A Coherent Spin-Photon Interface in Silicon

X. Mi,¹ M. Benito,² S. Putz,¹ D. M. Zajac,¹ J. M. Taylor,³ Guido Burkard,² and J. R. Petta¹

¹Department of Physics, Princeton University, Princeton, New Jersey 08544, USA
²Department of Physics, University of Konstanz, D-78464 Konstanz, Germany
³Joint Quantum Institute/NIST, College Park, Maryland 20742, USA

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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\[^1\]

• In 2017 several groups\textsuperscript{[1,2]} reached strong charge-cavity coupling regime
  • see also FAM talk from 10.02.2017\textsuperscript{[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\textsuperscript{[4]}

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

similar work by the Vandersypen group\[1\]

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

- 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 $t_c$

**Fig:** Cavity transmission amplitude at the (0,1)$\leftrightarrow$(1,0) DQD charge transition

**Fig:** Interdot tunnel coupling as a function of middle barrier
inhomogeneous magnetic field yields spin-charge hybridization

\[
\begin{align*}
|0\rangle & \approx |-, \downarrow\rangle \\
|1\rangle & \approx \cos \frac{\phi}{2} |-, \uparrow\rangle + \sin \frac{\phi}{2} |+, \downarrow\rangle \\
|2\rangle & \approx \sin \frac{\phi}{2} |-, \uparrow\rangle - \cos \frac{\phi}{2} |+, \downarrow\rangle \\
|3\rangle & \approx |+, \uparrow\rangle
\end{align*}
\]

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

[1] M. Benito et al., arXiv:1710.02508v1
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similar work by the Vandersypen group\textsuperscript{[1]}

\textsuperscript{[1]} N. Samkharadze \textit{et al}., Science (2018), DOI: 10.1126/science.aar4054
Strong Spin-Photon Coupling

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

Fig: Linecut for DQD1

$g_s > \gamma_s, \kappa$
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]

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

\[ g_s = \frac{g \mu_B B_x^M}{t_c} \cdot g_c \quad g_s = \frac{g \mu_B B_x^M}{E_{\text{Orb}}} \cdot g_c \]

\[ \frac{E_{\text{Orb}}}{t_c} \approx 200 \]
Electrical Control of Coupling – Knob 2

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

![DQD energy level spectrum](image)

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

![Spin coupling and dephasing rates](image)

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

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• spin state readout in dispersive regime
• phase shift in cavity transmission on resonance ($\Delta$ – qubit-cavity detuning)

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

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

Fig: Rabi oscillations between spin-up and spin-down states as a demonstration of coherent spin control
• 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\(^2\)

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