Triangulating tunneling resonances in a point contact

SAND2011-1874C

Nathan Bishop[1]

Carlos Borras Pinilla[2,3], Harold Stalford[2], Ralph Young[1], Greg Ten Eyck[1], Joel Wendt[1], Kevin Eng[1,4], Michael Lilly[1], Malcolm Carroll[1]

1. Sandia National Laboratories
2. University of Oklahoma
3. Universidad Industrial de Santander-Colombia
4. HRL Laboratory

This work was supported by the Laboratory Directed Research and Development program at Sandia National Laboratories. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under Contract DE-AC04-94AL85000.

LABORATORY DIRECTED RESEARCH & DEVELOPMENT

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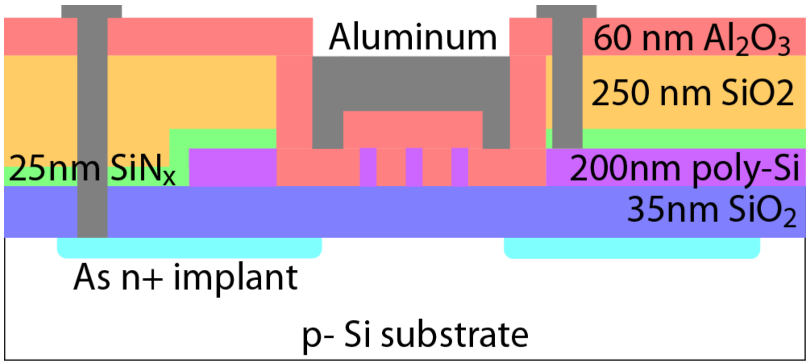
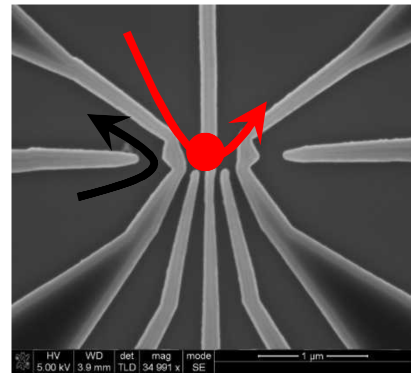
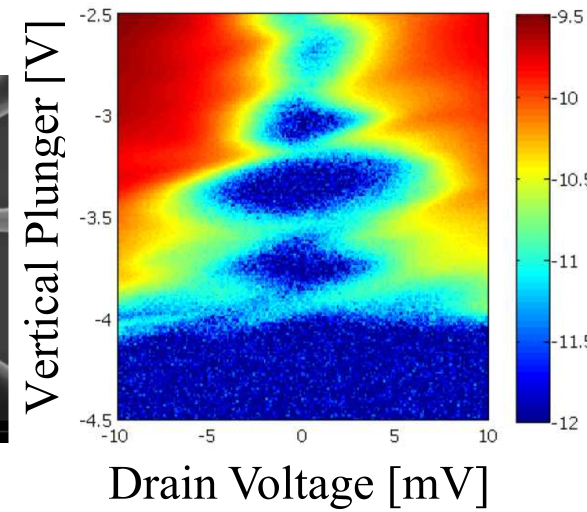
Si MOS devices at Sandia

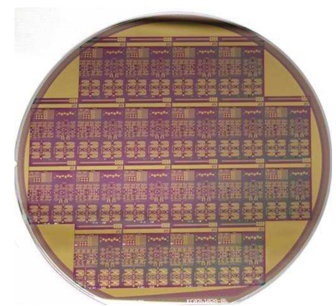






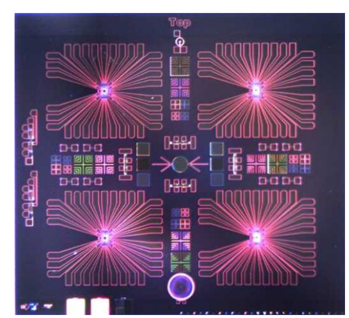
- Oxide growth
- Polysilicon deposition and patterning
- Ohmic contact implant and anneal
- Nitride and pre-metal dielectric dep.
- Silicide and metallization

Front end



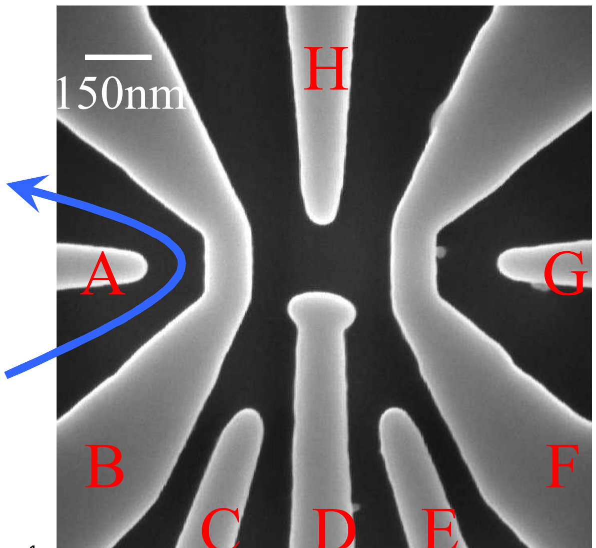
- E-beam litho and polysilicon patterning
- Implant dopant atoms
- Strip metal and re-oxidize polysilicon
- Second dielectric (ALD Al_2O_3) dep.
- Final metallization

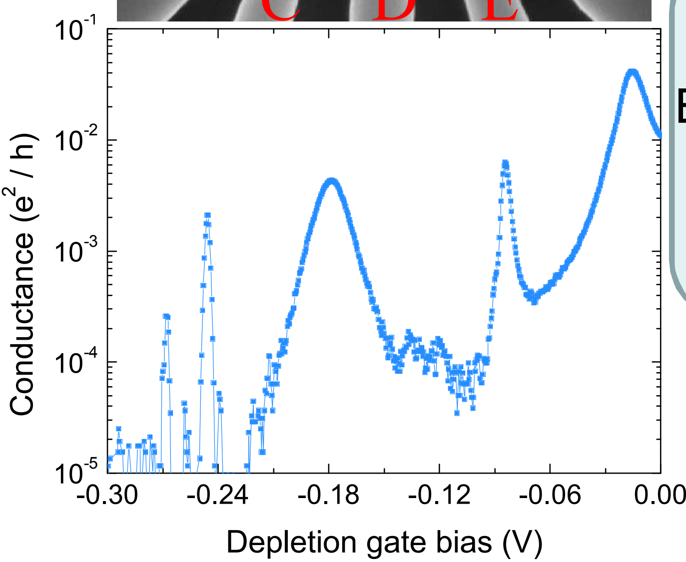
Back end

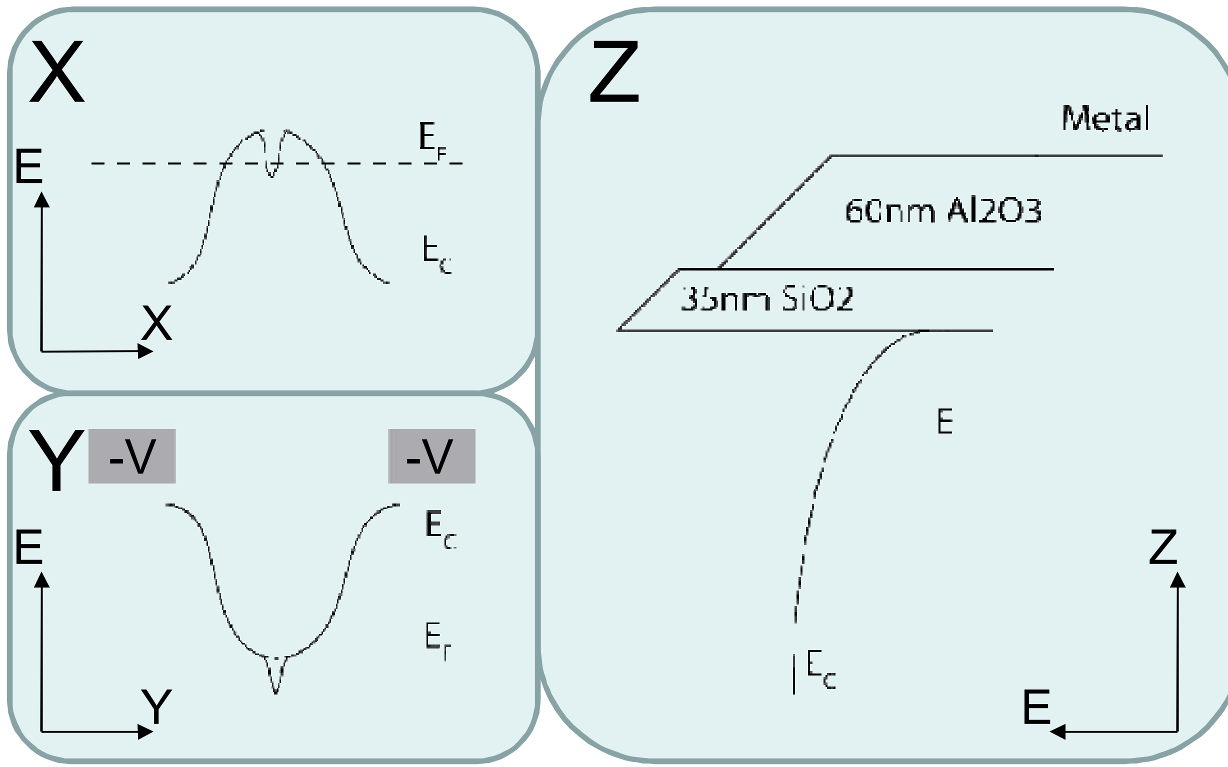


E.P. Nordberg et al., APL 2009 E.P. Nordberg et al., PRB 2009

Constriction with antimony donors implanted







100 keV antimony implant
T ~ 250mK, V_{sd} = 0.5 mVrms

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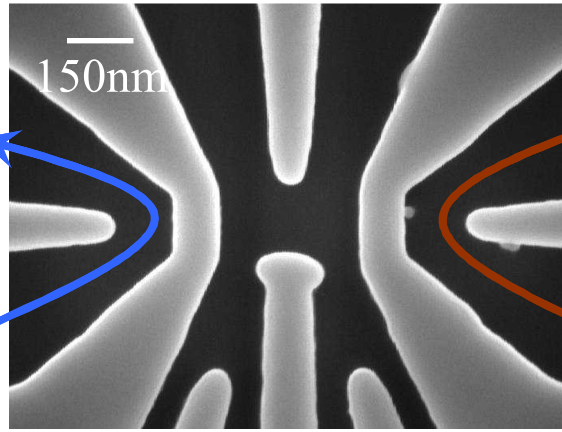
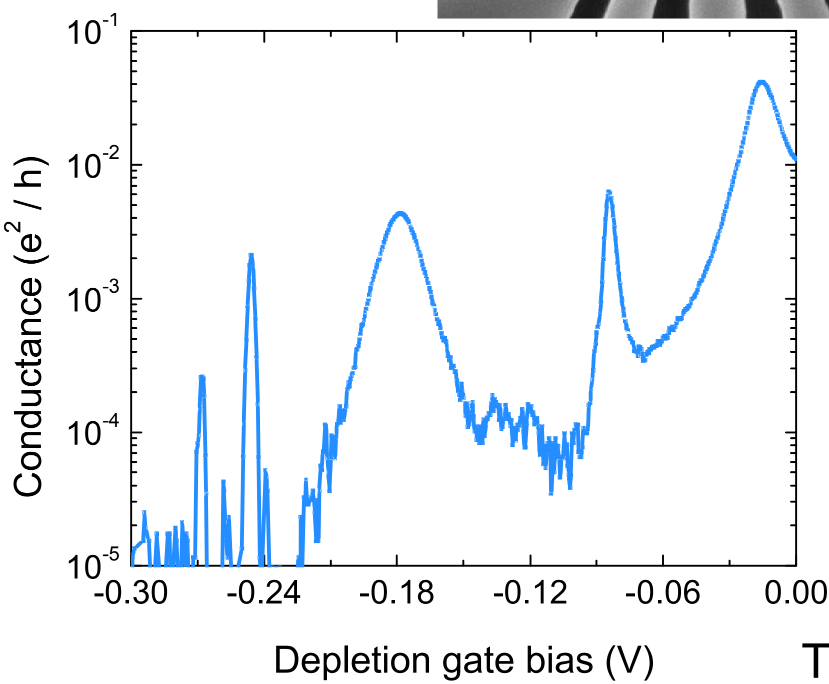
Control vs. implanted

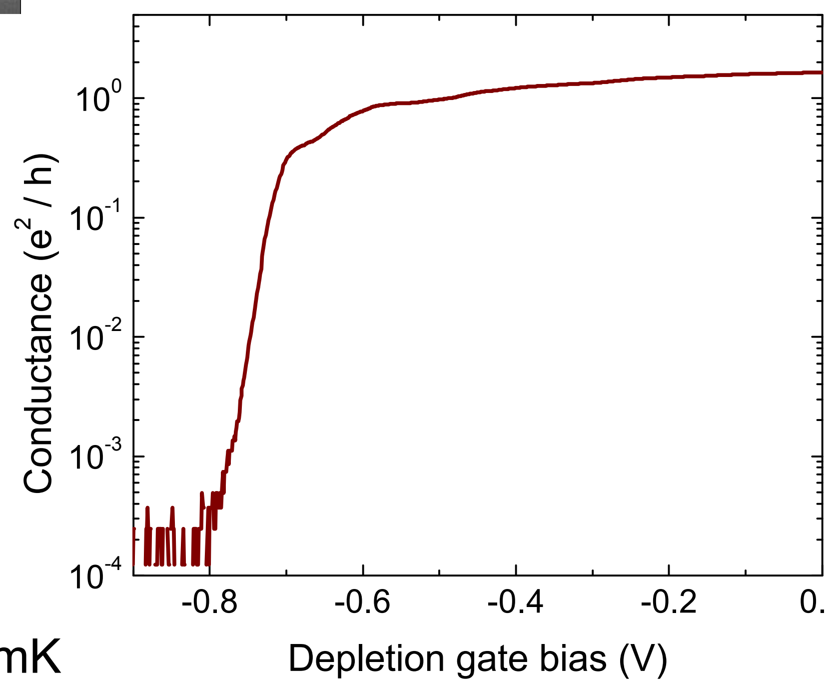
Antimony allows high temperature post-implant processing.



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

Sample type	Q_{fb} (q/cm^2)	D_{it} (q/cm^{2}eV)
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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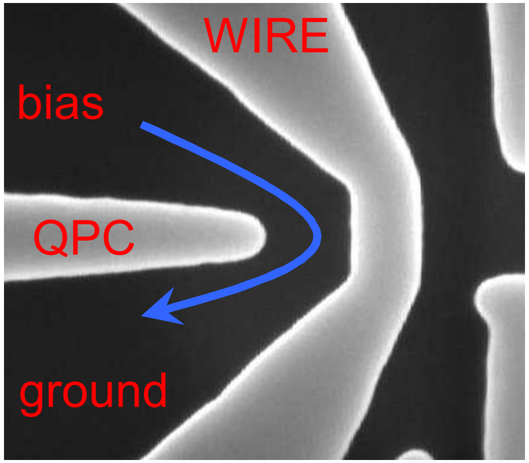
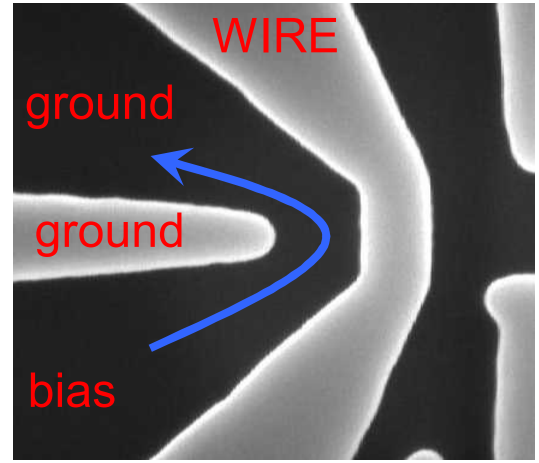
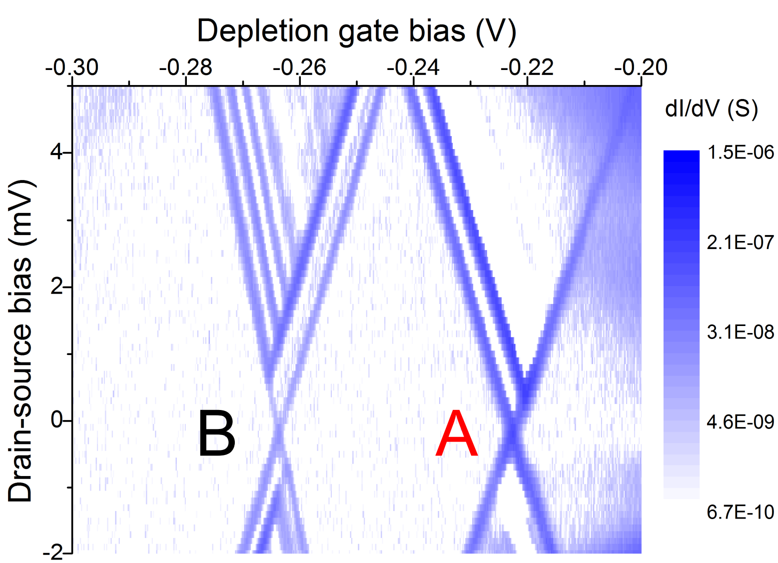
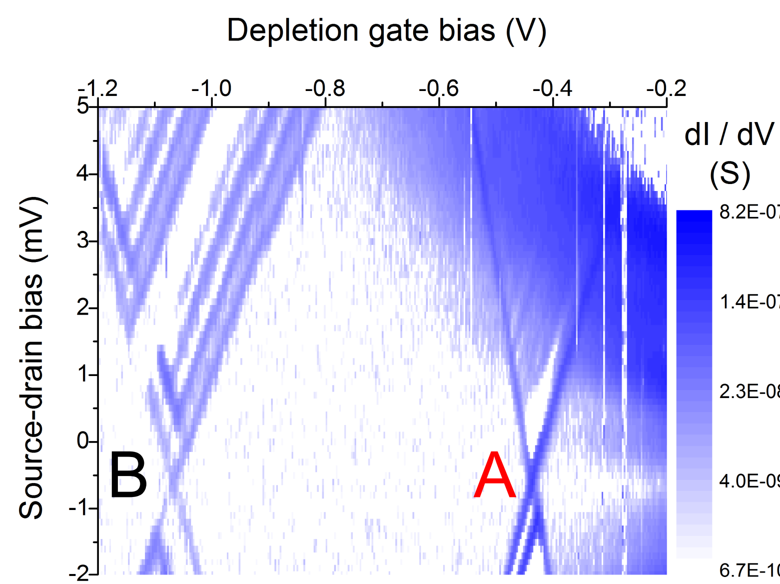
Extracting capacitance









Positive slope $= C_{GATE} / (C_{Total} - C_S)$

Negative slope $= C_{GATE} / C_S$

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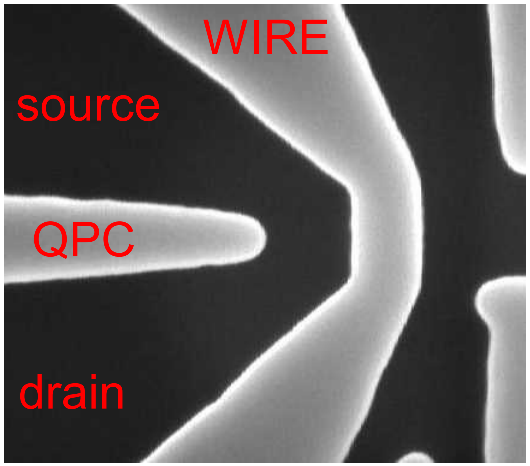
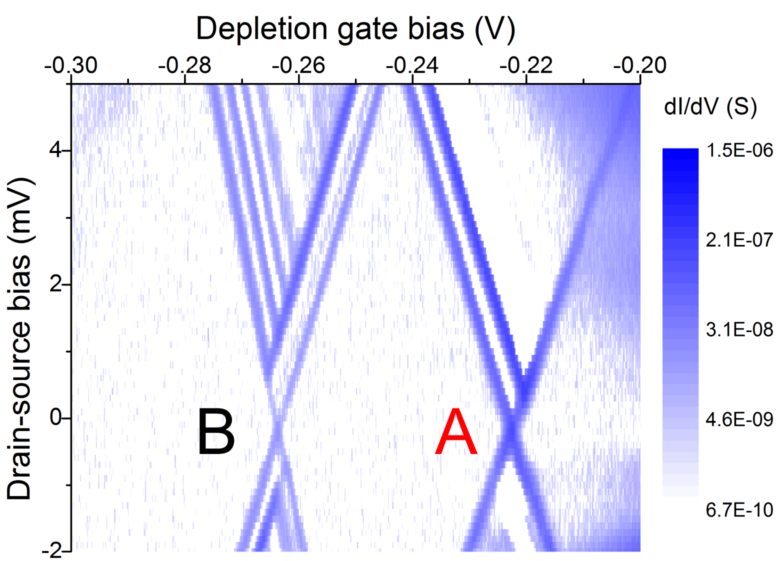
Capacitance ratio





Ratio	Point B	Point A
C_{source} / C_{total}	0.436	0.378
C_{drain} / C_{total}	0.393	0.474
C_{wire} / C_{total}	0.014	0.019
C_{QPC} / C_{total}	0.134	0.099
C_{TG} / C_{total}	0.008	0.012
Total:	98.5%	98.2%

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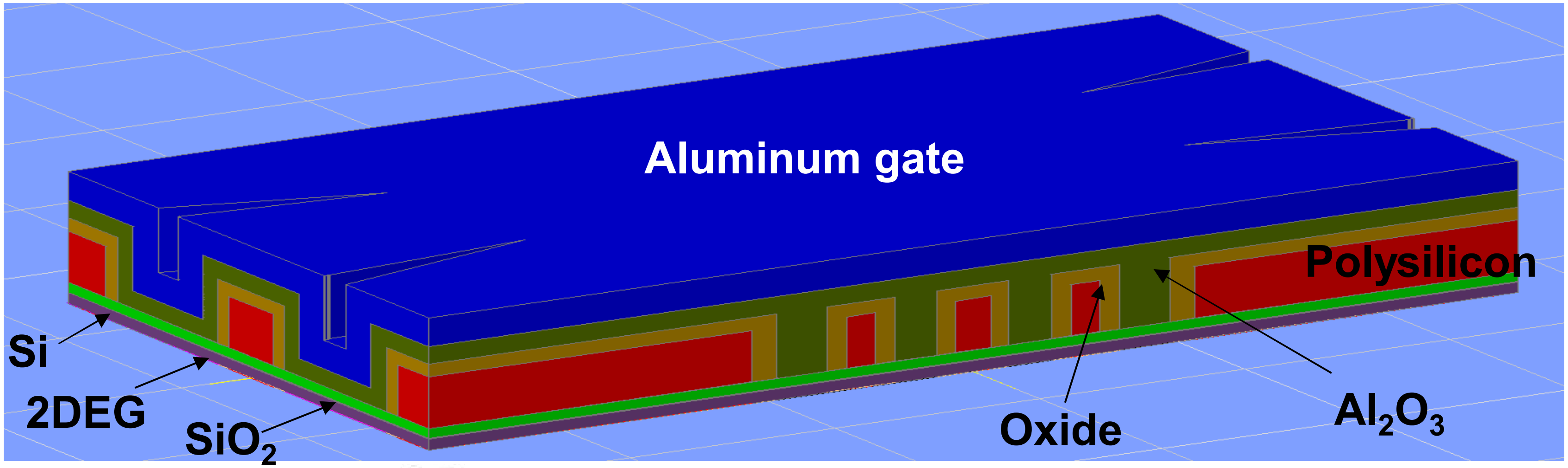
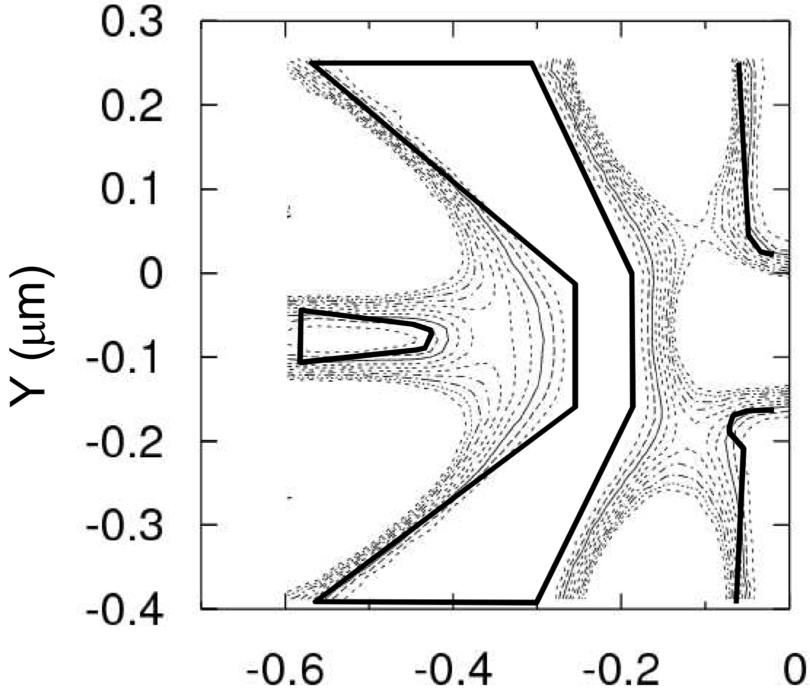
Electrostatic model

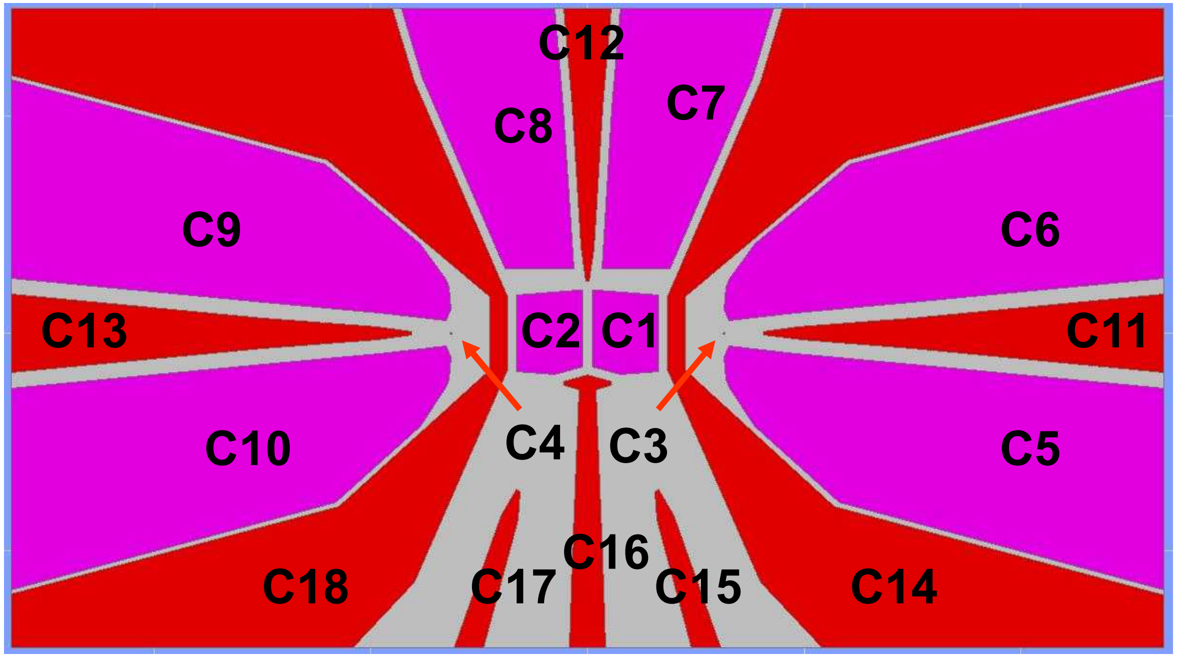




Density contours in 1×10^{11} cm^{-2} increments from 1×10^{11} to 1×10^{12} cm^{-2}

V_{tg} = 18V, all others = 0V

Capacitive model



		S438	(aF)		C3 & C4:	1.8nm	radius	Donor	Implant	10nm	depth		C1 & C2:	QD's	(RY's Sim)					
		QD	QD	Donor	Donor	2DEG-SE	2DEG-NE	2DEG-NNE	2DEG-NNW	2DEG-NW	2DEG-SW	E. QPC	V. Gate	W. QPC	E. Q	E. P.	C. P.	W. P.	W. Q	Top G
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
QD	1	68.5917	-15.4877	-0.1204	-0.0204	-3.5873	-3.0517	-11.8335	-3.1399	-1.2549	-1.4843	-0.2484	-1.7458	-0.1214	-11.1903	-0.6631	-5.6034	-0.4491	-2.2456	-6.3446
QD	2	-15.4877	68.4966	-0.0206	-0.1184	-1.4891	-1.2510	-3.1314	-11.8363	-3.0481	-3.5656	-0.1207	-1.7356	-0.2484	-2.2385	-0.4503	-5.5851	-0.6591	-11.1480	-6.3628
Donor	3	-0.1204	-0.0206	2.7979	-0.0002	-0.8659	-0.8474	-0.1170	-0.0327	-0.0228	-0.0260	-0.0953	-0.0062	-0.0023	-0.4767	-0.0160	-0.0324	-0.0078	-0.0323	-0.0759
Donor	4	-0.0204	-0.1184	-0.0002	2.7611	-0.0257	-0.0225	-0.0323	-0.1155	-0.8402	-0.8544	-0.0023	-0.0061	-0.0935	-0.0318	-0.0077	-0.0319	-0.0157	-0.4693	-0.0736
2DEG-SE	5	-3.5873	-1.4891	-0.8659	-0.0257	391.2932	-51.9558	-6.7144	-3.5652	-3.6557	-4.4334	-51.6689	-0.5257	-0.4058	-108.6078	-3.9582	-4.2818	-1.4031	-5.1752	-138.9746
2DEG-NE	6	-3.0517	-1.2510	-0.8474	-0.0225	-51.9558	386.4215	-16.3242	-4.7106	-3.6170	-3.6428	-51.5746	-0.8370	-0.3684	-106.2514	-1.4039	-2.1148	-0.8245	-4.4215	-133.1987
2DEG-NNE	7	-11.8335	-3.1314	-0.1170	-0.0323	-6.7144	-16.3242	215.9327	-24.7744	-4.7113	-3.5555	-0.8729	-29.4635	-0.3973	-52.6689	-0.6863	-1.5295	-0.5767	-5.5480	-52.9642
2DEG-NNW	8	-3.1399	-11.8363	-0.0327	-0.1155	-3.5652	-4.7106	-24.7744	215.6451	-16.3406	-6.6975	-0.3961	-29.3706	-0.8743	-5.5421	-0.5788	-1.5291	-0.6832	-52.4839	-52.9758
2DEG-NW	9	-1.2549	-3.0481	-0.0228	-0.8402	-3.6557	-3.6170	-4.7113	-16.3406	386.3316	-51.8335	-0.3674	-0.8370	-51.6140	-4.4113	-0.8278	-2.1134	-1.4005	-106.4272	-133.0122
2DEG-SW	10	-1.4843	-3.5656	-0.0260	-0.8544	-4.4334	-3.6428	-3.5555	-6.6975	-51.8335	390.2942	-0.4034	-0.5247	-51.8362	-5.1429	-1.4017	-4.2545	-3.9172	-108.7392	-137.9844
E. QPC	11	-0.2484	-0.1207	-0.0953	-0.0023	-51.6689	-51.5746	-0.8729	-0.3961	-0.3674	-0.4034	316.8823	-0.0626	-0.0392	-7.8193	-0.2033	-0.2675	-0.1029	-0.4728	-202.1467
V. Gate	12	-1.7458	-1.7356	-0.0062	-0.0061	-0.5257	-0.8370	-29.4635	-29.3706	-0.8370	-0.5247	-0.0626	198.2384	-0.0629	-3.2945	-0.0713	-0.3264	-0.0710	-3.2299	-125.8808
W. QPC	13	-0.1214	-0.2484	-0.0023	-0.0935	-0.4058	-0.3684	-0.3973	-0.8743	-51.6140	-51.8362	-0.0392	-0.0629	317.2109	-0.4735	-0.1038	-0.2688	-0.2037	-7.9298	-202.2619
E. Q	14	-11.1903	-2.2385	-0.4767	-0.0318	-108.6078	-106.2514	-52.6689	-5.5421	-4.4113	-5.1429	-7.8193	-3.2945	-0.4735	930.5588	-30.1907	-12.0956	-1.8729	-6.4402	-571.5868
E. P.	15	-0.6631	-0.4503	-0.0160	-0.0077	-3.9582	-1.4039	-0.6863	-0.5788	-0.8278	-1.4017	-0.2033	-0.0713	-0.1038	-30.1907	99.2164	-21.9354	-1.2404	-1.8864	-33.5535
C. P.	16	-5.6034	-5.5851	-0.0324	-0.0319	-4.2818	-2.1148	-1.5295	-1.5291	-2.1134	-4.2545	-0.2675	-0.3264	-0.2688	-12.0956	-21.9354	175.0828	-21.8002	-12.0778	-79.3580
W. P.	17	-0.4491	-0.6591	-0.0078	-0.0157	-1.4031	-0.8245	-0.5767	-0.6832	-1.4005	-3.9172	-0.1029	-0.0710	-0.2037	-1.8729	-1.2404	-21.8002	99.1811	-30.2491	-33.5721
W. Q	18	-2.2456	-11.1480	-0.0323	-0.4693	-5.1752	-4.4215	-5.5480	-52.4839	-106.4272	-108.7392	-0.4728	-3.2299	-7.9298	-6.4402	-1.8864	-12.0778	-30.2491	930.6425	-571.4622
Top G	19	-6.3446	-6.3628	-0.0759	-0.0736	-138.9746	-133.1987	-52.9642	-52.9758	-133.0122	-137.9844	-202.1467	-125.8808	-202.2619	-571.5868	-33.5535	-79.3580	-33.5721	-571.4622	2481.7889

with Harold Stalford, Ralph Young

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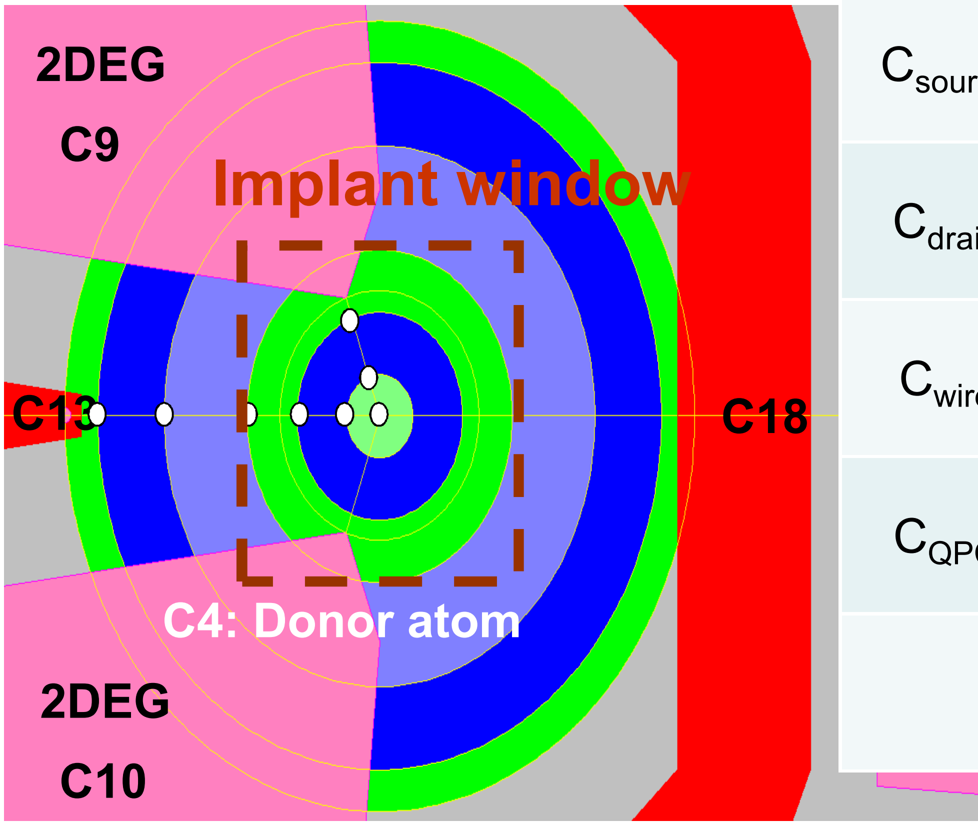
Capacitive results



Ratio	Point B		Point A	
	Expt.	Sim.	Expt.	Sim.
C_{source} / C_{total}	0.436	0.435	0.378	0.379
C_{drain} / C_{total}	0.393	0.392	0.474	0.473
C_{wire} / C_{total}	0.014	0.013	0.019	0.019
C_{QPC} / C_{total}	0.134	0.132	0.099	0.095
Total:	0.985		0.982	

with Harold Stalford,
Ralph Young

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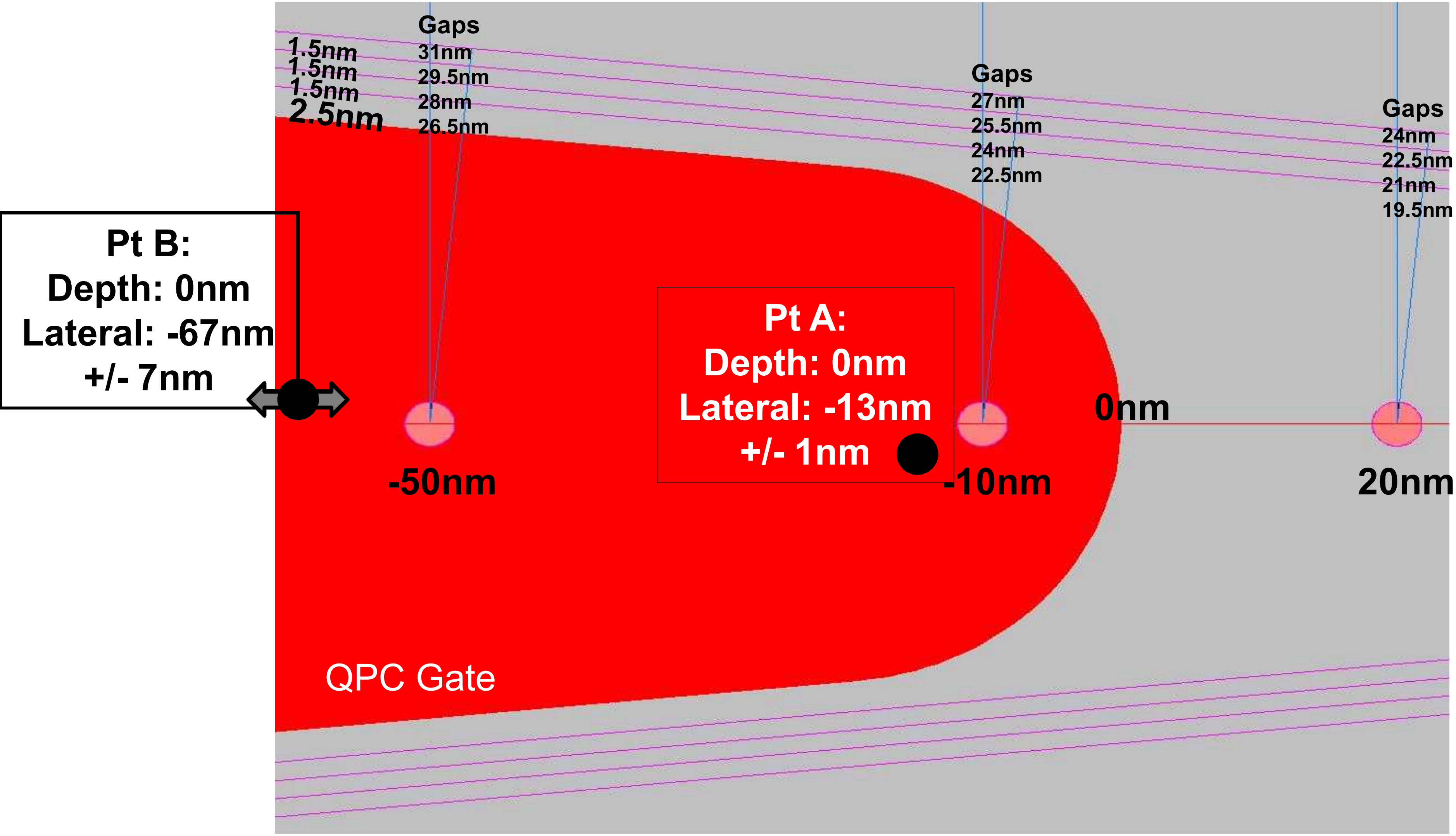
Pts A & B Dot Locations



Conclusions

- In implanted devices, we must decide whether tunneling resonances are due to donors or defects.
- Capacitive measurements locate the resonant states in the point contact with high confidence.
- Applicable to all systems, for donor or gate-defined quantum dots.

Acknowledgements

Quantum Team:
Ed Bielejec
Steve Carr
Malcolm Carroll
Kent Childs
Kevin Eng
Robert Grubbs
Paul Hines
Mike Lilly
TzuMing Lu
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
Andrea Morello
Andrew Dzurak
Dan Tomlinson
William Lee
Michelle Simmons

Quantum Information S&T

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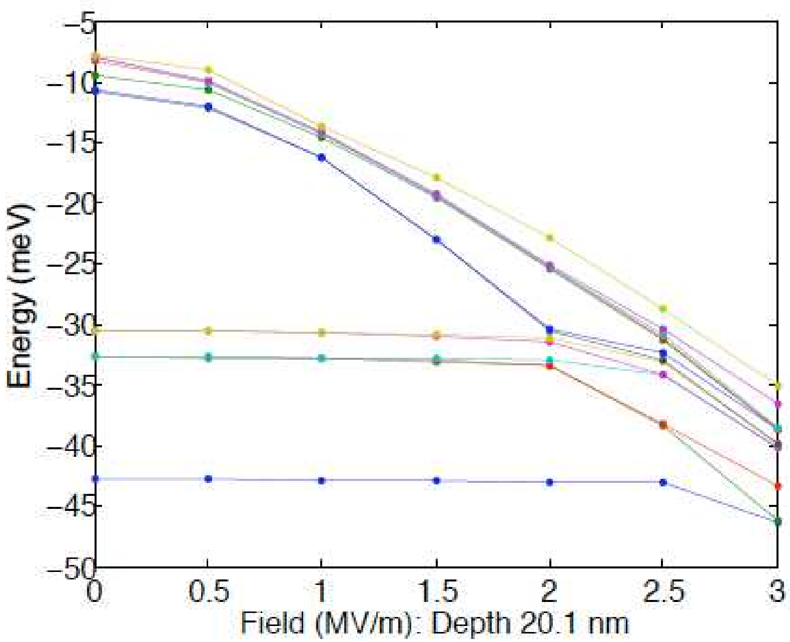
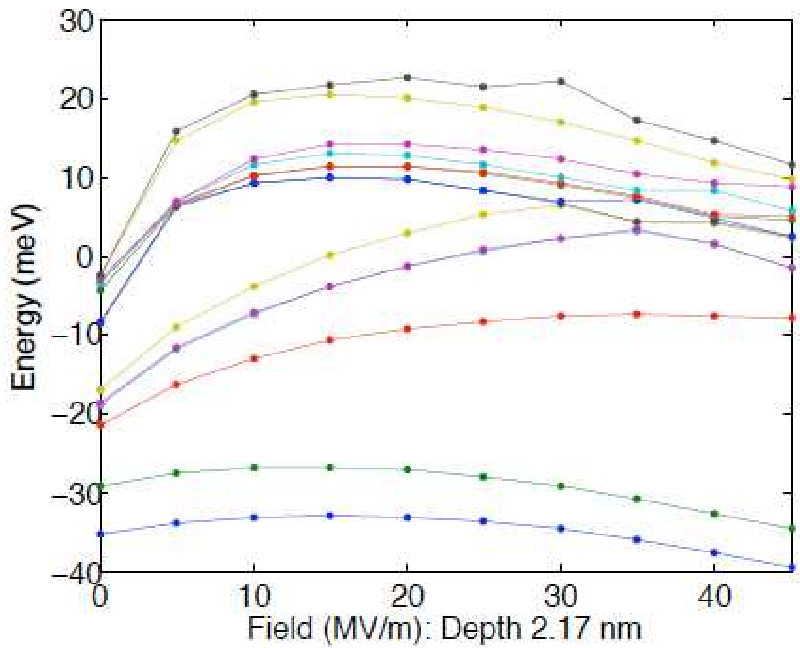
Spectroscopy: Stark shifts

Deeply buried donor



Donor near interface



with Rajib Rahman

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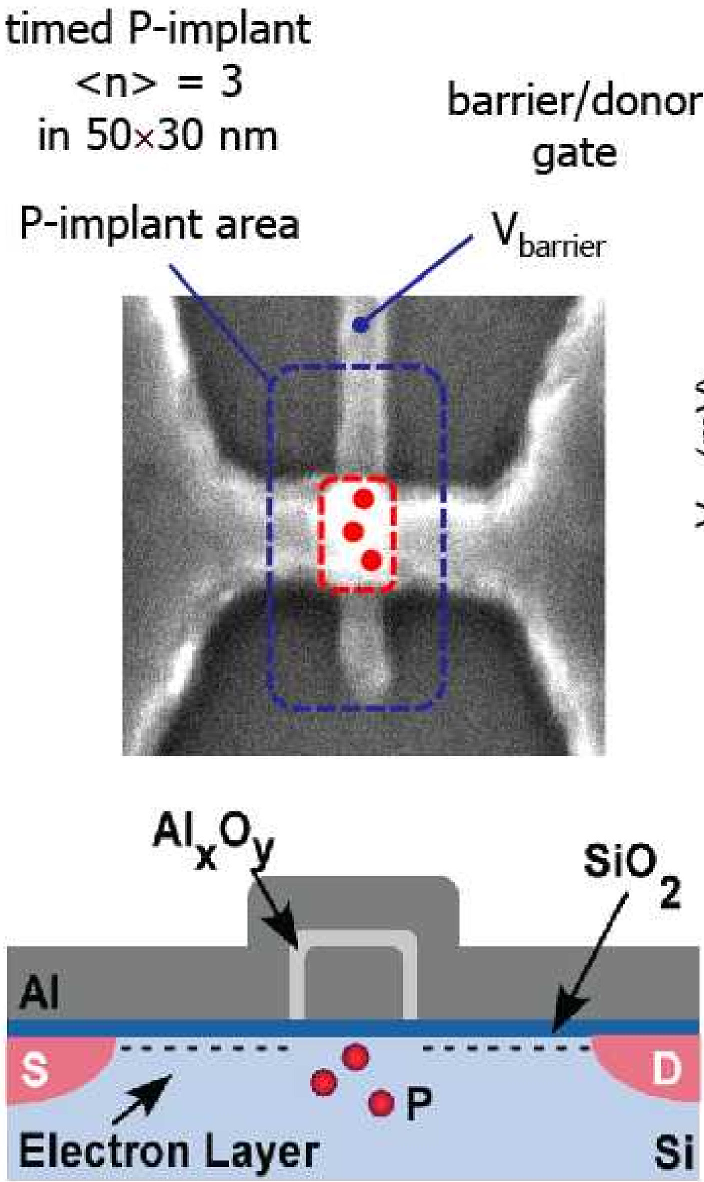
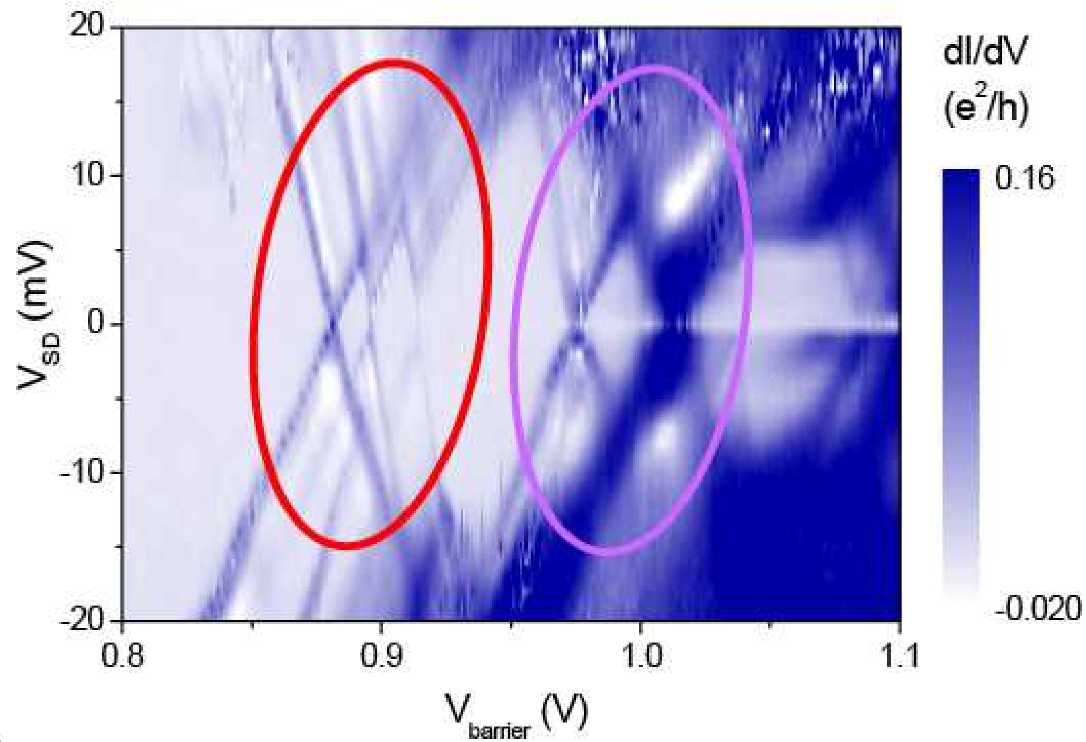
Previous work



Tan et al., Nano Lett. 2010



Long coherence times in Si:P
T2 = 0.6 seconds.

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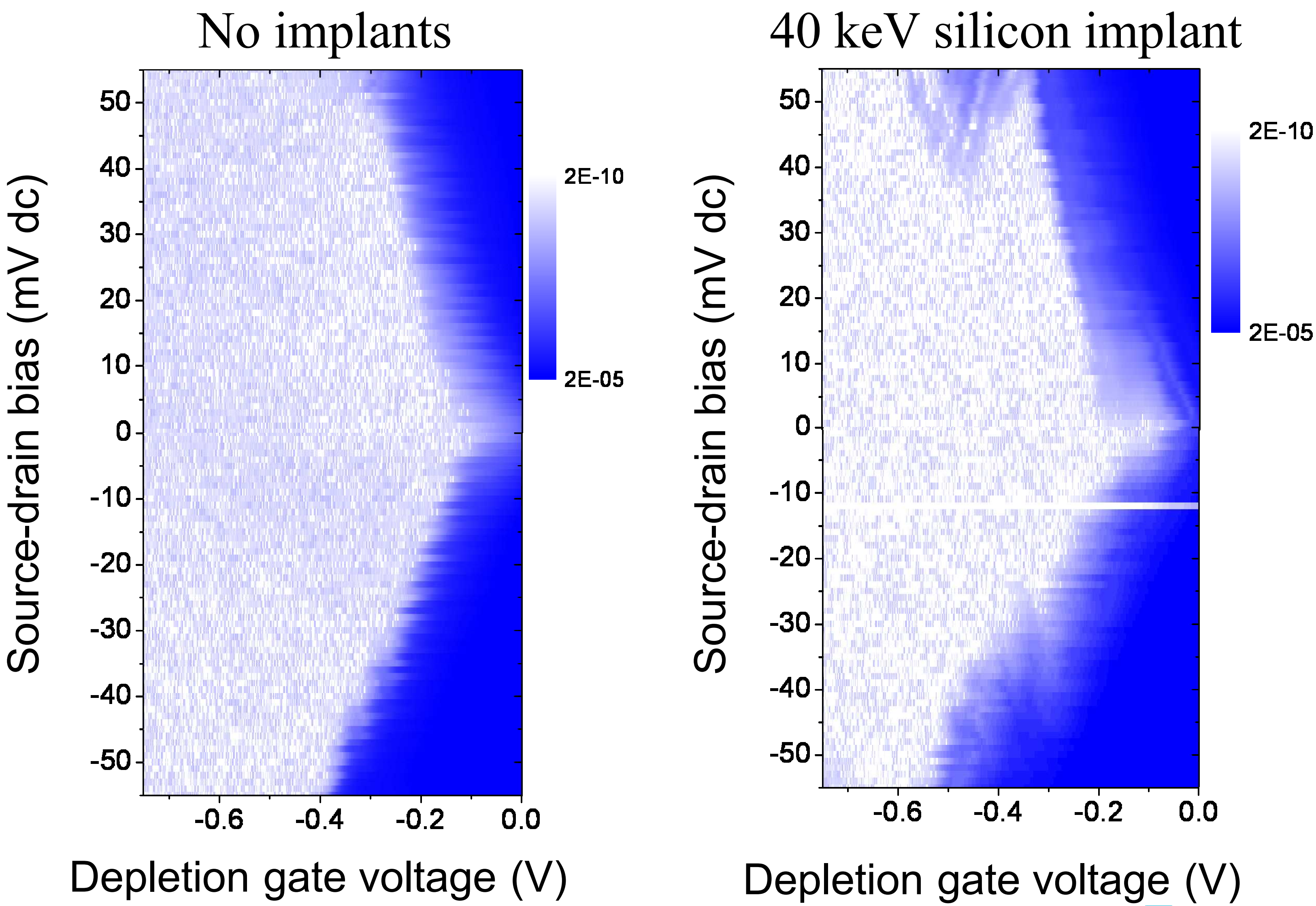
Control sample: Silicon implant



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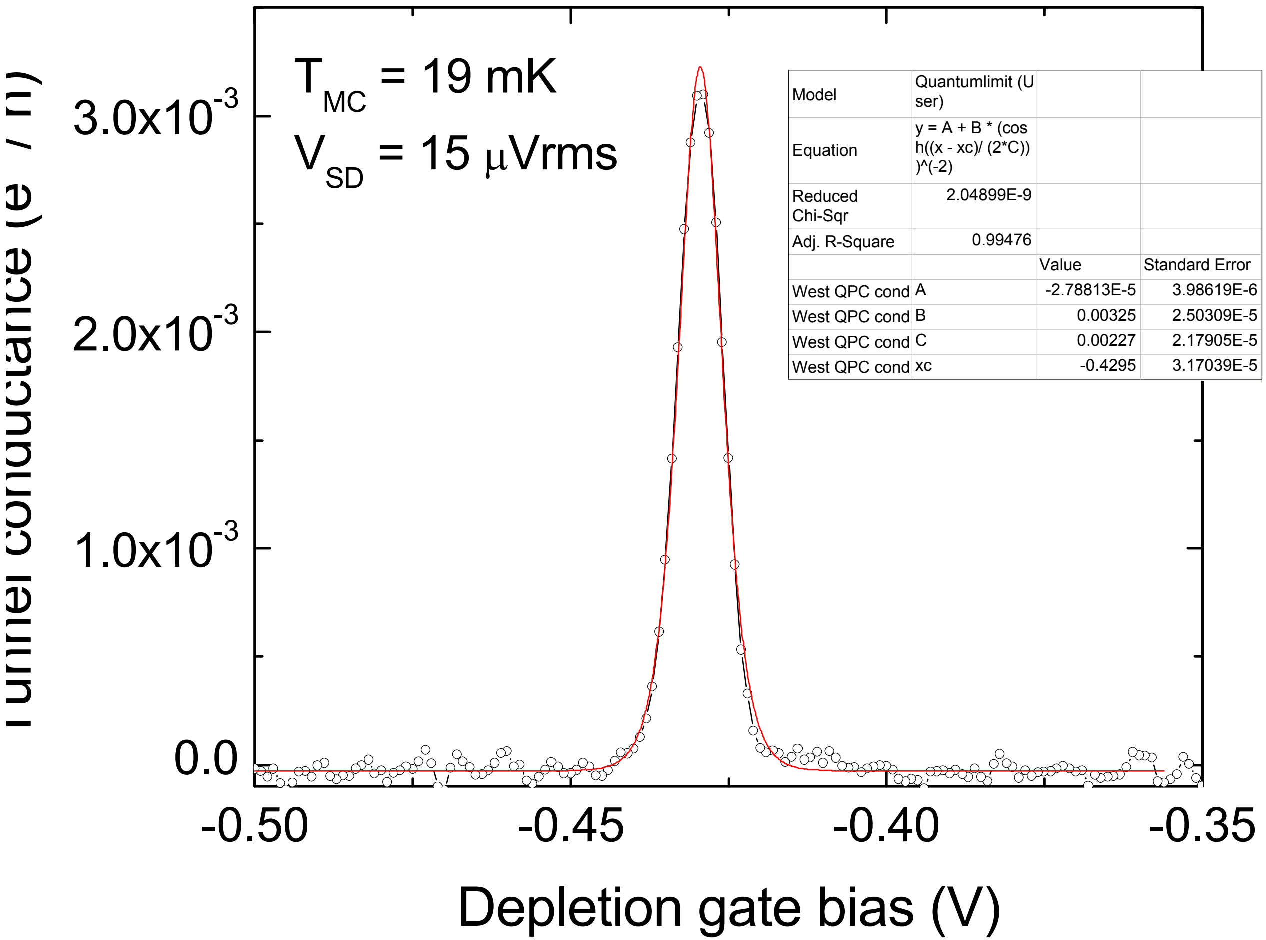
Lever arm analysis

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

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

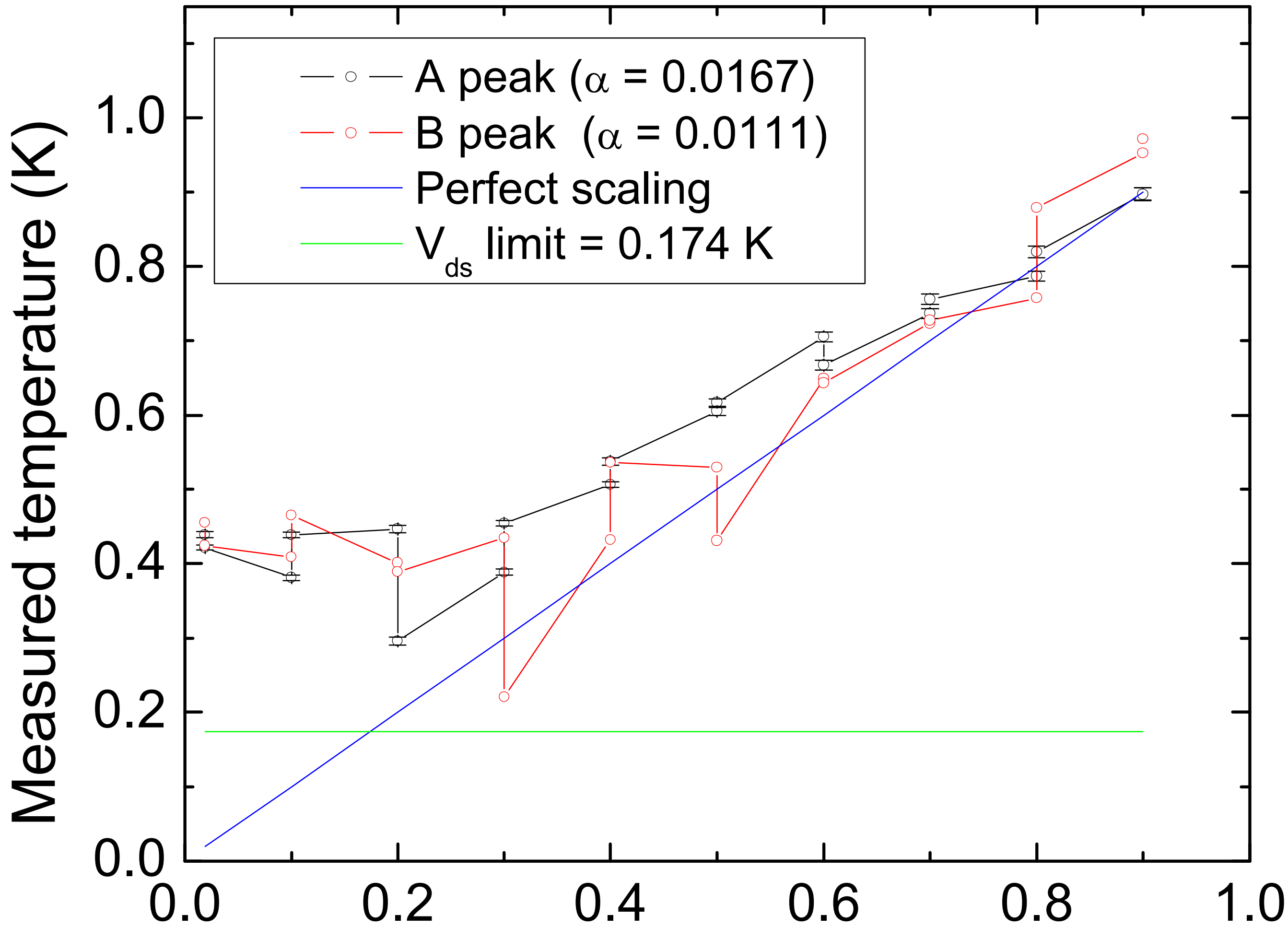
$$\alpha = \frac{2k_BT_{measured}}{\delta V}$$



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

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

Lever arm analysis



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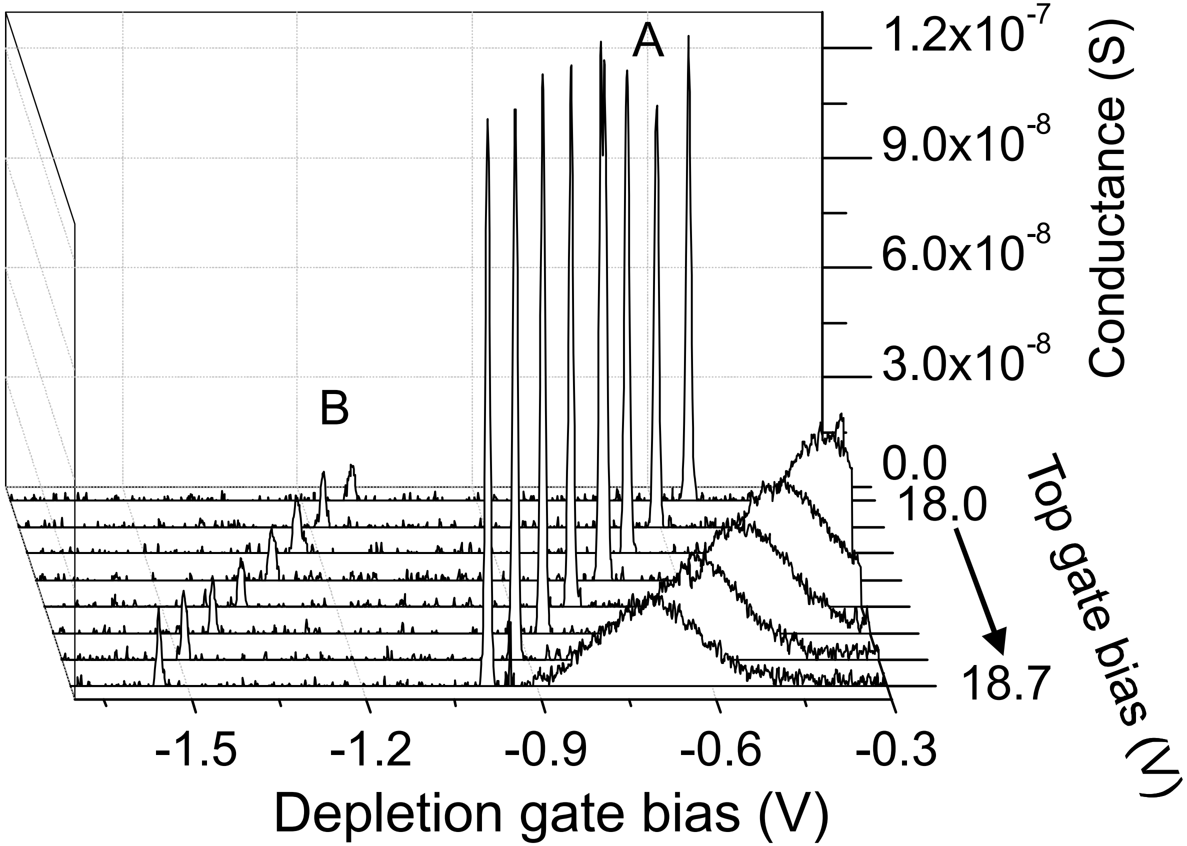
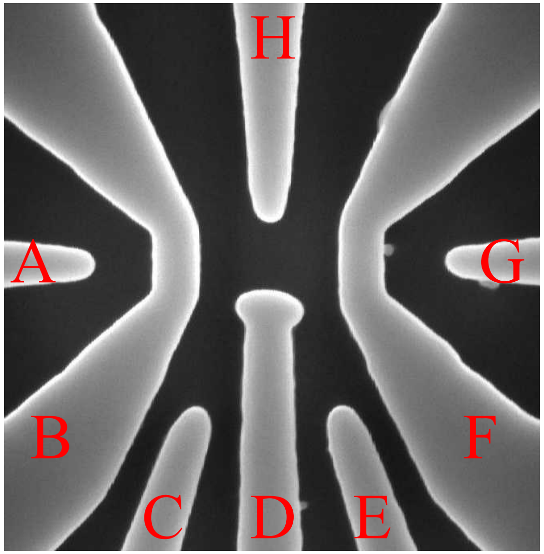
Top gate lever arm

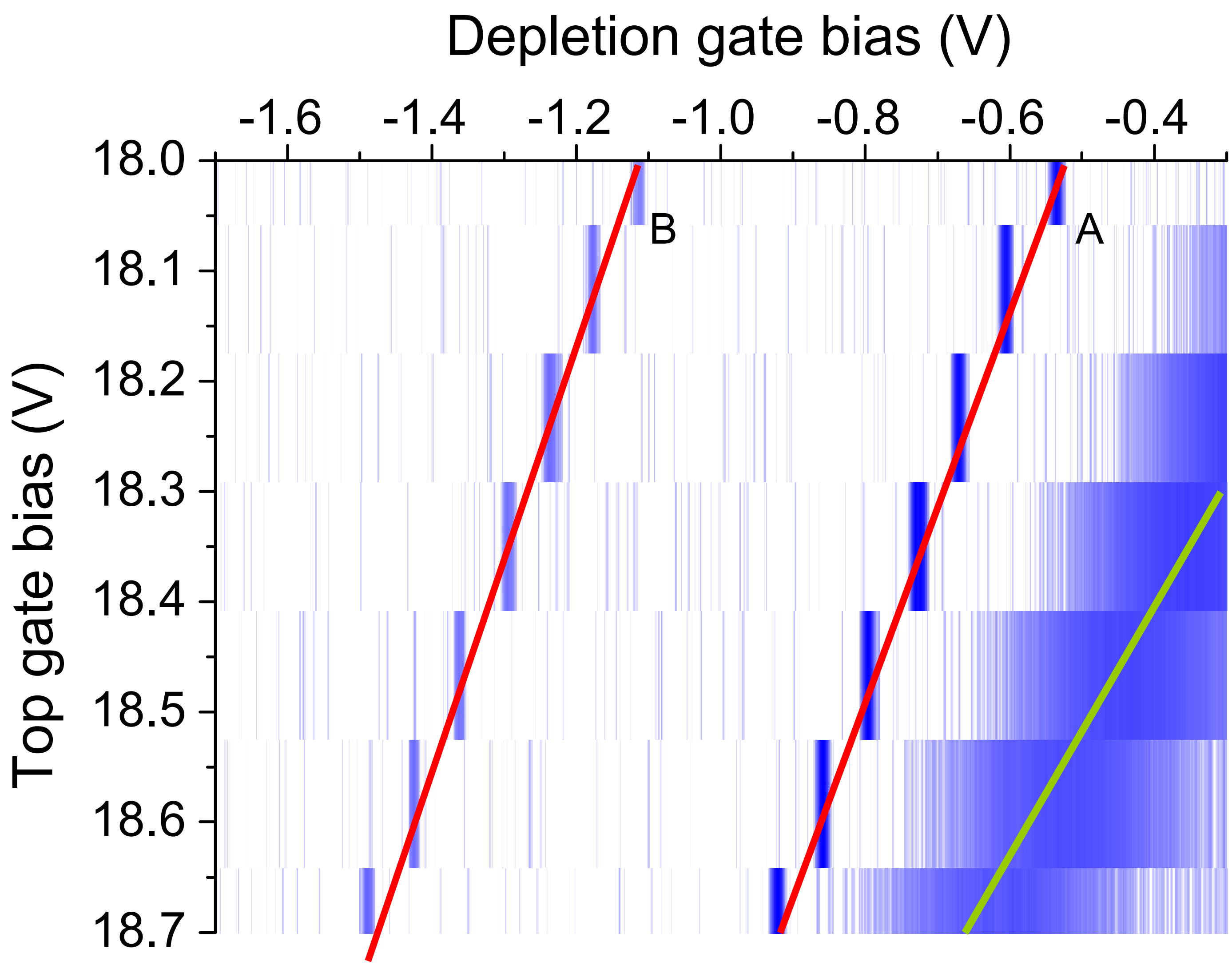


A slope:
$dV_{Poly} / dV_{TG} = -0.639$

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



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!

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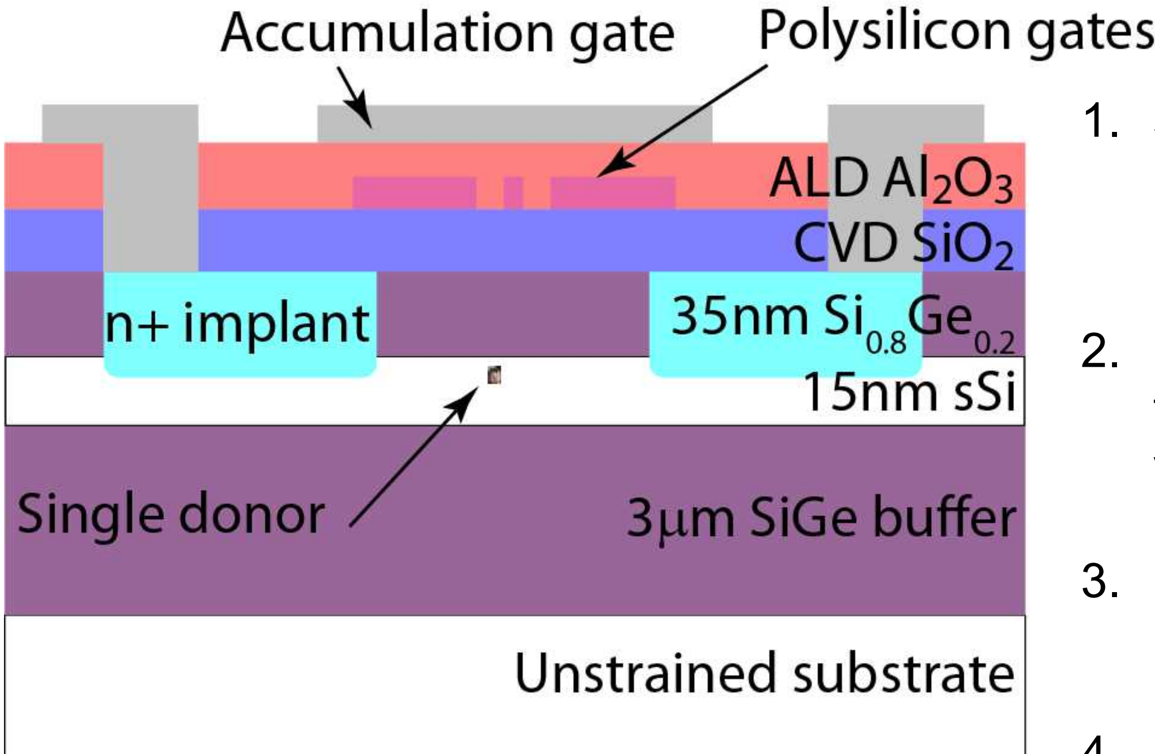
Advantages of Si-SiGe interface

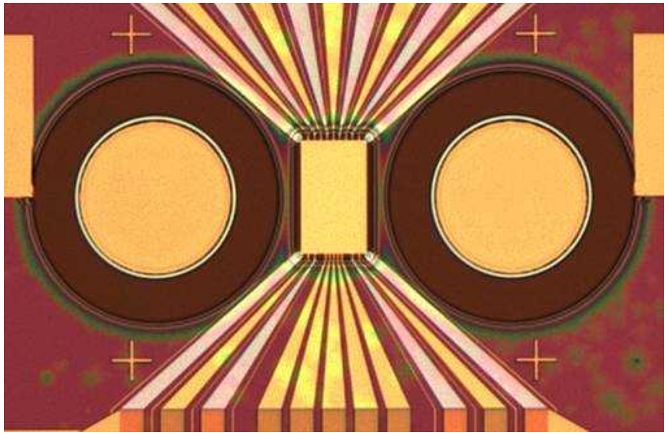


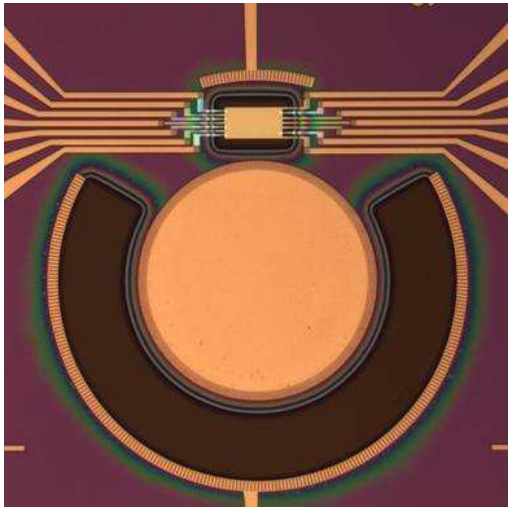
Film stack showing goal: DQD with SiGe dielectric on relaxed SiGe buffer layer.

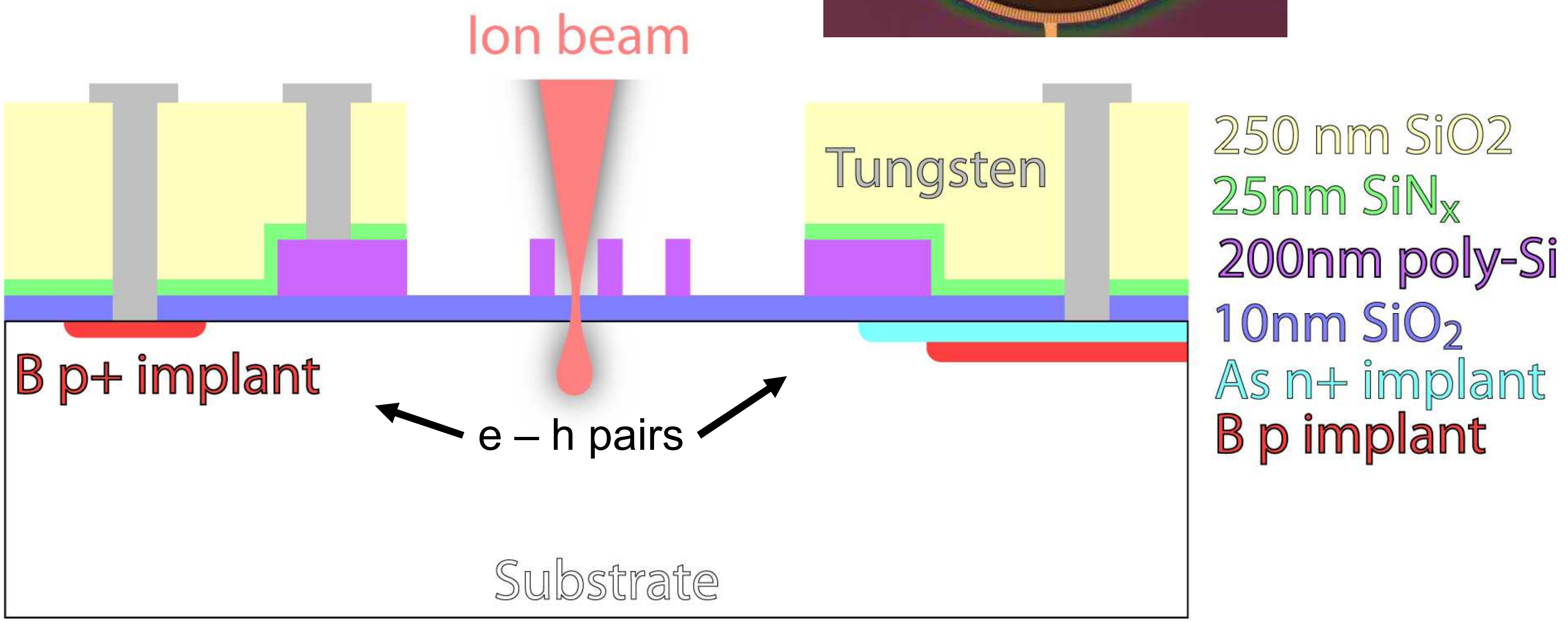
1. sSOI allows us to integrate SiGe dielectrics into our normal MOSFET process.
2. SiGe dielectric constant higher than SiO2, lowering gate voltages.
3. Si-SiGe interface is clean, reducing charge noise.
4. Electron g-factor differs in Si and SiGe, potentially allowing controlled spin rotations.

sSOI substrate characterization for STM donor lithography, with SiGe dielectric. Collaboration with Michelle Simmons, and new STM litho program at Sandia!

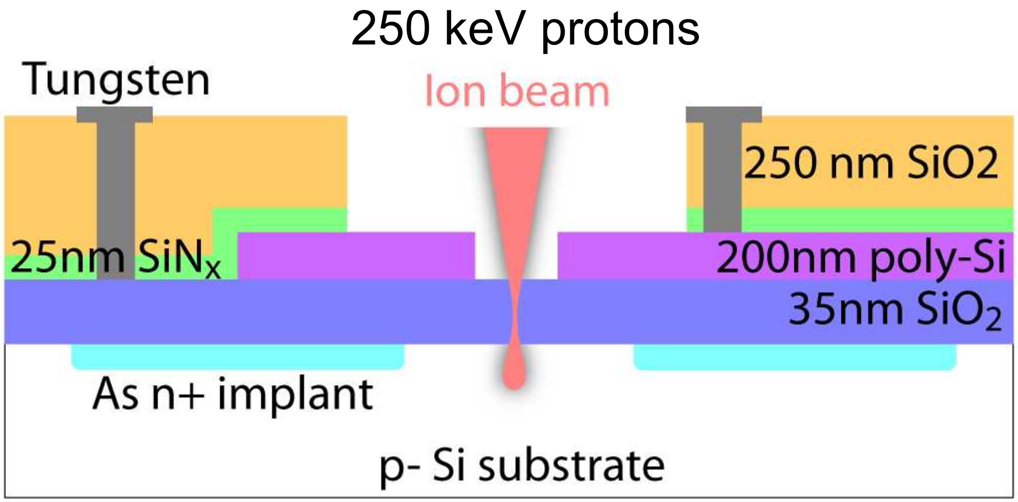
Detecting single dopant atoms

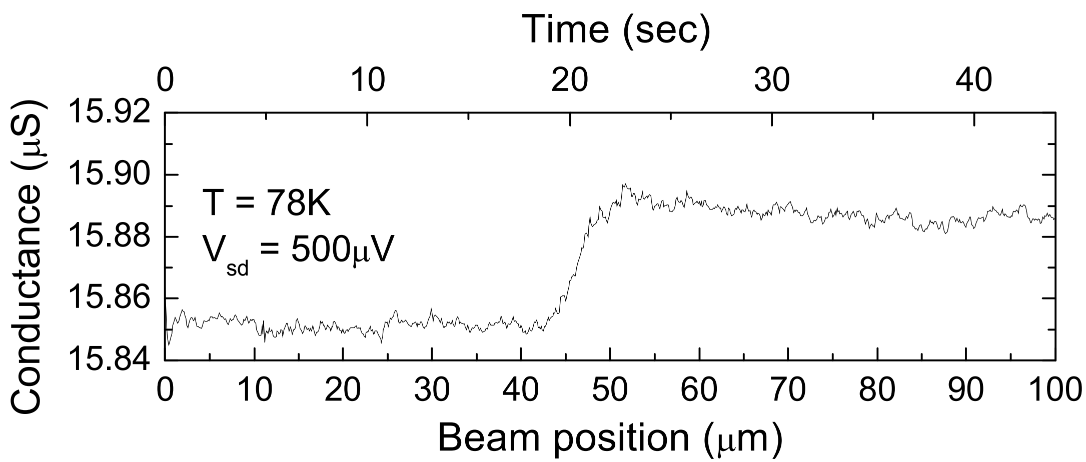


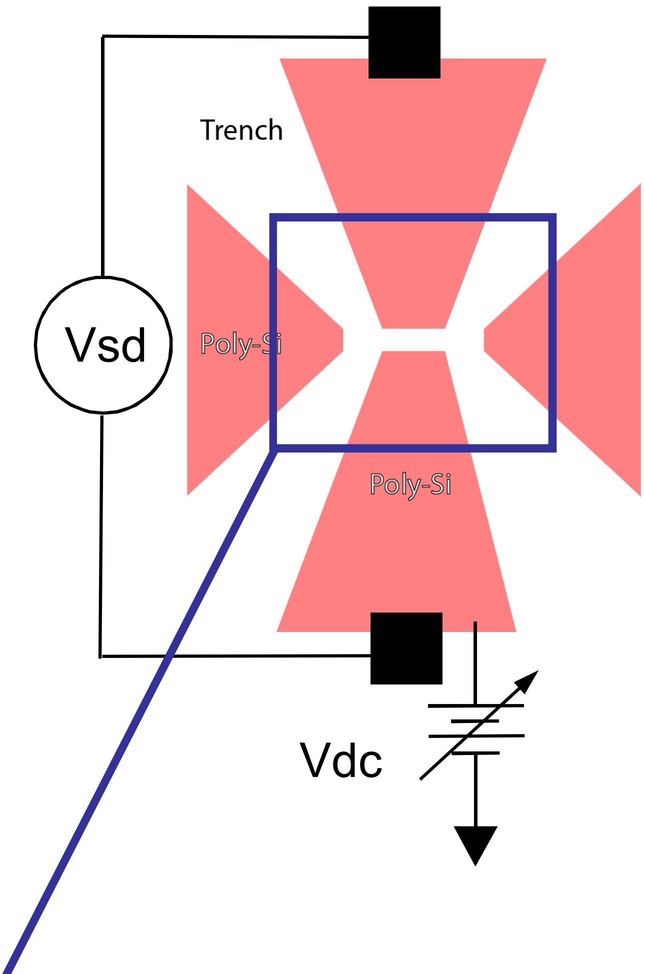




Use the device as a detector

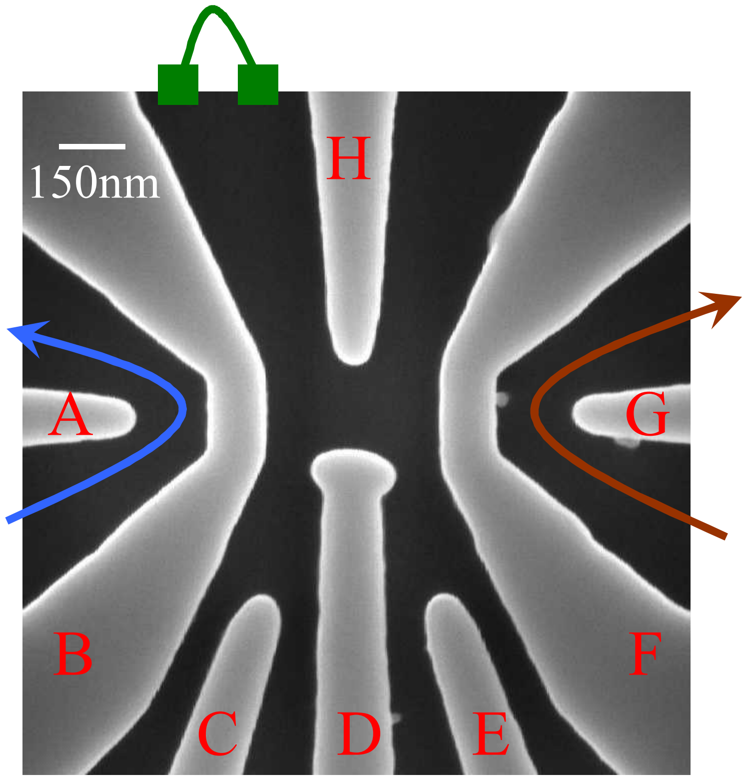


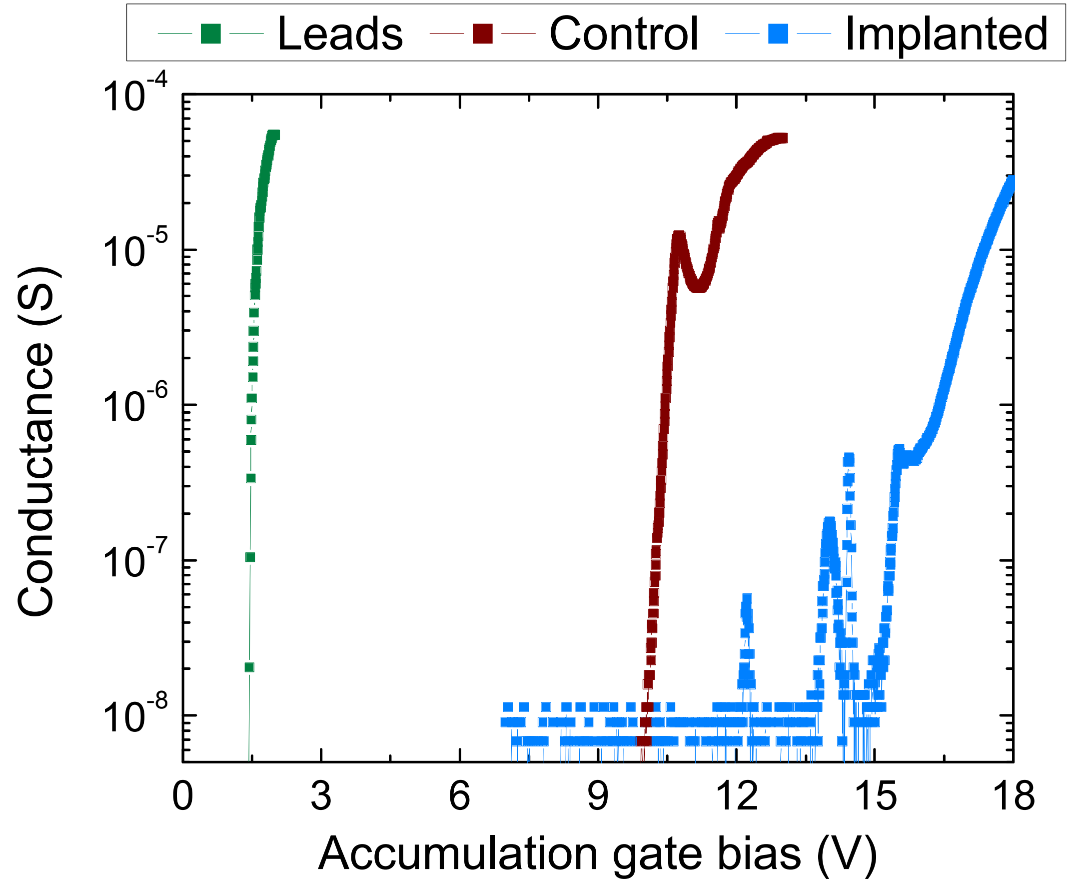




Proton beam raster window

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

Ion implant damage

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