Gate-reflectometry dispersive readout and coherent control of a spin qubit in silicon

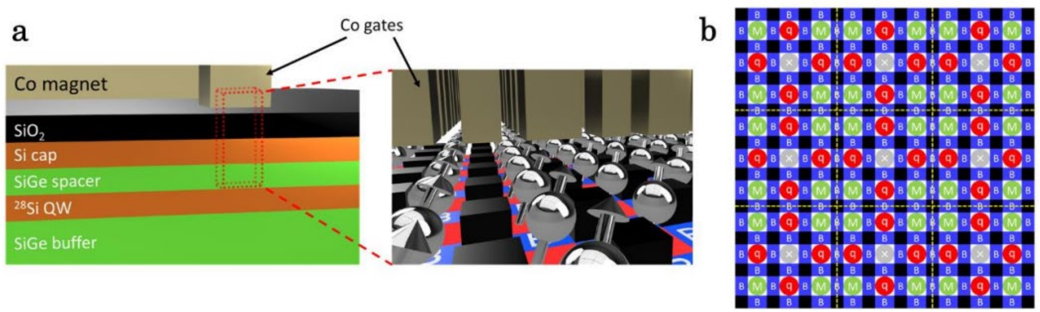
Crippa, R. Ezzouch, A. Apra, A. Amisse, R. Laviéville, L. Hutin,
M. Vinet, M Urdampilleta, T. Meunier, M. Sanquer, X. Jehl, R. Maurand &
S. De Francesci

Nature Communications **10:2776** (2019)

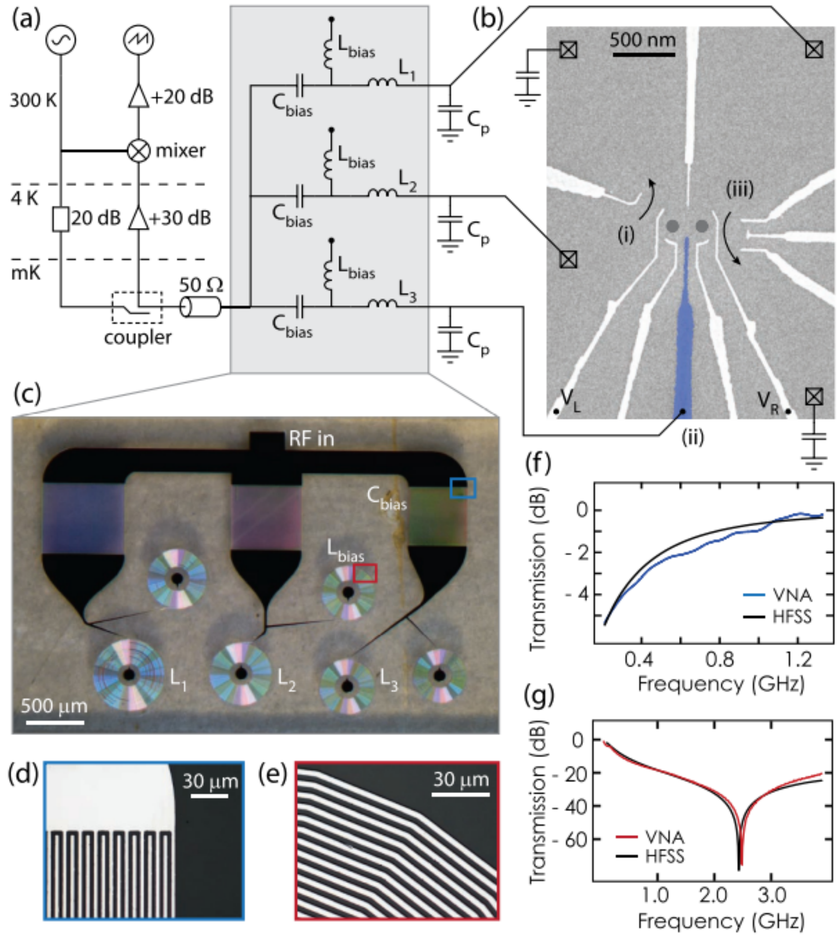
SPIN Journal Club 22.11.2021

Rafael Eggli

Motivation

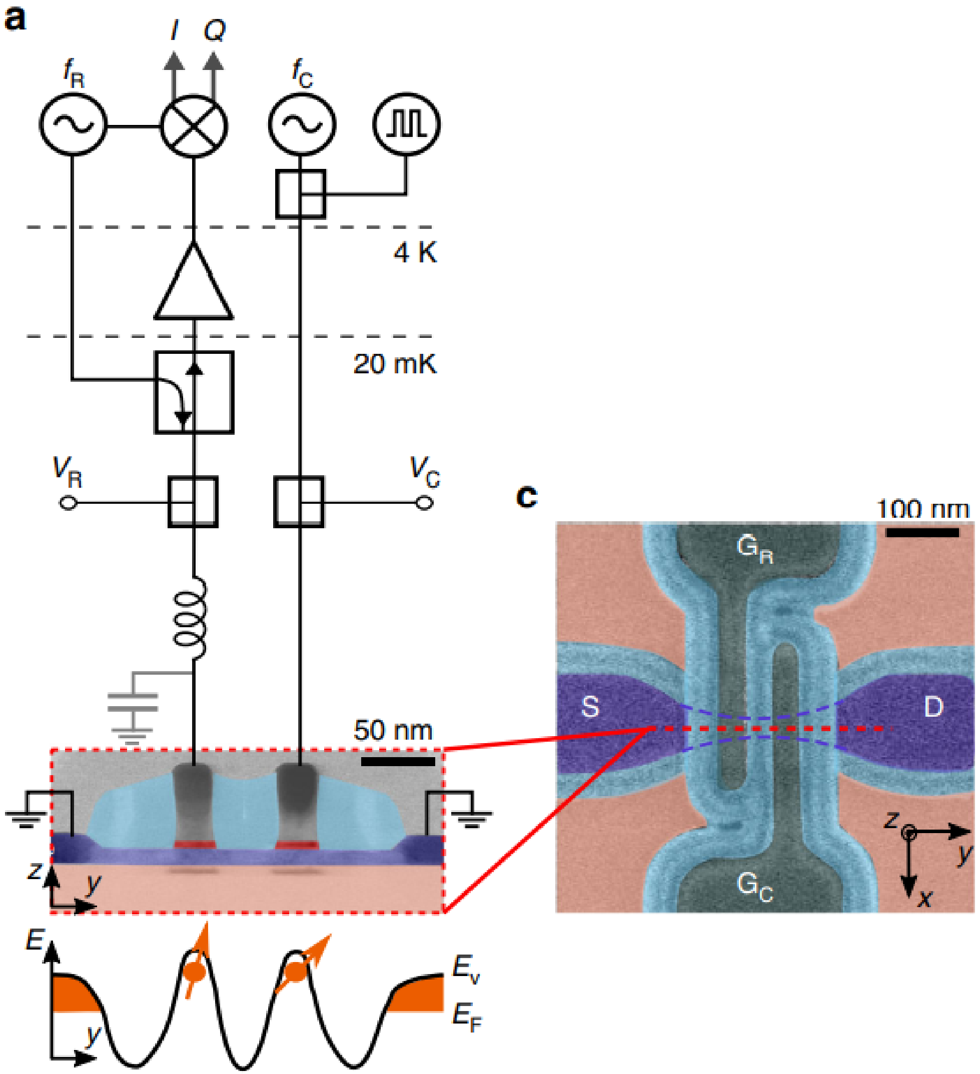


- Scalable readout techniques needed for larger qubit arrays[1]
- Gate-dispersive readout:
  - Minimal footprint -> uses dot-defining gates
  - Multiplexing -> Off-chip integration[2]
  - Single-shot readout of spins realized[3,4]
- Isolating dots from Fermi reservoirs: T > 1K feasible
- Why this old paper?
  - SET-based charge sensing not feasible with FinFETs (screening due to wrap-around gates)
  - Current efforts in Basel & at IBM around gate-dispersive sensing
  - We try to replicate similar experiments



[1] Tadokoro, M. et al. arXiv:2106.11124 ; [2] Hornibrook, J. M. et al. *APL* **104**, 103108 (2014) ;
[3] West, A. et al. *Nat. Nano*. **14**, 437-441 (2019); [4] Urdampilletta et al. Nat. Nano. 14, 737-741 (2019)

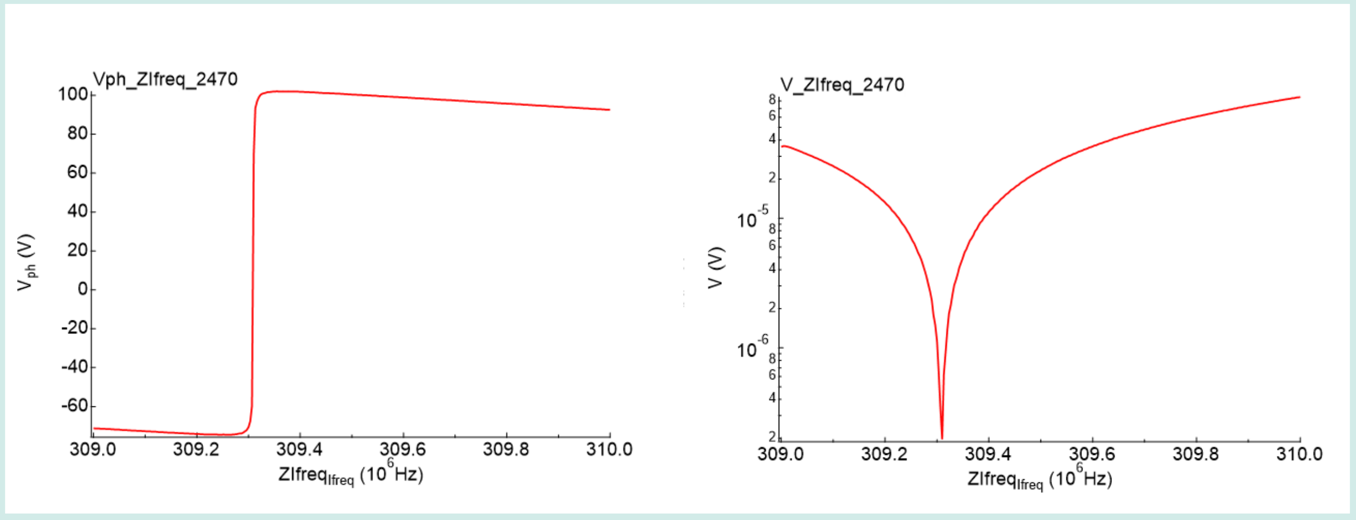
Device & Reflectometry Setup



- P-doped (Boron) source & drain with Si channel on SiO$_2$
- Channel/Fin: 11nm thick, 35nm wide
- Gates: Poly-Si on TiN (no Oxide!)[1]

- Operated at 20mK

- Standard tank circuit with lumped-element inductors (220nH):
  - Resonance frequency $f_0 = 339\ MHz$
  - Rather shallow resonance and loaded Q $\simeq$ 18
  - Limited by impedance matching



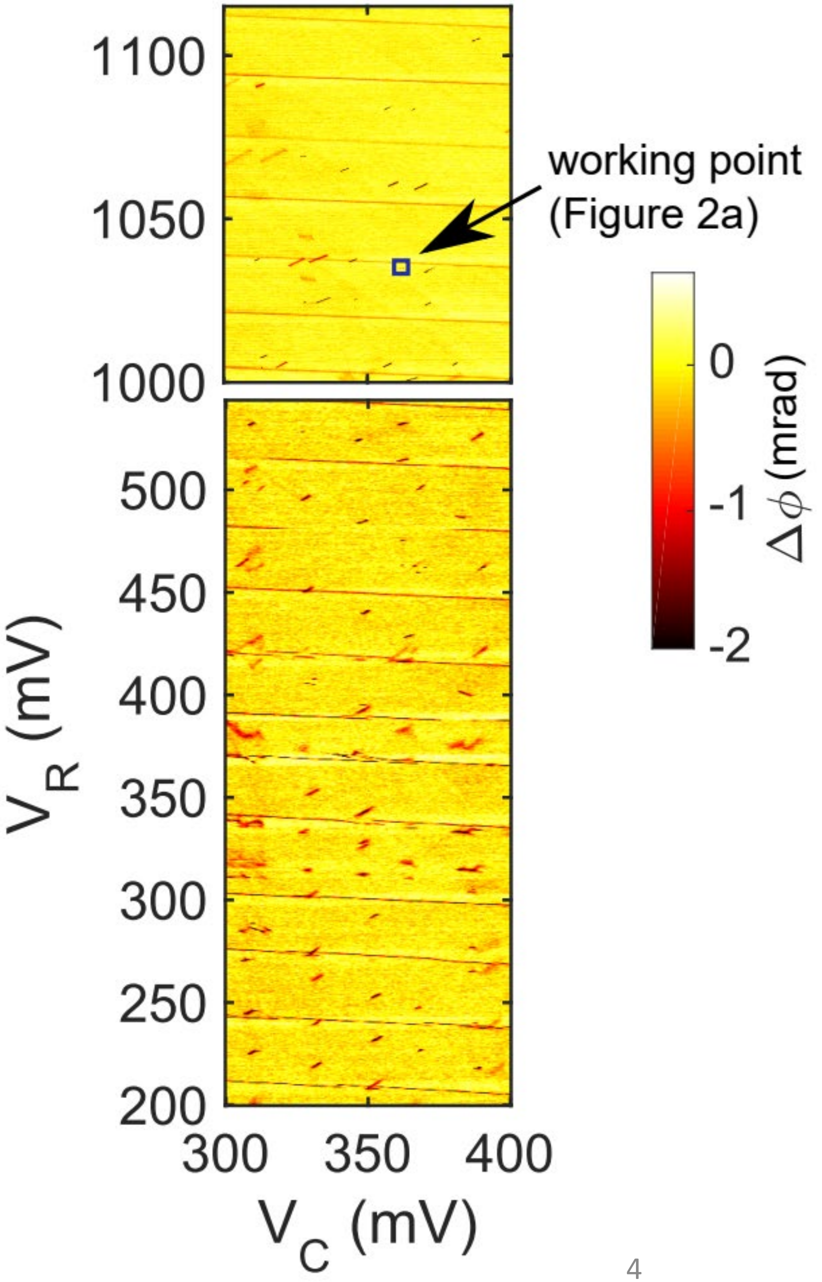
---

[1] Maurand, R. et al. *Nat. Comms.* **7,** 13575 (2016)

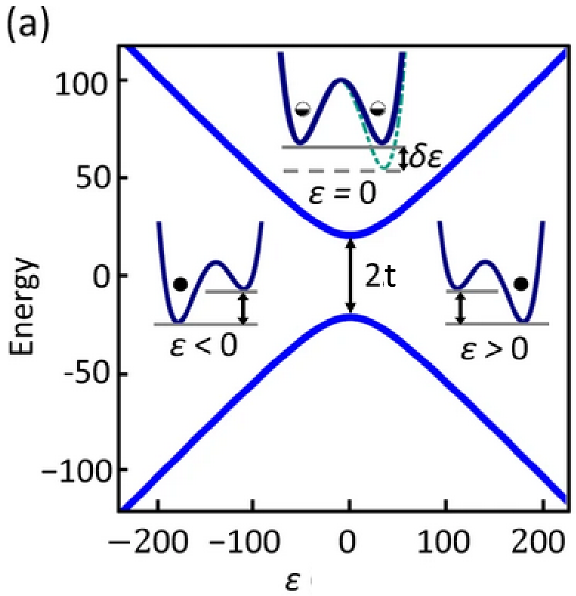
Dispersive Charge Sensing

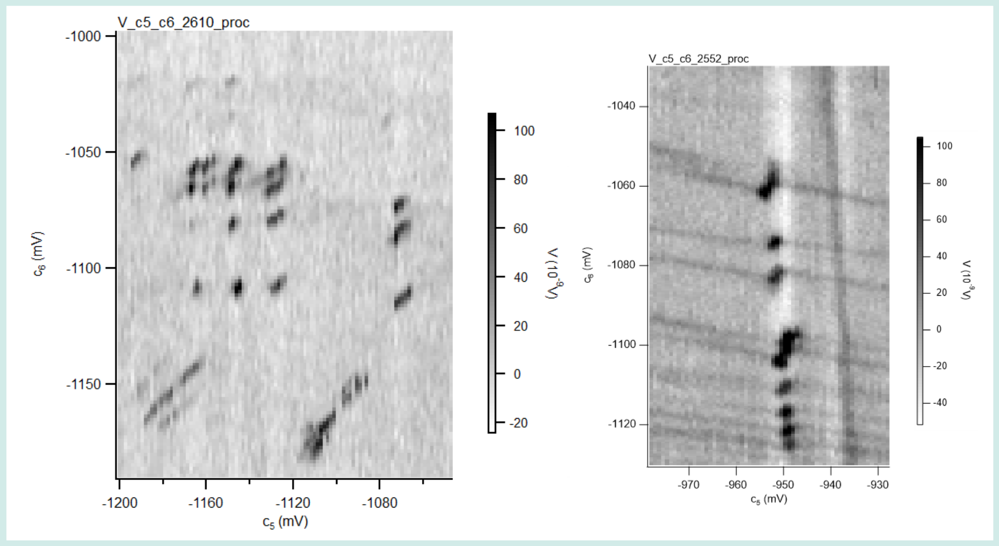
- Tunneling in proximity to sensor gate causes dispersive shift[1]
- $\Delta\phi \propto C_Q = -\alpha^2 \frac{\partial^2 E}{\partial \varepsilon^2} \xrightarrow{\text{interdot, } \varepsilon \sim 0} \alpha^2 \frac{e^2}{2t}$
- Including resonator frequency f_0 and tunnel rate γ:
- $\Delta\phi \propto \alpha^2 \frac{e^2}{2t}\left(\frac{1}{1+\left(\frac{2\pi f_0}{\gamma}\right)^2}\right)$ -> Only sensitive for transitions near f_0

- Hybridisation of charge states at $(n+1, m) \leftrightarrow (n, m+1)$ [2]
- Expect to see interdot transitions in absence of leads



(a)





---

[1] Colless, J.I. et al. *PRL* **110,** 046805 (2013); [2] Yang, Y.C. et al. npj Quant. Inf. **5.** 12 (2019)

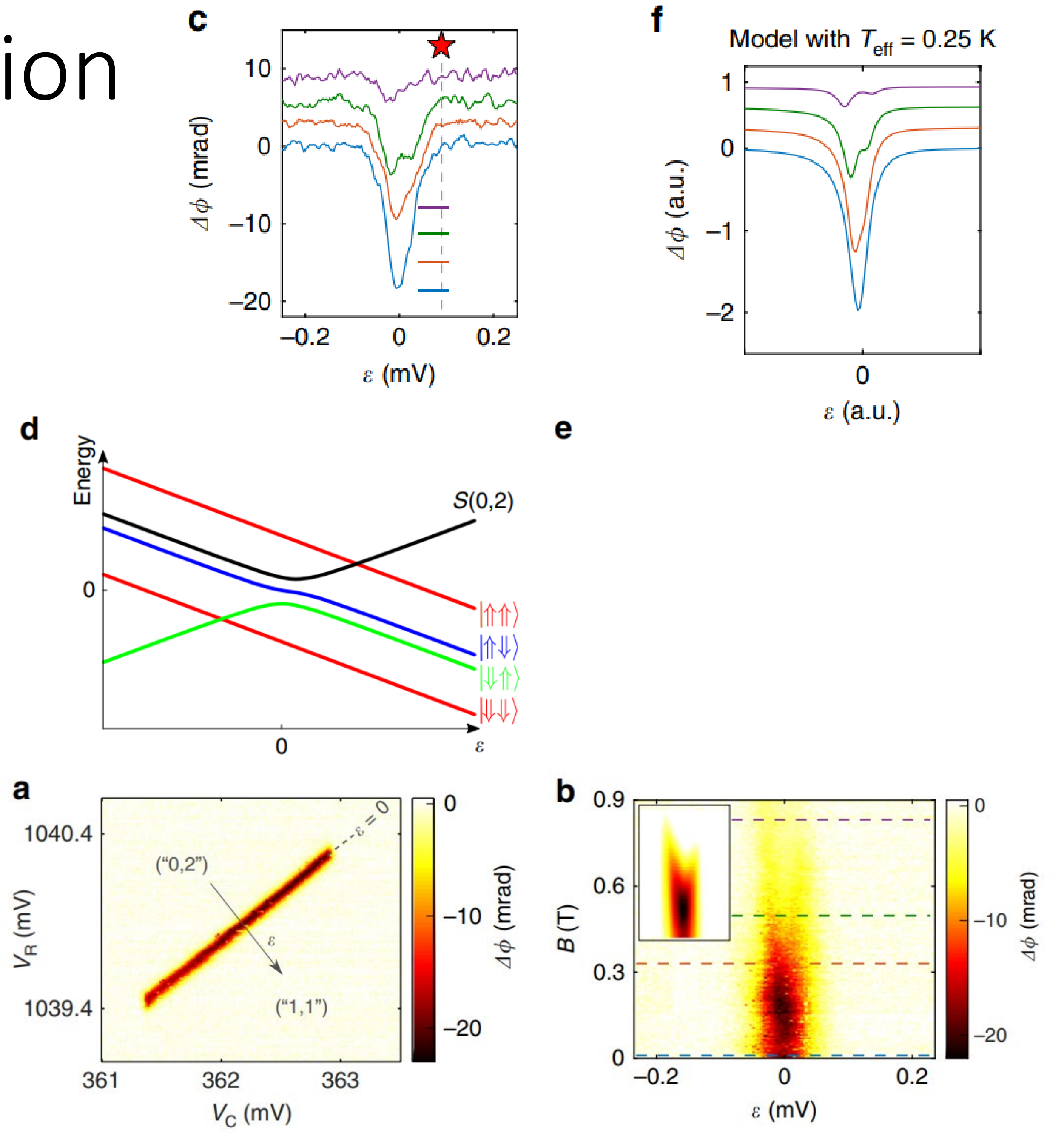
Quasi (0,2) ↔ (1,1) Transition

- Magnetic field-dependent splitting of baseline
- B along nanowire axis
- Assume small Spin-Orbit/Spin-Flip-Cotunneling compared to t and E_z
- Hamiltonian in Singlet-Triplet basis: $\{T_+(1{,}1); T_0(1{,}1); T_-(1{,}1); S(1{,}1); S(0{,}2)\}$

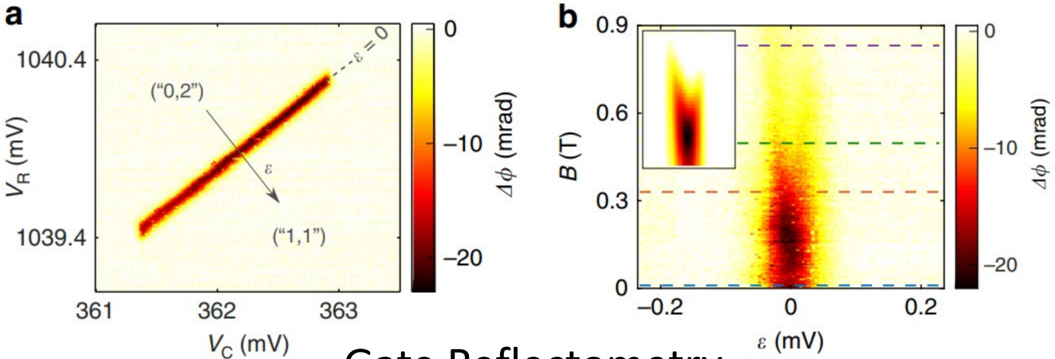
$$H' = \begin{pmatrix} -\frac{1}{2}\epsilon + \frac{1}{2}(g_L^* + g_R^*)\mu_B B & 0 & 0 & 0 & 0 \\ 0 & -\frac{1}{2}\epsilon & 0 & \boxed{\frac{1}{2}(g_L^* - g_R^*)\mu_B B} & 0 \\ 0 & 0 & -\frac{1}{2}\epsilon - \frac{1}{2}(g_L^* + g_R^*)\mu_B B & 0 & 0 \\ 0 & \boxed{\frac{1}{2}(g_L^* - g_R^*)\mu_B B} & 0 & -\frac{1}{2}\epsilon & \boxed{t} \\ 0 & 0 & 0 & \boxed{t} & \frac{1}{2}\epsilon \end{pmatrix}$$

- Only S_e, S_g & T_0 contribute to C_Q
- Boltzmann-distributed state probability
- Many resonator cycles!

- Qualitatively reproduces the observed data, yielding: $t = 6\ \mu eV,\ \ T_{eff} = 250\ mK,\ \ g_L^* = 1.62,\ \ g_R^* = 2.12$

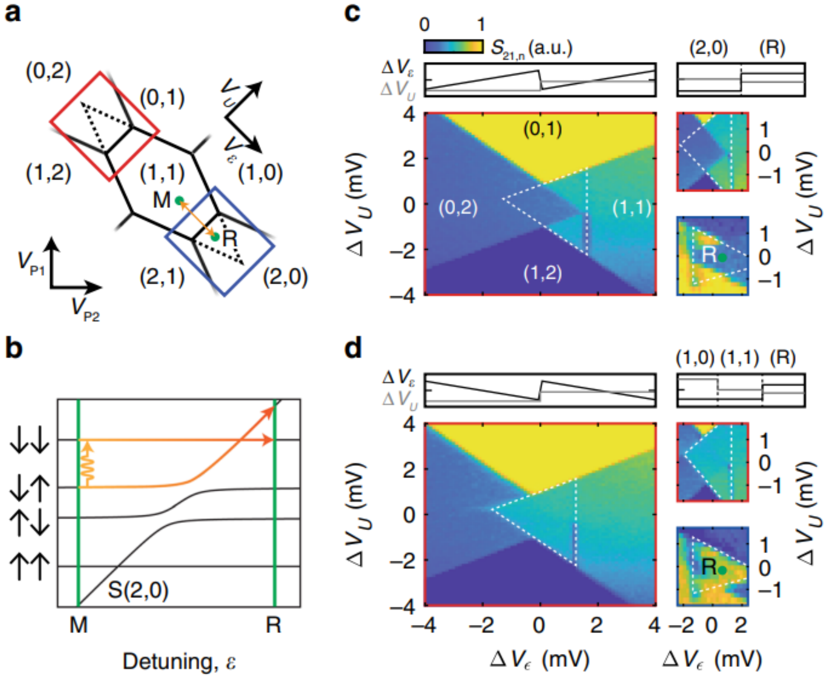


Comparison to DC measurements

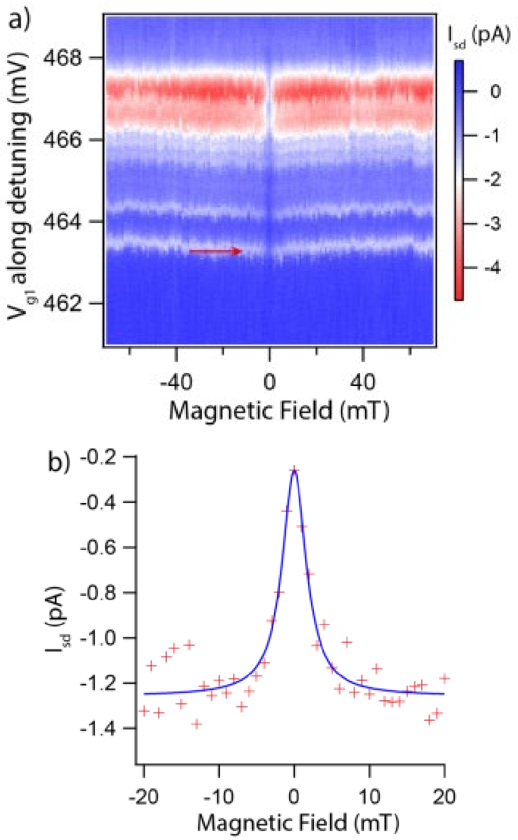


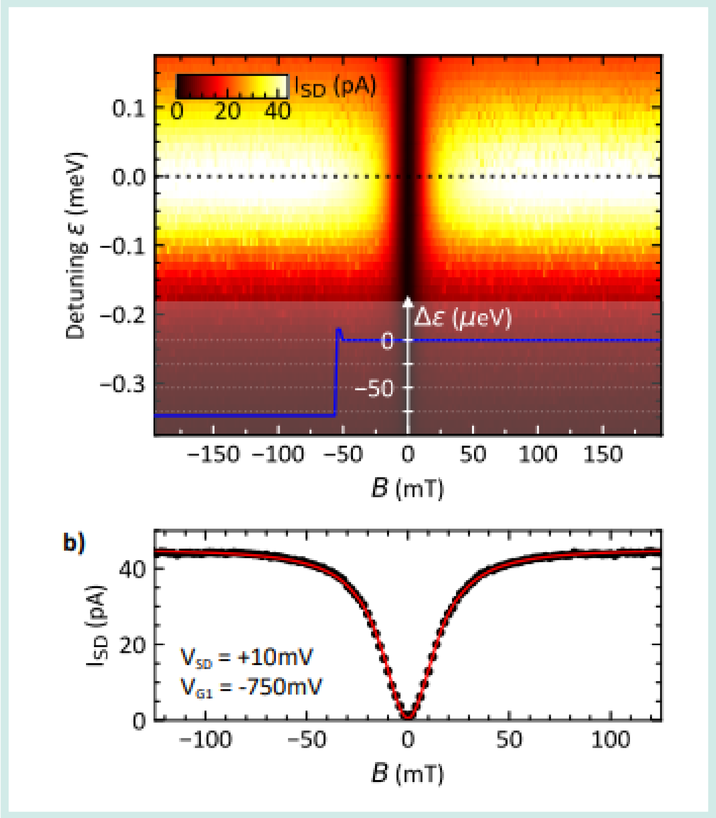
Gate Reflectometry

- Very different signatures than in DC or charge sensor readout !!



RF Sensor Dot based PSB readout[3]





Pauli Spin Blockade in DC[1,2]

---

[1] Maurand, R. et al. *Nat. Comms.* **7,** 13575 (2016); [2] Geyer, S. et al. *APL.* **118,** 104004 (2021);
[3] Hendrickx, N.W. et al. *Nat. Comms.* **11,** 3478 (2020)

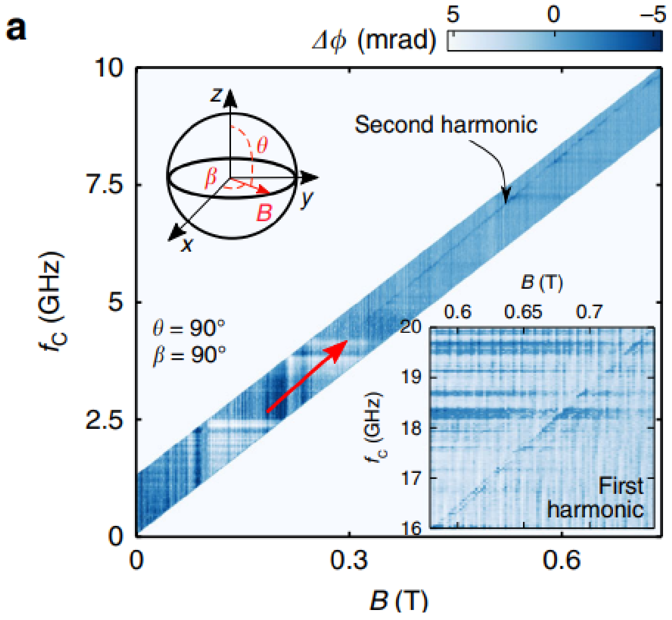
EDSR

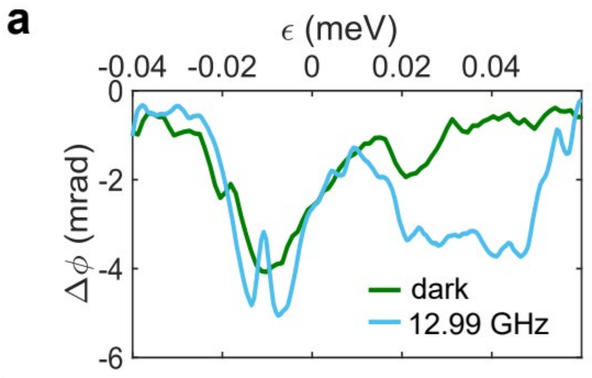
- Predict resonance frequency from model
- $B = 0.52\ T$ -> doublepeak visible
- Broadening of T_0 peak , $f_C = 12.99\ GHz$
- "Shallow" $(1,1)$ configuration

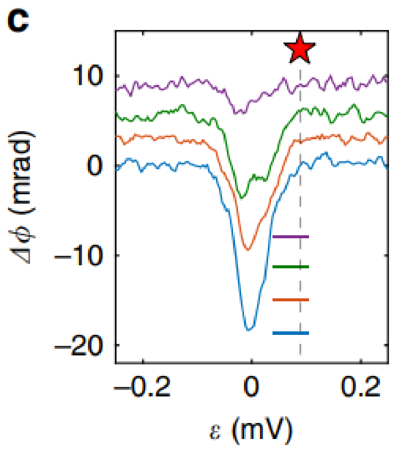
- 2nd harmonic stronger than 1st
- B along nanowire axis
- Effective hole $g = 1.735$

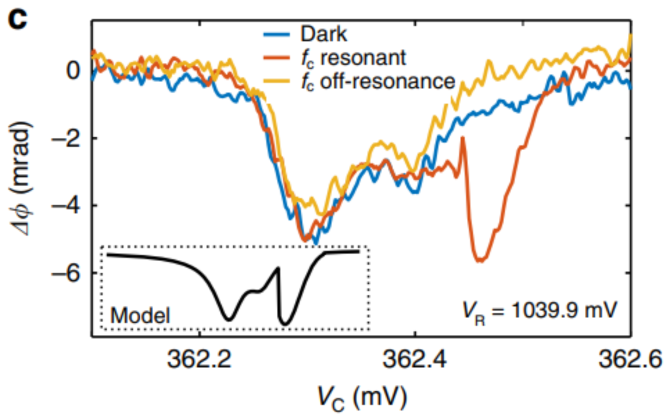
- Drive $T_- \leftrightarrow T_0$ transition, Power = -80 dBm
- Broadening of double-peak at baseline with continuous wave

- Lineshape fits model
- Balanced T_-, T_0 pop.







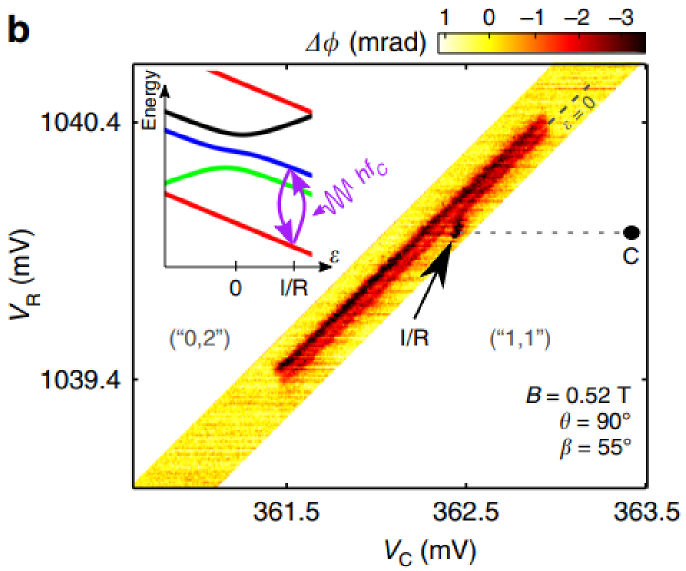


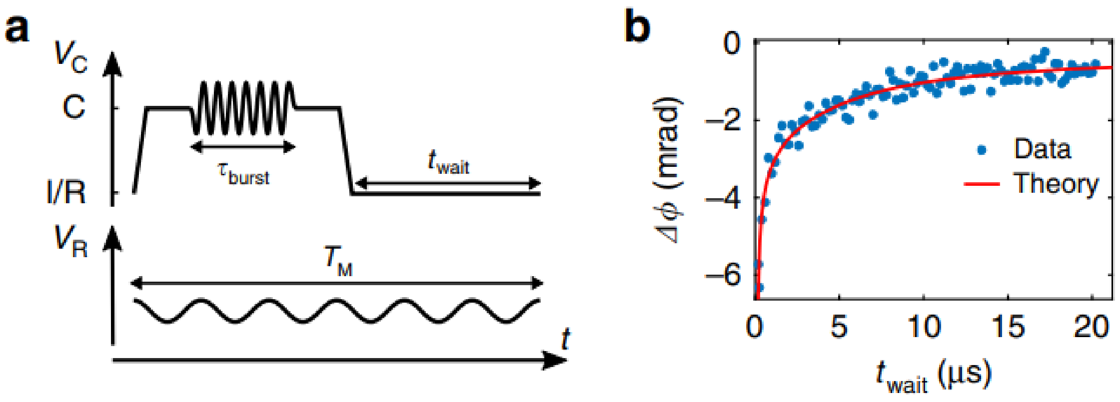
Qubit Control & Readout

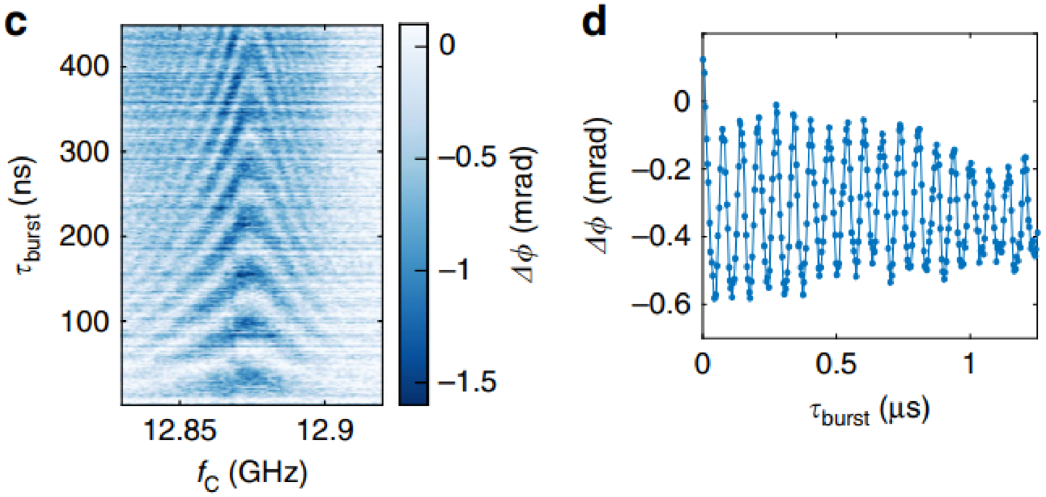
- Most pronounced T_0 peak for initialisation & readout
- B perpendicular to nanowire and 30° out-of-plane
- Control pulse: 1mV into $(1,1)$ region
- Reflectometry tone constantly on & monitored

- Spin lifetime $(\pi - pulse\ at\ C)$:
  - At R/I: $T_1 = 2.7 \pm 0.7\ \mu s$
  - At C: $T_1 > 10\ \mu s$

- Rabi Chevron with $f_R = 15\ MHz$
- 30 measurements averaged, $t_{int} = 100\ ms$

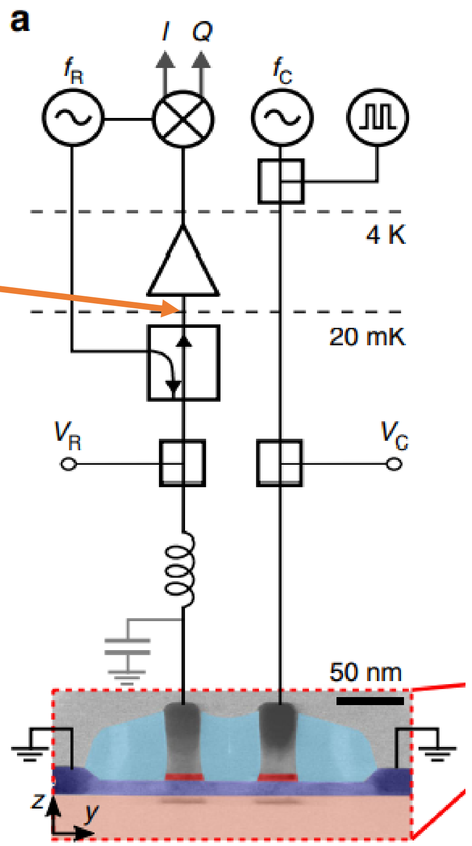






Discussion

- Strategies to boost T_1
  - RF isolators between amplifier & coupler
  - No high-K dielectric in gate stack
- Magnetic field anisotropies:
  - Possible impact on T_1
  - Potential large g-factor/g-factor difference anisotropy
    - Better readout contrast?
  - Rabi frequency maximization
- Technical optimizations (higher Q, parametric amplification etc.)
  - Single shot readout (so far, way too slow)
- What about temperature?
  - Investigate population distribution at higher T
  - Is this readout scheme applicable to FinFETs?



$$H' = \begin{pmatrix} -\frac{1}{2}\epsilon + \frac{1}{2}(g_L^* + g_R^*)\mu_B B & 0 & 0 & 0 & 0 \\ 0 & -\frac{1}{2}\epsilon & 0 & \frac{1}{2}(g_L^* - g_R^*)\mu_B B & 0 \\ 0 & 0 & -\frac{1}{2}\epsilon - \frac{1}{2}(g_L^* + g_R^*)\mu_B B & 0 & 0 \\ 0 & \frac{1}{2}(g_L^* - g_R^*)\mu_B B & 0 & -\frac{1}{2}\epsilon & t \\ 0 & 0 & 0 & t & \frac{1}{2}\epsilon \end{pmatrix}$$

Thanks for your attention!

Questions?