University of Basel

Gate modulation of the hole singlet-triplet qubit frequency in germanium

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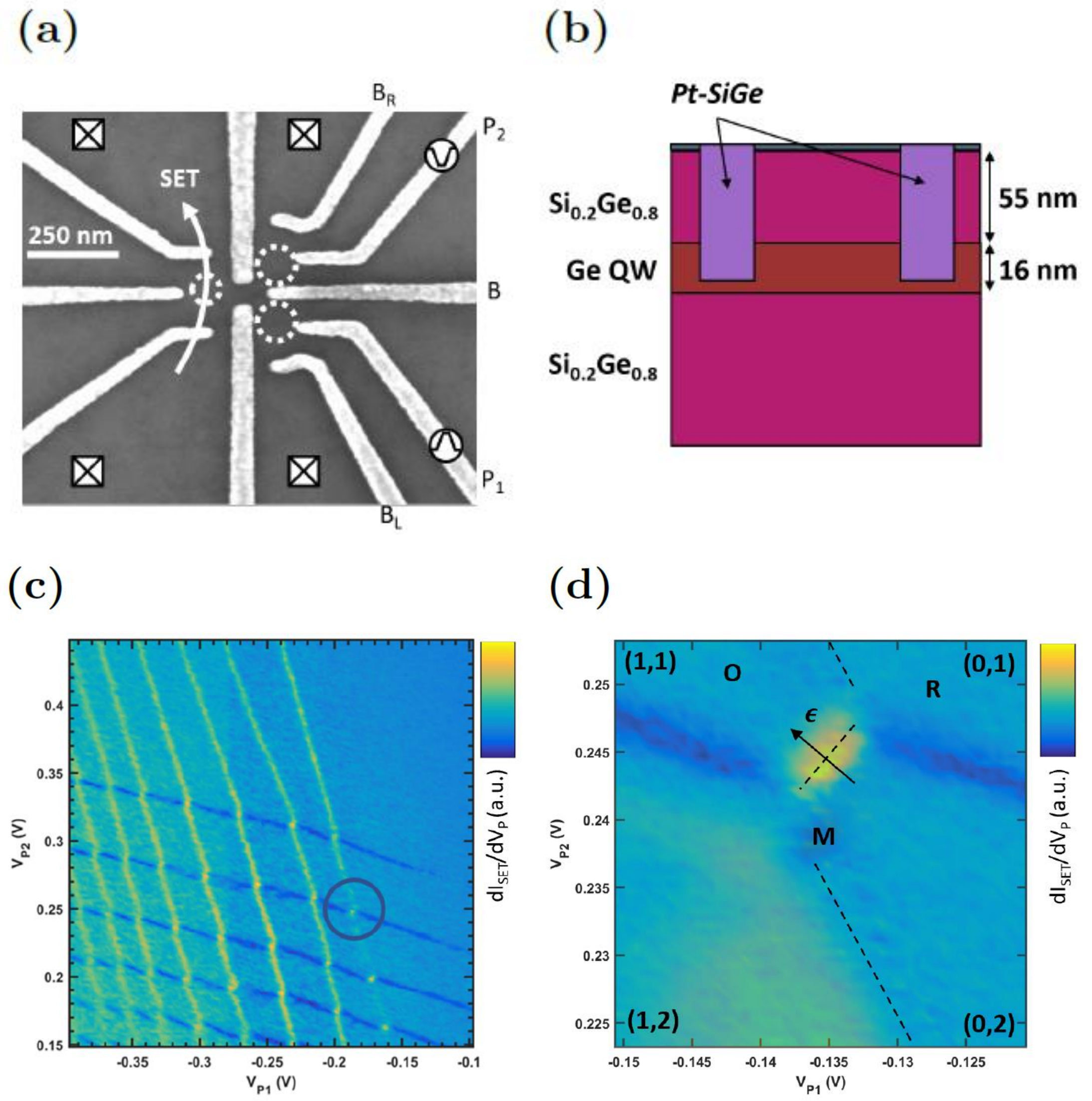
Motivation

- all-electrical qubit control
- strong spin-orbit coupling
- site-dependent g-tensor
- S-T_- qubit frequency – strong function of barrier gate voltage
- an order of magnitude change of g-factor with 12 mV change of the gate voltage
- strain profile

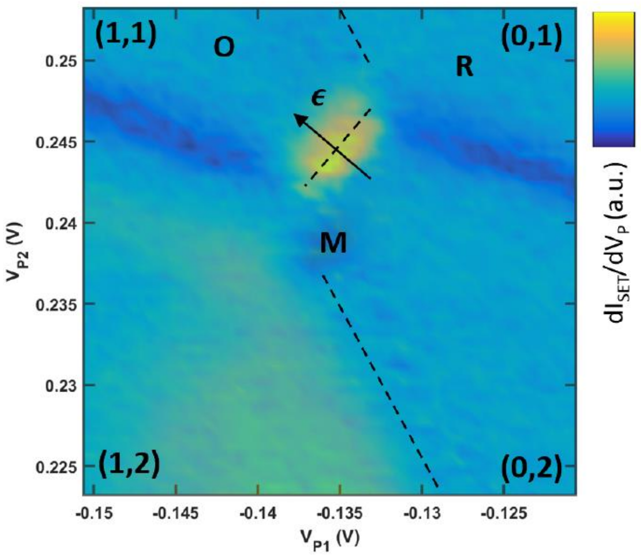
Device

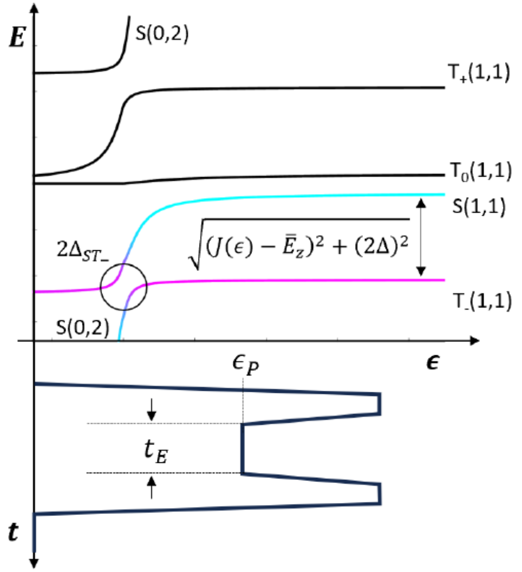


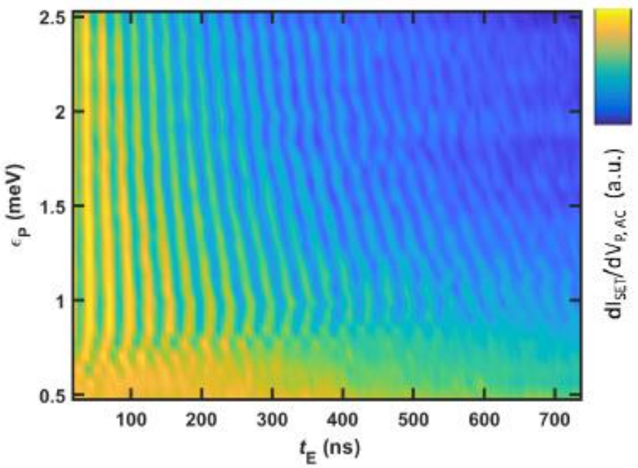
- Ge/SiGe heterostructure
- 2D hole gas accumulated using global top gate
- P_1, P_2 - plungers
- V_B – controls the coupling between the dots
- all experiments done at (1,1)-(0,2)
- SET change sensing
- detuning:

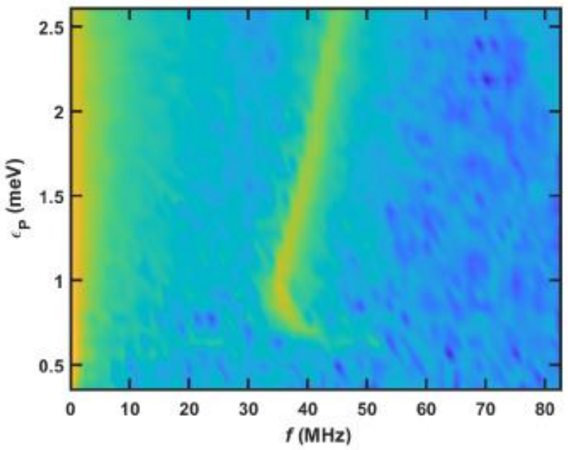
$$\epsilon = \alpha_2 V_{P2} - \alpha_1 V_{P1}$$

Experiment









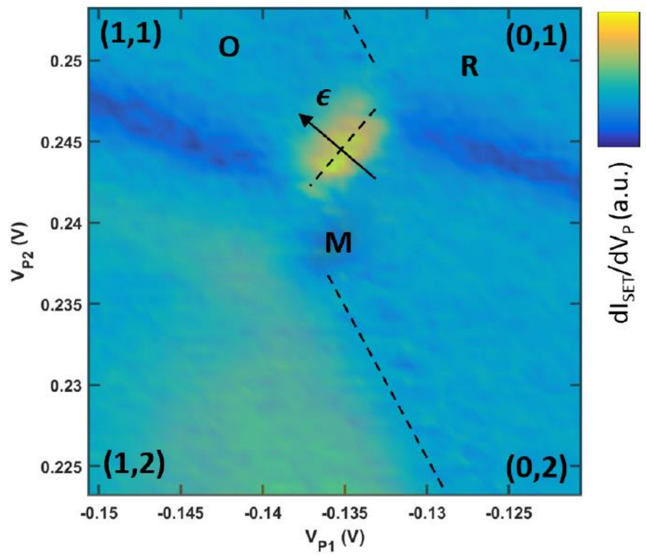
- $S_{02} - S_{11}$ hybridization due to the tunnel coupling

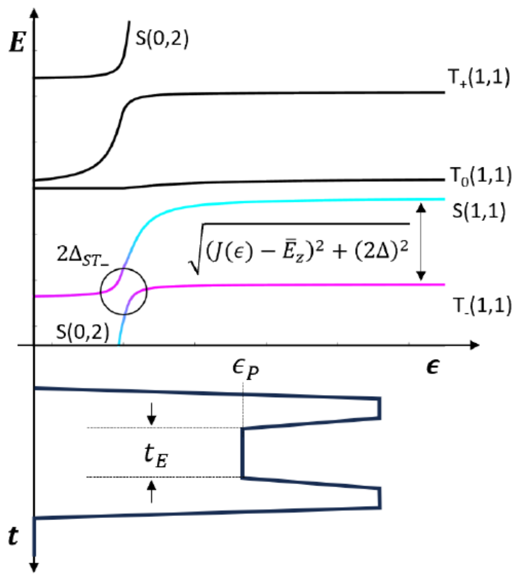
  $|S\rangle = \sin(\Omega/2)|S_{02}\rangle - \cos(\Omega/2)|S_{11}\rangle$

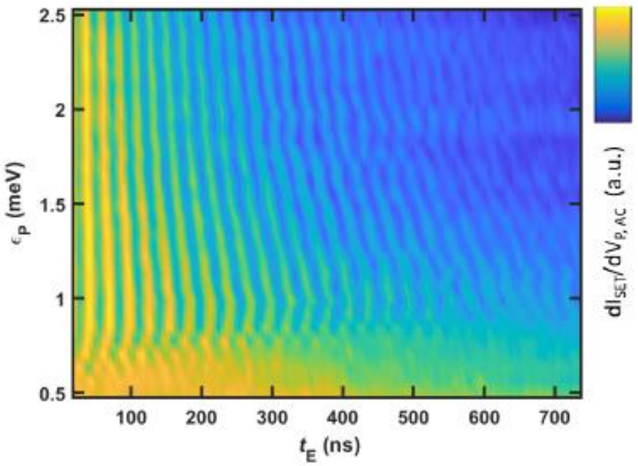
- $\Omega = \arctan\left(\frac{2\sqrt{2}t_c}{\epsilon}\right)$ - mixing angle
- three triplet states
- permanent magnet on the PCB $|B| = 4.6$ mT
  - lifts the degeneracy of triplet states
  - 4.4 mT in-plane field
  - 1.2 mT out-of-plane field
- splits $|T_-\rangle$ and $|T_0\rangle$ by $\overline{E}_z$

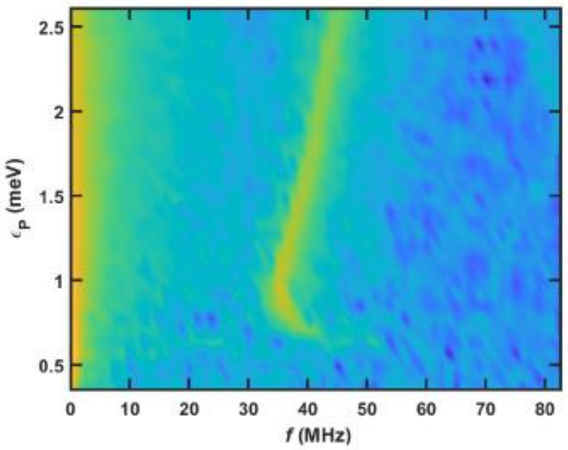
- initialization into S(0,2) at M
- pulse P1 and P2, separate holes: mixture of $|S\rangle = \frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)$ and $|T_-\rangle = |\downarrow\downarrow\rangle$
- evolution for t_E at ϵ_P

Experiment







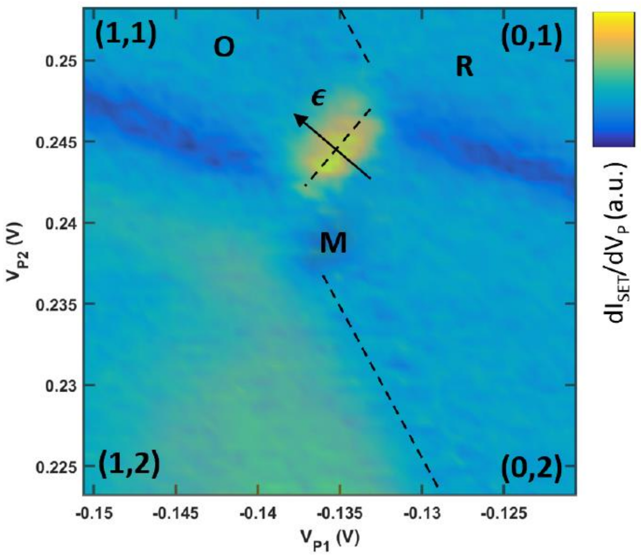


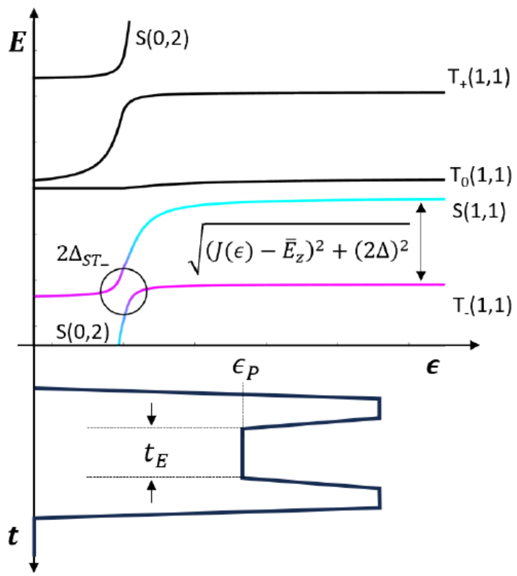
- qubit frequency: $hf = \Delta E_{ST\_}$
- large detuning: $\overline{E}_z$
- minimum at S-T_ anticrossing: $2\Delta_{ST\_}$
- minimum – chevron pattern at 1 meV
- {|S⟩, |T_⟩} dynamics

$$H = \begin{pmatrix} -J(\epsilon) & \Delta \\ \Delta & -\overline{E}_z \end{pmatrix}$$

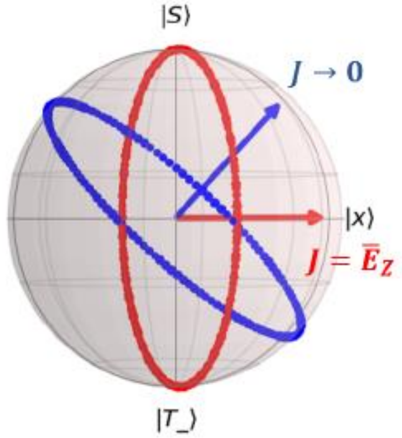
- exchange energy: $J(\epsilon) = -\frac{\epsilon}{2} + \sqrt{\frac{\epsilon^2}{4} + 2t_c^2}$
  energy difference between |S⟩ and $|T_0\rangle$
- S-T_ coupling: $\Delta = \left|\Delta_{so} \sin\left(\frac{\Omega}{2}\right) + g_a \mu_B B \cos\left(\frac{\Omega}{2}\right)\right|$
  - spin-orbit splitting
  - effective Zeeman splitting, anisotropy of the g-tensors
- | T_ ⟩ and $|T_0\rangle$ slitting: $\overline{E}_z = \overline{g}\mu_B B$
  - average g-factor

Experiment





(d)



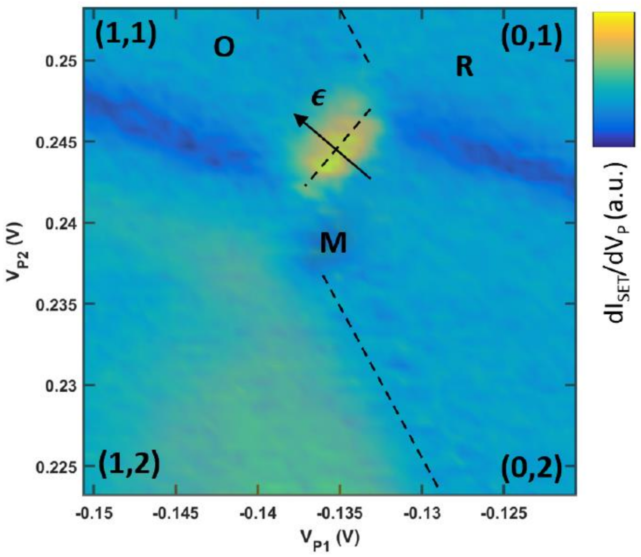
- qubit frequency: $f = \frac{1}{h}\sqrt{(J - \overline{E}_z)^2 + (2\Delta)^2}$
- at S-T_- anticrossing: $J = \overline{E}_z$, X rotations
- large detunings: $J \to 0$, z-axis rotations

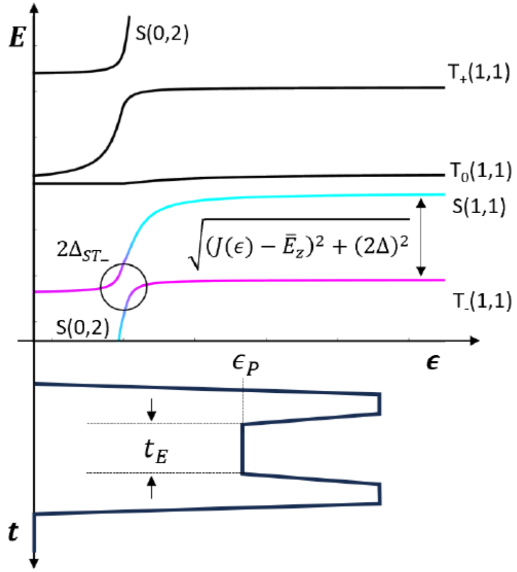
- $\{|S\rangle, |T_-\rangle\}$ dynamics

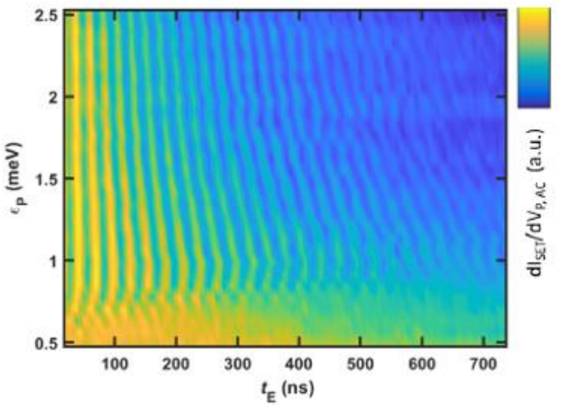
$$H = \begin{pmatrix} -J(\epsilon) & \Delta \\ \Delta & -\overline{E}_z \end{pmatrix}$$

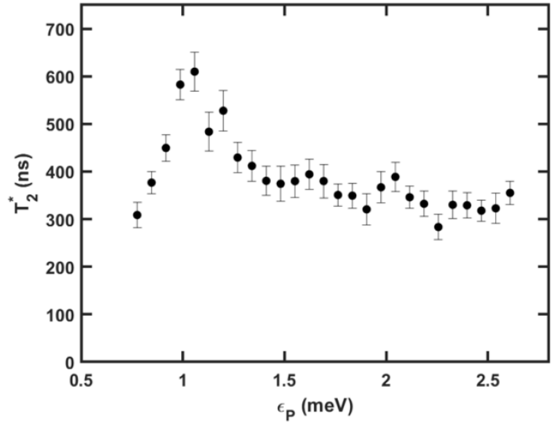
- readout at M using Pauli spin blockade
- reset at R before repeating

Experiment









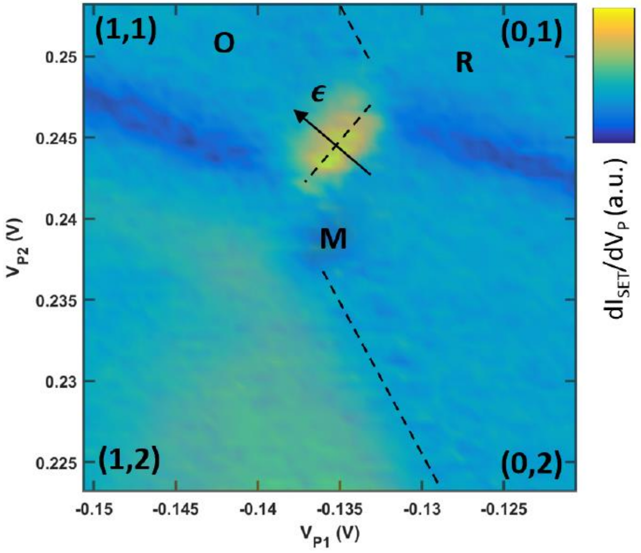
- qubit frequency: $f = \frac{1}{h}\sqrt{(J-\overline{E}_z)^2+(2\Delta)^2}$
- at S-T$_-$ anticrossing: $J = \overline{E}_z$, X rotations
- large detunings: $J \to 0$, z-axis rotations

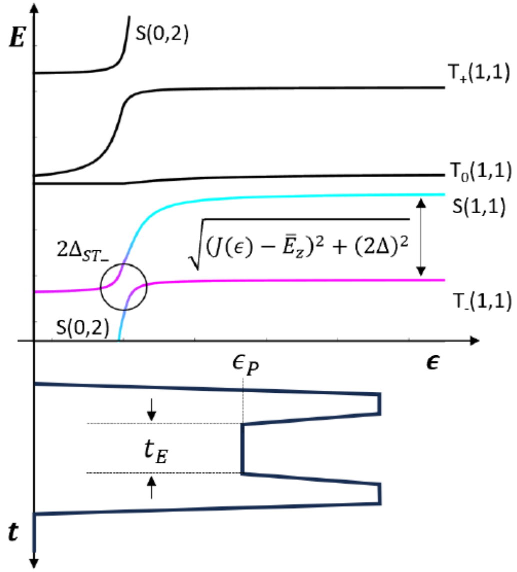
- {|S⟩, |T$_-$⟩} dynamics

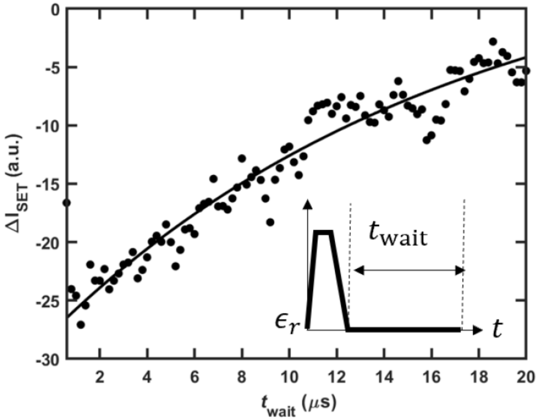
$$H = \begin{pmatrix} -J(\epsilon) & \Delta \\ \Delta & -\overline{E}_z \end{pmatrix}$$

- readout at M using Pauli spin blockade
- reset at R before repeating
- fit T2*: $P = Ae^{-(t/T_2^*)^2}\cos(\omega t + B) + Ce^{-t/D} + \bar{E}$
  - maximum in T2* at 1 meV, residual decay: δΔrms = 0.8 neV
  - decay at the large detuning: δEz,rms = 3 neV

Experiment

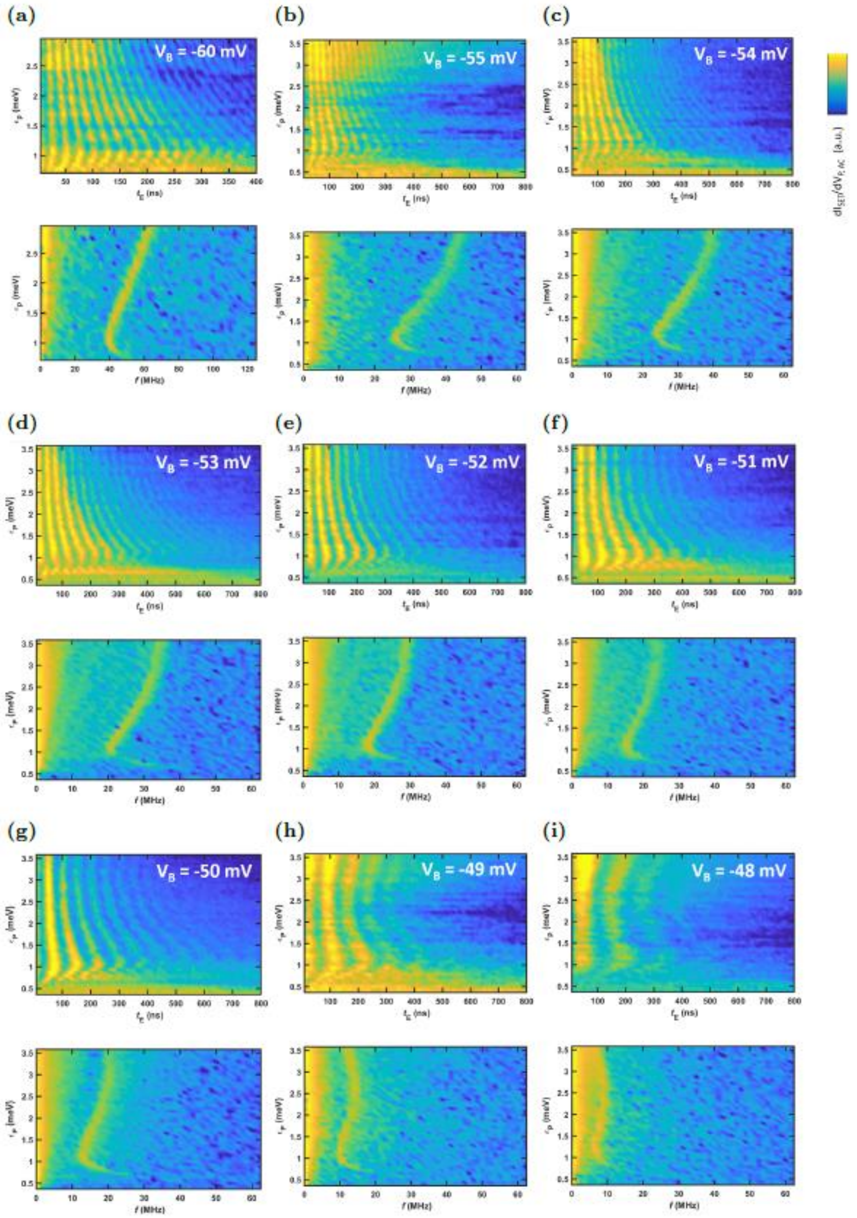


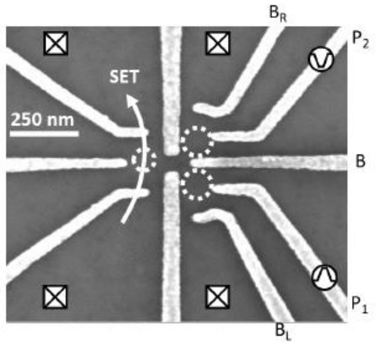




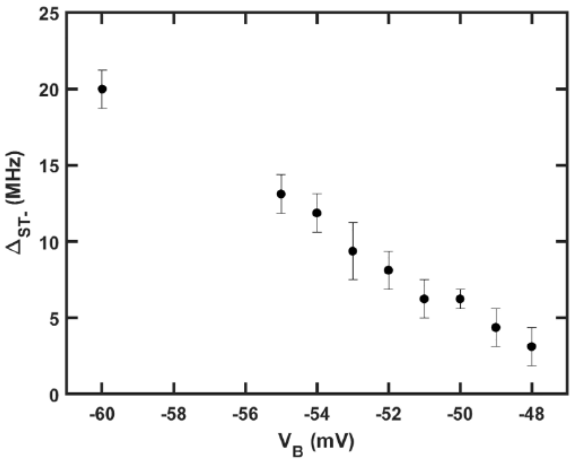
- T1 – varying wait time at the readout position ϵ_r
- fit T1 using: $P = Ae^{-(t/T_1)} + B$
- T1 = $17.2 \pm 3.2\ \mu s$

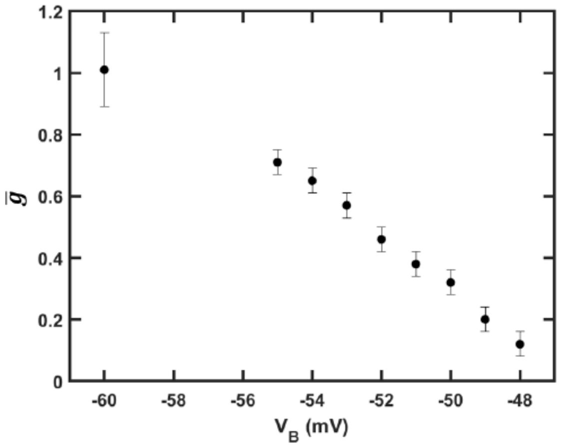
Experiment





- dramatic change of f as function of VB
- extract $\overline{g}$ from $f \sim \overline{E}_z/h$ at large detunings
- extract Δ_{ST_-} from $2\Delta_{ST_-}/h$ at minimum frequency





Conclusion

- coherent oscillations between S and T-
- dephasing time T_2^* = 600 ns
- relaxation time T_1 = 17.2 us
- strain induced change of qubit frequency