Controlled dc Monitoring of a Superconducting Qubit


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In this Letter, we investigate a modified S-Sm-S JJ design of a qutrit to function as a field-effect transistor (FET). By switching the FET between being conducting (“on”) or depleted (“off”) using a gate voltage, we are able to implement a controlled transition between the transport and cQED measurement configurations. We demonstrate that the additional tunability does not compromise the quality of the qutrit in the cQED configuration, where the FET is off. We further demonstrate control of the qutrit relaxation as the FET is turned on, continuously increasing the coupling of the junction to the environment, in agreement with a simple circuit model. Finally, we demonstrate strong correlation between cQED and transport data by comparing the measured qutrit frequency spectrum with the switching current directly measured in situ.

Devices were fabricated on a high resistivity silicon substrate covered with a 20 nm NbTiN film. The nanowire region, qubit-capacitor island, electrostatic gates, on-chip gate filters, readout resonator, and transmission line were patterned by electron-beam lithography and defined by reactive-ion etching techniques; see Fig. 1(a). The full-shell InAs/Al epitaxial hybrid nanowire is placed at the bottom of the qubit island; see Fig. 1(b) [18]. Two gateable regions are formed by selective wet etching of the Al in two ~150 nm segments defined by electron-beam lithography, aligned with two independent bottom gates, which are separated from the nanowire by a 15-nm-thick HfO2 dielectric. The three superconducting segments—ground, qubit island with capacitance $C_q$, and dc bias $V_J$—are then contacted with ~200 nm sputtered NbTiN; see Fig. 1(b). In this circuit, when the FET is on, dc current or voltage probes the local DOS are directly accessible with dc transport but not with cQED. The prospect of combining these techniques potentially allows a deeper understanding of JJ-based quantum systems.

In this Letter, we investigate a modified S-Sm-S JJ design of a qutrit that combines dc transport and coherent cQED qutrit measurements. The device is realized in an InAs nanowire with a fully surrounding epitaxial Al shell by removing the Al layer in a second region (besides the JJ itself) allowing that region to function as a field-effect transistor (FET). By switching the FET between being conducting (“on”) or depleted (“off”) using a gate voltage, we are able to implement a controlled transition between the transport and cQED measurement configurations. We demonstrate that the additional tunability does not compromise the quality of the qutrit in the cQED configuration, where the FET is off. We further demonstrate control of the qutrit relaxation as the FET is turned on, continuously increasing the coupling of the junction to the environment, in agreement with a simple circuit model. Finally, we demonstrate strong correlation between cQED and transport data by comparing the measured qutrit frequency spectrum with the switching current directly measured in situ.
the distance between the two peaks in $d_{IB}=d_{VB}$ sinusoid (orange).

In the cQED configuration, we tune the qubit frequency $f_{Q}$ while measurements are available [blue box in Fig. 1(c)]. Depleting the FET allows the device to operate as a qubit, where measurements of the heterodyne demodulated transmission $V_{H}$ allow qubit state determination and $V_{Q}$ allows tuning the qubit frequency $f_{01}$ over several gigahertz [red box in Fig. 1(c)].

Setting the voltage on the FET gate to $V_{FET} = +4 \text{ V}$, which turned the FET fully conducting, and the voltage on the qubit JJ to $V_{Q} = -2.9 \text{ V}$ makes the voltage drop predominantly across the qubit JJ. In this configuration, the differential conductance $dI_{B}/dV_{B}$ probes the convolution of the DOS on each side of the JJ; see Fig. 1(d). Keeping in mind a simple model of JJ spectroscopy [9], we interpret the distance between the two peaks in $dI_{B}/dV_{B}$ as $4\Delta/e = 4 \times 190 \mu\text{V}$, where $\Delta$ is the induced superconducting gap. In the cQED configuration, with $V_{FET} = -3 \text{ V}$ and $V_{Q} = -2.5 \text{ V}$, coherent Rabi oscillations are observed by varying the duration $\tau$ of the qubit drive tone at the qubit frequency $f_{01} = 4.6 \text{ GHz}$. Following the drive tone, a second tone was applied at the readout resonator frequency, $f_{R} \sim 5.3 \text{ GHz}$, to perform dispersive readout where $V_{H}$ is measured; see Fig. 1(e). These experiments are carried out in a dilution refrigerator with a base temperature of $\sim 10 \text{ mK}$ using standard lock-in and dc techniques for the transport measurements and using heterodyne readout and demodulation techniques for the cQED measurements [19].

Having demonstrated the ability to probe the qubit JJ with both transport and cQED techniques, we next compare performance to a nominally identical gate with transport lead. Scanning electron micrographs of the two devices are shown in Figs. 2(a) and 2(b). The measured relaxation times $T_{1}$ are shown for a range of qubit frequencies $f_{01}$ controlled by $V_{J}$ in Fig. 2(c). Relaxation times $T_{1}$ were measured by applying a $\pi$ pulse, calibrated by a Rabi experiment at $f_{01}$, followed by a variable wait time $\tau$ before readout; see Fig. 2(c), inset. $T_{1}(V_{Q})$ were then extracted by fitting $V_{H}(\tau)$ to a decaying exponential. We observe no systematic difference in $T_{1}$ between the devices, demonstrating that the addition of a transport lead does not compromise the performance in the cQED configuration.

We next monitored $dI_{B}/dV_{B}$ for $f_{01}$ and $T_{1}$ as $V_{FET}$ was varied from off (cQED regime) to on (transport regime). Measurements of $dI_{B}/dV_{B}$ [Fig. 3(a)] illustrate how the FET was turned conducting as $V_{FET}$ was increased. Qubit frequency $f_{01}$ was measured by two-tone spectroscopy, where a drive tone with varying frequency $f_{d}$ was applied for $2 \mu\text{s}$, followed by a readout tone at $f_{R}$. A Lorentzian fit is used for each $V_{FET}$ to extract $f_{01}$; see Fig. 3(b), insets. We attribute the weak dependence of $f_{01}$ on $V_{FET}$ to cross talk between the two gates.

Following each spectroscopy measurement, a $T_{1}$ measurement was immediately carried out, see Fig. 3(c), yielding a nearly gate independent $T_{1} \sim 6 \mu\text{s}$ for $V_{FET} < -2 \text{ V}$. At $V_{FET} \sim -2 \text{ V}$, we observe a sudden drop in $T_{1}$, followed by a short revival at $V_{FET} \sim -1.8 \text{ V}$. We associate the revival in $T_{1}$ with the corresponding drop in $dI_{B}/dV_{B}$ observed in...
FIG. 3. (a) Differential conductance $dI_B/dV_B$ as a function of FET gate voltage $V_{\text{FET}}$ at high bias $V_B = 1.0$ mV, to approximate normal-state resistance. (b) Qubit frequency $f_0$ as a function of $V_{\text{FET}}$ using two-tone spectroscopy. Insets: Lorentzian fits (orange) to data points in the main panel as indicated by the corresponding features in Fig. 3(a). We attribute this nonmonotonicity to the formation of quantum dots in the FET, which is commonly observed in nanowire JJs near the pinch-off values [20]. For $V_{\text{FET}} > -1.5$ V, $f_0$ and $T_1$ can no longer be resolved, consistent with increasing $dI_B/dV_B$. We note that the $dI_B/dV_B$ curve in Fig. 3(a) was shifted horizontally by a small amount (0.1 V) to align features in $dI_B/dV_B$ with corresponding features in $T_1$. This was done to account for gate drift, as the cQED and transport measurements were performed sequentially over the course of several days.

We develop a circuit model of qubit relaxation in the leaded device. Within the model, the qubit circuit is coupled through the FET to a series resistance $R_F$ and a parallel capacitance $C_F$ representing an on-chip filter on the lead [21]. The coupling to the environment via the (superconducting) FET junction is modeled as a gate tunable Josephson inductance $L_{\text{FET}}$, giving a total environment impedance $Z_{\text{env}} = i\omega L_{\text{FET}} + (1/R_F + i\omega C_F)^{-1}$. This impedance can be viewed as a single dissipative element with resistance given by

$$R_{\text{env}} = \frac{1}{\text{Re}[Y_{\text{env}}]} = L_{\text{FET}}^2/R_F^2(C_F/\omega)^3 + \frac{1}{R_F(1 - 2L_{\text{FET}}C_F\omega^2)}.$$  

with admittance $Y_{\text{env}} = 1/Z_{\text{env}}$ [22]. The relaxation rate associated with the lead is given by $\gamma_{\text{lead}} = 1/R_{\text{env}}C_Q$, yielding a total decay rate $\gamma_{\text{tot}} = (\gamma_{\text{nonleaded}} + \gamma_{\text{lead}})R_{\text{FET}}$, where $\gamma_{\text{nonleaded}}$ is the decay rate associated with relaxation unrelated to the lead. We estimate $L_{\text{FET}} = \hbar/2eI_{c,\text{FET}}$ [23], where $I_{c,\text{FET}}$ is the critical current of the FET, which we in turn relate to the normal-state resistance $R_{n,\text{FET}}$ via the relation $I_{c,\text{FET}} = \sqrt{\gamma_{\text{tot}}}/2e$ [24], yielding

$$L_{\text{FET}} = hR_{n,\text{FET}}/\pi\Delta.$$  

$R_{n,\text{FET}}$ can be found from $dI_B/dV_B$ in Fig. 3(a) by subtracting the voltage drop across the line resistance, $R_{\text{line}} = 57$ k$\Omega$, and assuming no voltage drop across the qubit JJ, justified by $I_{c,\text{FET}} < I_c$, where $I_c$ is the critical current of the qubit JJ. From electrostatic simulations we estimate $C_Q = 38$ f$F$ [25]. We take $\omega = 2\pi T_{01}$, where $T_{01} = 4.6$ GHz is the average $f_{01}$ in Fig. 3(b), and $\Delta = 190$ $\mu$eV from Fig. 1(d). Combining Eqs. (1) and (2) with the measured $1/T_1$ yields the $\gamma_{\text{lead}}$ in Fig. 4 using $R_F = R_{\text{line}}$ and $C_F = 0.1$ p$F$ as the best fit parameter. We note that electrostatic simulations give $C_F \sim 0.5$ p$F$, in reasonable agreement with the best fit value. We define $\gamma_{\text{nonleaded}} = 1/T_1^{\text{mean}}$, where $T_1^{\text{mean}} = 5.8$ $\mu$s is the mean value of the $T_1$ at $V_{\text{FET}} < -2$ V. Using this estimate for $\gamma_{\text{nonleaded}}$, we calculate the total relaxation time based on the transport data (orange line in Fig. 4), showing excellent agreement with the measured values. The $T_1$ limit based on the contribution of the lead saturates at $T_1^{\text{lead}} \sim 1$ ms, indicating that leaded gatemon devices can accommodate large improvements in gatemon relaxation times. We mainly attribute the current level of relaxation times to dielectric losses. This is based on measurements of test resonators from the same substrates yielding quality factors of $Q \sim 10^3$, with $T_1 \sim Q/(2\pi f_{01})$ being roughly consistent with the observed $T_1$. Although optimizing the qubit
for the correlation between critical current \( I_c \) and qubit gate voltage \( V_Q \). Switching current \( I_s \) (blue points) from the edge of the zero-resistance state for increasing sweep at \( V_{FET} = +4 \) V to turn the FET conducting. (b) Qubit frequency \( f_{01} \) from two-tone spectroscopy as a function of \( V_Q \), acquired at \( V_{FET} = -3 \) V to deplete the FET. The area of missing data at 5.0–5.6 GHz is due to \( f_{01} \) crossing the resonator frequency \( f_R \). (c) Correlation between transport and cQED data. \( f_{01} \) from (b) (red) extracted as in Fig. 3(b), inset. \( f_{01} \) from \( I_s \) (blue) extracted by applying an RCSJ model to the data in (a) (see text).

Combining transport and cQED measurements allows for the correlation between critical current \( I_c(V_Q) \) and \( f_{01}(V_Q) \) to be observed directly [27]. The critical current \( I_c \) is extracted from \( dI_B/dV_B \) and \( I_B \) while sweeping \( V_B \) and \( V_Q \). We extract the voltage drop and differential resistance across the qubit junction, \( V_J \) and \( dV_J/dI_B \), by inverting \( dI_B/dV_B \) and subtracting \( R_{line} \). In doing this, we assume that there is no voltage drop across the FET junction, since \( I_c < I_{c,FET} \). The qubit resonance \( f_{01} \) is measured over the same \( V_Q \) range using two-tone spectroscopy; see Fig. 5(b). We note that the two-photon transition to the next harmonic is also observed for some \( V_Q \), visible at a slightly lower frequency than \( f_{01} \), given by the anharmonicity.

The relation between the two measurements is shown in Fig. 5(c). In order to estimate \( I_c(V_Q) \), we first extract the switching current \( I_s(V_Q) \) from the data, taken as the \( I_s \) at which \( dI_B/dI_B \) is maximal, while sweeping \( I_B \) from negative to positive values [blue dots in Fig. 5(a)]. Bright features at high bias \( (I_B > I_s) \) are likely associated with multiple Andreev reflection [28]. To extract \( I_c \) from the measured \( I_s \), we model the qubit as an underdamped RCSJ (resistively and capacitively shunted junction) Josephson junction with a sinusoidal current-phase relation \( I = I_c \sin \phi \). Furthermore, we note the small difference between the return current \( I_r \) (same definition as \( I_s \) at negative \( I_B \)) is slightly smaller than \( I_s \) [19]. In this case, \( I_s \) corresponds to the current of equal stability between the resistive and nonresistive state [29]. Under this condition, and for large quality factors \( Q \gg 1 \), the ratio \( I_s/I_c \) depends on quality factor \( Q = R \sqrt{2 e I_c C_Q / \hbar} \) as

\[
I_s/I_c = (2 + 4/\pi) Q^{-1} + (2 + \pi) Q^{-2},
\]

where \( R = (1/R_j + 1/R_{line})^{-1} \) and \( R_j \) is the shunt resistance [29]. In RCSJ theory \( R_j \) is proportional to the normal-state resistance of the junction \( R_N \) [9] with the proportionality depending on both the DOS inside the proximitized superconducting gap and temperature. As these parameters are not simultaneously accessible in our setup, we take the proportionality as a fit parameter. By doing so, we find \( R_j \) to be equal to \( R_N \). We then apply the Ambegaokar-Baratoff relation \( I_s R_j = \pi \Delta / 2 e \) [24], which allows us to extract \( I_c \) by inverting Eq. (3) numerically [30]. The extracted \( I_c \) in turn, yield values for \( Q \) in the range 10–20, consistent with our initial assumptions. For these values of \( Q \), the RCSJ model takes the electron temperature to be >50 mK to account for the weak asymmetry in \( I_s \) and \( I_c \) [19]. Finally, we relate \( I_c \) to \( f_{01} \) by using the numerical solution of the standard transmon Hamiltonian, \( H = 4 E_C(n - n_g)^2 - E_J \cos(\phi) \) [31], with \( E_J = \hbar I_c / 2 e \) and \( E_C / \hbar = e^2 / 2 \hbar C_Q = 512 \) MHz, at the charge degeneracy point with offset charge \( n_g = 0.5 \).

A comparison of the measured and estimated \( f_{01} \) is shown in Fig. 5(c). The model (RCSJ) curve is shifted horizontally by 0.05 V to align the features at \( \sim 2.5 \) V and can be attributed to cross talk between the two gates as \( V_{FET} \) is varied from the dc to the cQED configuration, consistent with independent calibration measurements. A clear correlation is observed between the two measurement techniques, especially evident from the matching of local minima and maxima of both spectra and the overall agreement of the absolute values. We attribute the residual quantitative discrepancy to the simplifying assumptions used to determine the shunt resistance of the RCSJ model, which likely do not capture the possible gate dependence of the subgap DOS of the qubit JJ. In addition, the assumption of sinusoidal CPR will break down as the qubit JJ is opened due to increasing mode transmission in the semiconductor junction, leading to small overshoots of the model as perhaps seen around \( V_Q \sim 0 \) V.

In summary, we have demonstrated the compatibility of dc transport and cQED measurement techniques in gate- mon qubits. This method may extend to other material platforms such as two-dimensional electron gases [15] or graphene [16,27,32]. Furthermore, we achieve a controllable relaxation rate potentially relevant for a range of qubit applications such as tunable coupling schemes [33,34] and controlled qubit relaxation and reset protocols [35,36]. In addition, we have demonstrated clear correlation between dc transport and cQED measurements motivating future
extensions, such as studying CPRs [8] or probing channel transmissions by studying multiple Andreev reflections [12] combined with cQED experiments [10,13,14]. Combining well-established transport techniques in quantum dot physics with qubit geometries may also be an interesting research direction [37]. Potentially, this geometry is also a promising platform to coherently probe Majorana zero modes in cQED measurements [38], as transport signatures have been demonstrated, both in half-shell nanowires [39] and full-shell wires [40,41].

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[30] Numerical code and data accompanying the analysis of Fig. 5(c) are found at https://github.com/anderskringhoj/de_qubit.