Virtual-photon-mediated spin-qubit–transmon coupling

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Spin qubits and superconducting qubits are among the promising candidates for realizing a solid state quantum computer. For the implementation of a hybrid architecture which can profit from the advantages of either approach, a coherent link is necessary that integrates and controllably couples both qubit types on the same chip over a distance that is several orders of magnitude longer than the physical size of the spin qubit. We realize such a link with a frequency-tunable high impedance SQUID array resonator. The spin qubit is a resonant exchange qubit hosted in a GaAs triple quantum dot. It can be operated at zero magnetic field, allowing it to coexist with superconducting qubits on the same chip. We spectroscopically observe coherent interaction between the resonant exchange qubit and a transmon qubit in both resonant and dispersive regimes, where the interaction is mediated either by real or virtual resonator photons.
A future quantum processor will benefit from the advantages of different qubit implementations. Two prominent workhorses of solid state qubit implementations are spin- and superconducting qubits. While spin qubits have a high anharmonicity, a small footprint and promise long coherence times, superconducting qubits allow fast and high fidelity readout and control. A coherent link, which couples both qubit systems controllably over distances exceeding the physical size of the spin qubit, typically hundreds of nanometers, by several orders of magnitude is required to create an integrated scalable quantum device. An architecture to provide such a link is circuit quantum electrodynamics (circuit QED), where microwave photons confined in a superconducting resonator couple coherently to the qubits. Circuit QED was initially developed for superconducting qubits, where long-distance coupling enables two-qubit gate operations. Recently, coherent qubit-photon coupling was demonstrated for spin qubits in few electron quantum dots. However, coupling a spin qubit to another distant qubit has not yet been shown. One major challenge for an interface between spin and superconducting qubits is that spin qubits typically require large magnetic fields, to which superconductors are not resilient.

We overcome this challenge by using a spin qubit which relaxes on exchange interaction. This resonant exchange (RX) qubit is formed by three electrons in a GaAs triple quantum dot (TQD). We implement the qubit at zero magnetic field without reducing its coherence compared to earlier measurements at finite magnetic field. The quantum link is realized with a frequency-tunable high impedance SQUID array resonator, which couples the RX and the superconducting qubit coherently over a distance of a few hundred micrometers. The RX qubit coupling strength to the resonator and its decoherence rate are tunable electrically. We find that their ratio is comparable to previously reported values for spin qubits in Si. We demonstrate coherent coupling between the two qubits first by resonant and then by virtual photon exchange in the high impedance resonator. We electrostatically tune the RX qubit to different regimes, where the qubit states have either a dominant spin or charge character.

**Results**

**Sample and qubit characterization.** The design of our sample is illustrated schematically in Fig. 1a. It is similar to ref. 29, where a semiconductor charge qubit was used instead of a spin qubit. An optical micrograph can be found in the Methods section. The superconducting qubit we use is a transmon as its Josephson energy exceeds the charging energy by about two orders of magnitude (see characterization below). The transmon consists of an Al SQUID grounded on one side and connected in parallel to a shunt capacitor. We tune the transition frequency $\nu_T$ between the transmon ground state and first excited state by changing the flux $\Phi_T$ through the SQUID loop with an on-chip flux line.

The transmon and the RX qubit are capacitively coupled to the same end of a SQUID array resonator, which we denote as coupling resonator in the following, with electric dipole coupling strengths $g_T$ and $g_{RX}$. The other end of the coupling resonator is connected to DC ground. It is fabricated as an array of Al SQUID loops, which enables the tuning of its resonance frequency $\nu_C$ from $4 - 7$ GHz within the detection bandwidth of our measurement setup with a magnetic flux $\Phi_C$ produced by a coil mounted close to the sample. In addition, the resonator has a high characteristic impedance that enhances its coupling strength to both qubits (see Supplementary Note 1). The transmon flux $\Phi_T$ has a negligible effect on $\nu_C$.

The transmon is also capacitively coupled to a 50 $\Omega$/2 coplanar waveguide resonator with a coupling strength $g_{RX}/2\pi \approx 141$ MHz. Throughout this article, we refer to this resonator as the read-out resonator, because it allows us to independently probe the transmon without populating the coupling resonator with photons. The read-out resonator has a bare resonance frequency $\nu_R = 5.62$ GHz and a total photon decay rate $\kappa_R/2\pi = 5.3$ MHz. As illustrated in Fig. 1a, the coupling and the read-out resonator are probed by measuring the reflection of a multiplexed probe tone at frequency $\nu_p$. In addition, we can apply a drive tone at frequency $\nu_d$ that couples to both qubits via the resonators. For the experiments presented in this work, the probe tone power is kept sufficiently low for the estimated average number of photons in both resonators to be less than one.

In Fig. 1b we characterize the transmon with two-tone spectroscopy. The first tone probes the read-out resonator on resonance ($\nu_p = \nu_R$), while the second tone is a drive at frequency $\nu_d$ that is swept to probe the transmon resonance. Once $\nu_d = \nu_R$, the transmon is driven to a mixed state, which is observed as a change in the resonance frequency of the dispersively coupled read-out resonator. This frequency shift is detected with a standard heterodyne detection scheme as a change in the complex amplitude $A = I + iQ$ of the signal reflected from the resonator. In Fig. 1b, centered at $\nu_d = \nu_R(\nu_F)$, we observe a peak in $|A - A_0|$. Here, $A_0$ is the complex amplitude in the absence of the second (drive) tone. From a fit of the transmon dispersion to the multi-level Jaynes-Cummings model and by including the position of higher excited states of the transmon probed by two photon transitions (not shown), we obtain the maximum Josephson energy $E_{J,max} = 18.09$ GHz and the transmon charging energy $E_C = 0.22$ GHz (for details see Supplementary Note 2). Note that the parameters for all theory fits in this article can be found in Supplementary Note 4.

At a distance of a few hundred micrometers from the transmon SQUID, we form a TQD by locally depleting a two-dimensional electron gas in a GaAs/AlGaAs heterostructure with the Al top gate electrodes shown in Fig. 1c. One of the electrodes extends to the coupling resonator to enable electric dipole interaction between photons and TQD states. Another electrode allows us to apply RF signals at frequency $\nu_{dRX}$. We use a QPC charge detector to help tune the TQD to the three electron regime. The symmetric $(1,1,1)$ and the asymmetric $(2,0,1)$ and $(1,0,2)$ charge configurations are relevant for the RX qubit as they are lowest in energy. We sweep combinations of voltages on the TQD gate electrodes to set the energy of the asymmetric configurations equal and control the energy detuning $\Delta$ of the symmetric configuration with respect to the asymmetric ones (see Fig. 1d).

There are two spin states within $(1,1,1)$ that have $S = S_z = 1/2$ equal to the spin of two states with asymmetric charge configuration, which form a singlet in the doubly occupied dot. An equivalent set of states with $S = 1/2, S_z = -1/2$ exists. As the resonator response is identical for both sets of states, considering only one is sufficient (see Supplementary Note 3 for a detailed discussion). This results in a total of four relevant states for the qubit11. The tunnel coupling $t_f \ (t_c)$ between the left (right) quantum dot and the middle quantum dot hybridizes these states, which leads to the formation of the two RX qubit states $|0_{RX}\rangle$ and $|1_{RX}\rangle$. For $\Delta < 0$, $|0_{RX}\rangle$ and $|1_{RX}\rangle$ have predominantly the $(1,1,1)$ charge configuration but different spin arrangement. Consequently, with increasingly negative $\Delta$, the spin character of the qubit increases, which reduces the qubit dephasing due to charge noise. This comes at the cost of a reduced admixture of asymmetric charge states and therefore a decrease in the electric dipole coupling strength $g_{RX}$. In contrast, for $\Delta > 0$ the RX qubit states have dominantly the asymmetric charge configurations $(2,0,1)$ and $(1,0,2)$. The qubit therefore has a dominant charge...
character, which increases, together with $g_{RX}$, with increasing positive $\Delta$. Independent of $\Delta$, the RX qubit states have the same total spin and spin $z$-component such that they can be driven directly by electric fields and be operated in the absence of an applied external magnetic field. This is in contrast to other spin qubit implementations, which rely on engineered or intrinsic spin-orbit interaction for spin-charge coupling.

Four similar RX qubit tunnel coupling configurations were used in this work as listed in the Methods section. We use two-tone spectroscopy to characterize the RX qubit dispersion: we apply a probe tone on resonance with the coupling resonator, drive the qubit via the gate line and tune its energy with $\Delta$. The spectroscopic signal in Fig. 1e agrees with the theoretically expected qubit dispersion for qubit tunnel coupling configuration 3 (see the Methods section).

**Resonant interaction.** First, we investigate the resonant interaction between the coupling resonator and the RX qubit. To start with, both qubits are detuned from the coupling resonator. Then, we sweep $\Delta$ to cross a resonance between the RX qubit and the coupling resonator. We observe a three similar RX qubit tunnel coupling configuration 3 (see the Methods section).

We now demonstrate that the two qubits interact coherently via resonant interaction with the coupling resonator. For this purpose, we first tune the transmon and the coupling resonator into resonance, where the hybrid system forms the superposition states $|\pm\rangle = (|0_T, 1_C\rangle \pm |1_T, 0_C\rangle)/\sqrt{2}$ of a single excitation in either the resonator or the qubit. Then, we sweep $\Delta$ to tune the RX qubit through a resonance with both the lower energy state $|\pm\rangle$ and the higher energy state $|+\rangle$. In the $|S_{11}\rangle$ spectrum in optimized TQD gate design with an increased overlap of the resonator gate with the underlying quantum dot. The spin qubit and the coupling resonator photons are strongly coupled since $g_{RX} > \kappa_C, Y_{2,RX}$, with the RX qubit decoherence rate $Y_{2,RX}/2\pi = 11$ MHz and the bare coupling resonator linewidth $\kappa_C/2\pi = 4.6$ MHz. The decoherence rate is determined independently with power dependent two-tone spectroscopy. We disperse detune the coupling resonator with $\Phi_C$ from the RX qubit and extrapolate the width of the peak observed in the two-tone spectroscopy response (c.f. Fig. 1e) to zero drive power.

Next, we characterize the interaction between the transmon and the coupling resonator. We tune the transmon through the resonator resonance by sweeping $\Phi_T$. For this measurement, the RX qubit is far detuned in energy. We resolve the hybridized states of the transmon and the resonator photons in the measured $|S_{11}\rangle$ spectrum in Fig. 2b. They are separated in energy by the vacuum Rabi mode splitting $2g_T/2\pi = 360$ MHz illustrated in Fig. 2c. In green, we perform power dependent two-tone spectroscopy to extract the transmon linewidth by probing the read-out resonator. We obtain $Y_{2,T}/2\pi = 0.7$ MHz, which we estimate to be limited by Purcell decay. Consequently, the strong coupling limit $g_T > \kappa_C, Y_{2,T}$ is also realized for transmon and coupling resonator.
Fig. 2 Resonant interaction. The schematics at the top of the graphs indicate the energy levels of the RX qubit ($\nu_{\text{RX}}$), coupling resonator ($\nu_{\text{C}}$), and transmon ($\nu_{\text{T}}$). Theory curves in the absence (presence) of coupling are shown as dashed black (red) lines. a Reflected amplitude $|S_{\text{RX}}|$ as a function of RX detuning $\Delta$ and probe frequency $\nu_p$ for RX qubit tunnel coupling configuration 2. b Reflected amplitude $|S_{\text{RX}}|$ as a function of relative transmon (Tmon) flux $\Phi_{\text{T}}/\Phi_0$ and $\nu_p$. The states $|\pm\rangle$ are discussed in the main text. c Cuts from panel a at $\Delta/h \approx -7.6$ GHz (black) and from panel b at $\Phi_{\text{T}}/\Phi_0 \approx 0.3$ (green) as marked with arrows in the respective panels. The black trace is offset in $|S_{\text{RX}}|$ by 0.1. Theory fits are shown as red dashed lines. d $|S_{\text{RX}}|$ as a function of $\Delta$ and $\nu_p$ for RX qubit tunnel coupling configuration 2. The states $|\pm\rangle$ are discussed in the main text. The black and blue arrows are referred to in f, the purple arrow is discussed in the text. e Result of master equation simulation for parameters in d. The values for $|S_{\text{RX}}|$ are scaled to the experimental data range in d. f $|S_{\text{RX}}(\nu_p)|$ at $\Delta/h \approx -9.8$ GHz and $\Delta/h \approx -5.6$ GHz as marked with the corresponding colored arrows in panels d, e. The blue trace is offset in $|S_{\text{RX}}|$ by 0.2.

Fig. 2d, avoided crossings are visible at both resonance points. This indicates the coherent interaction of the three quantum systems which form the states $|\pm\rangle$. The second label indicates a symmetric or antisymmetric superposition of the RX qubit state with the transmon-resonator $|\pm\rangle$ states. The splitting $2g_{\text{p}}$ between $|\pm\rangle$ and $|\mp\rangle$ is extracted from the $|S_{\text{RX}}|$ reflection measurements in Fig. 2f. We obtain $2g_{\text{p}}/2\pi = 84$ MHz at $\Delta/h \approx -5.6$ GHz and $2g_{\text{p}}/2\pi = 63$ MHz at $\Delta/h \approx -9.8$ GHz. The fits in Fig. 2f. The smaller $g_{\text{p}}$ compared to $g_{\text{r}}$ is due to the decrease of the RX qubit dipole moment with more negative $\Delta$. The RX qubit, the transmon and the resonator are on resonance ($\nu_{\text{RX}} = \nu_{\text{T}} = \nu_{\text{C}}$) between the avoided crossings in Fig. 2d at $\Delta/h \approx -7.8$ GHz (see purple arrow). There, the splitting of the dips in the reflection spectrum is enhanced by $\approx 16$ MHz compared to the off-resonant splitting of $|\pm\rangle$ at $\Delta/h \approx -11.4$ GHz in Fig. 2d (see Supplementary Note 1). This enhancement is an experimental signature of the coherent resonant interaction of all three quantum systems in good agreement with the theoretical value $2g_{\text{p}} = 2\sqrt{g_{\text{T}}^2 + g_{\text{RX}}^2}/2\pi \approx 15$ MHz calculated from independently extracted parameters.

The experimental observation in Fig. 2d is well reproduced by a quantum master equation simulation shown in Fig. 2e and further discussed in Supplementary Note 2.

**RX qubit optimal working point.** While $g_{\text{RX}}/\nu_{\text{RX}}$ is limited by Purcell decay and therefore does not depend on $\Phi_{\text{T}}$, $g_{\text{RX}}/\nu_{\text{RX}}$ changes with $\Delta$. For obtaining the data shown in Fig. 3a, we use power dependent two-tone spectroscopy via the coupling resonator to measure $g_{\text{RX}}/\nu_{\text{RX}}$ as a function of $\Delta$. We observe an increase of $g_{\text{RX}}/\nu_{\text{RX}}$ as the charge character of the qubit is increased with $\Delta$. Compared to ref. 15, the data in Fig. 3a covers a larger range in $\Delta$, in particular for $|\Delta| > t_{1\text{r}}^\pi$. The data suggests a lower limit of $g_{\text{RX}}/\nu_{\text{RX}} = 6.5$ MHz for $\Delta \leq 0$. This is in agreement with refs. 44 and 15, where the RX qubit was operated at a finite magnetic field of a few hundred mT. Hence, our experiment indicates that the RX qubit can be operated near zero magnetic field without reducing its optimal coherence. In our experiment, the maximum external magnetic field determined by $\Phi_{\text{T}}$ is of the order of 1 mT. To model the RX qubit decoherence in Fig. 3a, we consider an ohmic spectral density for the charge noise as well as the hyperfine field of the qubit host material that acts on the spin part of the qubit (see Supplementary Notes 2 and 3). Theory and experiment in Fig. 3a match for a width $\sigma_p = 3.48$ MHz of the hyperfine fluctuations in agreement with other work on spin in GaAs.45-47 This suggests that $g_{\text{RX}}/\nu_{\text{RX}}$ is limited by hyperfine interactions.

The colored data points in Fig. 3a were measured for a smaller RX-qubit-coupling resonator detuning compared to the black data points (numbers are given in Fig. 3 caption). The smaller detuning is used for the virtual interaction measurements discussed below. We observe an increase of $g_{\text{RX}}/\nu_{\text{RX}}$ for small qubit-resonator detuning compared to large detuning. This increase is about one order of magnitude larger than our estimated difference of Purcell decay and measurement induced dephasing for those different data sets (see Supplementary Note 4). In contrast, for the transmon that is insensitive to charge noise, we do not observe this effect. This suggests that the effect is due to charge noise induced by the coupling resonator.

As $g_{\text{RX}}/\nu_{\text{RX}}$ increases with $\Delta$ in Fig. 3a, the RX qubit coupling strength $g_{\text{RX}}/\nu_{\text{RX}}$ to the coupling resonator increases. This implies the existence of an optimal working point for the RX qubit, where $g_{\text{RX}}/\nu_{\text{RX}}$ is maximal. While a distinct optimal point is not discernable for the black data points in Fig. 3b, the averaged value of $g_{\text{RX}}/\nu_{\text{RX}} \approx 9$ in the spin dominated regime for $-6 < \Delta/h < 0$ GHz is about a factor of 1.7 larger than values reported so far for Si spin qubits3,14. In contrast, for the colored data points we observe an optimal working point at $\Delta/h \approx -3.3$ GHz since $g_{\text{RX}}/\nu_{\text{RX}}$ is reduced at small qubit-resonator detuning in Fig. 3b compared to the black data points at large detuning due to the influence of the coupling resonator on $g_{\text{RX}}/\nu_{\text{RX}}$ discussed above.

Virtual photon coupling. In the following, we investigate the RX-qubit-transmon interaction mediated by virtual photons in the coupling resonator at the RX qubit working points marked in color in Fig. 3a. The two qubits are resonant while the coupling resonator is energetically detuned, such that the photon excitation is not dominant in the superposed two-qubit eigenstates. This coupling scheme, illustrated in Fig. 3c, is typically used for superconducting qubits to realize two-qubit operations12. We measure the virtual coupling at the optimal working point ($\Delta/h \approx -3.3$ GHz), at $\Delta/h \approx -9.9$ GHz and at $\Delta/h \approx 10.2$ GHz, where $g_{\text{RX}}/\nu_{\text{RX}}$ in Fig. 3a saturates, as well as in the intermediate regime at $\Delta/h \approx 3.4$ GHz. While the RX qubit is tuned through a resonance with the transmon by changing $\Delta$, they are both detuned by $\Delta_C \equiv \nu_C - \nu_T \approx 3g_{\text{C}}$ from the coupling resonator. To realize this detuning for every working point, we adjust the qubit and resonator energies with $\Phi_{\text{T}}$, $t_{1\text{r}}$, $\nu_{\text{T}}$, $\nu_{\text{C}}$, and $\nu_{\text{RX}}$. The resulting avoided crossings at $\Delta_{\text{res}}$ for both resonators are shown in Fig. 3d. The avoided crossing at $\Delta_{\text{res}} = 0$ is maximal. While a distinct optimal point is not discernable for the black data points in Fig. 3d, the averaged value of $g_{\text{RX}}/\nu_{\text{RX}} \approx 9$ in the spin dominated regime for $-6 < \Delta/h < 0$ GHz is about a factor of 1.7 larger than values reported so far for Si spin qubits3,14. In contrast, for the colored data points we observe an optimal working point at $\Delta/h \approx -3.3$ GHz since $g_{\text{RX}}/\nu_{\text{RX}}$ is reduced at small qubit-resonator detuning in Fig. 3d compared to the black data points at large detuning due to the influence of the coupling resonator on $g_{\text{RX}}$ discussed above.
and $\Phi_C$. We drive the RX qubit at frequency $\nu_{\text{RX}}$ (see Fig. 1a) and investigate its coupling to the transmon by probing the dispersively coupled read-out resonator at its resonance frequency ($\nu_R = \nu_T \approx 5.6$ GHz). This measurement is shown in Fig. 3d for the working point at $\Delta/h \approx -9.9$ GHz. For large transmon-spin qubit detuning ($\Delta/h < -10$ GHz), the spectroscopic signal of the transmon is barely visible as the drive mainly excites the bare RX qubit. The signal increases with $\Delta$ as the RX qubit approaches resonance with the transmon, such that driving the RX qubit also excites the transmon due to their increasing mutual hybridization. On resonance, we resolve the two hybridized spin-qubit-transmon states $|\pm\rangle_C \approx (|0_{\text{RX}}, 1_T\rangle \pm |1_{\text{RX}}, 0_T\rangle)/\sqrt{2}$ by a line width. These states are separated in energy by the virtual-photon-mediated exchange splitting $2J \approx 2\xi_{\text{RX}}g_T/\Delta_C$. The splitting is enhanced at the other working points in Fig. 3e–g, for which the RX qubit control parameter $\Delta$ and consequently $\xi_{\text{RX}}$ is larger. The result of a master equation simulation shown in Fig. 3e agrees well with the experimental observation. The influence of the RX qubit decoherence rate $\gamma_{2,RX}$ on the virtual interaction measurement is quantified in Fig. 3h, where we show averaged measurements of the two-tone spectroscopy signal from Fig. 3d–g at $\Delta$ as indicated by arrows in the corresponding panels. The fits of a master equation model in Fig. 3h show excellent quantitative agreement with the experimental curves. As discussed in detail in Supplementary Note 3, fit parameters previously obtained from Fig. 2 were adjusted to account for significant power broadening in these measurements. The exchange splitting is best resolved at the optimal working point, corresponding to the solid green curve in Fig. 3h, where we obtain $2J/2\pi \approx 32$ MHz from the fit.

**Discussion**

In conclusion, we have implemented a coherent link between an RX qubit and a transmon. The link either utilizes real or virtual microwave photons for the qubit–qubit interaction. The RX qubit was operated in both spin and charge dominated regimes. We found an optimal working point at which the ratio between its resonator coupling and its decoherence rate is maximal and comparable to state of the art values achieved with spin qubits in Si. We also reported that the coupling resonator potentially introduces charge noise that can have significant impact on the RX qubit coherence. The performance of the quantum link in this work is limited by the minimum decoherence rate of the qubit, which is determined by hyperfine interaction in the GaAs host material. Once the spin coherence is enhanced by using hyperfine free material systems such as graphene, it is also possible to couple a gate pulse to the tunable coupling resonator.
the coherence properties of the RX qubit are retained at zero magnetic field in contrast to other spin qubit implementations, the quantum device architecture used in this work is compatible for realizing a high-fidelity transmon–spin-qubit and spin-qubit–spin-qubit interface in a future quantum processor.

Methods
RX qubit tunnel coupling configurations. Throughout this work, we use the four RX qubit tunnel coupling configurations listed in Table 1. The measurements to extract the tunnel couplings are explained in Supplementary Note 1. Different configurations were necessary for two reasons. To realize the virtual interaction scheme in Fig. 3c for different RX qubit working points while keeping the same transmon flux, the tunnel couplings had to be adjusted. The current in the transmon flux line was kept below a level at which an increase in the refrigerator temperature was observed. This ensured that the device operation took place at the lowest accessible measurement temperature. Second, when readjusting the RX qubit after a random charge rearrangement occurred in the host material, which was observed on the time scale of days, identical tunnel coupling configurations could not be achieved.

Details of sample and measurement scheme. In Fig. 4a we show a false-colored optical micrograph of the part of the sample that was illustrated schematically in Fig. 1a. The microwave read-out scheme is also indicated. The sample is measured in a dilution refrigerator with a base temperature of 10 mK. The four quantum systems are highlighted in different colors. A magnified image of the transmon is shown in Fig. 4b. One side of the SQUID loop is grounded, the other is connected to a big shunt capacitor (highlighted in green). We control the transmon transition frequency with a current I through an inductively coupled flux line. The transmon is capacitively coupled to one end of a λ/2 50 Ω (read-out) resonator, which is shown to the full extent in Fig. 4c. It is capacitively coupled to a transmission line that is used for resonator read-out.

Data availability
The data of this study are available from the corresponding author on reasonable request.

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Table 1 Tunnel couplings

| RX qubit config. | t_i/ℏ (GHz) | t_j/ℏ (GHz) |
|------------------|-------------|-------------|
| 1                | 9.91        | 8.26        |
| 2                | 9.22        | 8.73        |
| 3                | 8.52        | 8.18        |
| 4                | 8.80        | 8.77        |

RX qubit tunnel coupling configurations used in this work

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Author contributions

A.J.L., J.V.K. and P.S. fabricated the sample. A.J.L. and J.V.K. performed the measurements with input from B.K. A.J.L. analyzed the data. A.J.L., C.M. and J.C.A.U. wrote the paper with input from all authors. C.B. grew the heterostructure under the supervision of W.W. C.M. developed the circuit QED theory. J.C.A.U. derived the hyperfine noise model under the supervision of S.N.C. and M.F. A.W., T.I. and K.E. supervised the experiment.

Competing interests

The authors declare no competing interests.

Additional information

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