In situ tuning of dynamical Coulomb blockade in hybrid nanowire devices

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Electron interactions in quantum devices can exhibit intriguing phenomena. One example is assembling an electronic device in series with an on-chip resistor. The quantum laws of electricity of the device is modified at low energies and temperatures by dissipative interactions from the resistor, a phenomenon known as dynamical Coulomb blockade (DCB). The DCB strength is usually non-adjustable in a fixed environment defined by the resistor. Here, we design an on-chip circuit for InAs-Al hybrid nanowires where the DCB strength can be gate-tuned in situ. InAs-Al nanowires could host Andreev or Majorana zero-energy states. This technique enables tracking the evolution of the same state while tuning the DCB strength from weak to strong. We observe the transition from a zero-bias conductance peak to split peaks for Andreev zero-energy states. Our technique opens the door to in situ tuning interaction strength on zero-energy states.

Hybrid semiconductor-superconductor nanowires provide an excellent platform for the realization of various quantum electronic devices such as supercurrent transistors [1], Cooper pair splitters [2], gate tunable qubits [3], Andreev quantum point contacts [4] and possible Majorana zero modes (MZMs) [5, 6]. These devices can combine the pairing correlations from the superconductor with low dimensional gate-tunable carrier densities from the semiconductor, thus attracting much interest in both fundamental and application-wise research perspectives. A fascinating prediction is the MZMs [7, 8] which hold promise toward topological quantum computations. Though enormous experimental efforts have been spent in the quest for signatures of MZMs [9–14], the major uncertainty comes from Andreev bound states (ABSs) [15] which can form in the same device and mimic MZM signatures [16–23]. Both MZMs and ABSs can lead to similar zero-bias peaks (ZBPs) in tunneling conductance spectroscopy. Therefore, one of the top priorities along this roadmap is finding an effective diagnostic tool to distinguish these two scenarios.

Interactions could stabilize MZMs and suppress ABS signals. The mechanism is that interaction-induced renormalization sharpens the transitions between different physics to different fixed points [24]. One example is to add an on-chip resistor (a few kΩ) in series with the MZM device [25]. The resistor provides a dissipative electromagnetic environment. Small tunnel junctions embedded in this interacting environment can reveal a conductance dip near zero energy at low temperatures [26–40]. This “dissipative tunneling” is also dubbed environmental Coulomb blockade or dynamical Coulomb blockade (DCB). Since “dissipation” in the hybrid nanowire literature usually refers to soft gaps [41, 42], to avoid confusion, in this paper we adopt the term “DCB” to describe this interaction effect. The DCB strength scales with the environmental impedance that is determined by the on-chip resistor. A larger resistor leads to a stronger zero-bias conductance suppression. The key idea of the proposal [25, 43] is that increasing the DCB strength splits ABS-induced ZBPs by suppressing the conductance at zero bias. As for MZMs, the ZBP is mediated by symmetric resonant Andreev reflections [44–47]. These topological ZBPs could survive the DCB suppression and stay at the quantized value of $2e^2/h$ as long as the DCB strength is below a threshold (environmental impedance less than the resistance quantum $h/2e^2$) [25].

In recent experiments [48, 49], we have introduced DCB into hybrid InAs-Al nanowire devices where the ABS-induced ZBPs can be indeed suppressed (split). The circuit design is two-terminal where the nanowire and the resistor are connected in series. The drawback of this design is that the DCB strength is non-adjustable for a fixed barrier once the resistor has been fabricated. This makes it difficult to judge whether the measured split peaks originate from a zero-energy ABS due to DCB or just a finite-energy ABS which also leads to split peaks even without DCB. Moreover, the resistance of the resistor could only be estimated indirectly, introducing another error source. This possible error can also affect the accuracy of ZBP heights since the nanowire resistance is obtained by subtracting the resistor resistance from the
total resistance of the two-terminal circuit. In this paper, we demonstrate a new circuit with a three-terminal design that solves these problems. The DCB strength can be in situ tuned using a gate voltage on the third terminal. This technique enables us to track the evolution of the same zero-energy ABS from ZBP to split peaks by increasing the DCB strength. The resistances of the resistor and the nanowire can also be accurately measured. Our technique equips nanowire devices with a powerful knob which may facilitate more interaction-related physics experiments (not necessarily MZMs).

Figure 1a shows the scanning electron micrograph (SEM) of Device A. An InAs-Al wire is contacted by three Ti/Au electrodes (yellow). The middle electrode is connected in series with a thin resistive Cr/Au film (red, 10/2 nm in thickness), serving as the on-chip resistor. The resistance of the film, \( R \sim 11.7 \text{k}\Omega \), can be directly measured using the three-terminal set-up (see Fig. S1 for details). This is not feasible in previous two-terminal designs where \( R \) can only be indirectly inferred \([48, 49]\). The InAs nanowire diameter is \( \sim 36 \text{ nm} \) and the Al thickness \( \sim 7 \text{ nm} \). The wire growth details can be found at Ref. [50]. Three side gates (yellow, Ti/Au, thickness 5/70 nm) are used: TG tunes the barrier part; SG tunes the proximitized bulk; SW serves as a DCB switch.

The basic idea is sketched in Figs. 1b and 1c. A voltage, \( V_{\text{bias}} \), is applied to the first electrode. The current \( I \) is measured after passing through the InAs-Al wire, the second electrode and the film (\( R \)). The differential conductance of the InAs-Al wire is calculated as \( G = dI/dV \), where \( V = V_{\text{bias}} - I \times R \). The remaining InAs segment is connected to the third electrode (terminal) extending all the way to the bonding pad on the chip. The bonding pad is connected to a fridge line whose room-temperature end is floated. The large capacitance of the pad (\( C \sim 10 \text{p}\text{F} \)) short-circuits the high-frequency quantum fluctuations. Since the DCB strength is determined by the environmental impedance for a frequency range from 0 to tens of GHz, the capacitor \( C \) can significantly reduce this high-frequency impedance if the InAs segment is opened by SW. In this way, even though the DC current solely flows through the InAs-Al wire and \( R \), the third terminal (opened for DC and grounded for high frequency) can reduce the DCB contribution of \( R \). We call this regime weak DCB or even no DCB, depending on the SW tunability of the segment conductance. A zero-energy ABS, formed near the barrier, will be resolved as a ZBP. The fridge base temperature (\( T \)) is non-zero. If \( 0 \text{ K} \) could be reached, no matter how weak the DCB strength is, the zero-bias tunneling \( G \) could always be suppressed to zero, splitting the ABS-induced ZBPs. More negative gate voltage on SW can pinch off the InAs segment and restore the DCB due to \( R \) (Fig. 1c). In this strong DCB regime, an ABS-induced ZBP will split due to the strong suppression of \( G \) at zero bias. The right panels sketch the conductance line shapes (not in scale) in these two cases. Similar ideas of tuning DCB using a gate switch and large capacitors have been previous implemented in the system of two dimensional electron gases [31, 32, 37].

In Figure 2 we characterize the DCB strength in Device A. A perpendicular magnetic field of 1 T (see Fig. 1c for the \( B \) orientation) drives the device normal. DCB effects in a normal tunnel junction are well studied [26–29]. Figs. 2a-b show the characteristic suppression near zero-bias and the \( T \) dependence at \( V_{\text{SW}} = 10 \text{ V} \) (segment fully opened, weak DCB) and -20 V (segment pinched off, strong DCB). Fig. S1 shows the segment conductance as a function of \( V_{\text{SW}} \). The suppression (at base \( T \)) of zero-bias \( G \) in the weak DCB regime is indeed weaker than the strong DCB case. We used the logarithmic scale for the \( y \) axis to highlight the difference in low \( G \). Note that the tunnel transmissions for Figs. 2a and 2b are similar, as reflected by the \( G_s \) at high \( T \) (0.9 K). Keeping the same transmission is important for this comparison since the DCB strength can also be modified by the barrier transparency and scales with the Fano factor [31, 32, 40].
A more quantitative description of the “zero-bias dip” is the power law: $G \propto \max(k_B T, eV)^r$ \cite{28}, another hallmark of conventional DCB. The exponent $r$ determines the effective environmental impedance ($r \times h/e^2$) and the DCB strength. Fig. 2c shows the extracted zero-bias $G$s at different $T$s from Figs. 2a and 2b. The dashed lines are the temperature power-law fits ($G \propto T^{2r}$), revealing $r$ of 0.16 for the weak and 0.33 for the strong DCB cases. The deviations below 100 mK suggests a gradual saturation of the device electron $T$.

Figure 2d plots all the curves in Figs. 2a and 2b (over half of the bias branch) using the dimensionless units: $G(V,T)/G(0,T)$ for the $y$ axis and $eV/k_BT$ for the $x$ axis. All the curves “collapse” onto a single universal line with minor deviations (grey line for the strong and red for the weak DCB regimes). The “linear trend” in this log-log plot for the regions of $|eV/k_BT| > 1$ suggests the power law for $V$. The universal line is a prediction of the conventional DCB theory and obtained by performing numerical differentiation on the formula \cite{33}: $I(V,T) \propto V^{2r} \Gamma(r + 1 + ieV/2\pi k_BT)/\Gamma(1 + ieV/2\pi k_BT)^2$, where $\Gamma$ is the Gamma function. $r$ is the value extracted from Fig. 2c. For $T < 100$ mK, we used the extracted electron $T$ from Fig. 2c in the $eV/k_BT$ calculation for the $x$ axis in Fig. 2d. For more power law analysis and its SW tunability, see Fig. S2 for Device A, Fig. S3 for Device B and Fig. S4 for Device C.

After establishing DCB and its gate-tunable strength in the normal state regime, we now study ABSs in the superconducting regime by aligning $B$ parallel to the nanowire axis (Device A). In Figure 3a, a finite-energy ABS at zero field, revealed as two subgap peaks, moves to zero energy at $B \sim 0.7$ T. In the weak DCB regime (upper), this process reveals a level crossing and a ZBP at 0.7 T (Fig. 3b). In the strong DCB regime (lower), the crossing becomes anti-crossing and the ZBP splits at 0.7 T. This peak splitting does not originate from a finite-energy ABS but reflects the DCB effect on a zero-energy ABS. We can confirm this by tracing the same state back to the weak DCB regime. The small differences of $V_{TG}$ (and $V_{SG}$) between the weak and strong DCB regimes are to compensate for the residue crosstalk with SW, ensuring that the same ABS is being monitored during the DCB tuning.

The transition from “level-crossing-ZBP” in the weak DCB regime to “anti-crossing-split-peaks” in the strong DCB regime for the same ABS is enabled by our new

\[G(0, T) = \frac{e}{h} \text{eV}^2 \Gamma(r + 1) \Gamma(1 + \frac{eV}{2\pi k_BT})^2 \]
technique, the three-terminal circuit design (the main advance of this work). This transition can also be revealed in the gate scans of the same ABS, see Figs. 3c-d. The overall $G$ of the ABS in Fig. 3, $\sim e^2/h$, is significantly higher than that in Fig. 2, suggesting a higher barrier transparency. Higher transparency can “weaken” the DCB effect [31, 32, 40]. To verify the validity of our technique in this transparency regime, in Fig. S5 we show the power law of the normal state $G$ and the SW-tunable $r$ at $G \sim e^2/h$. Note the suppression of conductance in the normal state and superconducting (ABS) regime may differ. In the normal state, $G \propto T^{2r}$, while for ABS, $G \propto T^{4r}$ or $T^{8r}$ due to Andreev reflections. The exponents of $8r$ and $4r$ originate from the coherent and incoherent Andreev reflections, respectively [43]. Other values of exponents are also possible when different processes mix together. Nevertheless, the tunable $r$ (by SW) combined with the qualitative change from ZBP to split peaks constitute a powerful tool to in situ identify ABSs. Fig. S6 shows additional scans for intermediate $V_{SW}$ values between 10 V and -20 V, as well as $V_{TG}$ scans.

Whether tuning the DCB strength could split an ABS-induced ZBP or not depends on many factors, e.g. the device temperature, the details of the ABS and to what extend can $r$ be tuned or varied. Figs. S7 and S8 show results from Device B where the tunable range of $r$ is smaller: from $\sim 0.05$ to 0.13. This smaller $r$ makes the suppression (splitting) of ABS-induced ZBPs less effective: only part of the ZBP ranges in the parameter space show this splitting by increasing $r$ (Fig. S7). Fig. S8 monitors the continuous change of a finite-energy ABS.

The ZBPs so far are all smaller than $2e^2/h$ which are obviously not MZMs but ABS-induced. A natural follow-up question is: how will $2e^2/h$-ZBPs evolve by varying the DCB strength? A previous theoretical work [25] predicts that the height of MZM-induced ZBPs will not be affected for $r < 0.5$ and will robustly stick to the quantized value. While ZBPs forming $2e^2/h$ plateaus are rare [14], finding them in our three-terminal circuit and testing their stability by tuning $r$ are the goal of our future study. In Figure 4 we address a related question by studying a ZBP fine-tuned to $2e^2/h$.

![FIG. 4. (a) Gate dependence of a ZBP whose height is fine-tuned to $2e^2/h$ in the weak (left) and strong (right) DCB regimes. (b) Zero-bias line cuts from (a). (c) Waterfall plots for the left half of the gate ranges in (a). The top curves correspond the the gate voltages indicated by the bars in (b). (d) Waterfall plots for the other half of the gate range. The $y$ axis is in logarithmic scale.](image)
I. ACKNOWLEDGMENT

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Supplementary Information for “In situ tuning of dynamical Coulomb blockade in hybrid nanowire devices”

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Device Fabrication. The InAs-Al nanowires were transferred from the growth chip via clean room tissues onto a highly p-doped Si chip covered with 300-nm-thick silicon dioxides. Selective etching of Al on InAs-Al nanowires was performed for 10 seconds at 50 °C using Transene Aluminum Etchant Type D. The etch window was patterned using electron beam lithography (EBL). Then, Cr/Au films (10/2 nm in thickness) were evaporated next to the nanowires, acting as the dissipative resistors. Ti/Au contacts and gates were evaporated in another EBL round. Before the evaporation, argon plasma etching was performed for 70 s at a power of 55 W and a pressure of 52 mTorr to obtain good ohmic contacts on the InAs nanowires.

Measurement Setup. All transport measurements were performed in a Bluefors dilution refrigerator equipped with a 6-1-1 T vector magnet, except for the measurements of Figs. S1c-f which were carried out in an Oxford dilution fridge in another cool down. Copper powder filters and RC filters were placed on the mixing chamber plates of both dilution refrigerators. The differential conductance was measured at 40.17 Hz using a standard lock-in technique. The detailed measurement parameters for each raw data can be found in the corresponding raw data file.

Data Analysis. The analysis of the data has been briefly described in the main text of this paper. For a detailed analysis, we refer to the online repository which contains the raw data and analysis scripts.

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Fig. S 1. Circuit basic calibration. (a) Simplified schematic of the circuit diagram for the switch (SW) channel calibration. (b) The channel conductance as a function of SW gate voltage. The filter resistance and $R$ are subtracted: $G = 1/(dV_{Bias}/dI - R - 2 \times R_{Filter})$. The bias voltage is set to 1 mV to reduce possible effects of superconductivity and dynamic Coulomb blockade (DCB). The SW channel is pinched off (for the black and gray curves) at $V_{SW} = -20 V$, corresponding to the strong DCB regime. The weak DCB regime corresponds to the SW channel being opened ($V_{SW} = 10 V$). The black and gray curves were measured closely before the measurement of Figs. 2-4 while the red and rose curves were measured after. (c) Four-terminal circuit for the dissipative film calibration. (d) Differential resistance of the film, $R_{Film} = dV/dI$, as a function of bias voltage and magnetic field ($B$). (e) $I$-$V$ curves of the dissipative film at different $B$ values. The slope resolves a resistance of 11.76 k$\Omega$, slightly larger than the value in (d) (the lock-in method). (f) Temperature dependence of the film resistance using lock-in and DC methods. Resistance from the lock-in method is $\sim$200 $\Omega$ lower than the DC values. This is because that $G_{SW}$ was low (corresponds to $\sim$46 k$\Omega$) during the measurement of (d). Together with the lead and junction capacitance ($\sim$15 nF) they act as a low-pass filter for the lock-in (measurement frequency at 40.13 Hz). The DC value is more accurate and used for $R_{Film}$ throughout the analysis. The film resistance shows little change over $B$, bias and temperature, therefore could be treated as a constant value. (g) Three-terminal circuit for calibrating the dissipative films of Device B and Device C. (h) The film and filter resistance, $R_{Filter} + R_{Film} = dV/dI$, in Device B as a function of bias and $B$. (i) $I$-$V$ curves for Device B whose slope matches the values in (h). Note that $G_{SW}$ here is high (corresponds to $\sim$ 3 k$\Omega$), therefore the DC and lock-in methods gave the same resistance value. (j) Temperature dependence of the dissipative film in Device B. The filter resistance is subtracted. The error bars are estimated based on the fluctuations in (h). (k) $I$-$V$ curve of the dissipative film (and one fridge filter) in Device C at 140 mK. Black dots are measured data and the line is the linear fit.
Fig. S 2. DCB characterization in Device A. (a) Superconducting gap calibration in the weak DCB regime ($V_{SW} = 10$ V) with line cuts shown in (b). The green curve is in the pinched off regime with a relatively large residue conductance background. (c) Gap-DCB transition driven by a perpendicular $B$ (in-plane) in the weak (upper) and strong (lower) DCB regimes. (d) Line cuts at 0 T (blue) and 1 T from (c), resolving the gap and DCB dip, respectively. (e) Re-plotting the red and black curves in (d) in the logarithmic scale to highlight the low conductance difference. Note that the conductance is normalized by its value at the most negative bias. The DCB suppression (dip) for the black curve is stronger than for the red curve. (f) Gate dependence of the normal state DCB dip in the weak (upper) and strong (middle) DCB regimes. The lower panel illustrates the power law ($T^r$) exponent $r$, extracted from the temperature dependence of the zero-bias conductance. The right axis translates this $r$ to effective impedance $R = r \times \hbar/e^2$. The strong DCB regime shows a larger $r$ value than that in the weak DCB regime. The data and analysis in Fig. 2 correspond to one line cut in (f). (g) Plotting the other half bias range of Figs. 2a and 2b using dimensionless unit (like Fig. 2d). (h) Temperature dependence of the zero-bias conductance at a different $V_{TG}$ value (another line cut from (f)) in the weak (red) and strong (black) DCB regimes. (i) Plotting all the curves (at different temperatures and half of the bias voltage range) at this gate voltage using dimensionless units, similar to Fig. 2d.
Fig. S 3. DCB characterization in Device B. (a) Device SEM. (b) Conductance of the SW channel as a function of $V_{SW}$. The bias voltage is set to 1 mV. The black and gray curves correspond to different measurements. Based on this pinch off curve, the weak DCB regime corresponds to $V_{SW} = 30$ V while $V_{SW} = -40$ V for the strong DCB regime. (c-f) DCB calibration of Device B in the weak and strong regimes, similar to Figs. S2 (c-f). (g) Temperature dependence of the DCB dip in the weak (upper) and strong (lower) regimes, corresponding to a line cut in (f). (h) The zero-bias conductance extracted from (g) in the weak and strong DCB regimes. The power law exponent $r$ is extracted by fitting the range of $T > 100$ mK. (i) Re-plotting (g) using dimensionless units. The x-axis has a linear scale from -0.1 to 0.1 and a log scale outside. The lines are the universal curves, obtained based on $I(V, T) \propto V^r |\Gamma (r+1 + \frac{ieV}{2\pi k_BT})/\Gamma (1 + \frac{ieV}{2\pi k_BT})|^2$ where $\Gamma$ is the Gamma function, $r$ is the power-law exponent extracted from (h) and $T$ is the temperature. For $T < 100$ mK, the electron temperature extracted from the power law in (h) is used.
Fig. S 4. DCB characterization in Device C. All the panels are similar to the ones in Fig. S3.

Fig. S 5. DCB calibration in Device A at high barrier transparencies similar to Figs. 3-4. (a-g) similar to the ones in Figs. S4c-i.
Fig. S 6. Additional data of Fig. 3 at intermediate V_{SW} values. (a) B scans of the ZBP at different V_{SW}s. The left and the right ones are the same with Fig. 3a. (b) Waterfall plots of (a). Lower: 0 to 0.7 T, upper: 0.7 to 1 T. (c) V_{SG} scans of the ZBP at different V_{SW}s. The left and the right ones are the same with Fig. 3c. (d) Waterfall plots of (c). The case of V_{SW} = -10 V seems to have a stronger DCB strength than the V_{SW} = 0 V case, suggesting the non-monotonic tuning of DCB by V_{SW} which is consistent with Fig. S1b. (e) V_{TG} scans of the ZBP at different V_{SW}s.

Fig. S 7. In situ tuning of DCB on a zero-energy ABS in Device B. (a) V_{TG} scans of the ABS at different V_{SW}s. The ZBP in the weak DCB regime (left) becomes split peaks in the strong DCB regime (right). (b) Waterfall plots of (a). (c, d) V_{SG} scans of the ABS in the weak (upper) and strong (lower) DCB regimes. (e, f) B scans of the ABS in the weak (upper) and strong (lower) DCB regimes. (g, h) Line cuts from (e, f). The middle panels show the B range where the ZBP gets split by tuning DCB. The right panels do not show this transition. This is probably due to the small dissipative resistor of Device B (Figs. S1j and S3f): r can only be varied from 0.05 to 0.13.
Fig. S 8. In situ tuning of DCB on a finite-energy ABS in Device B. (a) Gate dependence of a finite-energy ABS (split peaks) at different $V_{SW}$. (b) Zero-bias line cuts from (a). (c) Waterfall plots of (a). For clarity, only the gate ranges on the left sides of the bars in (b) are shown. The zero-bias conductance is suppressed more in the stronger DCB regime for this ABS.

Fig. S 9. Additional data for Fig. 4. (a) $V_{SC}$ scans of the ABS. $V_{TC}$ is fixed and indicated by the bars in Fig. 4(b). (b) Zero-bias line cuts from (a). (c) Waterfall plots of (a). The upper panels correspond to the $V_{SC}$ ranges on the left sides of the bars in (b). The lower panels correspond to the $V_{SC}$ ranges on the right sides of the bars in (b). The lower panels use logarithmic scale to highlight the low conductance difference.