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Transport and electrically detected magnetic resonance measurements of few donor semiconductor nanostructures

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[4] Department of Materials, Oxford University

1. **Coherence of donor electron spins at interfaces**

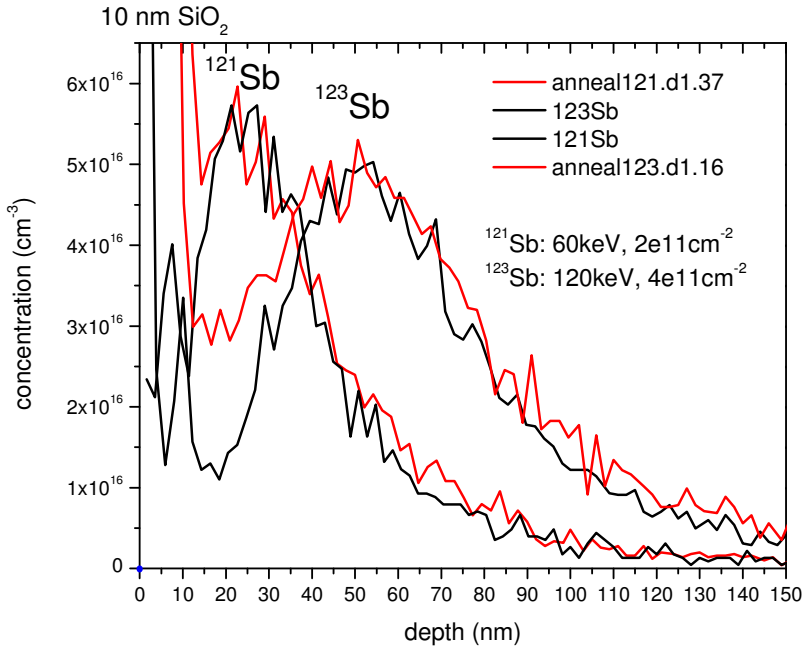
2. **Electrical detection of magnetic resonance of donor electron spins in micron scale transistors**

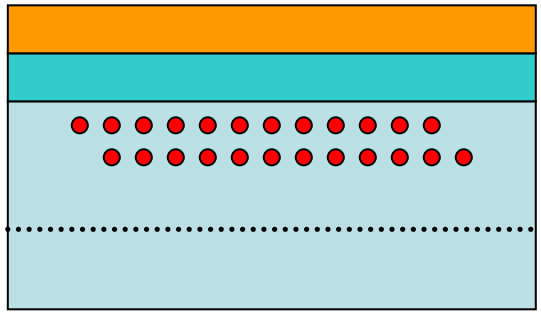
3. **Transport spectroscopy of 50 nm scale FinFets**

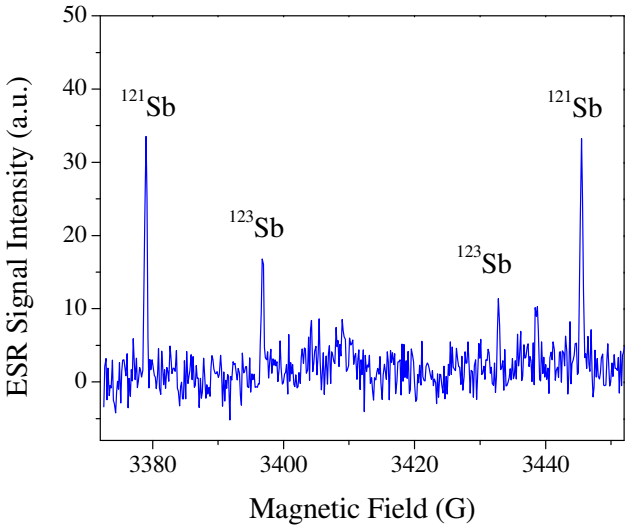
What limits T_2 of integrated donors ?

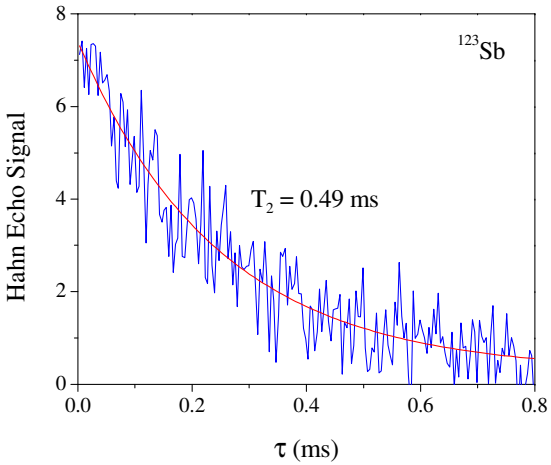
EPR Spectrum at 5.2 K - two implants ^{121}Sb and ^{123}Sb

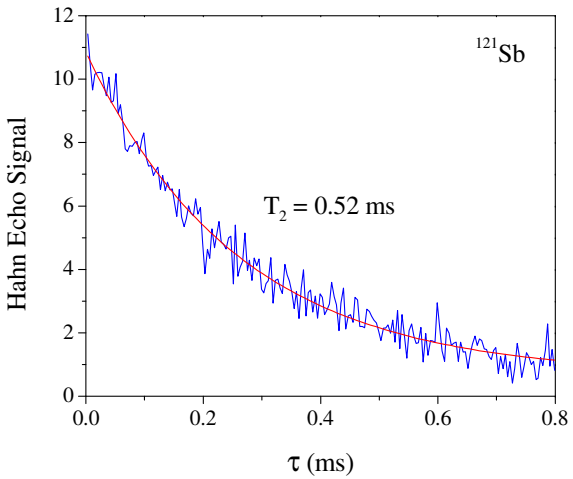
A. Tyryshkin, S. Lyon, M. Carroll, T. Schenkel, et al.











What limits T_2 of integrated donors ?

- isolated donors in 28-Si: quite long
  - Lyon/Tyryshkin 2010
- donors at interfaces: ~ 0.3 to 2 ms
  - Schenkel/Lyon et al., Appl.Phys.Lett. '06
- donors during device operation
  - during EDMR in transistors: T_1~100 ns (C. C. Lo, et al., Appl. Phys. Lett. '07)

- **what are the coherence limiting noise sources for integrated donors ?**

- **ways to preserve coherence for integrated donors ?**
  - →clever control pulses
  - →better oxides (~D_{it}~10^{10} /cm^2 eV)
    - → effect of re-oxidation post implant ?
  - → forming gas effects ? H_2 vs. D_2?
  - → noise spectrum H-Si vs. SiO_2/Si ?
  - → epitaxial cap layers (SiGe-Si, …) ?
  - → optimal electrical gating ?

interface	peak dopant depth (nm)	T_2 (ms, 5.2 K)
SiO_2 (Sandia) (no re-ox anneal)	25	0.52
H-Si	25	-
SiO_2 (Sandia)	50	0.49
H-Si	50	-
SiO_2 (Berkeley)	50	0.3
H-Si	50	0.75
SiO_2 (Berkeley)	150	1.5
H-Si	150	2.1

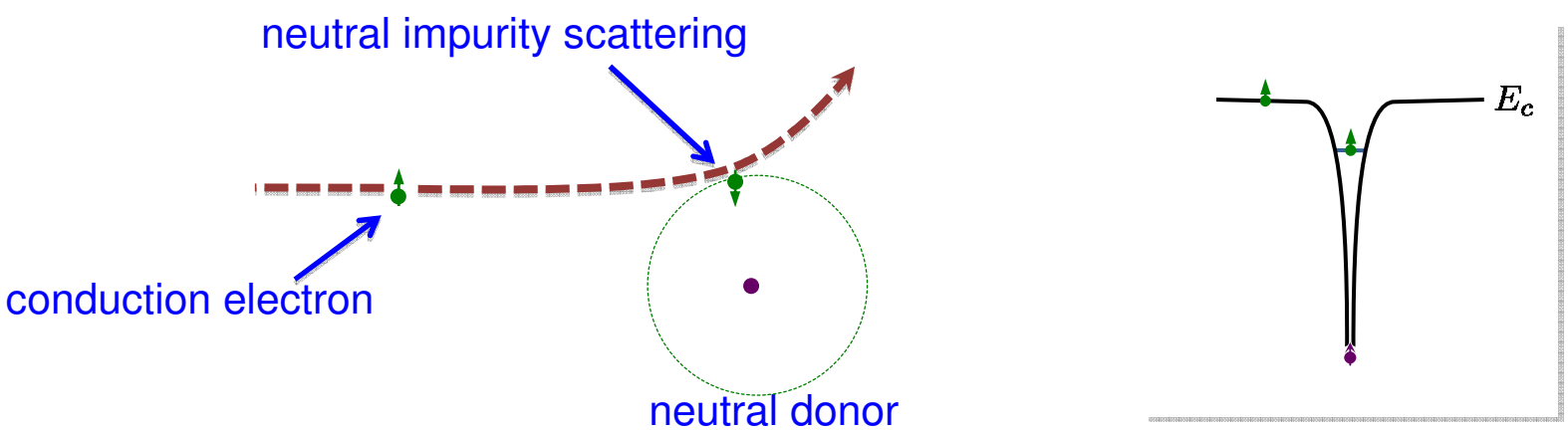
1. Coherence of donor electron spins at interfaces

2. **Electrical detection of magnetic resonance of donor electron spins in micron scale transistors**

3. Transport spectroscopy of 50 nm scale FinFets

Spin Readout Mechanism

- Single nuclear spin-state detection for donor qubits by spin-dependent neutral impurity scattering[1]:



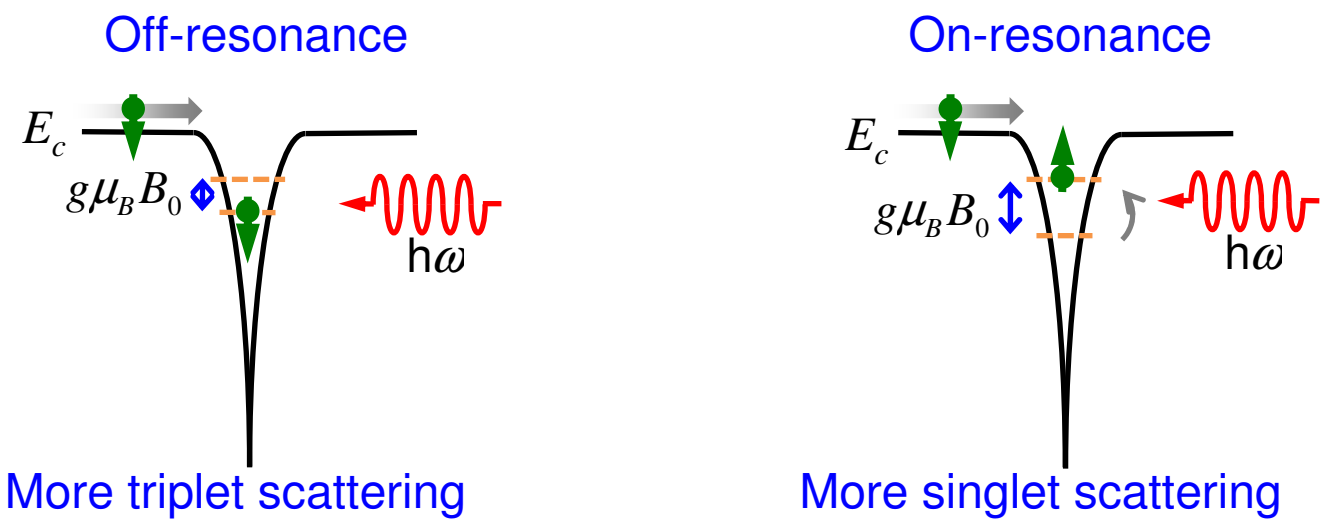
- start with measurement of micron scale devices with ~10^{4}-10^{6} donors[2] and scale to 50 nm scale single donor devices

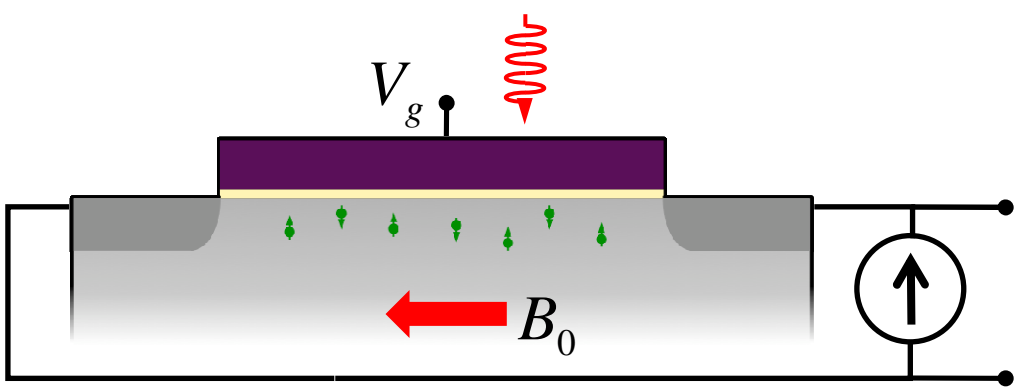
[1]Sarovar et al., PRB, 78, 245302 (2008)

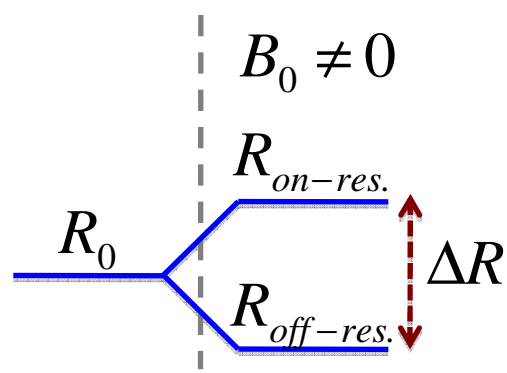
[2]Lo et al., APL, 91, 242106 (2007)

Electrical detection of spin-dependent scattering

- Electrically Detected Magnetic Resonance:

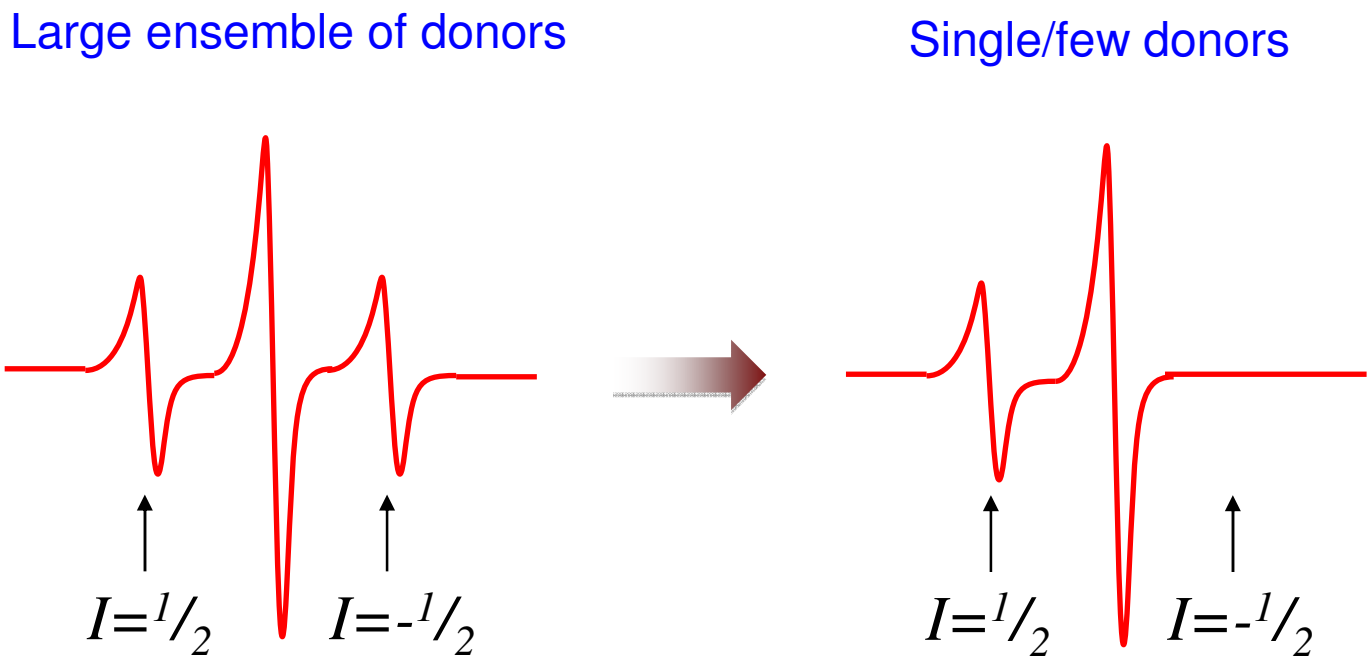






Towards single nuclear spin readout

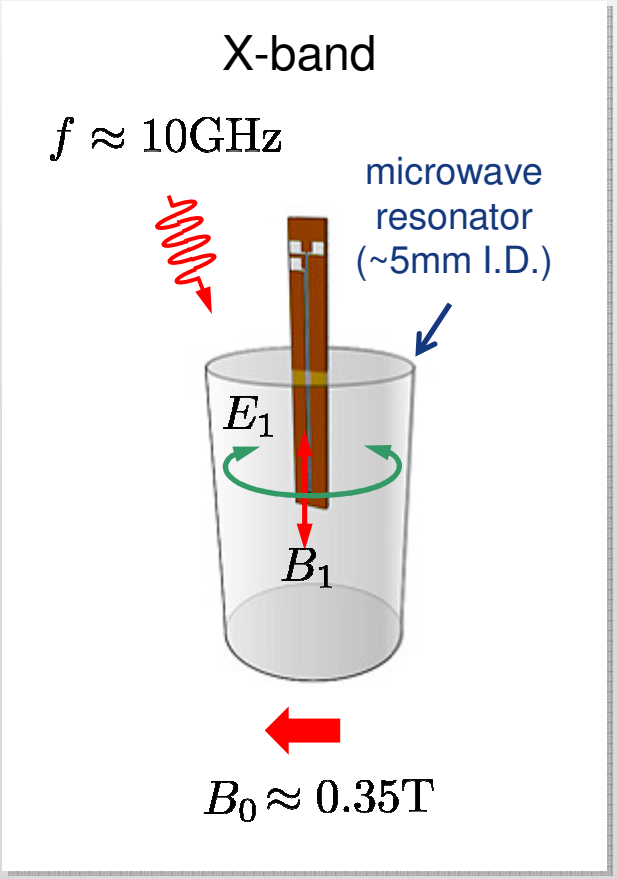
- Nuclear spin-state readout by spin-dependent scattering:

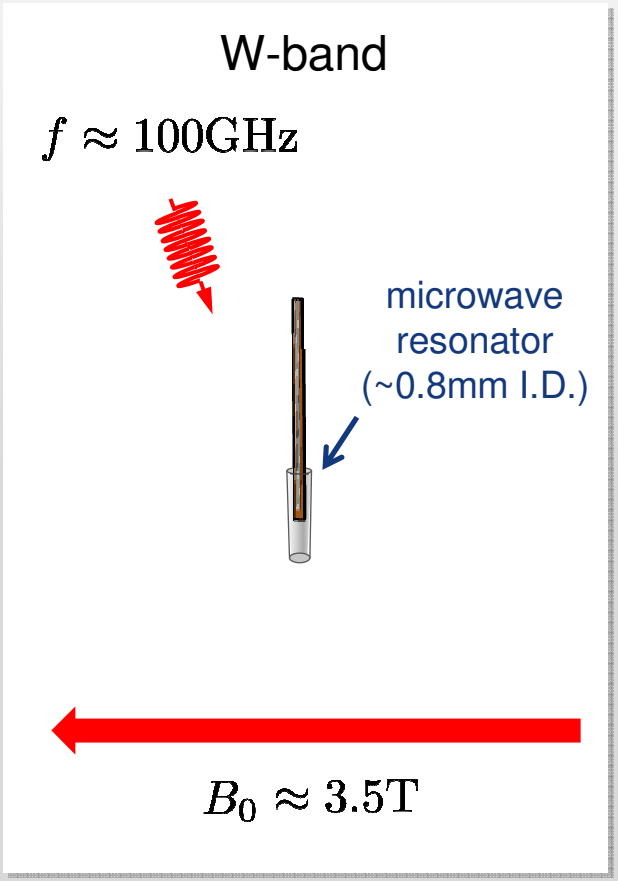


•Sarovar et al., PRB, 78, 245302 (2008)
•nuclear spin memory and electron to nuclear spin quantum information transfer: J. Morton, et al., Nature 455, 1085 (2008)

Electrically Detected Magnetic Resonance

- Device mounted in a Electron Spin Resonance (ESR) microwave resonator





Lo et al., APL, 91, 242106 (2007)

EDMR at 100 GHz with w-band cavity

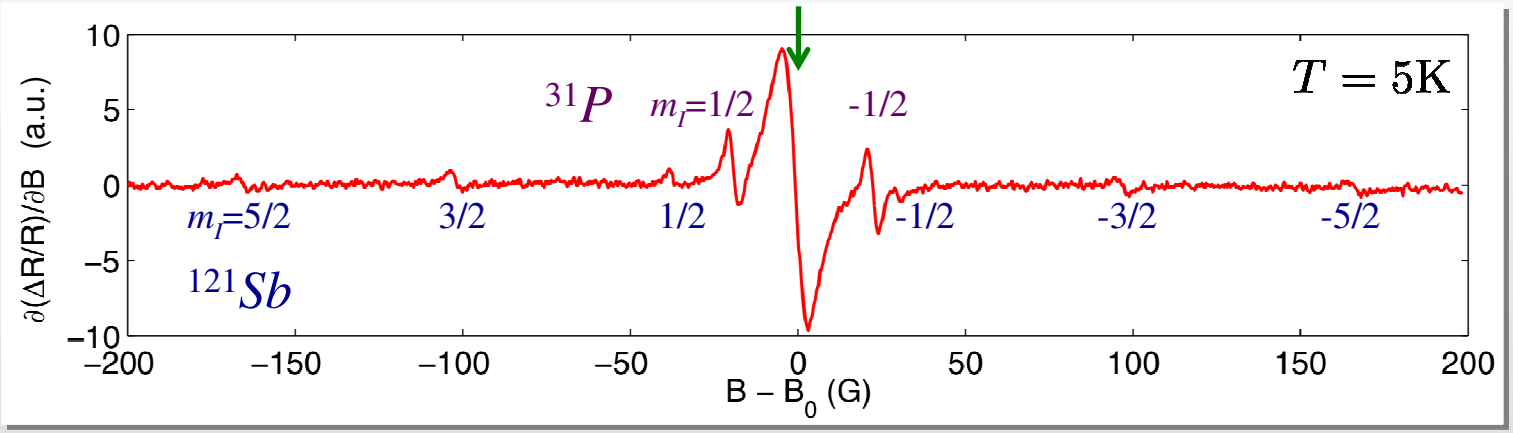
measurements co. John Morton, Volker Lang, et al., Oxford University

- found dR/R<0, resistivity decreases on resonance (found also at x-band)
  - dV=0.4 mV , DC voltage measurement
  - conflict with earlier models of spin dependent transport, analysis in progress
- observed temperature dependence of EDMR signal rules out bolometric contributions
- determined magnetic field scaling of dR/R, found approx. linear scaling for donors and quadratic scaling for 2DEG electrons

EDMR spectra at 10 and 100 GHz

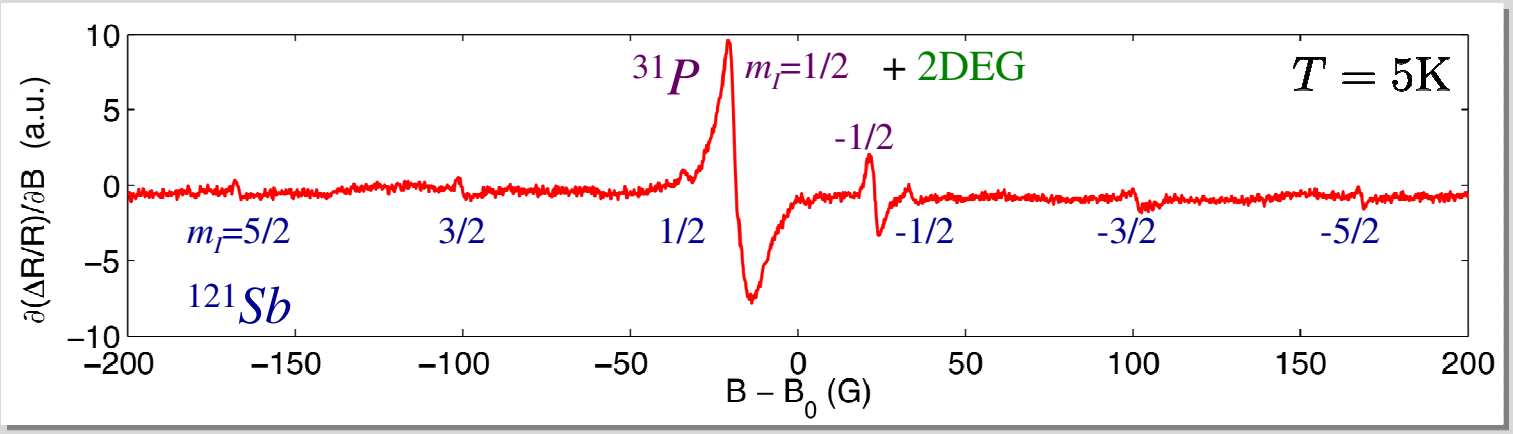
- X-band

$f = 9.7\mathrm{GHz}$ $B_0 = 3458\mathrm{G} = 0.3458\mathrm{T}$

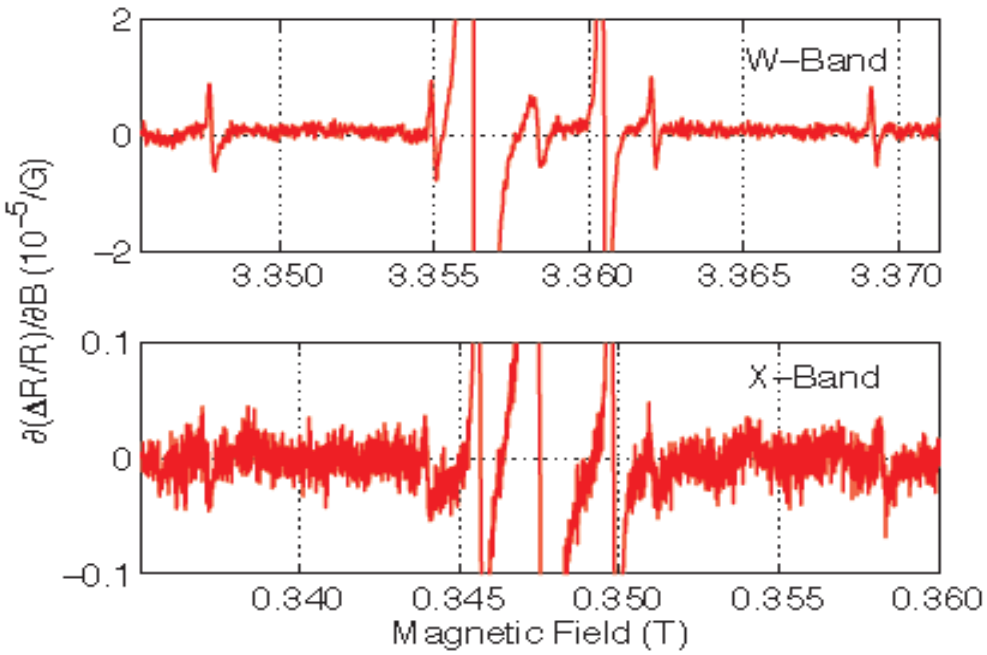


- W-band

$f = 94\mathrm{GHz}$ $B_0 = 33552\mathrm{G} = 3.3552\mathrm{T}$



Scaling of spin readout signals with magnetic field
x-band: 0.3 T → w-band: 3 T



- expected resonant current changes to scale ~B^2, due to 2DEG polarization ~B and rapid exchange of spin polarization between 2DEG and donor electrons
- found ~B^2 scaling for 2DEG signal and ~B scaling for donor signal

peak ratios after fitting:

2DEG	125
P line	26
As line	21

Device Details

- 160µm long triple-gate device
  - 1um thick 28-Si epi layer
  - All gates have been shorted together for this set of experiments.
- channel dopants
  - ^{31}P and ^{75}As (center 40µm region only)

Measurement Details

- all measurements were taken with in-plane B-field only.
- all measurements were taken with a modulation amplitude of 2G and modulation frequency of 5k or 5.02k Hz.

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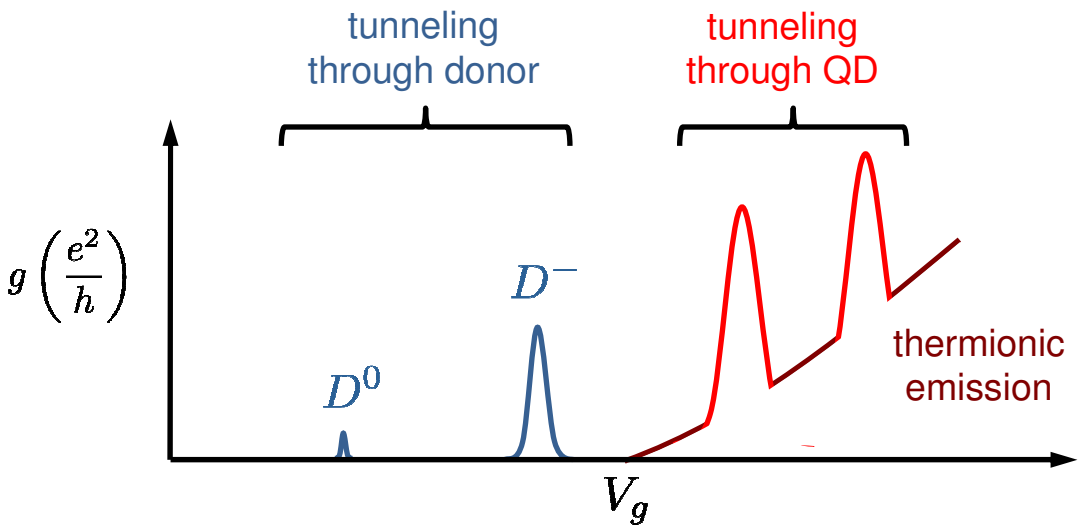
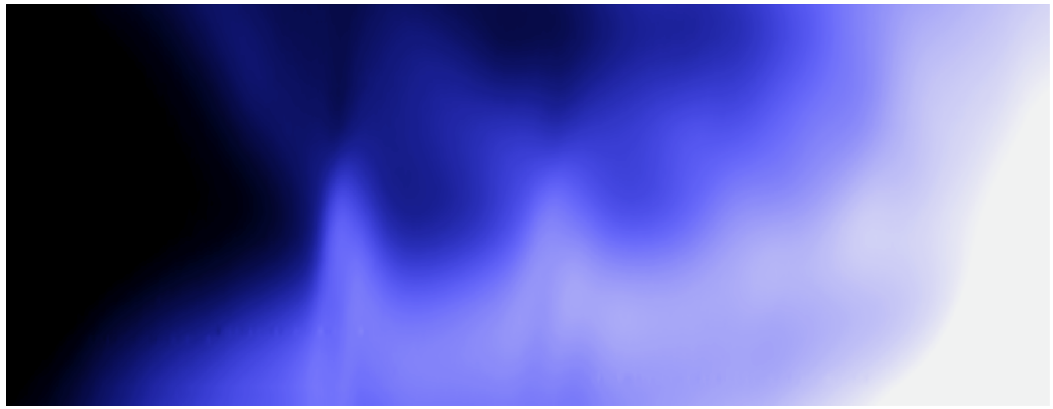
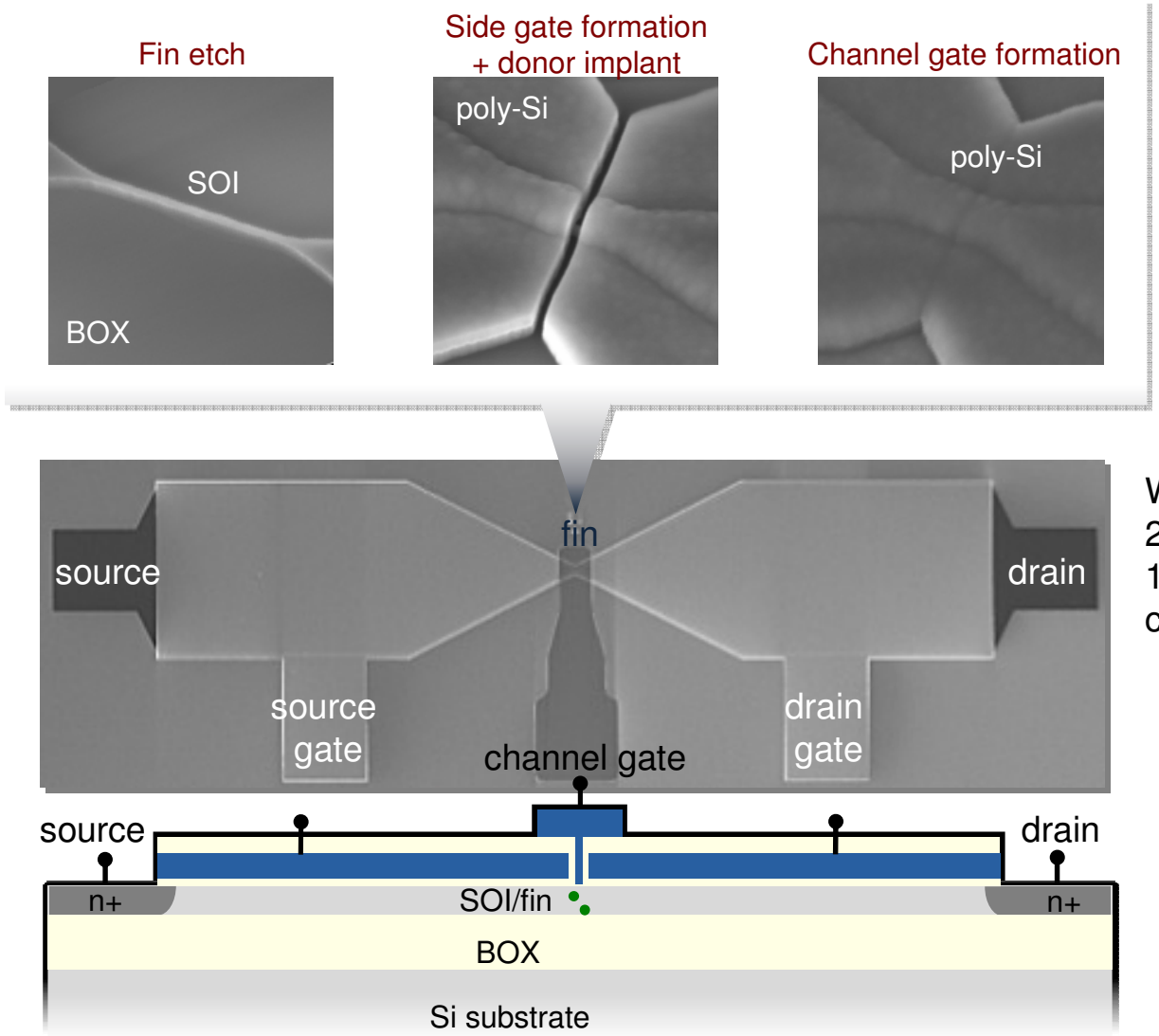
3. Transport spectroscopy of 50 nm scale FinFets

Transport spectroscopy of few donor FinFets





triple-gate FinFETs

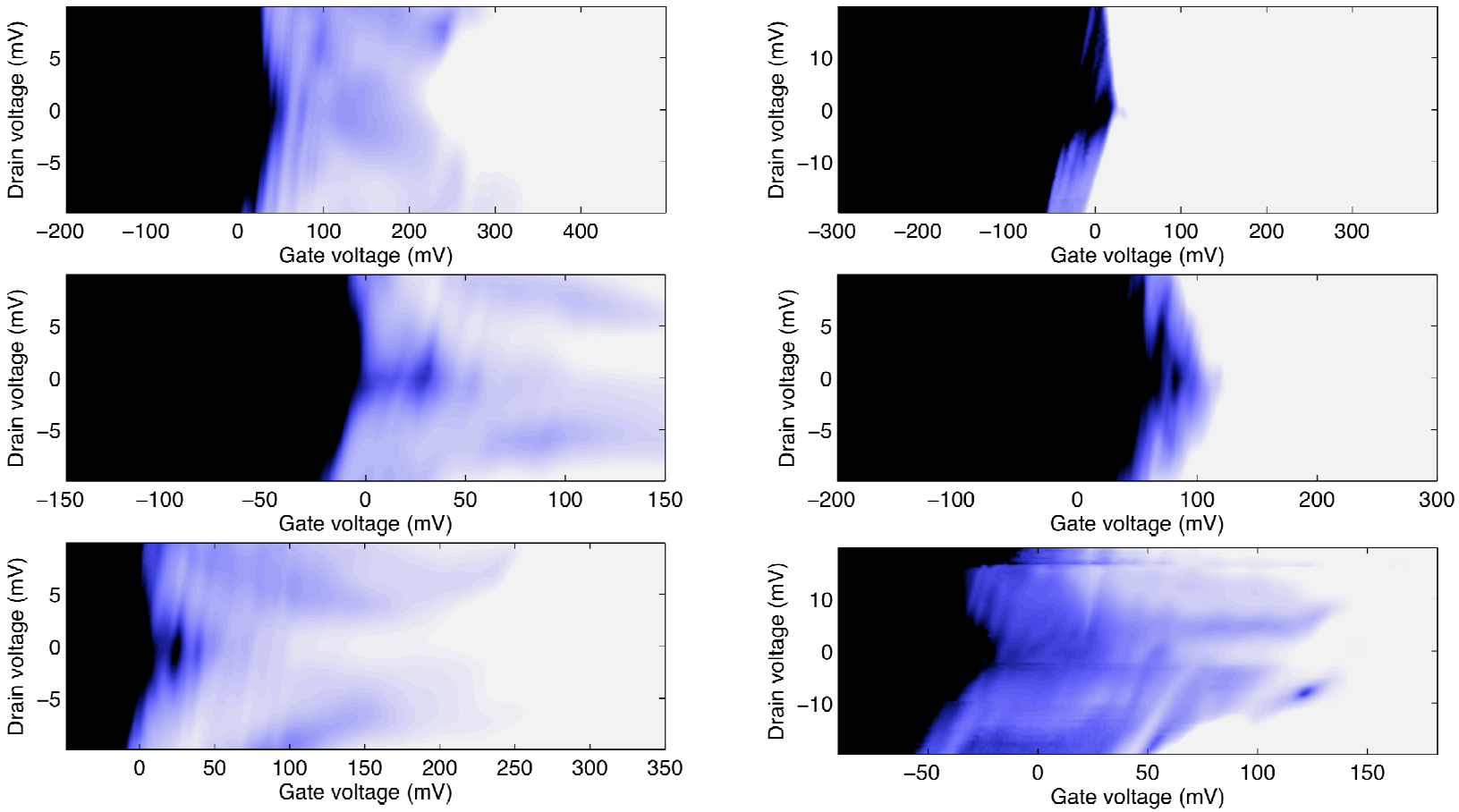


Width / Length: 50 to 200 nm
10 to 100 donors in channels

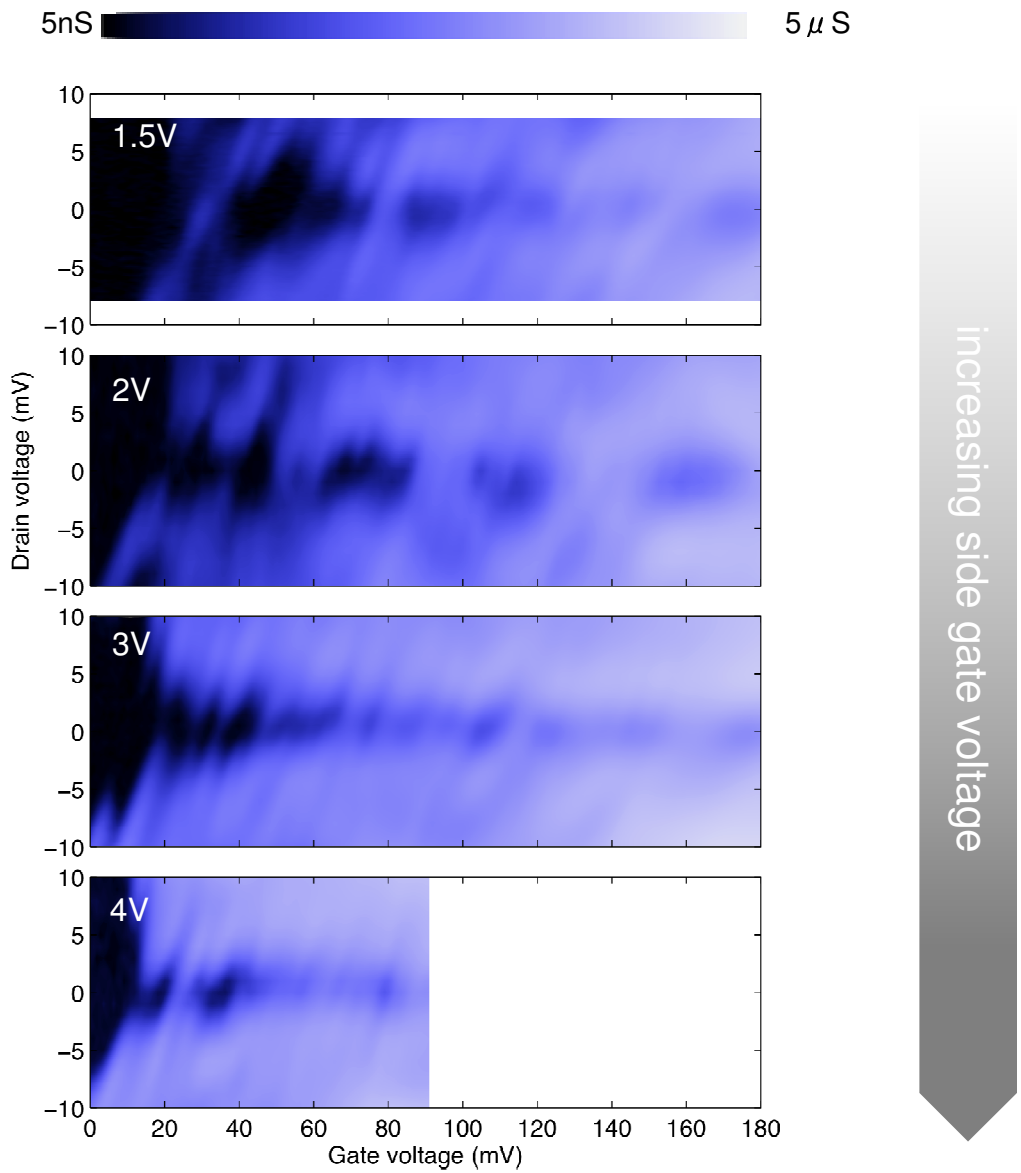
side gates for:
1.Spin-equilibration in leads for EDMR measurements
2.Prevention of accidental channel doping from n+ source/drain regions

Transport measurements in liquid helium (4.2K)

- Measured 10+ devices at 4.2K
  - Most show some oscillations/blockade-like structure at turn-on, then conductivity increases rapidly



Side gate effect: Squeezing the quantum dot



$$T = 300 - 450\text{mK}$$

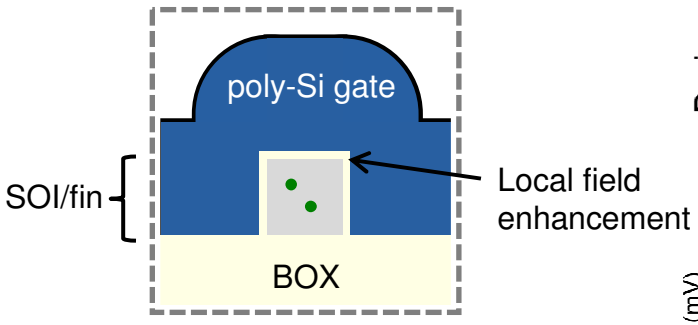
$$l_l = 76\text{nm}, w_l = 70\text{nm}$$

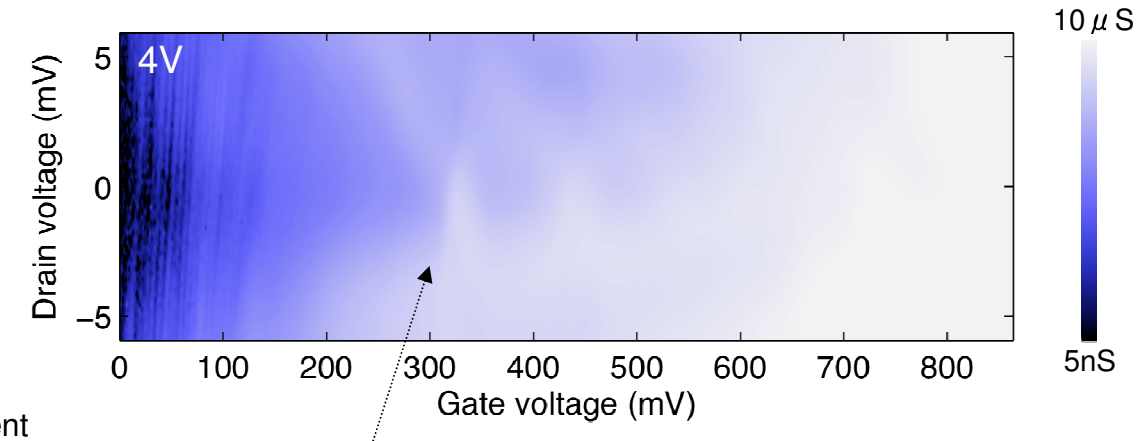
- Coulomb diamonds due to electron confinement in the Fin

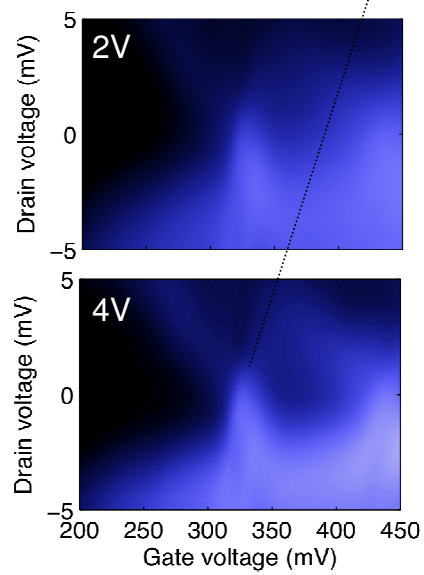
Evidence for transport through single donor atoms (4.2K)

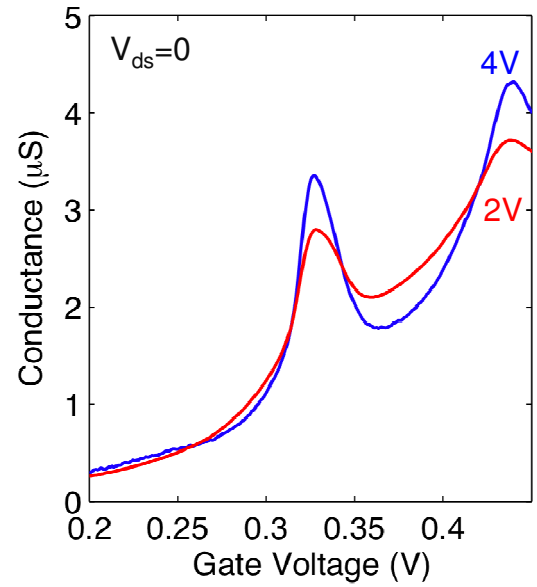
- several devices show strong resonance peaks *after* turn-on:

- Corner effects in FinFETs





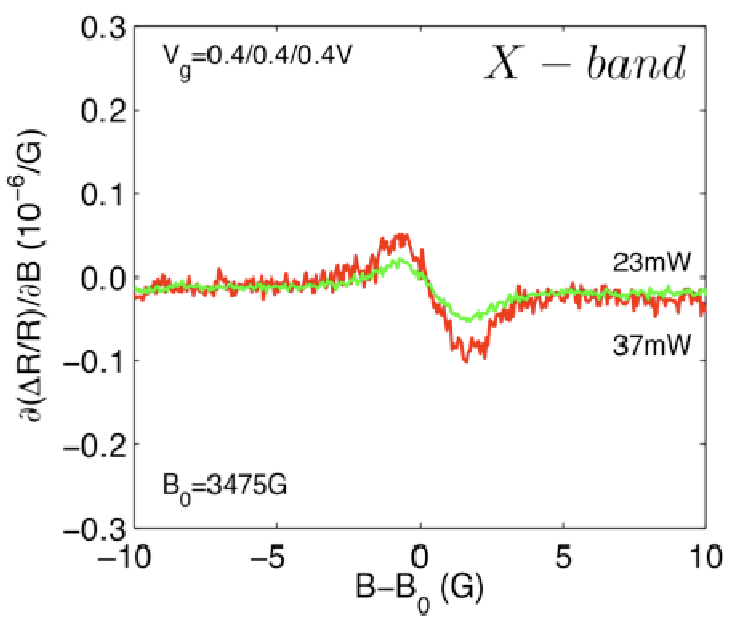


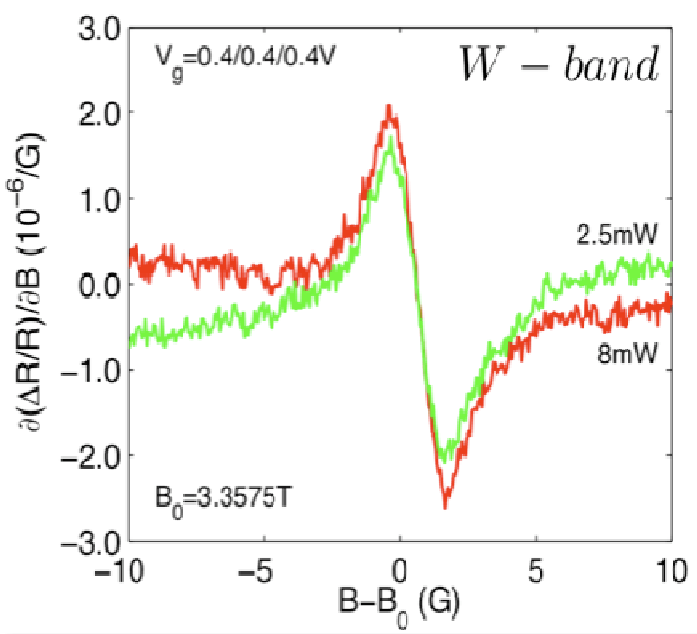


$$l_l = 76\text{nm}, w_l = 50\text{nm}$$

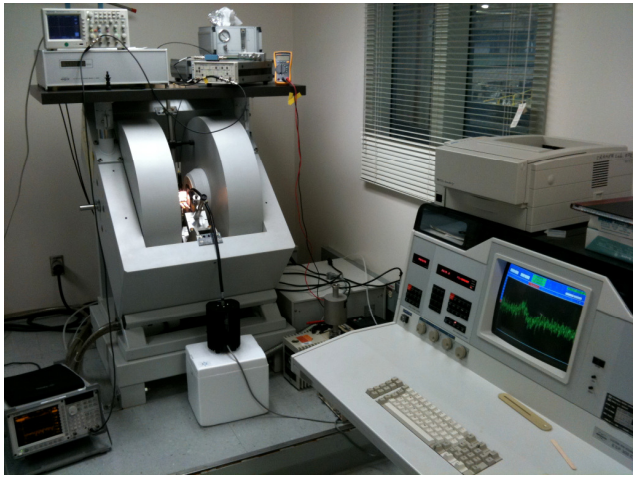
Initial EDMR attempts with FinFets

- EDMR with triple-gate FinFETs
  - Only observed 2DEG signal (likely from side gates)

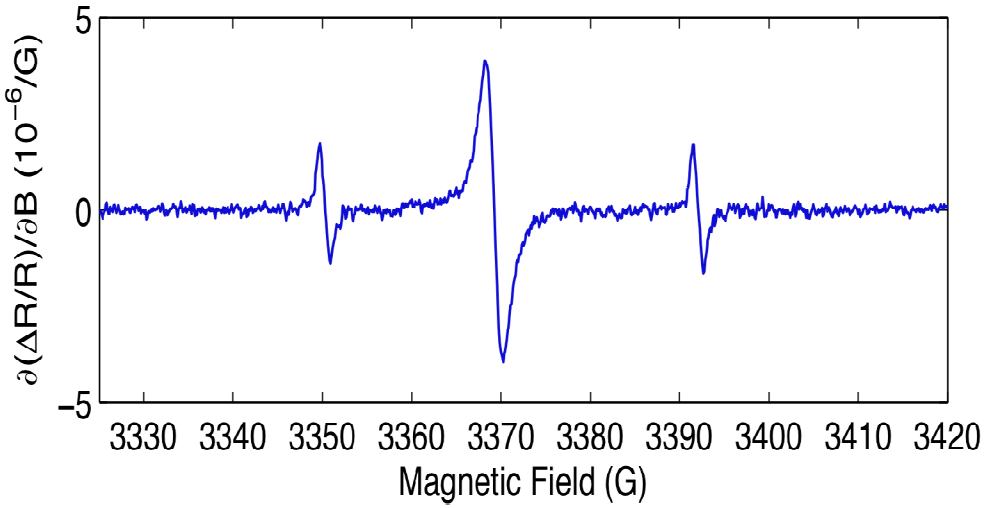


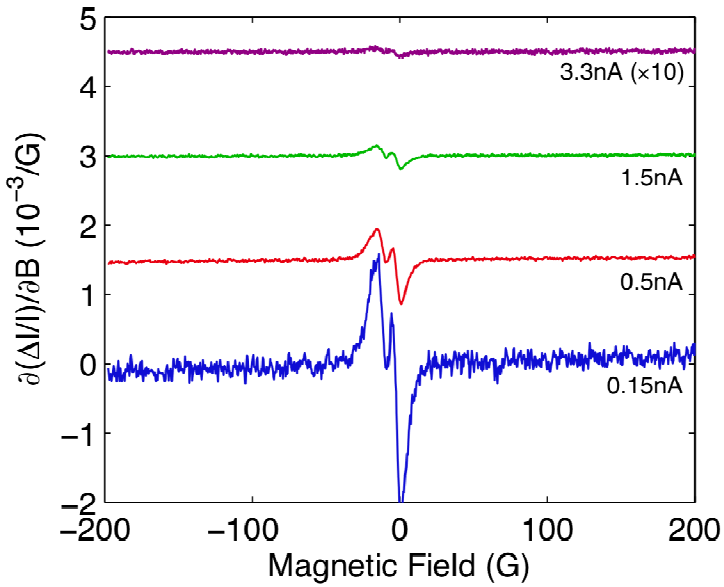


EDMR with Bruker ESP300E at LBNL



- have set up a cw x-band ESR / EDMR capability at LBNL for basic testing, optimization and device screening
- pulsed and low temperature measurements at Princeton

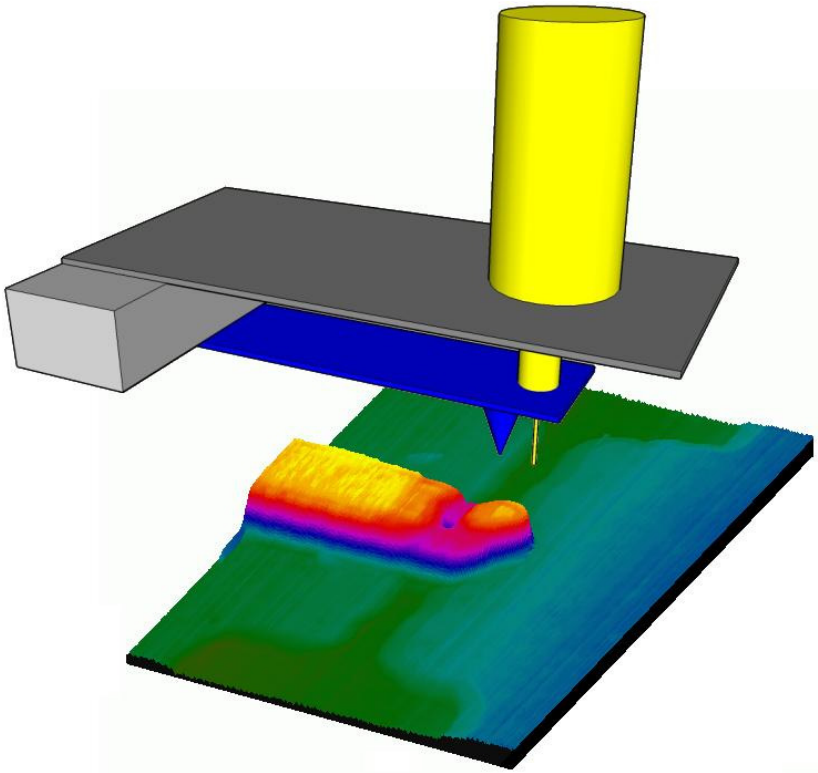




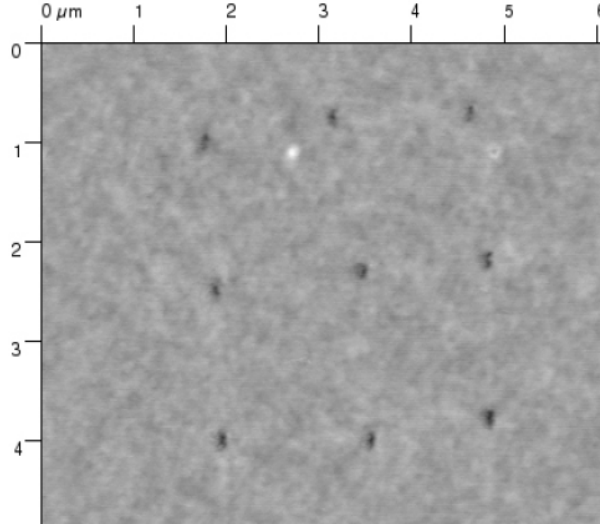
- aFET6-28Si1-327 (160x × 0 μ m^2)
- 3 × 10^{16}/cm3 ^{31}P in 1 μ m ^{28}Si epi layer

- FR308, 200nm × 300nm
- SDR, with illumination, no Sb donor signal detected - yet

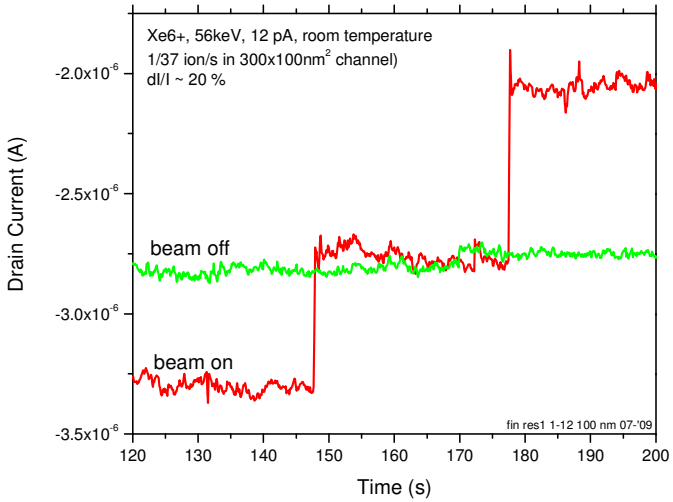
Single Ion Implantation with Scanning Probe Alignment



A. Persaud, et al., Nano Letters 5, 1087 (2005)

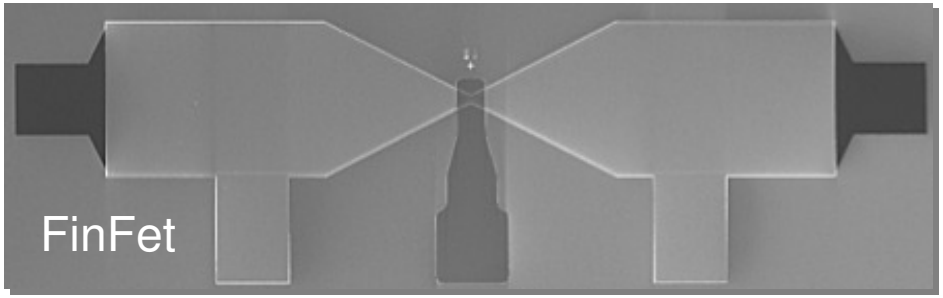


array of 90 nm dots in PMMA from ion implantation with scanning probe alignment

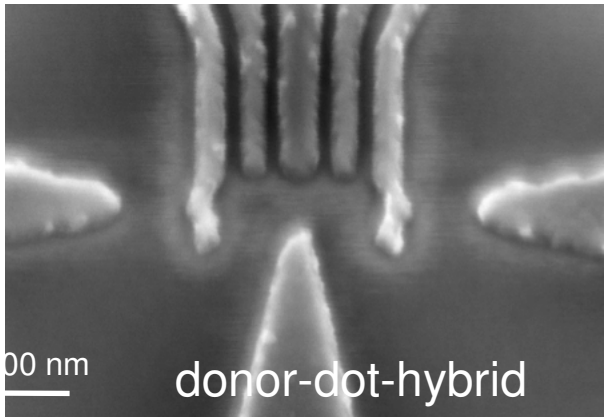


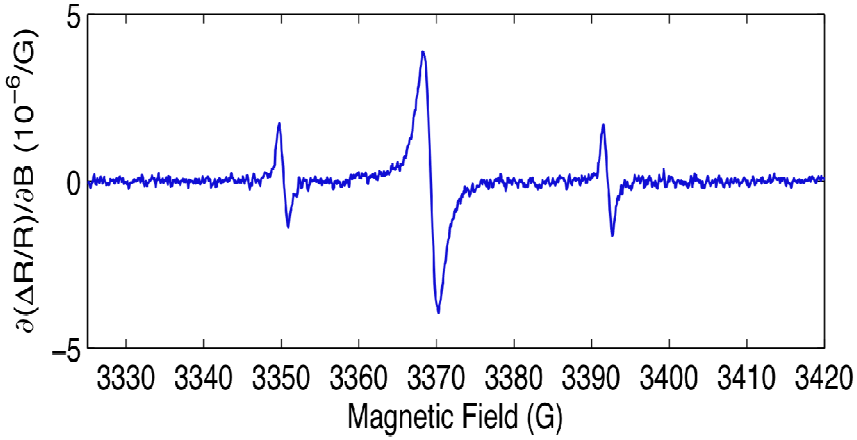
Single ion impact signals from a FinFet at room temperature

Next step: EDMR on single donor transport resonances, single donor spin readout and control



and





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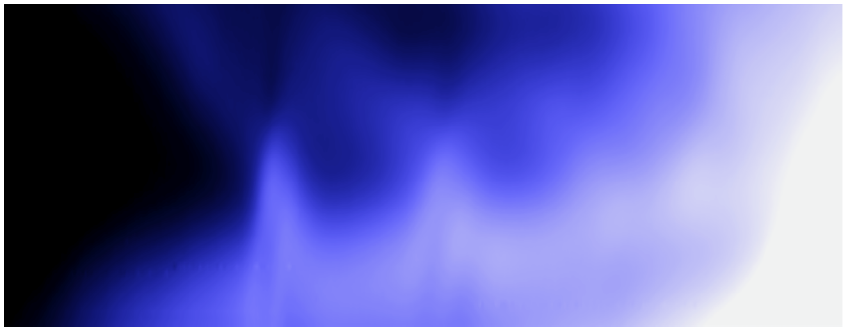

goal:
observe current changes when a single donor electron spin is driven with microwaves, in single ion implanted devices

Acknowledgments

- **PostDocs**
  - Arun Persaud
  - Mohan Sarovar
- **Graduate students**
  - Christoph Weis, LBNL & TU Ilmenau
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  - Staff of The Molecular Foundry at LBNL
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  - Stephen Lyon, Princeton University
  - Alexei Tyryshkin, Princeton University
  - Birgitta Whaley, UC Berkeley
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  - John Morton, Oxford
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  - Ivan Chakarov, Silvaco, Santa Clara, CA
  - Rogerio de Sousa, University of Victoria
  - Ivo Rangelow, Technical University Ilmenau
  - Malcolm Carroll, Sandia National Laboratory

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•http://www-ebit.lbl.gov/

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An experiment in deterministic doping

1. measure a device / transistor
2. add one dopant atom into a desired location
3. some processing (e. g. annealing)
4. measure the device again and see transport signatures of the single dopant
5. implement function based on transport signatures from single dopant (e. g. coherent spin manipulation for quantum computing, or classical computing with spin as a state variable)

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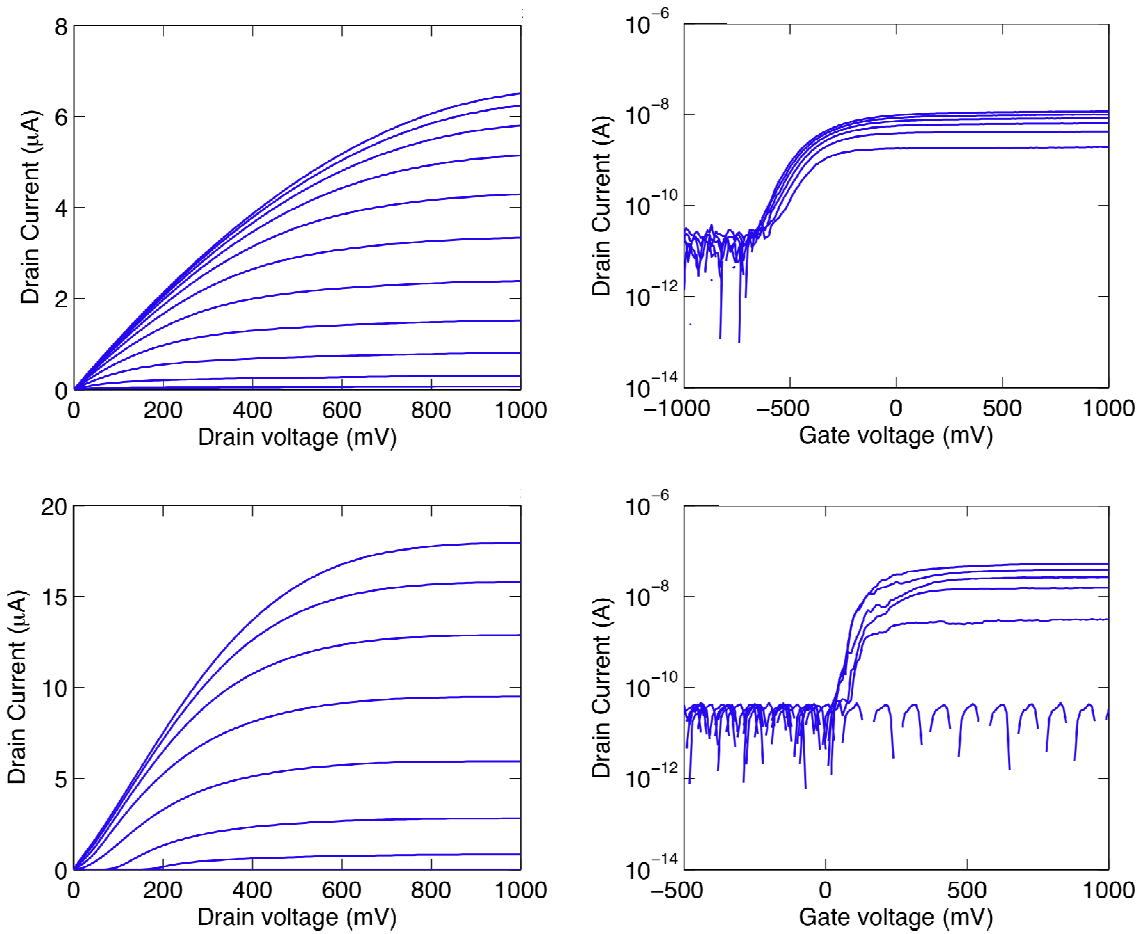
Large bias *I-V* characterization of triple-gate FinFETs

$I_d - V_d$ $\qquad$ $I_d - V_g$

$298K$

$4.2K$

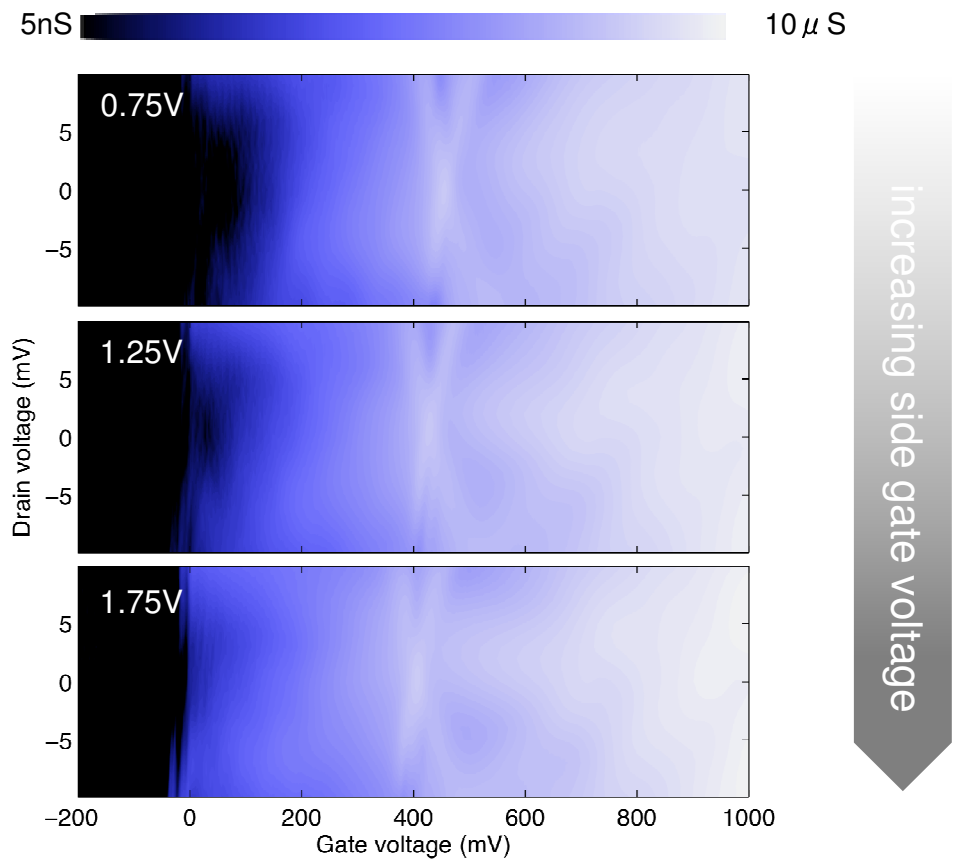


- Schottky-junction like *I-V* at low temperature due to barriers formed around spacers

$$w_l = 100nm \quad l_l = 76nm$$

Transport measurements in liquid helium (4.2K)

- Two “lucky” devices show strong resonance peaks *after* turn-on:



- Single strong resonance peak, no evidence of additional Coulomb peaks as would be expected from quantum confinement in the fin.

$$l_l = 100\text{nm}, w_l = 50\text{nm}$$