A coherent spin–photon interface in silicon

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2020-11-06

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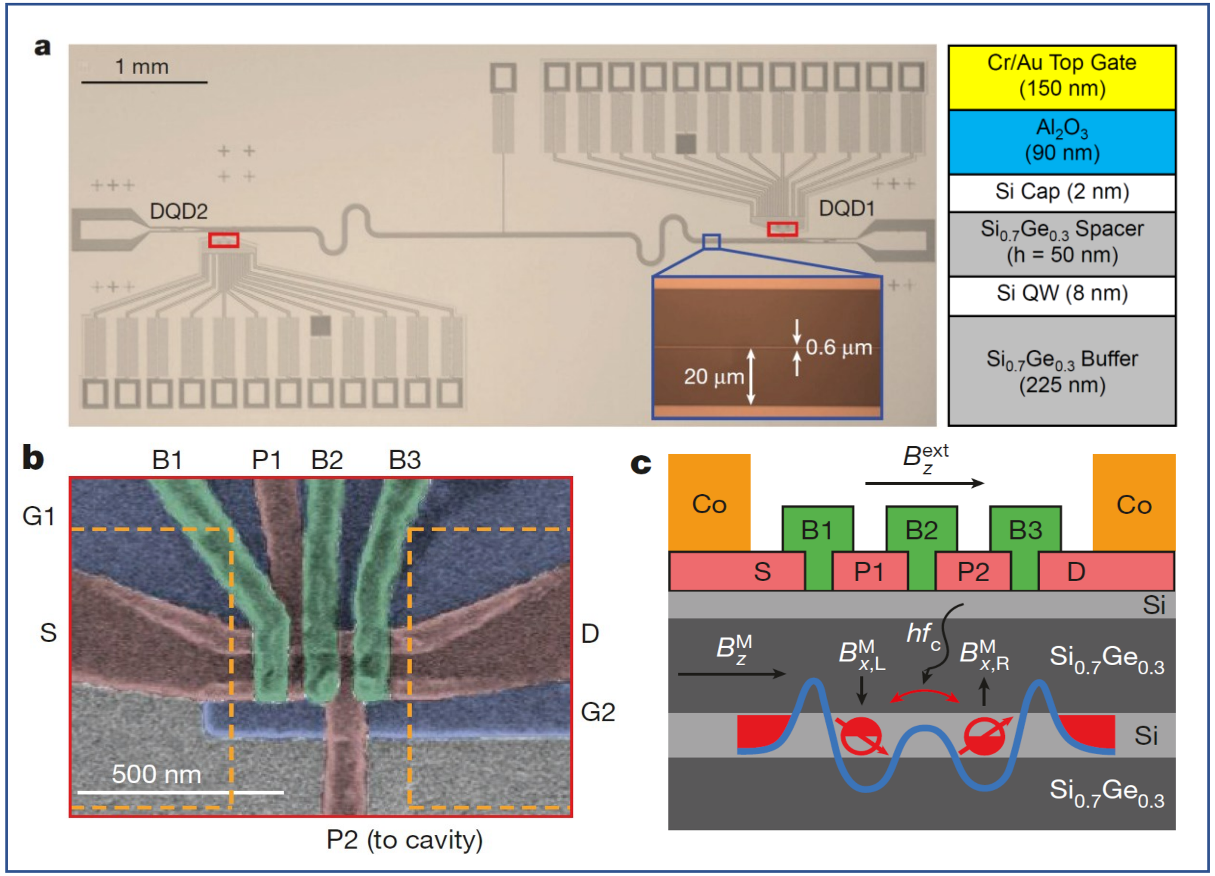
$$\text{photon} \underset{E\text{-}d}{\longleftrightarrow} \text{charge} \underset{B}{\longleftrightarrow} \text{spin}$$

Charge-photon hybridization



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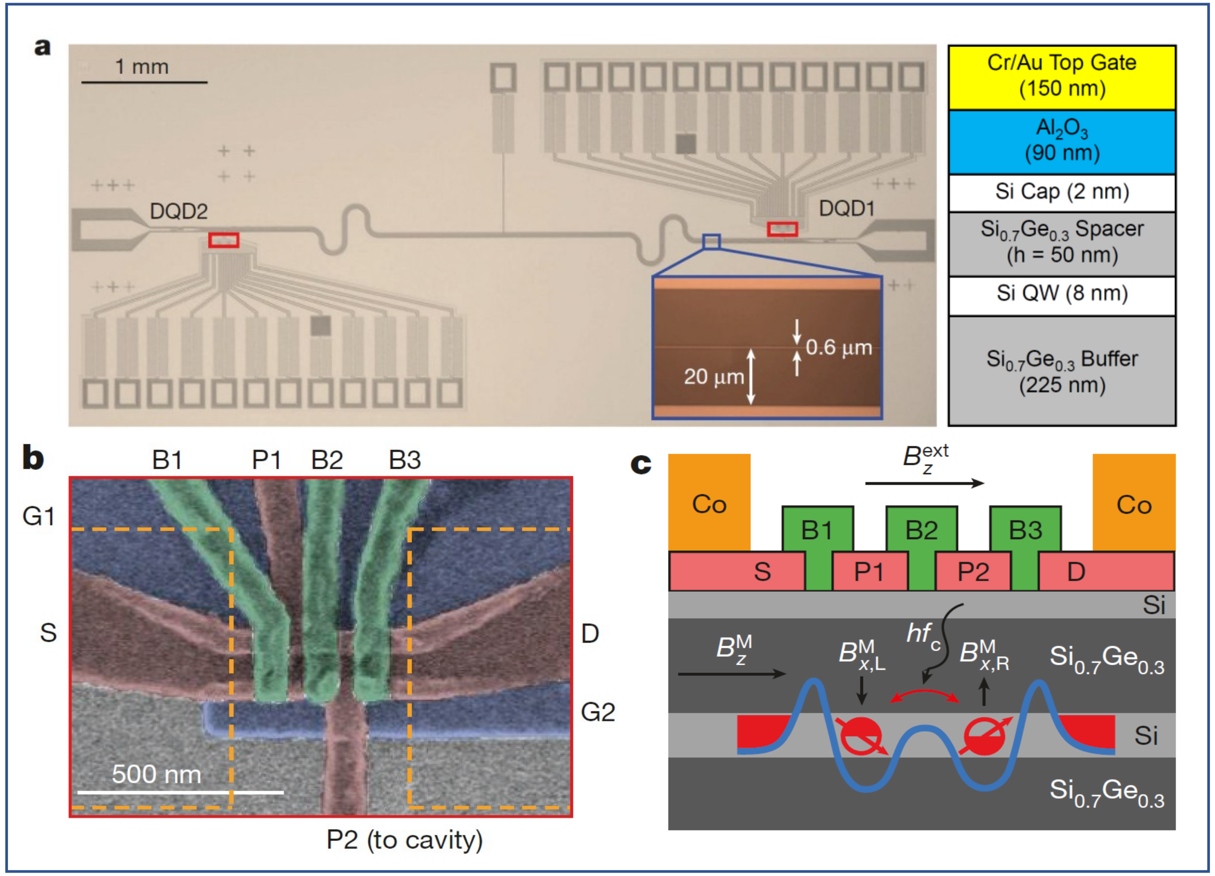

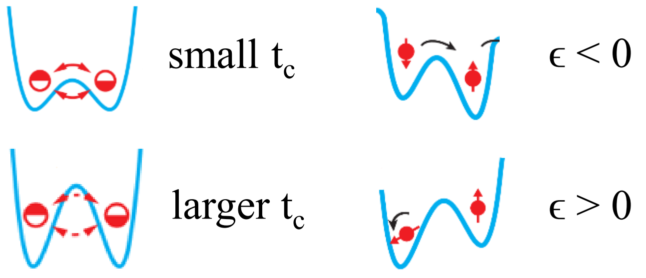

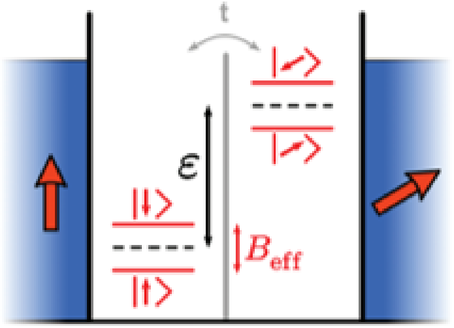

Viennot, J. J. et al. Coherent coupling of a single spin to microwave cavity photons. Science 349, 408–411 (2015).

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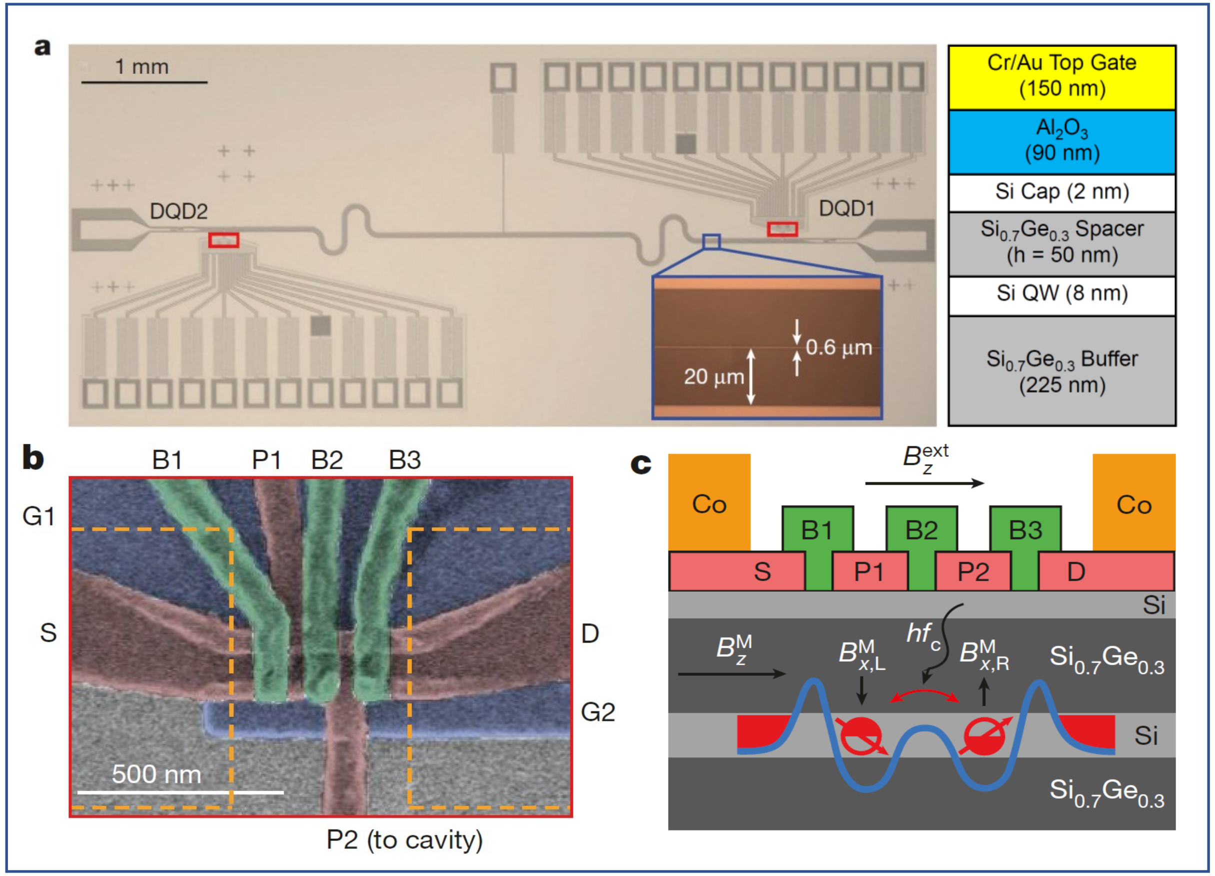

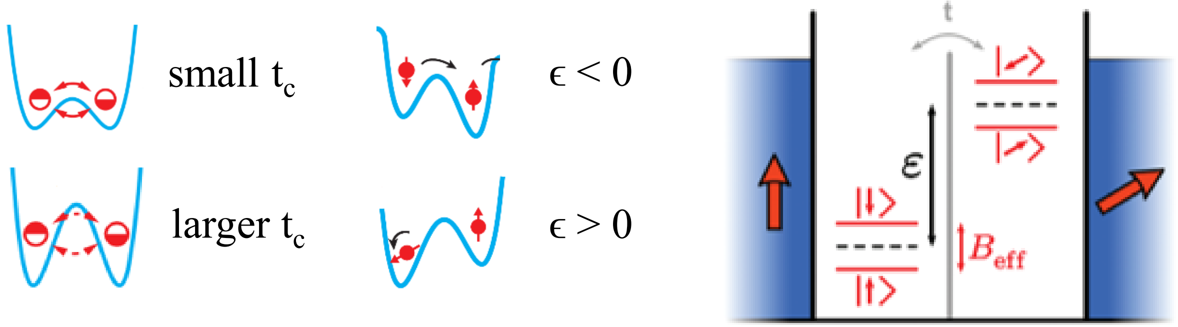

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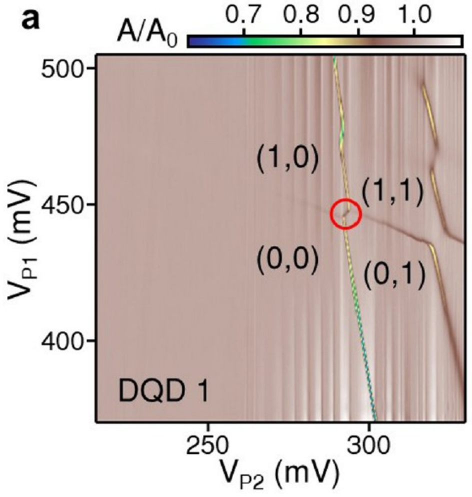

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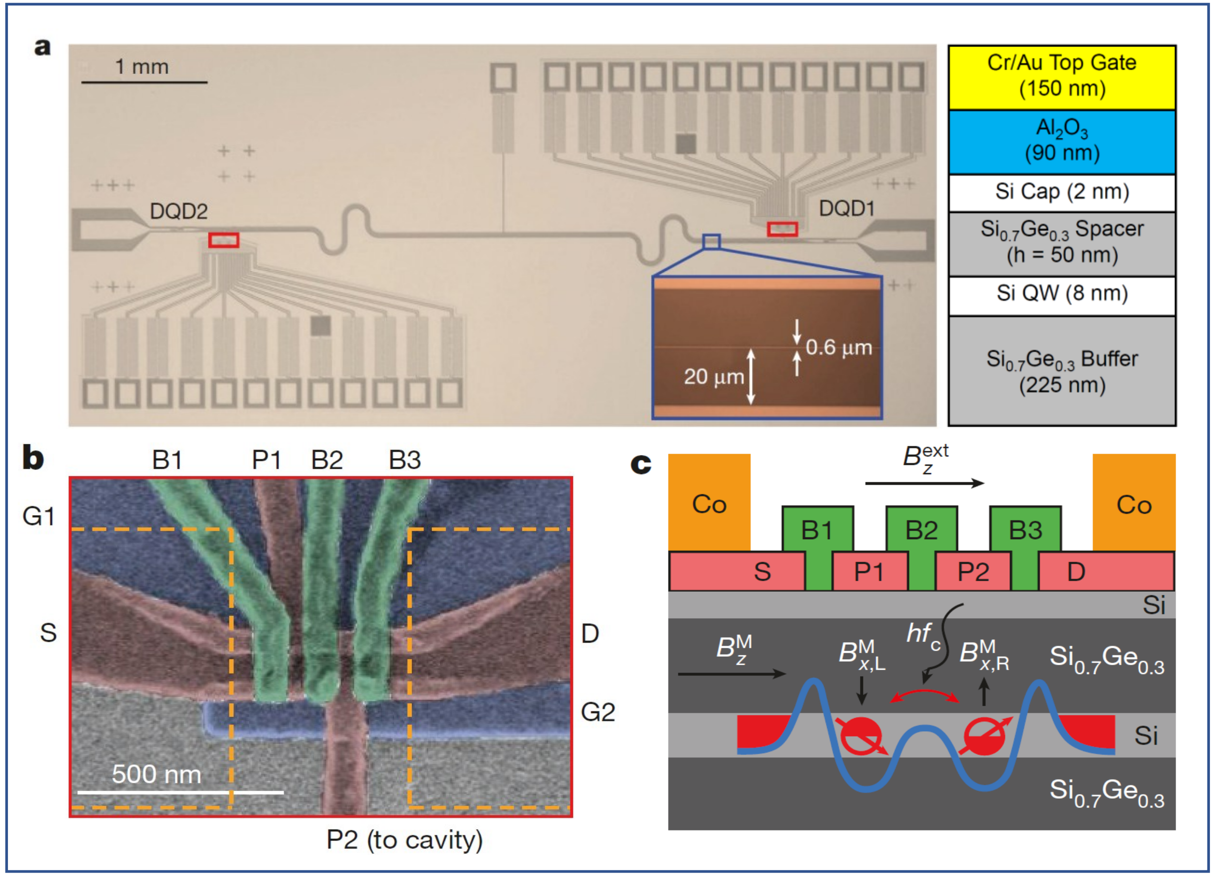

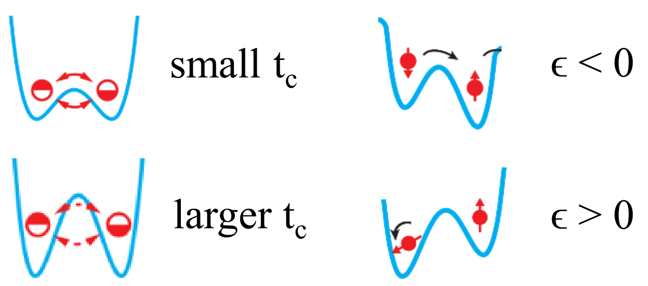

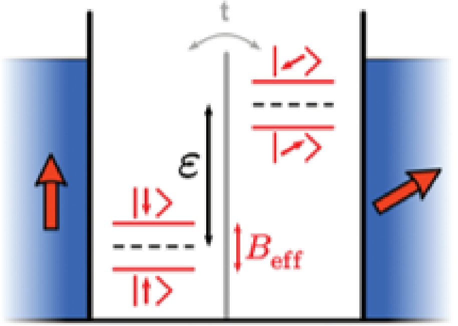

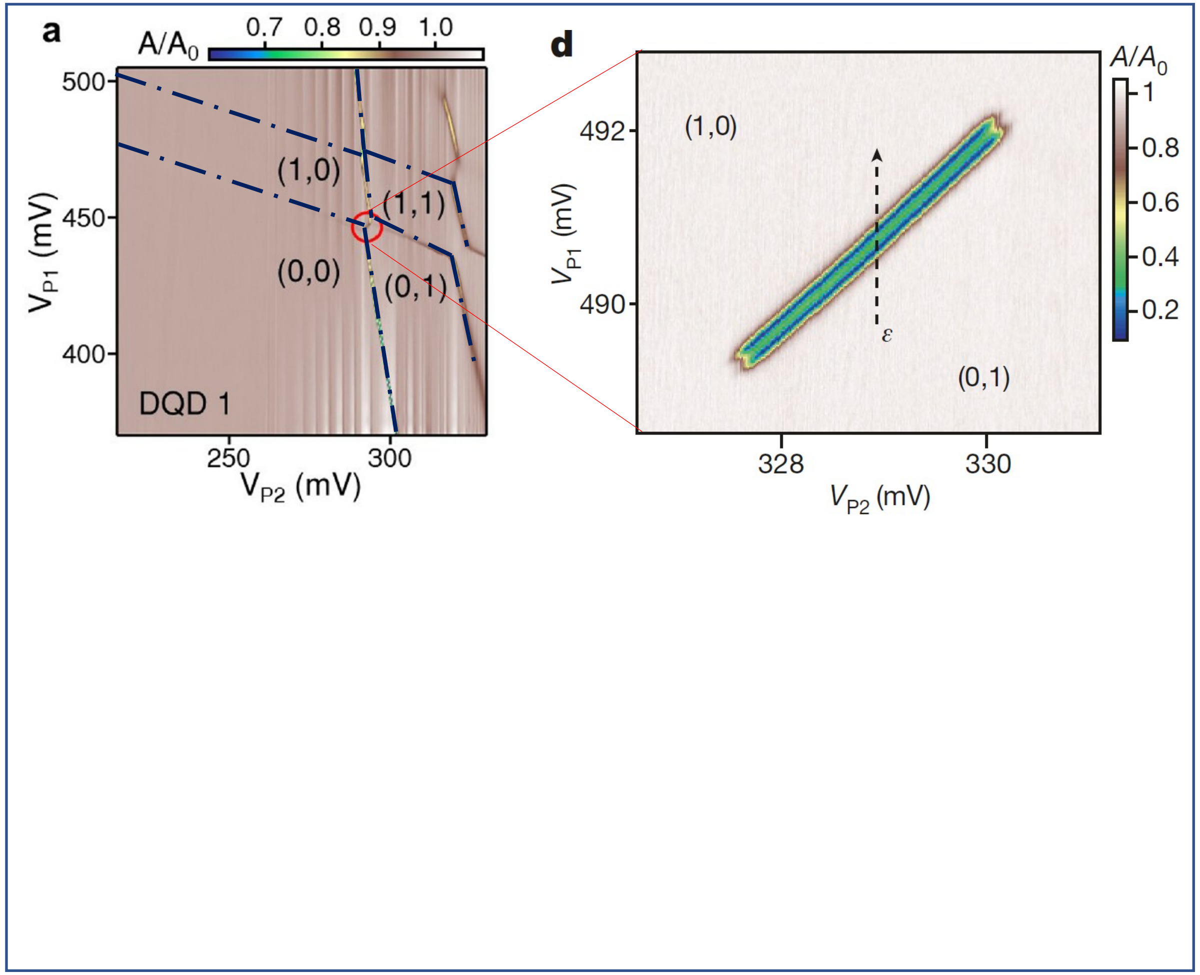

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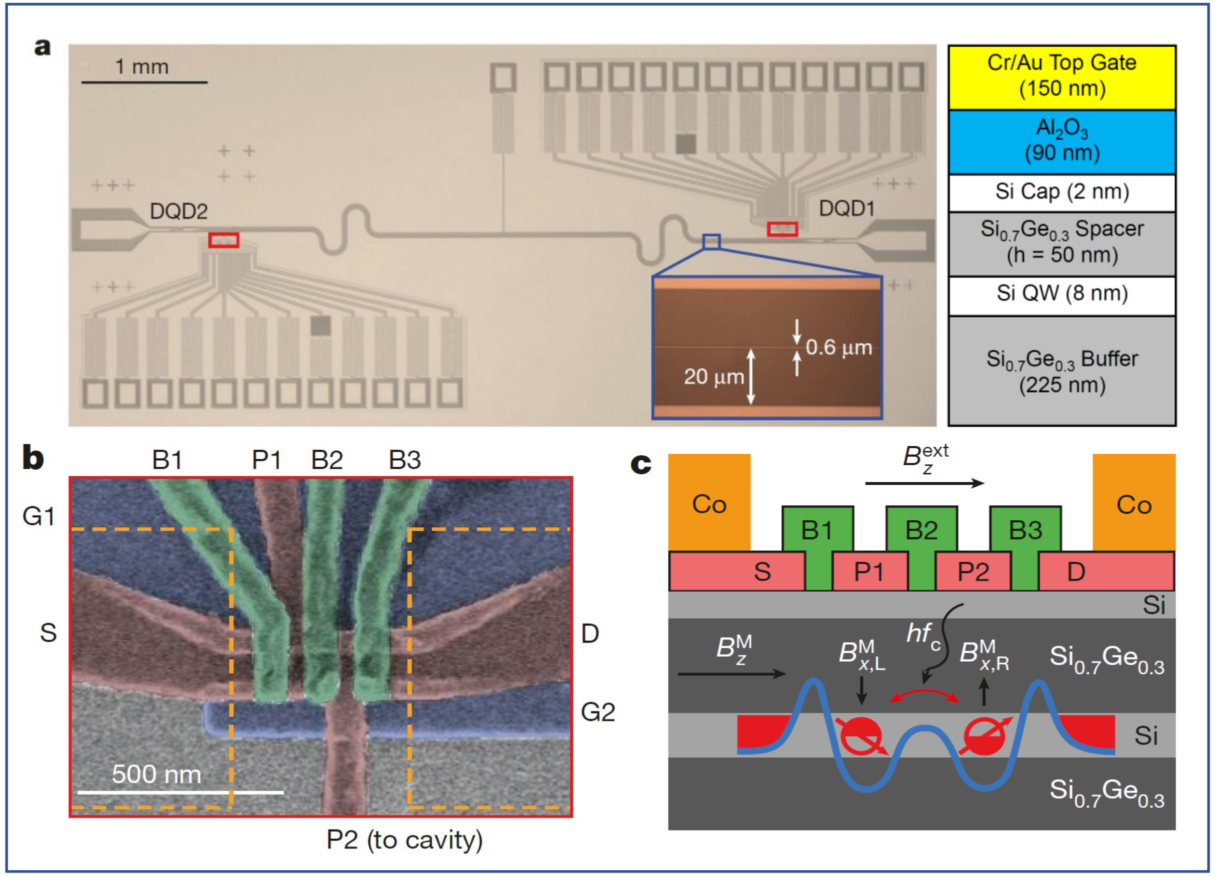

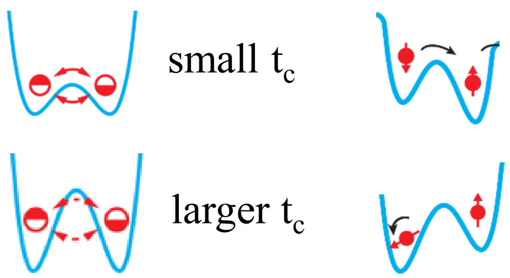

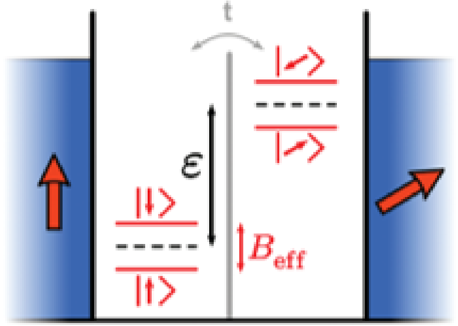

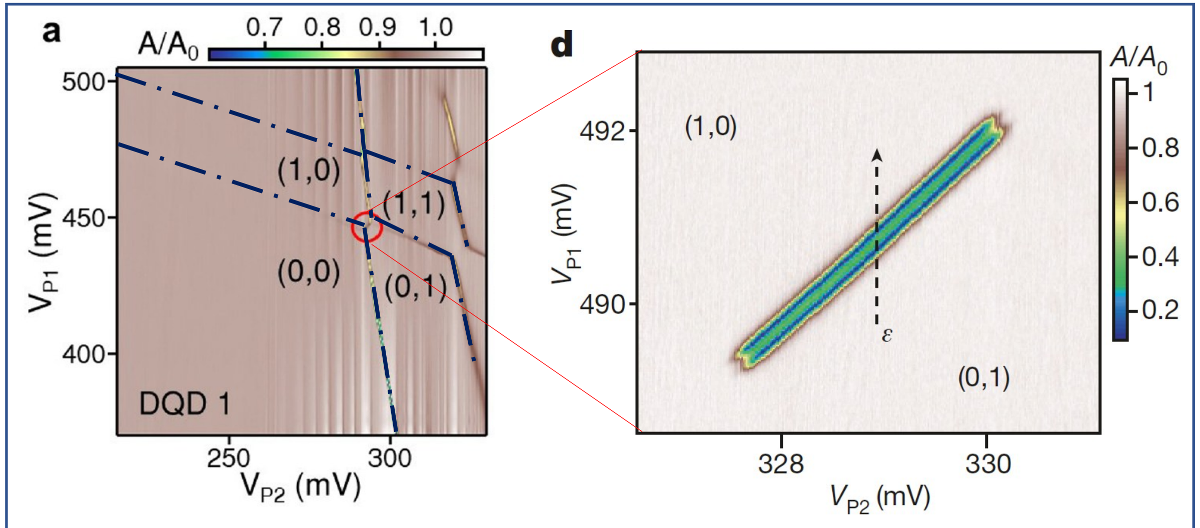

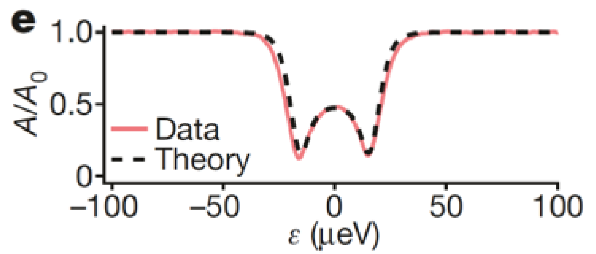

charge photon coupling rate:
$g_c/2\pi = 40$ MHz
charge decoherence rate:
$\gamma_c/2\pi = 35$ MHz
photon decay rate:
$\kappa/2\pi = 1.3$ MHz
inter-dot tunnel coupling:
$2t_c/h = 2.9$ GHz

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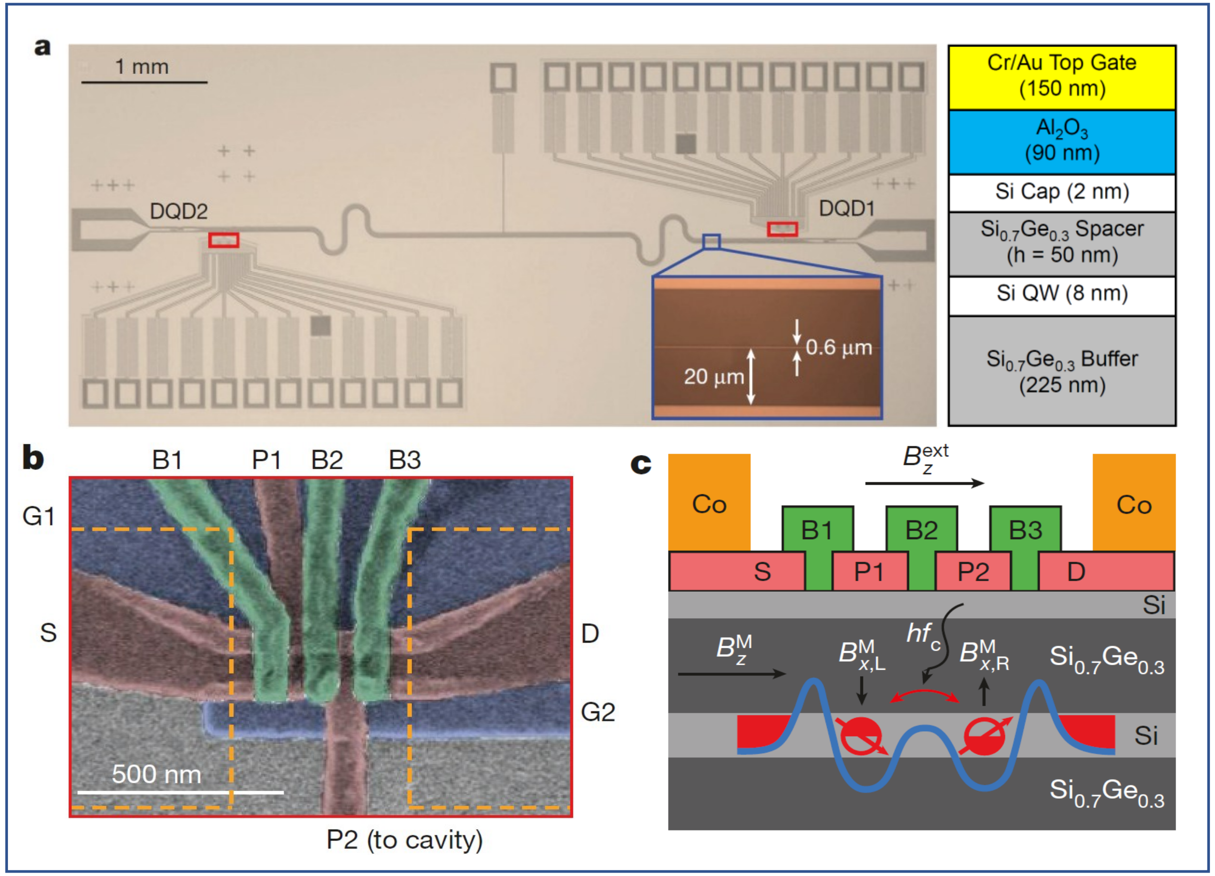
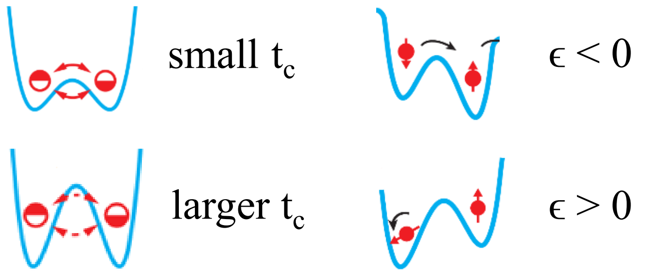
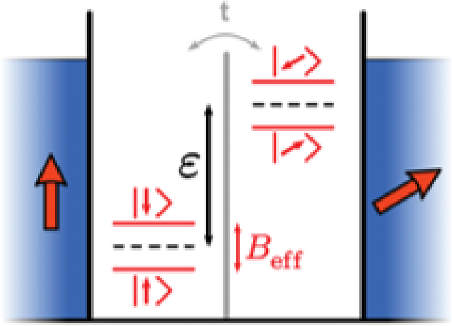
Charge-photon hybridization







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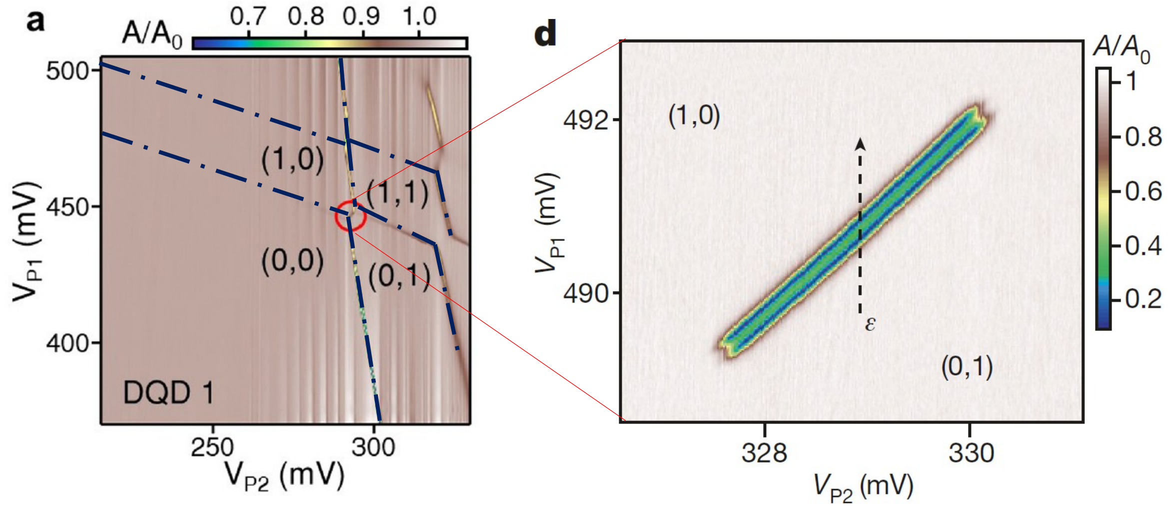
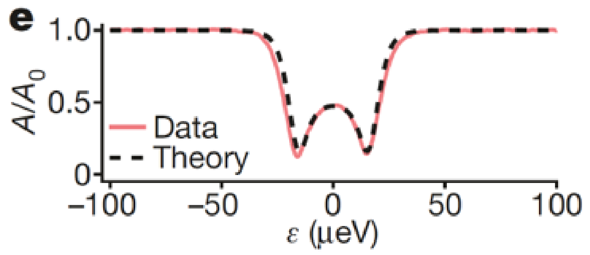
$$H_0 = \frac{1}{2}(\varepsilon\tau_z + 2t_c\tau_x + B_z\sigma_z + B_x^M\sigma_x\tau_z)$$

$$a_{out,i} = \sqrt{\kappa_i}a - a_{in,i}$$

Cavity transmission

$$A = \frac{-i\sqrt{\kappa_1\kappa_2}}{-\Delta_0 - i\kappa/2 + g_c\sum_{n=0}^{2}\sum_{j=1}^{3-n} d_{n,n+j}\chi_{n,n+j}}$$





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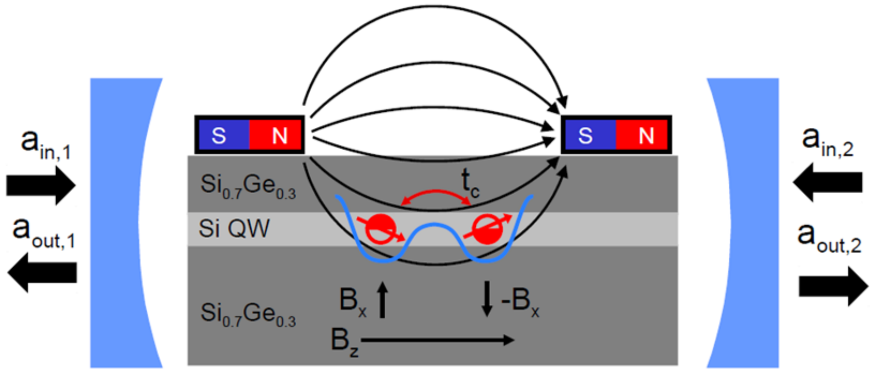
Spin-photon hybridization



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Spin-photon hybridization

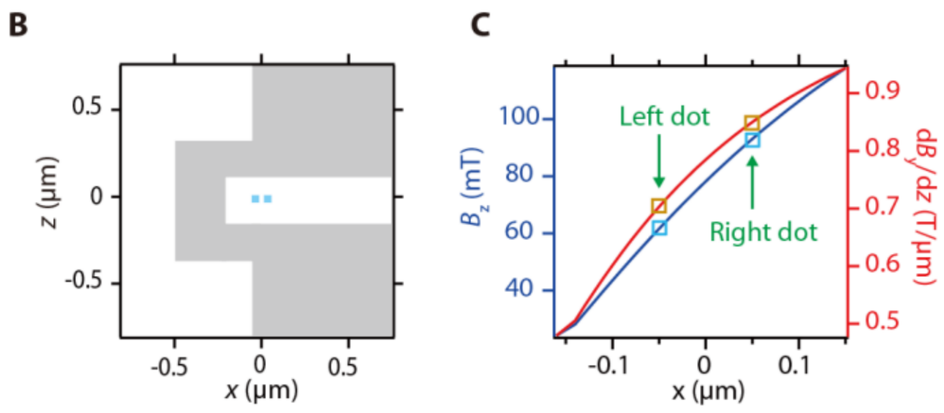
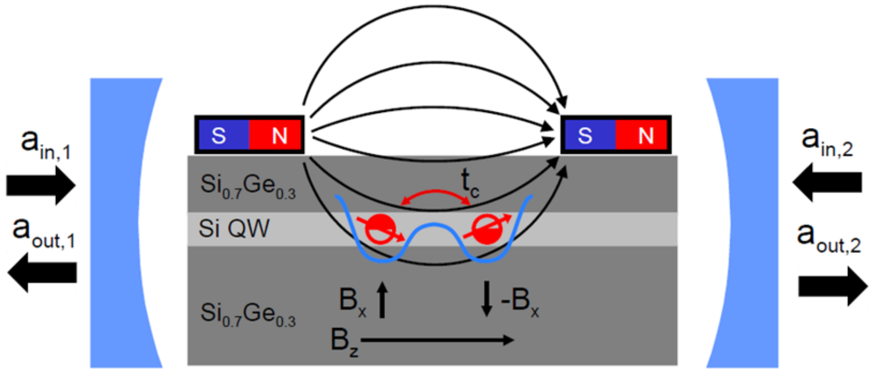


Illustration of micro-magnet

Takeda, K. et al. A fault-tolerant addressable spin qubit in a natural silicon quantum dot. Sci. Adv. 2, e1600694 (2016).



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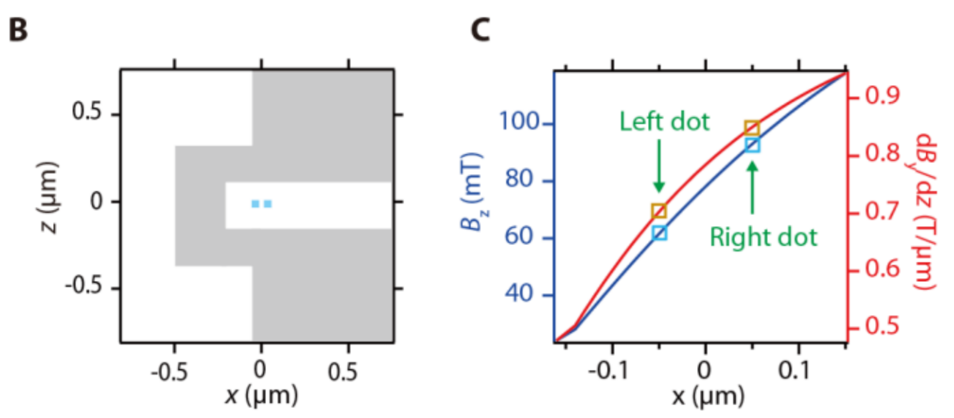
Spin-photon hybridization

$$E_Z = g\mu_B B_{tot}$$ Zeeman energy

$$B_{tot} = \sqrt{[(B^M_{x,L} + B^M_{x,R})/2]^2 + (B^M_z + B^{ext}_z)^2}$$



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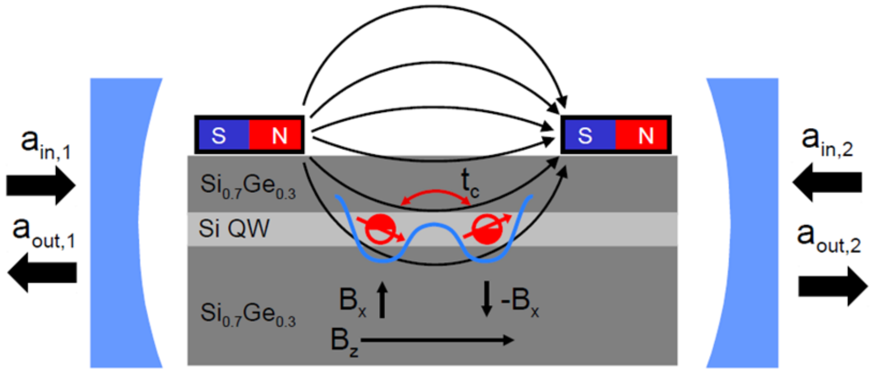

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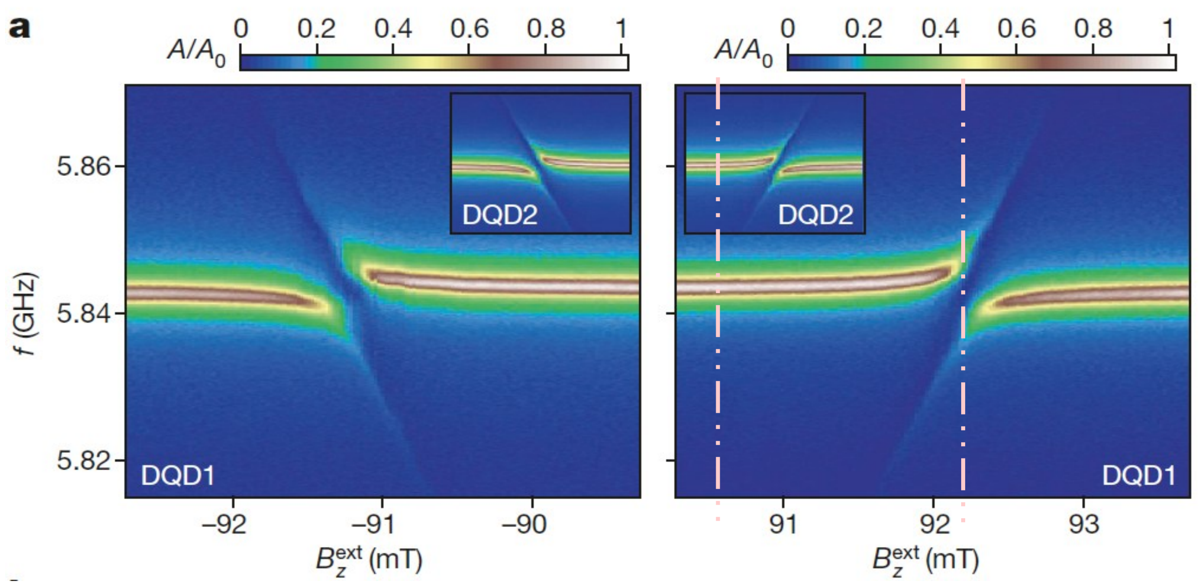
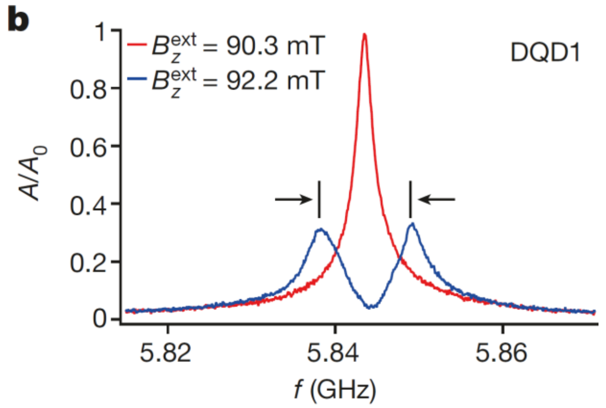
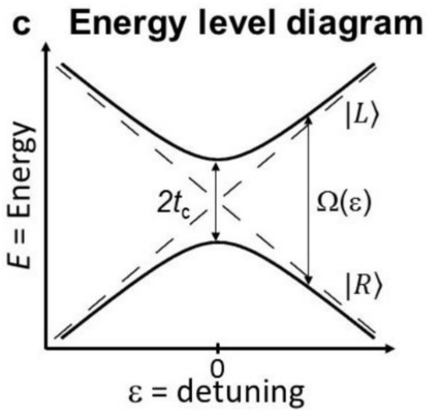




spin photon coupling rate:
$g_s/2\pi$ = 5.5 MHz
spin decoherence rate:
$\gamma_s/2\pi$ = 2.4MHz
photon decay rate(at finite B):
$\kappa/2\pi$ = 1.8 MHz
inter-dot tunnel coupling:
$2t_c/h$ = 7.4 GHz

DQD containing single electron -> charge qubit



$$H_{\mathrm{JC}} = H_{\mathrm{a}} + H_{\mathrm{c}} + H_{\mathrm{int}}$$

$$H_a = \frac{\epsilon}{2}\sigma_z + t\sigma_x$$

diagonalize

$$H_{\mathrm{a}} = \frac{1}{2} f_{\mathrm{a}} \sigma_{\mathrm{z}}$$

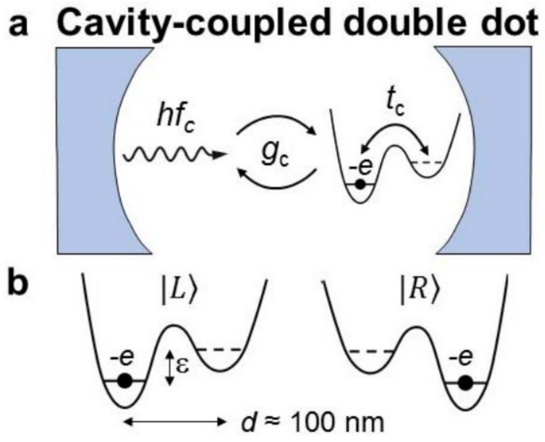
$$f_{\mathrm{a}} = \sqrt{\epsilon^2 + 4t_{\mathrm{C}}^2}/h$$

Orbital energy

$$H_{\mathrm{c}} = hf\left(a^\dagger a + \tfrac{1}{2}\right)$$

$$H_{\mathrm{int}} = h(g_{\mathrm{c}}/2\pi)\sin\theta(a^\dagger\sigma^- + a\sigma^+)$$

$$\sin\theta = 2t_{\mathrm{C}}/\sqrt{\epsilon^2 + 4t_{\mathrm{C}}^2}$$



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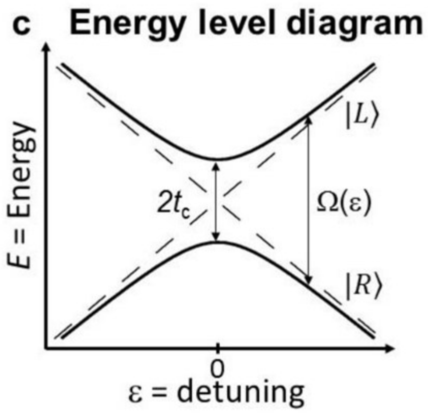

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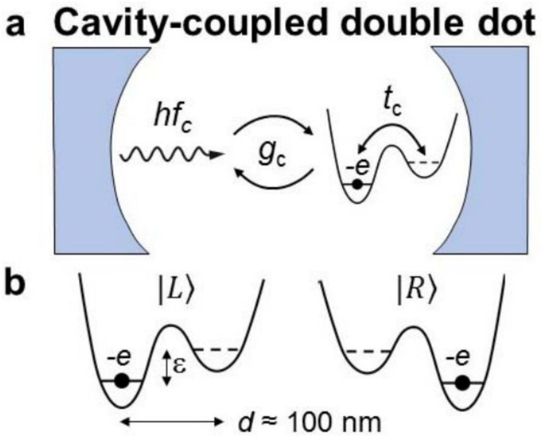

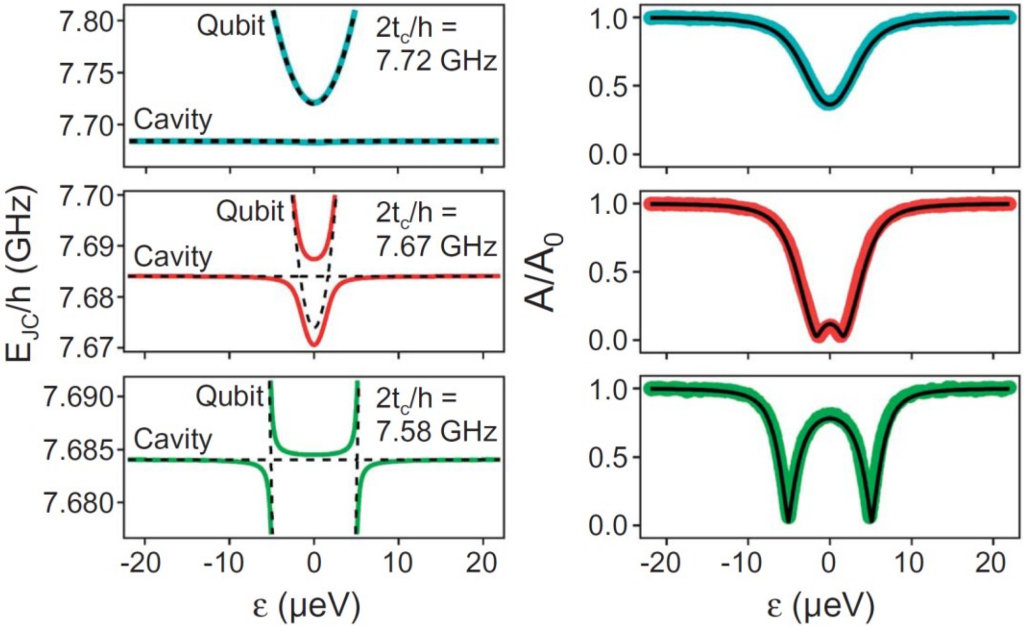

Mi, X., Cady, J. V., Zajac, D. M., Deelman, P. W. & Petta, J. R. Strong coupling of a single electron in silicon to a microwave photon. Science 355, 156–158 (2017).

Spin-photon coupling mechanism

$$H_0 = \frac{1}{2}\left(\epsilon\tau_z + 2t_c\tau_x + B_z\sigma_z + B_x\sigma_x\tau_z\right)$$

$$H_{\mathrm{I}} = g_c\left(a + a^\dagger\right)\sum_{n,m=0}^{3} d_{nm}\left|n\right\rangle\left\langle m\right| \qquad g_c = eE_0 d$$

$$E_{3,0} = \pm\frac{1}{2}\sqrt{(2t_c + B_z)^2 + B_x^2}$$

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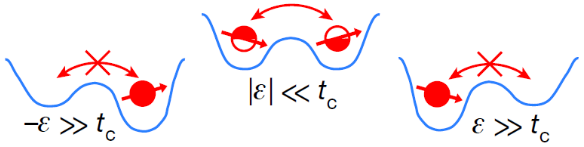

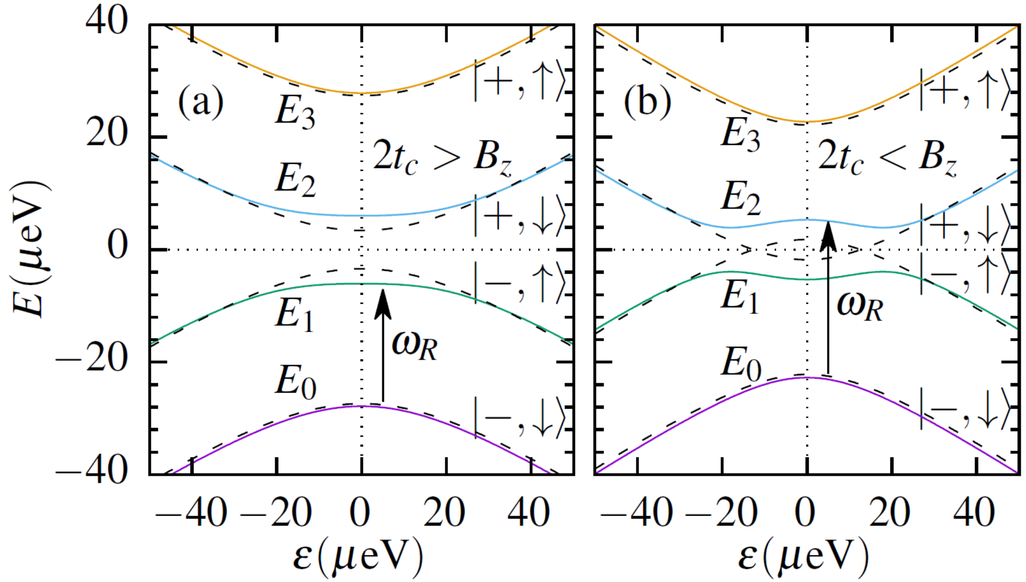

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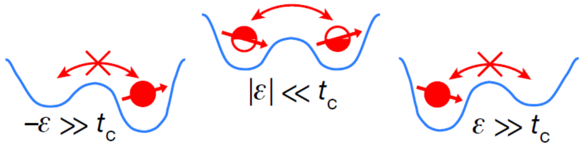

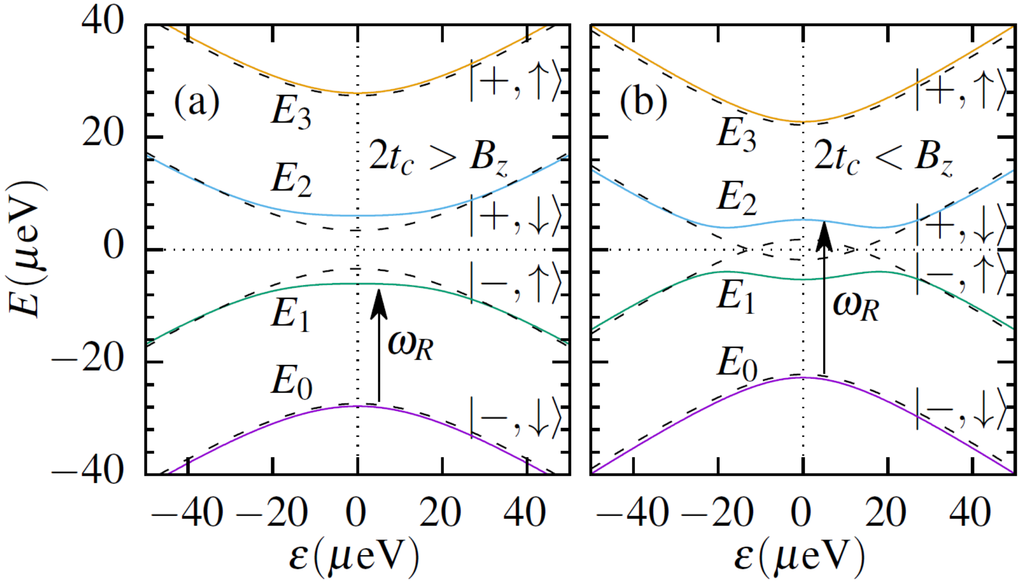

$$\{\left|+,\uparrow\right\rangle, \left|-,\uparrow\right\rangle, \left|+,\downarrow\right\rangle, \left|-,\downarrow\right\rangle\}$$

$$r = \sqrt{(2t_c - B_z)^2 + B_x^2} \qquad \Phi = \arctan\frac{B_x}{2t_c - B_z}$$

$$\theta = \arctan\frac{\epsilon}{2t_c}$$

Spin-orbit mixing angle

$$d^{\mathrm{orb}} = \begin{pmatrix} \sin\theta & -\cos\theta & 0 & 0 \\ -\cos\theta & -\sin\theta & 0 & 0 \\ 0 & 0 & \sin\theta & -\cos\theta \\ 0 & 0 & -\cos\theta & -\sin\theta \end{pmatrix}$$

$$H_0^{\mathrm{orb}} = \frac{1}{2}\begin{pmatrix} \Omega + B_z & 0 & B_x\sin\theta & -B_x\cos\theta \\ 0 & -\Omega + B_z & -B_x\cos\theta & -B_x\sin\theta \\ B_x\sin\theta & -B_x\cos\theta & \Omega - B_z & 0 \\ -B_x\cos\theta & -B_x\sin\theta & 0 & -\Omega - B_z \end{pmatrix}$$

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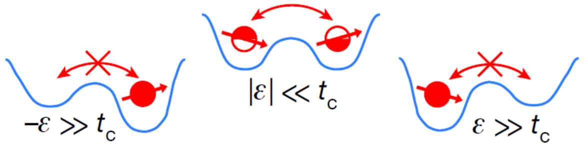

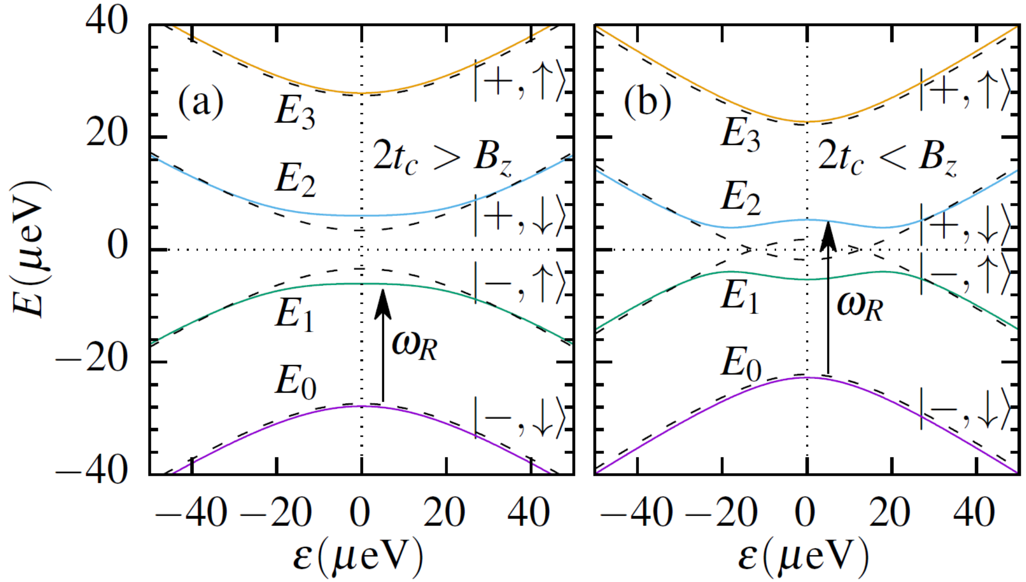

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$$H_0^\mathrm{orb}(\epsilon = 0) = \frac{r}{2}\begin{pmatrix} \frac{2t_c + B_z}{r} & 0 & 0 & -\sin\Phi \\ 0 & -\cos\Phi & -\sin\Phi & 0 \\ 0 & -\sin\Phi & \cos\Phi & 0 \\ -\sin\Phi & 0 & 0 & \frac{-2t_c - B_z}{r} \end{pmatrix}$$

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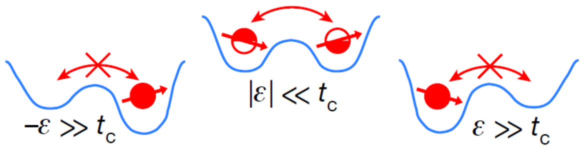

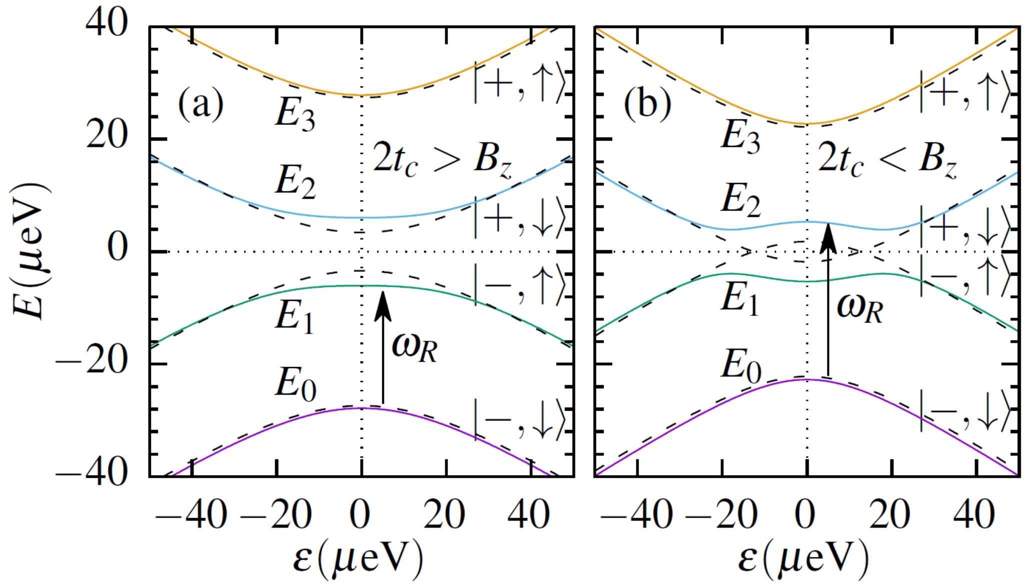

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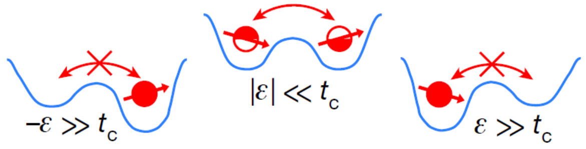

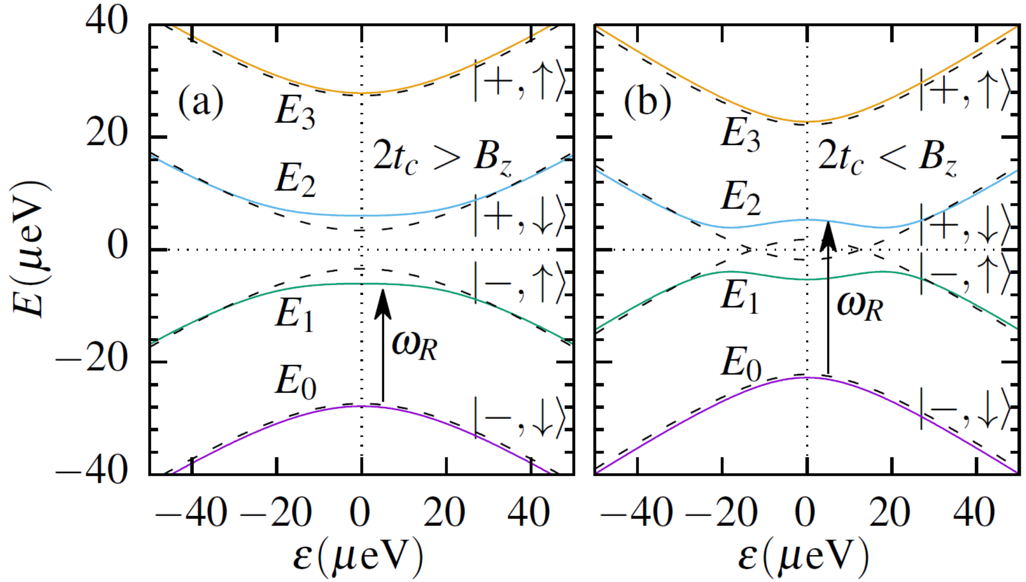

$$\{|+,\uparrow\rangle, |-,\uparrow\rangle, |+,\downarrow\rangle, |-,\downarrow\rangle\}$$

$$r = \sqrt{(2t_c - B_z)^2 + B_x^2} \qquad \Phi = \arctan\frac{B_x}{2t_c - B_z}$$

$$\theta = \arctan\frac{\epsilon}{2t_c}$$

Spin-orbit mixing angle

$$d^{\mathrm{orb}} = \begin{pmatrix} \sin\theta & -\cos\theta & 0 & 0 \\ -\cos\theta & -\sin\theta & 0 & 0 \\ 0 & 0 & \sin\theta & -\cos\theta \\ 0 & 0 & -\cos\theta & -\sin\theta \end{pmatrix}$$

$$H_0^{\mathrm{orb}}(\epsilon = 0) = \frac{r}{2}\begin{pmatrix} \frac{2t_c + B_z}{r} & 0 & 0 & -\sin\Phi \\ 0 & -\cos\Phi & -\sin\Phi & 0 \\ 0 & -\sin\Phi & \cos\Phi & 0 \\ -\sin\Phi & 0 & 0 & \frac{-2t_c - B_z}{r} \end{pmatrix}$$

Benito, M., Mi, X., Taylor, J. M., Petta, J. R. & Burkard, G. Input-output theory for spin-photon coupling in Si double quantum dots. Phys. Rev. B 96, 235434 (2017).

Spin-photon coupling mechanism

$$H_0 = \frac{1}{2}\left(\epsilon\tau_z + 2t_c\tau_x + B_z\sigma_z + B_x\sigma_x\tau_z\right)$$

$$H_\mathrm{I} = g_c\left(a + a^\dagger\right)\sum_{n,m=0}^{3} d_{nm}\,|n\rangle\langle m| \qquad g_c = eE_0 d$$

$$E_{3,0} = \pm\frac{1}{2}\sqrt{(2t_c + B_z)^2 + B_x^2}$$

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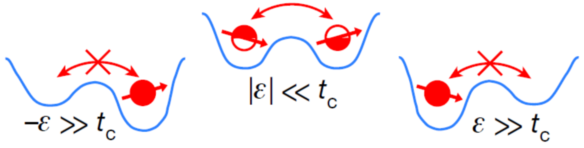

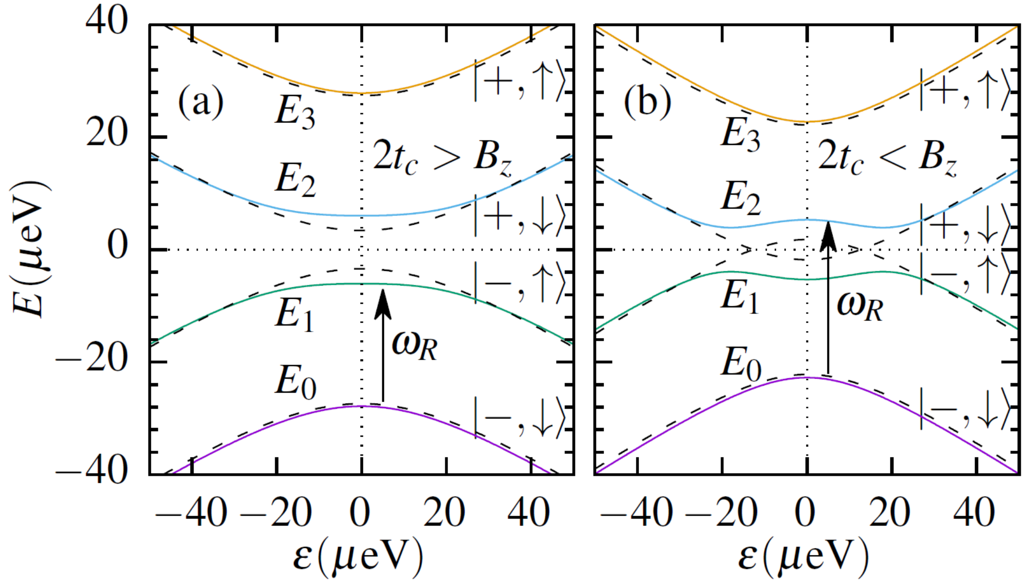

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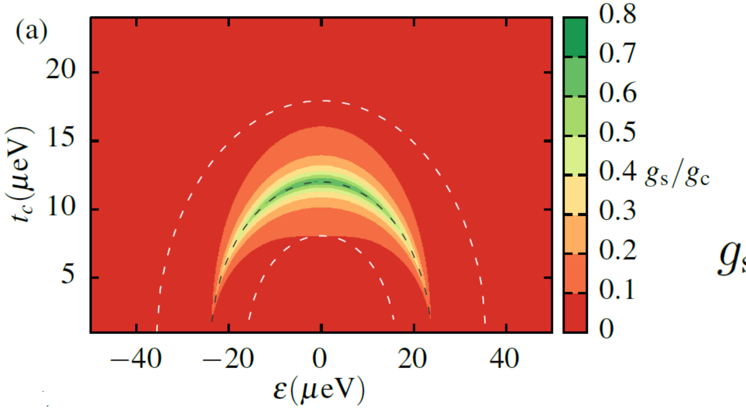
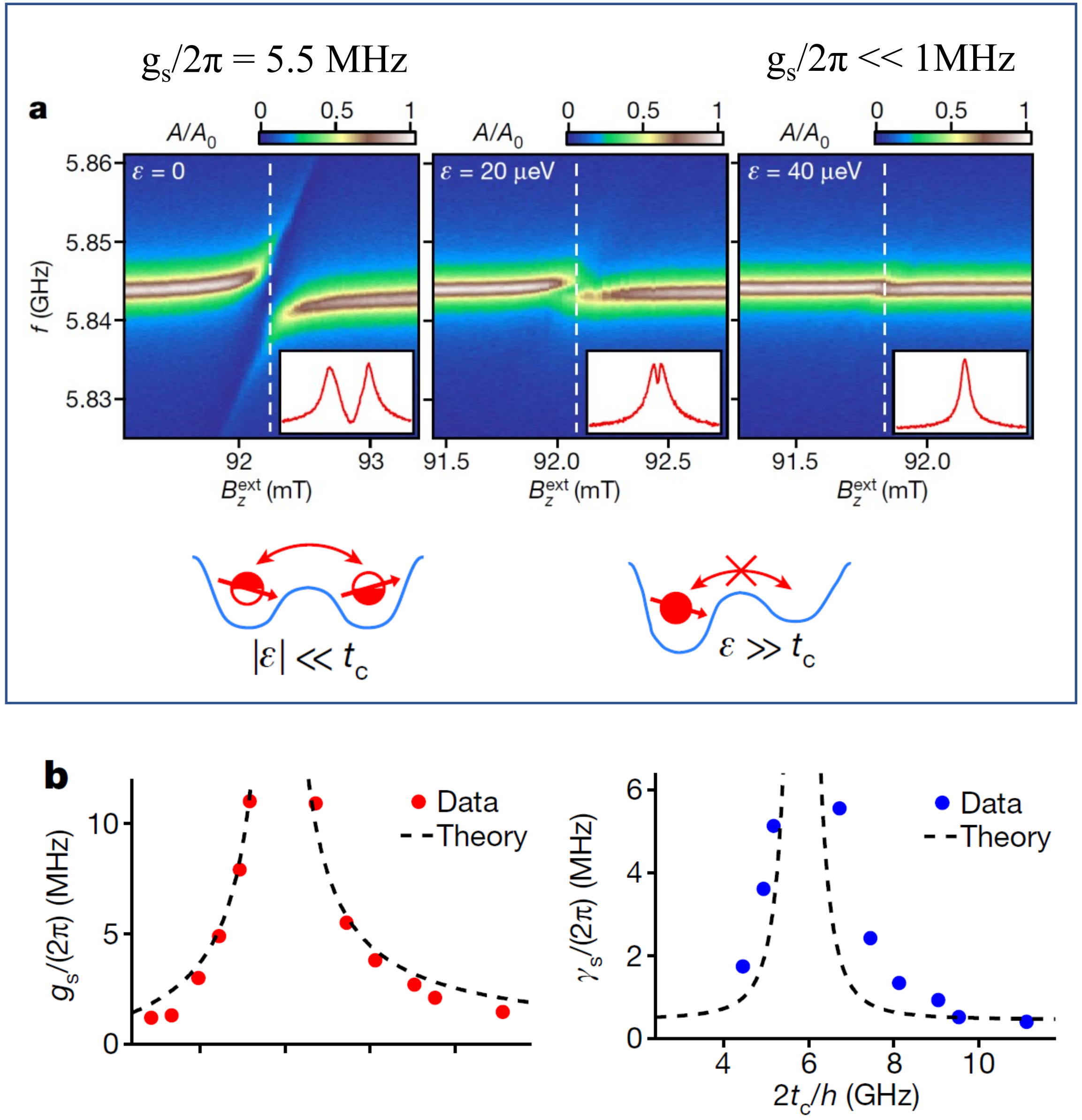


$$g_s = g_c|d_{01(2)}| \simeq -\sin\frac{\Phi}{2}$$

Benito, M., Mi, X., Taylor, J. M., Petta, J. R. & Burkard, G. Input-output theory for spin-photon coupling in Si double quantum dots. Phys. Rev. B 96, 235434 (2017).

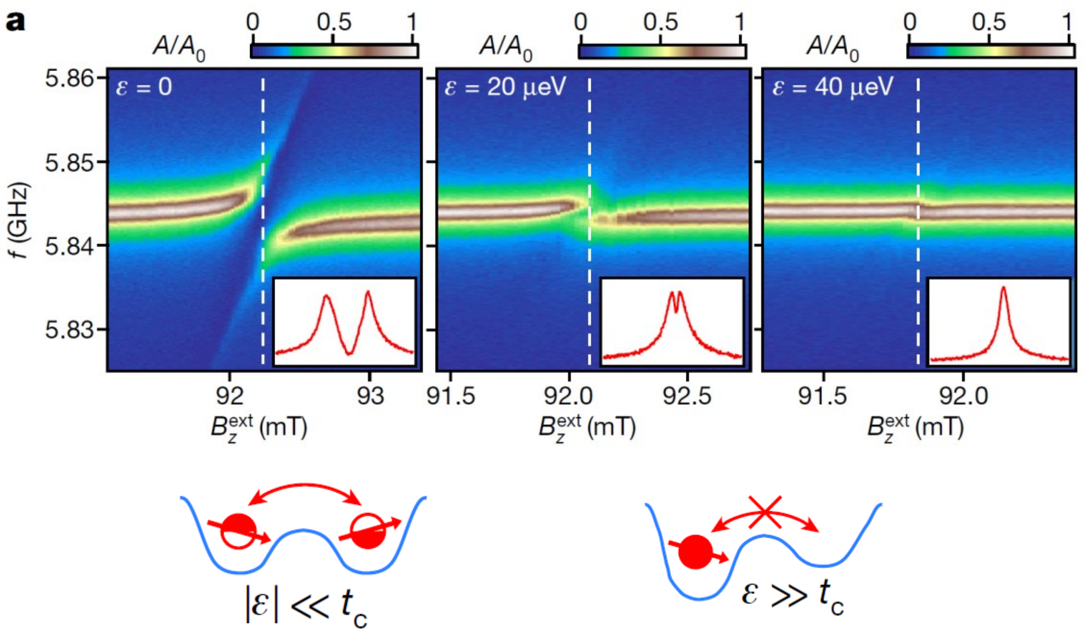
Electrical control of Spin-photon coupling & Dispersive readout of single spin

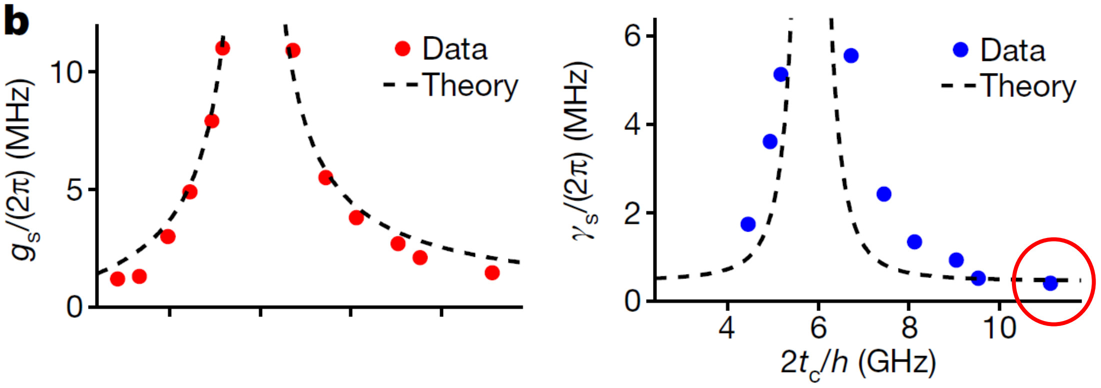


Electrical control of Spin-photon coupling & Dispersive readout of single spin

$g_s/2\pi = 5.5$ MHz

$g_s/2\pi << 1$MHz

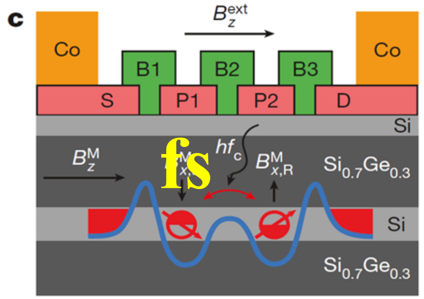


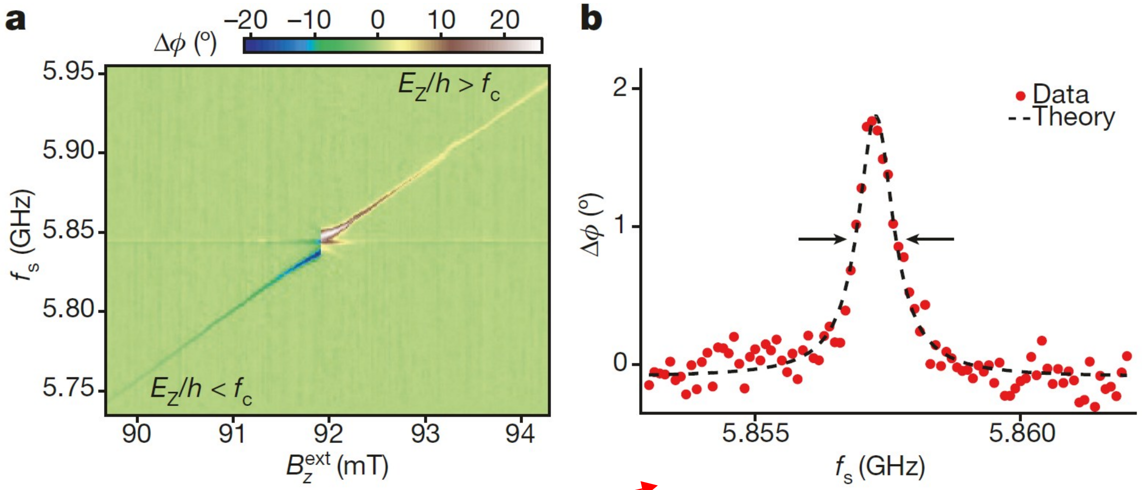


Dispersive regime:

$$|\Delta/(2\pi)| \gg g_s/(2\pi)$$

$$\Delta\phi \approx \tan^{-1}[2g_s^2/(\kappa\Delta)]$$

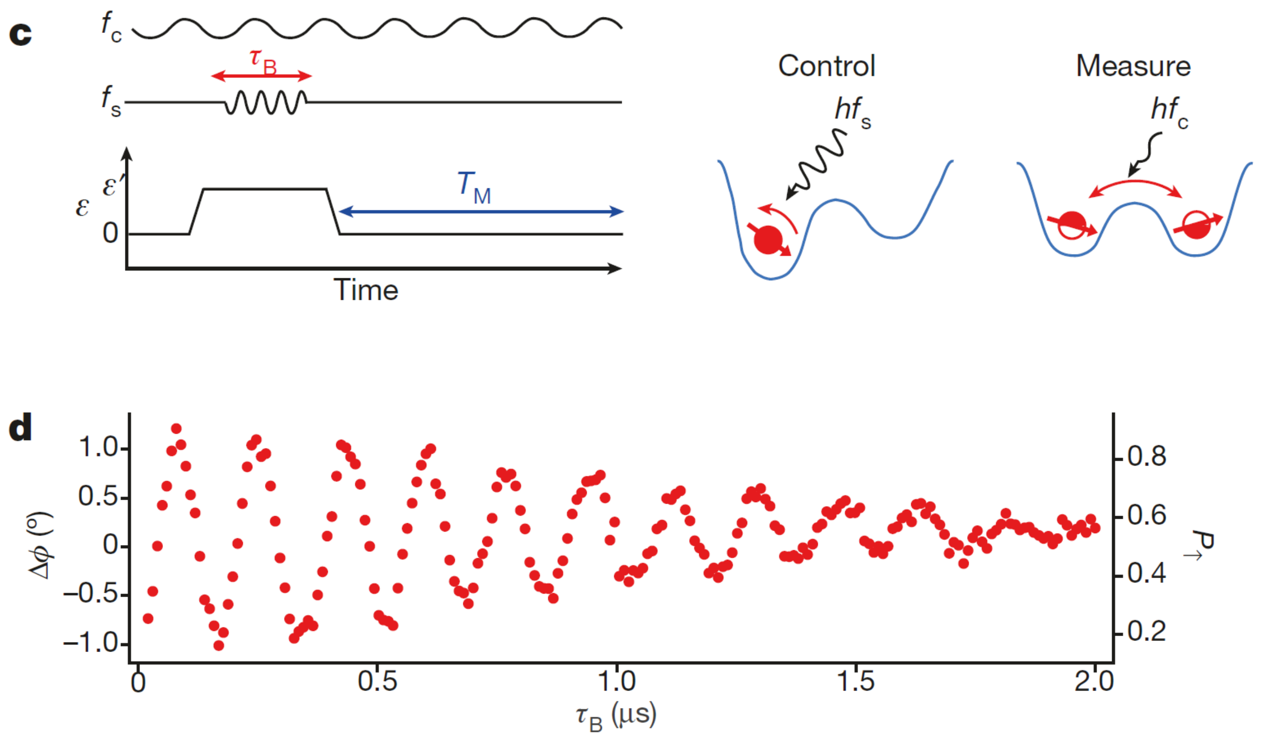




spin decoherence rate:

$\gamma_s/2\pi = 0.41$ MHz

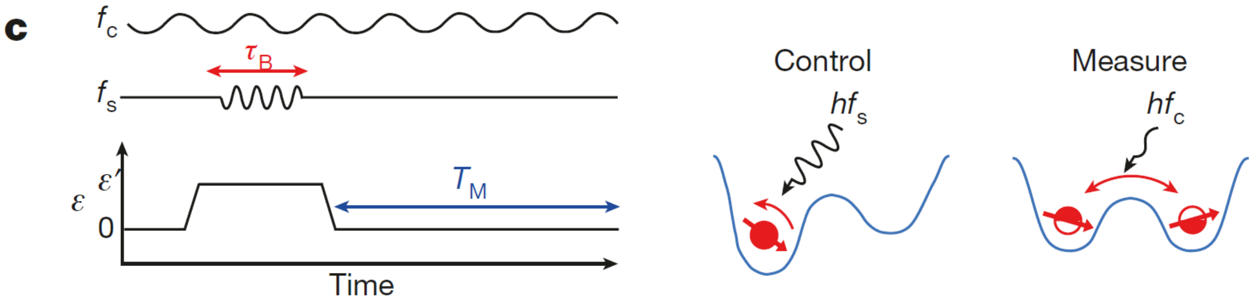
Dispersive readout of single spin

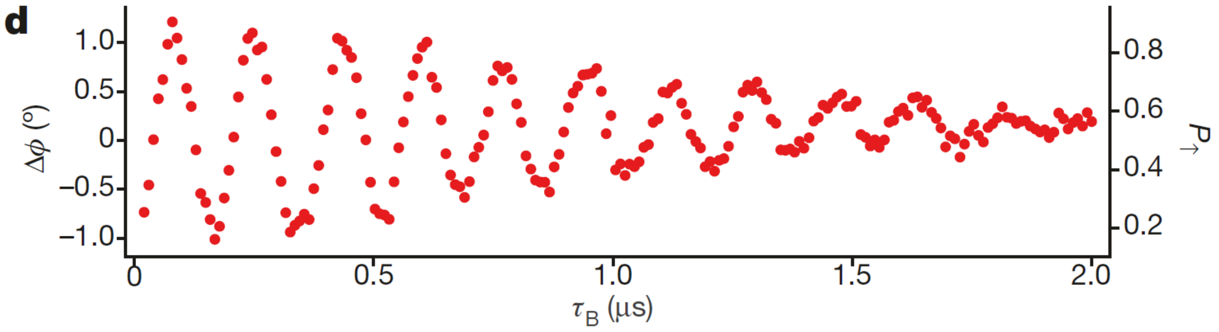


Rabi frequency:

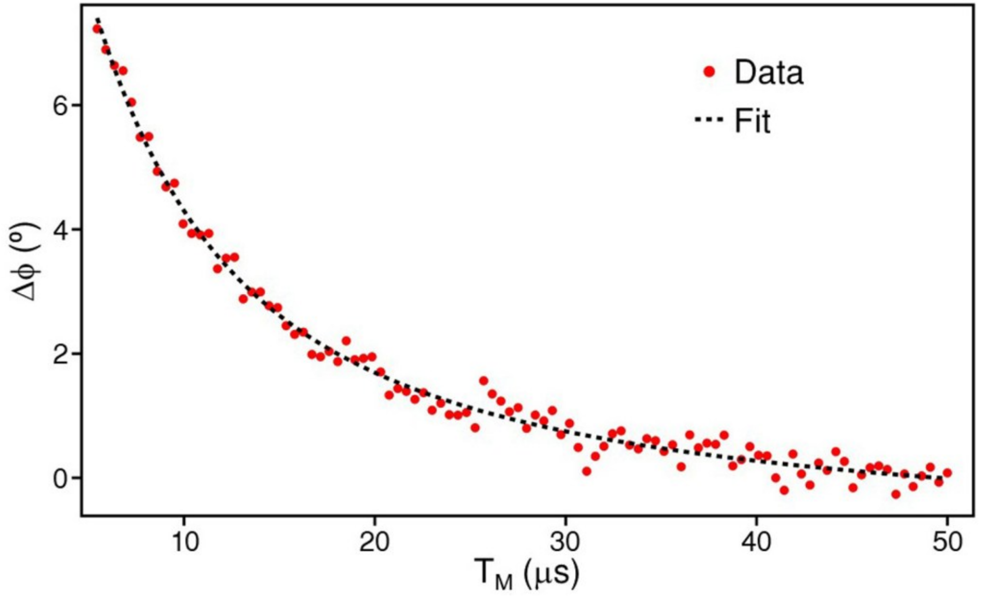
f_R= 6 MHz

Dispersive readout of single spin





Spin relaxation at ϵ=0



$$\phi_0 + \phi_1(T_1/T_M)[1 - \exp(-T_M/T_1)]$$

Rabi frequency:

f_R= 6 MHz

Spin relaxation time:

$T_1(\epsilon=0) = 3.2$ μs

$$P_\uparrow = (1/2)(1 + \Delta\phi/\phi_{\uparrow,r})$$

$$\phi_{\uparrow,r} = \phi_\uparrow(T_1/T_M)[1 - \exp(-T_M/T_1)] = 1.5°$$

Proposal of project

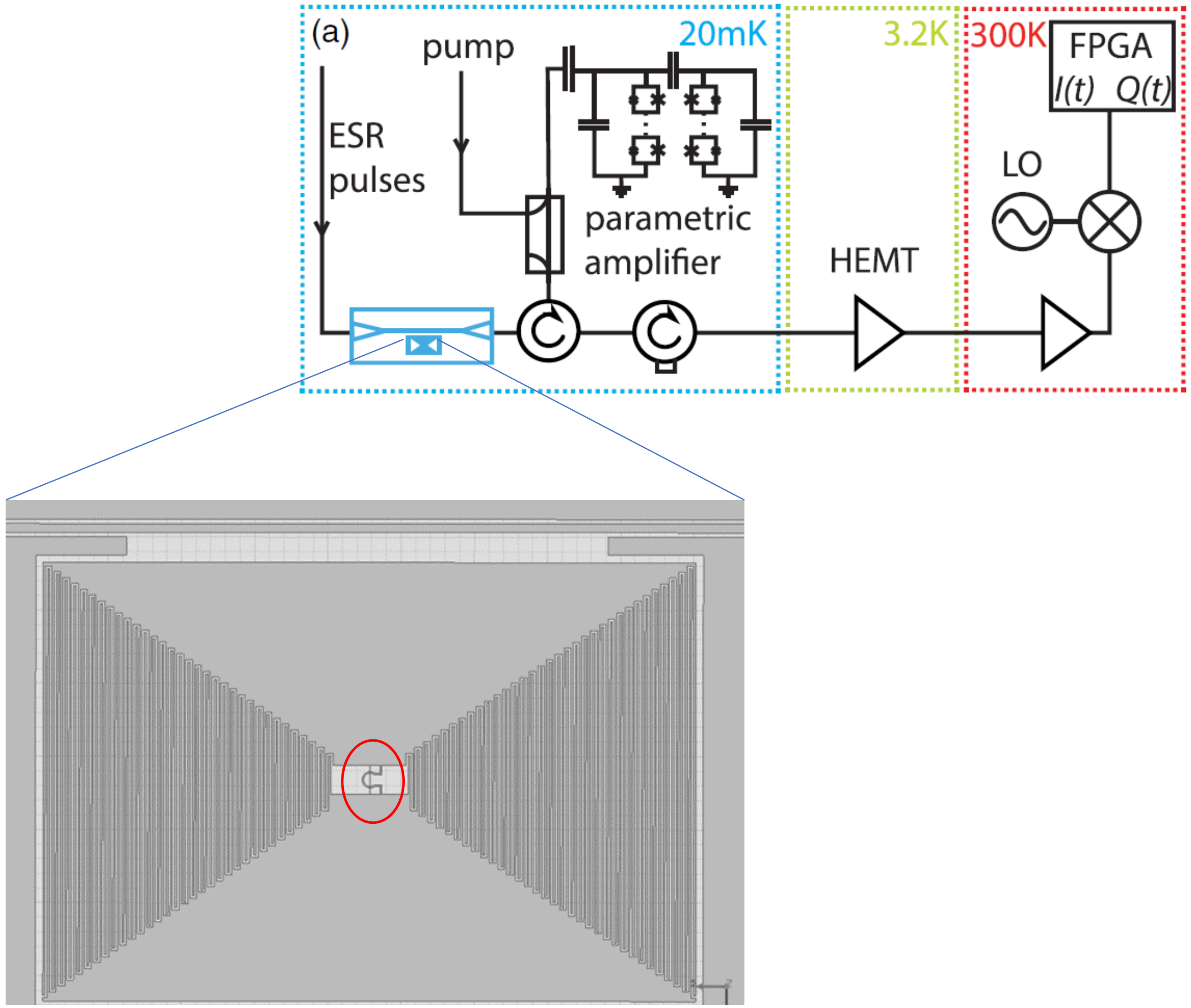
Aim:

Inductively coupling spins to SC resonators through magnetic dipole interaction

Coupling strength:

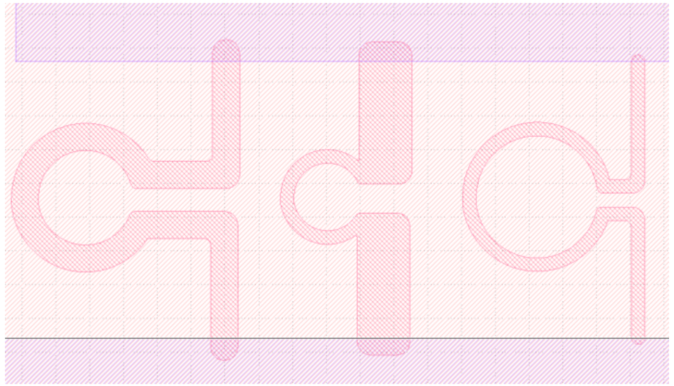
$$g_0 = b_1 g \mu_B \omega_{\mathrm{res}} / \sqrt{8\hbar Z}$$

Oscillating magnetic field per unit current

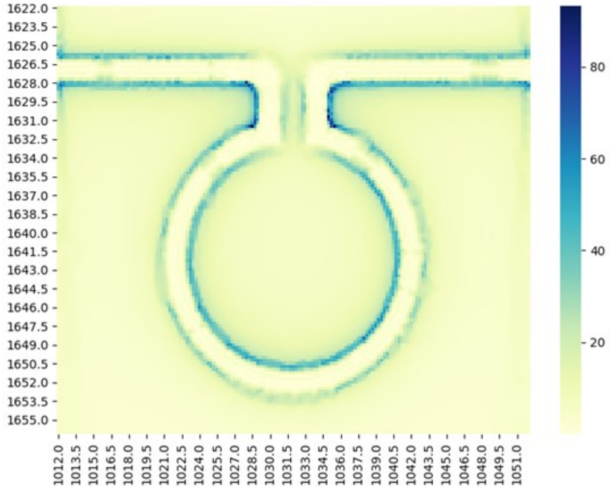


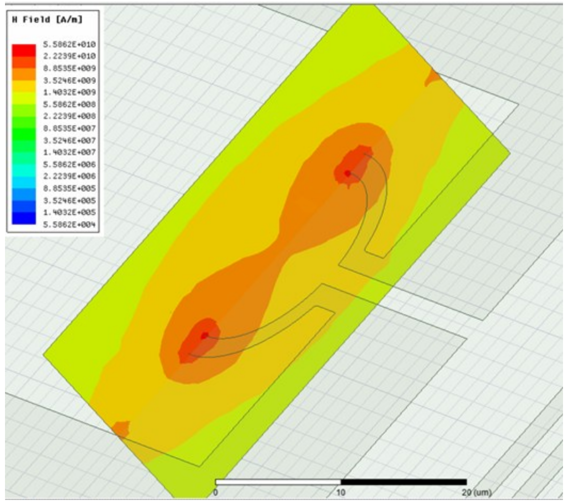
Eichler, C. et al. Electron spin resonance at the level of 10^4 spins using low impedance superconducting resonators. Phys. Rev. Lett. 118, 037701 (2017).

B field within the loop

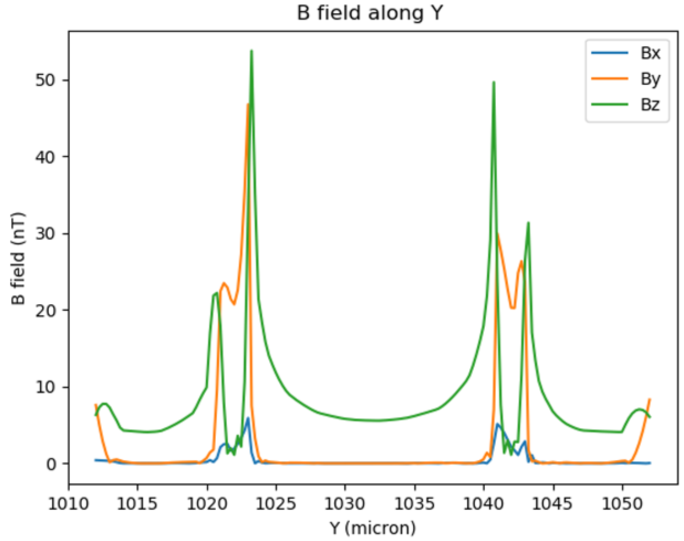


Macro to generate different loops



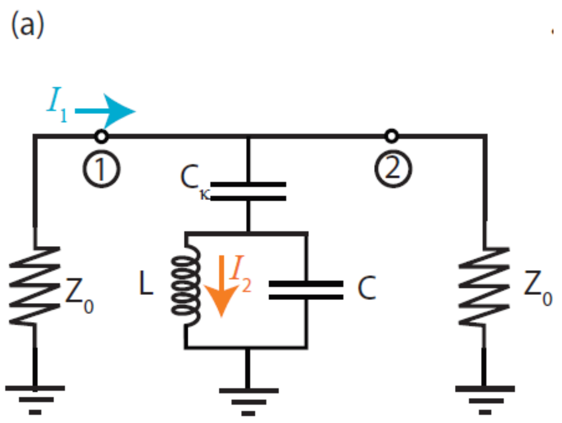


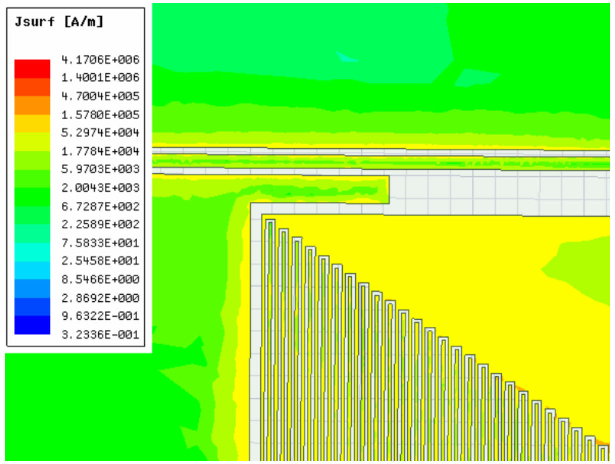
B tend to be small within the loop

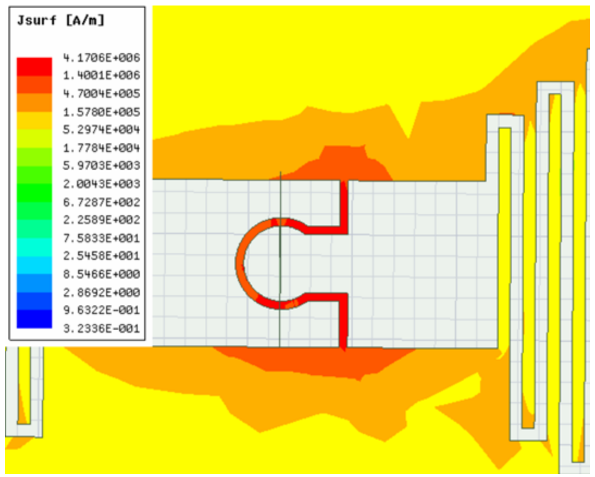


Highest achieved B on the center is 10 nT

Calculation of characteristic impedance





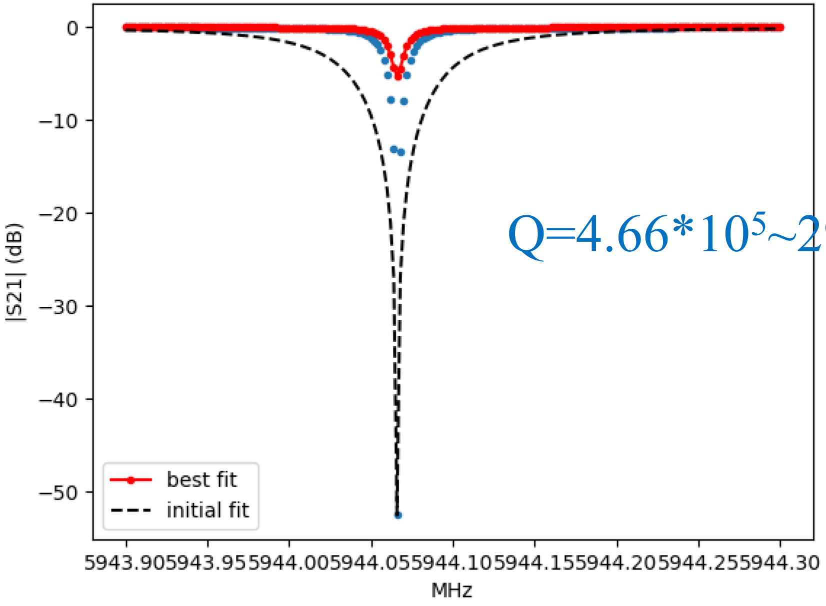


$$i\omega_{\text{res}} L I_2 + \frac{I_1}{i\omega_{\text{res}} C_\kappa} = 0$$

$$\omega_{\text{res}}^2 = 1/L_{\text{tot}}(C + C_\kappa)$$

$$L = \frac{Z_0}{2\omega_{\text{res}}} Q \left(\frac{I_1}{I_2}\right)^2 \sim 106 \text{ pH}$$

$$Z = \omega_{res} L = 4\ \Omega\ \sim 25\ \Omega$$



Q=4.66*10^5~29.7*10^5