# Input-output theory for spin-photon coupling in Si double quantum dots

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The interaction of qubits via microwave frequency photons enables long-distance qubit-qubit coupling and facilitates the realization of a large-scale quantum processor. In various current devices, strong-coupling to a single photon has been demonstrated for superconducting qubits and semiconductor charge qubits. Although qubits based on electron spins in semiconductor quantum dots exhibit longer relevant coherence times for quantum applications, they have proven challenging to couple to microwave photons due to small dipole moments.

In this theoretical work [1] we show that a sizable coupling for a single electron spin is possible via spin-charge hybridization using a magnetic field gradient in a silicon double quantum dot. Our analysis of the hybrid system consisting of a double quantum dot coupled to a microwave cavity confirms that, with the recent advances in silicon double quantum dots fabrication and control, spin-photon coupling with a sufficiently low spin decoherence rate is achievable with this setup, potentially allowing the strong-coupling regime.

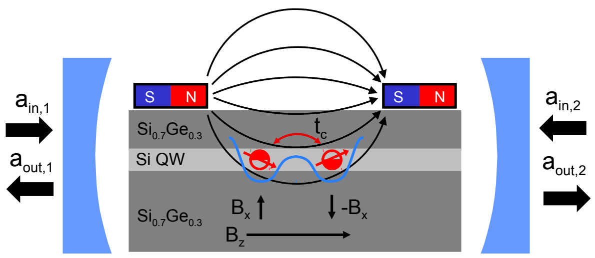


Figure 1: Schematic illustration of the Si gate-defined double quantum dot influenced by a homogeneous external magnetic field, $B_z$, and the inhomogeneous perpendicular magnetic field created by a micromagnet, with opposite direction at the positions of the two quantum dots, $\pm B_x$. The double quantum dot is electric-dipole-coupled to the microwave cavity represented in blue. The cavity field is excited at the left and right ports via $a_{\mathrm{in},1}$ and $a_{\mathrm{in},2}$, and the output can be measured either at the left ($a_{\mathrm{out},1}$) or right port ($a_{\mathrm{out},2}$).

Based on parameters already shown in recent experiments, we predict optimal working points to achieve a coherent spin-photon coupling, an essential ingredient for the generation of long-range entanglement. Our predictions are in good agreement with recent measurements [2] which demonstrate strong coupling with spin-photon coupling rates of more than $10\,\mathrm{MHz}$. These results open a direct path towards entangling single spins using microwave frequency photons. Furthermore, we employ input-output theory to identify observable signatures of spin-photon coupling in the cavity output field, which can provide guidance to the experimental search for strong coupling in such spin-photon systems and opens the way to cavity-based readout of the spin qubit.

The physical system consists of a gate-defined Si double quantum dot that is embedded in a superconducting cavity; see Fig. 1. The electric-dipole interaction couples the electronic charge states in the double quantum dot to the cavity electric field. The introduction of an inhomogeneous magnetic field, as sketched in Fig. 1, hybridizes the charge states of a double quantum dot electron with its spin states, indirectly coupling the cavity electric field to the electron spin. The cavity is driven by a coherent microwave tone and the strong coupling between a single electron spin and a single photon is evidenced by the observation of two "vacuum-Rabi-split" peaks in the cavity transmission.

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

[2] X. Mi, M. Benito, S. Putz, D. M. Zajac, J. M. Taylor, Guido Burkard, and J. R. Petta, *A Coherent Spin-Photon Interface in Silicon*, arXiv:1710.03265