Electrostatic Force Microscopy to Study Single Dopant Atoms Encapsulated in Silicon

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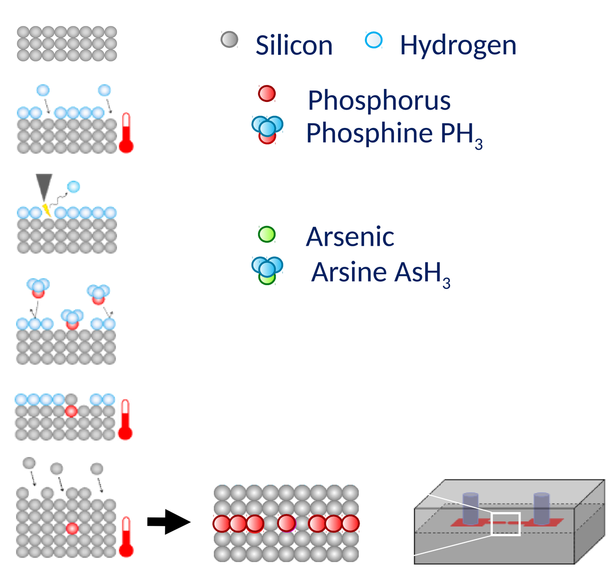
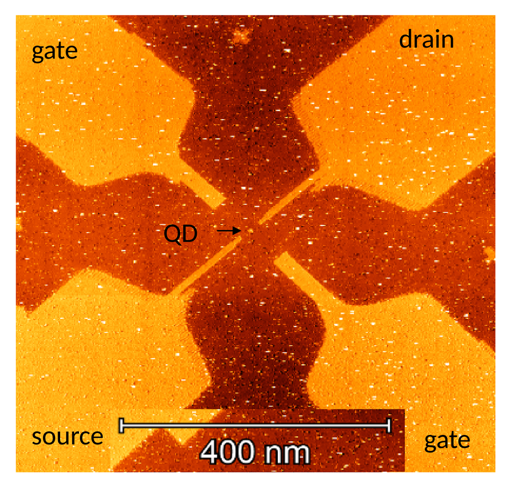
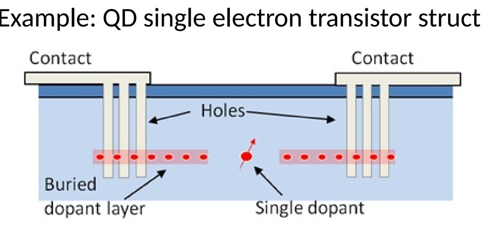
1. Motivation

Hydrogen resist lithography allows atomically precise placement of P or As atoms on silicon. Then, dopants are encapsulated with an additional layer of silicon [1,3,5].





Example: QD single electron transistor structure

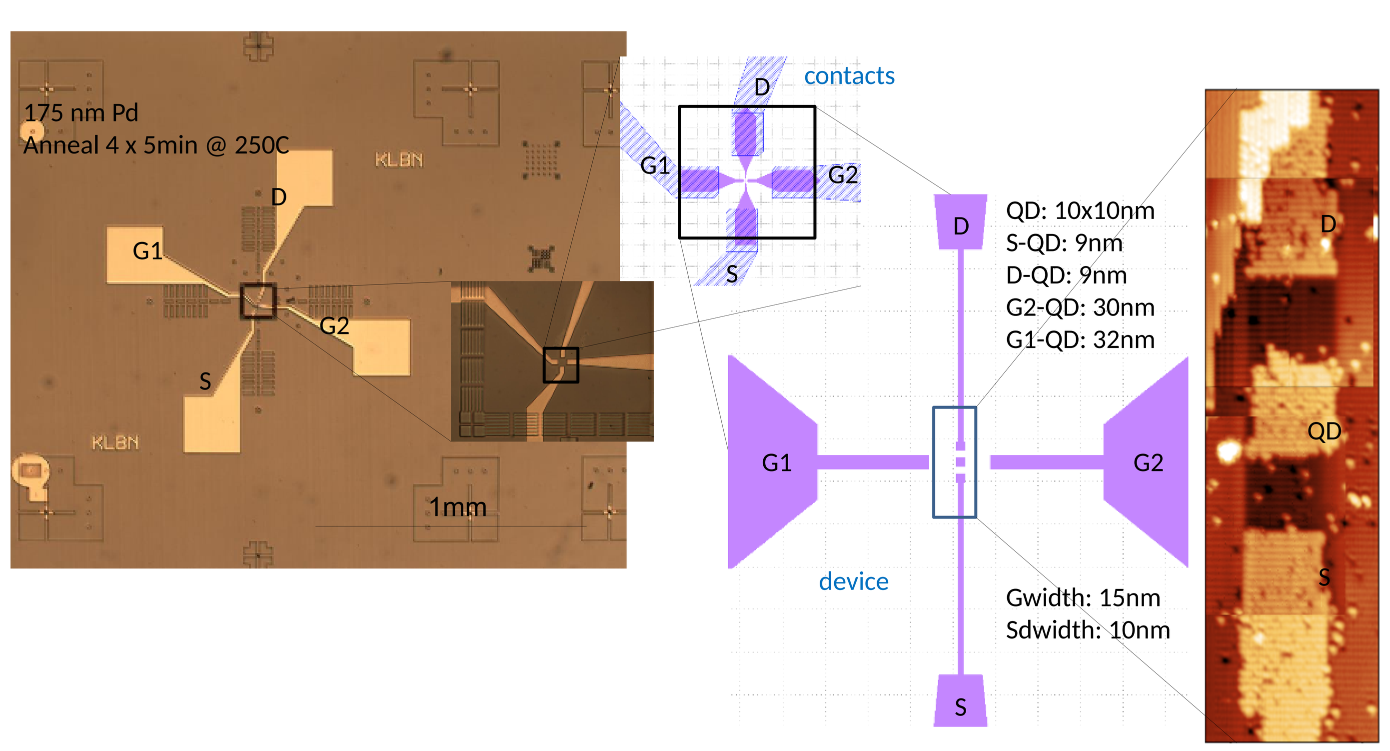


Many interesting questions arise:

1. How big is the coupling between dopant atoms?
2. What is the coherence time?
3. How far do dopant atoms diffuse in the silicon crystal?
4. How are the energy levels affected by the environment?

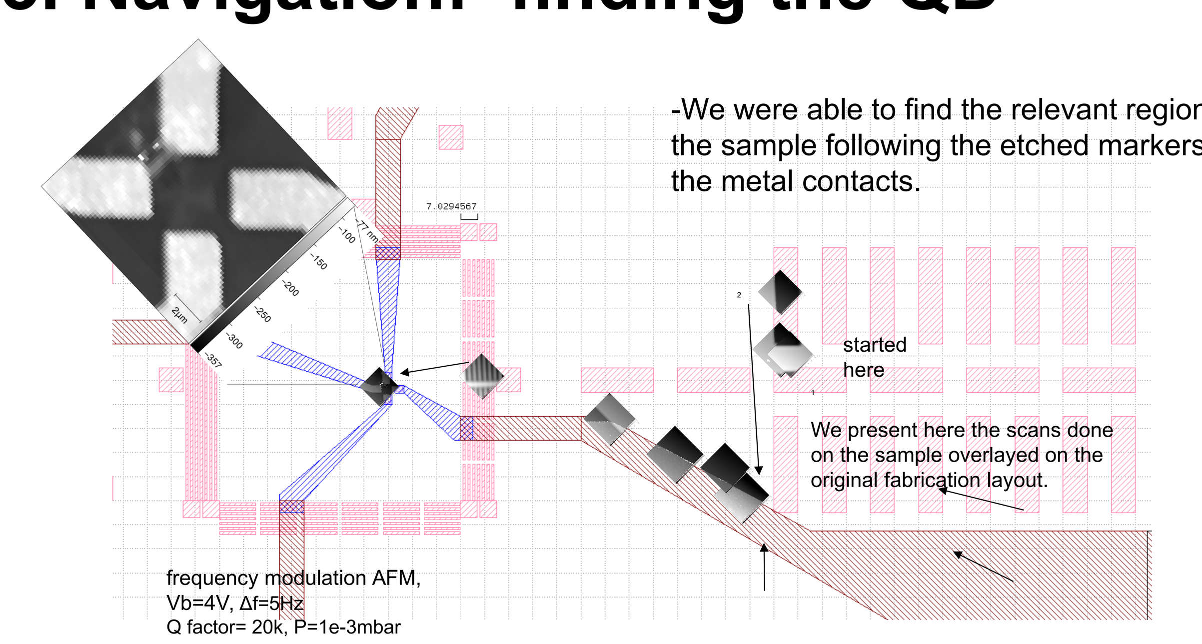
2. Sample

We studied a contacted Single Electron Transistor sample with a single 10x10nm Quantum Dot



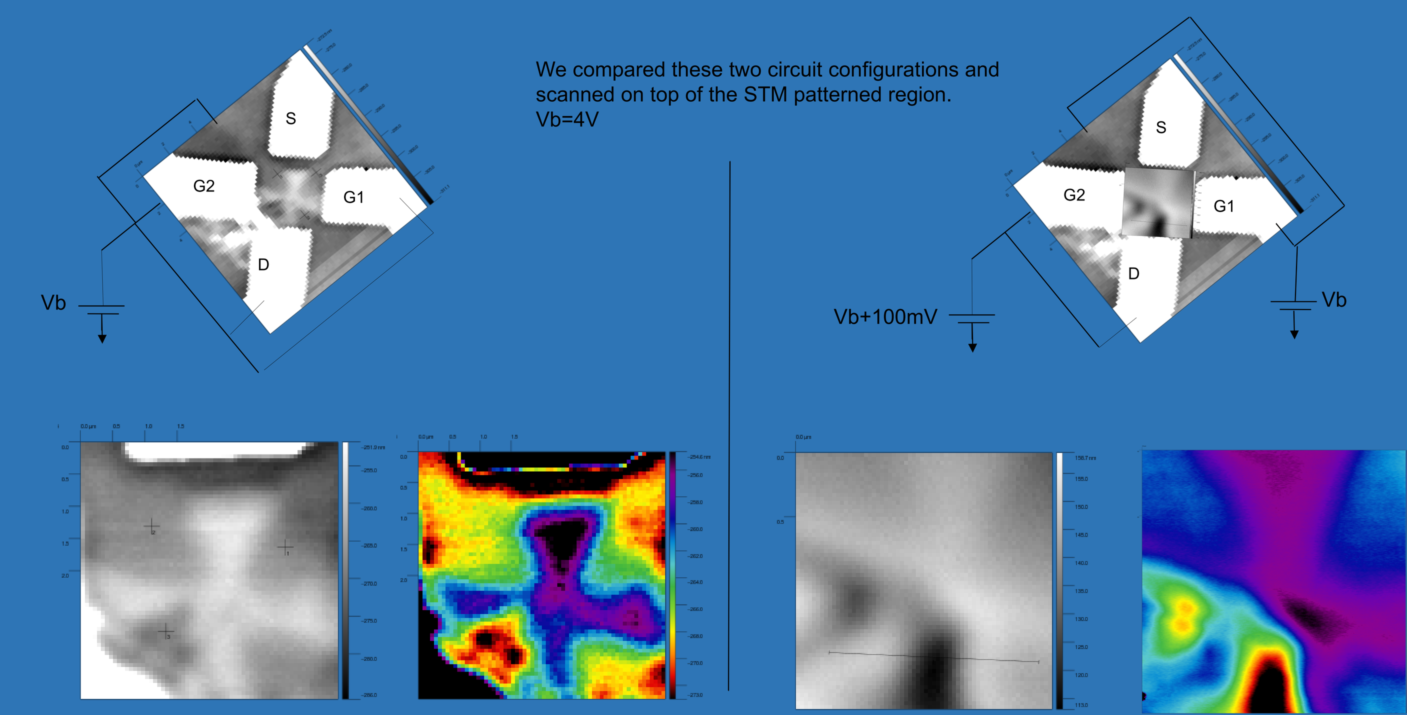
3. Navigation: finding the QD

-We were able to find the relevant region on the sample following the etched markers and the metal contacts.



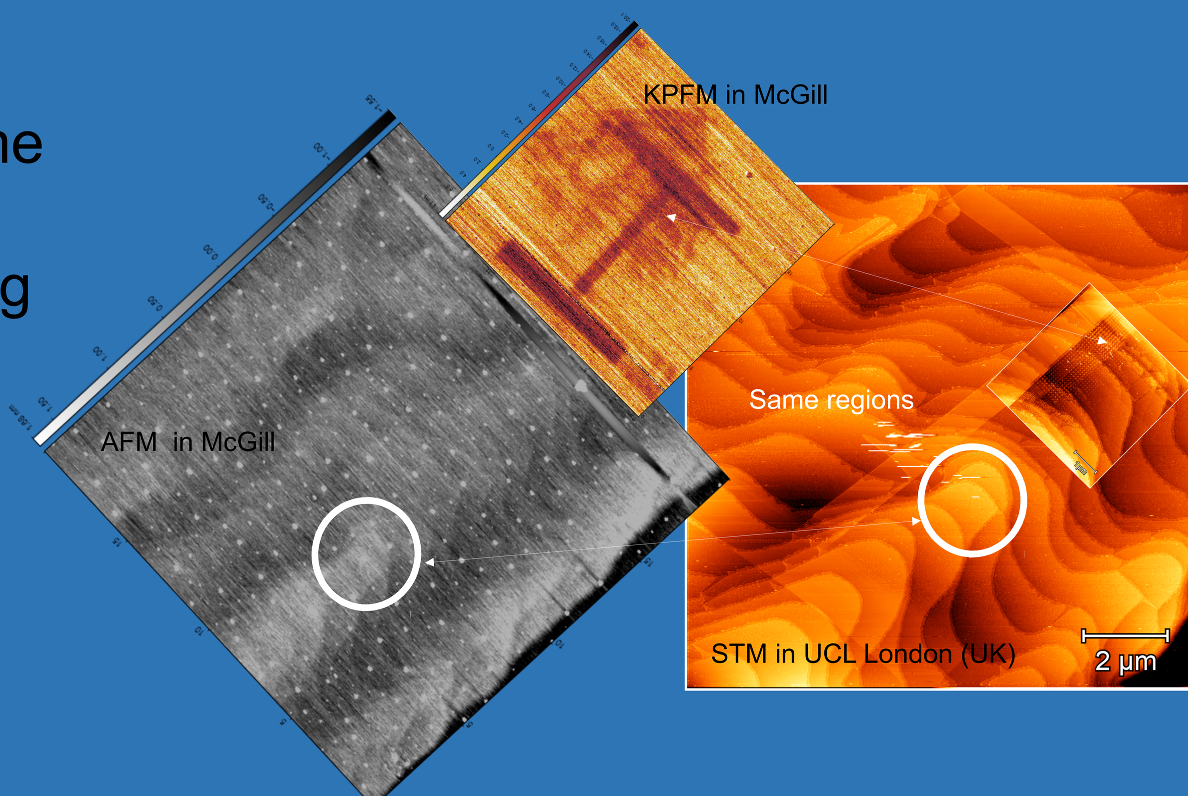
4. Preliminary Results:

4.1 We can control the voltage of the STM dopant defined regions.

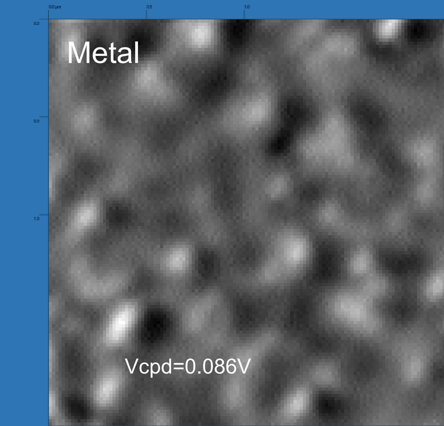


Topography images in grayscale and in color. The electrostatic force causes the measured fore to change. Left, same potential in all the sample. Right, 100mV DC voltage applied to the Gate2 and the drain with respect to Gate1 and the electrode at the back of the sample.

4.2 We can identify the same terraces in the the target region using etched markers, native silicon terraces and KPFM.

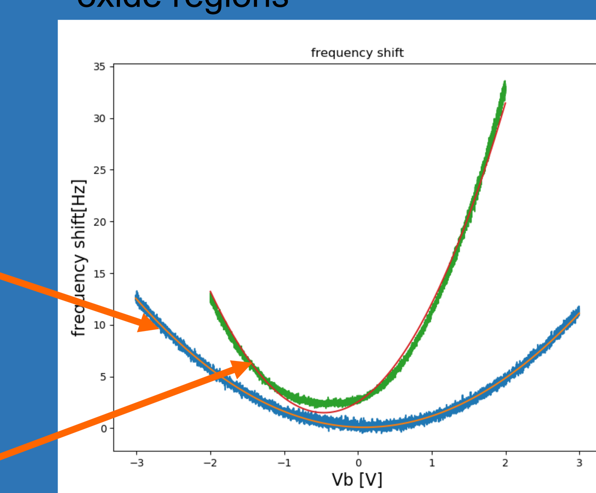


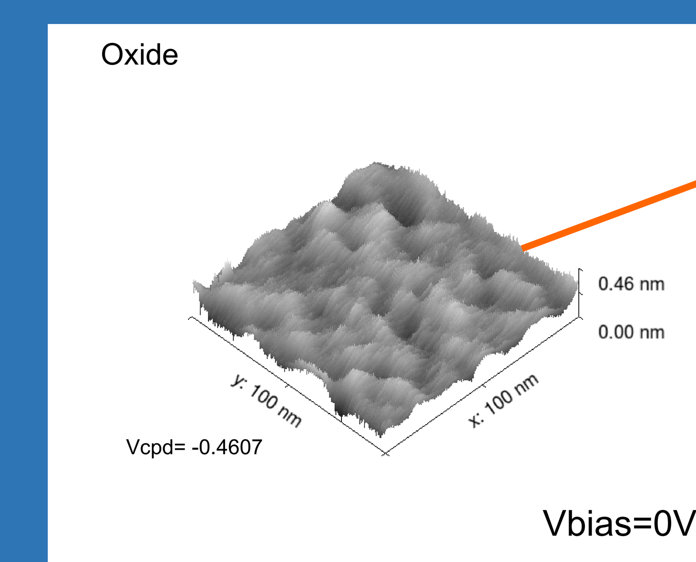
4.3. The microscope works at low temperature (4.5 K)



NC-AFM scan
T=4.5K
P=1e-3mbar
Δf=5Hz
Vbias=4V

KPFM parabolas of the metal and oxide regions

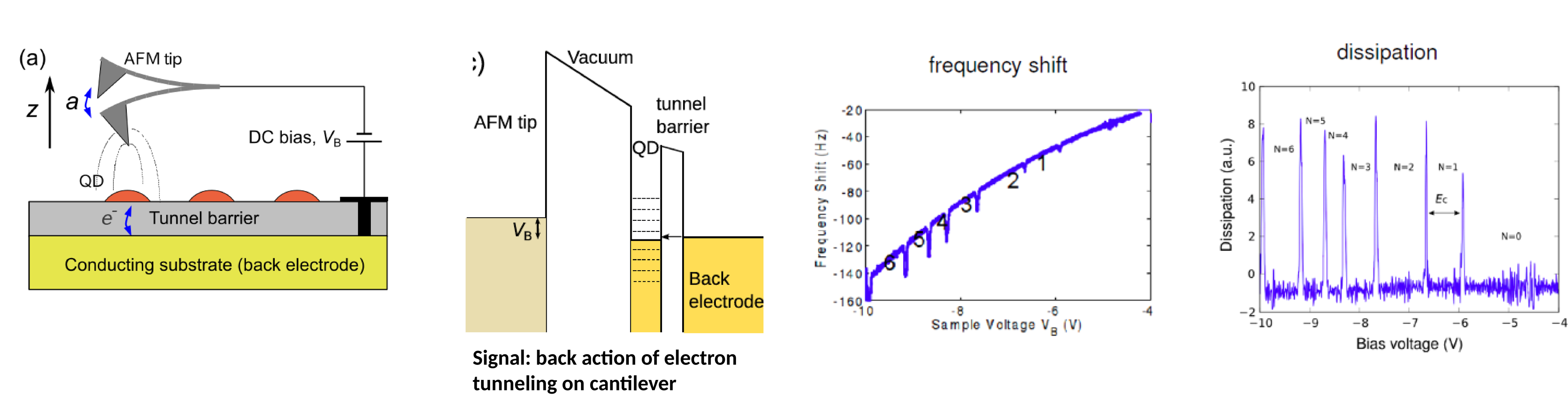




Scans taken at low temperature over the metal and the silicon. The silicon is covered by a layer of silicon dioxide. The height is consistent with vertical atomic resolution.

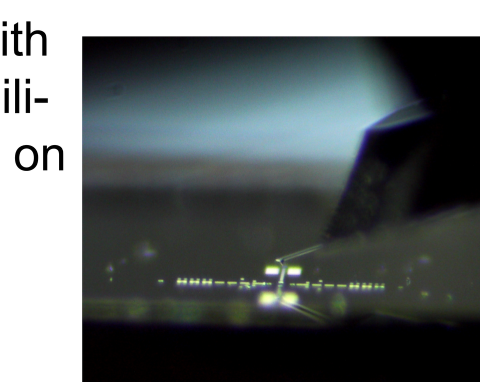
Spectroscopy technique

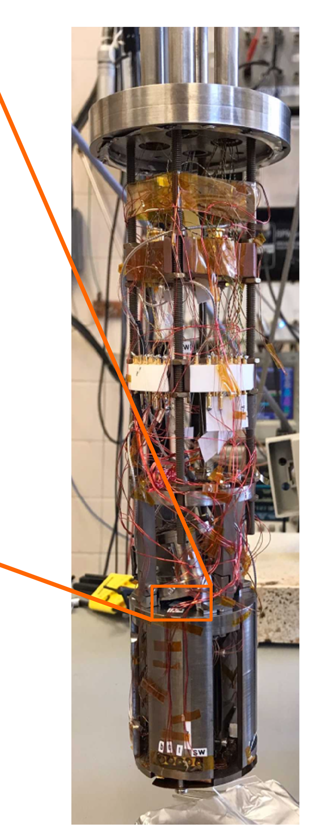
The tip can be used as a both, a movable gate and a single electron sensor [2]



5. Novel Microscope at McGill University

Low Temperature AFM with coarse positioning capabilities. The design is based on a previous AFM with no coarse positioner [2].





Features:

- Optical access for prepositioning.
- 11.4µm scan range.
- 2mm x4mm coarse motion range
- Capacitive position sensors [4]
- Optical cantilever excitation [2]

6. Outlook

- Optimize Navigation remains challenging at low temperatures
- Find QD fast. Perform bias spectroscopy on them.
- Reduce size of QDs to single atom limit.

7. References

[1] T. Stock *et al.*, ACS Nano 14,3, 3316–3327 (2020).
[2] Y. Miyahara, *et al.*, Nanotechnology 28, 064001 (2017).
[3] X. Jehl, *et al.*, J. Phys.: Condens. Matter 28, 10 (2016)
[4] Field and Barentine, RSI 71, 2603 (2000)
[5] Simmons, *et al.*, Molecular Simulation, 31:6-7, 505-515 (2006)

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