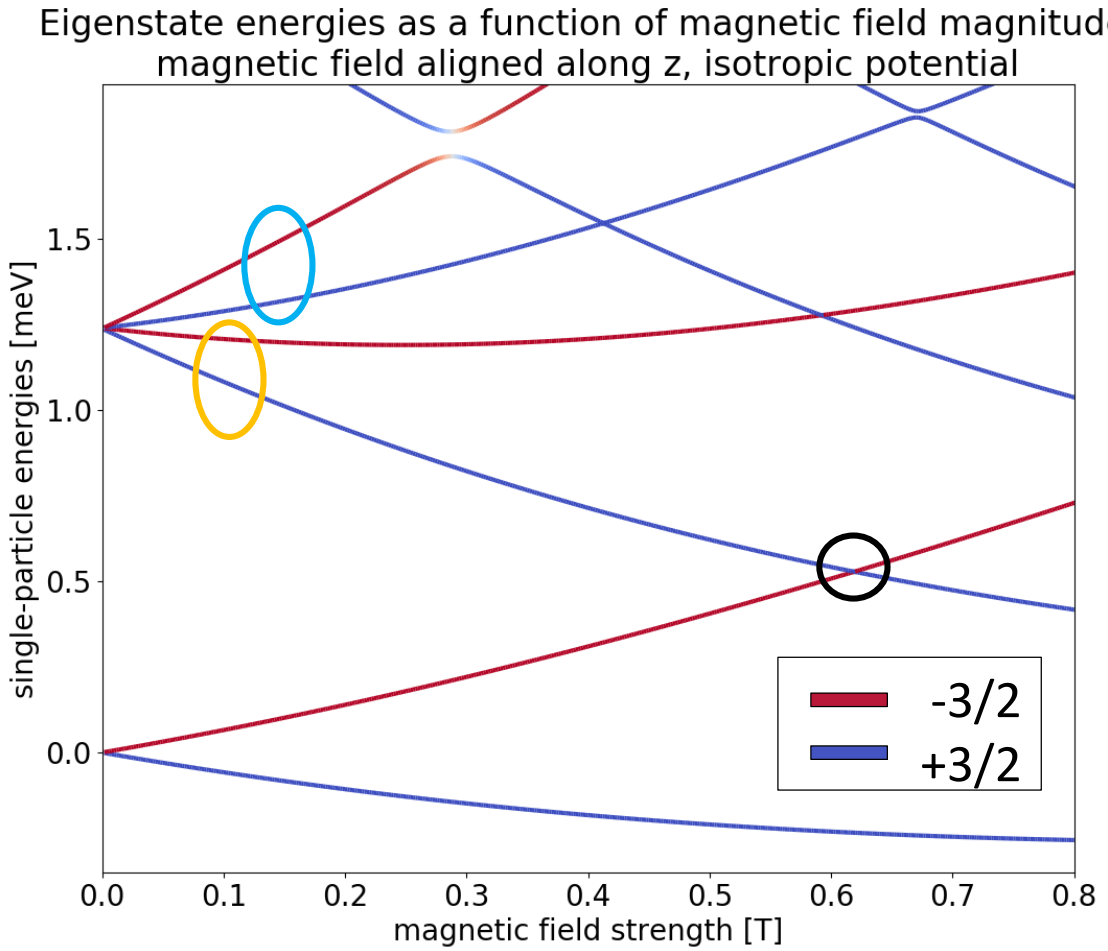
Voltage converted to energy

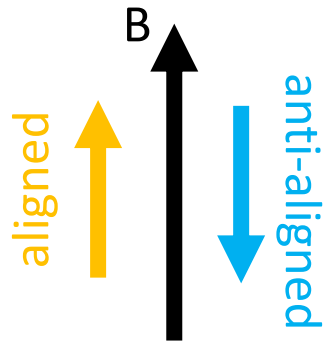
- g-factor extracted using the energy difference between the first two states, $\Delta E = g\mu_B B$



Simulation

- Single-particle states
- Luttinger Hamiltonian eigenstates were derived numerically from a COMSOL-generated potential



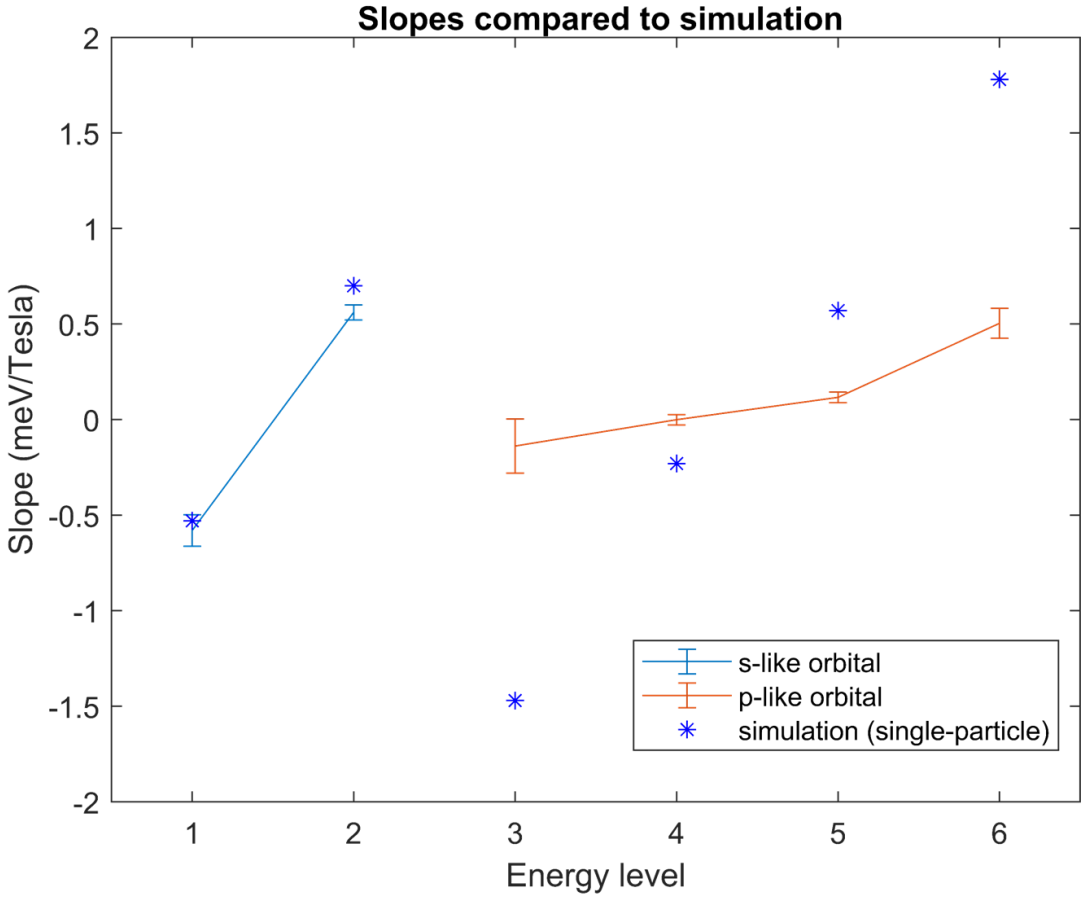


Orbital angular momentum outweighs spin alignment

- For comparison with experiment, the potential was scaled in x and y, to match this anti-crossing seen near $B = 0.6\mathrm{T}$
- Slopes of these single-particle states were averaged over the same fit range used in the magnetospectroscopy data

Results

- Great agreement in the s-like orbital
- Signs and trend of magnitudes are reproduced in the p-like orbitals
- Complex behaviors likely require inclusion of hole-hole interactions to more accurately reproduce



	Simulation	Experiment
In-plane	0	0.3^2
Out-of-plane	21.25	15.7(22)

$$g_{\perp}/g_{\parallel} = 52$$

[1] A.V. Nenashev et al. Phys. Rev. B, 67, 205301, 2003. https://doi.org/10.1103/PhysRevB.67.205301

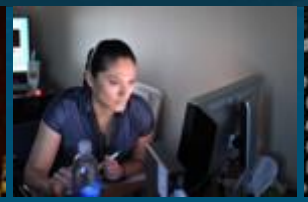
[2] N.W. Hendrickx, et al. Nat. Comms. *11*, 3478, 2020. https://doi.org/10.1038/s41467-020-17211-7

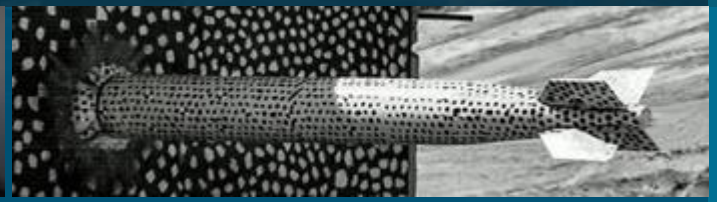
Discussion and Future outlook

- Measurements in the single-hole regime avoid the complex orbital effects
- We see a large *g*-factor asymmetry in agreement with theory
- The complex behavior in higher orbitals allows for dramatic tunability, through both the occupation of the dot, and the *B*-field strength
- Understanding the difference between the single- and multi-hole regime can inform the design of future qubit experiments in this material
- Results are currently on the arXiv, being submitted for publication

Effective out-of-plane g-factor in strained-Ge/SiGe quantum dots
A.J. Miller et al. arXiv, 2102.01758, 2021.
https://arxiv.org/abs/2102.01758v1

Thank you for your time!





Presented by

Andrew J. Miller[1]

Mitchell Brickson[1], Will J. Hardy[1], Chia-You Liu[2], Jium-Yun Li[2], Andrew D. Baczewski[1], Michael P. Lilly[3], Tzu-Ming Lu[3], Dwight R. Luhman[1]

[1] Sandia National Laboratories

[2] National Taiwan University

[3] Sandia National Laboratories, Center for Integrated Nanotechnologies

This work was supported by the Laboratory Directed Research and Development Program at Sandia National Laboratories and was performed, in part, at the Center for Integrated Nanotechnologies, a U.S. DOE, Office of Basic Energy Sciences user facility.

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Results from all scans