How a single defect can affect silicon nano-devices

Ted Thorbeck

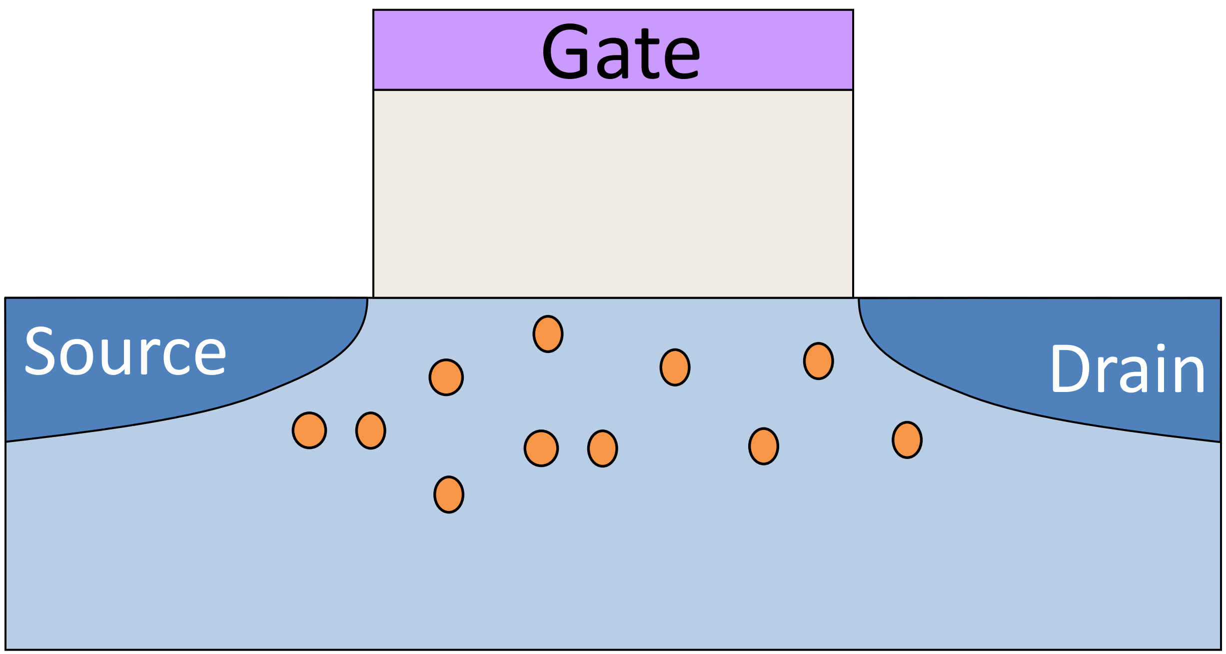
tedt@nist.gov

National Institute of Standards and Technology
U.S. Department of Commerce

University of Maryland

The Big Idea

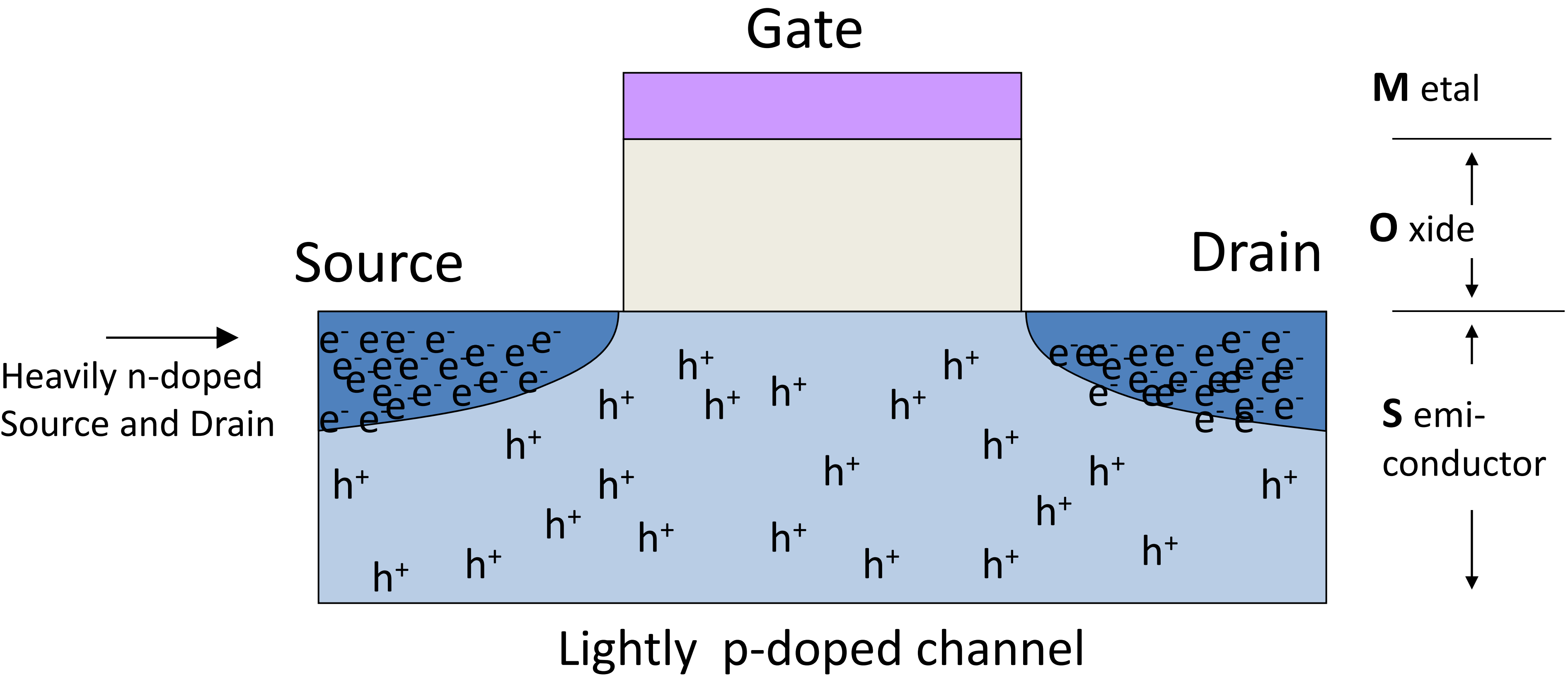
- As MOS-FETs continue to shrink, single atomic scale defects are beginning to affect device performance



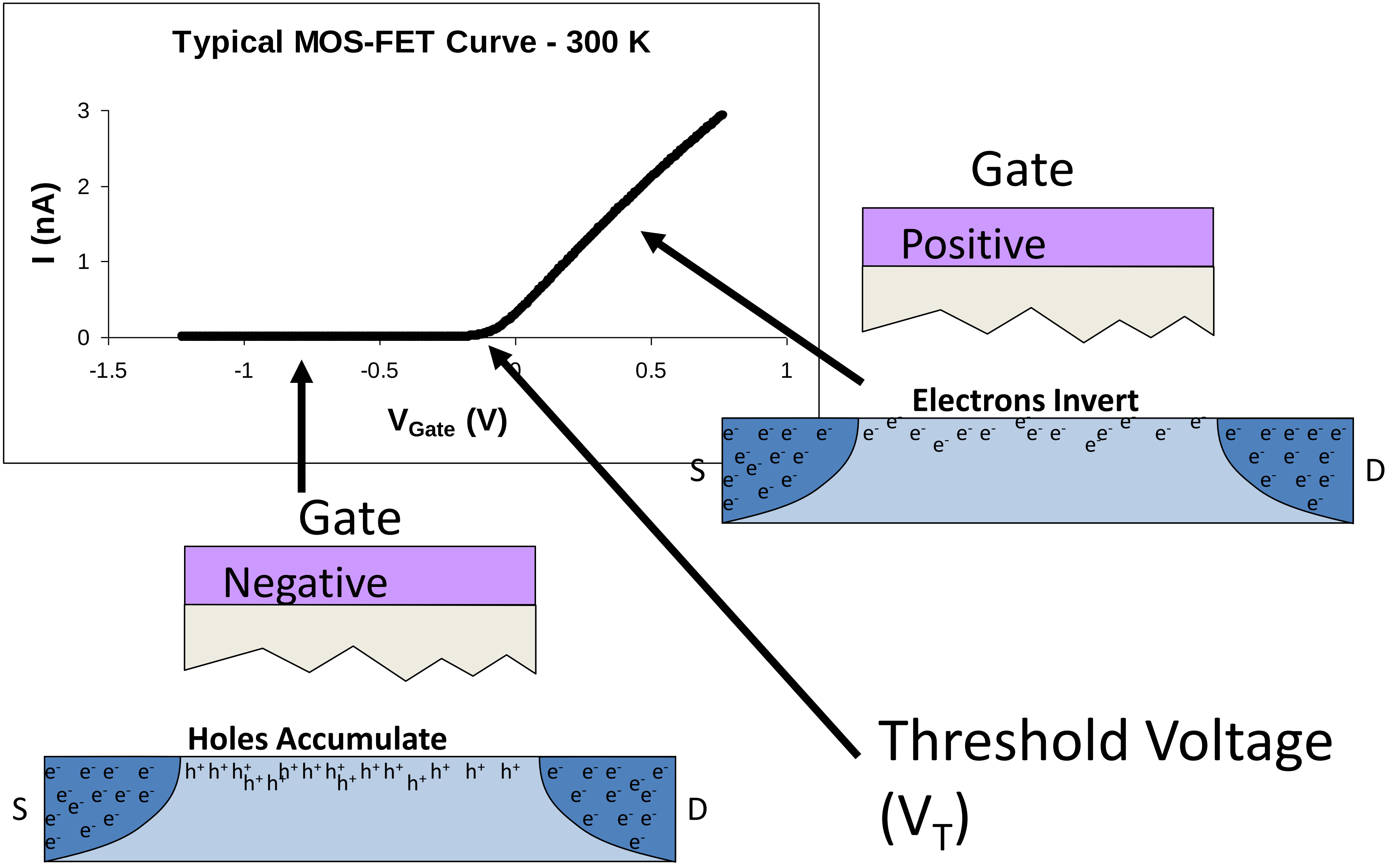
Outline

- The impact of a single atom on a MOSFET
- Locating a single atom in a transistor
- The potential for a single atom

Review of MOS-FETs I

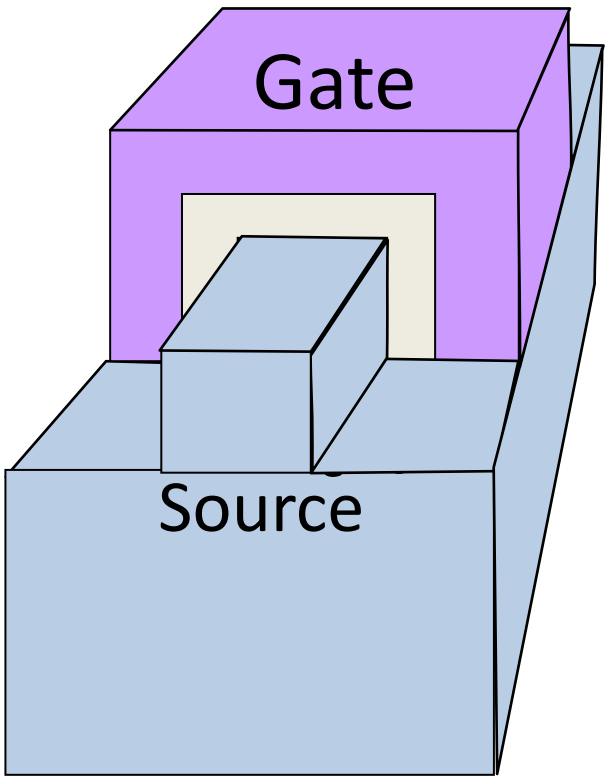


Review of MOS-FETs II

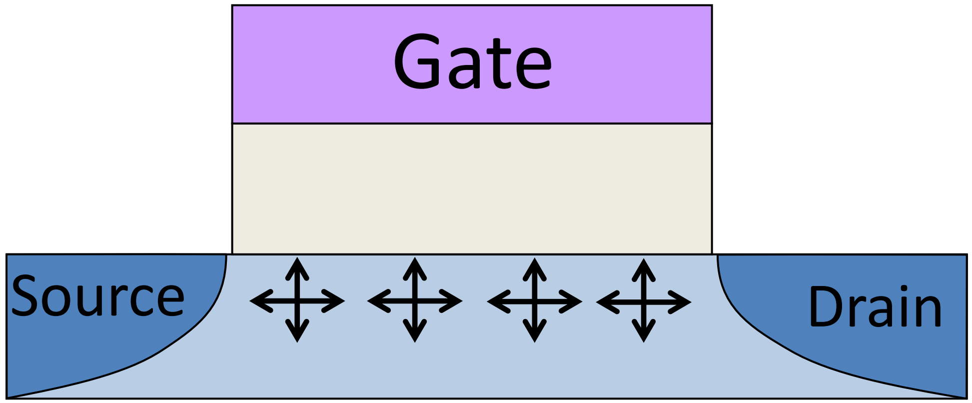


Not just shrinking….

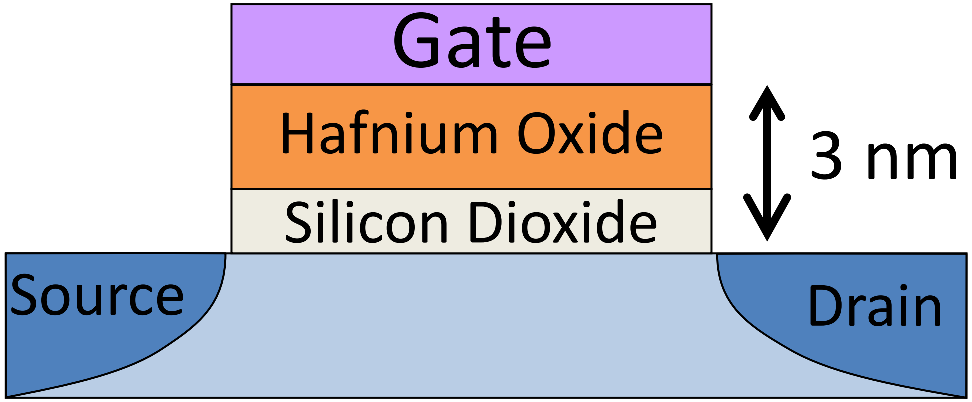
Planar to 3D



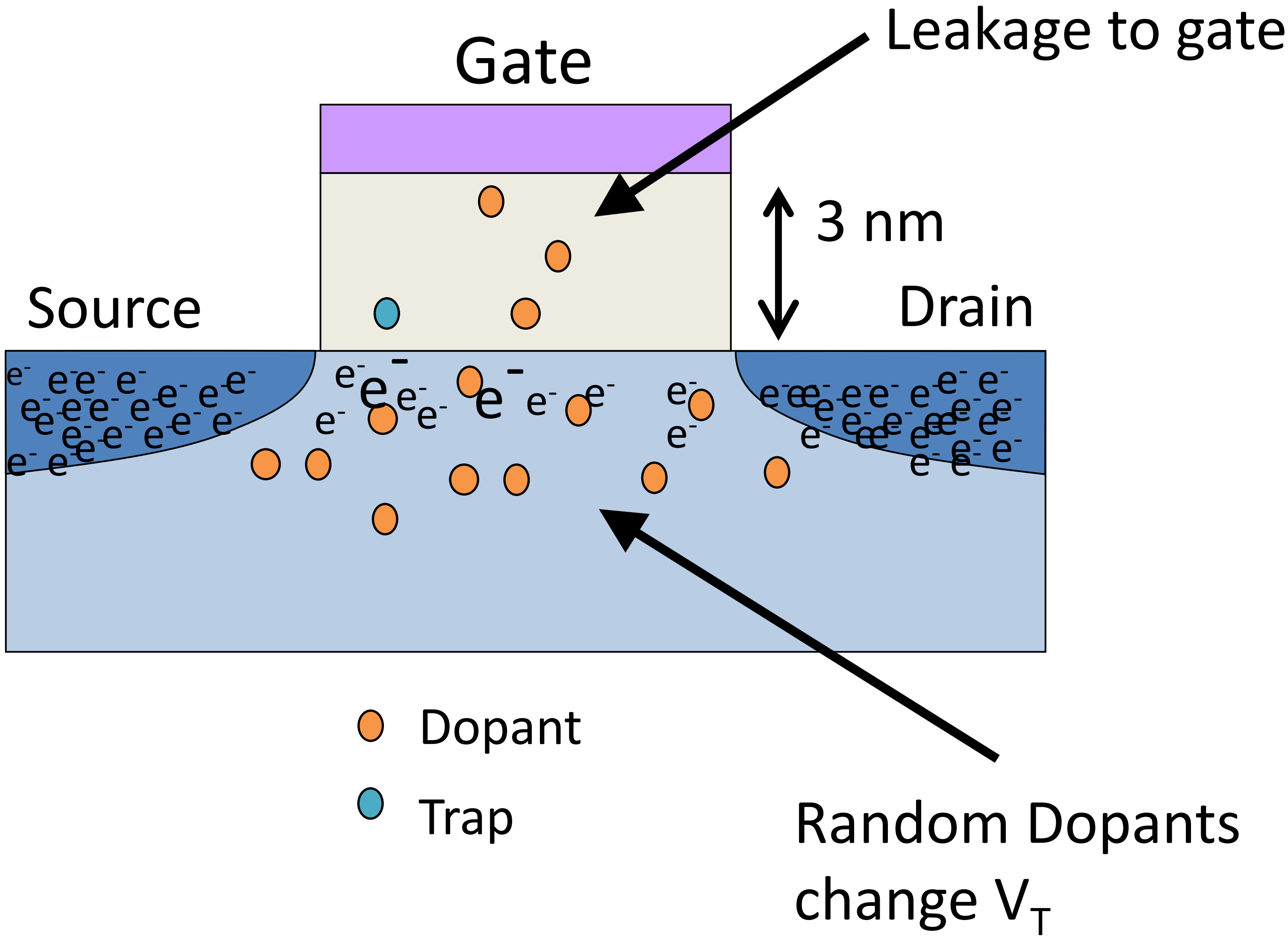
Strain



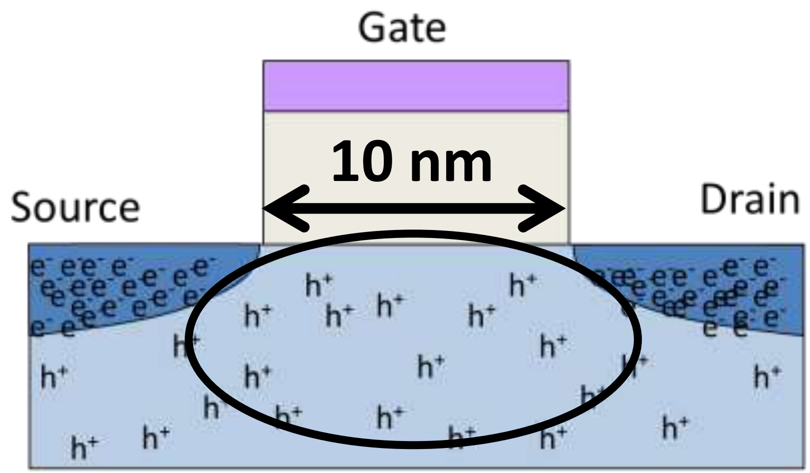
High-κ dielectrics



Atomic Scale Defects

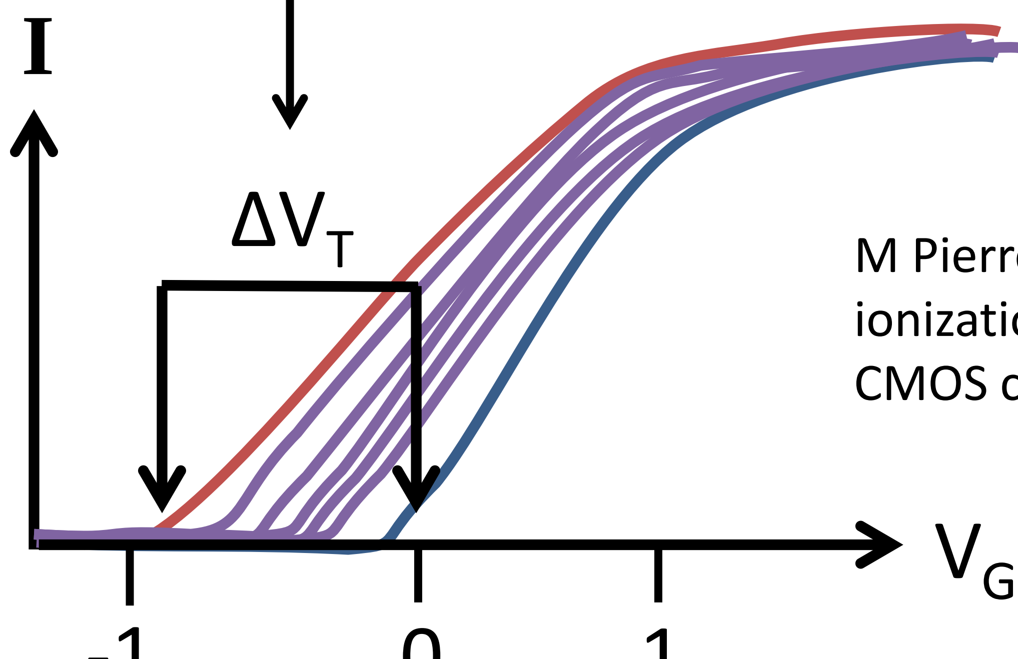


Threshold Voltage



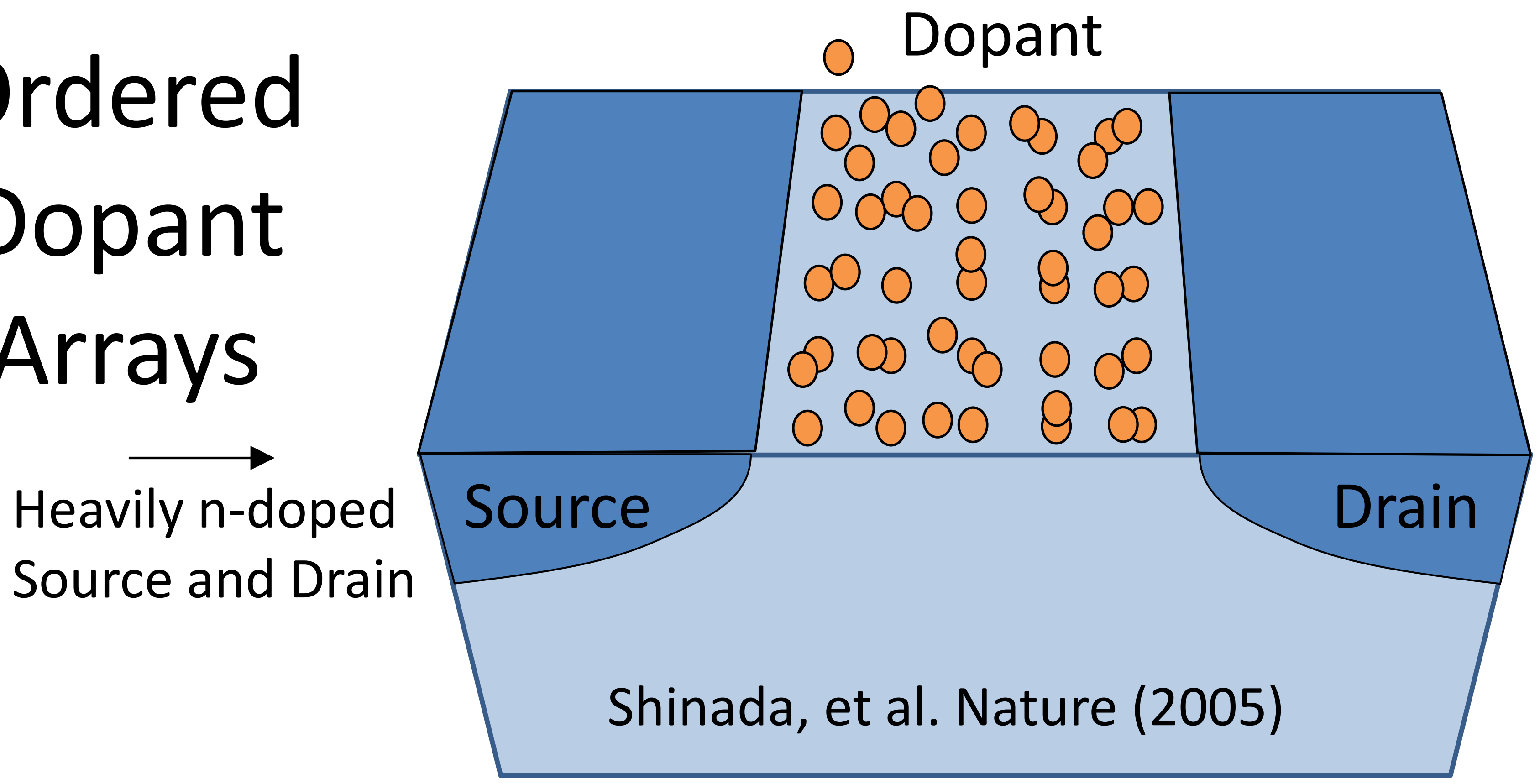
25 devices studied,
$\Delta V_T \approx 1$ V

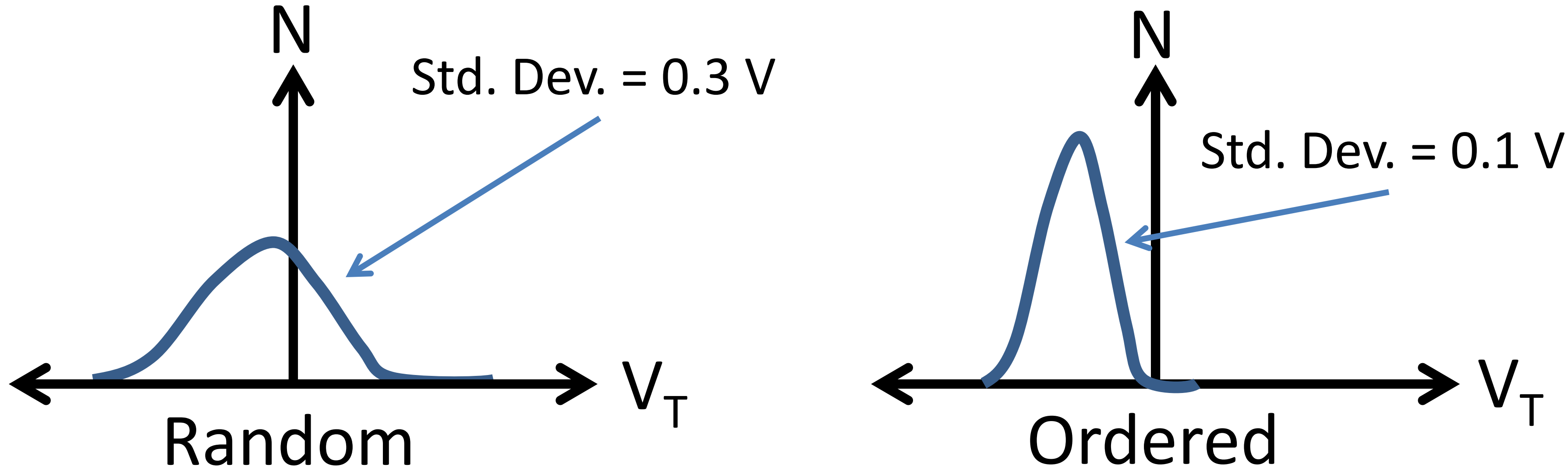
~ 10s of
dopants



M Pierre, et al. "Single-donor ionization energies in a nanoscale CMOS channel," Nature Nano, 2010

Ordered Dopant Arrays





Outline

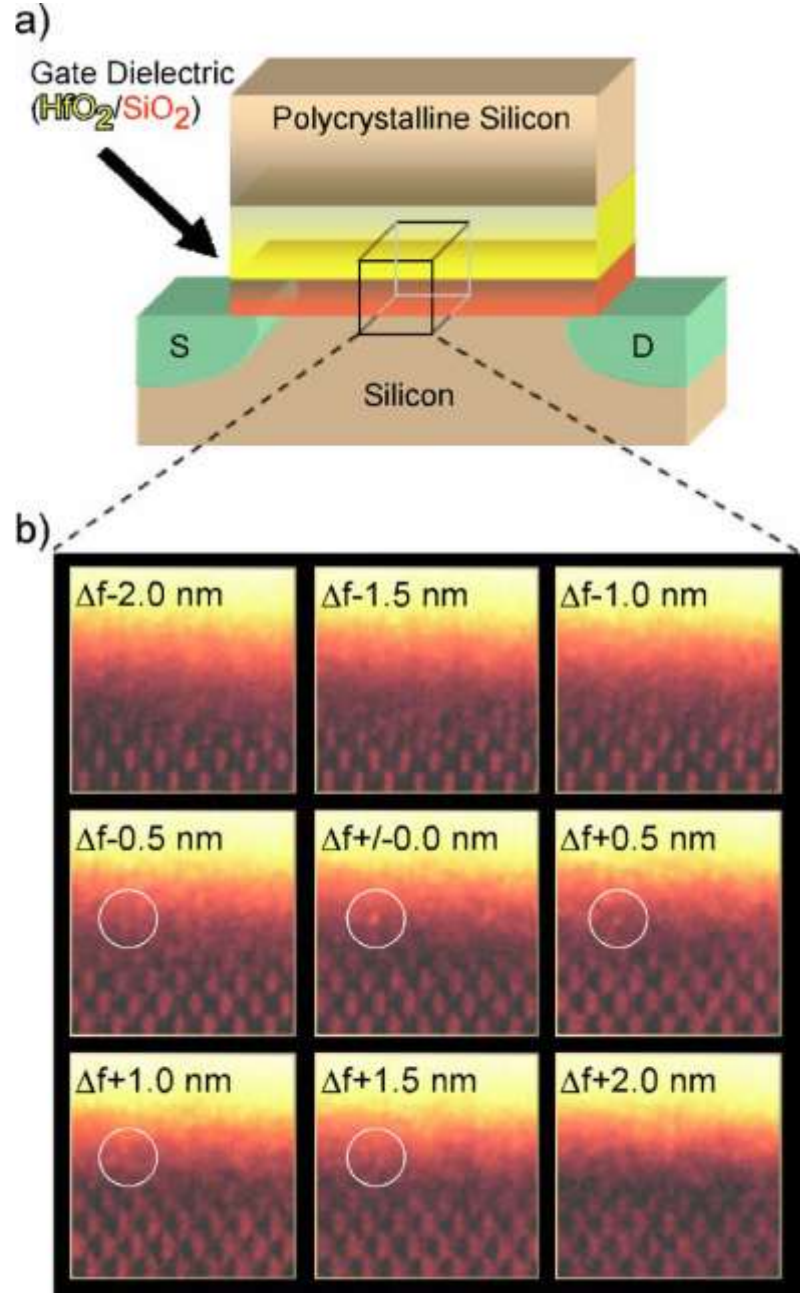
- The impact of a single atom on a MOSFET
- Locating a single atom in a transistor
- The potential for a single atom

Looking for a single atom

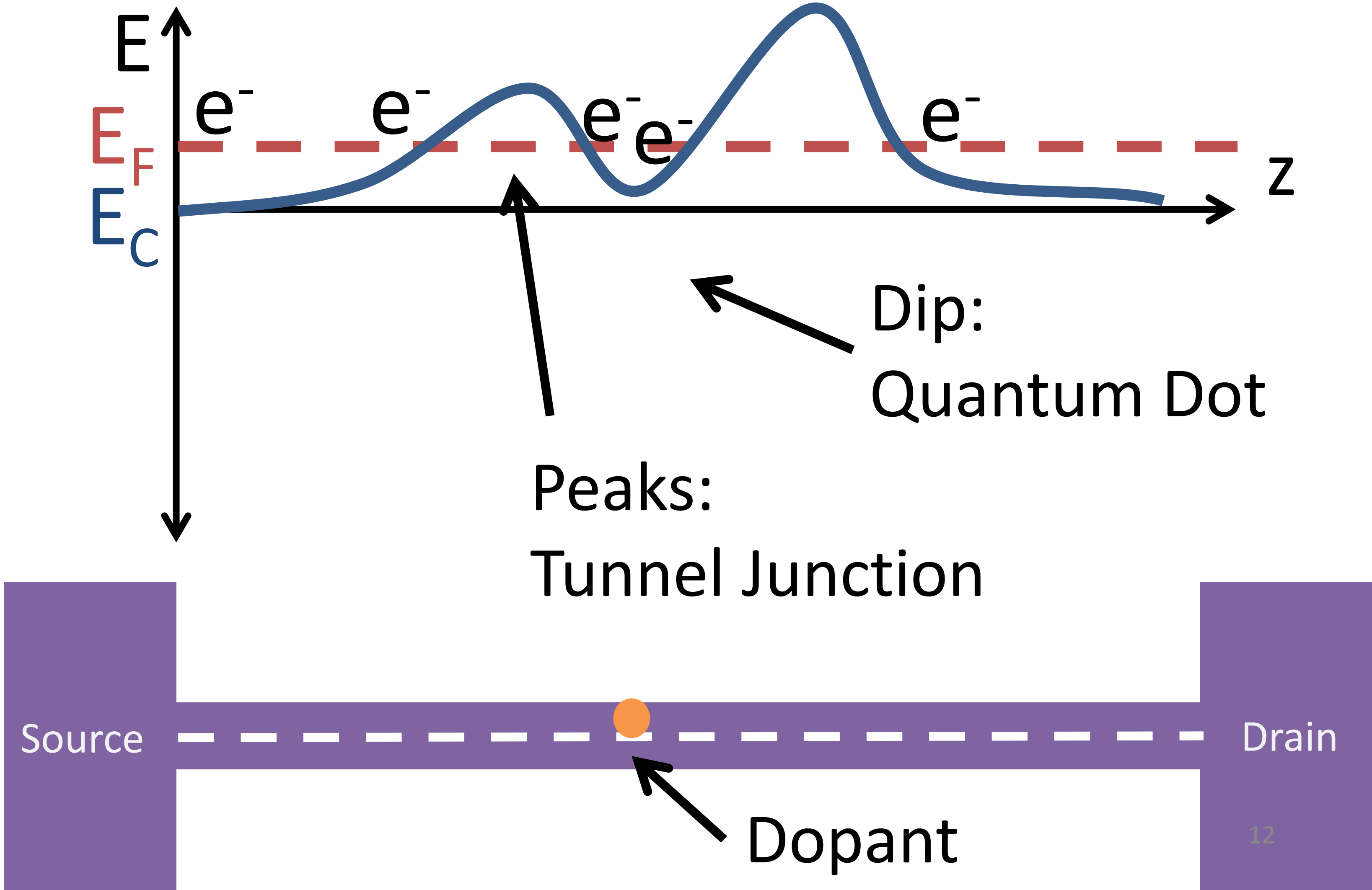
Annular dark-field scanning-TEM

Need to chop up device to look at it

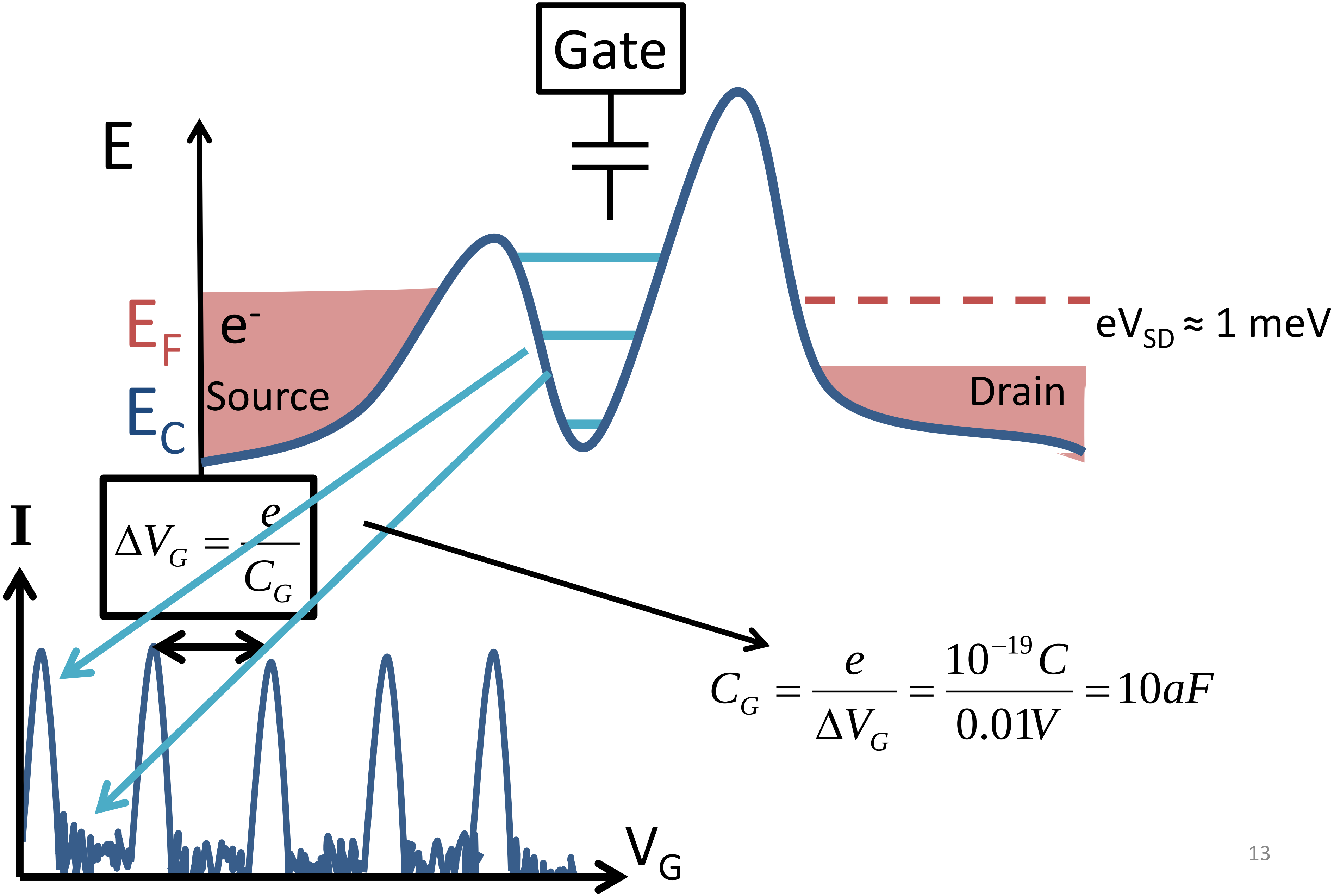
K. Van Benthem, et al.
"Three-dimensional imaging of individual hafnium atoms inside a semiconductor"
Applied Physics Letters, 87 03104 (2005)



The Basic Idea: Cryogenic Temperatures



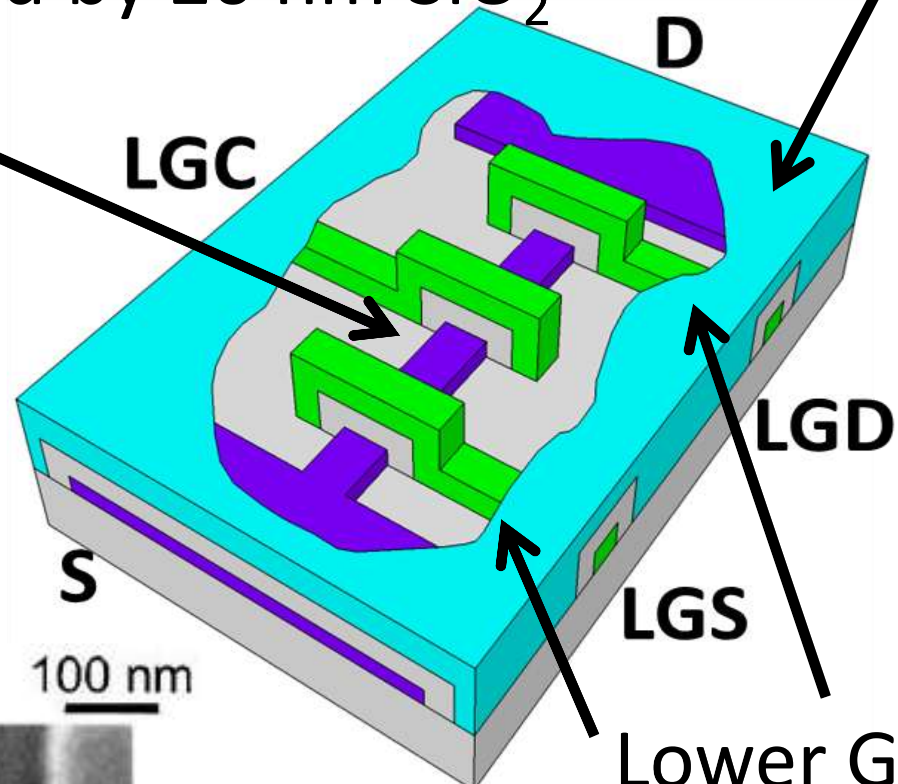
The Basic Idea: Coulomb Blockade



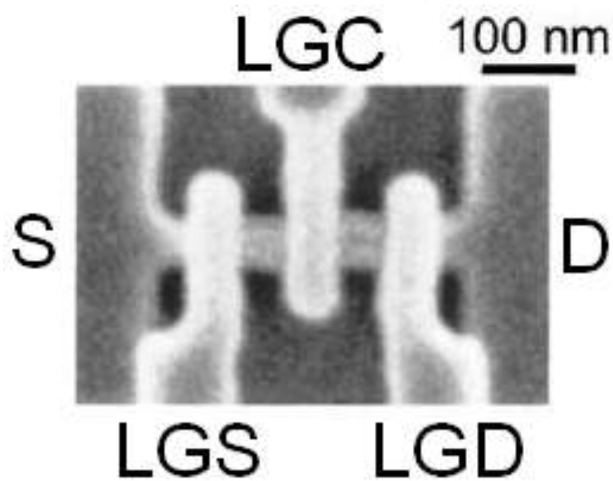
$$C_G = \frac{e}{\Delta V_G} = \frac{10^{-19}C}{0.01V} = 10aF$$

Nanowire
- ~20 nm x 20 nm x 500 nm
- Surrounded by 20 nm SiO_2

Upper Gate
- Heavily doped Poly

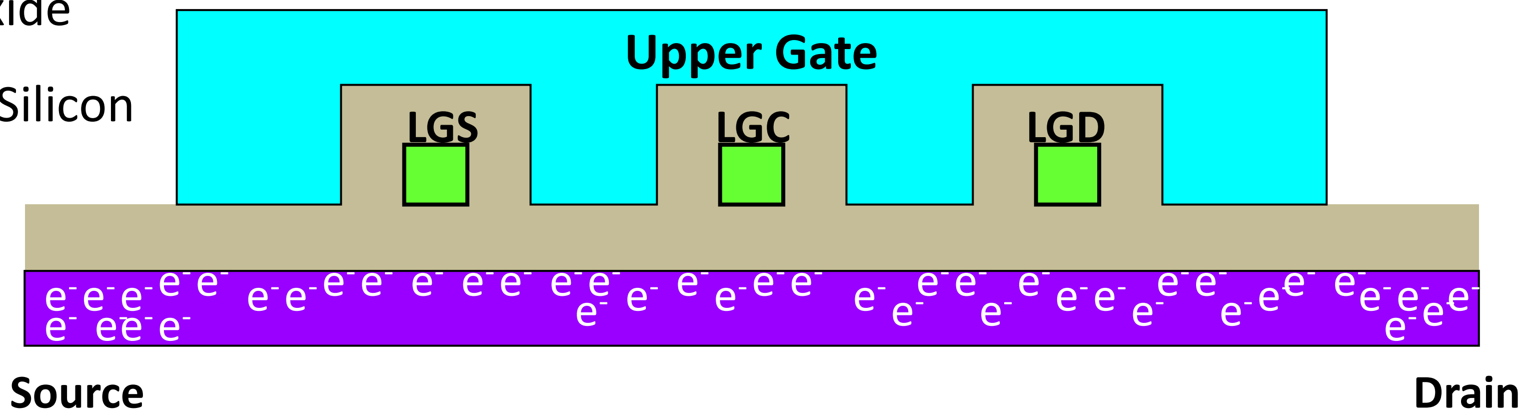


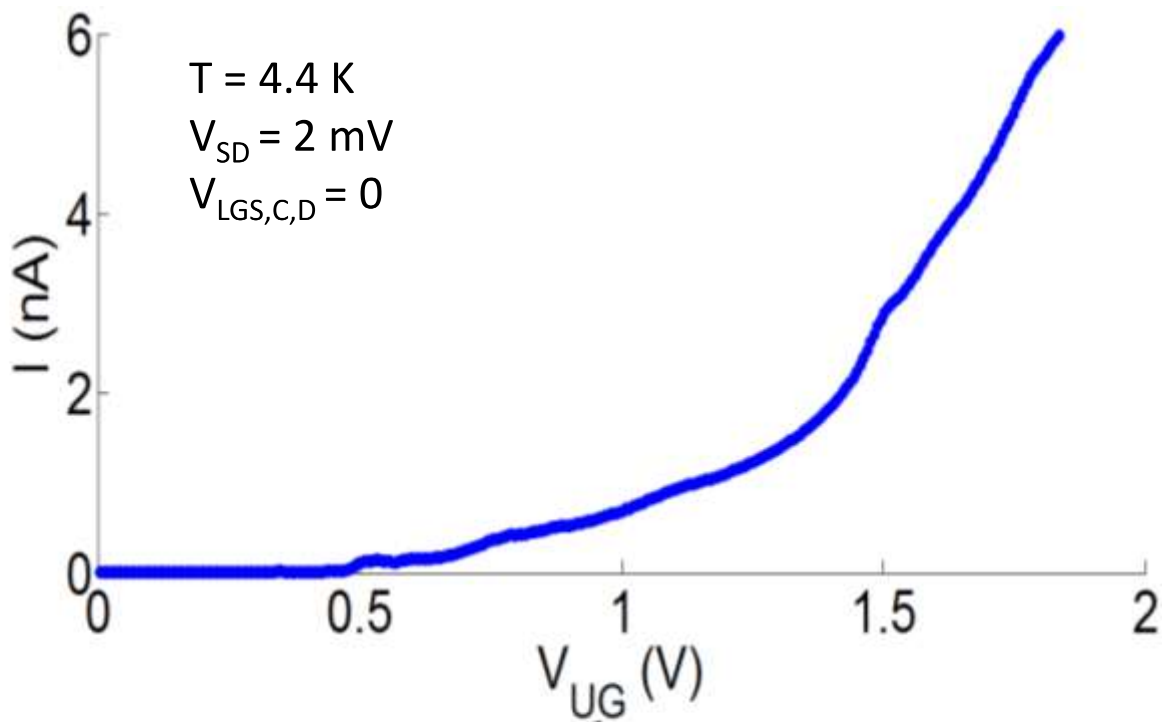
A. Fujiwara, et al.
APL 88, 053121 (2006)



Lower Gates
- Heavily doped Poly
- 10 – 40 nm long
- 3 independent gates

Positive voltage on upper gate inverts wire





Poly Upper Gate

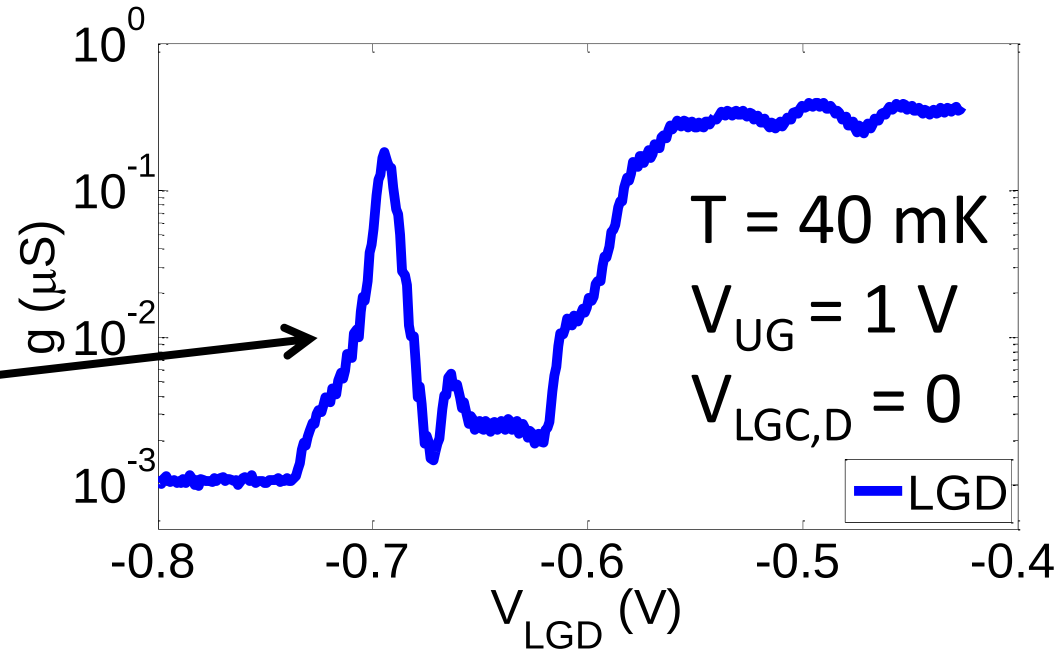
Poly Lower Gate

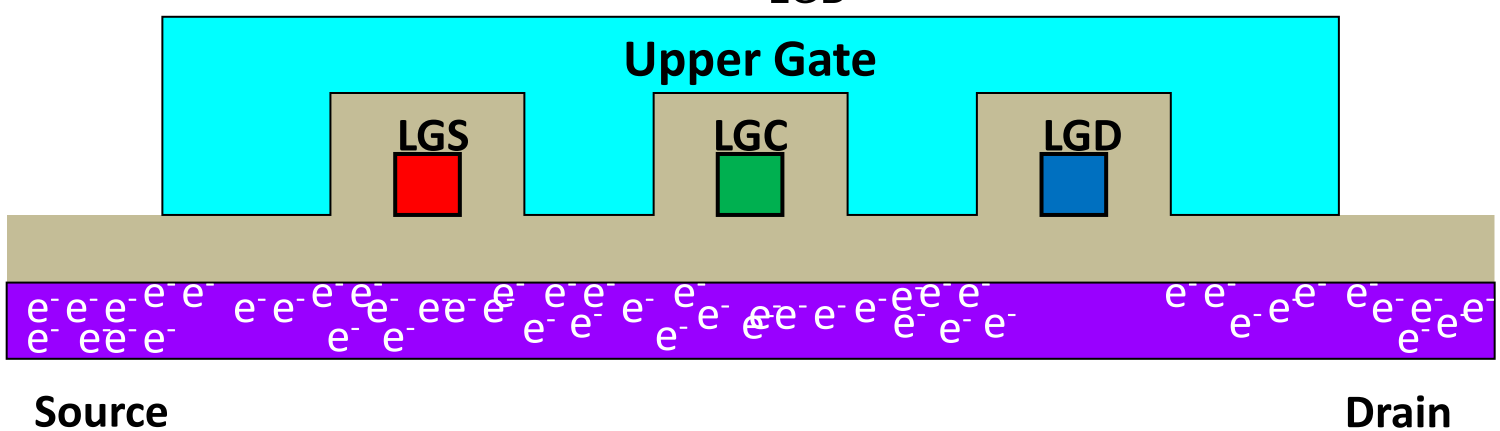
Silicon Dioxide

Crystalline Silicon

Negative voltages on lower gates form tunnel barriers

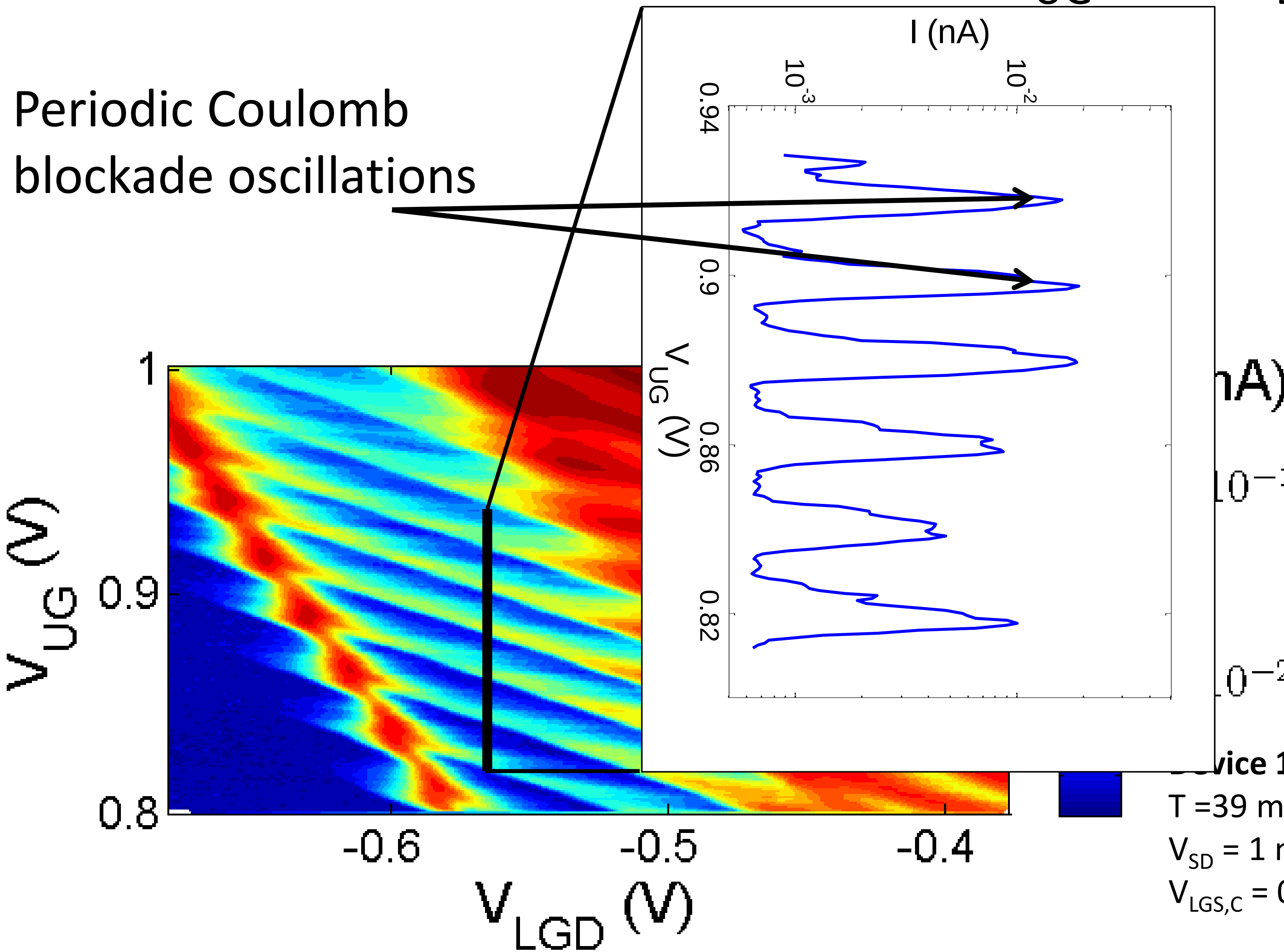
Peaks correspond to transport through QDs





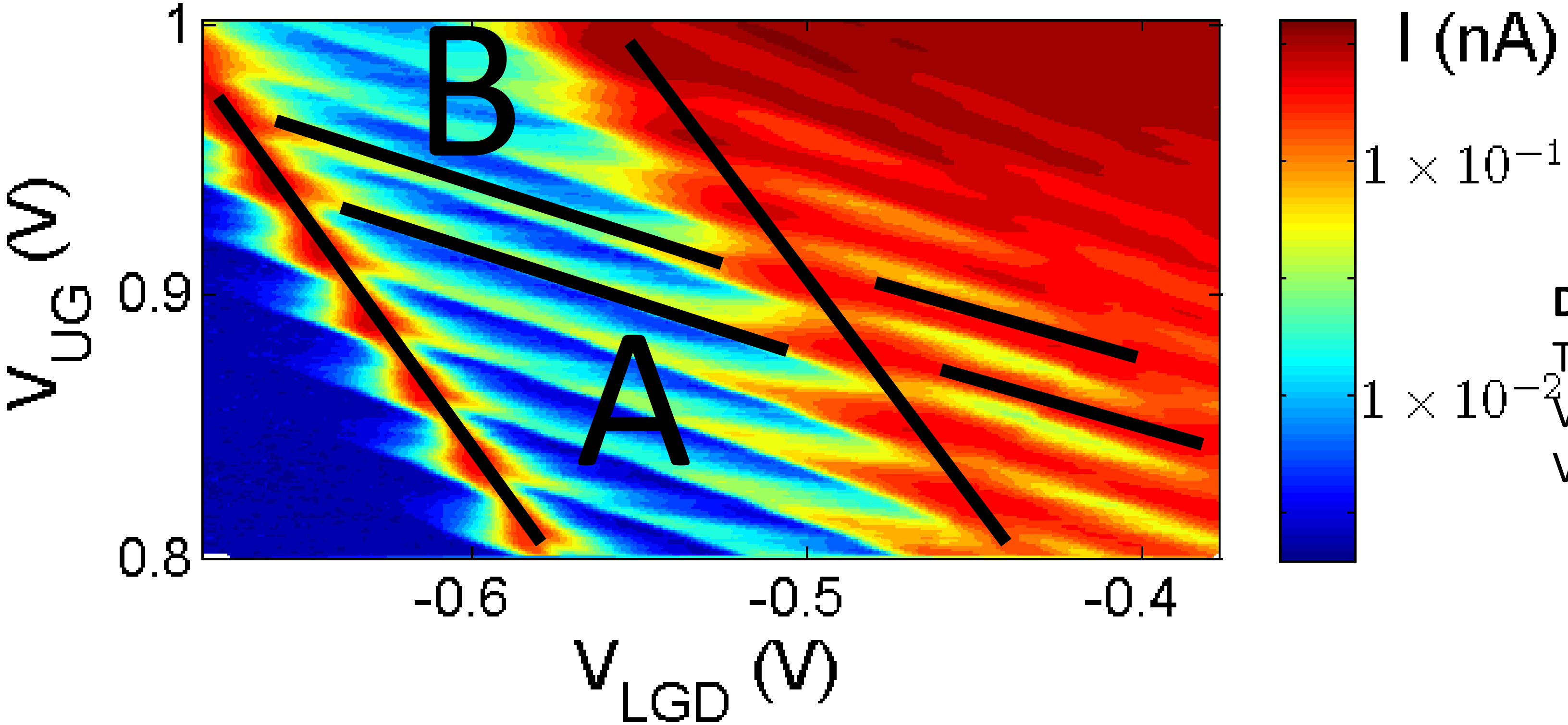
Measure current while scanning V_{UG} and V_{LGD}

Periodic Coulomb blockade oscillations



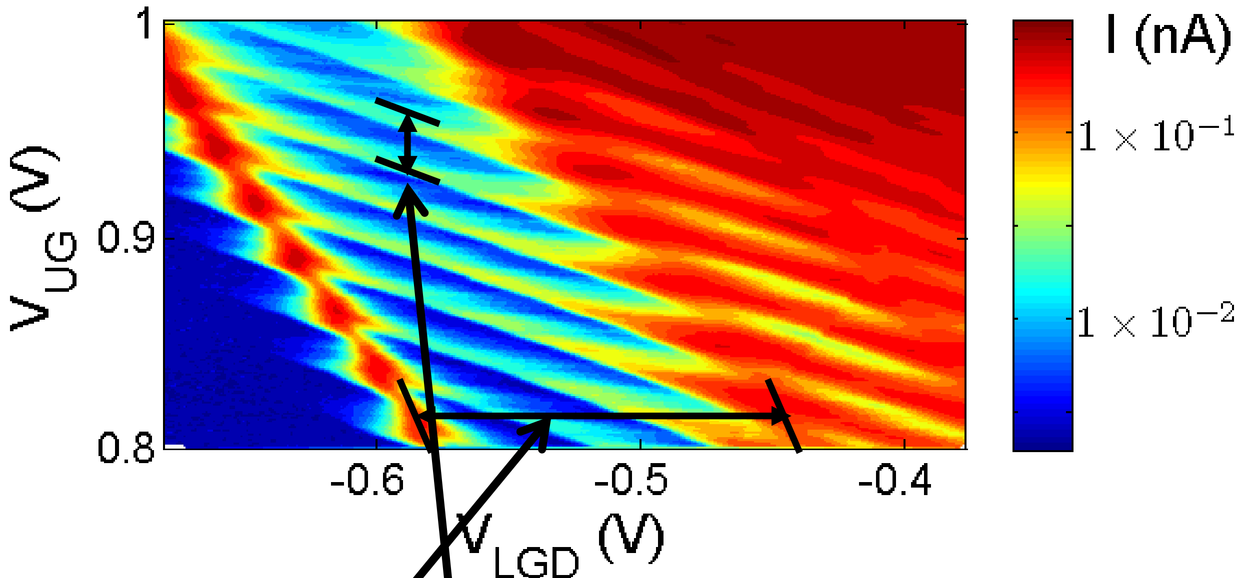
Device 1:
T =39 mK
V_{SD} = 1 mV
$V_{LGS,C}$ = 0

- 2 flavors of QDs
  - A: few periods, more strongly coupled to LGD
  - B: many periods, more strongly coupled to UG



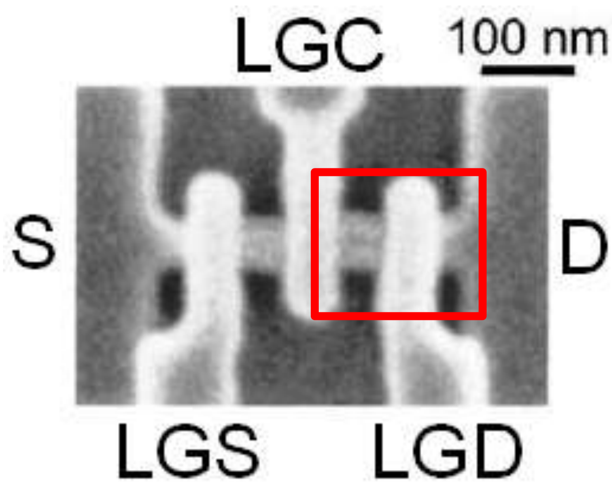
Device 1:
T =39 mK
V_{SD} = 1 mV
$V_{LGS,C}$ = 0

Measure Gate Capacitances

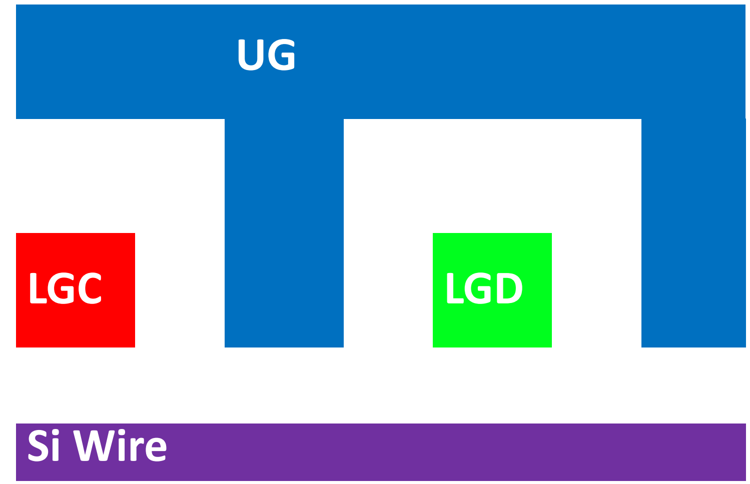


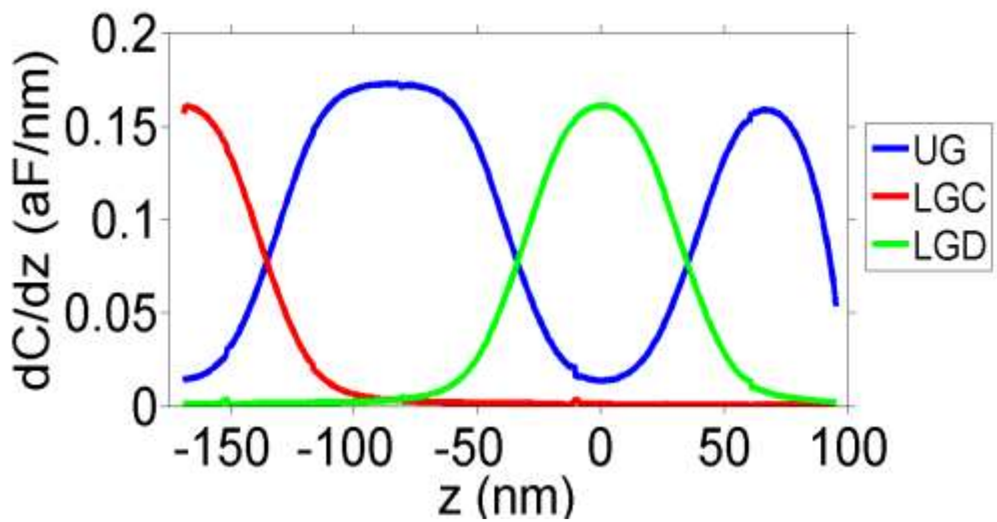
	LGD (aF)	UG (aF)	Ratio LGD/UG	LGC (aF)
Dev. 1: Dot A	2.3 + 0.3 - 1.3	1.3 + 0.2 - 0.6	1.71 ± 0.02	< 0.1
Dev. 1: Dot B	3.2 ± 0.2	7.9 ± 0.3	0.41 ± 0.01	< 0.1

Locate the Dot



Simulated ½ device in FASTCAP



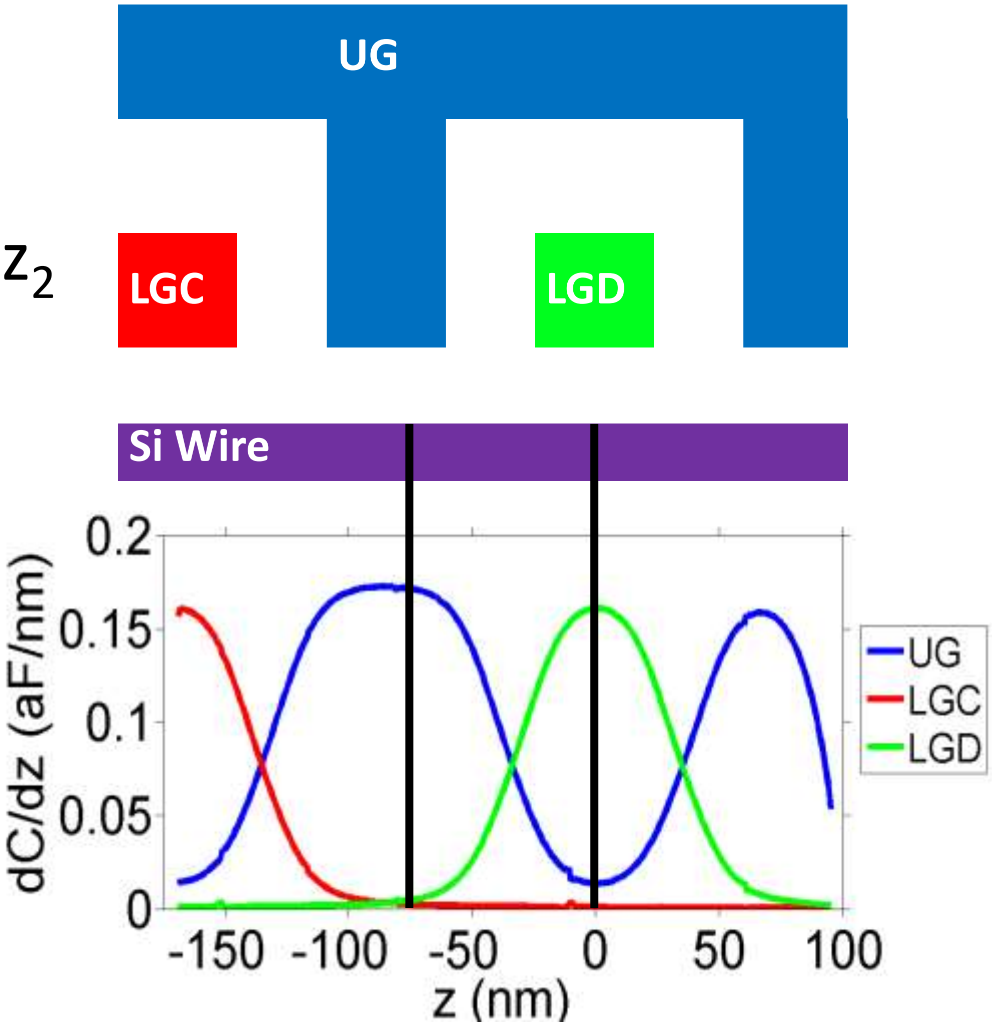


Locate the Dot

- Measure gate capacitances
- Simulate capacitances to 1 nm slices of wire
- Integrate between z_1 and z_2

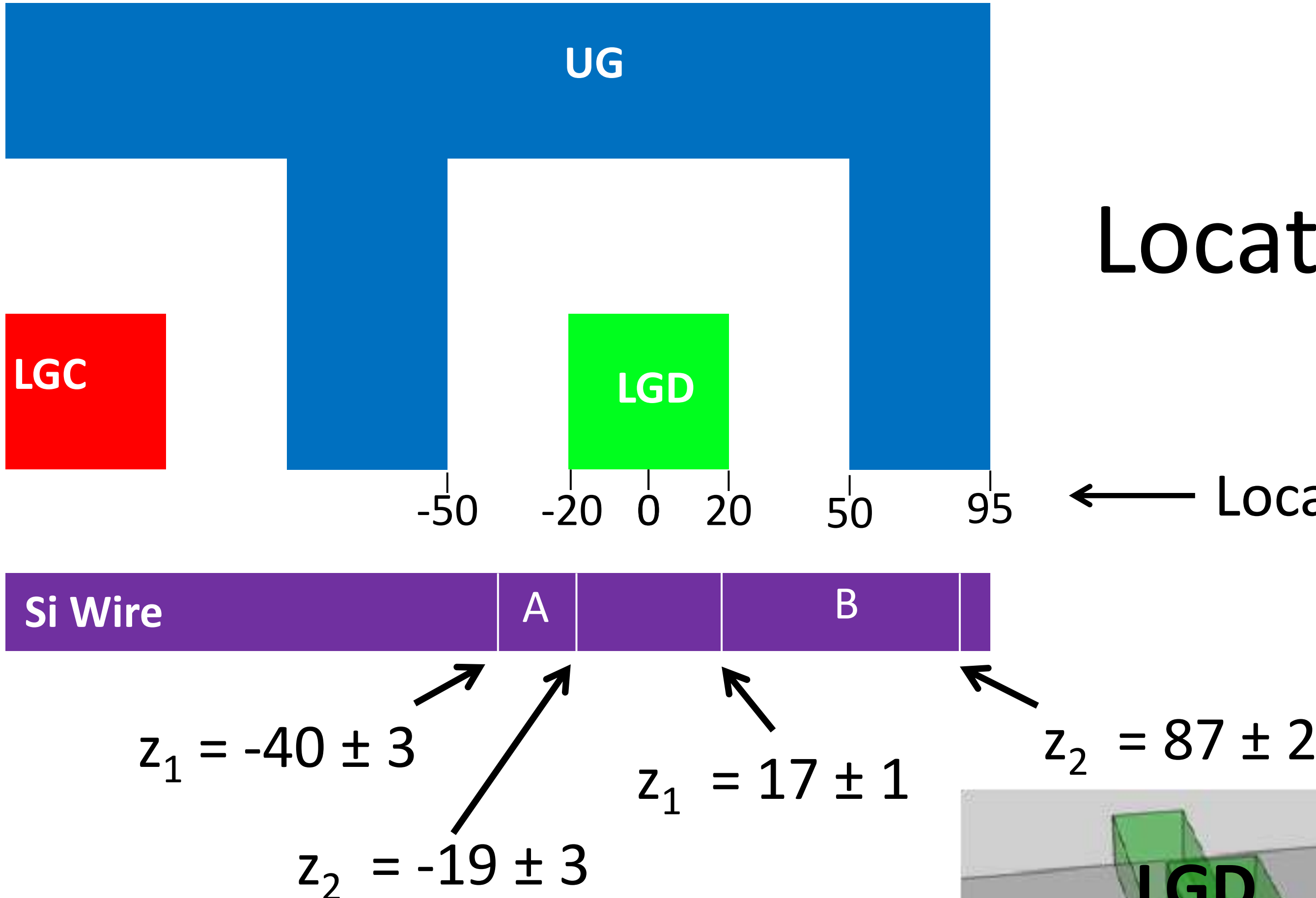
$$C_{sim} = \int_{z_1}^{z_2} \frac{dC}{dz} dz$$

- For what z_1 and z_2 does $C_{sim} = C_{meas}$ for all gates

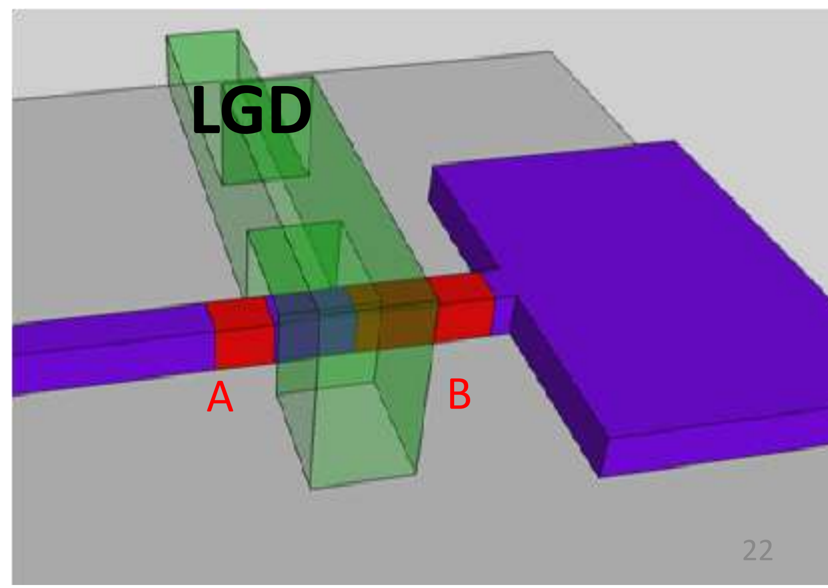


	LGD (aF)	UG (aF)	Ratio LGD/UG	LGC (aF)
Dev. 1: Dot B	3.2 ± 0.2	7.9 ± 0.3	0.41 ± 0.01	< 0.1

Location of Dots



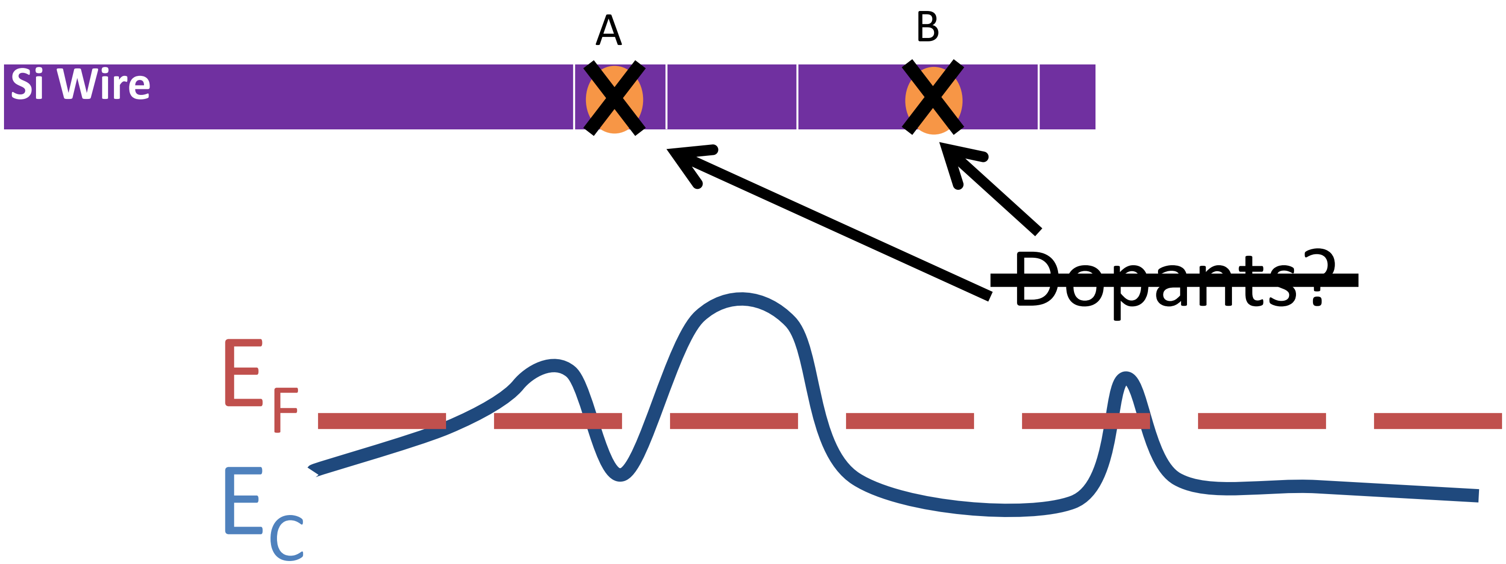
Between LGD and UG



~~Dopant Location?~~

We see same QDs in multiple devices

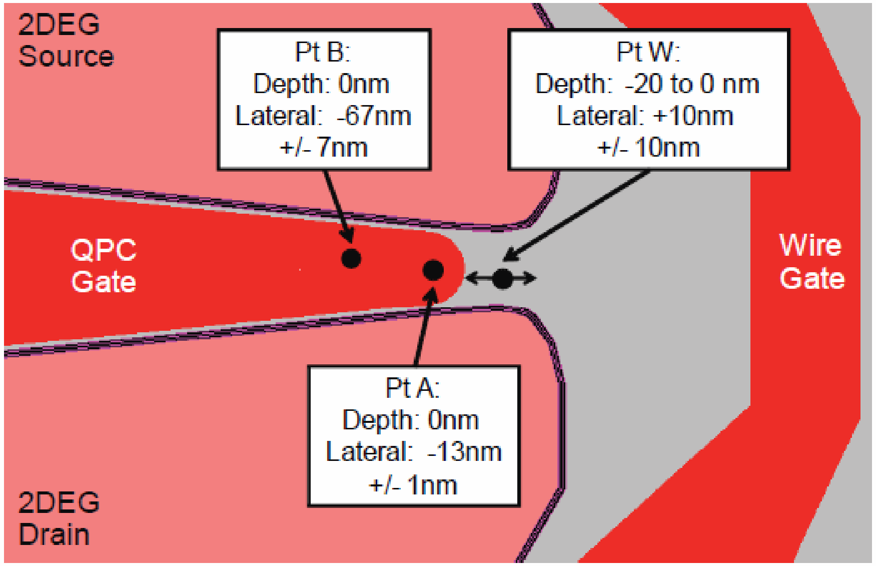
- -The cause appears systematic
- -Strain from temperature change and oxide growth
- -Could help make faster finFETs



Deduced conduction band modulation

Finding a Dopant

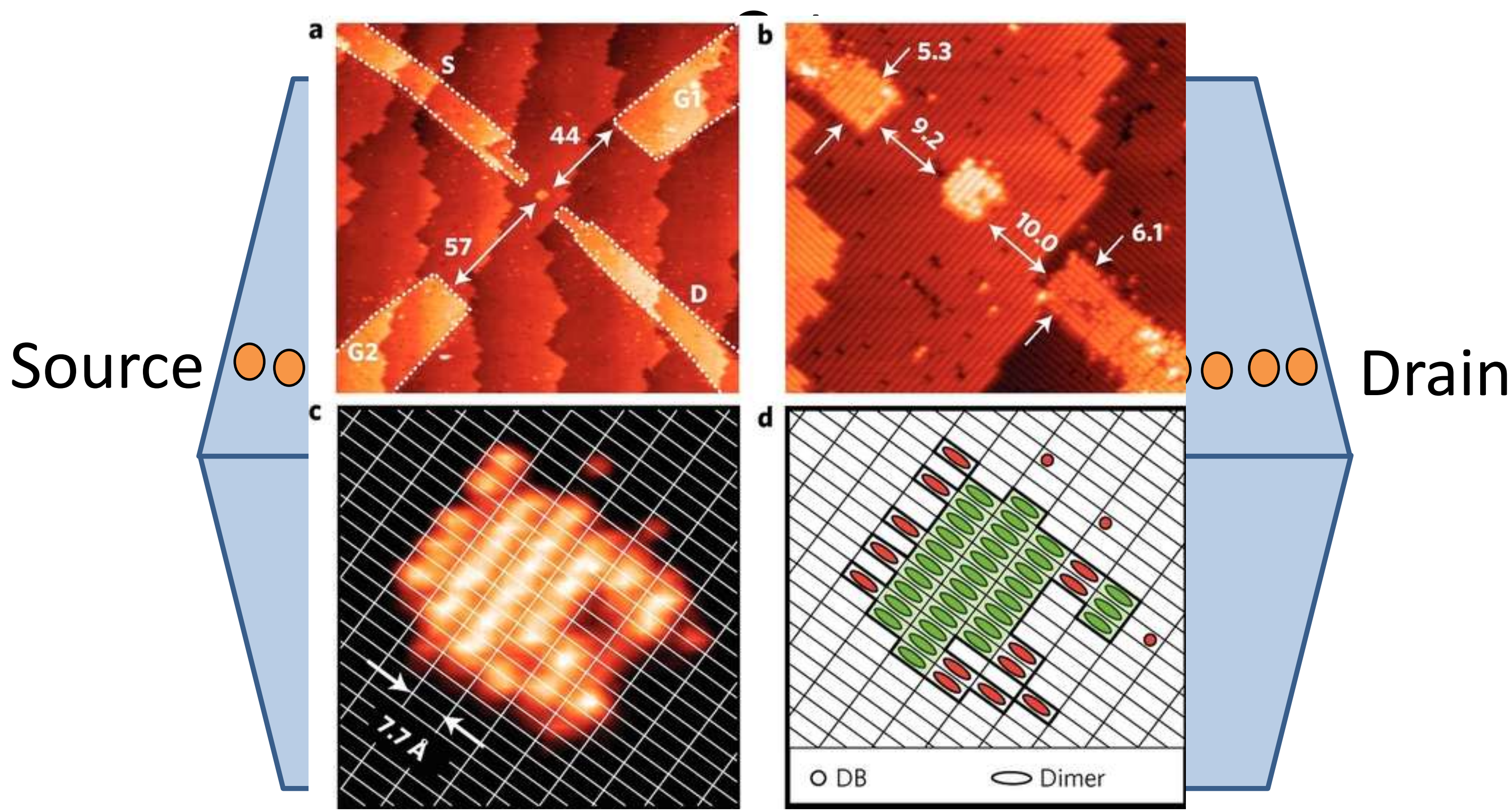
- Very similar technique has been used to located individual dopants and interface traps
  - Nathaniel Bishop, et al; "Triangulating tunneling resonances in a point contact" Arxiv 1107.5104 (2011)



Outline

- The impact of a single atom on a MOSFET
- Locating a single atom in a transistor
- The potential for a single atom

Ultimate Transistor?



Similar to:

Cheng Cen, et al. “Oxide Nanoelectronics on Demand” Science 323, 1026 (2009)

Martin Fueschsle, et al. “Spectroscopy of few-electron single-crystal silicon quantum dots” Nature Nano, 5, 502 (2010)

Beyond the transistor

- World looks different on the atomic-scale
  - Quantum regime
- This is a problem for current transistors
  - Tunneling to the gate
- Could this “quantumness” become useful

Quantum Search

“Classical” Computer: To search x100 boxes takes x100 as long

“Quantum” Computer: To search x100 boxes takes x10 as long

Number of Boxes	Old Computer	New Computer	Quantum Computer
10	10 µs	10 ns	10 ns
1000	1000 µs	1000 ns	100 ns

Conclusions

- MOSFETs are reaching the point where the placement of a single atom can affect device performance
- New tools allow the location of a single atom to be determined within a MOSFET
- The quantum nature of a single atom could one day allow for much more powerful devices

Collaborators

Neil Zimmerman

Panu Koppinen

Michael Stewart

Ted Thorbeck (tedt@nist.gov)