Silicon Quantum Computing

Spatially resolved transport spectroscopy of few donor clusters in silicon

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Didier D. St Médar

Gilles Buchs
Benoit Voisin
Sven Rogge

Silicon Quantum Computing, Sydney, Australia.
ARC Centre for Quantum Computation and Communication Technology, UNSW Sydney, Australia

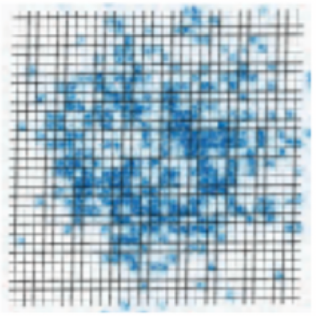
Quantum Simulation

Various platforms for quantum simulation

Each platforms has its own advantages and limitations

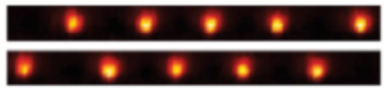
Optical lattices

U/t ~ 7.2



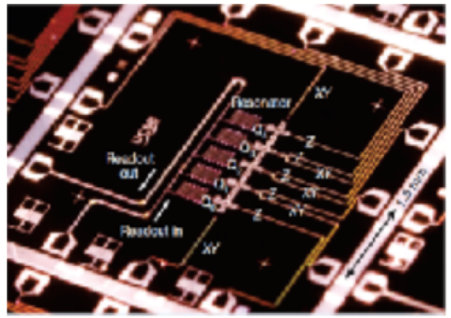
Greif *et al*, Nature (2016)

Trapped Ions



Islam *et al*, Nature (2013)

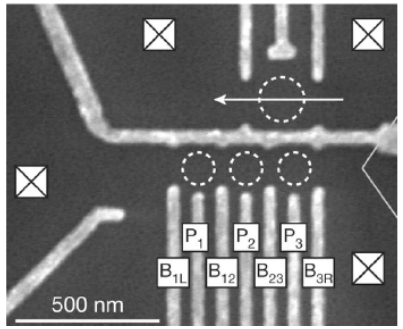
Superconducting Qubits



Barends *et al*, Nature (2014)

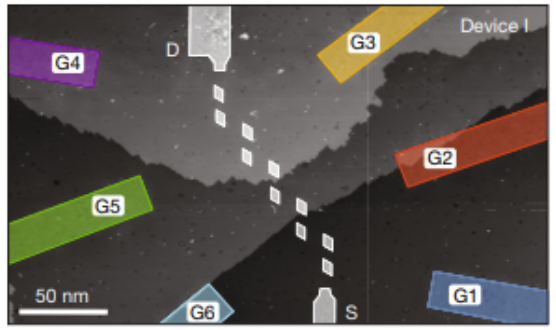
Semiconductors

U/t ~ 7.1

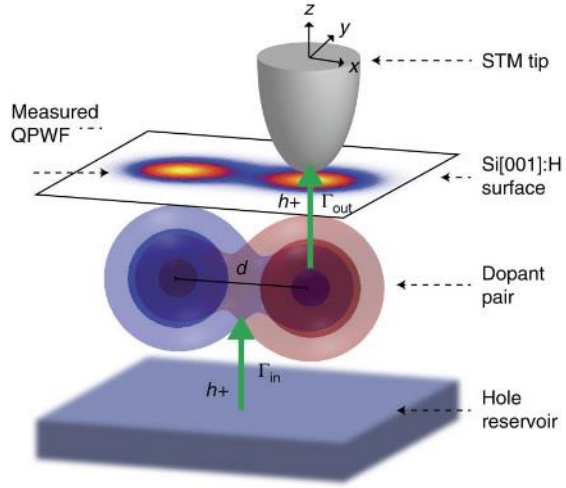


Hensgens *et al*, Nature (2017)

Dopants in silicon



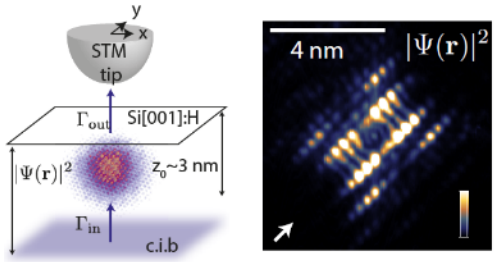
Kiczynski *et al*, Nature (2022)



Salfi *et al*, *Nature Comm* (2016)

For **donors** in silicon (in STM):

- ✓ strong coupling *t*
- ✓ low interaction strength U/t ~ 3.5, donors U~50 meV
- ✓ **Quantum state imaging available =** insights on valley & coupling



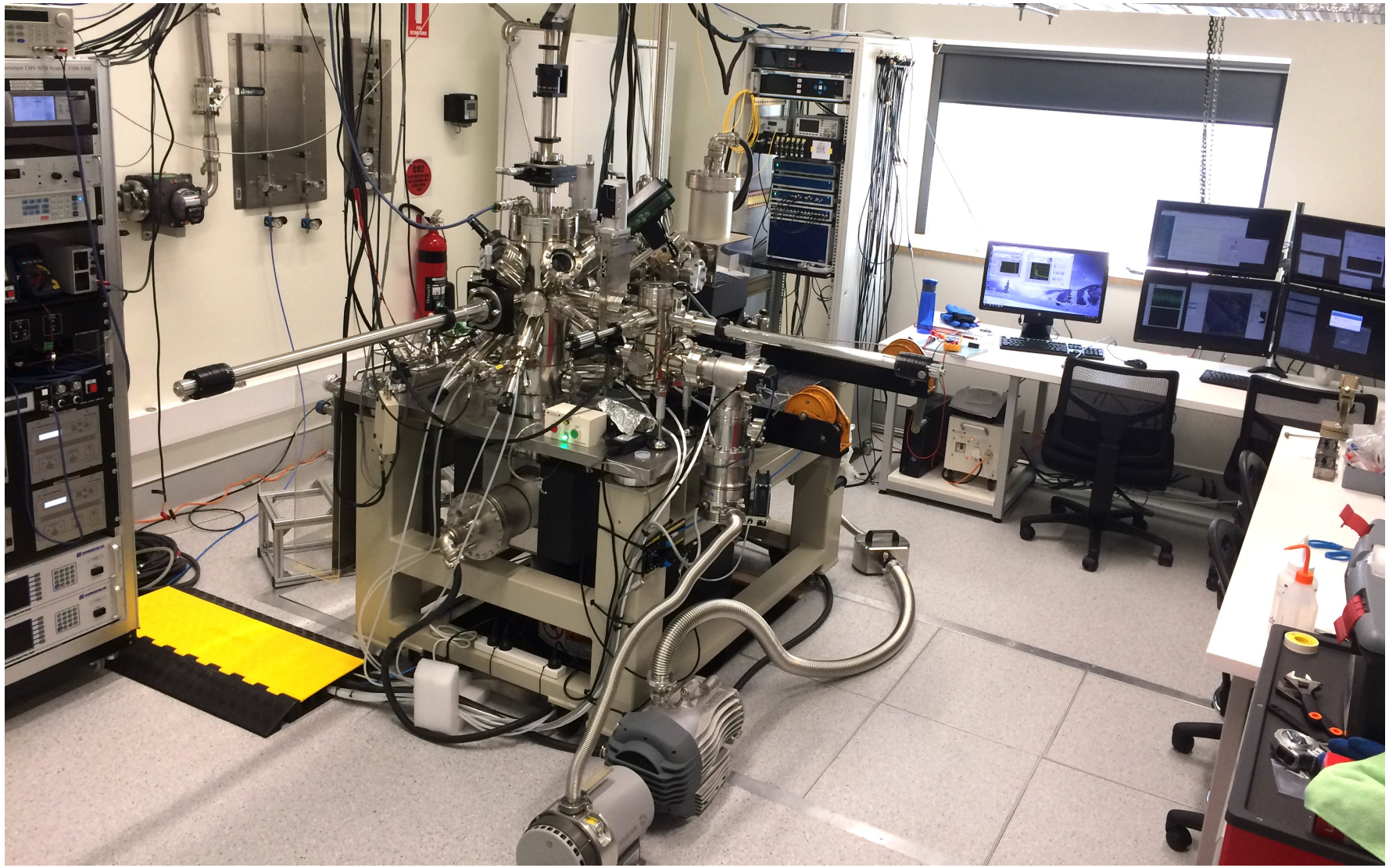
Salfi *et al*, *Nature Mat* (2014)
Voisin *et al*, *Nature Comm* (2020)
M. Usman *et al*, *Nature Nano* (2016)

- ✗ **No spin degree of freedom so far**.
- ✗ **No engineered sites,**
  (previous sample dopants randomly distributed)

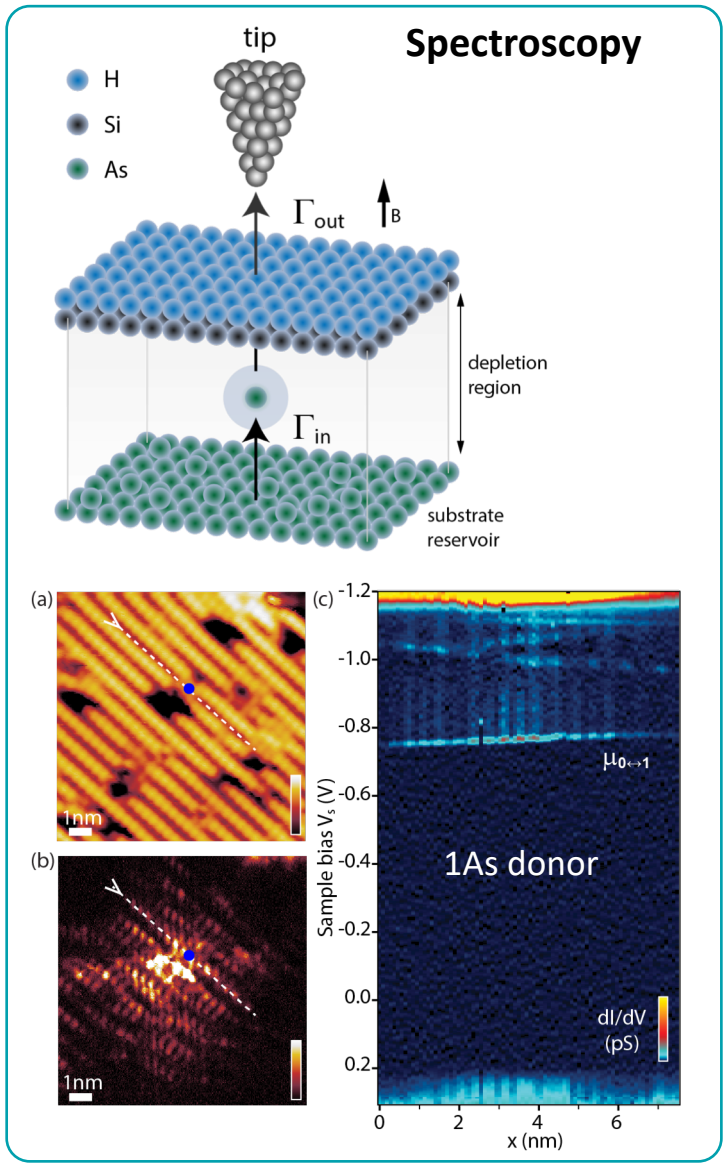
d.stmedar@unsw.edu.au

The lab

Unisoku STM @ UNSW

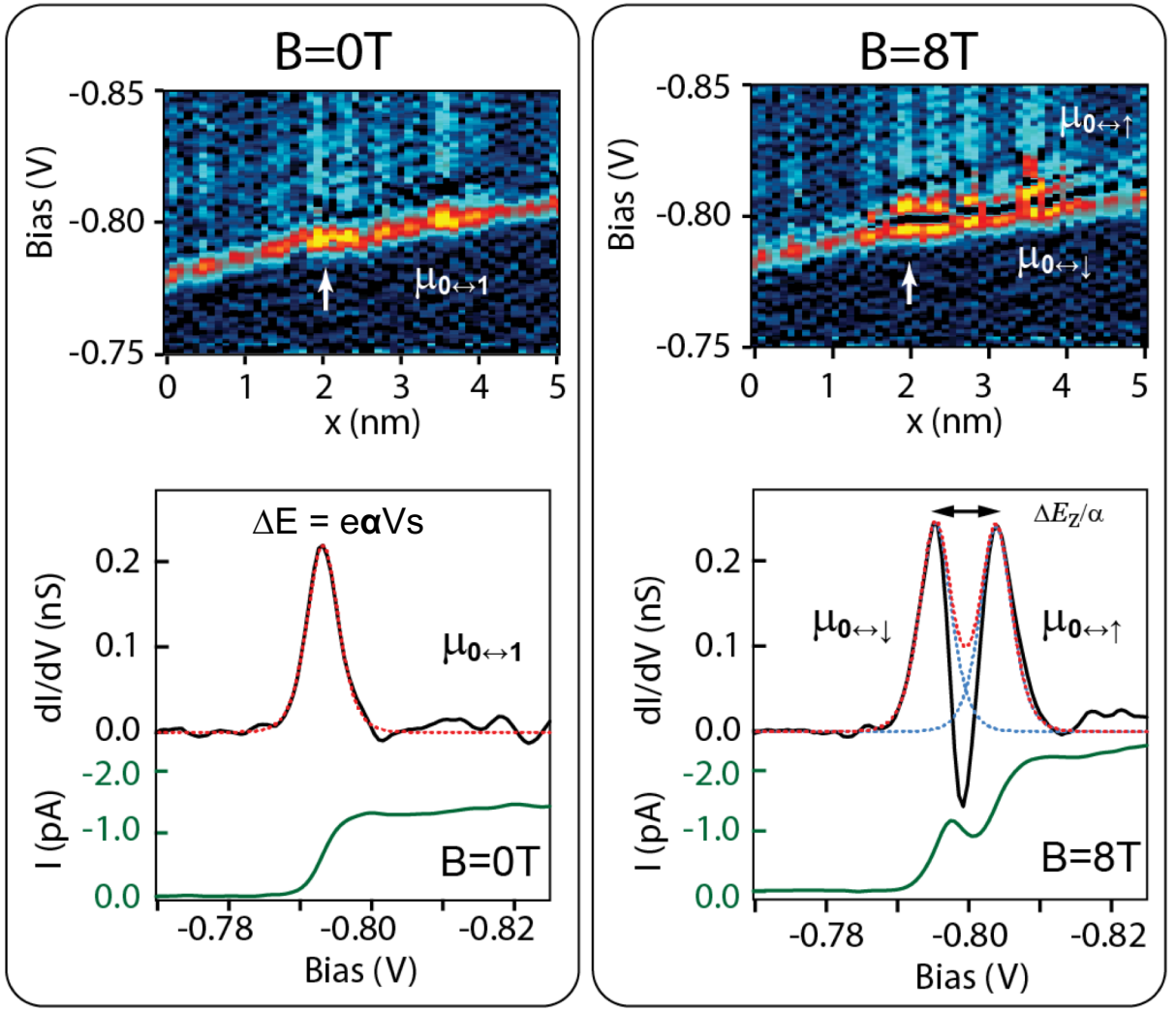


Spatially resolved magneto spectroscopy of a single donor



Voisin *et al*, *J. Phys.: Condens. Matter* (2015)
Salfi *et al*, *Nature Mat* (2014)

Zeeman splitting of single donor in an STM at 2 Kelvin

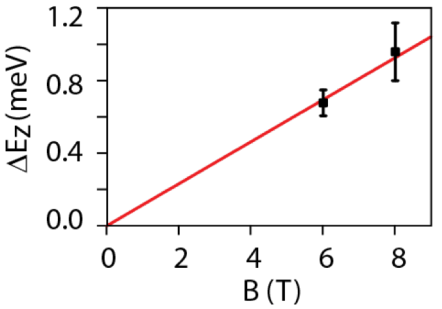


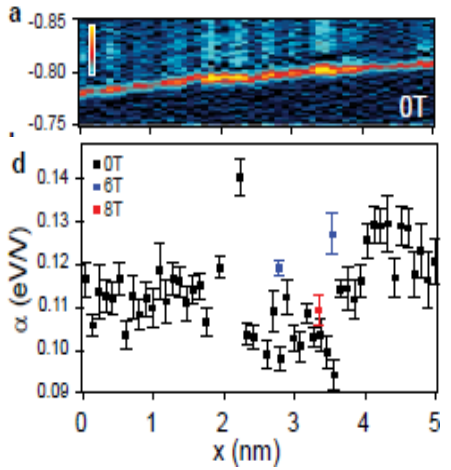
Thermal broadening
~0.617 meV (2K)

We get **alpha** from **thermal fit**

StMedar *et al*, (2022) in prep

We get absolute **alpha** from **Zeeman splitting**





noise in alpha from back-reservoir

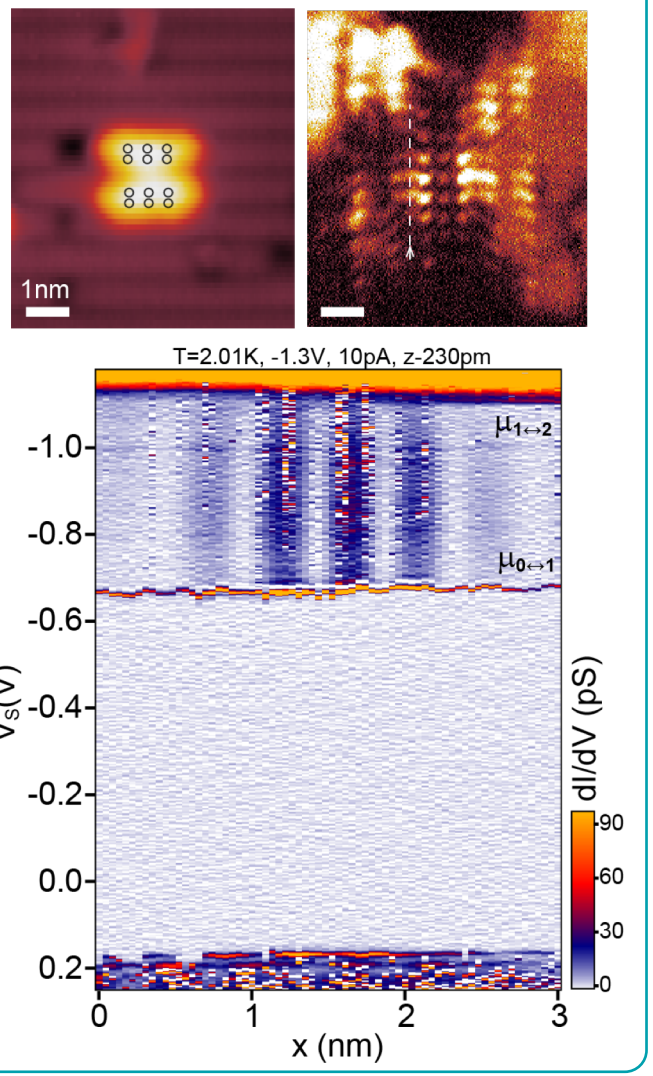
d.stmedar@unsw.edu.au

Spectroscopy of engineered few-donor Si:P quantum dots

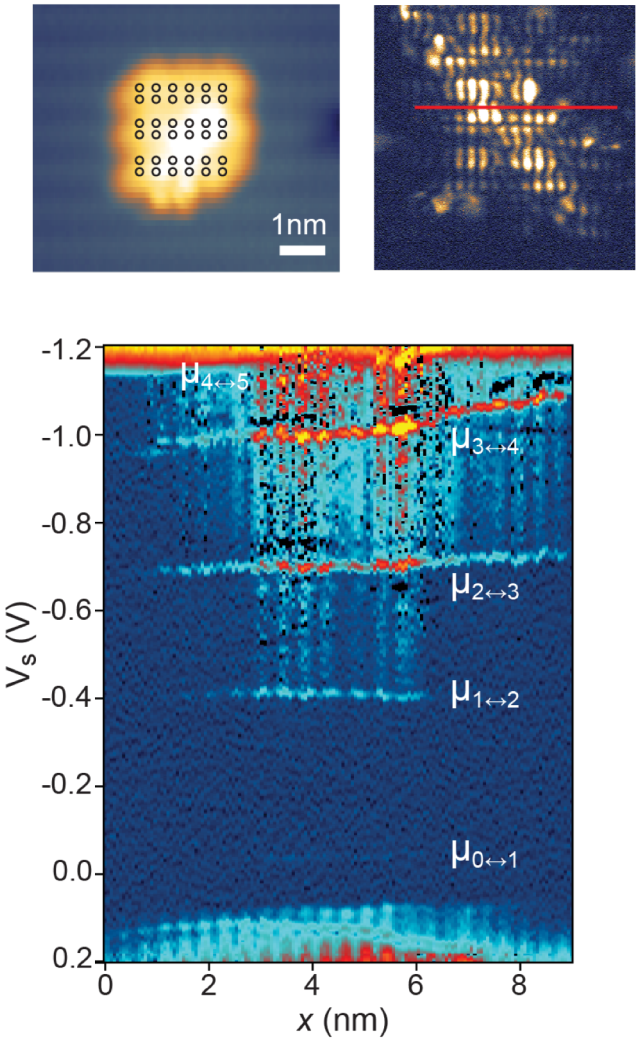
Motivation: Characterize the building blocks of a dopant based analog quantum simulator.

Engineered few donors quantum dots

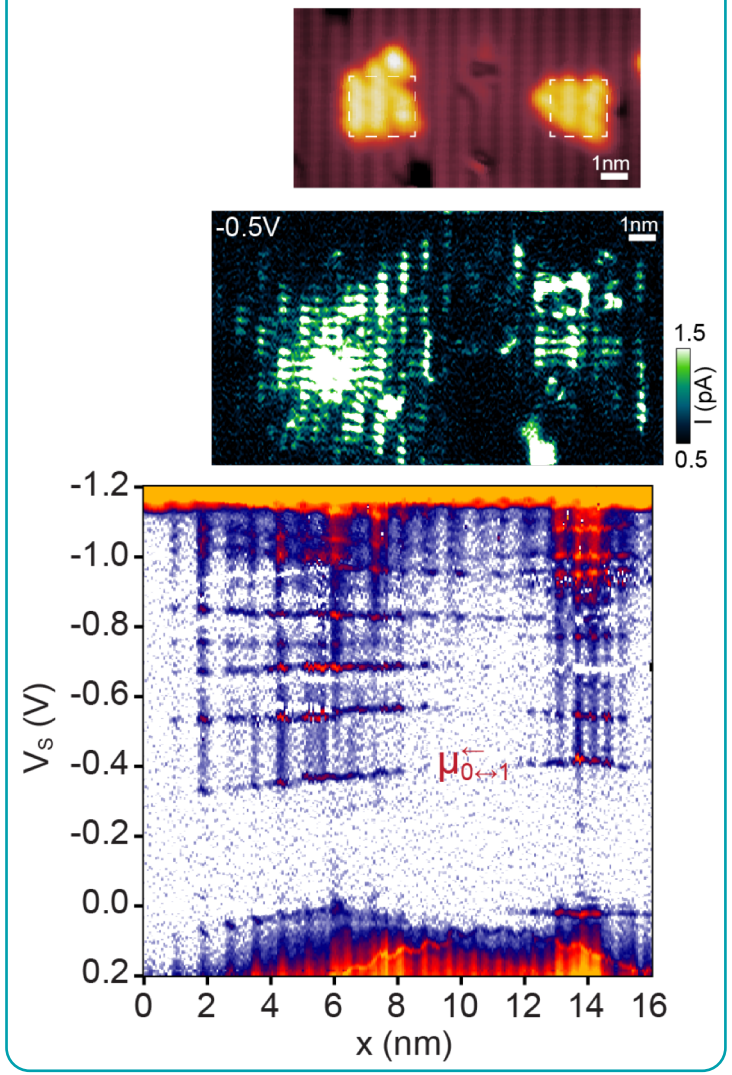
1P



3P



Double QD



Capacitive Transport model
To understand the electronic transitions + charging energies

StMedar *et al*, (2022) in prep

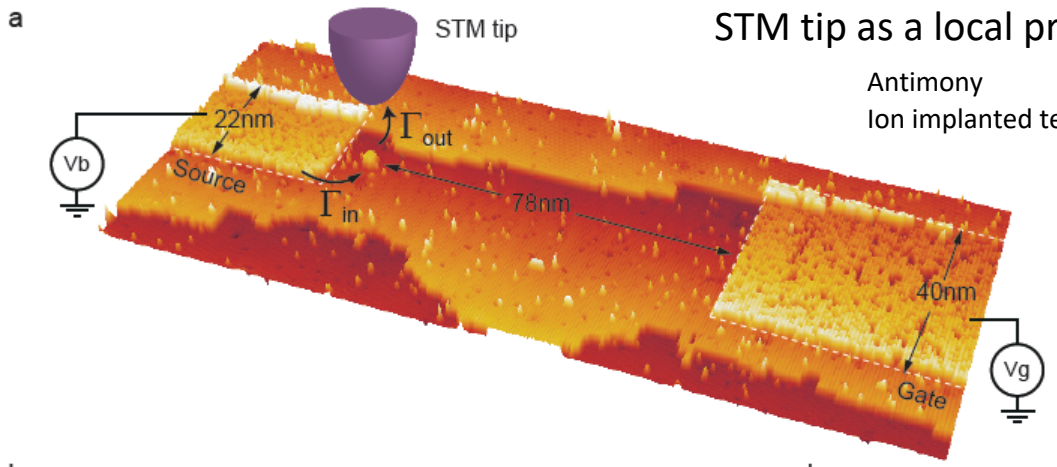
d.stmedar@unsw.edu.au

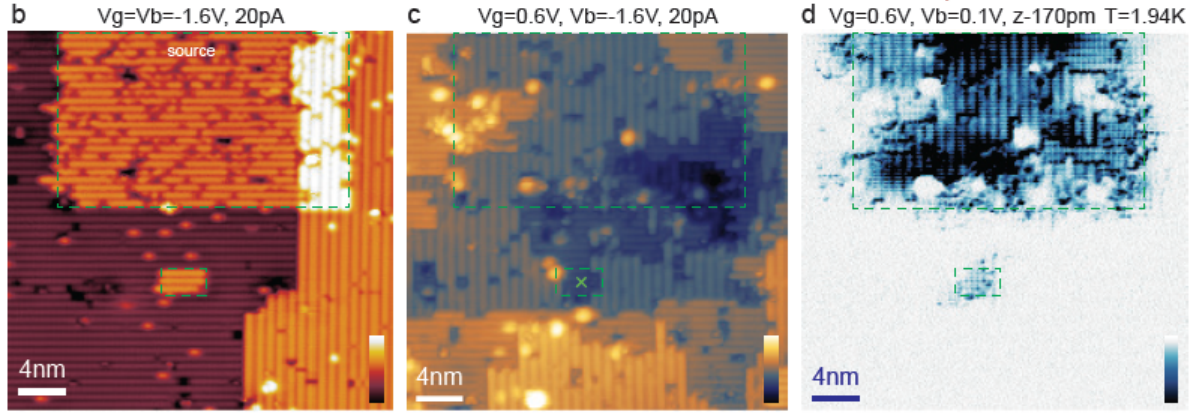
Multi-terminal Si:P STM devices

Silicon based STM platform for quantum simulations

*local gate control +
STM tip as a local probe

Antimony
Ion implanted terminals

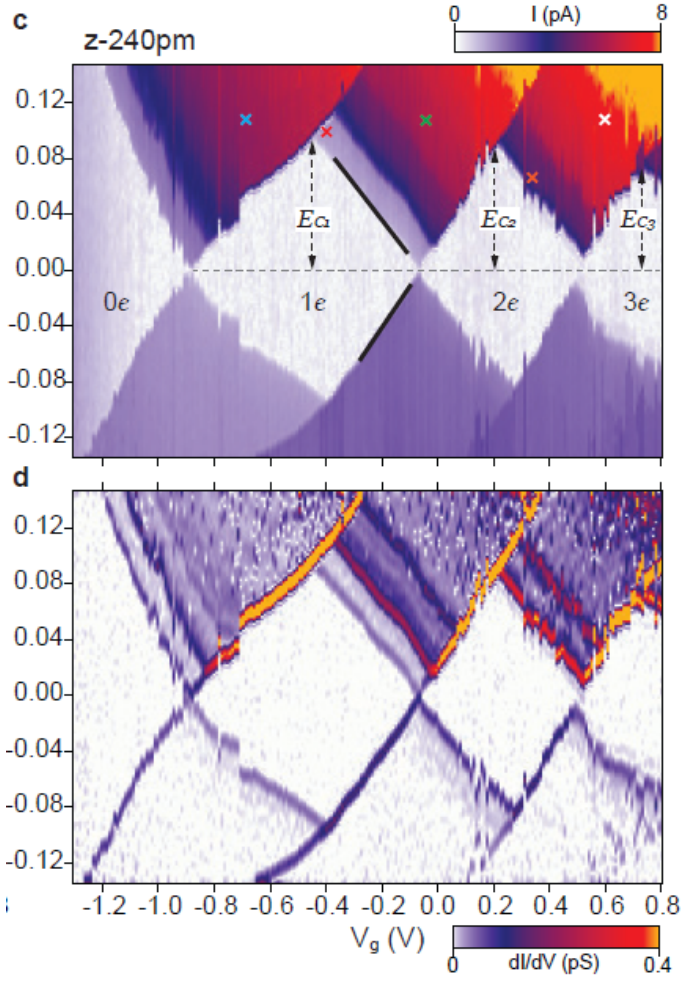


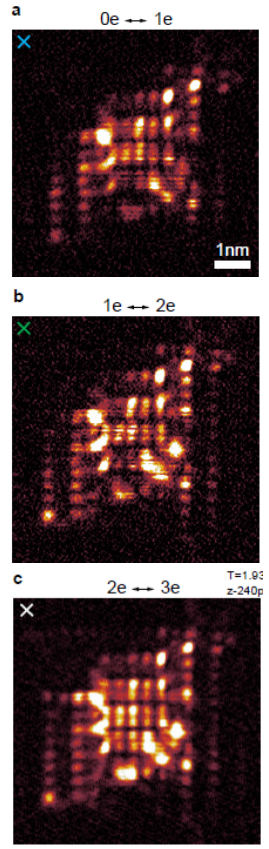


lithography | silicon growth | Quantum state imaging

Voisin *et al*, submitted
StMedar *et al*, (2022), in prep

e.g. 3P quantum dot (2K)





Access to excited states + Wave function mapping at different filling factors

→ theory to understand interactions in these QD
Rahman group @UNSW

d.stmedar@unsw.edu.au

Multi-terminal Si:P STM devices

Charging energies close to bulk

good agreement between experiments and existing literature

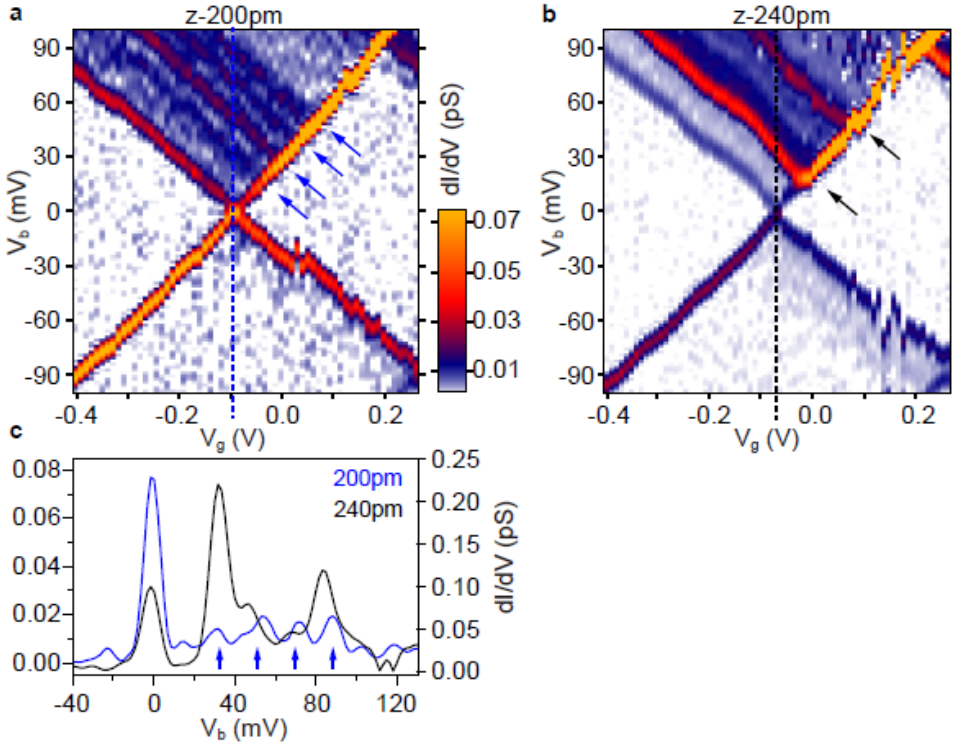
	3P	Weber, Nature Tech (2014)	*Weber, Phd thesis (2013)	Ye, Nature (2019)	Back-reservoir †
E_{C_1} [meV]	95 ± 3	92 ± 5	95.1	90 ± 18.5	19.1
E_{C_2} [meV]	81 ± 3	75 ± 5	53.6		15.1
E_{C_3} [meV]	66 ± 3	66 ± 5	43		15.9

	4P	Voisin, submitted	Weber, Nature Tech (2014)
E_{C_1} [meV]	133 ± 3	130 ± 5	133.9
E_{C_2} [meV]	80 ± 3		81.2
E_{C_3} [meV]	55 ± 3		70.2

Excited states spectroscopy

STM tip as a ***tuneable** local probe

Can change the coupling/tunnelling rate of donor to tip



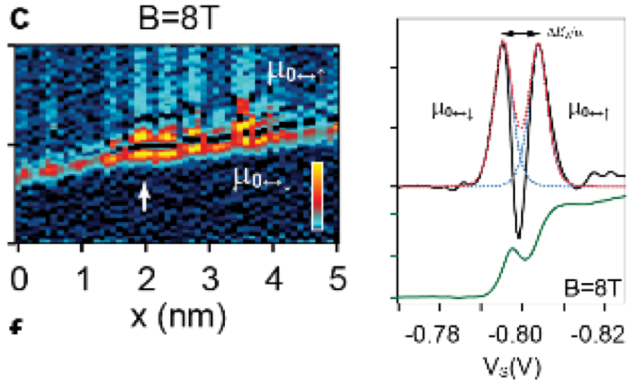
data we don't understand yet

d.stmedar@unsw.edu.au

Conclusion

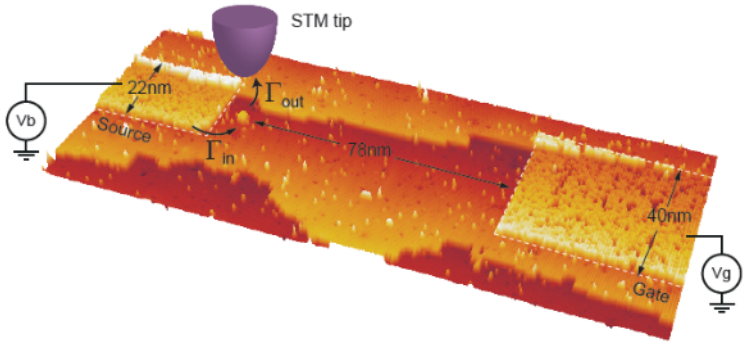
We showed in an STM experiments:

(1) Access to the spin degree of freedom (resolution of single donor)

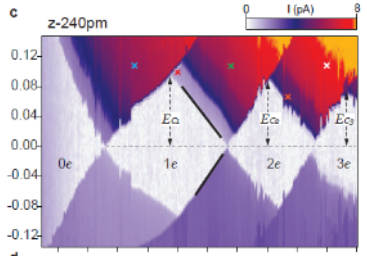


+ absolute value for alpha factor

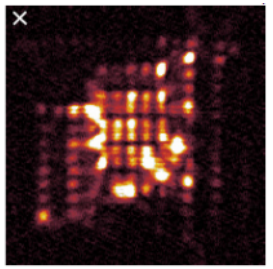
(2) Local gate control and in-situ spectroscopy of few donor quantum dots



access to excited states



Quantum state imaging



Towards spin-based quantum simulation with dopants in silicon, with the STM tip as local spectral function probe.
e.g. mapping of exotic ground states of matter away from half-filling.

d.stmedar@unsw.edu.au

d.stmedar@unsw.edu.au

Theory (donor cluster simulation)
A M Saffat-Ee Huq and Rajib Rahman
(UNSW)

Theory (quantum simulation)
David Mikhail and Stephan Rachel
(University of Melbourne)

Sb Ion implantation
Brett Johnson and Jeffrey McCallum
(University of Melbourne)

Cleanroom Facility
Australian National Fabrication Facility
NSW Node (UNSW)

THANK YOU