A Coherent Spin-Photon Interface in Silicon

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arXiv:1710.03265v1
09.10.2017

FAM talk - Florian Froning - 16.02.2018

Motivation

- electron spins in Silicon quantum dots
  - long coherence times
  - upscaling using standard semiconductor fabrication techniques
- long distance spin qubit coupling via interaction with microwave frequency photons
  - all-to-all connectivity
  - various proposals[1]

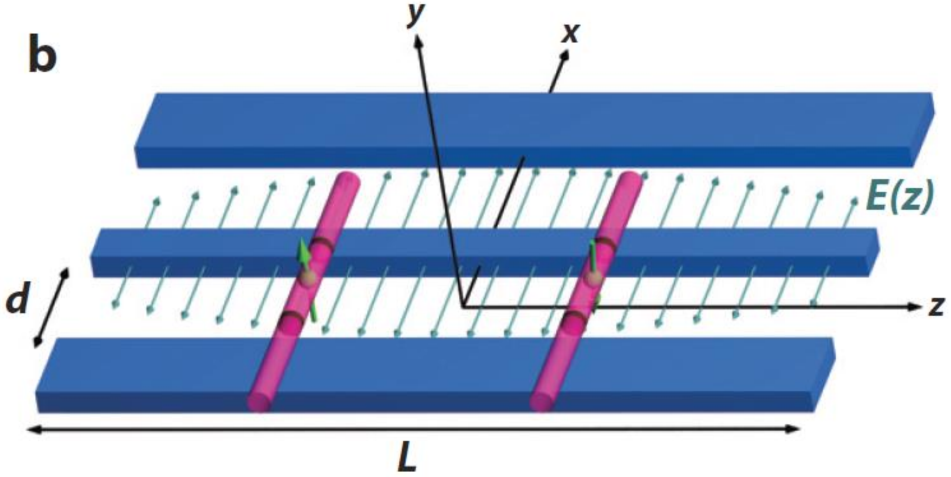
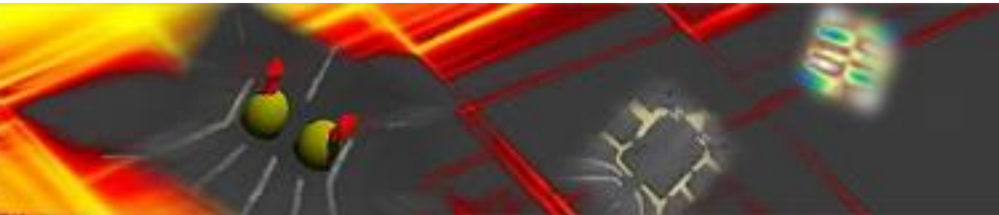


Fig: Long range qubit coupling via microwave cavity[1]



[1] C. Kloeffel, D. Loss, Annu. Rev. Condens. Matter Phys. **4**, 51 (2013)

Recap

- In 2017 several groups[1,2] reached strong charge-cavity coupling regime
  - see also FAM talk from 10.02.2017[3]
  - large impedance resonators increase coupling
  - high quality factor resonators
- Outlook: spin-cavity coupling by spin-charge hybridization
  - external magnetic field gradient
  - strong spin-orbit interaction
  - resonant exchange qubits[4]

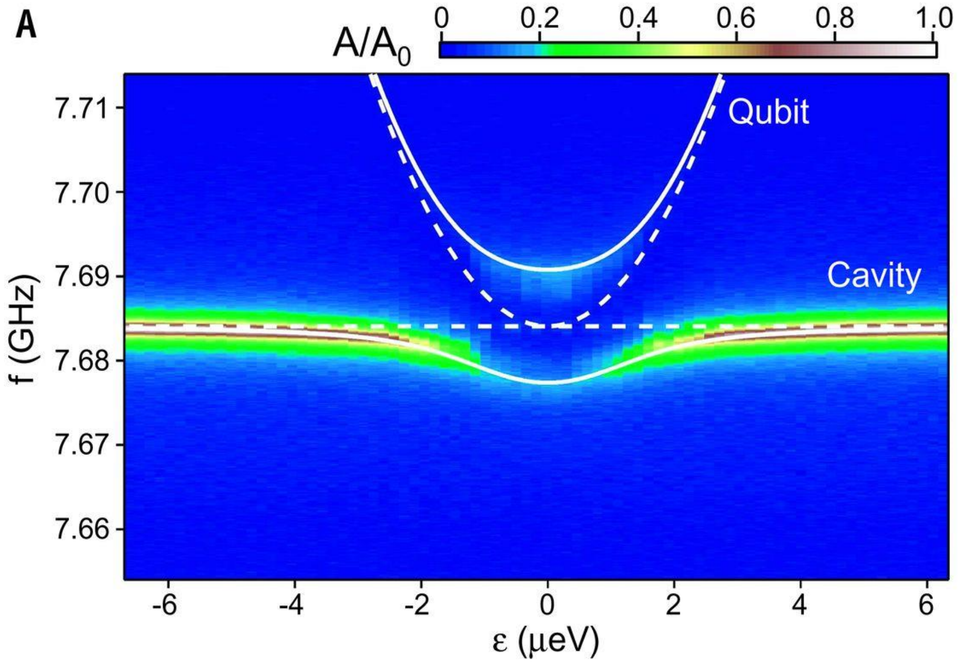
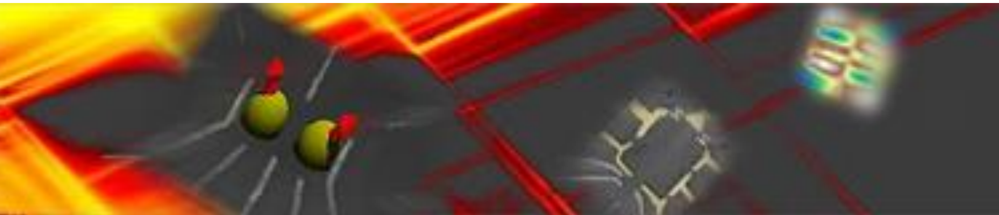


Fig: Demonstration of strong qubit-cavity coupling[1]

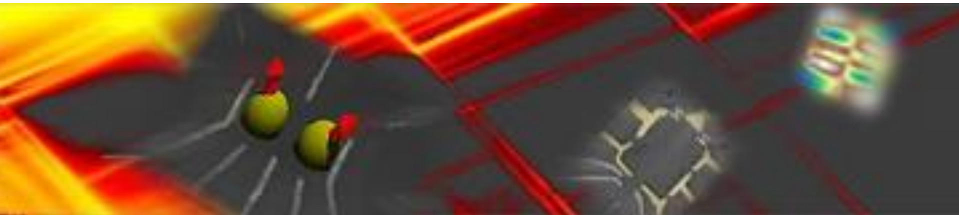


[1] X. Mi *et al.*, Science **355**, 155-158 (2017)
[2] A. Stockklauser *et al.*, PRX **7**, 011030 (2017)
[3] FAM talk 10.02.2017
[4] A. J. Landig et al., arXiv:1711.01932v1

Outline

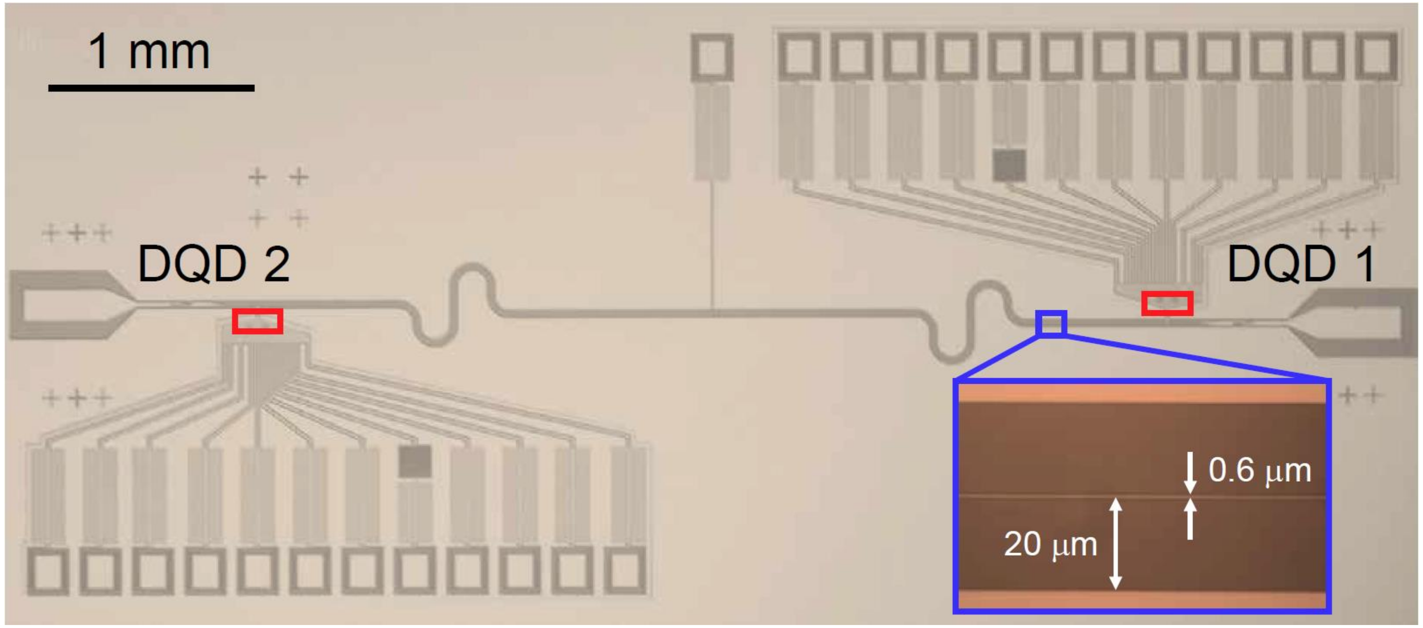
- Spin-Photon Interface
- demonstration of strong spin-photon coupling
- electrical control of spin-photon coupling
- single spin readout

similar work by the Vandersypen group[1]



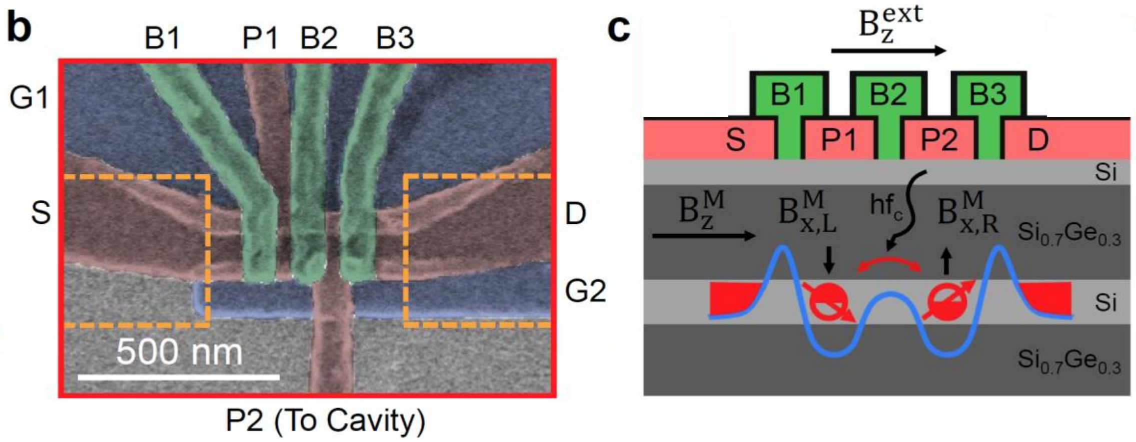
[1] N. Samkharadze *et al.*, Science (2018), DOI: 10.1126/science.aar4054

Spin-Photon Interface



- ✓ Nb cavity
- ✓ f_c = 5.846 GHz
- ✓ Q_c = 4,700
- ✓ $\kappa/2\pi$ = 1.3 MHz
- ✓ high impedance Z_r

Spin-Photon Interface



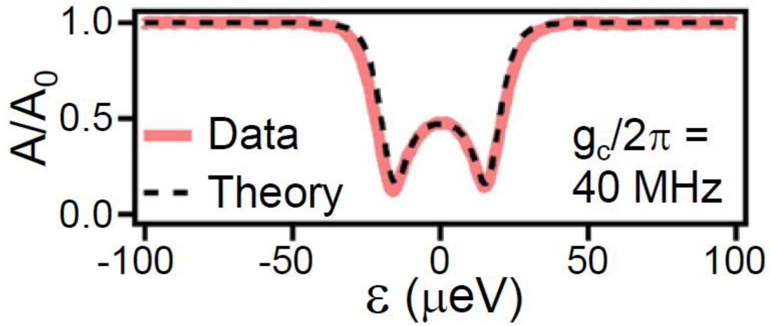


Fig: Cavity transmission amplitude at the (0,1)↔(1,0) DQD charge transition

- ✓ Si/SiGe heterostructure
- ✓ double quantum dot
- ✓ single electron
- ✓ charge coupling $g_c/2\pi$ = 40 MHz
- ✓ charge dephasing $\gamma_c/2\pi$ = 35 MHz
- ✓ tunable interdot tunneling t_c

strong charge coupling

$$g_c > \gamma_c, \kappa$$

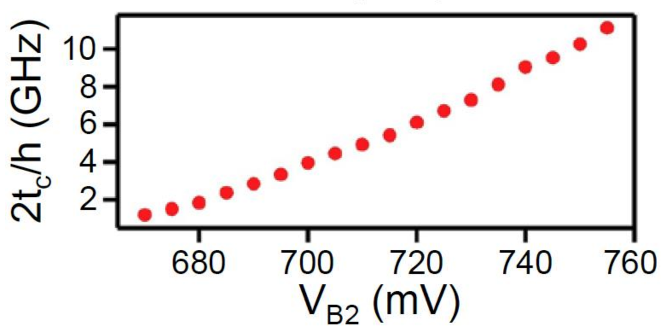
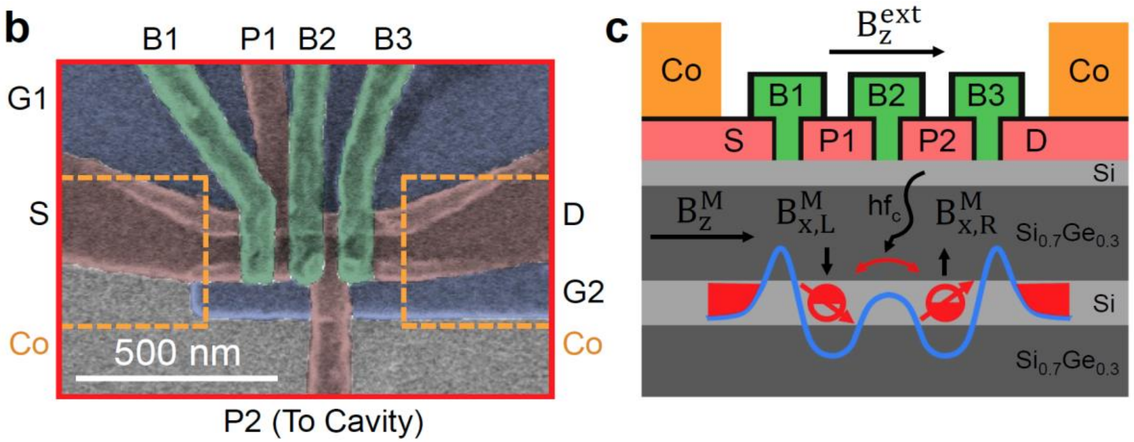


Fig: Interdot tunnel coupling as a function of middle barrier

Spin-Photon Interface



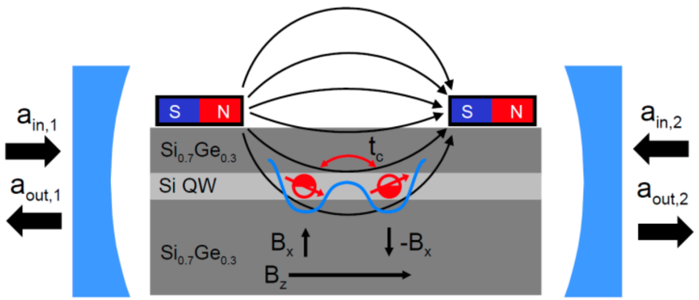


Fig: Schematic illustration of the device structure[1]

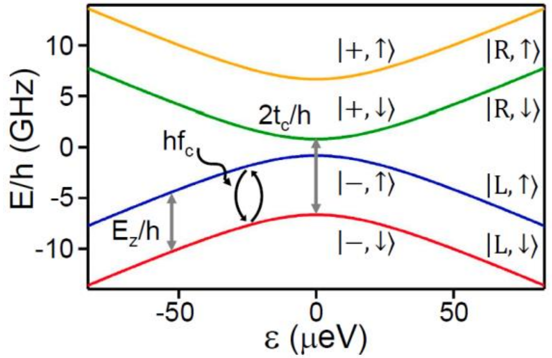


Fig: energy level scheme of the DQD system as a function of dot detuning

- ✓ inhomogeneous magnetic field yields spin-charge hybridization

$$|0\rangle \approx |-,\downarrow\rangle$$
$$|1\rangle \approx \cos\frac{\Phi}{2}|-,\uparrow\rangle + \sin\frac{\Phi}{2}|+,\downarrow\rangle$$
$$|2\rangle \approx \sin\frac{\Phi}{2}|-,\uparrow\rangle - \cos\frac{\Phi}{2}|+,\downarrow\rangle$$
$$|3\rangle \approx |+,\uparrow\rangle$$

[1] M. Benito *et al.*, arXiv:1710.02508v1

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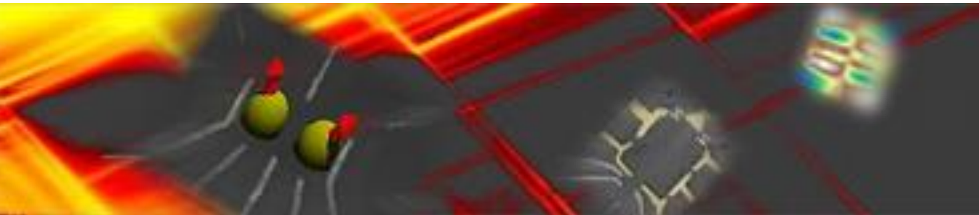

[1] N. Samkharadze *et al.*, Science (2018), DOI: 10.1126/science.aar4054

Strong Spin-Photon Coupling

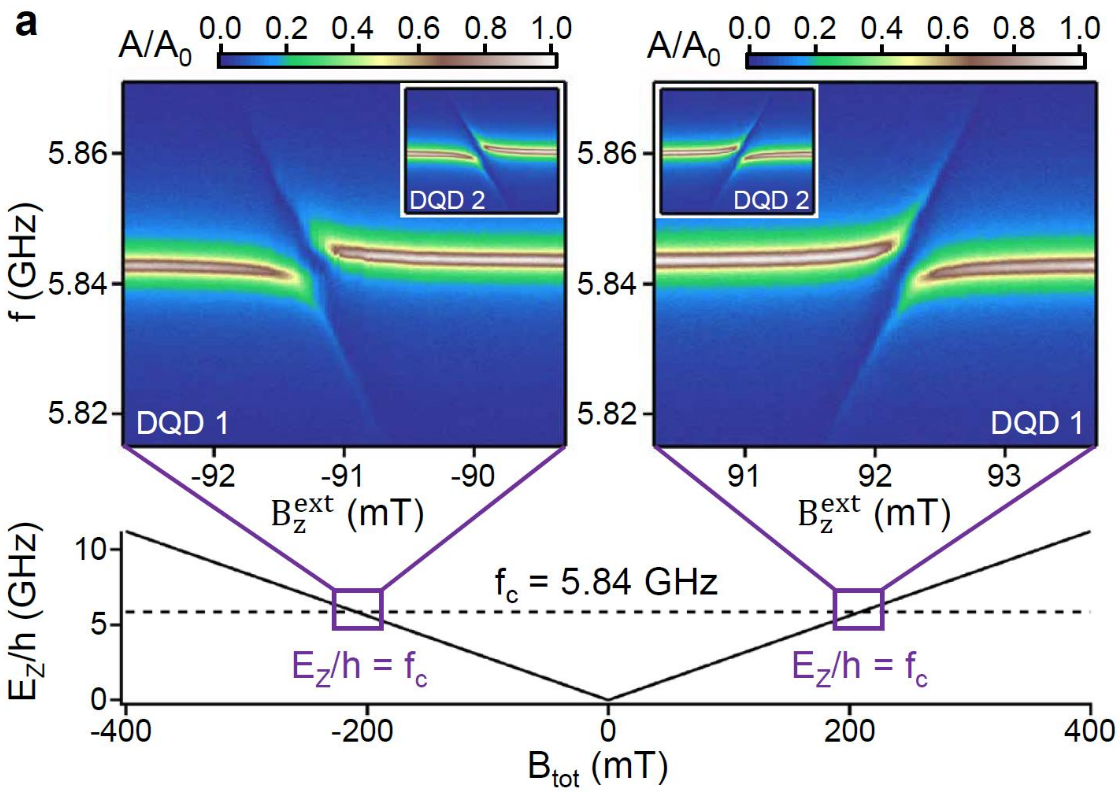

Fig: Normalized cavity transmission amplitude A/A_0 as function of the qubit Zeeman splitting

- strong coupling results in mode splitting
- coupling $g_s/2\pi$ = 5.5 MHz
- $\kappa/2\pi$ = 1.8 MHz, $\gamma_s/2\pi$ = 2.4 MHz

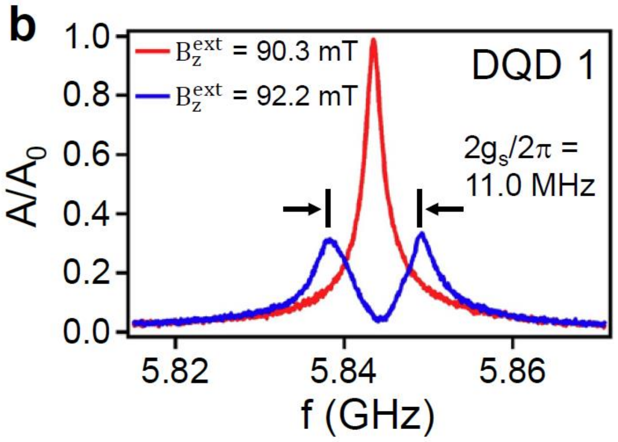

Fig: Linecut for DQD1

strong spin coupling

$$g_s > \gamma_s, \kappa$$

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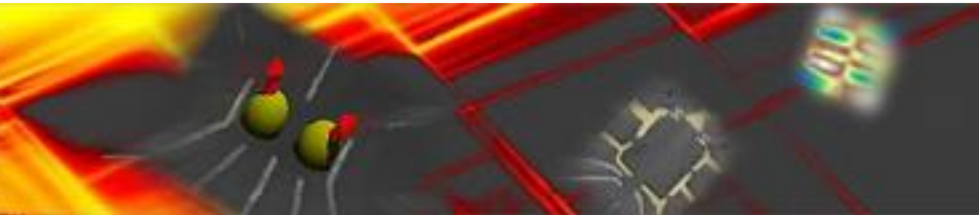
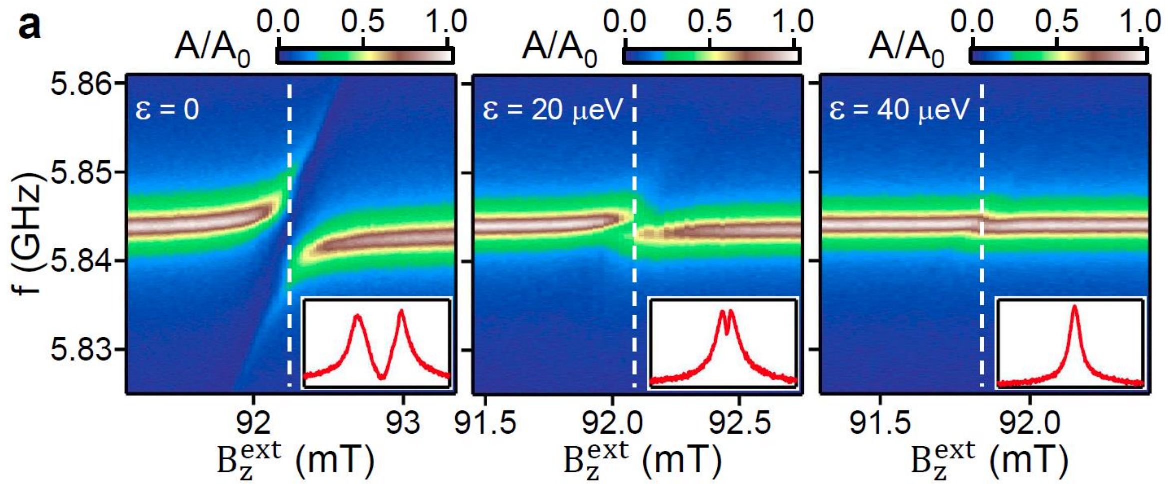


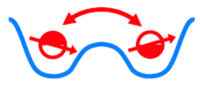
[1] N. Samkharadze *et al.*, Science (2018), DOI: 10.1126/science.aar4054

Electrical Control of Coupling – Knob 1

- charge hybridization tunes coupling strength
- **delocalized** electron forms molecular (anti)bonding states
    - large displacement by cavity electric field
    - strong spin-photon coupling

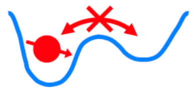


$|-\rangle, |+\rangle$



$|\varepsilon| << t_c$

$\varepsilon >> t_c$



$|L\rangle, |R\rangle$

$$g_s = \frac{g\mu_B B_x^M}{t_c} \cdot g_c \qquad g_s = \frac{g\mu_B B_x^M}{E_{Orb}} \cdot g_c$$

$$\frac{E_{Orb}}{t_c} \approx 200$$

Electrical Control of Coupling – Knob 2

- **interdot tunneling** modifies electric dipole coupling to cavity field
- spin-charge hybridization: very susceptible to charge noise, increasing γ_s

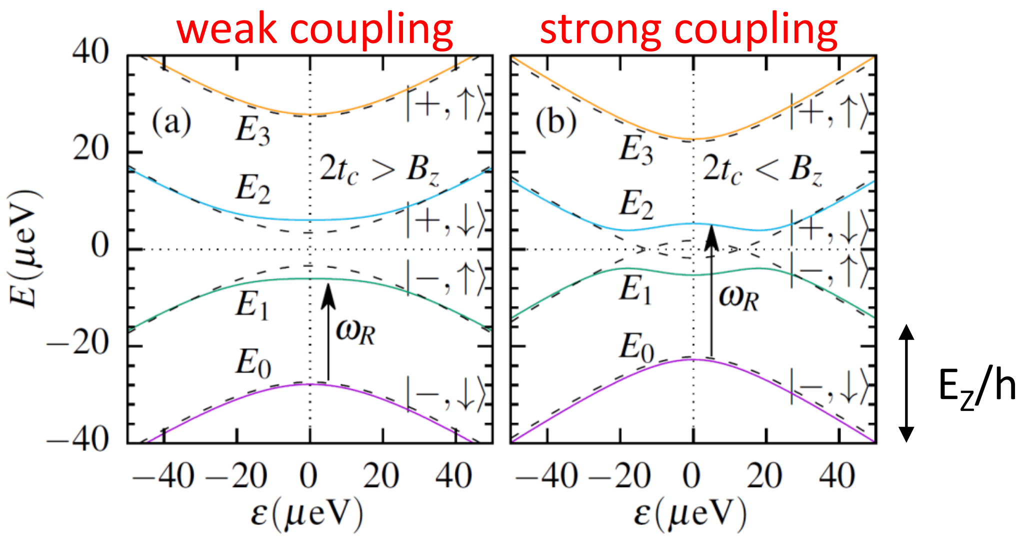


Fig: DQD energy level spectrum in the regime of weak and strong electric dipole coupling[1]

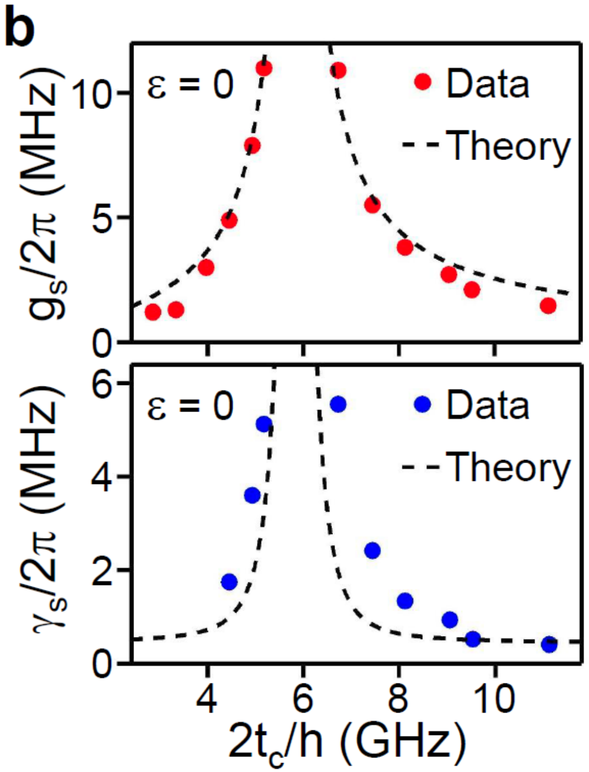


Fig: spin coupling and dephasing rates rapidly increase when interdot tunneling is approaching the Larmor precession frequency

[1] M. Benito *et al.*, arXiv:1710.02508v1

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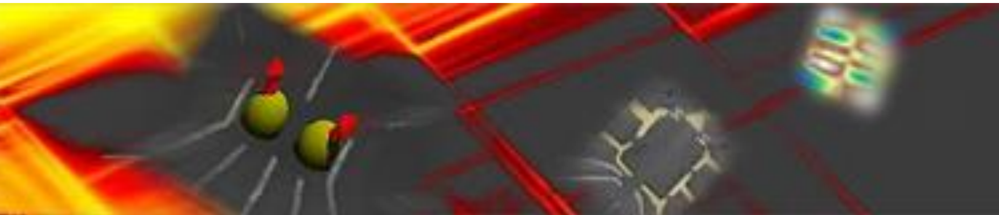

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Electron Spin Resonance

- spin state readout in dispersive regime
- phase shift in cavity transmission on resonance (Δ – qubit-cavity detuning)

$$\Delta\phi \approx \tan^{-1}\left(\frac{2g_s^2}{\kappa\Delta}\right)$$

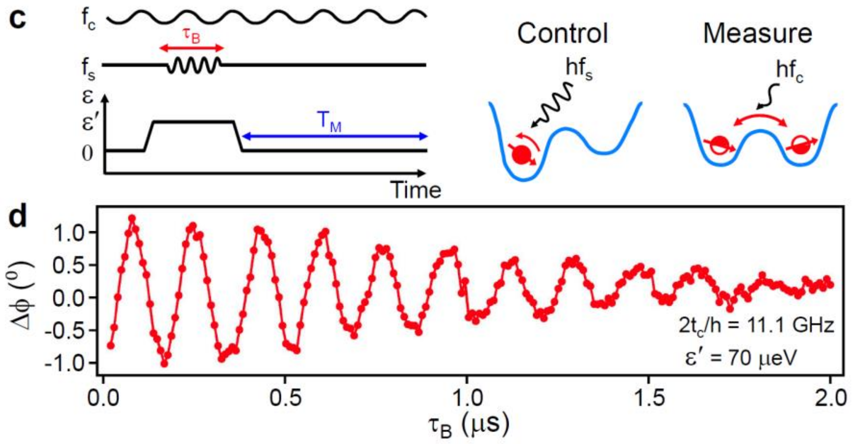


Fig: Rabi oscillations between spin-up and spin-down states as a demonstration of coherent spin control

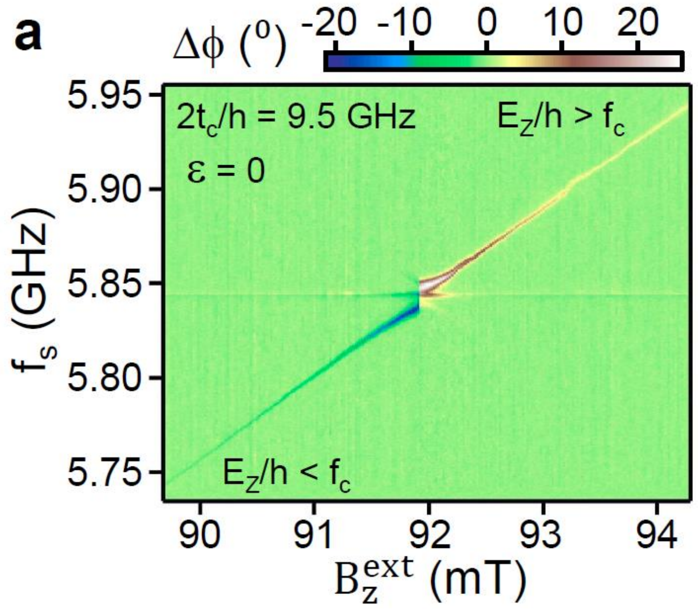


Fig: ESR signature in phase response of the cavity transmission. The change of sign reflects the sign change of the qubit-cavity detuning

Summary and Outlook

- strong coupling of single spin to microwave photon
- all electrical control of coupling and manipulation
- quantum non-demolition readout of single spin

- construction of ultra-coherent spin quantum computer
  - photonic interconnects and readout channels
  - implementation of surface code
  - all-to-all connectivity

- new advances in qubit gates[1] and quantum processors[2]

[1] D. M. Zajac *et al.*, Science **359**, 439-442 (2018)
[2] T. F. Watson *et al.*, arXiv:1708.04214, to be published in Nature

Jaynes-Cummings Model

- interaction of two-level system with resonator
- strong coupling regime: new eigenstates of the system
  - hybridized states are called „dressed states“
  - separated by (vacuum) Rabi frequency

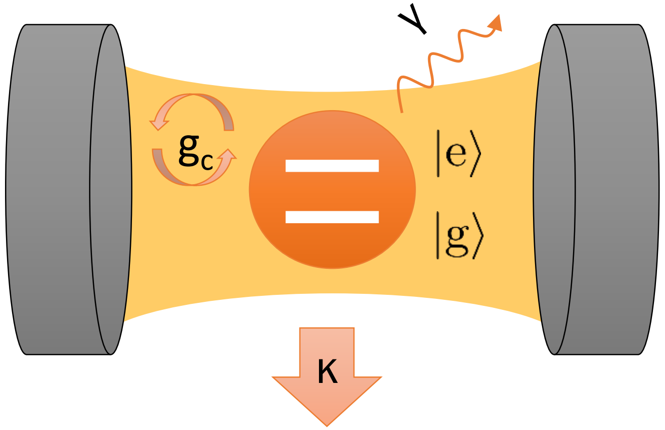


Fig: Qubit-cavity coupling scheme. gc – coupling strength, γ – qubit decoherence, κ – cavity losses

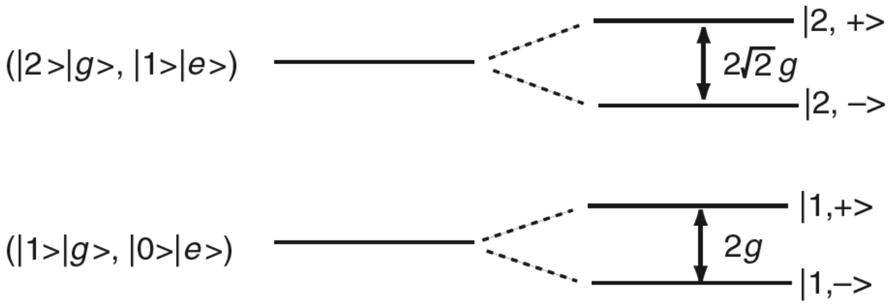
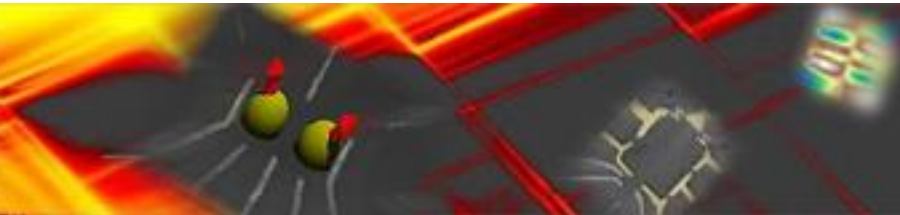


Fig: Dressed states for the energy eigenstates of the Jaynes-Cummings interaction[1]



[1] D.F. Walls, G.J. Milburn, *Quantum Optics* (Springer, 2008), Chapter 10.2