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Spins in silicon quantum devices are promising candidates for large-scale quantum computing. Gate-based sensing of spin qubits offers compact and scalable readout with high fidelity, however further improvements in sensitivity are required to meet the fidelity thresholds and measurement timescales needed for the implementation of fast-feedback in error correction protocols. Here, we combine radio-frequency gate-based sensing at 622 MHz with a Josephson parametric amplifier (JPA), that operates in the 500–800 MHz band, to reduce the integration time required to read the state of a silicon double quantum dot formed in a nanowire transistor. Based on our achieved signal-to-noise ratio (SNR), we estimate that singlet-triplet single-shot readout with an average fidelity of 99.7% could be performed in 1 µs, well-below the requirements for fault-tolerant readout and 30 times faster than without the JPA. Additionally, the JPA allows operation at a lower RF power while maintaining identical SNR. We determine a noise temperature of 200 mK with a contribution from the JPA (25%), cryogenic amplifier (25%) and the resonator (50%), showing routes to further increase the read-out speed.

Quantum computers require high-fidelity qubit measurement, which must be performed on a timescale faster than the decoherence time to perform quantum error correction [1]. Spin qubits formed in quantum dots (QDs) or donors in silicon are one of the most promising platforms for scalable quantum information processing due to their long coherence times and large integration density [2–7]. When scaling to large arrays of dense qubits [2–6][10] space for additional electrometers and reservoirs, typically required for readout based on spin dependent tunneling [8][9], is limited. Gate-based dispersive RF readout eliminates the need for such additional local structures by embedding the gates that define the QD into a resonant circuit and using Pauli spin blockade [17–22][24]. Recently, single-shot readout of the singlet-triplet states in a double QD has been demonstrated with gate-based sensors, using a variety of resonator parameters to achieve a range of readout fidelities (for a given integration time): 73% (2.6 ms) [25], 82.9% (300 µs) [26], 98% (6 µs) [27] to 99% (1 ms; using ancillary ‘sensor’ QD and reservoir) [28].

Amplifiers based on Josephson junctions have greatly improved signal-to-noise ratios (SNRs) in the field of superconducting circuits [29][36]. Adopting such approaches in the measurement of QDs at RF/microwave frequencies is expected to lead to corresponding improvements in SNR. This can in principle be achieved at operating frequencies of 4–8 GHz that are typical for Josephson-junction based amplifiers, as demonstrated using an InAs double QD, Josephson parametric amplifier (JPA) and coplanar waveguide resonator [37]. However, lower frequency operation (< 1 GHz) becomes necessary [38] for studying lower QD tunneling rates, at which exchange interaction is more easily controlled, and for enabling off-chip resonator fabrication. Suitable amplifiers are available in such a frequency range, for example: a JPA operating at 600 MHz with a noise temperature of $T_{\text{JPA}} = 105 \text{ mK}$ [39] or a SQUID amplifier chain with $T_{\text{SQUID}} = 52 \text{ mK}$ at 538 MHz [40]. Building on such developments, readout of a GaAs based quantum dot at 196 MHz with a noise temperature of 490 mK was recently reported using a SQUID amplifier [41].

In this Letter, we combine RF capacitive gate-based sensing of silicon QDs with Josephson parametric amplification to push the bounds of SNR that can be achieved using this technique. We use a well-matched lumped-element high Q resonator containing a NbN spiral inductor and a JPA that operates in the 500–800 MHz band and obtain an overall noise temperature $T_{\text{noise}} = 200 \text{ mK}$ at 621.9 MHz. We benchmark the sensitivity of the method using electronic transitions in a silicon multi-dot devices with large gate-coupling (wrap-around geometry) fabricated following CMOS processes.

The setup shown in Fig. 1(a) consists of i) the cryogenic RF delivery and amplification chain including the JPA (pink background); ii) a lumped-element LC resonator (green); and iii) the silicon quantum dot device (blue), see [49] for details. The LC resonator is probed
using an RF tone with power \( P_{rf} \) near resonant frequency \( f_R \). At this frequency, parametric changes in device capacitance, \( \Delta C_d \), due to cyclic single-electron tunneling produce changes in the reflection coefficient \( \Delta \Gamma = \left| \frac{\partial \Gamma}{\partial C_d} \right| \Delta C_d \). This effect translates into a change in the reflected power with an SNR given by

\[
\text{SNR} = |\Delta \Gamma|^2 \frac{P_{rf}}{P_n},
\]

where \( P_n \) is the noise power.

The optimal SNR is achieved by maximizing \( \Delta \Gamma \), maximizing \( P_{rf} \) (while remaining below power broadening) and minimizing \( P_n \). \( \Delta \Gamma \) is maximized for large loaded quality factor and small parasitic capacitance, which translates into a large resonator impedance, combined with large gate coupling and a well-matched resonator \[23\].

The noise power for an amplifier with gain \( G \) can be defined as \( P_{n, out} = Gk_B(T_{sys} + T_n)B \), where \( T_{sys} \) and \( T_n \) are the system and amplifier noise temperature (noise added by the amplifier) respectively, \( k_B \) is Boltzmann’s constant and \( B \) is the amplifier bandwidth. In semiconductor QD measurements, cryogenic high electron mobility transistor (HEMT) amplifiers operating at 4 K typically limit the effective noise temperature \( (T_{HEMT}) \) to a few Kelvin. By including an additional amplifier (such as a JPA) with gain \( G_{JPA} \) and lower noise temperature \( (T_{JPA}) \) at the beginning of the amplification chain, the effective noise temperature \( T_{noise} \) can be reduced:

\[
T_{noise} = T_{sys} + T_{JPA} + T_{HEMT} \frac{G_{JPA}}{G_{JPA}}.
\]

For a JPA operating at \( T = 10 \text{ mK} \) we expect a minimum of \( T_{JPA} = \frac{\hbar \omega}{2k_B} \coth \left( \frac{\hbar \omega}{2k_B T} \right) = 16.5 \text{ mK} \).

As shown in Fig. 1(a), the RF signal reflected from the quantum device passes the JPA (which works in reflection) via a circulator and is amplified at 4 K followed by further amplification and quadrature demodulation at room-temperature (not shown). Our JPA is a low-quality factor \( (Q_{JPA} < 100) \) superconducting resonator consisting of a SQUID loop array with tunable inductance shunted by a fixed capacitance \[13\], and is tunable in frequency from 500–800 MHz, as shown in Fig. 1(b), by passing a current \( I_{bias} \) through a coil that changes the flux through the nearby SQUIDs. The JPA is pumped via the signal input port and with power \( P_{JPA} \). At low drive power the JPA behaves like a linear resonator, while at high power the non-linearity of the Josephson junctions manifests in a frequency shift of the JPA to lower frequency until eventually the JPA reaches a bi-stable regime as shown in Fig. 1(c) \[43\]. In the regime useful for parametric amplification, the phase of the reflected pump signal varies rapidly with the pump power, as shown in Fig. 1(d), which represents the transfer function of the JPA.

The dynamic range of this JPA is of the order of \(-130 \text{ dBm} \), making it unsuitable for the signal powers commonly used in previous reflectometry measurements \((-90 \text{ to } -80 \text{ dBm}) \) \[18\]. Here, we overcome this limitation using a high quality factor \( LC \) resonator that is well-coupled to the input line, achieving a drive amplitude required to obtain a dispersive response at lower input power. The resonator circuit is formed by the parallel combination of a NbN spiral inductor \( L = 170 \text{ nH} \), parasitic capacitance and the geometric quantum dot device capacitance \( (C_p + C_d = 380 \text{ fF}) \), all coupled to the RF line via a coupling capacitor \( (C_c = 37 \text{ fF}) \). We observe a resonance in the reflection coefficient \( \Gamma = |\Gamma| \exp(i\phi) \) at \( f_R = 1/2 \pi \sqrt{L/(C_c + C_p + C_d)} = 621.9 \text{ MHz} \) with a loaded quality factor of \( Q_{load} = 966 \), impedance \( Z = \sqrt{L/(C_p + C_c + C_d)} = 650 \Omega \), return loss of 3 dB and phase shift > 180° (over-coupled) as shown in Fig. 2(b). When operating at a charge instability in the QD device, the resonator reaches perfect matching. We operate the JPA in phase-preserving mode, where there is an offset \( \Delta f = f_{JPA} - f_R \) between the JPA pump frequency.
The effective noise temperature $T$ of the JPA, when tuned close to the readout resonator frequency (3-dB-bandwidth of 6 MHz), is shown in Fig. 2(d). JPA gain and estimated system noise temperature at $f_{rf}$ as a function of RF input power showing saturation at high input power (1-dB-compression at $-121$ dBm).

Near resonance, when tuning the JPA close to the device resonance, we achieve a gain of 17 dB at $f_{rf}$ = 6 MHz. This puts $f_{JPA}$ at the edge of the readout resonator to avoid power broadening due to leakage of the pump signal while maximizing gain at $f_{rf}$. When tuned and pumped, we achieve a gain of 17 dB at $f_{rf}$ as shown in Fig. 2(c). The decrease in gain near $f_{rf}$ is likely due to large impedance variations of the resonator close to resonance and imperfect matching to 50 Ω.

Next, we use conventional methods to measure the charge sensitivity $[14, 49]$ with and without the JPA, which provides a device-specific benchmark on the performance of our gate-based sensor normalized to the gate charge sensitivity $[14, 49]$ with and without the JPA, including a schematic of the on-PCB components and bond-wires, the NbN spiral inductor, and the quantum dot device on a separate chip. When operating close to a bifurcation point $[34, 45, 46]$, we observe a signal in the phase as shown in Fig. 3(c) due to a capacitive shift of the resonance corresponding to $\Delta C_{Q} = 0.5 fF$ at the maximum. In Fig. 2(d) power broadening of the transition is shown. No broadening occurs for $P_{rf}$ below $-120$ dBm, while the transition is significantly broadened above $-110$ dBm. Due to the high $Q_{load}$ of the resonator, only a small input power, compatible with the dynamic range and saturation of the JPA, is required to perform readout and we calculate the RF disturbance at the device gate as $V_{PP}^{PP} = \frac{2h\nu_{rf}P_{RF}^{PP}}{C_{Q} + |\Gamma|C_{load}}Q_{load}V_{in}^{PP}$ (e.g. $V_{PP}^{PP} = 13 \mu V$ at $P_{rf} = -130$ dBm).

Next, we characterize and compare the improvements in the SNR of gate-based readout using a quantum dot-to-reservoir transition (DRT) in one CMOS silicon nanowire field-effect transistor device and an inter-donor/dot charge transition (IDT) in another device with nominally identical dimensions $[13, 22, 49]$. Although we cannot unequivocally determine the nature of the impurity, it presents signatures of a phosphorous atom (see $[49]$ for doping concentration and details on the IDT). QDs form in the corners of the nanowire, as shown in schematic line-cuts of the device along the gate and source-drain direction in Fig. 3(a,b), and have a strong gate coupling $\alpha_{rf} = 0.86$, while the donor resides deeper in the channel. When operating at the DRT we observe a signal in the phase as shown in Fig. 3(c) due to a capacitive shift of the resonance corresponding to $\Delta C_{Q} = 0.5 fF$ at the maximum. In Fig. 2(d) power broadening of the transition is shown. No broadening occurs for $P_{rf}$ below $-120$ dBm, while the transition is significantly broadened above $-110$ dBm. Due to the high $Q_{load}$ of the resonator, only a small input power, compatible with the dynamic range and saturation of the JPA, is required to perform readout and we calculate the RF disturbance at the device gate as $V_{PP}^{PP} = \frac{2h\nu_{rf}P_{RF}^{PP}}{C_{Q} + |\Gamma|C_{load}}Q_{load}V_{in}^{PP}$ (e.g. $V_{PP}^{PP} = 13 \mu V$ at $P_{rf} = -130$ dBm).
responding reduction in the disturbance of the QD being measured, and its neighbors. When operating well below power broadening ($P_\text{rf} = -130$ dBm), the charge sensitivity achieved with the JPA is 0.25 μe$/\sqrt{\text{Hz}}$ compared to 0.5 μe$/\sqrt{\text{Hz}}$ without the JPA, outperforming previous measurements using RF-SET and gate-based approaches.

Finally, we estimate spin-readout fidelity using a donor-dot IDT of even parity that exhibits features of spin blockade. Figure 4(a) shows the IDT in the normalized phase response as a function of $V_{BG}$ and backgate voltage ($V_{BG}$), where the donor transition can be identified due to a stronger coupling to $V_{BG}$. We determined the effective charge occupation of the donor and QD using the magnetic field response and we calculate a gate coupling $\alpha_{\text{IDT}} = 0.36$ and tunnel coupling $\Delta_c = 20.9 \mu$eV, corresponding to a capacitive shift of $\Delta C_d = 0.5 \text{ fF}$.

Figure 4(b) shows an example of the phase response across a DRT (power broadened at $P_\text{rf} > 110$ dBm). We observe that multiple measurements of the SNR with the JPA on for $\tau_{\text{int}} < 10$ μs deviate from the extrapolation, which could be due to noise introduced by the JPA pump signal which is operated only 1 MHz offset the RF signal. Based on the signal and noise levels (as shown in Fig. 4(c)) we simulate the singlet and triplet readout probability densities to obtain a readout fidelity. The model includes terms to account for relaxation of the triplet during measurement and we assume $T_1 = 4.5$ ms reported in a similar Si-MOS QD device to demonstrate the improvement in integration time that can be achieved with the JPA. We obtain an average readout infidelity as a function of integration time which is shown in Fig. 4(d) for the JPA off and on. We find that $F_{\text{avg}} > 0.997$ can be reached at a SNR > 5 corresponding to an integration time of at least $\tau_{\text{int}} = 32$ μs with the JPA off and $\tau_{\text{int}} = 1$ μs with the JPA on allowing readout faster than the coherence time of electron spins in $^{28}\text{Si}$ ($T_2^* = 120$ μs).

We have demonstrated that the SNR of RF gate-based
readout of quantum dot devices can be improved using a JPA. We observe a SNR improvement of 8 dB for both dot-to-reservoir and inter-donor/dot transitions when the JPA is operated closed to the RF frequency in phase-preserving mode at 17 dB gain. We have analyzed the performance of the JPA in an external magnetic field, commonly applied in spin qubit devices, and find no disturbance on the JPA performance up to a field of $B_z = 3$ T at the device. The SNR improvement we see is currently limited by the gain of the JPA. Assuming a JPA gain of 23 dB or more, the contribution of the cryogenic amplifier would become negligible. Additionally, the noise added by the JPA can be squeezed below the quantum limit when operating in phase-sensitive mode. Changes in the circuit such as additional isolators between the JPA and readout resonator as well as additional line attenuation and filtering could be beneficial towards achieving larger gain, a lower system noise temperatures and prevent leakage of the JPA pump signal into the readout resonator. In addition, the measurement speed in this implementation is, in principle, limited by the bandwidth of our high-$Q$ readout resonator: increasing the coupling to the line or, preferentially, moving to a higher frequency of the resonator circuit while maintaining high loaded $Q$ should allow sub-microsecond fault-tolerant gate-based spin readout. Further development could reduce the footprint of the high $Q$ resonators, to achieve an integrated and scalable readout architecture with the potential of reduced circuit losses and parasitics. Using a traveling wave parametric amplifier (TWPA) with increased bandwidth, frequency multiplexing of multiple resonators could be achieved.

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