LABORATORY DIRECTED RESEARCH & DEVELOPMENT

Spectroscopy and capacitance measurements of tunneling resonances in an Sb-implanted point contact

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Sandia National Laboratories

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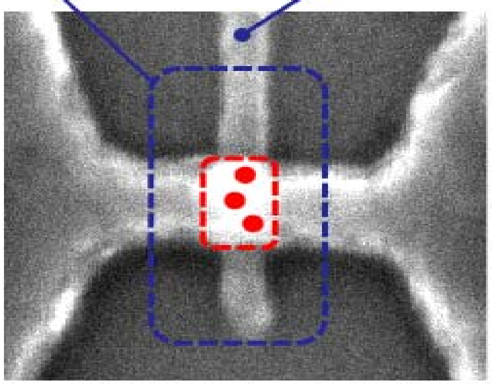
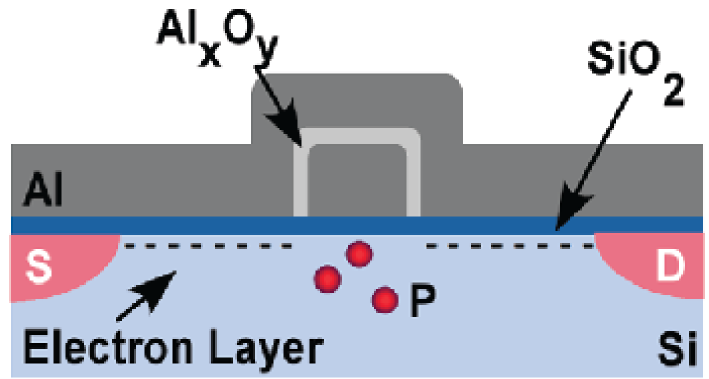
Outline

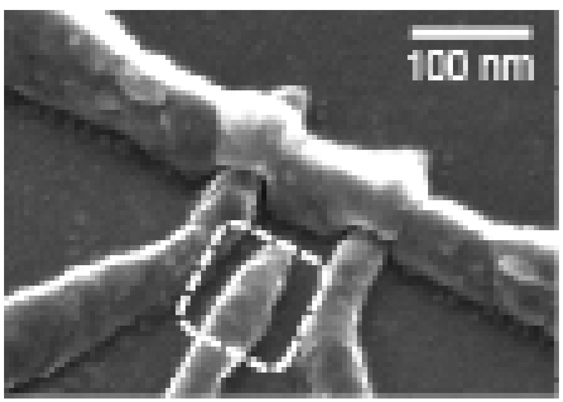
- Our design and relation to previous work
- Silicon MOS quantum dots as sensitive charge sensors
- Donor transport device structure
- Comparison between experiment and capacitive model
- Future work – excited state spectroscopy and charge sensing
- Conclusion

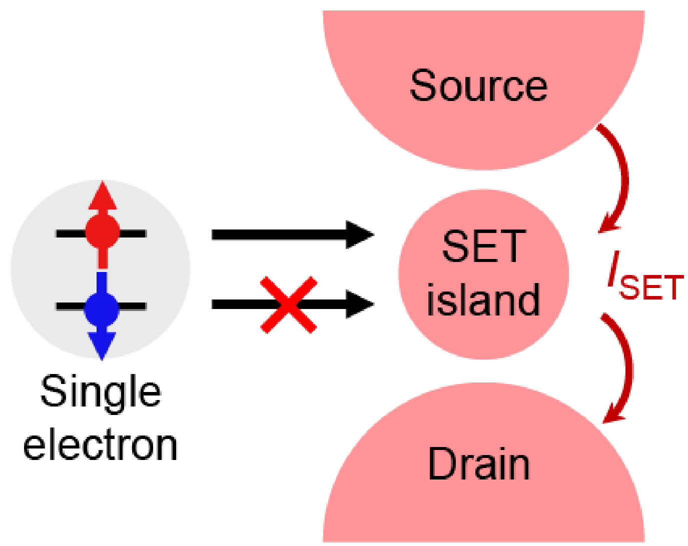
Some previous work



Tan et al., Nano Lett. 2010

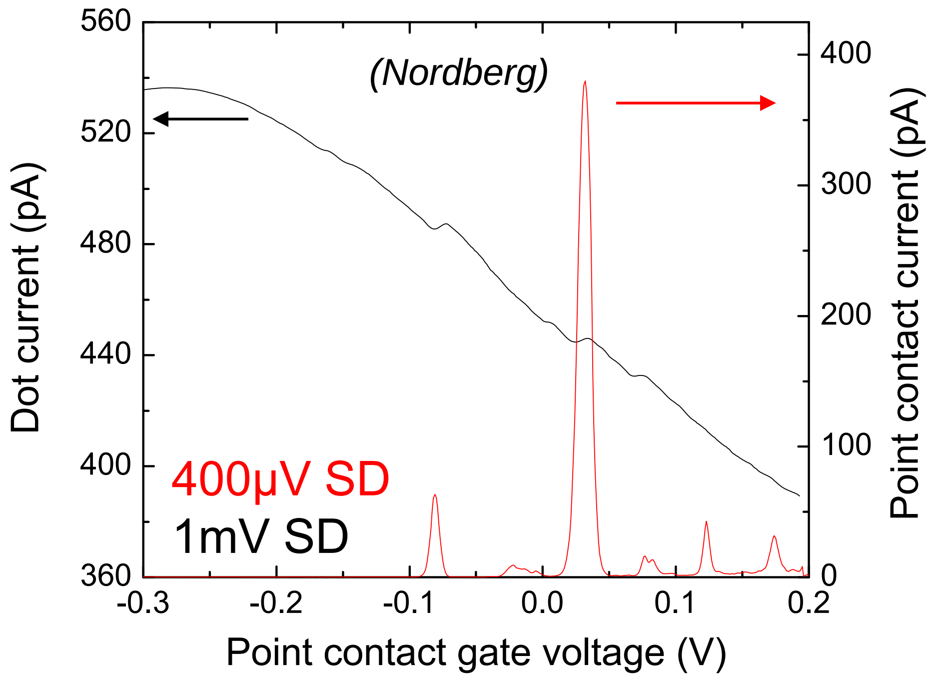


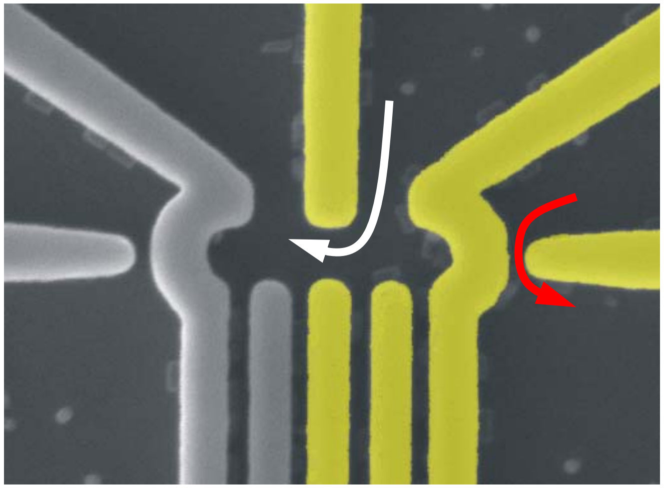




Morello et al., *arxiv* 2010

Si MOS quantum dots as charge sensors





- Reverse normal usage: use a quantum dot to sense changes in a point contact.
- Can be used to sense the spin state of a donor embedded in the point contact.

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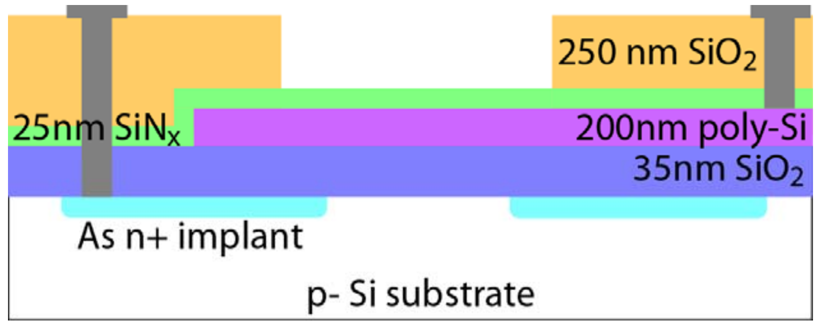
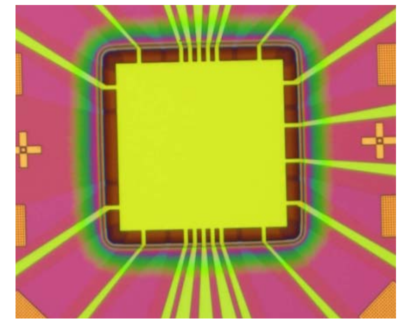
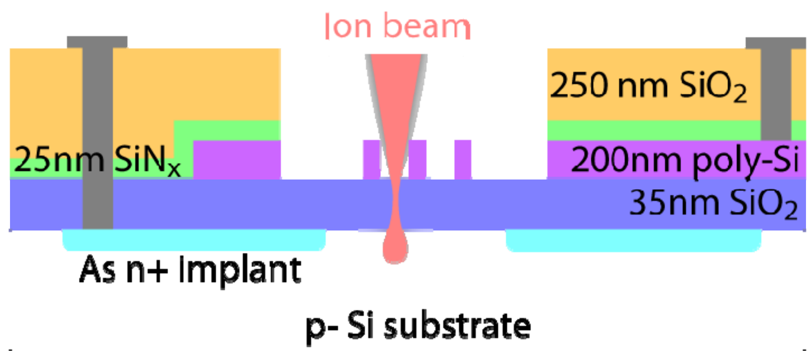
Si MOS process flow

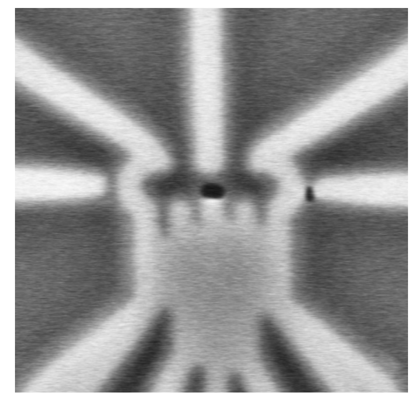
- Oxide growth
- Polysilicon deposition and patterning
- Ohmic contact implant and anneal
- Nitride and pre-metal dielectric dep.
- Silicide and metallization



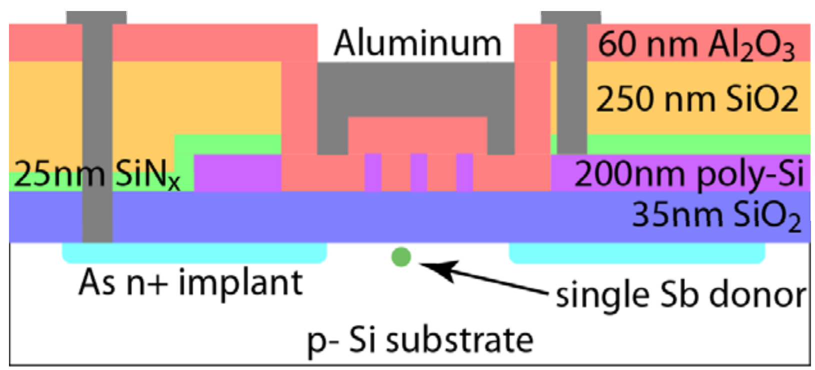


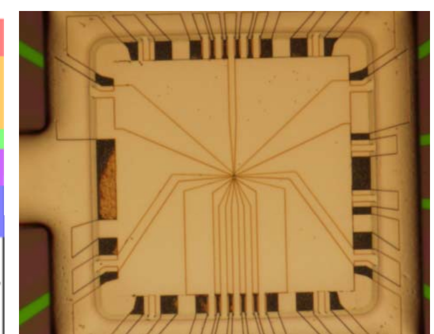
- E-beam litho and polysilicon patterning
- More EBL and Sb implantation





- Strip metal and re-oxidize polysilicon
- Second dielectric (ALD Al_2O_3) dep.
- Final metallization





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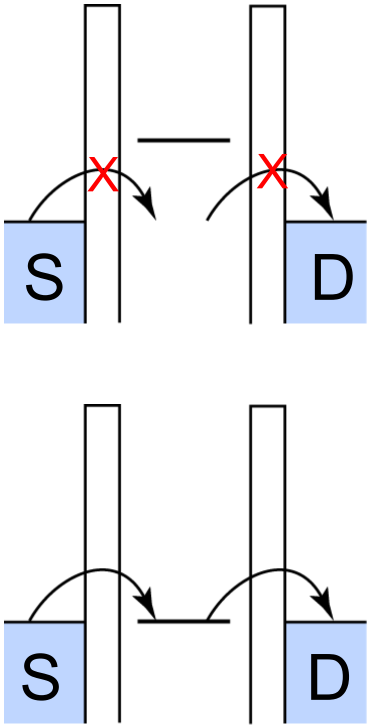
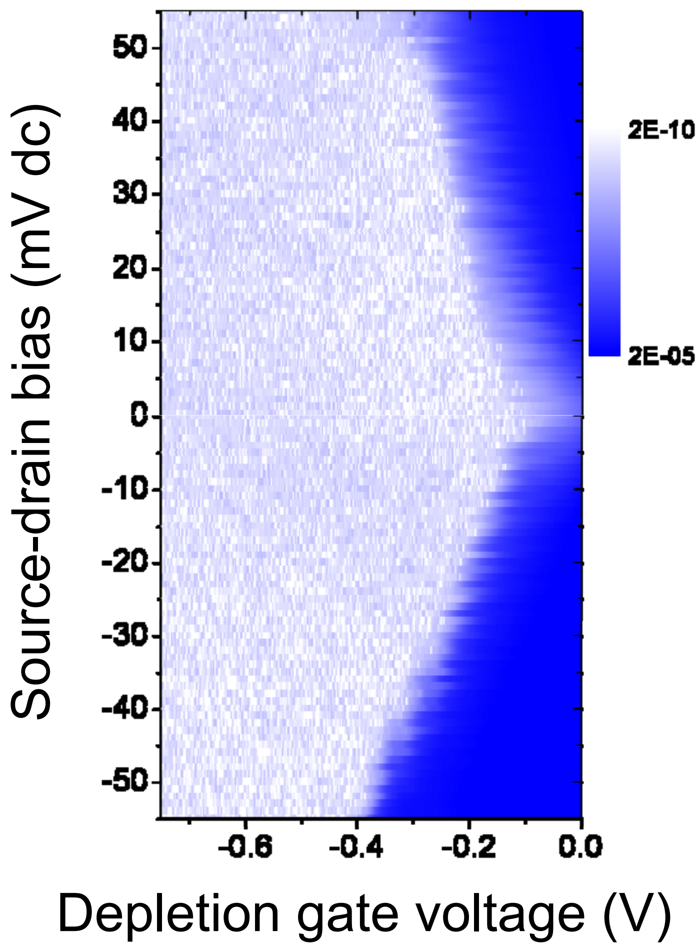
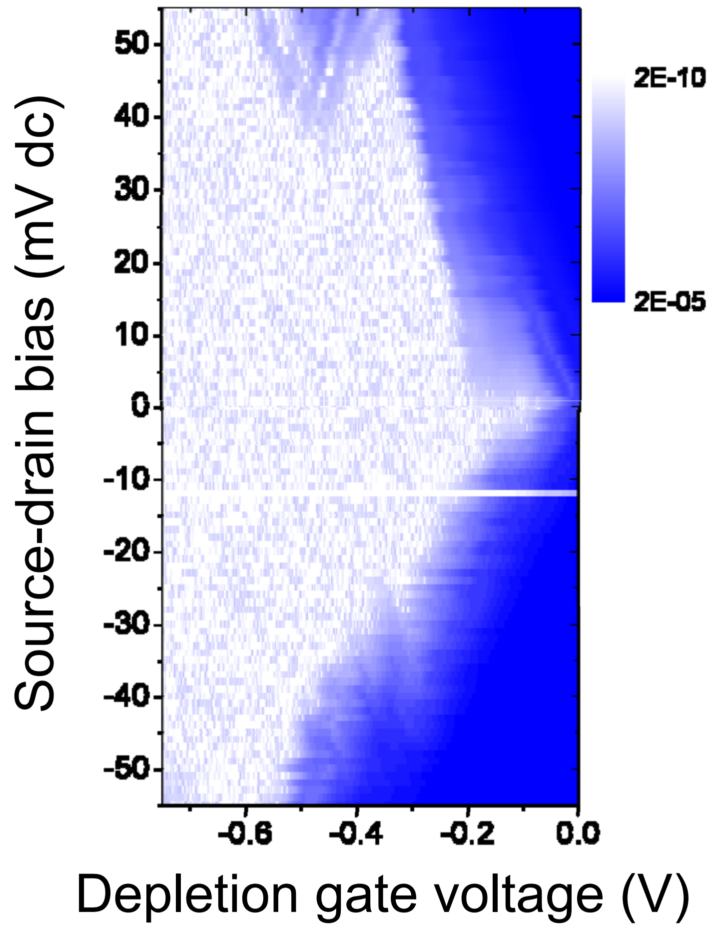
Control sample: Silicon implant



No implant



40 keV silicon implant
4×10^{11} cm^{-2} dose



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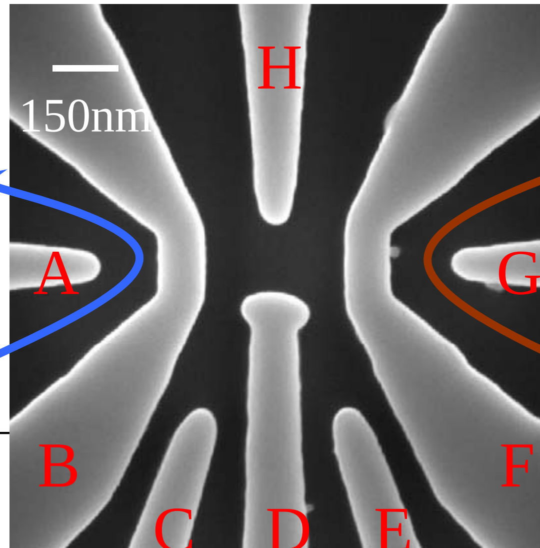
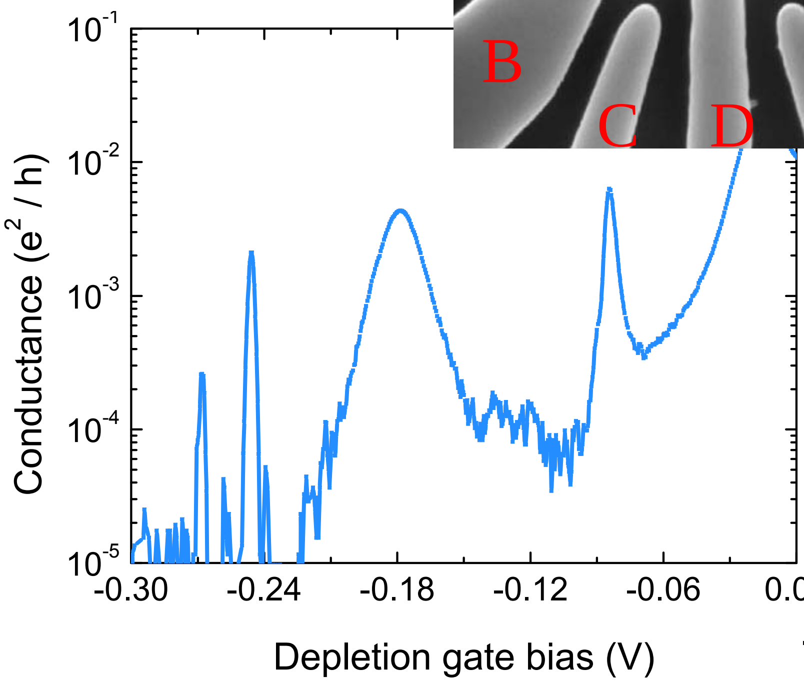
Control vs. implanted

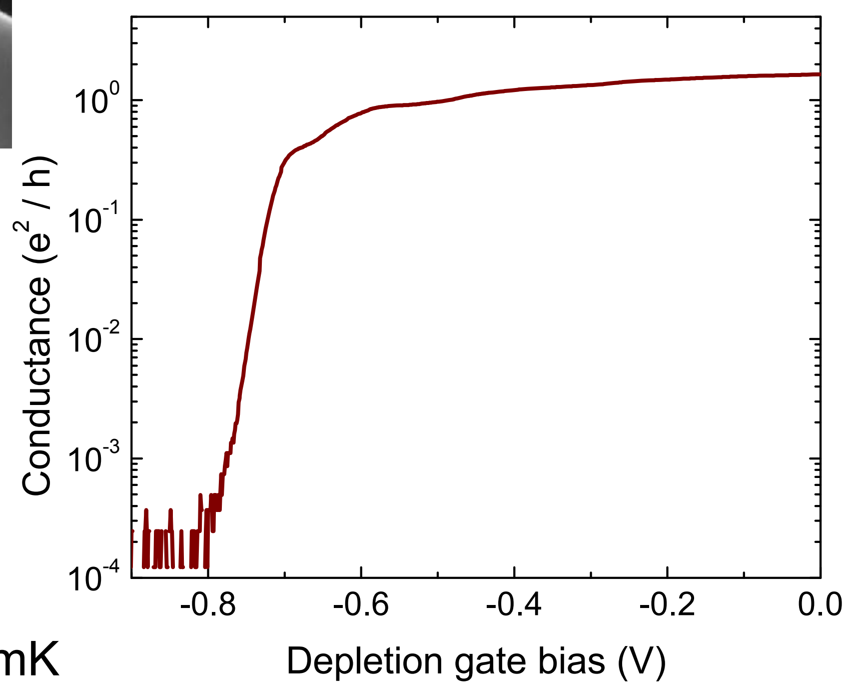
Antimony allows high temperature post-implant processing.

100 keV antimony
4×10^{11} cm^{-2} dose



Sample type	Q_{fb} (q/cm^2)	D_{it} (q/cm^2eV)
Normal process	$+ 5 \times 10^{10}$	1×10^{10}
Silicon implant + RTA (Donor device equivalent dose)	$+ 3 \times 10^{11}$	2×10^{11}
Silicon implant + reoxidation	$+ 1 \times 10^{11}$	1×10^{10}





T ~ 250mK
Vsd = 0.5 mVrms

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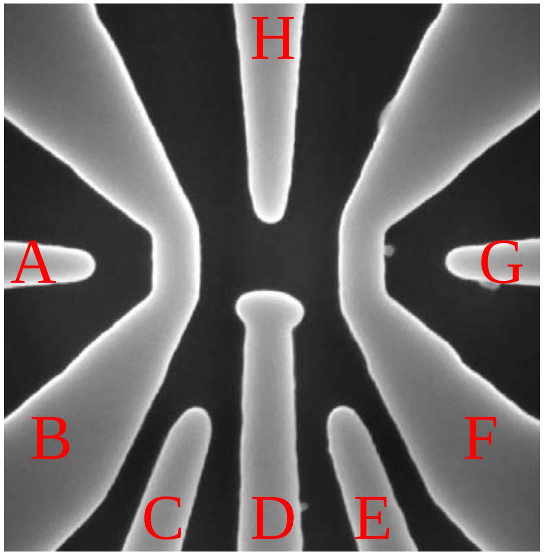
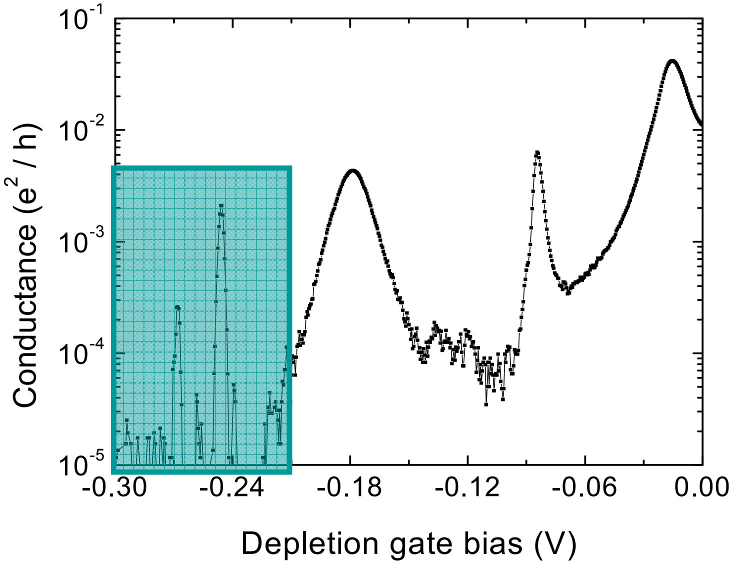
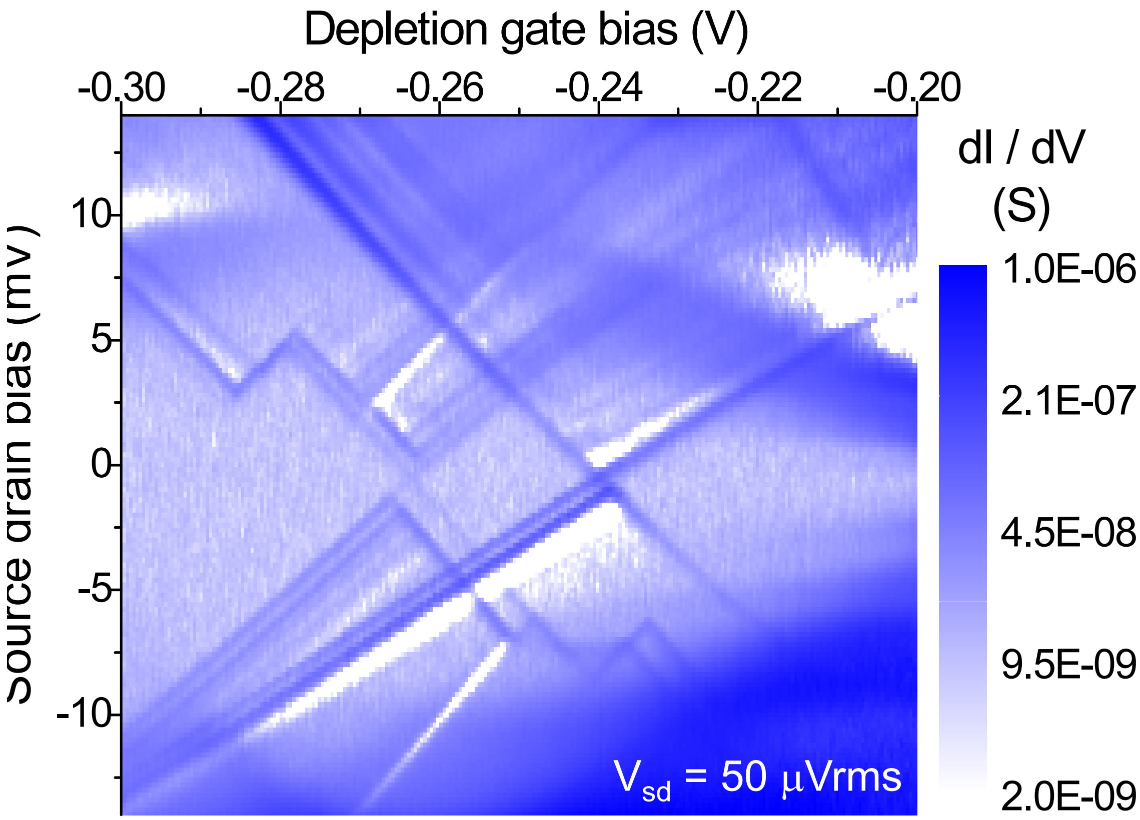
Tunneling spectroscopy







<u>Relevant features:</u>

1. Aliasing – nearby charge environment
2. Excited states – structure of donors / dots
3. Slope of lines – capacitance

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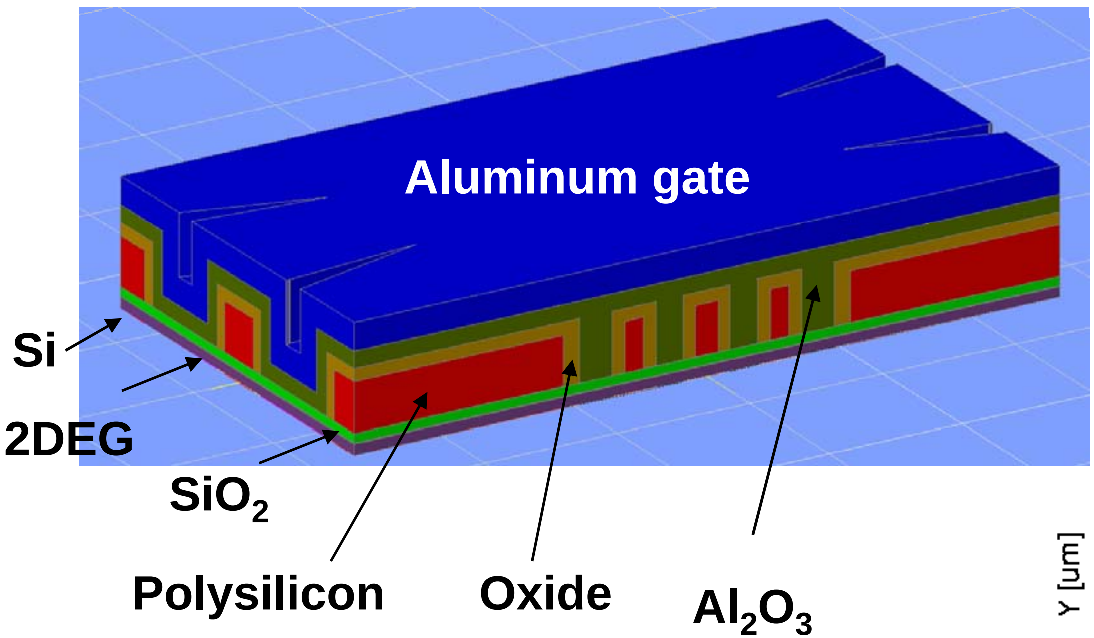
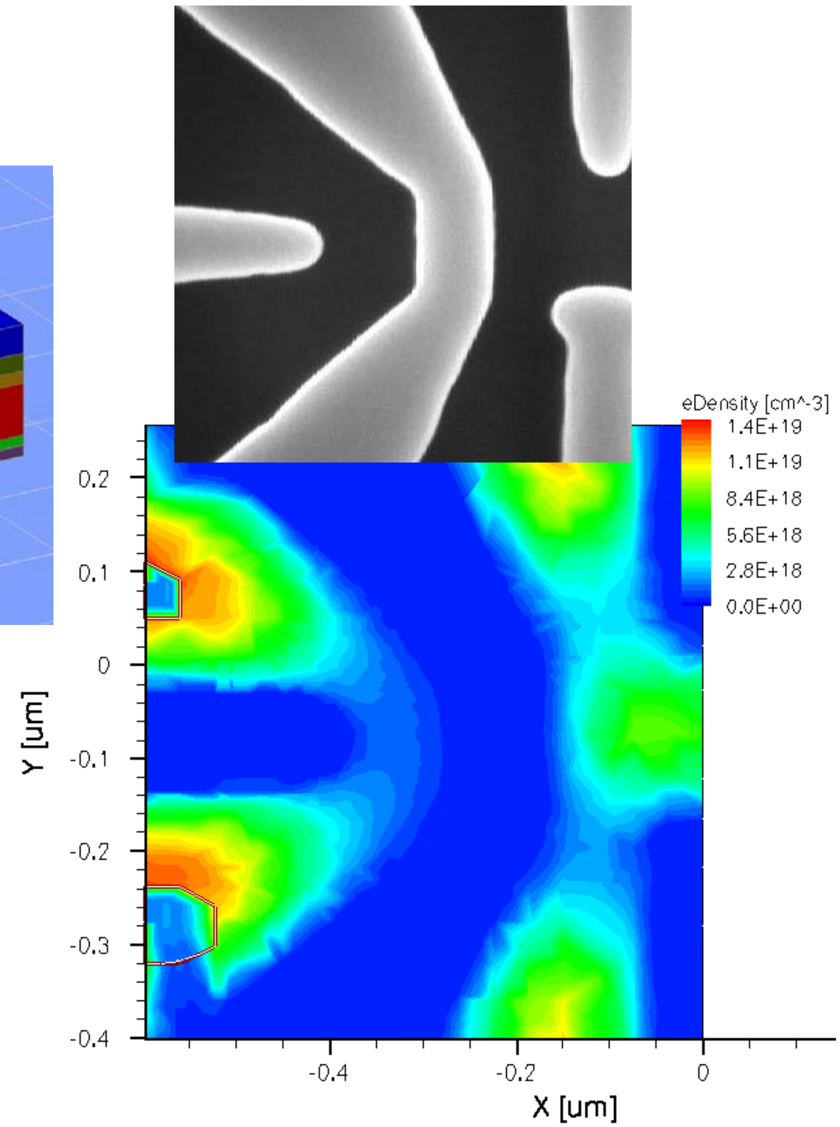
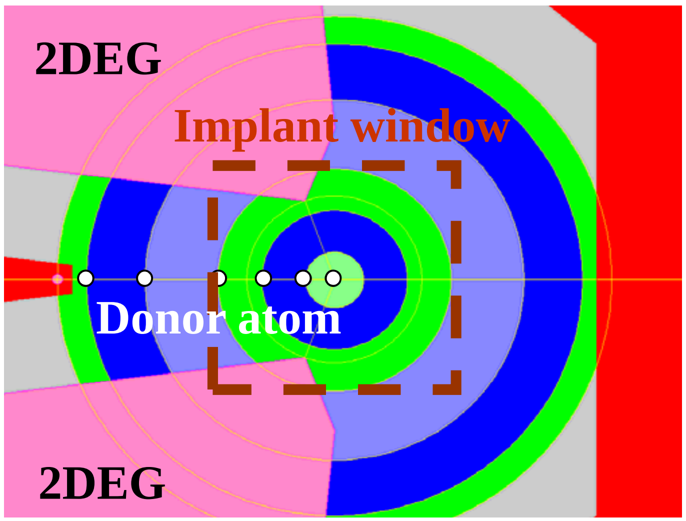
Capacitive model

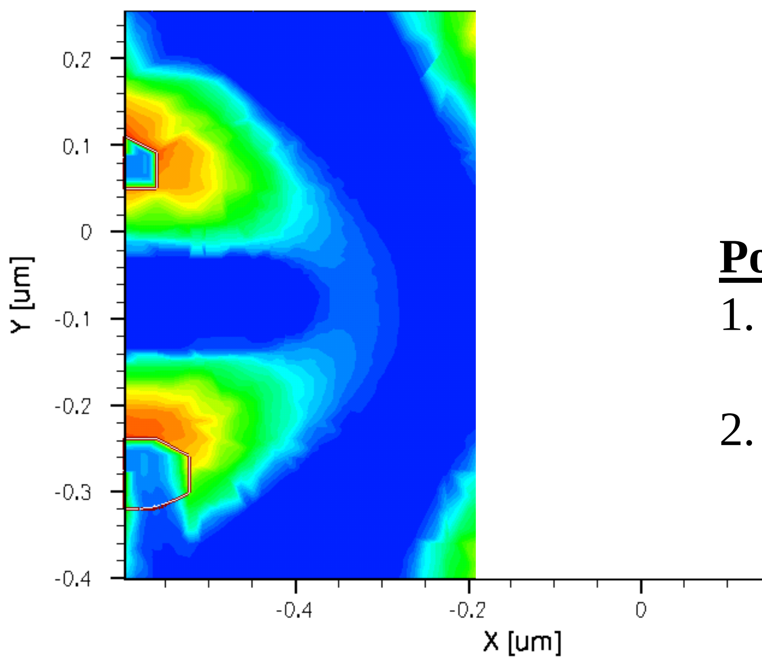


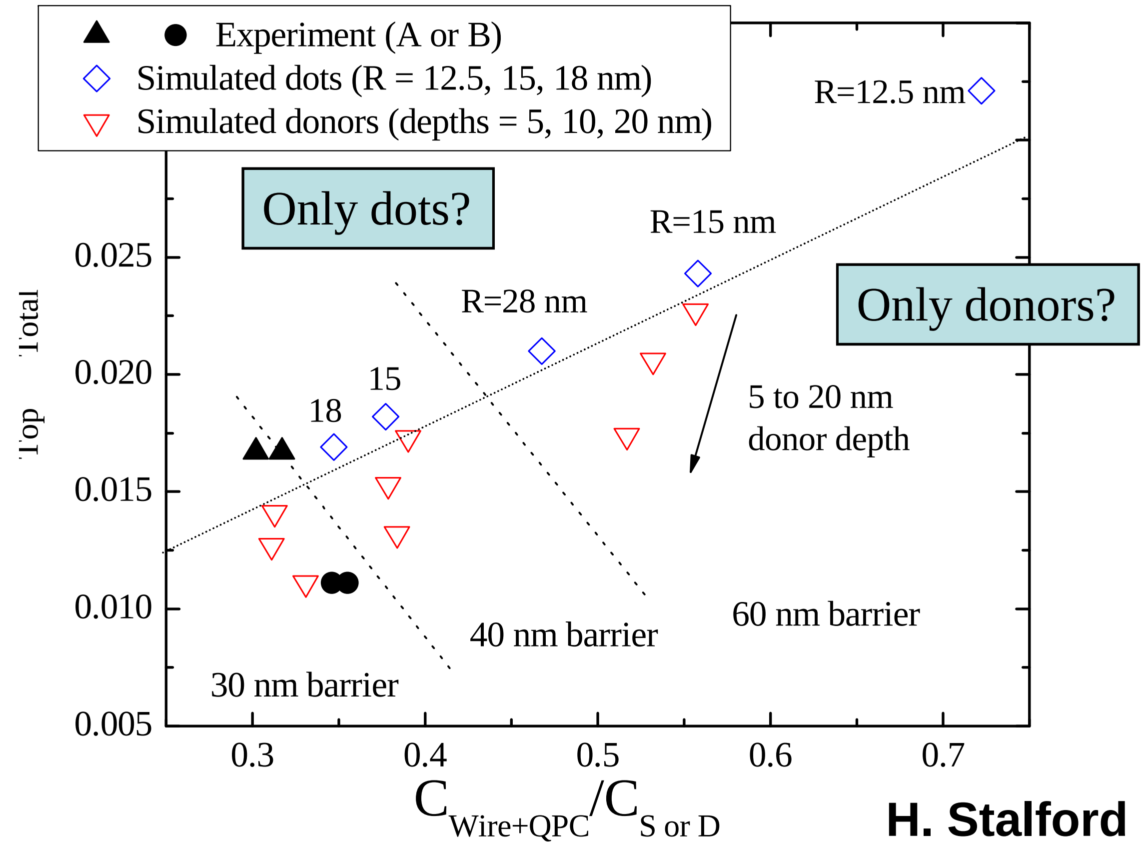


Harold Stalford, Ralph Young

Triangulation of Resonances







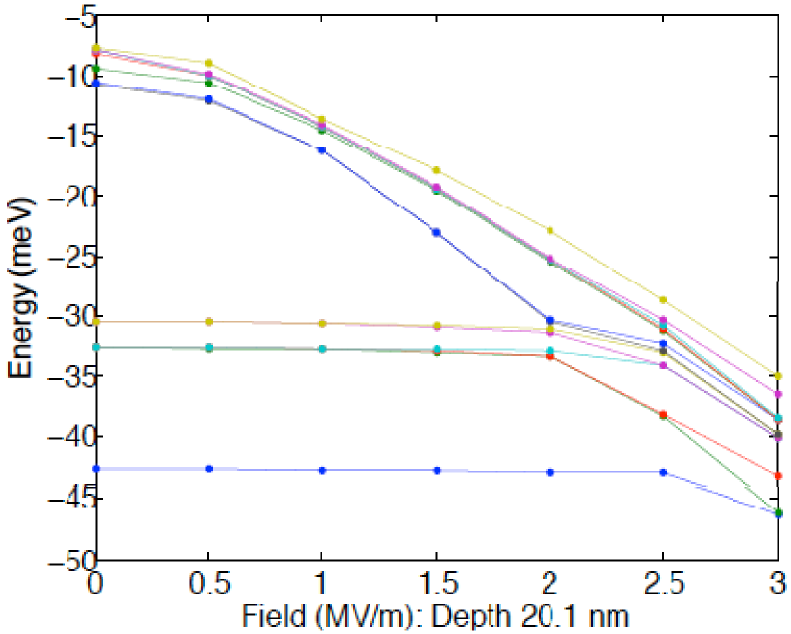
H. Stalford

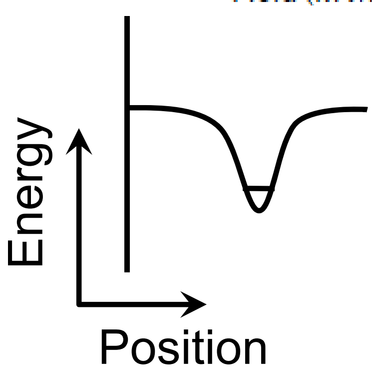
Position and size determination

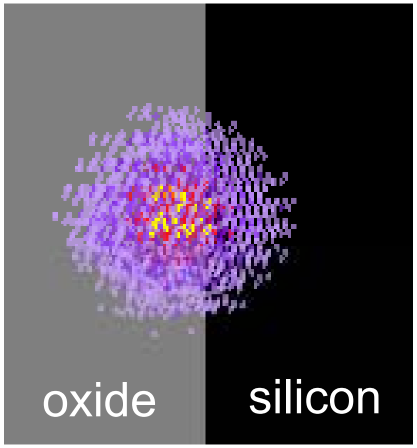
1. Capacitance ratios are sensitive to small differences in geometry
2. Top gate, S/D and lateral gates cover all three spatial directions
   - Is resonance below the surface?
   - Still in progress

Spectroscopy: Sb in Si

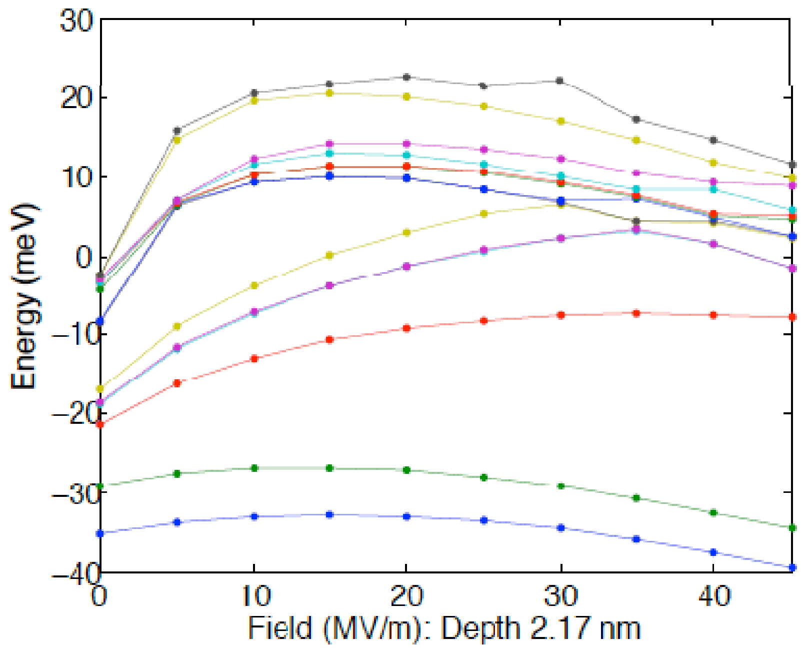
Deeply buried donor

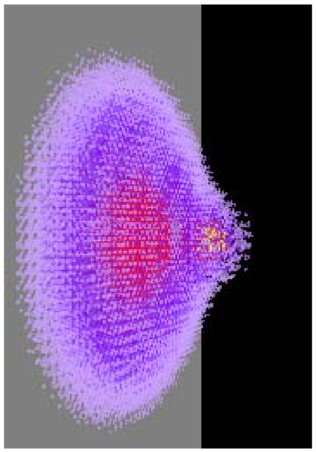


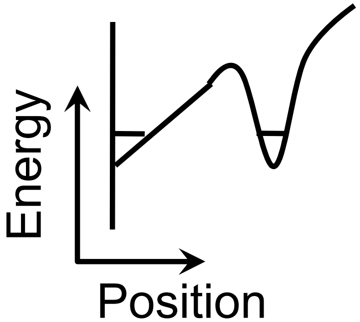




Donor near interface







Rajib Rahman

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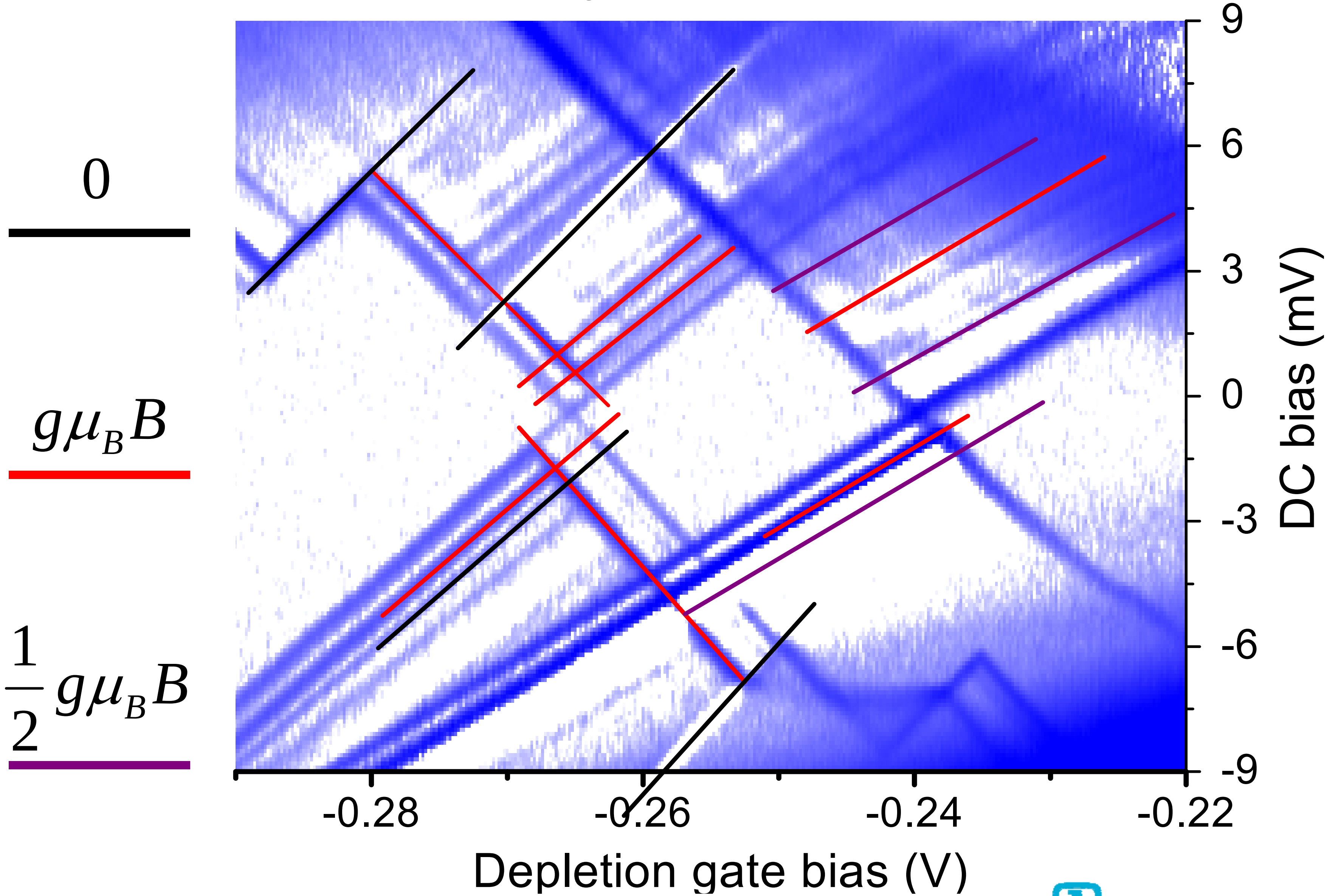
Spectroscopy: excited states



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Conclusions

- Fabricated unique device which enables a wide variety of possible experiments.
- Identified tunneling resonances in implanted point contacts, which are rare in clean controls.
- Capacitive measurements locate the resonant states in the point contact, and are consistent with donors as the source.
- Charge sensing measurements ongoing.

Acknowledgements

Quantum Team:
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Kent Childs
Kevin Eng
Robert Grubbs
Paul Hines
Mike Lilly
Joel Means
Rick Muller
Eric Nordberg
Tammy Pluym
Rajib Rahman
Bev Silva
Harold Stalford
Jeff Stevens
Tom Tarman
Greg Ten Eyck

Quantum team cont'd:
Denise Tibbetts
Lisa Tracy
Joel Wendt
Wayne Witzel
Ralph Young

Australian collaborators:

Susan Angus
Andrew Dzurak
William Lee
Andrea Morello
Michelle Simmons
Dan Tomlinson

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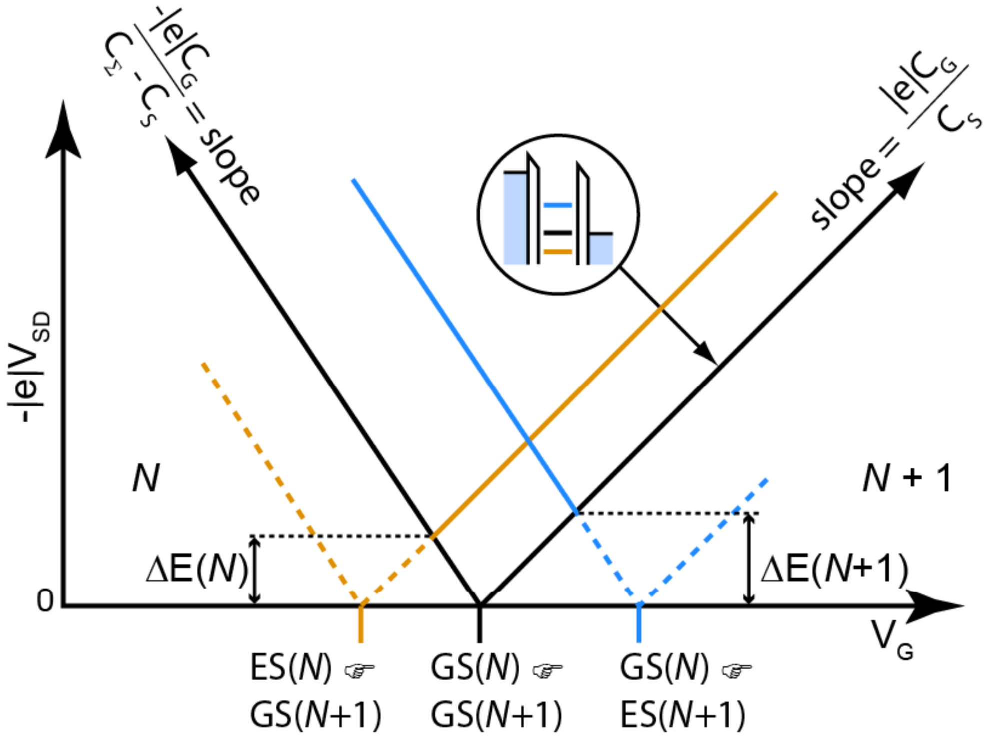
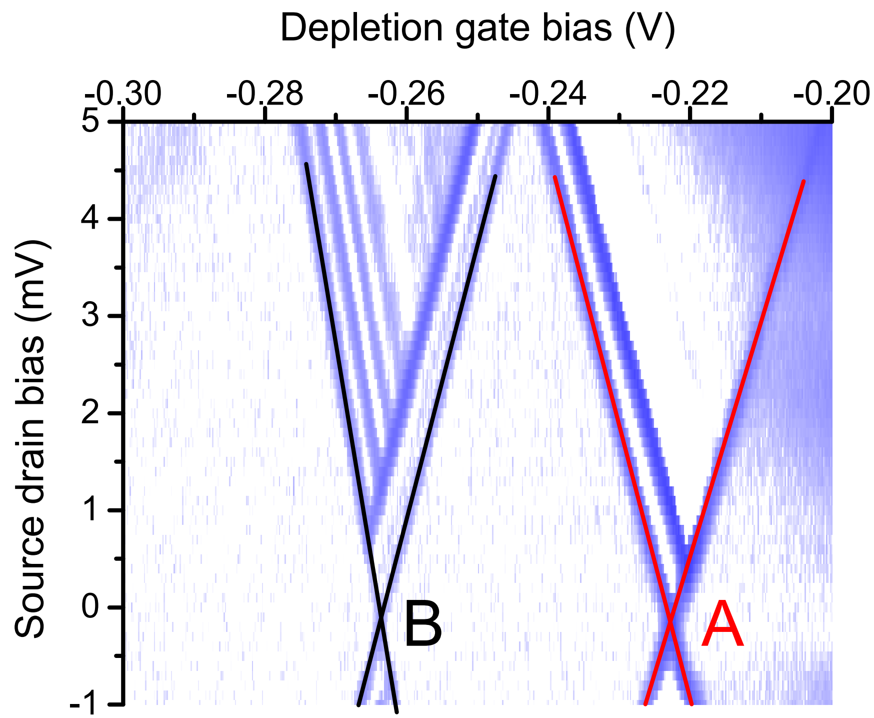
Extracting capacitance

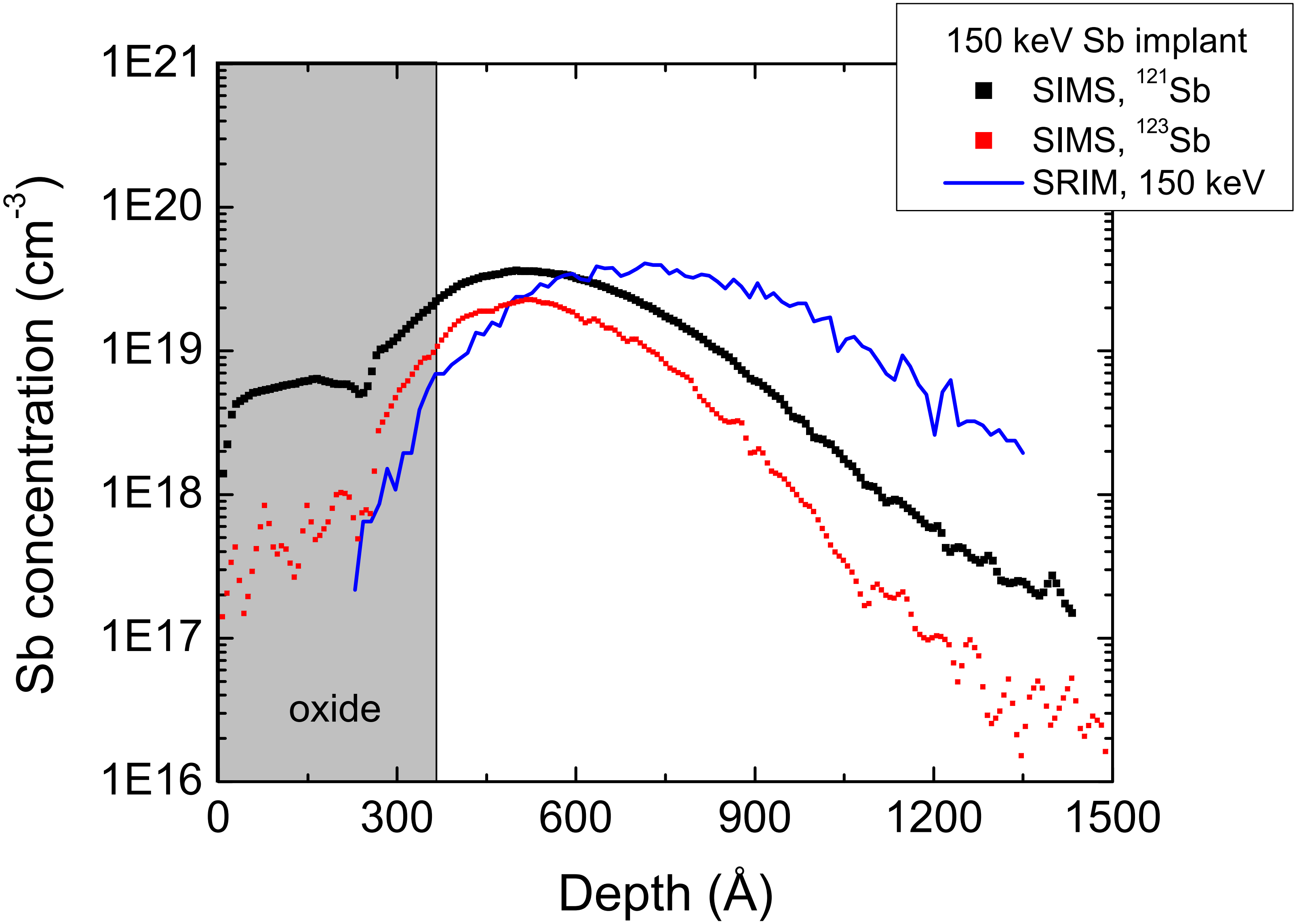




B peak slopes:
-0.281
0.417

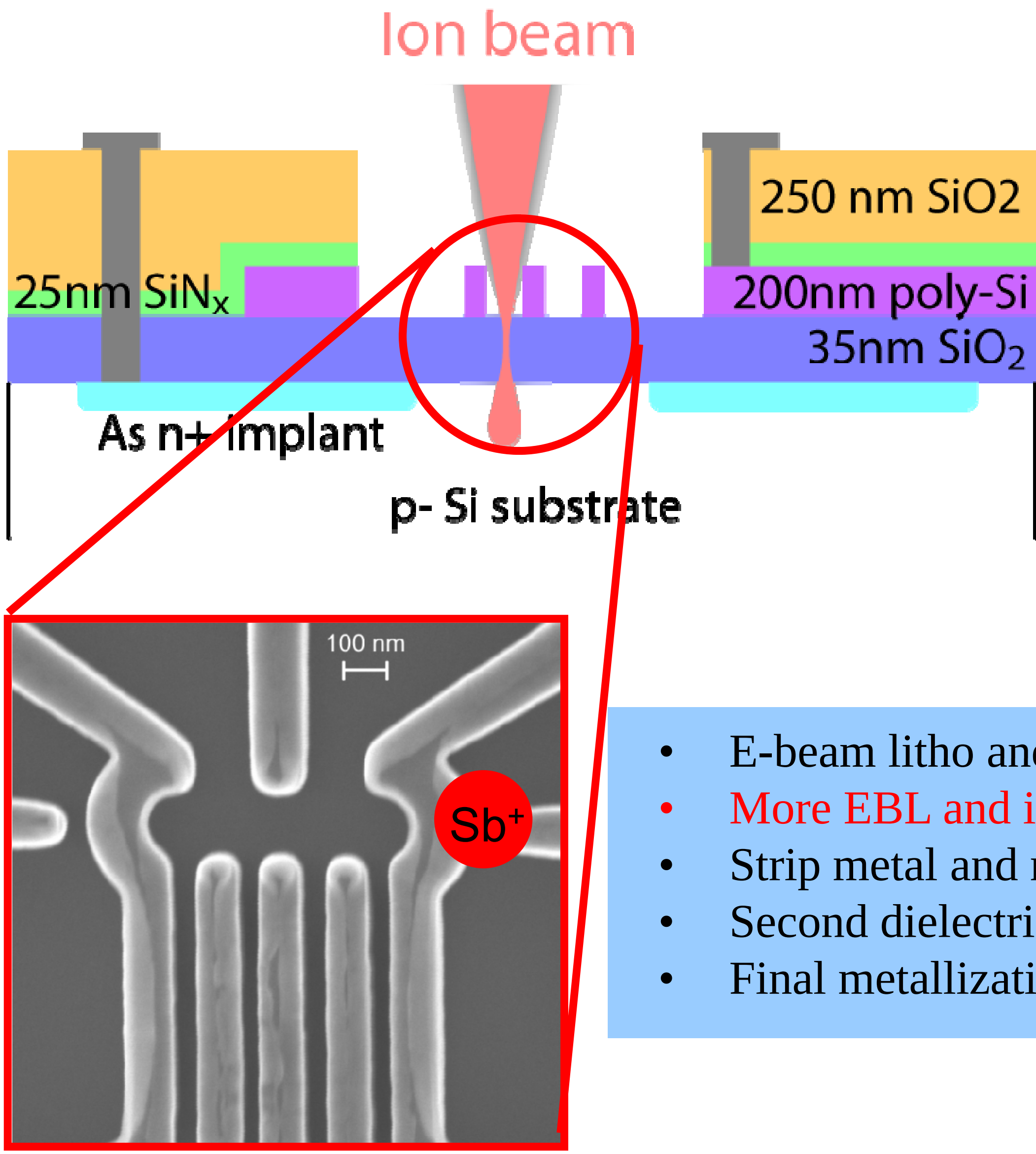
A peak slopes:
-0.249
0.277

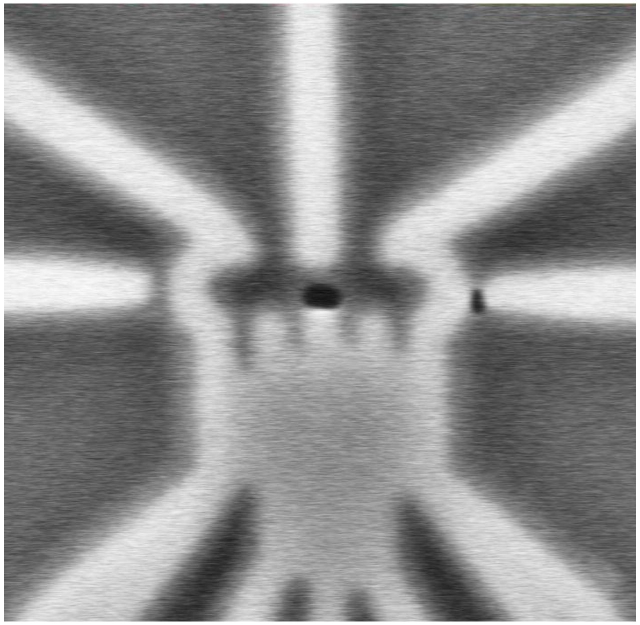
Donor distribution



SIMS by Tony Ohlhausen, SNL

Ion implantation





- E-beam litho and polysilicon patterning
- More EBL and ion implantation
- Strip metal and re-oxidize polysilicon
- Second dielectric (ALD Al_2O_3) dep.
- Final metallization

Back end

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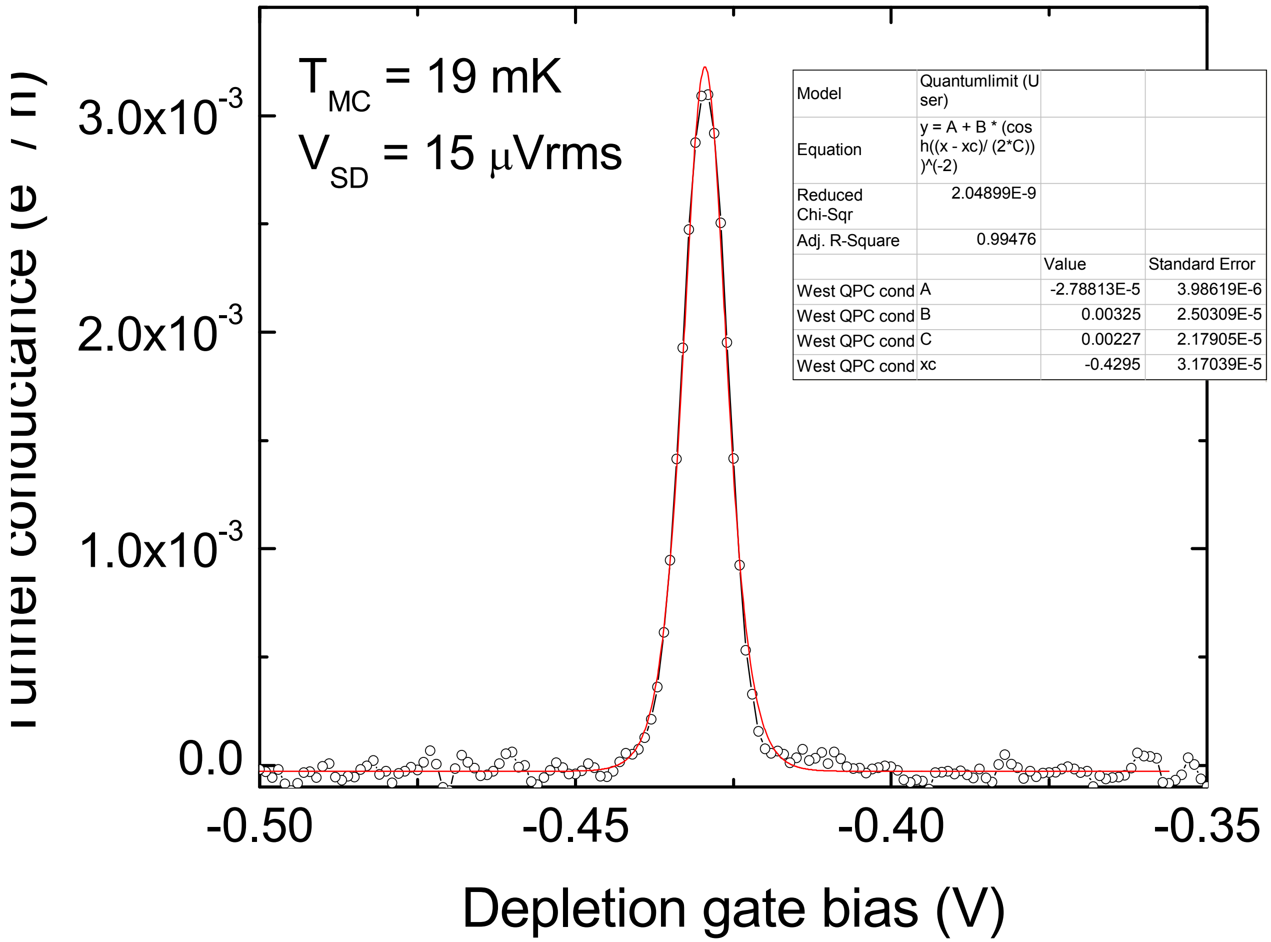
Lever arm analysis

$$\frac{G}{G_{MAX}} = \frac{\Delta E}{4k_B T}\cosh^{-2}\left(\frac{\alpha(V - V_0)}{2k_B T_{measured}}\right)$$



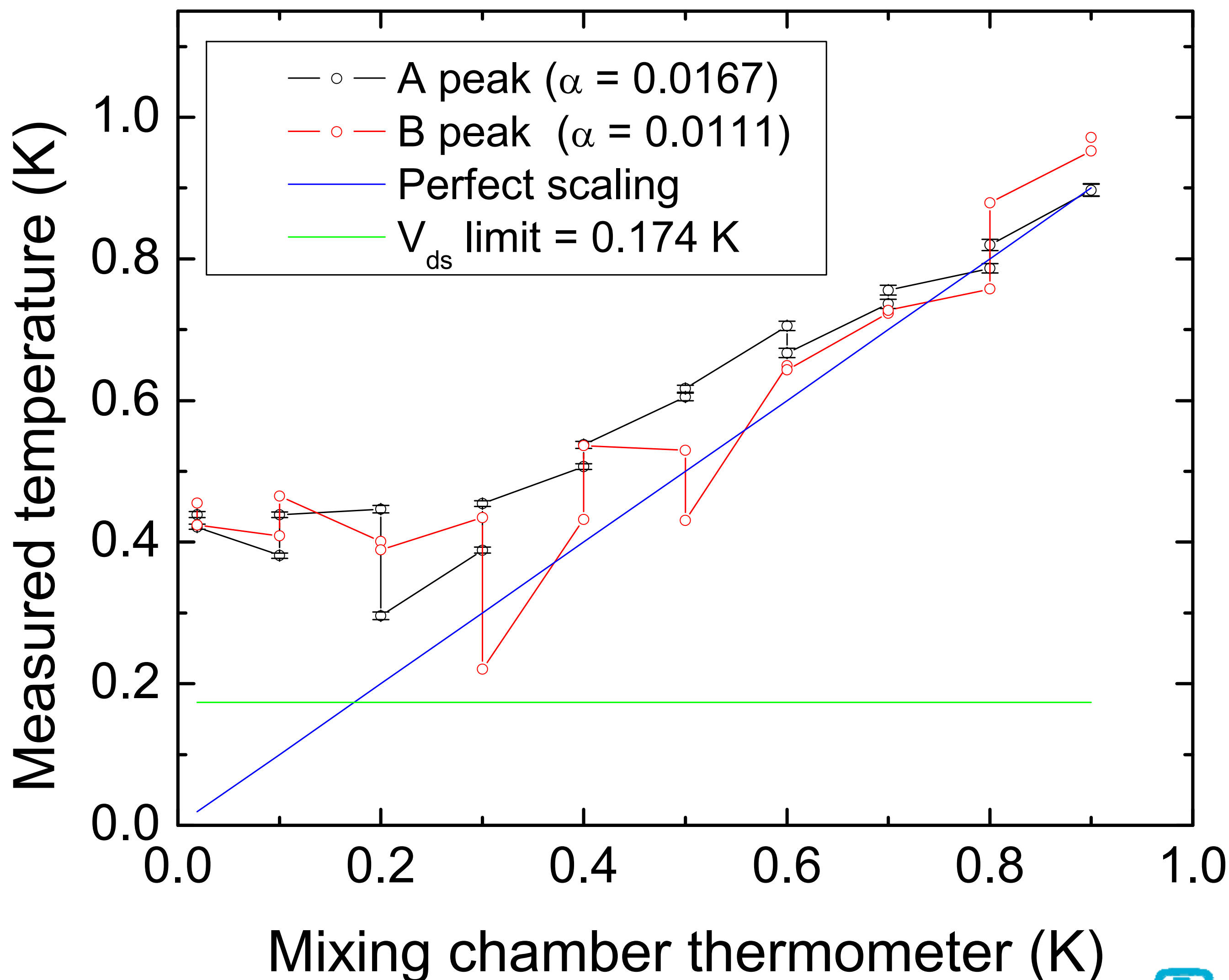
Model	Quantumlimit (User)		
Equation	y = A + B * (cosh((x - xc)/ (2*C)))^(-2)		
Reduced Chi-Sqr	2.04899E-9		
Adj. R-Square	0.99476		
		Value	Standard Error
West QPC cond	A	-2.78813E-5	3.98619E-6
West QPC cond	B	0.00325	2.50309E-5
West QPC cond	C	0.00227	2.17905E-5
West QPC cond	xc	-0.4295	3.17039E-5

$$\alpha = \frac{eC_G}{C_\Sigma}$$

$$\alpha = \frac{2k_B T_{measured}}{\delta V}$$

Kouwenhoven *et al*., Electron transport in quantum dots, NATO ASI 1997

Lever arm analysis



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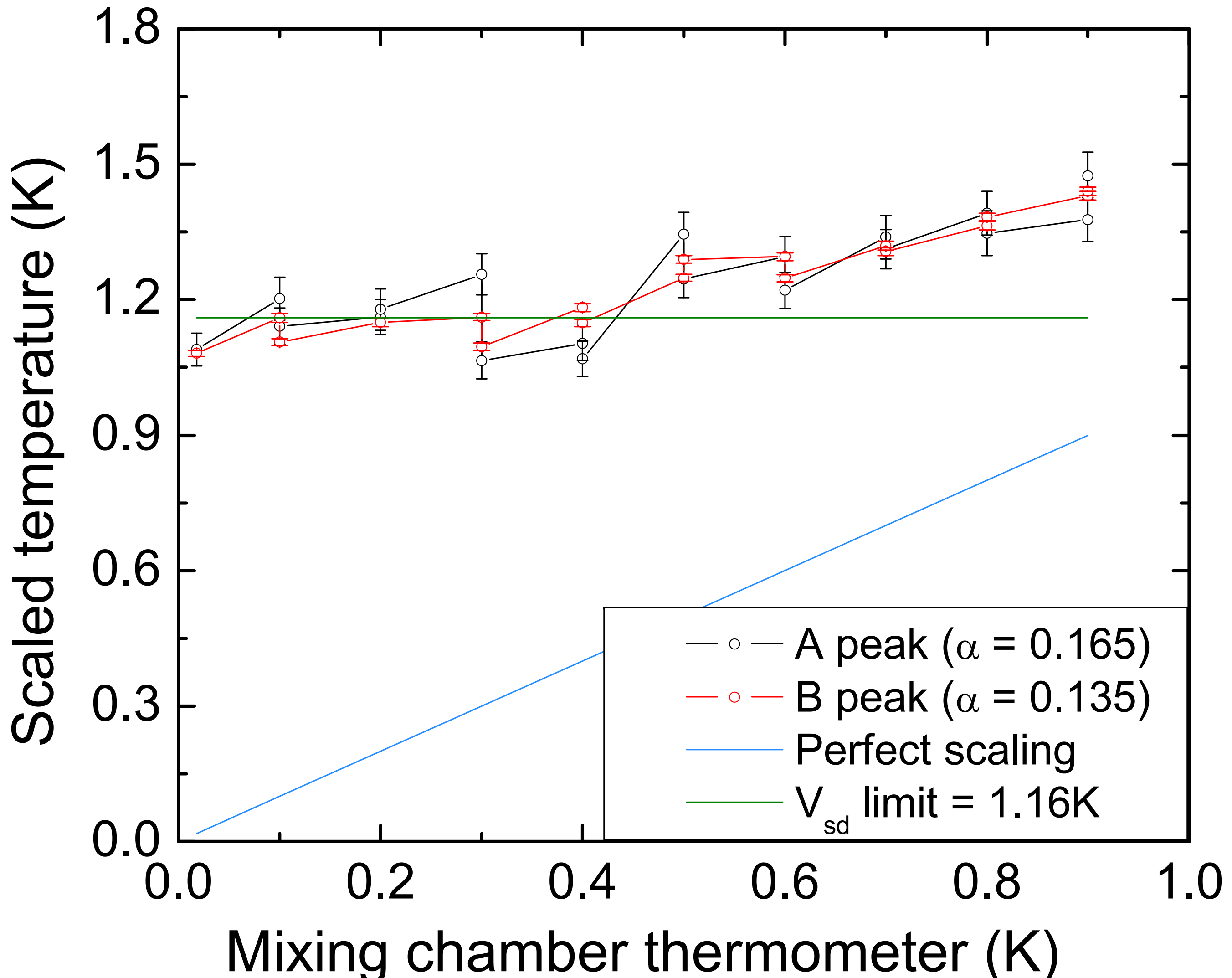
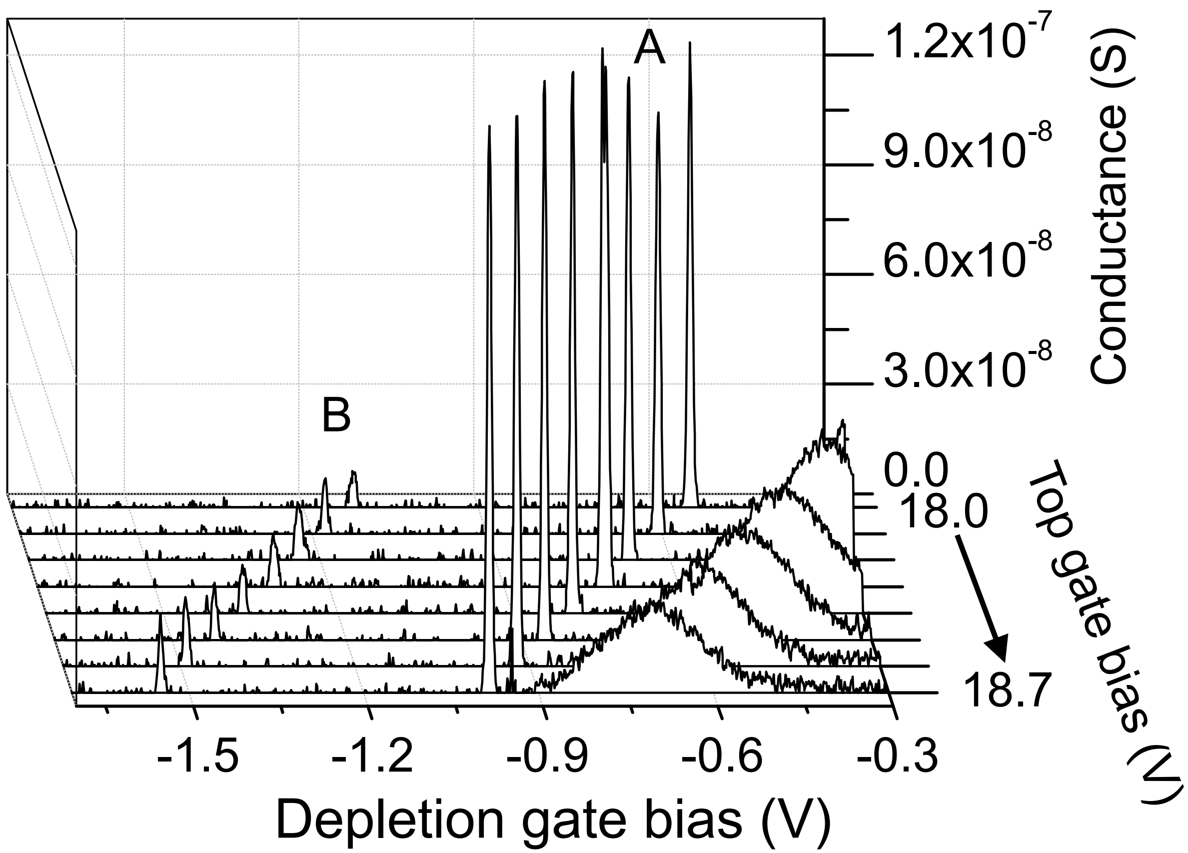
Poor scaling due to high V_{ds}

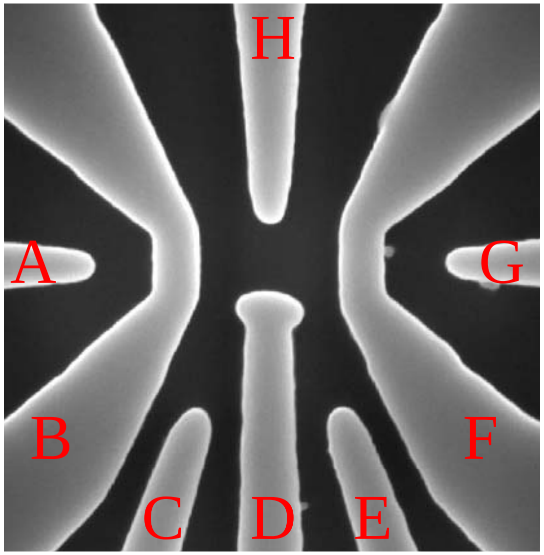


Top gate lever arm



A slope:
$dV_{Poly} / dV_{TG} = -0.639$

B slope:
$dV_{Poly} / dV_{TG} = -0.625$



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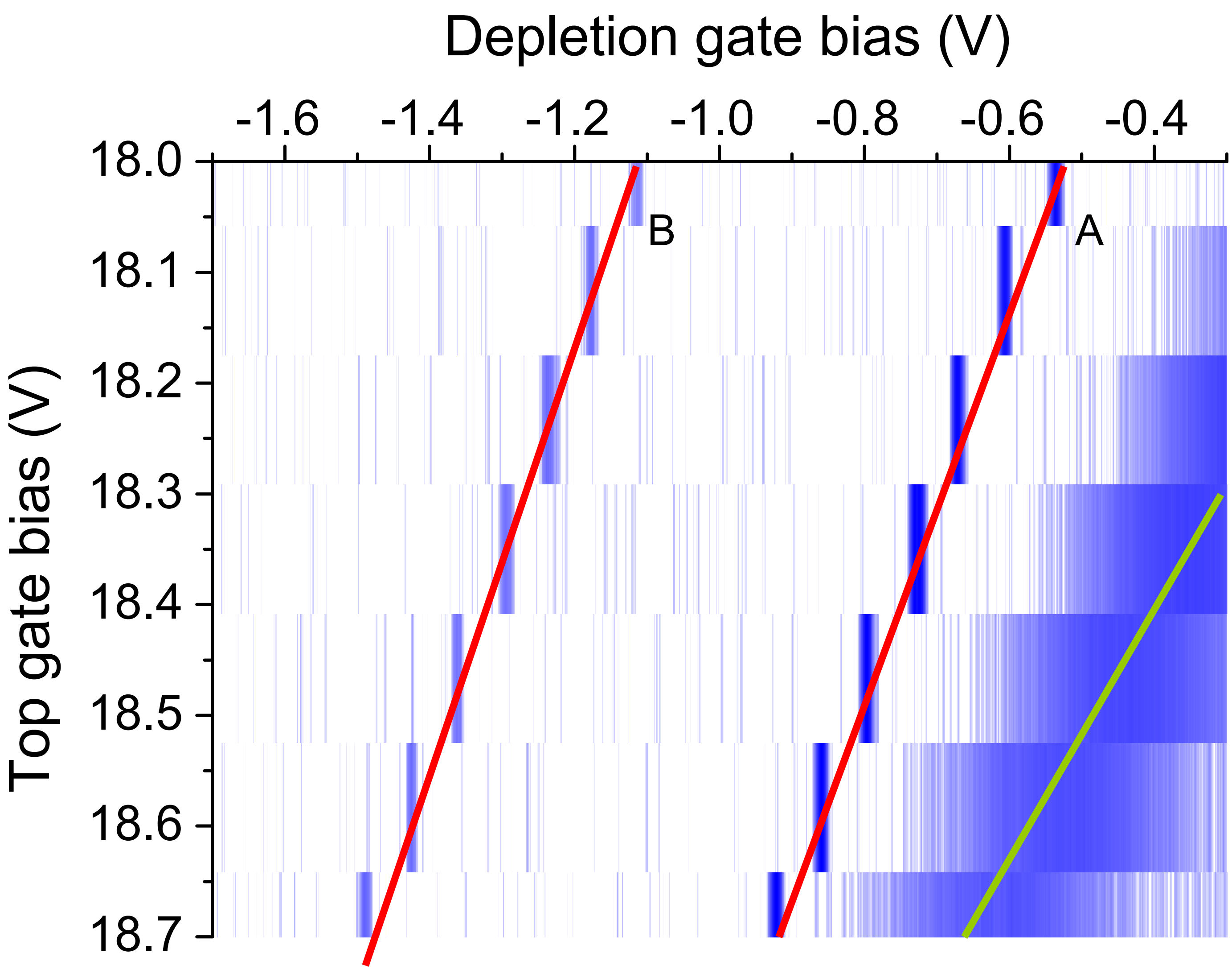
Top gate lever arm

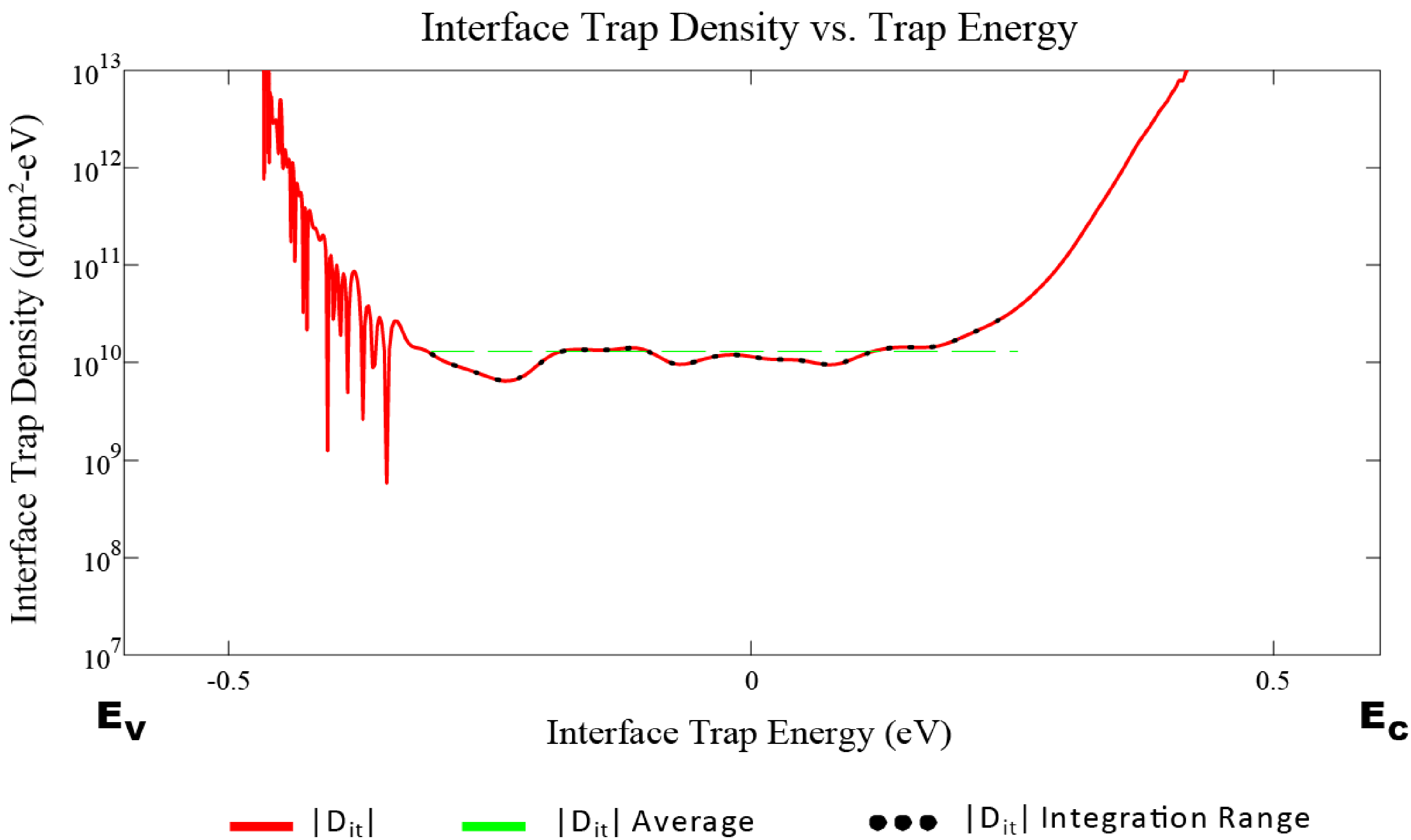


A and B have nearly identical top gate lever arm.
There is a disorder dot that does have a larger lever arm.

Disorder dot!

Ion implant damage

45 keV silicon implant, equivalent to 100 keV antimony implant
900 C furnace anneal, 24 minutes in O_2



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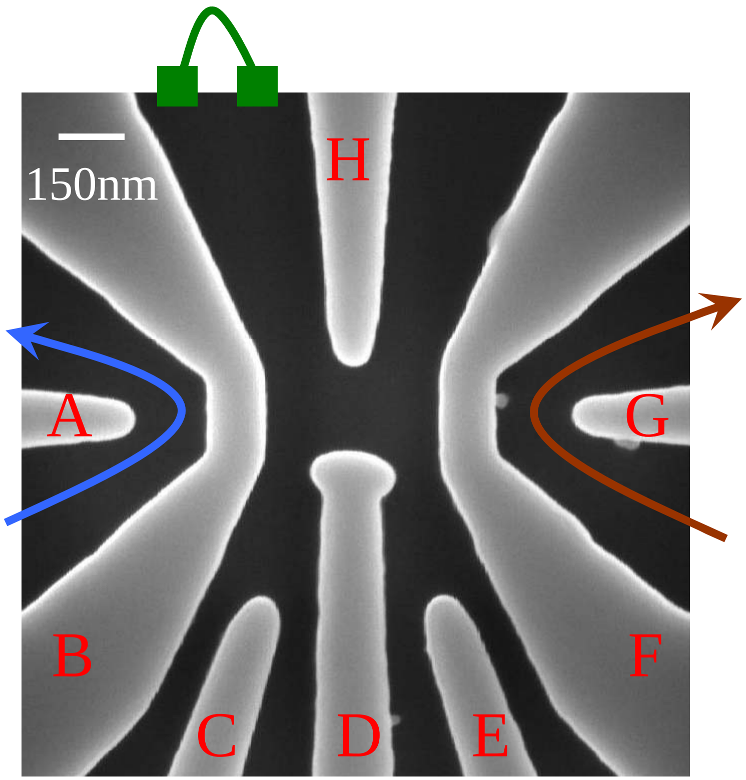
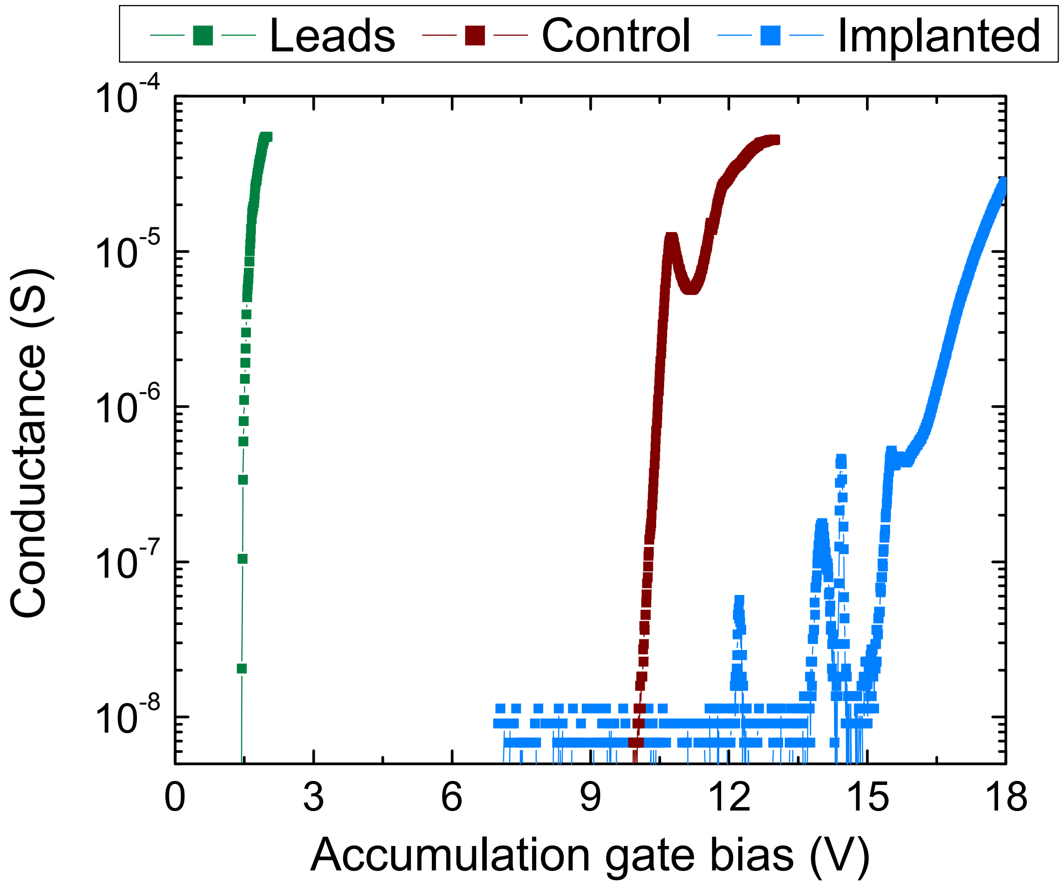
Threshold difference





Implant damage increases interface trap density and fixed charge, but mostly repaired after high temperature processing.

CV measurements of Dit and Qf by Greg Ten Eyck