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Dispersive sensing in hybrid InAs/Al nanowires

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ABSTRACT
Dispersive charge sensing is realized in hybrid semiconductor-superconductor nanowires in gate-defined single- and double-island device geometries. Signal-to-noise ratios (SNRs) were measured in both the frequency and time domains. Frequency-domain measurements were carried out as a function of frequency and power and yield a charge sensitivity of $1 \times 10^{-3} \text{ e} / \sqrt{\text{Hz}}$ for an $\sim 11$ MHz measurement bandwidth. Time-domain measurements yield SNR $> 1$ for a 20 $\mu$s integration time. At zero magnetic field, photon-assisted tunneling was detected dispersively in a double-island geometry, indicating coherent hybridization of the two superconducting islands. At an axial magnetic field of 0.6 T, subgap states are detected dispersively, demonstrating the suitability of the method to sensing in the topological regime.

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Readout of quantum systems on timescales short compared to coherence or relaxation times is typically performed by one of a few schemes: (i) the device is incorporated into a resonant circuit, allowing state-dependent changes in the damping or shift of the resonance to be measured,1–4 (ii) the quantum state is converted to charge, which is then detected by a nearby electrometer,5–8 or (iii) a state-dependent capacitive coupling to the system results in a frequency shift in the coupled resonant circuit that depends on the quantum state,9,10 the latter referred to as dispersive readout. In the context of topological qubits, several proposals for nonlocally encoding fermion parity in Majorana zero modes have been made.11–15 Some proposals use parity-to-charge conversion for readout,12 while others use state-dependent hybridization of the Majorana mode with an ancillary system, leading to a dispersive readout signal.13,14,16

Integrating readout circuitry into an existing electrostatic gate or ohmic contact is useful for reducing the device footprint and lead count.16–27 In this case, dispersive readout is performed by monitoring state-dependent shifts in the resonance frequency $f_R = (LC_{\text{tot}})^{-1/2}$ of an LC circuit connected to a gate, where $f_R$ is detuned from the qubit transition frequency. The total capacitance, $C_{\text{tot}}$, comprises geometric capacitance, $C_G$ (including parasitic contributions), quantum capacitance, $C_Q$, and tunnel capacitance, $C_T$.28 When the quantum system consists of a Coulomb island tunnel coupled to a reservoir, $C_Q$ arises from continuous charge transitions and is proportional to the curvature of energy with respect to the confining gate voltage.29 The maximum magnitude of $C_Q$ occurs at gate voltages corresponding to charge degeneracy, with opposite signs for ground and first excited states. $C_T$ is significant when the energy relaxation rate exceeds $f_R$. The dependence of $f_R$ on $C_Q$ provides the quantum state selectivity of the dispersive shift. Monitoring phase or magnitude of the signal reflected from the resonant circuit thus allows readout of the quantum state of the system.

Recent work on gate-based dispersive sensing has addressed semiconducting nanowires (NWs)16,24 and semiconductor quantum dots coupled to subgap states in semiconductor-superconductor NWs at zero magnetic field.25 Beyond qubit readout, dispersive sensing has been used to allow rapid tuning of quantum devices, yielding complementary information to conventional transport approaches.26 In this letter, we explore dispersive charge sensing in an epitaxial semiconductor-superconductor (InAs/Al) nanowire device configured to form either a single or double island depending on gate voltages. Since both proximity-induced superconductivity and high magnetic fields are needed for realizing the topological regime, we have focused particular attention on operation at magnetic fields compatible with topological superconductivity. At zero field, we extract a signal-to-noise ratio (SNR) of a gate-based dispersive sensor as a measure of its...
sensitivity. Time-domain measurements gave SNR > 1 for integration times >20 μs, as described in detail below. Applying a continuous microwave drive to a nearby gate induces photon assisted tunneling (PAT), indicating coherent hybridization of the two islands.

The device, shown in Fig. 1(a), is based on an InAs/Al NW with 7 nm of epitaxial Al grown on three facets of the hexagonal cross section. Following deposition of individual wires on a Si-SiOx substrate, three 100 nm segments of Al were removed by wet etching to provide tunable tunnel barriers. An insulating layer of HfO2 was then deposited over the wire and electrostatic gates labeled C1, C2, C3, and C4 were deposited, creating three segments of lengths ~2.5 μm, 1 μm, and 3.5 μm, separated by gate-voltage-controlled barriers of InAs only (see the supplementary material for fabrication details). The detector gate, labeled P2, and the right ohmic contact were bonded to superconducting spiral inductors fabricated on a separate sapphire chip to form a resonant circuit that was capacitively coupled to a conventional radio frequency (rf) reflectometry detection chain. Each resonator was also connected to bias resistors, allowing DC voltages to be applied to the gates. Data from two devices (D1 and D2) are presented. All measurements were made in a dilution refrigerator with a base temperature of ~20 mK equipped with a vector magnet (see the supplementary material for measurement details).

We initially consider zero magnetic field. Electrostatic gates C2 and C3 were set to the tunneling regime, forming a superconducting single island. A comparison of conductance measured via low-frequency transport using a lock-in amplifier vs reflectometry from the right ohmic contact is shown in Fig. 1(b). The conductance, g, around zero bias showed Coulomb blockade (CB) peaks as a function of plunger voltage Vp2. Finite bias conductance measurements yielded a charge energy of Ec = 60 μeV. CB oscillations had a period of two electron (2e) charge. This is expected for Δ > Ec, where Δ ~ 180 μeV is the induced superconducting gap and indicates low average quasiparticle poisoning. Figure 1(c) shows the ohmic reflectometer response as a function of plunger voltage Vp2 and rf readout frequency frf see the supplementary material for details. The resonance shows a state-dependent shift when crossing the island degeneracy [Fig. 1(d)]. As shown later, PAT was observed at frequencies ≥11 GHz, i.e., highly detuned from the readout resonators, indicating a state-dependent dispersive interaction between the resonator and the device.

In a lithographically similar device (D2), the gate sensor sensitivity at zero magnetic field was evaluated in a superconducting single-island regime, and the island had charging energy Ec = 105 μeV. A nearby gate [P3 in Fig. 1(a)] was modulated with a sinusoidal signal of fixed frequency (fM) and amplitude VMP. Positioning the island gate Vp2 on the side of a CB peak amplitude modulates the island charge and thereby the readout resonance, inducing sidebands that are symmetrically detuned by fM from the carrier frequency frf.

Figure 2(a) shows the signal reflected from the detector gate P2 recorded with a spectrum analyser with Δf = 13.4 Hz resolution bandwidth. Around the resonance frequency (~438 MHz), two sidebands are observed at fM = ±12 kHz. For the analysis that follows, the upper sideband was chosen. The signal-to-noise ratio (SNR) is given by the ratio of the height of the sideband to the noise floor in a given bandwidth. The SNR dependence on the rf carrier power Prf (before ~40 dB attenuation) is shown in Fig. 2(b). An initial increase in SNR up to around Prf = −35 dBm is observed followed by a decrease for larger power. This turnaround behavior can be explained by the trade-off between lifetime and power-induced broadening. Figure 2(c) shows the SNR dependence on fM for a fixed Prf = −35 dBm. A maximum SNR was observed at fM ~435 MHz. The full-width half-maximum of the SNR as a function of fM indicates an approximate resonator bandwidth of ~12.2 MHz.

With Pfr and fM set to maximize SNR [see Figs. 2(b) and 2(c)], a detection bandwidth of ~11 MHz was determined by measuring the modulation frequency fM at which SNR decreased by 3 dB, as shown in Fig. 2(d). We next evaluate the charge sensitivity S ≡ Δf(2ARF)−1/2 measured in the time domain, taking spectral resolution Δf = 13.4 Hz and SNR ~15 as a typical value for optimal detection parameters [see Figs. 2(b) and 2(c)]. The effective charge change induced

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**FIG. 1.** (a) Scanning electron micrograph of the nanowire device together with the relevant electrostatic gates labeled. (b) Coulomb blockade oscillations of the superconducting single-island defined between gates C2 and C3 as a function of plunger gate voltage Vp2 recorded in conductance g via lock-in transport (black) and dispersive lead sensing Vg (red), showing close matching. (c) Lead sensor signal Vg as a function of electrostatic plunger gate voltage Vp2 tuning the superconducting island over the Coulomb degeneracy as a function of readout frequency frf. (d) Line cuts from (c) on- (green) and off- (red) Coulomb degeneracy. Dispersive shift in frequency can be observed as the island is tuned over the degeneracy.

**FIG. 2.** (a) Spectrum reflected from the detector gate P2 under gate-modulation as described in the main text; two sidebands symmetrically detuned from resonance were observed. (b) Signal-to-noise ratio dependence on carrier power Pfr and (c) on carrier frequency ffr. (d) Signal-to-noise ratio as a function of modulation frequency fM. The 3 dB frequency, ~11 MHz, indicates the bandwidth of the measurement.
by modulation at amplitude $V_{\text{rf}} = 30 \text{ mV}_{\text{pp}}$ was found by comparing the amplitude of $V_{\text{3f}}$ ($30 \text{ mV}_{\text{pp}}$) to the amplitude needed to sweep over a full CB peak spacing ($950 \text{ mV}_{\text{pp}}$). The factor $1/\sqrt{2}$ accounts for the power collected from both sidebands. The resulting charge sensitivity was $S \sim 1 \times 10^{-3} e/\sqrt{\text{Hz}}$.

The time needed to obtain a particular SNR at optimal values of $f_{\text{RF}} = 438 \text{ MHz}$ and $P_{\text{RF}} = -40 \text{ dBm}$ was determined by comparing the difference, $\delta V$, in signal $V_{\text{CB}}$ on and off a CB peak with the noise of the measurement, which decreased with increasing signal averaging. In the single-island regime, gate P2 was pulsed on and off a CB peak with amplitude equivalent to $-0.3 e$ at a repetition frequency of $2 \text{ kHz}$. In-phase (I) and quadrature (Q) components were recorded with a time constant of $500 \text{ ns}$, averaged over an integration time $\tau$, and plotted in the complex $I - Q$ plane. Figure 3(a) shows an example with $\approx 1.1 \times 10^4$ points averaged for $\tau = 20 \mu s$ each. SNR($\tau$) was found by fitting two 2D Gaussians, yielding signal $\delta V$ and noise, $2\sigma$. The time-domain SNR, given by $\delta V / 2 \sigma(\tau)$, is shown in Fig. 3(b). SNR $\sim 1$ is reached for an integration time of $\tau \sim 20 \mu s$.

Figure 4(a) shows $V_{\text{T}}$ measured using a dispersive sensor on gate P2 (see Fig. 1(a)) rather than an ohmic contact. Coulomb diamonds were observed with the device configured as a single island at $B = 0$. Each measured point in Fig. 4 was averaged 100 times, yielding a measurement time of $60 \mu s$ per point. At high bias, $V_{\text{PP}} > 0.2 \text{ mV}$, the period of Coulomb oscillations was halved compared to low bias, indicating that low-bias transport was predominantly carried by Cooper pairs. Figure 4(b) shows the phase response of the demodulated signal. The readout frequency was chosen to optimize the $1e$ charge transitions leading to a nonmonotonic response for $2e$ charge transitions that had a larger capacitive shift of the resonator. The estimated gate sensor geometric capacitance $C_g = e / \delta V_g \approx 0.55 \text{ fF}$, where $\delta V_g$ is the gate space periodicity of the island plunger P2. This makes $C_g \approx 0.4 C_C$ using the normal-state charging energy of the island.

Application of a parallel magnetic field, $B$, induced subgap states in the nanowire and an evolution from $2e$ to $1e$ periodic CB oscillations, as shown in Fig. 4(c), where an average $V_{\text{T}}$ was subtracted at each field. $1e$ periodic CB oscillations correspond to a state at zero-energy in the superconducting gap, though not necessarily a discrete state. To keep maximum detection contrast at each magnetic field value, the readout frequency was adjusted to compensate for changing kinetic inductance of the resonator. The jump at $B \approx 0.4 \text{ T}$ was likely due to electrostatic background charges in the NW environment. The detected signal did not degrade at magnetic field ranges compatible with tuning into a topological state in similar wires.39

The gate voltage $V_{\text{P2}}$ for Fig. 4(c) was selected based on the appearance of a discrete state in the spectrum at a high magnetic field, whereas Fig. 4(a) is at zero magnetic field where subgap states are not present. Previous studies have shown that in hybrid InAs/Al nanowires, the potential should be tuned to induce a discrete state in the subgap spectrum of the nanowire.

The lifetime of the excited state was too short to measure directly but could be estimated using PAT in a double-dot configuration. At zero field, the $2e$-periodic double-dot charge stability diagram as a function of voltages $V_{\text{P2}}$ and $V_{\text{P4}}$ takes on a familiar honeycomb pattern as seen in Fig. 5(a). The gate sensor detected two types of transitions: internal, between the two islands, and external, to the left superconducting lead. Transitions to the right normal lead could also be discerned, though with less visibility. Spectroscopy was performed by irradiating the sample with microwaves of frequency $f_{\text{RF}}$. When $f_{\text{RF}}$ was comparable to or larger than the tunneling rate of Cooper pairs across the junction, $\hbar f_{\text{RF}} > E_J$, where $E_J$ is the Josephson energy, characteristic PAT features were observed in the charge stability diagram as seen in Fig. 5(b). As usual, PAT signatures appear as parallel features along the detuning axis. To quantifiy the interdot coupling, $f_{\text{RF}}$ was swept with the system tuned on $V_{\text{P4}}$ to cross the interdot charge transitions when gate P2 was also swept. The resulting 2D plot, shown in Fig. 5(c), reveals the emergence of PAT features above $11.3 \text{ GHz}$, placing a rough lower bound on $E_J$. This extends our previous work on PAT in hybrid double-dot systems to the technique of dispersive readout.

Finally, we note that the detection sensitivity presented here is comparable to previous reports of gate-based sensing. For example, using similar inductors, Colless et al. report a charge sensitivity of $6.3 \times 10^{-3} e/\sqrt{\text{Hz}}$ with a $10 \text{ MHz}$ detection bandwidth, compatible with our result. However, we do not reach the highest sensitivities realized using gate-based sensing in nanowire transistors ($37 \times 10^{-6} e/\sqrt{\text{Hz}}$ and $1.3 \times 10^{-6} e/\sqrt{\text{Hz}}$, respectively), rf-quantum
In conclusion, gate and lead-based dispersive sensing techniques were applied to Coulomb blocked single- and double-islands in hybrid semiconductor-superconductor InAs/Al nanowires. The results will be useful in employing gate and lead-assisted tunneling indicated that coherent hybridization of two superconducting islands gave an estimate for the Josephson coupling between islands, $E_J \sim 11.3$ GHz. Magnetic field compatibility of the gate sensor up to 0.6 T was demonstrated, compatible with tuning into the topological regime.

See the supplementary material for specific information regarding parameters of the resonant circuit and measurement techniques used and device fabrication methods.

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