nature COMMUNICATIONS

ARTICLE

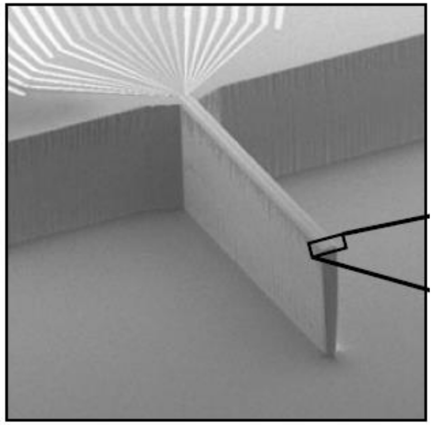
Check for updates

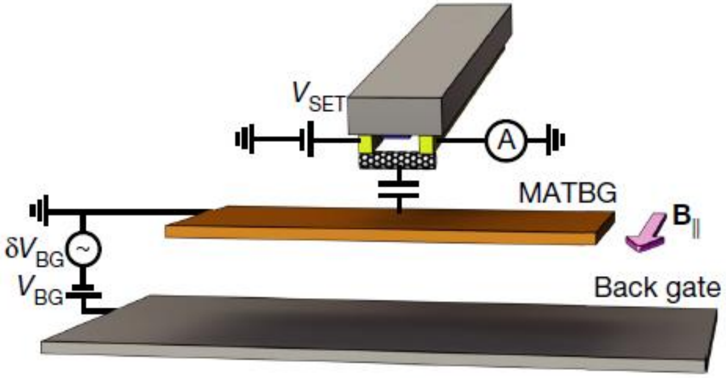
https://doi.org/10.1038/s41467-020-16001-5 OPEN

Atomic-like charge qubit in a carbon nanotube enabling electric and magnetic field nano-sensing

I. Khivrich[1] & S. Ilani[1]✉

Scanning probe of electric and magnetic fields



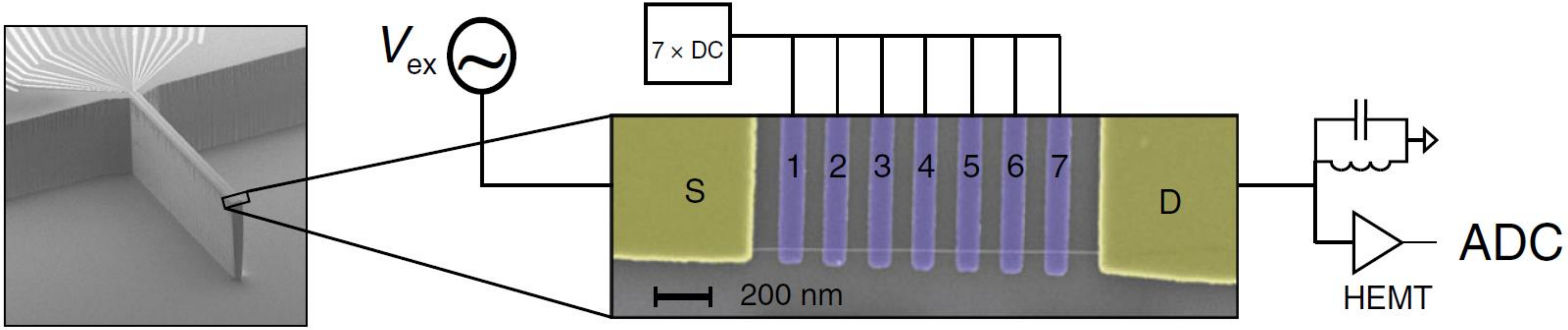


Advantages qubits defined in carbon nanotubes (CNTs) for scanning probe microscopy:

- Very high sensitivity to electric fields
  (voltages, currents, charges, electronic density of states, …
- Sensitive to magnetic fields
- Relatively high resolution (QD size)
- Low invasiveness

Rozen et al., Nature 592, 214 (2021)

Device: carbon nanotube suspended over gates



- To be used as scanning probe
- Here: on-chip characterization

Fabrication

nature nanotechnology

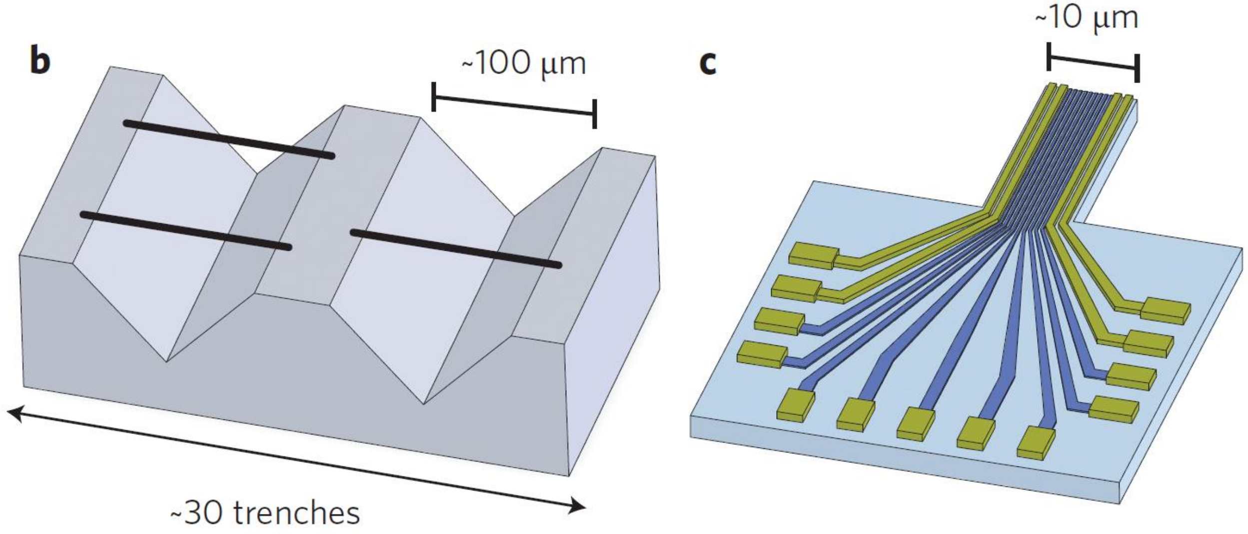
LETTERS

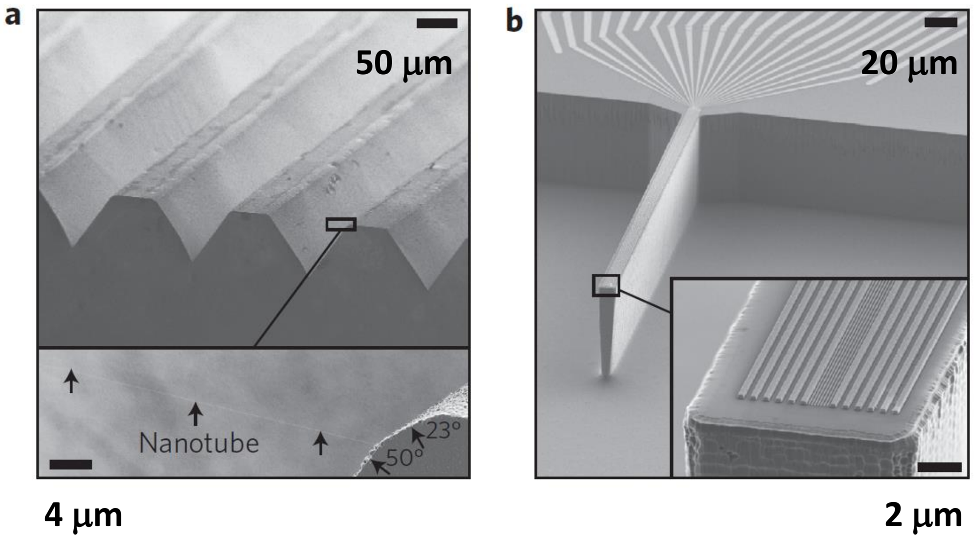
PUBLISHED ONLINE: 4 AUGUST 2013 | DOI: 10.1038/NNANO.2013.143

Realization of pristine and locally tunable one-dimensional electron systems in carbon nanotubes

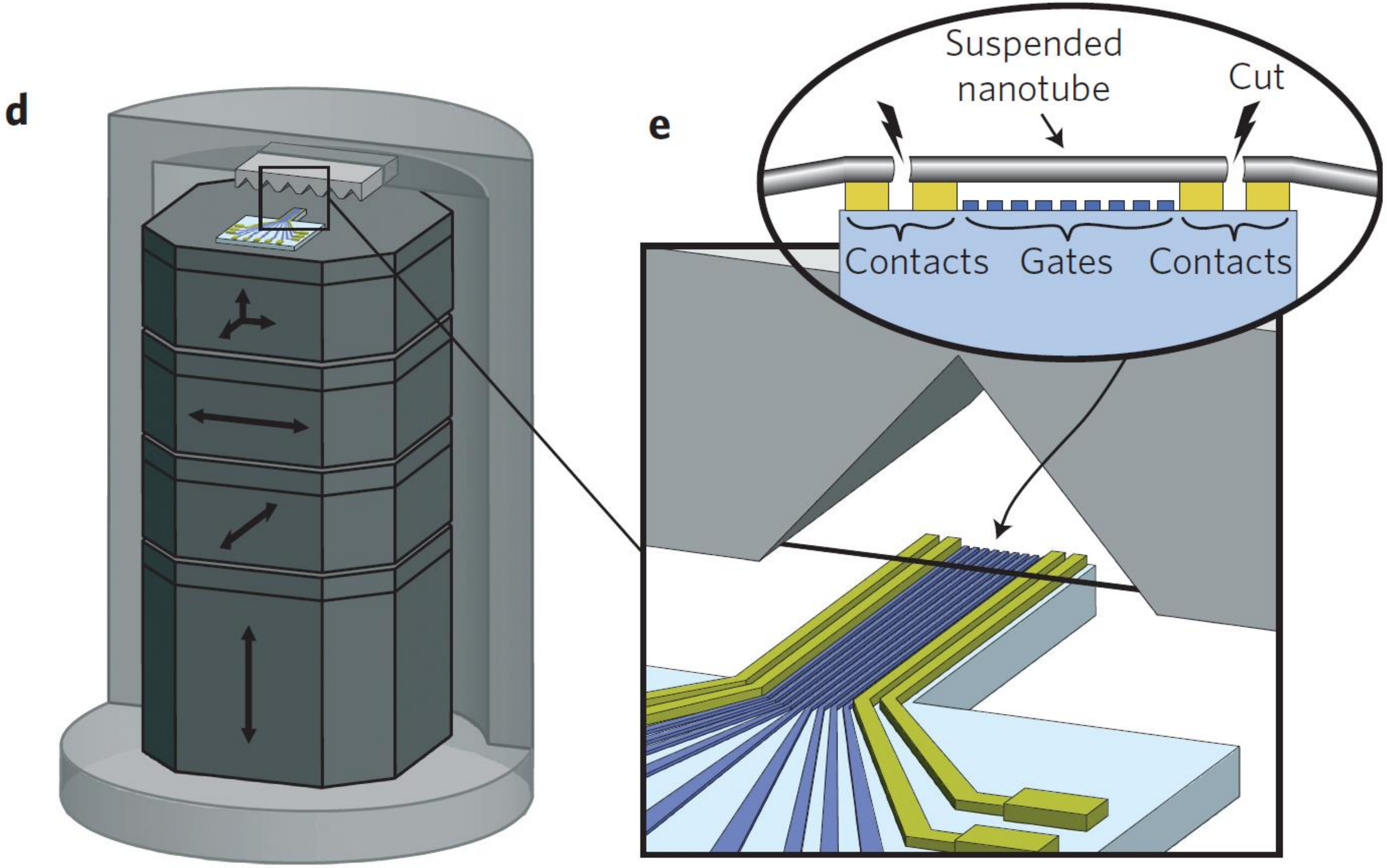
J. Waissman[1,2†], M. Honig[1†], S. Pecker[1†], A. Benyamini[1†], A. Hamo[1†] and S. Ilani[1]*

Fabrication



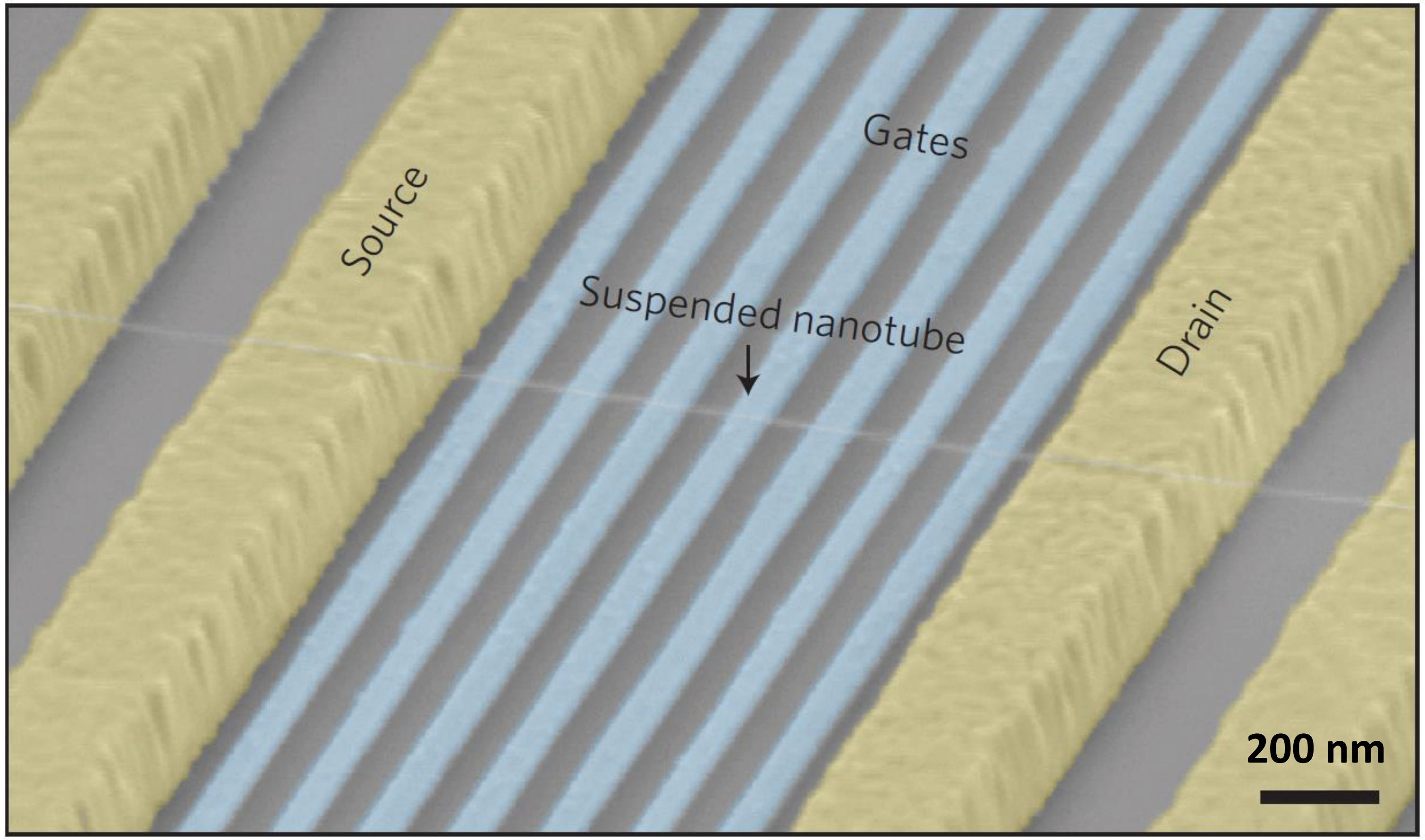


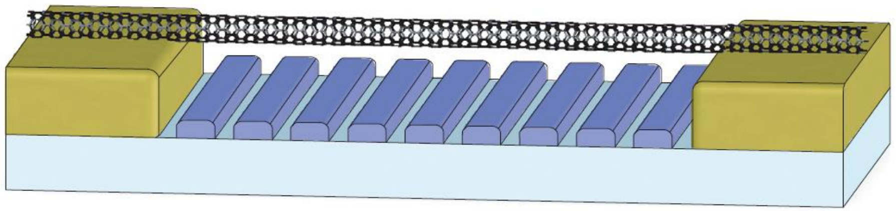
Fabrication



- All inside a fridge @ 4K
- Argon ion etching in load-lock to improve contacting CNT

Fabrication





Here:
- CNT length = 1.2μm
- Suspension height: 60 nm
- 7 gates

Other recent research using these devices (Ilani group)

Nanomechanical pump–probe measurements of insulating electronic states in a carbon nanotube
Khivrich et al., Nat. Nanotechnol. 14, 161 (2019)

Simultaneous voltage and current density imaging of flowing electrons in two dimensions
Ella et al., Nat. Nanotechnol. 14, 480 (2019)

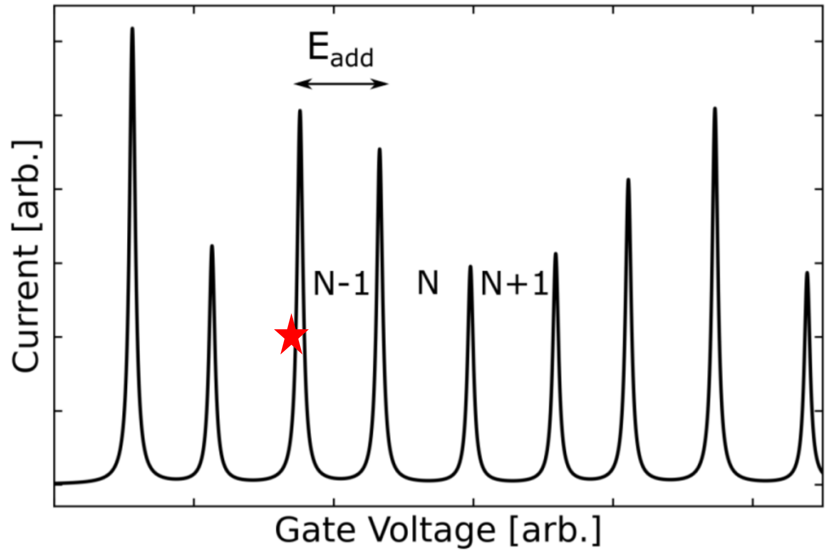
Imaging the electronic Wigner crystal in one dimension
Shapir et al., Science 364, 870, 2019)

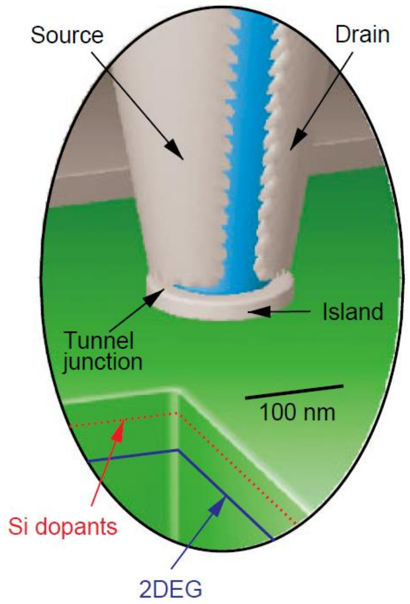
Visualizing Poiseuille flow of hydrodynamic electrons
Sulpizio et al., Nature 576, 75 (2019)

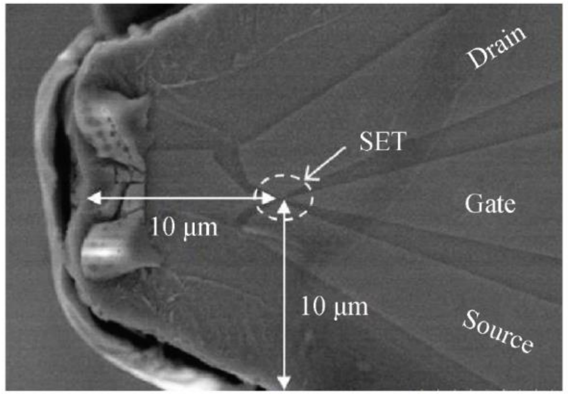
Cascade of Phase Transitions and Dirac Revivals in Magic Angle Graphene
Zondiner et al., Nature 582, 203 (2020)

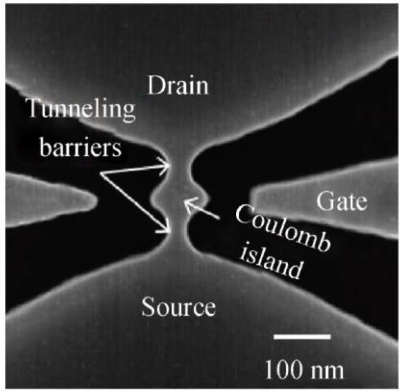
Entropic evidence for a Pomeranchuk effect in magic-angle graphene
Rozen et al., Nature 592, 214 (2021)

Scanning SET



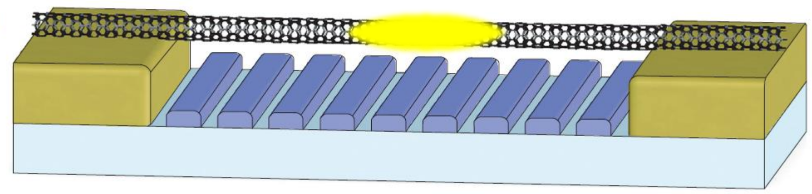


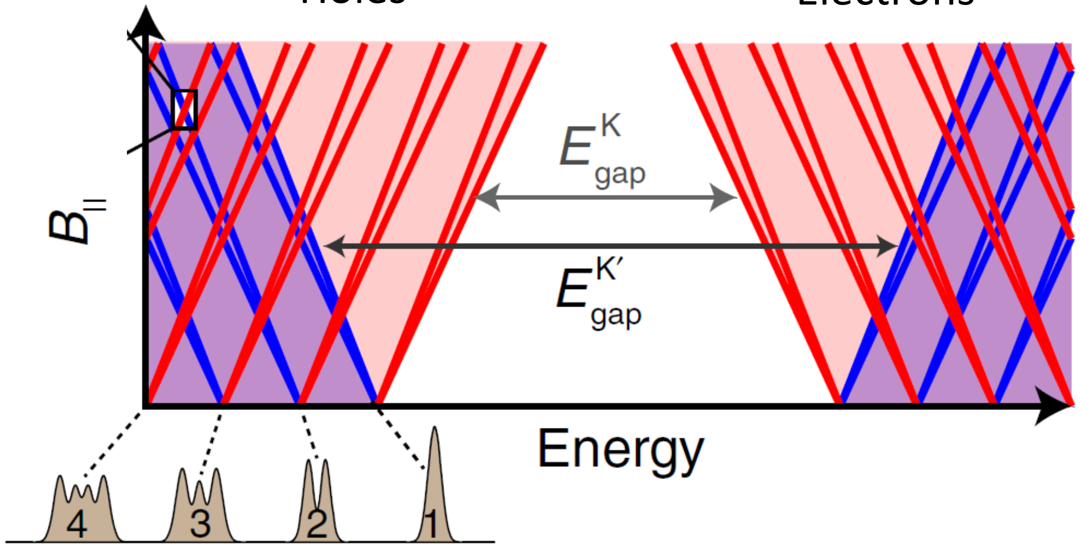




Yoo et al., Science 276, 579 (1997)
Lina et al., J. Semicond. 37, 044008 (2016)

Qubit states

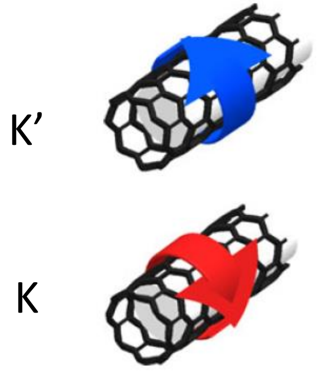




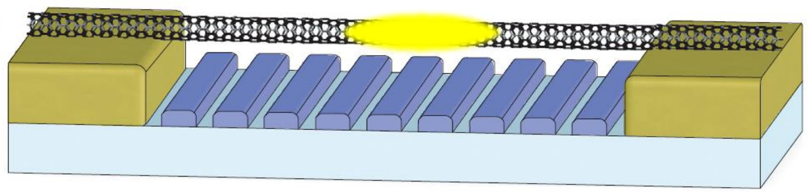
- B // to CNT axis

Electronic harmonic oscillator levels in CNT:

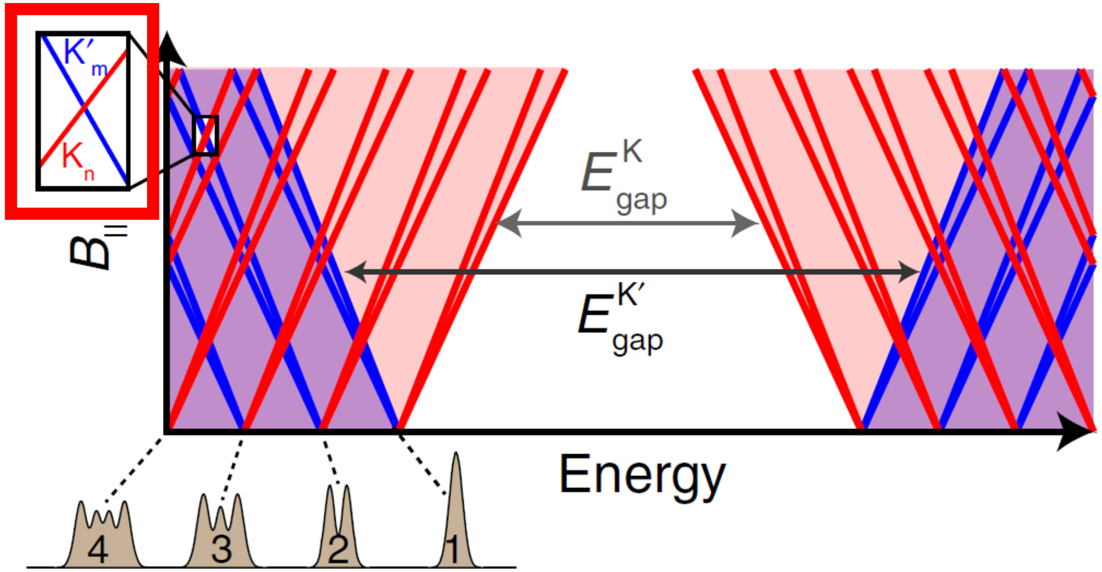
- 4-fold degenerate:
    - Spin (up, down)
    - Valley (K, K')
- Increase in level number leads to more extended wave functions



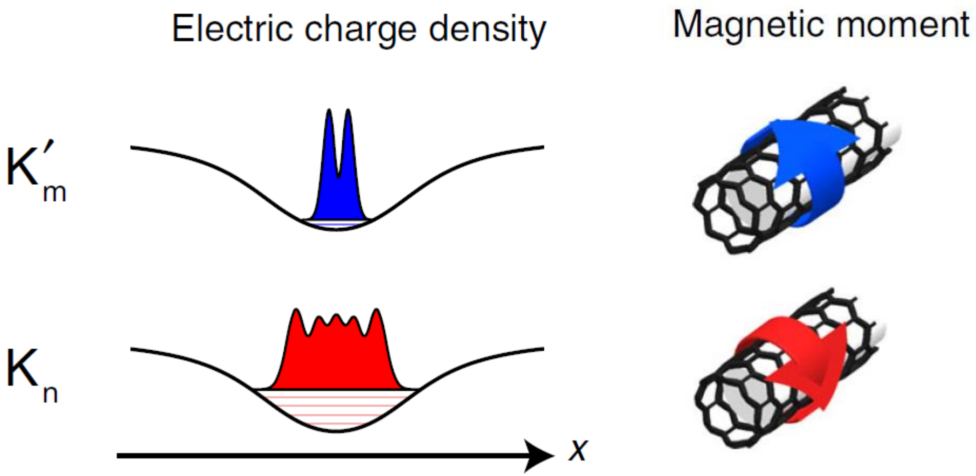
Qubit states

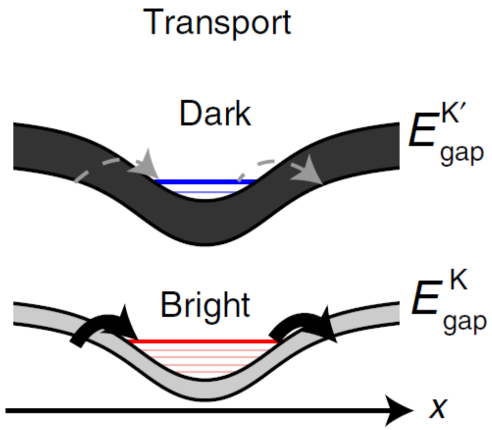


- Choose high K and low K’



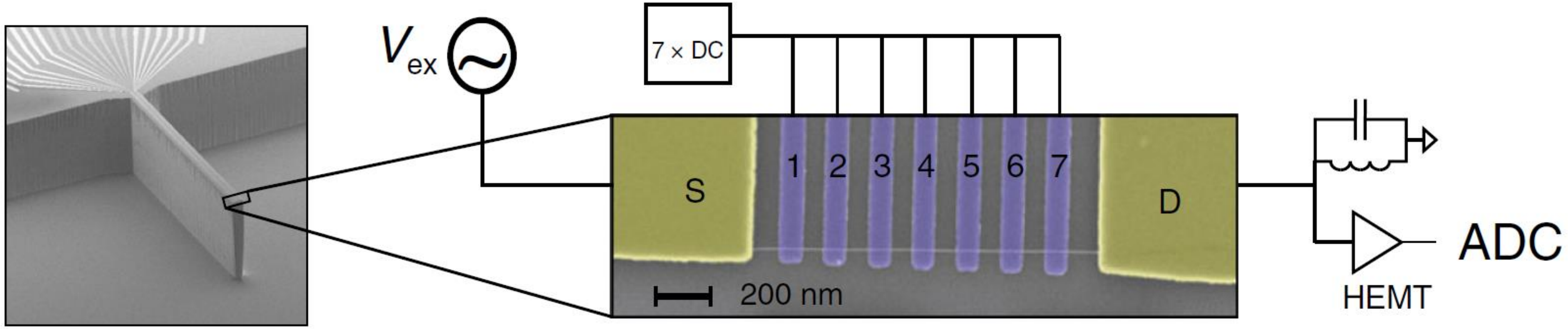
- B // to CNT axis



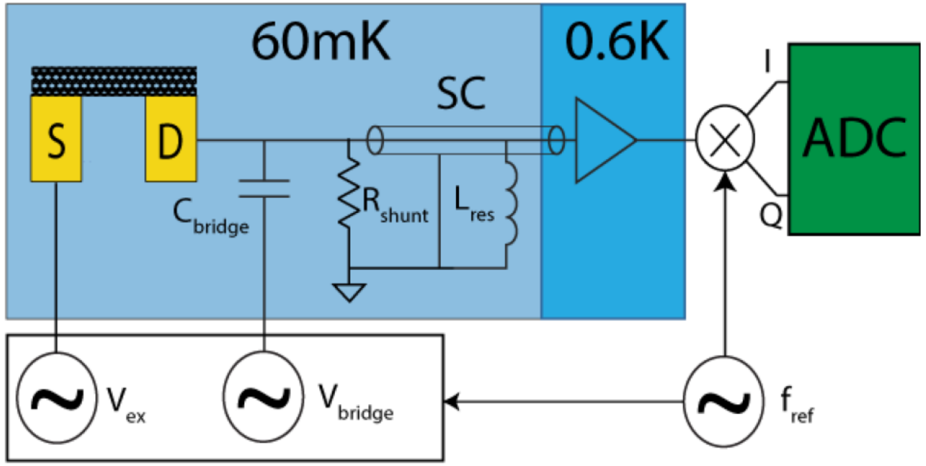


- Electric moment
- Opposite spins, to minimize decay

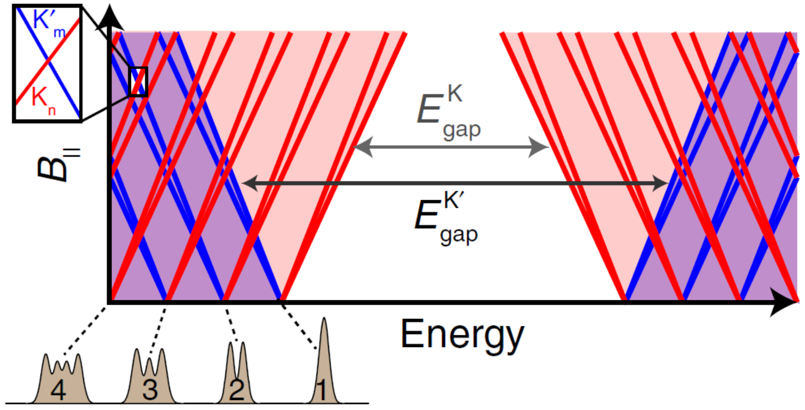
Measurement details



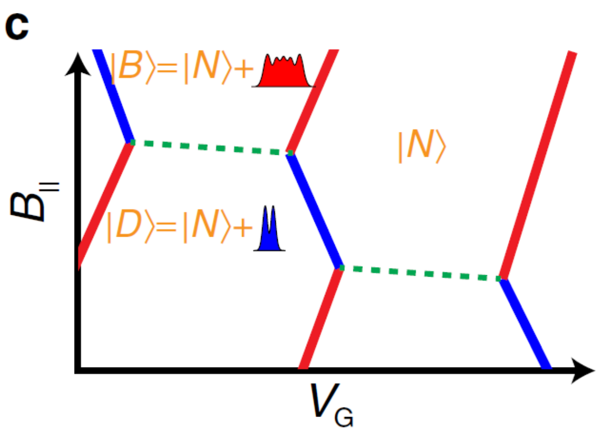
- Electron temperature: 60 mK
- Lock-in measurement using LC-circuit:
  - f = 1.45 MHz
  - V_{ac} = 15 μV_{rms}

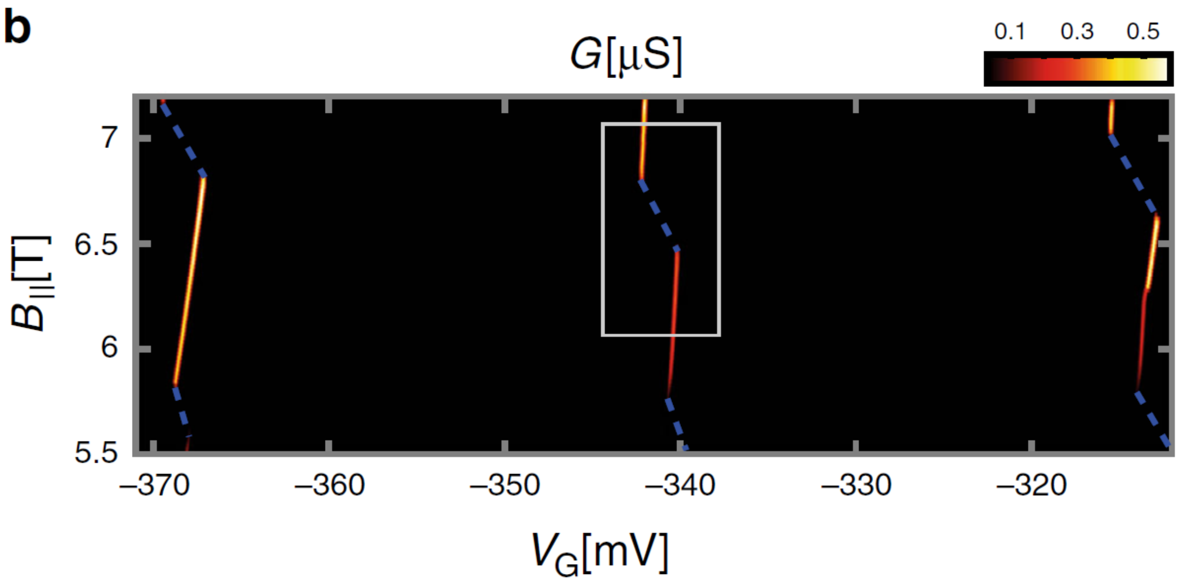


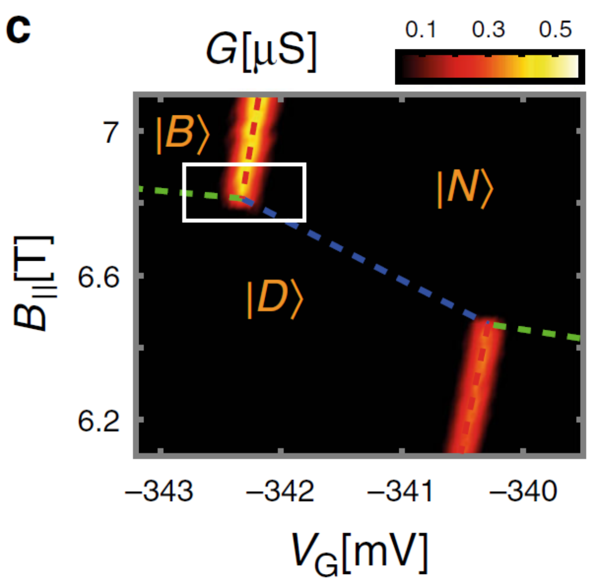
Charge stability diagram



+ Charging energy =



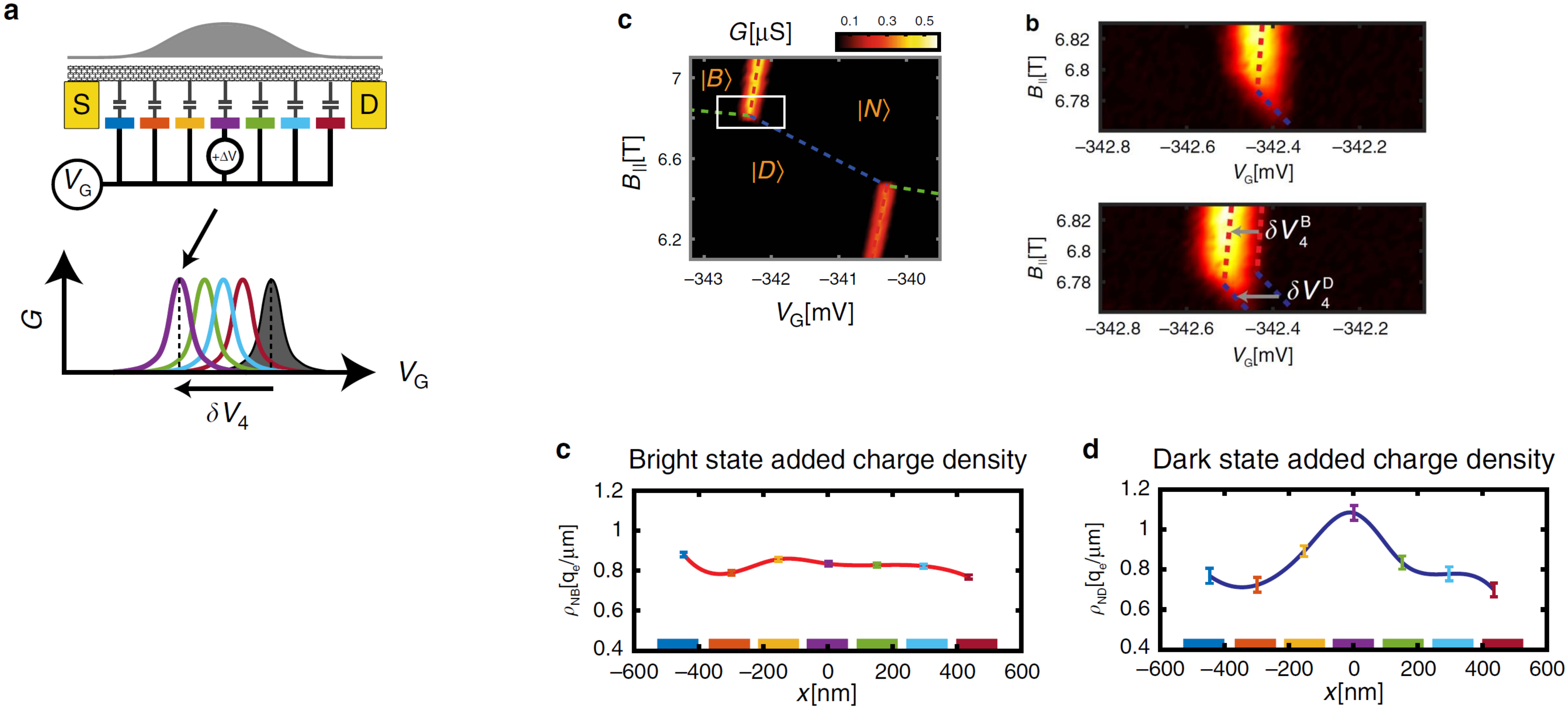




$|B\rangle = |N\rangle + K_n$

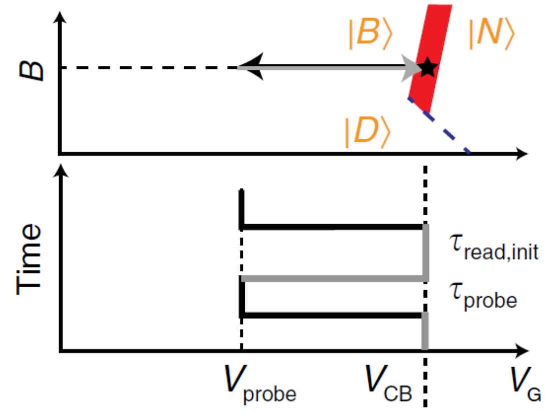
$|D\rangle = |N\rangle + K'_m$

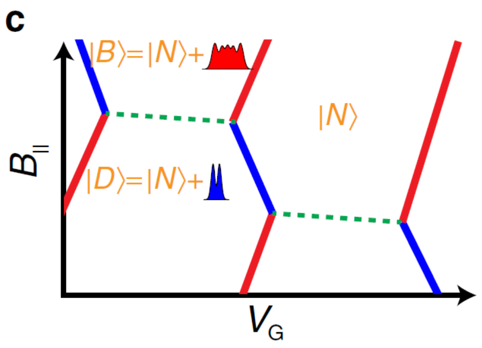
Spatial charge distributions of the two qubit states



- Resolution: ~100 nm

Pulsed measurements: detection of qubit transition



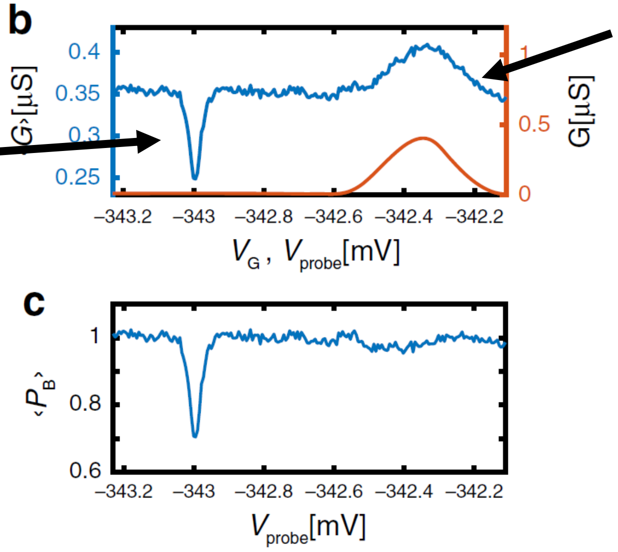


1) Initialize in |B>
2) Pulse to |B> - |D> transition
3) Read-out
4) Repeat

$$\langle G\rangle = \left(G\left(V_{\rm probe}\right)\tau_{\rm probe} + G(V_{\rm CB})\langle P_{\rm B}\rangle\tau_{\rm read,init}\right)/\left(\tau_{\rm probe}+\tau_{\rm read,init}\right)$$

- τ_{probe} = 0.8 μs
- $\tau_{read,init}$ = 5 μs

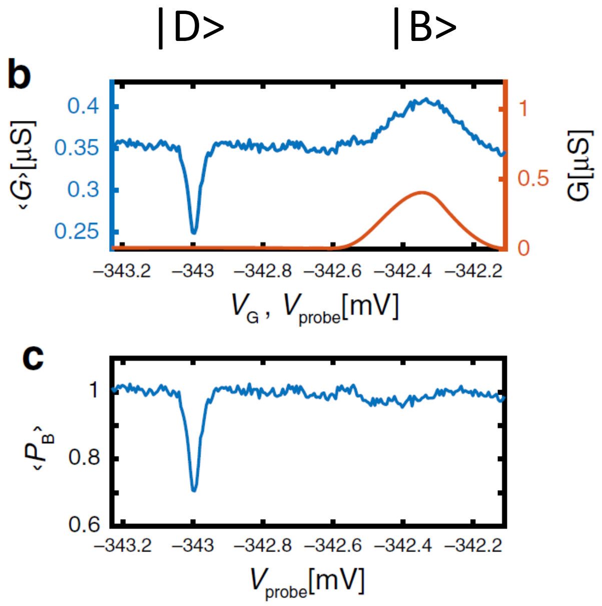
|D> |B>

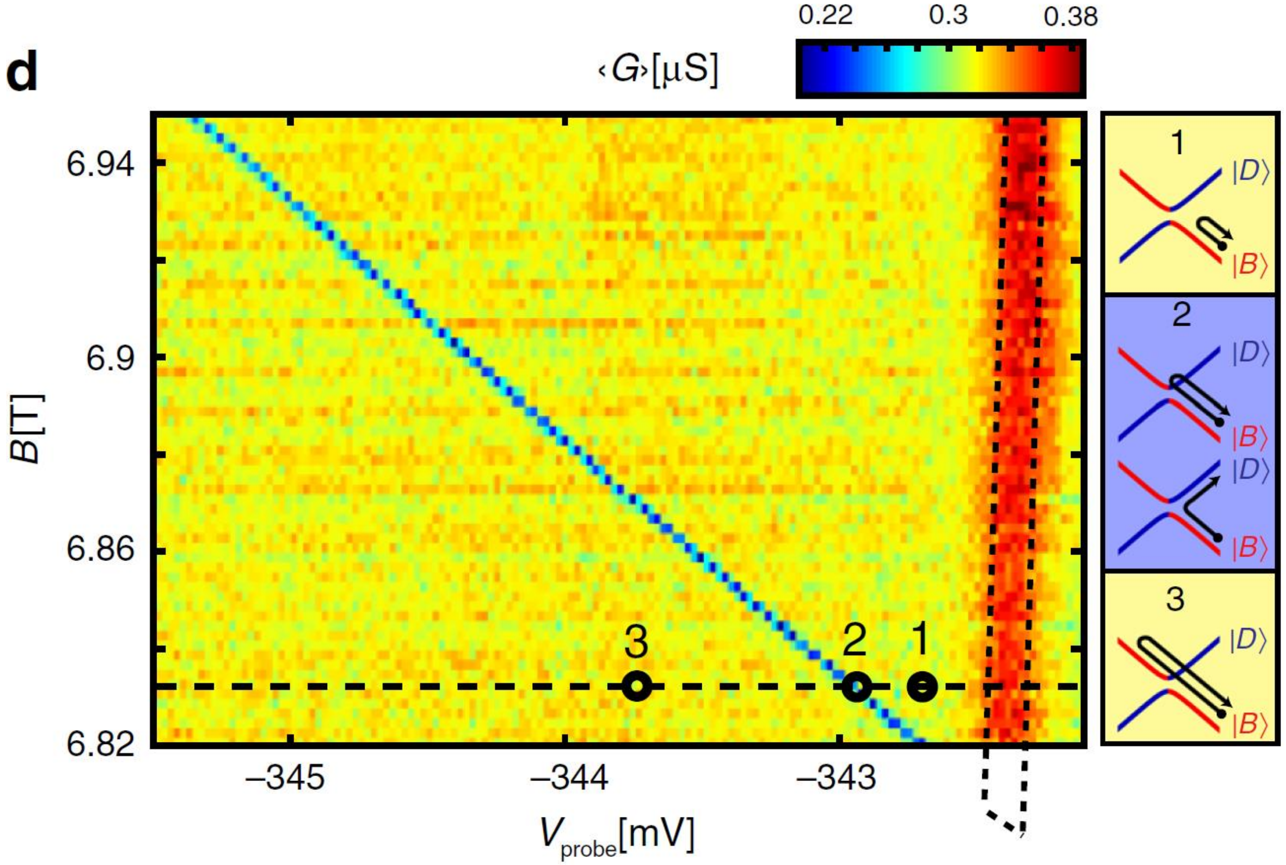


Qubit transition:
40μV

Coulomb peak:
Thermally limited to 200μV

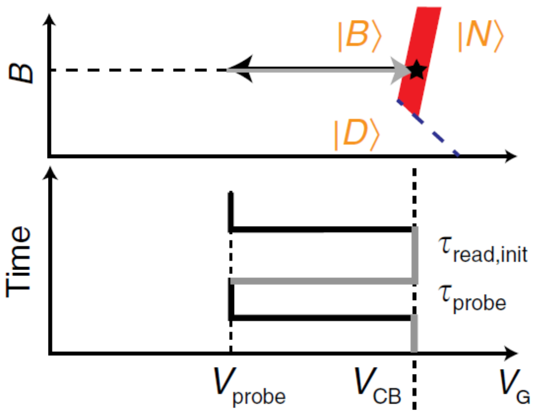
Pulsed measurements: detection of qubit transition



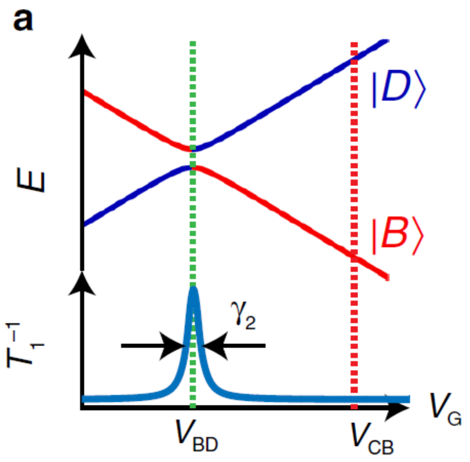


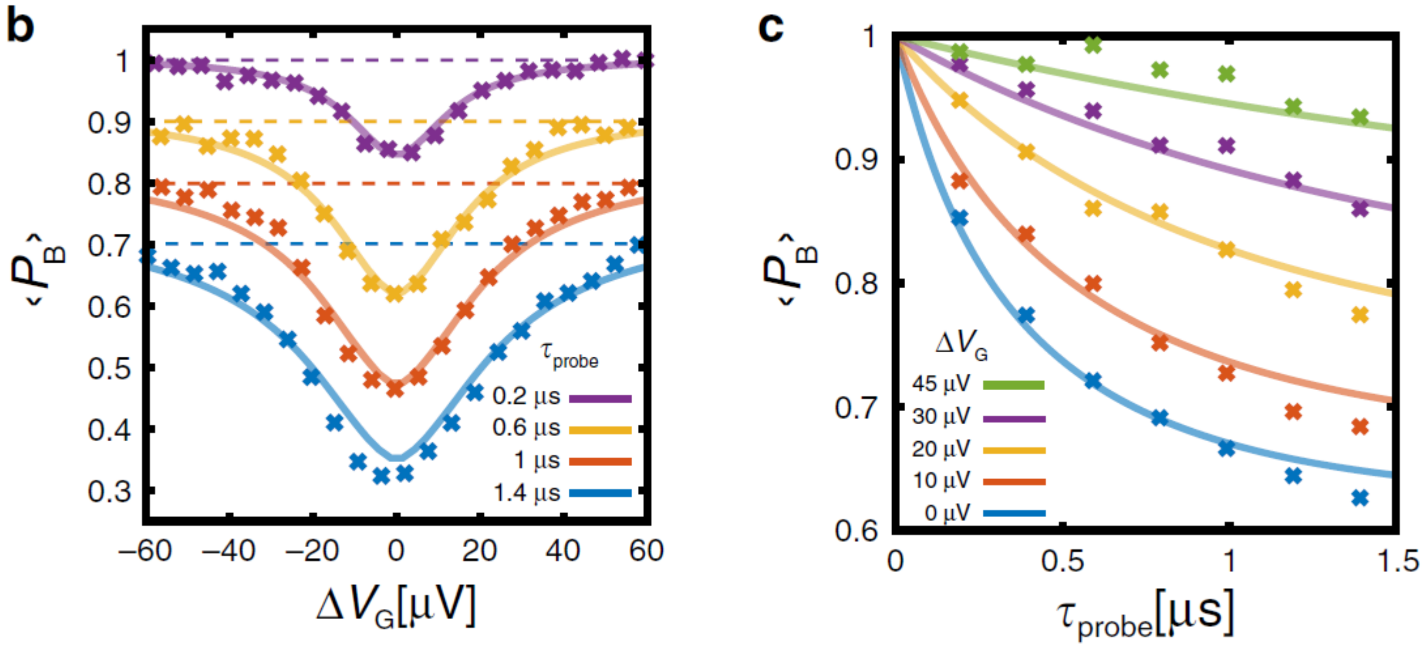
- slope: sensitive to voltages and magnetic fields

Transition rate



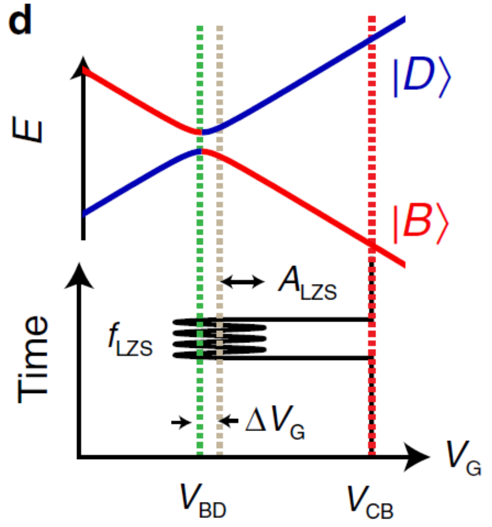
- Vary τ_{probe}
- $\tau_{read,init} = 5\ \mu s$

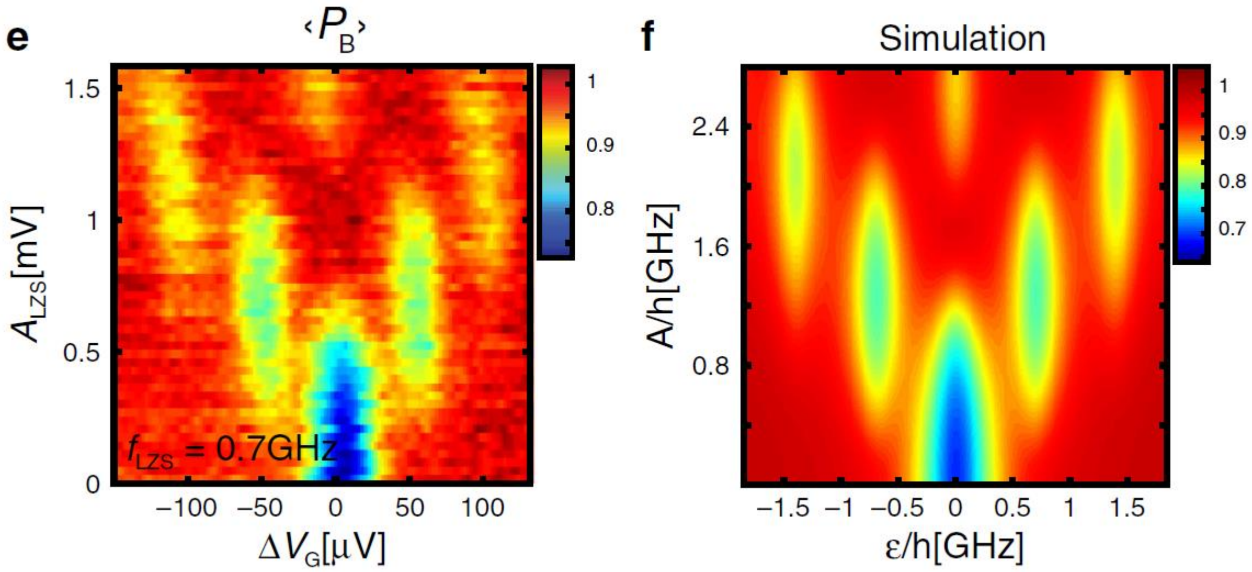




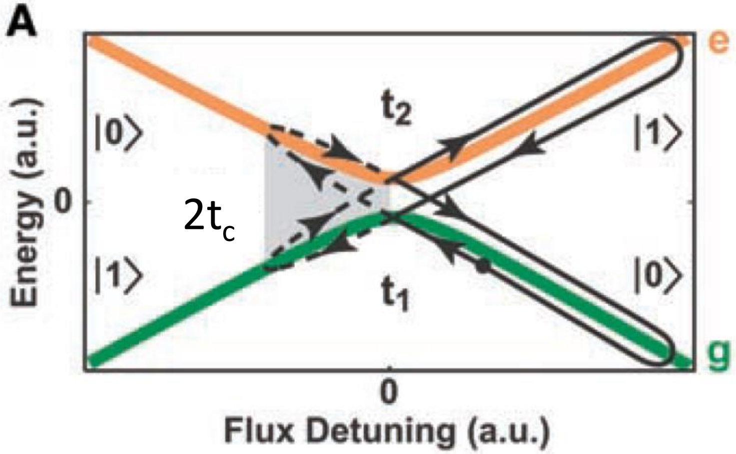
$T_1 = 1\ \mu s$

Landau-Zener-Stückelberg interferometry





$$V_G(t) = V_{BD} + \Delta V_G + A_{LZS}\ \sin(2\pi f_{LZS} t)$$



$$P_{LZ} = \exp\left(-2\pi \frac{(2t_c)^2}{\hbar v}\right)$$

$$v = \mathrm{d}E/\mathrm{d}t$$

Width: T_2^* = 0.9ns (charge noise)

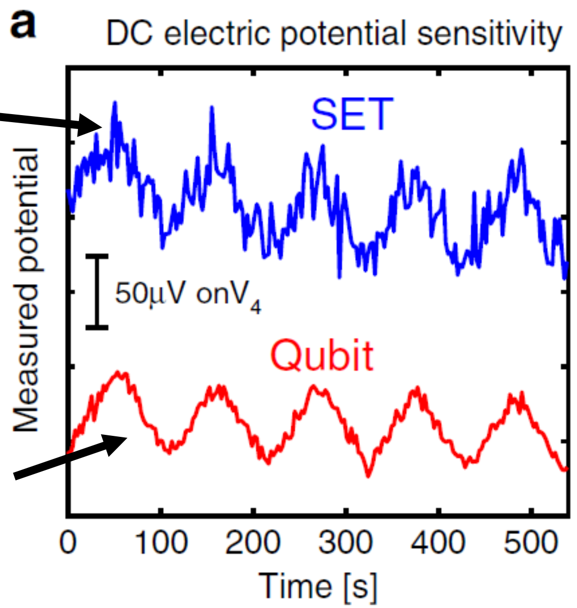
Compare:
- T_2^* = 13 ns (on-chip spin-valley qubit)
- $T_2^* \sim 1\ \mu$s (spin qubit coupled to cavity)

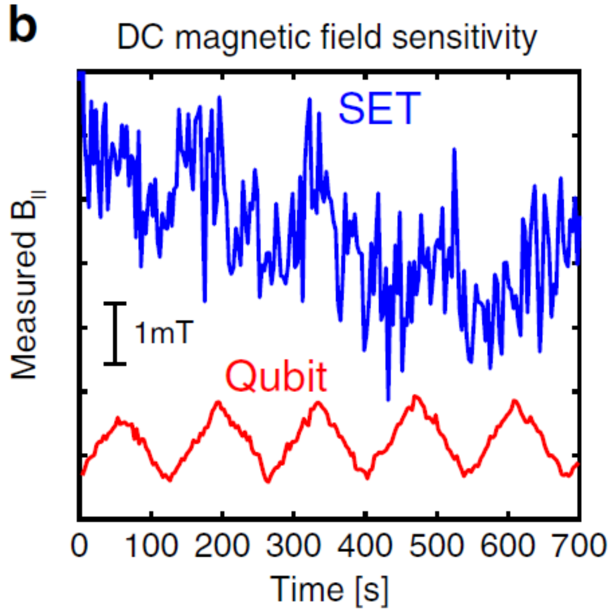
W. D. Oliver et al., Science 310, 1653 (2005)

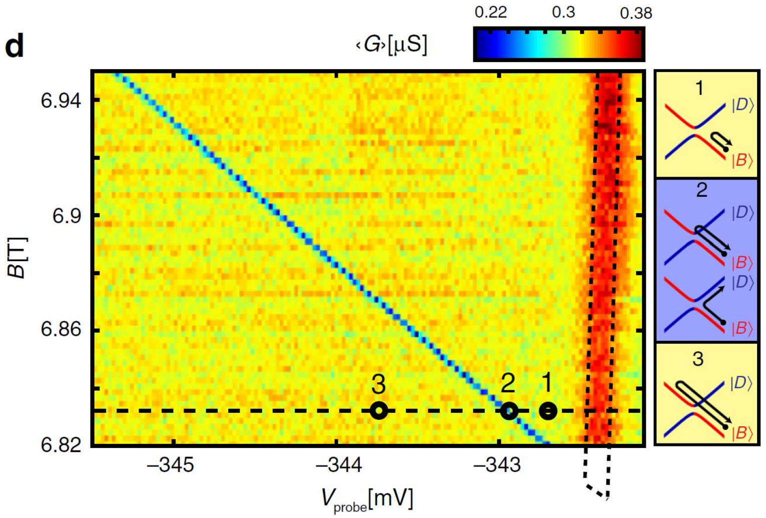
Sensitivities

On Coulomb peak

On qubit transition







- 60 neV/Hz$^{1/2}$
- 600 nV/Hz$^{1/2}$

- 39 μT/Hz$^{1/2}$

Compare:

CNT SET sensitivity: 2μV/Hz$^{1/2}$

Scanning NV ac field sensitivity: 100 nT/Hz$^{1/2}$
(stationary NV: 4 nT/Hz$^{1/2}$ (DC), 1.3 nT/Hz$^{1/2}$ (AC))

Scanning SQUID sensitivity: 5nT/Hz$^{1/2}$

Ella, Ilani et al., Nat. Nanotechnol. 14, 480 (2019)
Marchiori et al., arXiv: 2103.10382

Outlook

- Use as scanning probe
- Improve sensitivities (high contact resistance, magnet fluctuations)
- Higher than dilution temperatures
- Increase resolution (100 nm here)

Thank you!

Charge distributions

$$\delta \mathrm{E}_i^{\beta} = \int dx\, \rho_\beta(x)\phi_i(x)$$

$\phi_i(x)$, can be calculated using electrostatic simulations

global voltage shift $\delta \mathrm{V}_i^{\beta_1,\beta_2}$

$$\delta \mathrm{V}_i^{\beta_1,\beta_2} \sum_j v_j \left(\delta \mathrm{E}_j^{\beta_1} - \delta \mathrm{E}_j^{\beta_2}\right) = \Delta \mathrm{V} \left(\delta \mathrm{E}_i^{\beta_1} - \delta \mathrm{E}_i^{\beta_2}\right)$$

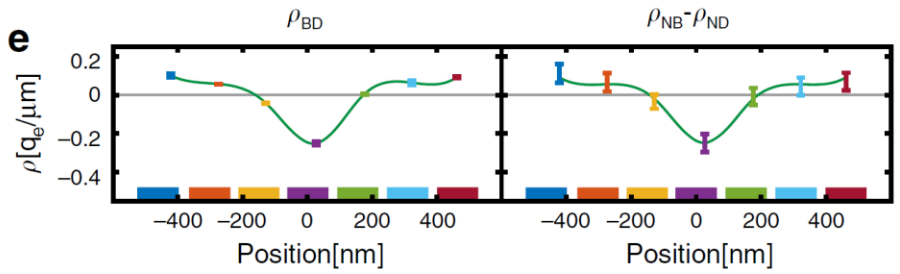
$$\rho_{\beta_1}(x_i) - \rho_{\beta_2}(x_i) = \frac{\delta \mathrm{V}_i^{\beta_1,\beta_2}}{\Delta \mathrm{V}} N$$

Relaxation and decoherence

$$H = \frac{\epsilon(t)}{2}\sigma_z + \frac{\Delta}{2}\sigma_x$$

$$T_1^{-1}(\epsilon) = \gamma_1 + \frac{\Delta^2}{\gamma_2 + \frac{\epsilon^2}{\gamma_2}}$$

The dominant decoherence mechanism results from noise in ϵ leading to decay of the Bloch vector to the Z axis with rate γ_2. In addition, a less significant noise in Δ leads to decay to the XY plane with rate γ_1.



e
ρ_{BD}
ρ_{NB}-ρ_{ND}
ρ[q_e/μm]
0.2
0
−0.2
−0.4
−400 −200 0 200 400
Position[nm]
−400 −200 0 200 400
Position[nm]

Gate-dot capacitances