Quasiparticle tunneling as a probe of Josephson junction quality and capacitor material in superconducting qubits

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Non-equilibrium quasiparticles are possible sources for decoherence in superconducting qubits because they can lead to energy decay or dephasing upon tunneling across Josephson junctions (JJs). Here, we investigate the impact of the intrinsic properties of two-dimensional transmon qubits on quasiparticle tunneling (QPT) and discuss how we can use quasiparticle dynamics to gain critical information about the quality of JJ barrier and device performance. We find the tunneling rate of the non-equilibrium quasiparticles to be sensitive to the choice of the shunting capacitor material and their geometry in qubits. In some devices, we observe an anomalous temperature dependence of the QPT rate below 100 mK that deviates from a constant background associated with non-equilibrium quasiparticles. We speculate that high transmission sites/defects within the oxide barriers of the JJs can lead to this behavior, which we can model by assuming that the defect sites have a smaller effective superconducting gap than the leads of the junction. Our results present a unique in situ characterization tool to assess the uniformity of tunnel barriers in qubit junctions and shed light on how quasiparticles can interact with various elements of the qubit circuit.

There has been a tremendous amount of work recently undertaken towards building a scalable fault-tolerant quantum computer based on superconducting qubits [1, 2]. Some architectures seek to utilize quantum error correction protocols [3, 4] to mitigate errors caused by non-ideal behavior of physical qubits. However, the coherence times of such qubits still need to be enhanced to meet the requirements for the error correction threshold [5, 6]. One possible mechanism that can limit the qubit coherence times is the presence of non equilibrium quasiparticles [7–20], which are broken Cooper pairs out of the superconducting condensate at low temperatures. When a quasiparticle tunnels across the Josephson junction (JJ), there is a possibility of exchanging energy with the qubit, leading to depolarization. Additionally, the associated change in charge parity can induce a small shift in qubit frequency, producing pure dephasing [13]. Although the exact mechanism of non-equilibrium quasiparticle generation is an open question, studies suggest that external radiation [21, 22], including stray infrared photons [23, 24], ionizing radiation from environmental radioactive materials, and cosmic rays [19], lead to a higher density of broken Cooper pairs (i.e. quasiparticles). In this paper, we will focus on how intrinsic changes in two dimensional (2D) transmons such as capacitor metallization or geometrical design affect the density of non-equilibrium quasiparticles and their interaction with the JJs. We provide a novel method for probing the homogeneity of JJ barriers within the qubits by analyzing the temperature dependent behavior of quasiparticle tunneling (QPT). Finally, we will address the question of what limitation quasiparticles and the quality of the JJs impose on qubit performance and coherence.

Our measurements are based on the change in charge parity which switches sign whenever a single quasiparticle tunnels across the junction. This process is detectable since the tunneling generates a small shift in the qubit transition frequency. We focus on superconducting transmons with sufficiently large energy splittings between the odd and even charge parity branches for either the first or second excited states. Such a charge dispersion generally calls for designing qubits with smaller \( E_J / E_C \) ratio than usual transmons, where \( E_J \) is the Josephson energy and \( E_C \) is the charging energy [25]. For this study, the \( E_J / E_C \) ratio ranged between 20 and 50 for various types of qubits. We employ an experimental scheme pioneered in Refs. [13, 16] that uses a Ramsey pulse sequence to map the charge parity state to the transmon state and thus record a time sequence of the charge parity switches that displays quasiparticle tunneling events. A Fourier transform of this time sequence reveals a characteristic Lorentzian power-spectral-density spectrum (PSD) whose characteristic frequency roll-off provides the mean QPT rate. The details of the measurements can be found in the Supplementary information.

Our 2D transmon qubits are fabricated on high resistivity Si substrates, where approximately 200–400 nm thick metallization is sputter deposited and lithographically patterned using reactive ion etching to form large, coplanar capacitor paddles [26] from a variety of materials choices (see Supplementary information). Single Al/AlOx/Al junctions (see Fig. 1a) are formed using a standard Dolan bridge technique [27] and e-beam lithography. The shunting capacitor paddles are coupled to on-chip coplanar waveguide resonators enabling the read-out and qubit control. Although the standard superconductor used in such paddles is Nb, we have investigated qubits made of alternative superconducting materials, such as Ta, Al and NbN. Figure 1b shows a scanning electron microscopy (SEM) image of a standard trans-
mon with Nb paddles that are separated by a 20 µm gap. We have studied various transmons with different capacitor designs where we changed the distance between the paddles as well as the dimensions and the shape of the paddles; characteristic parameters of the qubits investigated in this study are summarized in Table 1. All devices were placed in a light-tight enclosure and measured in a cryogen-free dilution refrigerator with a base temperature of ~12 mK.

![Image](image_url)

**FIG. 1:** (a) Scanning electron microscopy (SEM) image of a JJ in one of our transmon qubits showing the superconducting Al leads sandwiching a thin layer of AlOx layer. The scale bar corresponds to 100 nm. (b) SEM image of a standard transmon incorporating a single Al/AlOx/Al JJ and Nb capacitor paddles. The scale bar corresponds to 100 µm. (c) QPT and relaxation rates vs. qubit design for a set of qubits with Nb paddles, including medians. The cartoons depict the various qubit designs used in this work from A to G.

| Design | Style         | Capacitor gap (µm) | Paddle area (µm²) |
|--------|---------------|--------------------|-------------------|
| A      | non-tapered   | 1.5                | 300x60            |
| B      | non-tapered   | 20                 | 480x60            |
| C      | non-tapered   | 20                 | 500x60            |
| D      | tapered       | 70                 | 440x120           |
| E      | non-tapered   | 70                 | 500x120           |
| F      | non-tapered   | 250                | 480x200           |
| G      | tapered       | 250                | 430x180           |

TABLE I: qubit parameters

To study the impact of the non-equilibrium quasiparticles on coherence, we compare the energy relaxation rate \( \Gamma_1 \equiv 1/\tau_1 \) to QPT rate obtained at the base temperature. Figure 1c shows such data for standard Nb qubits as a function of qubit design with increasing capacitor gap and paddle area. The QPT rates appear to be extremely slow among all the designs, making the parity switching times exceptionally long, ranging from 1 ms to up to 1.5 s. Thus, the qubits are not significantly disturbed by the QPT events during their average lifetimes. The observed QPT rates are substantially lower than those previously reported elsewhere, in which the parity switching times range between \( \mu s \) to ms [13, 16, 18, 28–32]. The median of \( \Gamma_1 \)s are at least two orders of magnitude larger than that of QPT rates suggesting that coherence of our standard devices is not currently limited by quasiparticle tunneling events.

The microscopic properties of superconductors that vary from material to material are partially dictated by the charge dynamics, i.e. densities of paired (Cooper pairs) and unpaired charge carriers (quasiparticles). One such microscopic parameter is the kinetic inductance, which arises from the inertia of the charge carriers and is inversely proportional to the superfluid density. The total kinetic inductance of a superconducting film is also inversely proportional to the cross-sectional area of the film. It can reach significantly high values for intrinsically low carrier density materials such as NbN and have an impact on the dynamics of quasiparticles. To determine how materials play a role in such dynamics and device performance, we explored alternative superconducting qubits where the capacitor paddles were made of Ta, Al and NbN and compared such devices with Nb qubits. Figure 2a and 2b show the comparison of QPT rate and qubit quality factor \( \Gamma = 2\pi f_0 T_1 \) of alternative superconductors to those of Nb for a set of larger qubit designs, where \( f_0 \) is the qubit transition frequency. One can see a discernible trend where Ta and Nb have comparable QPT rates, while NbN and Al have relatively larger values. This trend reverses when the quality factor is plotted against the same designs for the same type of qubits; the devices with Nb and Ta capacitors outperform those possessing Al and NbN capacitors in which the intrinsic QPT rate is greater. For a given qubit design, despite having the largest superconducting gap, NbN exhibits the lowest \( \Gamma \), which could be due to greater dielectric loss or possibly larger kinetic inductance [33].

In some of the devices, we observe a clear scaling in QPT with geometric parameters, such as qubit capacitor dimensions. The QPT rates of NbN devices are shown as a function of design with increasing area in paddles in Fig. 3a. The same data are shown in Fig. 3b which exhibit a nonlinear trend as a function of paddle area. The transmons with larger capacitor paddles are prone to absorb more radiation from environment leading to a higher QPT rate due to pair breaking photons. Another interesting observation one can make is that the tapered designs help to suppress the QPT related dissipation. Note the reduced QPT rate in a tapered design D (G) with respect to a non-tapered design E (F), despite possessing similar paddle areas. This suggests that the location of the paddles with respect to JJs is as important as paddle dimensions when determining the quasiparticle density in the devices [34]. In tapered designs, the distance between the capacitor paddle sides and the JJ is reduced, possessing much shorter Al leads (see the inset of Fig. 3a). This configuration may provide a more...
FIG. 2: Comparison of (a) quasiparticle tunnel rate and (b) quality factor $Q = 2\pi f_0 T_1$ of qubits with various designs and capacitor paddles composed of different superconductor materials such as Nb, Ta, Al and NbN.

effective trapping mechanism for quasiparticles diffusing from the capacitor pads to the Al leads. Furthermore, the paddles of non-tapered designs have long and narrow constrictions while such constrictions are absent in tapered designs. These constrictions might contribute to larger kinetic inductance in non-tapered designs, leading to their higher QPT rates. Finally, the lack of narrow constrictions in tapered designs could result in less current crowding, which we speculate could also lead to lower QPT rates in tapered designs.

To better understand how the design of the qubits can affect the quasiparticle generation and to determine the role of the tapering on QPT, we apply finite element method, electromagnetic simulations of our device geometries using HFSS (Ansys, Inc). In this model, we treat a single transmon qubit as an antenna by considering the reciprocity between radiation absorbed by this qubit and radiation emanating from the qubit in its excited state within a lossy environment. We calculate the real part of the admittance $\text{Re}[Y(\omega)]$ of the qubit junction, which is proportional to the effective relaxation time from this loss mechanism, $\text{Re}[Y(\omega)]/C_q$, where $C_q$ is the total capacitance of the qubit [35]. Because the magnitude of $\text{Re}[Y(\omega)]$ depends inversely on the square root of the conductivity of the qubit environment in the limit of low loss, we use a normalized quantity to compare the different designs. This metric follows an exponential trend with respect to qubit paddle area as shown in Fig. 3c and is expected to be linearly proportional to the relaxation rate [10, 36]. Mean values of experimentally obtained QPT rates for NbN and Al qubits are plotted in Fig. 3d as a function of simulated $\text{Re}[Y(\omega)]$, confirming a linear dependence as the model dictates. However, the slopes of linear fits to the data from tapered and non-tapered designs are substantially different, reflecting the greater sensitivity that non-tapered capacitors possess to environmental radiation due to the possible mechanisms discussed earlier. Note that the vertical axes of NbN and Al devices differ by factor of 2.8, which could be attributed to a difference in surface impedance of the paddle metallization.

Having established that both the material composition and geometrical design of the transmon paddles play an important role on QPT, we now turn our focus on the relation between the JJ quality and QPT rates. The QPT-induced relaxation rate scales linearly with quasiparticle density, which is an exponential function of the superconducting gap and temperature [37]. We utilize the temperature dependence of the QPT rate to infer QP distributions and evaluate the oxide barrier uniformity of the JJs. Figure 4a shows such data from 10 qubits with NbN paddles on the same chiplet (design-E) sharing the same fabrication conditions. One can clearly observe two different forms of temperature behaviour of quasiparticle tunneling at low temperatures. Despite the variation in QPT rate at the base temperature, the blue curves display a behavior consistent with a distribution of conventional, non-equilibrium quasiparticles and an upturn in QPT with increasing temperatures signaling that
thermal quasiparticles dictate the tunneling across the junction. The red curves, however, demonstrate an unusual departure from the characteristic flat background of non-equilibrium quasiparticles at low temperatures before thermal quasiparticles dominate. We observed both type of temperature dependence in a substantial number of qubits regardless of material or geometry of the capacitor paddles; this suggests that the JJ is the primary element responsible for the anomalous characteristics rather than any other part of the qubit circuit.

If the JJ possesses an ideal tunnel barrier, i.e. the dielectric layer is homogenous and free of defects throughout the junction, the QPT rate can be modeled by [10]:

\[ \Gamma_{qp} \sim \Gamma_{qp}^{ne} + \sqrt{\frac{4\omega_k B T}{\hbar \pi}} e^{-\Delta_0/k_B T}, \]

where \( \Gamma_{qp} \) exponentially scales with a single superconducting gap \( \Delta_0 \). The term \( \Gamma_{qp}^{ne} \) represents the non-equilibrium quasiparticles and corresponds to the flat background in the temperature sweeps. Now we consider a JJ with regions of higher transmission associated with a series of suppressed effective energy gaps \( \Delta_i \), while the majority of the junction barrier corresponds to \( \Delta_0 \). The cartoon in the inset of Fig. 4a depicts the energy spectrum of effective energy gaps along the junction co-existing with the majority gap. The composite QPT rate can be written as a summation of parallel contributions associated with the majority gap and smaller effective energy gaps:

\[ \Gamma_{qp} = \Gamma_{qp}^{ne} + \sum_i \Gamma_{qp}^{i}, \]

For simplicity we consider only one additional channel representing the smallest effective gap, \( \Delta_1 \), which dominates the other parallel loss mechanisms. The QPT rate can be written as (see Supplementary information):

\[ \Gamma_{qp} \sim \Gamma_{qp}^{ne} + \sqrt{\frac{4\omega_k B T}{\hbar \pi}} \left[ e^{-\Delta_0/k_B T} + A e^{-\Delta_1/k_B T} \right], \]

where \( A \) represents a collection of terms associated with the higher transmission path:

\[ A = x_1 \frac{\pi}{\hbar \omega^2} \frac{\Delta_1}{R_1 C_q}, \]

\( x_1 \) refers to the relative fraction of quasiparticles tunneling through \( \Delta_1 \), its effective normal-state resistance \( R_1 \) and the total qubit capacitance \( C_q \).

Figure 4b shows fits (black curves) to the data from four representative NbN qubits. Two of these curves have conventional behavior with a nearly constant non-equilibrium QPT rate up to \( \sim 100 \text{ mK} \) and the other two show strong deviations. The inferred superconducting gaps for Al (\( \Delta_0 \)) are very similar regardless of the model used (i.e. one superconducting gap versus two gaps), which is not the situation for the reduced superconducting energy gaps (\( \Delta_1 \)). We speculate that the extent of variation in \( \Delta_1 \) is due to the difference in barrier quality of the junctions in different qubits despite being fabricated in the same manner and having the same design. This variability is endemic to many instances of Al/AlO\(_x\)/Al Josephson junction fabrication, which is usually observed in the critical current [38] or the corresponding junction frequency [39], and could result from subtle differences in the homogeneity of the angular deposition of Al, oxidation process, or photoresist quality across the wafers. We argue that differences in the trap density or oxide thickness within the junction, which have been proposed as responsible for critical current fluctuations and enhanced conductivity [40, 41], may also correspond to these paths of increased QPT.

We have also collected the QPT rate vs. temperature data and analyzed it according to the models described above for qubits where the paddle metallization is Nb, Ta, or Al. Figure 4c shows the histograms formed from the extracted fit parameters for the Al superconducting energy gap \( \Delta_0 \) and the smaller effective gap \( \Delta_1 \). Each histogram includes results from 30–60 qubits with various capacitor styles and demonstrates a relatively small variation of \( \Delta_0 \) with median values of designs ranging between 183 and 193 \( \mu \text{eV} \), which is consistent with literature values of the Al superconducting gap for similar films [8, 11, 42]. We confirmed our results with independent cryogenic current-voltage measurements (see Supplementary information), which found a superconducting gap value of 185 \( \mu \text{eV} \) for slightly larger junctions with 200 nm Nb paddle metallization. However, we observe a broader distribution of \( \Delta_1 \), with median values of various designs ranging from 5 to 30 \( \mu \text{eV} \), signaling a significant junction-to-junction variation. A majority of the analyses shows that the reduced effective superconducting gap associated with possible trap states or enhanced conduction in the junction is approximately 10% of the dominant Al gap (see Supplementary information).

In conclusion, we have demonstrated a few orders of magnitude improvement on quasiparticle switching times over reported values, which translates into exceptionally low QPT rates. These direct measurements of switching times appear to be much longer than qubit lifetimes giving evidence that quasiparticles will not limit the coherence in the near future as we are trying to reach higher coherence times. We have found that the quasiparticle dynamics is intimately related to material type and geometry of the capacitors shunting the JJs. We have observed low temperature anomalies in the tunneling rate of non-equilibrium quasiparticles that are proposed to originate from defects or trap states in the insulating barrier associated with either high transmission or lower effective superconducting gap. Thus, careful analysis of temperature dependence of the QPT provides a valuable in situ characterization of tunnel junctions within superconducting qubits.

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FIG. 4: a) Raw data of QPT rate vs. temperature for ten transmons with NbN capacitor paddles (with design-E). The functional form of the temperature dependence shows significant variation despite that they share the same fabrication conditions. Note the difference between red and blue curves. The inset is a cartoon illustrating the energy spectrum of a junction where the barrier has high transmission sites. (b) Fits (black curves) to the QPT rate vs. temperature data (colored markers) showing a good agreement and consistency of the inferred Al superconducting gaps from both models. (c) The histograms built from fit parameters for various qubits with different type of paddle metallization.

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I. SUPPLEMENTARY INFORMATION

A. Qubit fabrication

Transmon qubits employed in this study were fabricated using several different types of shunting capacitor metallizations. The films were deposited on high resistivity Si wafers after native silicon oxide removal with a HF solution. 200nm Nb was sputter deposited on Si(100) at room temperature, 200nm Ta on 15nm TaN (to form the alpha Ta phase) was sputter deposited on Si(100) at room temperature, 200nm NbN was reactively sputtered with an Ar and N₂ gas mixture on Si(100) at 550°C, and 200nm Al was sputtered on Si(111) at 300°C. Nb, Ta, and NbN were subtractively etched with a Cl₂ based reactive ion etch using standard lithography. Al/AlOₓ/Al junctions are formed by shadow mask evaporation using e-beam lithographic patterning of PMMA/MMA resist in contact with the capacitor. An ion mill was used immediately before the evaporation to remove the capacitor native oxide to improve contact.

B. Detection of charge-parity jumps

The protocol developed in the pioneering work of Riste [13] and Serniak [16, 17] was adopted for this work with one significant modification to facilitate QPT measurements on transmons with E_J/E_C ≃ 20 or higher. This method relies, as in previous work, on mapping the charge-parity (CP) state of the transmon to the transmon state using a Ramsey pulse sequence with delay time between the Ramsey π/2 pulses chosen to give ±π/4 evolution in phase with positive phase evolution for one CP state and negative for the other. The second Ramsey π/2 pulse is shifted 90° in phase to map this phase evolution to the ground state population for one CP state and the excited state for the other. Measurement of the transmon state before and after this Ramsey sequence gives the CP state. A rapid repetition of this sequence constitutes a time series of samples of the CP state thus observations of QPT events that switch the CP state. This time series is Fourier transformed, and the resulting power-spectral-density (PSD) of switching events fitted to a Lorenzian
function whose width yields the mean QPT rate. Several such PSD’s can be averaged to increase the SNR. These experiments are interleaved with simple Ramsey measurement of the CP splitting which is used to set the correct delay time to achieve the desired $\pi/4$ phase evolution. Drifting of the CP splitting due to changes in the overall charge environment of the transmon are detected this way, and if significant drift occurs during a sampling sequence (each typically lasting for a second or so), the data is discarded.

When $E_J/E_C$ is chosen to be large enough to minimize the charge sensitivity of the transmon qubit, the charge dispersion of the 0-1 transition becomes small enough that the Ramsey delay time becomes inconveniently long, reducing the CP state sampling rate and also impacting the fidelity of the CP state mapping due to increased probability of relaxation events. To measure QPT in such devices, we employ a modified pulse sequence. Immediately following the first measurement pulse, we transfer the populations of the 0 and 1 transmon states to the 1 and 2 states, respectively, using a pulse, we transfer the populations of the 0 and 1 transitions back to the 0 and 1 states by two more pulses before the second measurement pulse. The rest of the protocol proceeds as before, with Fourier transformation and fitting of a Lorentzian function to the PSD. In transmons with intermediate values of $E_J/E_C$, QPT rates can be determined using both the 0-1 and 1-2 transitions and compared. We consistently observe excellent agreement between the two methods, and generally higher overall CP mapping fidelity using the 1-2 transition.

The CP mapping technique relies on setting the rf carrier frequency midway between the charge-parity split transmon transition frequencies. We achieve this using a Ramsey pulse sequence with linearly increasing phase of the second Ramsey $\pi/2$ pulse to mimic an effective frequency offset. This allows the observation of the beat frequency between the two transition frequencies as well as the residual offset between the rf carrier and the average of the two frequencies, and permits accurate adjustment of the frequency.

### C. QPT model

Following the work of Catelani [10], we consider quasiparticle tunneling across the Josephson junction in a transmon qubit to be composed of parallel paths, including channels of high transmission probability [43]. In the case of a homogeneous junction, the total quasiparticle tunneling rate, $\Gamma_{tot}$, consists of both non-equilibrium and thermal quasiparticle contributions, where the latter can be related to the real part of the qubit admittance, $\text{Re}[Y]$, and the qubit capacitance, $C_q$:

$$\Gamma_{tot} = \Gamma_{ne} + \frac{\text{Re}[Y]}{C_q}$$

Let us assume that the superconducting gap of the junction leads, $\Delta_0$, is much larger than the thermal energy, $k_B T$, so that the Fermi-Dirac distribution, which governs the quasiparticle number density, can be approximated by $\exp(-E/k_B T)$, where $E$ is the quasiparticle energy. $\text{Re}[Y]$ can be simplified to form:

$$\text{Re}[Y] \sim \frac{1}{R_n} \left[ e^{\frac{\hbar}{2k_B T \pi}} + e^{-\frac{\hbar}{2k_B T \pi}} \right] K_0 \left( \frac{\hbar \omega}{2k_B T} \right) e^{-\Delta_0/k_B T}$$

where $R_n$ is the normal state resistance of the junction, $\omega$ is the qubit transition frequency and $K_0$ is the complete elliptic integral of the first kind. Through the use of the Ambegaokar-Baratoff relation [44], we can express $R_n$ in terms of the gap and junction inductance, $L_J$:

$$\frac{1}{R_n C_q} = \frac{\hbar}{\pi \Delta_0 L_J C_q} = \frac{\hbar \omega^2}{\pi \Delta_0}$$

where the last step simply reflects that the angular frequency is the square root of $1/(L_J C_q)$. Combining Eq.’s 5 to 7, and assuming that the qubit transition energy, $\hbar \omega >> k_B T$, we arrive at Eq. 1 in the main text:

$$\Gamma_{qp} \sim \Gamma_{ne}^{qp} + \sqrt{\frac{4 \omega k_B T}{\hbar \pi}} e^{-\Delta_0/k_B T}$$

If high transmission paths exist for quasiparticles to tunnel through the junction, $\text{Re}[Y]$ will now consist of both non-equilibrium and thermal quasiparticle contributions, where the latter can be related to the real part of the qubit admittance, $\text{Re}[Y]$, through the Ambegaokar-Baratoff relation [44], we can express $R_n$ as shown in Eq’s 3 and 4 in the main text.

$$\text{Re}[Y] \sim \frac{1}{R_n} \left[ e^{\frac{\hbar}{2k_B T \pi}} + e^{-\frac{\hbar}{2k_B T \pi}} \right] K_0 \left( \frac{\hbar \omega}{2k_B T} \right) e^{-\Delta_0/k_B T}$$

where $x_1$ refers to the relative fraction of quasiparticles that tunnel through this path and we again assume that $\Delta_1 >> k_B T$. However, we cannot apply the Ambegaokar-Baratoff relation to simplify $R_1$. In the limit of $\hbar \omega >> k_B T$, the resulting formula for the total QPT rate can be approximated as:

$$\Gamma_{qp} \sim \Gamma_{ne}^{qp} + \sqrt{\frac{4 \omega k_B T}{\hbar \pi}} e^{-\Delta_0/k_B T} + \frac{x_1 \pi}{\hbar \omega^2 R_1 C_q} e^{-\Delta_1/k_B T}$$
FIG. 5: (a) Fits provided by the model in Eq. 3 on the temperature dependence of the QPT data from nine qubits with Ta capacitor paddles. All qubits are from design-D.

D. Variation in Fit Parameters

We modeled the temperature dependence of QPT rate by using Eq. 3 for qubits with various capacitor paddle materials. Figure 5 shows fits (colored curves) to the measured data (colored markers) from nine design-D qubits with Ta capacitor paddles sharing the same deposition conditions. We applied the same analyses on various designs. The inferred fit parameters plotted against Ta qubit design are shown in Fig. 6a-d. The non-equilibrium QPT shows a geometrical dependence on the capacitor paddles as seen in Fig. 6a. We observe a relatively tight distribution of superconducting gap values for Al (Fig. 6b) and a wider distribution of $\Delta_1$ values (Fig. 6c), giving evidence for the variation in junctions depending on the defect density. The coefficient A values shown in Fig. 6d are consistently small, being of order $\approx 10^{-8}$. This is expected because of the small fraction of quasiparticles tunneling across $\Delta_1$.

FIG. 6: Extracted fit parameters provided by the model in Eq. 3 as a function of device design for the qubits with Ta capacitors. One can see the variation of the inferred values from design-A to G.

E. Cryogenic Current-voltage measurements

To corroborate the superconducting gap of Al used in our JJs, independent IV measurements were performed on larger junctions with the same thickness of Al at $\sim 12$ mK as shown in Fig. 7. The magnitude of the $\Delta_0$ is determined as 185 $\mu$eV from the knee of the IV characteristics, in good agreement with our estimations from temperature dependent QPT measurements.

FIG. 7: Cryogenic current-voltage measurements demonstrating the value of superconducting gap for Al thin film of the junctions.