Dispersive sensing in hybrid InAs/Al nanowires

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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,\(^1\)\(^-\)\(^4\) 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.\(^1\)\(^-\)\(^4\) Some proposals use parity-to-charge conversion for readout,\(^1\)\(^-\)\(^2\) while others use state-dependent hybridization of the Majorana mode with an ancillary system, leading to a dispersive readout signal.\(^1\)\(^-\)\(^4\)

Integrating readout circuitry into an existing electrostatic gate or ohmic contact is useful for reducing the device footprint and lead count.\(^10\)\(^-\)\(^16\) 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, \(C_T\). 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)\(^10\)\(^,\)\(^15\) and semiconductor quantum dots coupled to subgap states in semiconductor-superconductor NWs at zero magnetic field.\(^12\) Beyond qubit readout, dispersive sensing has been used to allow rapid tuning of quantum devices, yielding complementary information to conventional transport approaches.\(^13\)\(^,\)\(^14\)

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, was separated by gate-voltage-controlled barriers of InAs only (see the supplementary material for fabrication details). The detector gate, labeled P2, separated by gate-voltage-controlled barriers of InAs only (see the supplementary material for fabrication details).

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. The SNR dependence on fM from the carrier frequency Prf (before ~40 dB attenuation) is shown in Fig. 2(c). 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 Prf 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(2Δf)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

![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 Vp (blue) showing close matching. (c) Lead sensor signal Vp as a function of electrostatic plunger gate voltage Vp2 tuning the superconducting island over the Coulomb degeneracy as a function of readout frequency fR. (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.](image-url)

![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 Prf and (c) on carrier frequency fM. (d) Signal-to-noise ratio as a function of modulation frequency fM. The 3 dB frequency, ~11 MHz, indicates the bandwidth of the measurement.](image-url)
by modulation at amplitude \( V_{\text{mod}} = 30 \text{ mV} \) was \( \Delta V = e/(30 \text{ mV}/950 \text{ mV}) \approx 0.03e \), found by comparing the amplitude of \( V_{\text{mod}} \) to the amplitude needed to sweep over a full CB peak spacing (950 mV). The factor \( 1/\sqrt{2} \) accounts for the power collected from both sidebands. The resulting charge sensitivity was \( S = 1 \times 10^{-3} e/\sqrt{\text{Hz}} \).

The time needed to obtain a particular SNR at optimal values of \( f_{\text{d}} = 438 \text{ MHz} \) and \( P_{\text{d}} = -40 \text{ dBm} \) was determined by comparing the difference, \( \Delta V \), in signal \( V_{\text{eff}} \) 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 \( -0.3e \) at a repetition frequency of 2 kHz. In-phase (I) and quadrature (Q) components were recorded with a time constant of 500 ns, averaged over an integration time \( \tau \), and plotted in the complex \( I - Q \) plane. Figure 3(a) shows an example with \( \tau = 1.1 \times 10^4 \text{ points} \) averaged for \( \tau = 20 \text{ ms} \) each. SNR \( \tau \) was found by fitting to 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 \( \tau \sim 20 \mu \text{s} \).

Figure 4(a) shows \( V_{\text{tr}} \) 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 \( \mu \text{s} \) per point. At high bias, \( V_{\text{g}} > 0.2 \text{ mV} \), 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 a gate space periodicity of the island plunger P2. This makes \( C_g \approx 0.4 C_\text{C} \) 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 \( V_{\text{tr}} \) 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 \( B = 0.4 \text{ T} \) 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

![Figure 3](https://example.com/figure3.png)

**Figure 3.** (a) Two distinguishable states indicated in in-phase (I) and quadrature (Q) planes together with “Signal” \( \delta V \) defined as a separation between two IQ space maxima and “Noise” \( \sigma \) as induced broadening of the two maxima. (b) Signal-to-noise ratio \( \delta V/2\sigma \) as a function of integration time \( \tau \).

The gate voltage \( V_{P2} \) 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 16 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.

![Figure 4](https://example.com/figure4.png)

**Figure 4.** (a) Gate P2 sensing of Coulomb blockaded superconducting single-island recorded in magnitude \( V_{\text{tr}} \) and phase \( \phi \) of the demodulated signal as a function of island plunger voltage \( V_{P2} \) and bias \( V_{P4} \) Coulomb blockade evolution from the \( 2e \) to \( 1e \) periodic regime as a function of parallel to the nanowire axis magnetic field \( B \) and island plunger voltage \( V_{P2} \) (line average along the \( V_{P2} \) axis subtracted).
point contacts, or rf-SETs with typical sensitivities of $1 \times 10^{-3} \text{ eV/Hz}$. The latest results from silicon spin qubits using gate sensing reach a sensitivity of $4.1 \times 10^{-3} \text{ eV/Hz}$ with an estimated SNR = 6 for a 1 μs integration time. In our case, sensitivity could be further improved by, for example, decreasing the parasitic capacitance. The results will be useful in employing gate and lead-based dispersive sensing in topological qubit experiments without the requirement of fabricating nearby electrometers.

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. Characterization of gate sensing, using sideband modulation, at zero magnetic field, as a function of readout parameters, yielded charge sensitivities of the order of $1 \times 10^{-3} \text{ eV/Hz}$, with a detection bandwidth of ~11 MHz. In time-domain measurements, SNR of 1 was achieved for an integration time of 20 μs. Dispersive readout of photon assisted tunneling indicated that coherent hybridization of two superconducting islands gave an estimate for the Josephson coupling between islands, $E_J \approx 11.3 \text{ GHz}$. 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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