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ABSTRACT

In gate-based dispersive sensing, the response of a resonator attached to a quantum dot gate is detected by a reflected radio frequency signal. This enables fast readout of spin qubits and tune up of arrays of quantum dots but comes at the expense of increased susceptibility to crosstalk, as the resonator can amplify spurious signals and induce fluctuations in the quantum dot potential. We attach tank circuits with superconducting NbN inductors and internal quality factors \( Q_i > 1000 \) to the interdot barrier gate of silicon double quantum dot devices. Measuring the interdot transition in transport, we quantify radio frequency crosstalk that results in a ring-up of the resonator when neighboring plunger gates are driven with frequency components matching the resonator frequency. This effect complicates qubit operation and scales with the loaded quality factor of the resonator, the mutual capacitance between device gate electrodes, and with the inverse of the parasitic capacitance to ground. Setting qubit frequencies below the resonator frequency is expected to substantially suppress this type of crosstalk.

High-bandwidth readout of spin qubits can be achieved by radio frequency (RF) reflectometry, where an RF signal is reflected off a resonator that is either connected directly to a gate of the quantum dot (QD) that defines the spin qubit or to additional QDs that serve as charge sensors.\(^1\)\(^-\)\(^8\) The former approach is known as gate-based sensing and avoids the additional footprint of the charge sensors and the necessary leads connected to them.\(^4\)\(^-\)\(^8\) Rather than detecting the absolute charge state of the spin qubit system, this method detects charge susceptibility in the form of a quantum capacitance.\(^7\) Pauli spin blockade leads to a spin-dependent tunneling between two neighboring QDs, which is seen as a variation in the resonator load capacitance,\(^10\) thereby enabling the readout of spin states.

The sensitivity of gate-based dispersive readout can be improved by increasing the internal quality factor \( Q_i \) and reducing the parasitic capacitance \( C_p \) of the resonator.\(^11\) Both can be achieved by using a superconducting inductor fabricated from a thin film of a high-kinetic inductance material such as NbN, which also enables a small resonator footprint and is compatible with the magnetic fields necessary for spin qubit operation.\(^11\)\(^-\)\(^15\)

In this work, we show that attaching a high-quality factor resonator to the gate of a spin qubit device drastically increases the sensitivity of that gate to crosstalk with control pulses applied to neighboring gates, e.g., to manipulate the spin state via electric-dipole spin resonance (EDSR).\(^16\)\(^-\)\(^22\) We introduce a method of quantifying such AC crosstalk in a dispersive readout setup and apply it to a double QD in a Si fin field-effect transistor (finFET) device with a tank circuit connected to the barrier gate. The tank circuit is composed of a high-kinetic-inductance NbN nanowire, providing a high \( Q_i \approx 1500 \) and a low \( C_p \). The resonator is excited whenever control pulses on neighboring gate lines spectrally overlap with its resonance frequency, giving rise to a strongly amplified modulation of the barrier gate and thereby of the double-QD confinement potential. The amplitude of the crosstalk voltage induced on the barrier gate is measured in transport by analyzing the corresponding broadening of an interdot charge transition line. This provides an efficient way of characterizing AC crosstalk on the device level that does not rely on the tune-up and calibration of qubits.\(^23\)\(^-\)\(^26\)

In addition to unintentional driving of neighboring qubits,\(^27\) this ring-up may induce an oscillatory exchange coupling or a modulation...
of the qubit quantization axis in systems with strong spin–orbit interaction (SOI), intrinsic to holes in Si16,19 and Ge22,23, which possess highly anisotropic electric-field dependent g-tensors.29–31 This will lead to an unintentional and non-trivial unitary evolution of the qubits, which would be difficult to calibrate away for qubit operations.

We find that in our device, the main contribution to this type of crosstalk comes from capacitance between the bondpads of neighboring gate electrodes. Our electrical circuit model predicts that the crosstalk scales proportionally with the loaded quality factor \(Q_l\) and with the ratio between the crosstalk capacitance \(C_{ct}\) and \(C_p\). Above the resonator frequency \(f_r\), the crosstalk induced on the barrier gate saturates at a value of \(C_{ct}/C_p\), whereas for frequencies below \(f_r\), it is suppressed. These findings can aid in the design of spin qubit architectures with gate-based readout.

The QD devices consist of a fin patterned from bulk silicon, along with two gate layers each consisting of a silicon-oxide dielectric and a TiN gate metal patterned in a self-aligned process.32 For the first device (device A), a double QD is formed by accumulating holes underneath gates P1 and P2 in the second gate layer (GL2), while the tunnel coupling between the dots is tuned by the barrier gate B in the first-gate layer (GL1), see Fig. 1(a). Lead gates LL and LR (GL1) are used to accumulate charge reservoirs, which are tunnel coupled to the respective dots and contacted to source and drain contacts made of PtSi. All gates and the contacts are connected to tungsten bondpads through vias in a silicon-oxide encapsulation layer. Devices similar to the ones used here have been shown to host hole spin qubits with operation of both single- and two-qubit gates.16,33

High-kinetic-inductance superconducting nanowire inductors with a wire width of 400 nm are fabricated by dry etching a \(\sim 12\) nm thick film of NbN exhibiting a nominal sheet inductance of 66 \(\mu\)H per square, deposited on an intrinsic silicon substrate by DC magnetron sputtering. A scanning electron microscopy image of a typical inductor is shown in Fig. 1(d). One end of such an inductor with a nominal inductance of 1.5 \(\mu\)H was connected to the barrier gate of device A by wirebonding from the inductor chiplet to the QD chiplet. The other end of the inductor was connected to a (multiplexed) readout line on the printed circuit board (PCB) [Fig. 1(a)]. Such multi-module assemblies consisting of a resonator chiplet separated to the spin qubit device chiplet offer advantages in terms of separation of fabrication steps and choice of materials.24–26 Measurements are performed at \(\sim 20\) mK, the base temperature of a dilution refrigerator.

The resonator formed by this inductor together with \(C_p\) has a resonance frequency \(f_0\) of \(\sim 299\) MHz. The magnitude and phase response are plotted in Fig. 1(b). The superconducting nature of the inductor leads to a large \(Q_l\) of 1480 \(\pm\) 480, as determined from a fit of the resonance circle in the complex plane with the method outlined in Ref. 36. The large error bar in \(Q_l\) arises from the resonator being overcoupled, with a loaded quality factor of \(Q_l = 370 \pm 50\) that is dominated by the coupling quality factor of \(Q_k = 500 \pm 56\). Modeling the parasitic capacitance as a lumped element attached to the devices side of the inductor provides an estimate of \(C_{ct} = 0.19 \mu\)F. The resonance frequency does not exactly match the point at which the magnitude of the reflection coefficient \(|S_{11}|\) is minimal as displayed in Fig. 1(b). This is due to a rotation of the resonance circle in the complex plane, typically attributed to non-ideal interference effects.37

The resonator can be operated as a gate-based dispersive sensor by probing the reflected signal at resonance while sweeping the plunger gates. The obtained charge stability diagram of the double QD system is shown in Fig. 1(c) with clear dot-to-plunger transitions visible down to the last hole. Interdot transitions are also visible because gate B has different lever arms to the two dots. The signal amplitude is smaller than that of the dot-to-plunger transitions.

Interestingly, the charge stability diagram can also be observed in \(\Delta V_{out}\) when driving a neighboring plunger gate. Such an indirect excitation of the resonator indicates the presence of a finite crosstalk capacitance \(C_{ct}\) between that plunger gate and gate B. The measured phase of \(\Delta V_{out}\) when exciting an AC amplitude \(\Delta V_{pl}\) on gate P1 at

![FIG. 1. (a) Reflectometry setup with a NbN nanowire inductor on a separate Si chiplet, wire bonded on one side to the barrier gate of a Si finFET double QD device, and on the other side to a multiplexed readout line on a printed circuit board (PCB). Total parasitic capacitance \(C_p\) is given by capacitance to ground \(C_{p,0}\) and sum of crosstalk capacitances \(C_{ct}\). (b) Normalized reflection amplitude and phase of the resonator and corresponding fit, giving \(Q_l = 1478 \pm 480\) and \(Q_p = 500 \pm 56\). (c) Charge stability diagram of the finFET double-QD at fixed \(V_{pl} = -0.845\) V obtained by reflectometry at 299.3 MHz, revealing the few-hole regime with \((N_1, N_2)\) holes in the two QDs. (d) False-colored scanning electron microscope image of a similar NbN nanowire inductor with a wire width of 400 nm.](image-url)
resonance is shown in Fig. 2(a) around the $(0,1) - (1,0)$ charge region. We note that such crosstalk is distinct from the harmonic voltage conversion observed in Ref. 38, where it is induced by transitions of single charges at interdot and dot-to-lead transitions.

The crosstalk in this device is quantified by measuring the broadening of the interdot charge transition line in the source–drain current $I_{SD}$ and relating this to a ring-up peak voltage amplitude $\Delta V_B$ on gate B. We first determine the line broadening when directly exciting the tank circuit by a resonant AC drive with amplitude $\Delta V_B = 0$. Figure 2(c) shows scans of the interdot line along the DC voltage $V_{P2}$ and for different amplitudes $\Delta V_B$. The broadening is fit by a time-averaged sinusoidally shifted Lorentzian function, see Fig. 2(d) and supplementary material Sec. I for details. The amplitude of the broadening (i.e., half the distance between the extreme positions of the fitted Lorentzian peaks) is more than 400 times larger than $\Delta V_B$ and is a consequence of a resonant ring-up of the voltage on gate B. The amplitude $\Delta V_B$ of this ring-up is obtained by multiplying the broadening amplitude scanned along $V_{P1}$ by $\beta_{P1,P2}$, where $\beta_{P1,P2}$ denotes the ratio between voltage changes on gate B and on gate $P_i$ required to stay on the interdot line. We find $\beta_{P1,P2} = -0.23$ and $\beta_{B,P1} = 0.40$, see Sec. II of the supplementary material.

Figure 2(e) shows the obtained amplitude $\Delta V_B$ as a function of $\Delta V_B$ by individually fitting the scans of the interdot line along $P1$ and $P2$ and adjusting for the relative voltage ratios $\beta_{B,P1}$ and $\beta_{B,P2}$, respectively. We find a linear relationship with an average amplification factor of $100 \pm 3$. This value is consistent with the amplification factor as calculated from numerical simulation of the readout circuit (see Sec. III of the supplementary material).

Using the same method but for indirect excitation of the tank circuit by a resonant AC drive with amplitude $\Delta V_{P2}$, we find a significant ring-up of gate B with an amplitude $\Delta V_B$ that is 26.2 (20.3) times larger than the exciting amplitude on the $P1$ ($P2$) gate [Fig. 2(f)]. As we show next, this crosstalk-induced excitation of the resonator and thereby of the potential on gate B occurs for any signal that contains spectral components within the bandwidth of the resonator frequency.

In spin qubit experiments, baseband signals are typically applied to plunger gates when transitioning from a qubit manipulation point to a readout point in charge configuration space. The repetition of such baseband signals may lead to harmonics that excite the resonator gate. To illustrate this effect, we apply a square wave [Fig. 3(a), upper] or sawtooth wave [Fig. 3(a), lower] of varying frequency $f_{bb}$ to gate $P1$. We fit the broadening of the interdot line $\Delta V_B$ by sweeping the interdot detuning voltage $V_e$ (see Sec. IV of the supplementary material for definition) across the $(0,1) - (1,0)$ transition, as indicated in Fig. 2(b). When varying the baseband frequency $f_{bb}$, a crosstalk-induced broadening of the interdot line is observed every time a harmonic $n$ of the signal matches the resonator frequency $f_i$, see Fig. 3(a). Figure 3(b) shows the fitted interdot peak broadening $\Delta V_B$ as a function of $f_i/f_{bb}$ for a sawtooth wave. Excitations occur whenever $f_{bb} \times n = f_i$, indicated by the white dots in Fig. 3(a), with the expected Fourier amplitudes scaling with $1/n$. Similarly, only odd harmonics are observed for a square wave excitation. The adverse effect of this ring-up on the operation of QDs as qubits can be reduced for larger $n$ by filtering the baseband pulses. However, fast ramp times between different charge states may be necessary to fulfill diabaticity requirements when initializing spin states via rapid adiabatic passage.

When manipulating a spin qubit, a series of sinusoidal drive pulses are applied to the gates, see Fig. 3(c). We focus on a typical Rabi experiment where the duration $t$ of the drive pulses is varied in order to observe Rabi oscillations induced by EDSR. The fitted interdot peak broadening for such a pulse train with a repetition rate $1/T$ of 1 MHz is shown in Fig. 3(d), where both the drive pulse frequency $f_{drive}$ and the pulse duration $t$ are swept. The baseband amplitude is set to zero. The observed peak broadening as a function of $f_{drive}$ and $t$ matches the expected...
sinc function $\sin(x)/x$ expected for the Fourier transformation of a sinusoidal pulse of a finite length, with $x = \pi t (f_{\text{drive}} - f_c)$. Note that the observed pattern resembles but is not related to the typical Rabi chevron pattern observed when varying $f_{\text{drive}}$ and $t$ for pulses applied to a qubit. While the fringes of the sinc function can be reduced by using a Gaussian envelope of the drive pulses, the broadening of the Fourier spectrum remains and, therefore, extends the crosstalk into a bandwidth $1/t$ around $f_c$. We additionally resolve the effect of the repetition of the pulses with period $T$ as lines spaced by the repetition rate, as displayed in Fig. 3(e) for a fixed $t = 250$ ns.

The indirect excitation of the resonator can be reproduced in a discrete-element circuit model, see Sec. III of the supplementary material for details of the circuit diagram. The resonator is indirectly excited by a drive signal on the neighboring gate through a mutual capacitance $C_{\text{ct}}$. The total parasitic capacitance to ground, $C_p$, is given by the sum of $C_{p,0}$ and $C_{\text{ct}}$, which is kept constant at 0.19 fF. The amplification factors between $\delta V_{\text{B}}$ and $\Delta V_{P1}$ ($\Delta V_{P2}$) are found to match those in Fig. 2(b) by choosing $C_{\text{ct}}$ equal to 16.0 fF (11.9 fF) when exciting on P1 (P2). This can mostly be accounted for by the mutual capacitance between the corresponding bondpads, for which we find values of 12.1 fF (7.3 fF) using Ansys Maxwell (Table I). We assign the remaining coupling capacitance of around 4 fF to mutual capacitance between bond wires and to the PCB side of our setup. Capacitances between neighboring gates at the device level were found to be on the order of $\sim 0.5$ fF and therefore negligible.

### TABLE I. Simulated capacitance matrix between the bondpads of the gate electrodes for device A.

<table>
<thead>
<tr>
<th></th>
<th>P1 (fF)</th>
<th>B (fF)</th>
<th>P2 (fF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>51.8</td>
<td>12.1</td>
<td>1.7</td>
</tr>
<tr>
<td>B</td>
<td>12.1</td>
<td>42.0</td>
<td>7.3</td>
</tr>
<tr>
<td>P2</td>
<td>1.7</td>
<td>7.3</td>
<td>41.9</td>
</tr>
</tbody>
</table>

To further confirm that the observed crosstalk is dominated by the capacitance between bondpads, another Si finFET device (device B) was measured. This device has two nanogates in GL1 and three nanogates in GL2, as depicted in the inset of Fig. 4(b), with a 750 nH inductor attached to one of the first-gate-layer gates, named gate B.
This leads to the formation of a resonator with a resonance frequency of 454 MHz. Three of the other gates, labeled gate 1 (nearest neighbor), gate 2 (next-nearest neighbor), and gate 3 (next-next nearest neighbor), were individually excited with an AC drive tone of varying frequency, and the voltage amplitude $|\Delta V_{out}|$ transmitted through the resonator was measured. The transmitted signal peaks at the resonator frequency. The peak amplitude is a measure for the voltage amplitude at gate B induced by AC crosstalk. A discrete-element circuit model (see Sec. V of the supplementary material) was used to model the results. In this model, the various crosstalk capacitances between the different gates were obtained from electrostatic simulations, taking into account that the bondpad layout where the order of the bondpads is the same as that of the nanogates. The measured $|\Delta V_{out}|$ is presented in Fig. 4(a) along with the simulated results from the circuit model (solid lines). The transmission magnitude decreases with the distance of the excited gate to gate B, in good agreement with the simulation. We, thus, attribute the dominant source of crosstalk to the capacitance between gate electrodes in the bondpad layer.

The frequency dependence of the AC crosstalk $\Delta V_B/\Delta V_{res}$ is simulated for device A, see Fig. 4(b) for the case of $C_D = 11.9 \text{ fF}$. The maximum value of 20.3 is reached at $f_r$. For our typical case, $C_P \gg C_D$, this maximum value is well approximated by $Q C_D / C_P$. Below $f_r$, the crosstalk reaches a minimum and is suppressed. Above $f_r$, it saturates at a value of approximately $C_D / C_P = 6\%$. This suggests that placing qubit frequencies well below the resonator frequency is optimal to suppress crosstalk in architectures with gate-based dispersive qubit readout. Note that our model does not account for higher-order resonator modes, where additional resonances at higher frequencies would lead to crosstalk amplitudes well above this saturation value.

In conclusion, gate-based dispersive sensing has been used to measure the charge stability diagram of a Si finFET by simulating for device A, see Fig. 4(b) for the case of $C_D = 11.9 \text{ fF}$. The maximum value of 20.3 is reached at $f_r$. For our typical case, $C_P \gg C_D$, this maximum value is well approximated by $Q C_D / C_P$. Below $f_r$, the crosstalk reaches a minimum and is suppressed. Above $f_r$, it saturates at a value of approximately $C_D / C_P = 6\%$. This suggests that placing qubit frequencies well below the resonator frequency is optimal to suppress crosstalk in architectures with gate-based dispersive qubit readout. Note that our model does not account for higher-order resonator modes, where additional resonances at higher frequencies would lead to crosstalk amplitudes well above this saturation value.

The authors have no conflicts to disclose.

Author Contributions

Eoin G. Kelly: Formal analysis (equal); Investigation (equal); Methodology (equal); Validation (equal); Writing – original draft (equal); Writing – review & editing (equal). Alexei Orekhov: Formal analysis (supporting); Methodology (equal); Validation (equal); Writing – original draft (supporting); Writing – review & editing (supporting). Nico W. Hendrickx: Formal analysis (supporting); Methodology (supporting); Software (supporting); Writing – review & editing (supporting). Felix Julian Schupp: Resources (equal); Writing – review & editing (supporting). Matthias Mergenthaler: Resources (equal); Writing – review & editing (supporting). Andreas V. Kuhlmann: Funding acquisition (supporting); Writing – review & editing (supporting). Patrick Harvey-Collard: Conceptualization (supporting); Methodology (supporting); Writing – review & editing (supporting). Andreas Fuhrer: Conceptualization (supporting); Funding acquisition (supporting); Supervision (supporting); Validation (supporting); Writing – review & editing (supporting). Gian Salis: Conceptualization (lead); Formal analysis (equal); Funding acquisition (lead); Investigation (equal); Methodology (equal); Supervision (lead); Validation (equal); Writing – original draft (equal); Writing – review & editing (equal).

DATA AVAILABILITY

The data that support the findings of this study are openly available in Zenodo at https://doi.org/10.5281/zenodo.10259169, Ref. 44.


