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Local tunability in a multi-port SQUID by an injection current

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Abstract

The tunability in Josephson junctions is foundational to the superconducting classical and quantum applications. Here, we demonstrate the local manipulation of supercurrent realized in a superconducting quantum interference device (SQUID) with two Nb/TiO_x/Nb Josephson junctions that is biased at the TiO_x layer. Our measurements indicate that the multi-port device allows for an easy and *in situ* tunability of the supercurrent. The control mechanism can be finely explained by simple yet valid theoretical methods, which take an effective electronic temperature across the SQUID and the self inductive magnetic flux into account. Furthermore, we show that the phase difference and kinetic inductance of this device can be tuned locally via the injection current. Thus, the device provides perspective for several superconducting electronics such as tunable superconducting circuits, sensitive magnetometry, and fast digital elements.

Supplementary material for this article is available [online](#)

Keywords: SQUID, current injection, local tunability, parameters

(Some figures may appear in color only in the online journal)

1. Introduction

Controllability and coherence of superconducting order parameters play a significant role in quantum information science and engineering technology [1, 2]. Over the past few decades, superconducting quantum interference device (SQUID), combining the physical phenomena of flux quantization and Josephson effect [3–6], acts as the quantum two-level system and flux-tunable inductors have been successfully incorporated into superconducting circuits to realize the flux qubits [7, 8] and tunable resonators [9]. In such systems, external magnetic flux (Φ_e) has generally been utilized to control the supercurrent of the SQUID globally. However, from a

scientific-engineering perspective, the ability to control both the supercurrent, phase difference, and parameters locally is essential for next-generation functional quantum circuit integration [10–13]. Very recently, the local tunability of supercurrent has been demonstrated by introducing new materials and applying an electrostatic field, e.g. in 2D gases in InAs [14], graphene [15] and carbon nanotube [16], and in metallic nanowires [17, 18]. Nonetheless, a large gate voltage compared with the characteristic voltage of Josephson junction is required to change the carrier density in such field-effect superconducting devices which may limit its practical applications.

A promising alternative to locally manipulate supercurrent is achieved by sending a relatively small injection voltage into the N-part of a superconductor-normal metal-superconductor (SNS) Josephson junction [19, 20]. This concept to control the

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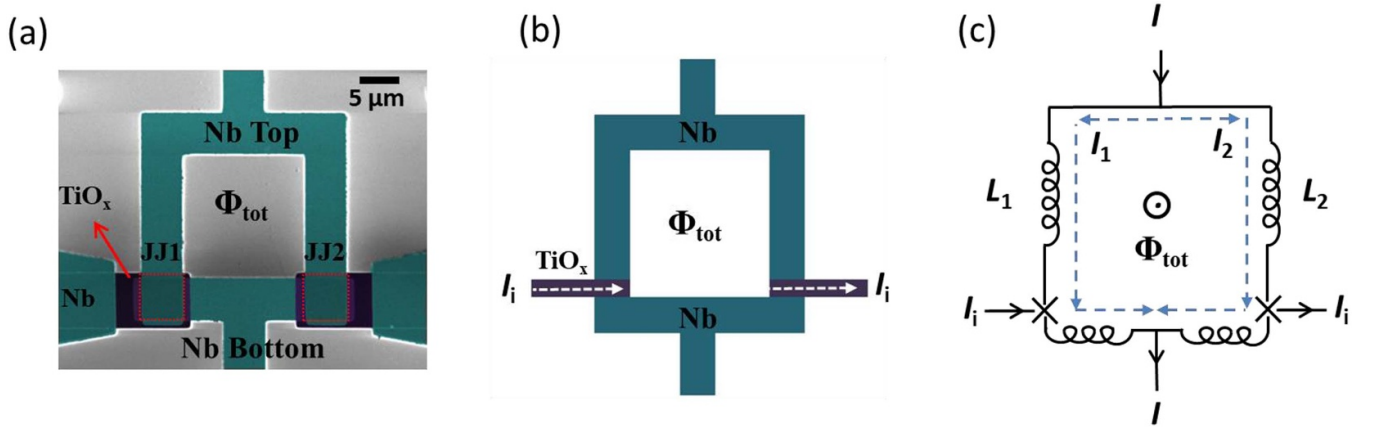


Figure 1. (a) False-color SEM of the current injection controllable SQUID. The cyan and purple areas are the Nb electrodes and the TiO_x layers, respectively. The areas enclosed by the red dashed line are the Nb/ TiO_x /Nb sandwiched Josephson junctions. The scale bar corresponds to 5 μm . (b) Schematic cross-section of the device. (c) The equivalent electrical circuit of our device. The inductances in the left and right arms of the loop are given by L_1 and L_2 , respectively. The bias current I flowing through the two Josephson junctions is I_1 and I_2 . The current I_i is injected from the barriers of junctions.

supercurrent has been successfully demonstrated in Josephson barriers in Au [21] and TiO_x thin films [22], 2D electron gas (2DEG) [23], and InAs nanowire [24]. Hence, controlling the Josephson junctions by the injection current flowing through an additional non-superconductive contact into the barrier has become a desirable alternative to gating.

In this paper, we demonstrate the local tunability in a multi-port SQUID with two Nb/ TiO_x /Nb Josephson junctions. In the device layout, we extend the TiO_x barrier outside the area of the junctions. The TiO_x layer is metallic, which allows us to send in-plane currents from the TiO_x barrier flowing through the SQUID. In this case, the biased injection currents locally modulate self inductive magnetic flux and increase the electronic temperature, causing the change of the phase difference and the critical current of the SQUID. To explain this observation, we developed a simple yet effective model that helps linearize the behavior of the SQUID for all bath temperatures. We also find the flux modulation depth of the critical current is increased by the injection current. This behavior is attributed to the kinetic inductance related to the London penetration length of our superconducting electrodes. Additionally, we obtained the specific capacitance value $C_s \sim 155 \text{ fF } \mu\text{m}^{-2}$ with the error of $18 \text{ fF } \mu\text{m}^{-2}$ in our junctions via the measurements. In contrast to previous works which demonstrated that the tunability of the parameters in SQUID was usually realized either through an external magnetic field or an additional injection current [25, 26], our multi-port SQUID exhibits other valuable characteristics: (a) it allows for the local manipulation of both the amplitude and phase of supercurrent by simply biasing the additional leads; (b) it can be easily integrated with different superconducting circuits, enhancing their functionality; and (c) it can be modulated rapidly, providing possible applications in the high-speed electronics. The local tunability, ease of integration, and relatively fast response speed make our device a good choice to develop several superconducting electronics with a wide range of possible applications.

2. Sample design and fabrication

Figure 1(a) shows the scanning electron microscope (SEM) image of a current injection controllable dc SQUID. The device was accomplished by patterning a 60 nm thick bottom Nb electrode on a sapphire substrate via the laser-writing photolithography and lift-off technique. Then the bottom Nb surface was etched down about 5 nm, and a 10 nm Ti layer was subsequently defined and sputtered on the top of the bottom Nb electrodes to obtain a good contact. We next oxidized the Ti layer in pure oxygen for 3 h at a pressure of 500 Pa to form the TiO_x barrier. The 60 nm Nb top electrodes are finally patterned, overlapping the TiO_x barrier and bottom Nb electrodes. The monolithic dc-SQUID is realized in the form of two $5 \times 5 \mu\text{m}^2$ vertical Nb/ TiO_x /Nb Josephson junctions, symmetrically incorporated into a $15 \times 15 \mu\text{m}^2$ Nb superconducting loop. The length of the TiO_x stripe is 10 μm , and its width is 7 μm . Figure 1(b) shows the schematic cross-section of our multi-port SQUID. As illustrated by the equivalent electrical circuit shown in figure 1(c), The bias current I flowing through the two Josephson junctions is I_1 and I_2 . We can write for the bias current $I = I_1 + I_2$ according to Kirchhoff's law. The TiO_x stripe lines are used to introduce a current injection I_i flowing through the SQUID from the barrier, thereby tuning the phase and amplitude of the Josephson coupling.

3. Measurements and results

We start the fundamental investigation of our SQUID by measuring its basic transport properties. Figure 2(a) shows current-voltage characteristics (IVC) at 2.8 K, which display a critical current (I_c) of about 125 μA and a small retrapping current (I_r) of about 110 μA . The values of the I_c and I_r were extracted using a threshold voltage of $V_{th} = 10 \mu\text{V}$. The hysteresis here can be attributed to the capacitance in the resistively and capacitively shunted junction model [22]. The clear

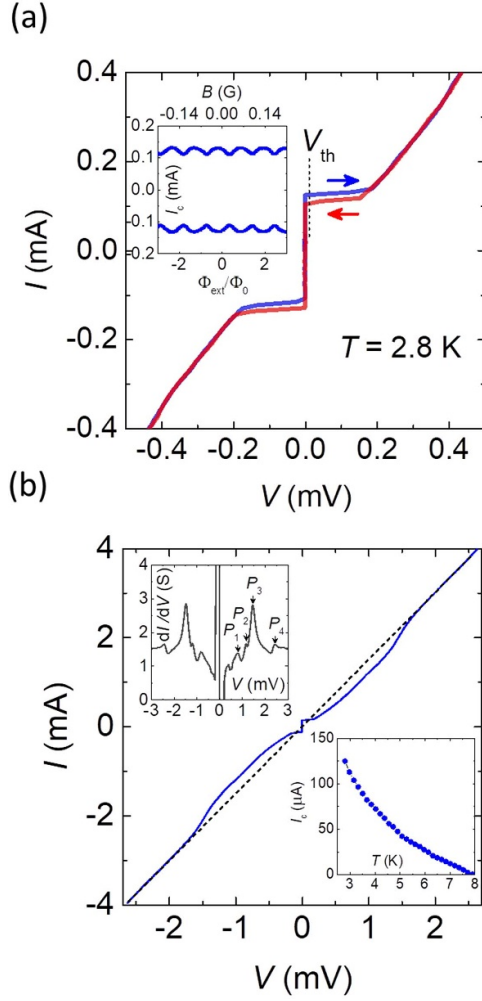


Figure 2. Transport properties. (a) The current–voltage characteristics (IVC) of our SQUID at a bath temperature of 2.8 K, with a current sweep from negative to positive (blue line) and vice versa (red line). The critical current I_c and return current I_r are obtained using threshold voltage $V_{th} = 10 \mu\text{V}$ as indicated by the black dashed line. The inset shows the critical current (I_c) oscillation under externally applied magnetic flux. (b) IVC on an expanded voltage scale at 2.8 K. The IVC above 2.6 mV, exhibited linear behavior, indicated by the black dashed line passing through the origin. The left inset shows the differential conductance (dI/dV) as a function of the voltage. MAR peaks are denoted by the arrows. The right inset shows the temperature dependence of the SQUID critical current I_c .

SQUID behavior can be seen from the inset of figure 2(a), the critical current I_c of our devices undergoes periodic oscillations in external magnetic field B . The period of the interference pattern is 0.07 G, corresponding to an effective area of about $295 \mu\text{m}^2$. The slight differences to the whole SQUID loop area ($\sim 225 \mu\text{m}^2$) may be caused by the flux focusing on the Nb loop electrodes [27]. From the device flux modulation depth $\Delta I_c/I_c^{\max}$, with ΔI_c being the difference between the maximum critical current $I_c^{\max}$ and the minimum critical current $I_c^{\min}$ under external magnetic flux Φ_e , we can derive the screening parameter β_L of the SQUID at 2.8 K via the β_L vs $\Delta I_c/I_c^{\max}$ calibration referring to [3]. Here, the $\beta_L \approx 4.7$ can be obtained. Moreover, the SQUID loop inductance $L \approx 12.5$

pH can be obtained by the equation $\beta_L = 2\pi I_c L / \Phi_0$, Φ_0 is the quantum flux.

To verify the accuracy of our above estimation, we calculate the SQUID loop inductance L from the composition of the device. In this way, the phase difference $\Delta\delta$ plays a vital role in the operation of SQUID, which is related by:

$$\Delta\delta = \delta_2 - \delta_1 = \frac{2\pi}{\Phi_0} (\Phi_e + \Phi_s) \quad (1)$$

where δ_1 and δ_2 are the phase difference of the two junctions, Φ_e is the externally applied magnetic flux, $\Phi_s = LJ$ is the self-flux from the loop circulating current J and the SQUID inductance L . We consider the contributions of the geometric inductance L_g and kinetic inductance L_k in the SQUID inductance. The $L_g \approx 8.9$ pH is straightforwardly calculated by the Comsol Multiphysics according to the device geometry. The kinetic inductance L_k is given by [28]:

$$L_k = \frac{\mu_0 \lambda^2 l}{wt} \quad (2)$$

where μ_0 is the vacuum permeability, w is the linewidth, λ is the London penetration depth of Nb electrodes, l is the length of loop circumference, and t is the thickness of the electrodes. $L_k \approx 4.7$ pH is calculated by using $\lambda_{\text{Nb}} = 130$ nm at 2.8 K [29]. In this case, the SQUID inductance $L = L_g + L_k \approx 13.6$ pH is derived, which is close to the value calculated by the modulation depth, indicating that the SQUID inductance obtained from the critical current modulation depth is reliable.

Figure 2(b) presents an expanded scale of IVC at 2.8 K. At a higher voltage above 2.6 mV, the IVC becomes linear (black dashed line), crossing the origin with the normal-state resistance R_n of 0.67Ω . The nonlinear IVC below 2.6 mV indicates the multiple Andreev reflection (MAR) in our devices [30], which can be clearly seen from the differential conductance (dI/dV) versus V curve shown in the left inset of figure 2(b). The MAR occurs at $V_n = 2\Delta_{\text{Nb}}/ne$, where n is an integer and $\Delta_{\text{Nb}} = 1.25$ meV is the superconducting gap of Nb. Here, the peaks P_1 (0.8 mV), P_2 (1.22 mV), and P_4 (2.45 mV) correspond to the subgaps for $n = 3, 2$, and 1 of the MAR, respectively. An additional main peak occurs at $P_2 = 1.5$ mV, indicating that our junction is in the essence of the SNIS (superconductor–normal metal–insulator–superconductor) type, similar to the previous report on a single junction [22]. The insulating layer in our device presumably originated from higher oxidation stages of TiO_x with $x = 2$ at the Nb/ TiO_x interface. The right inset of figure 2(b) shows the temperature dependence of critical current $I_c(T)$. The $I_c(T)$ curve presents a linear behavior for temperature between 5 K and 7.7 K and a negative curvature at temperature down to 2.8 K, a behavior which is very close to the previous report in Nb/Al/ AlO_x /Nb junctions [31].

To investigate the impact of the current injection on the SQUID properties, we swept the IVCs for different injection currents applied to the TiO_x stripes. Figure 3(a) shows a color-plot of differential resistance (dV/dI) as a function of bias current I , injection voltage I_i and normalized self flux (Φ_s/Φ_0), exhibiting clear periodic oscillations and suppressions in I_c .

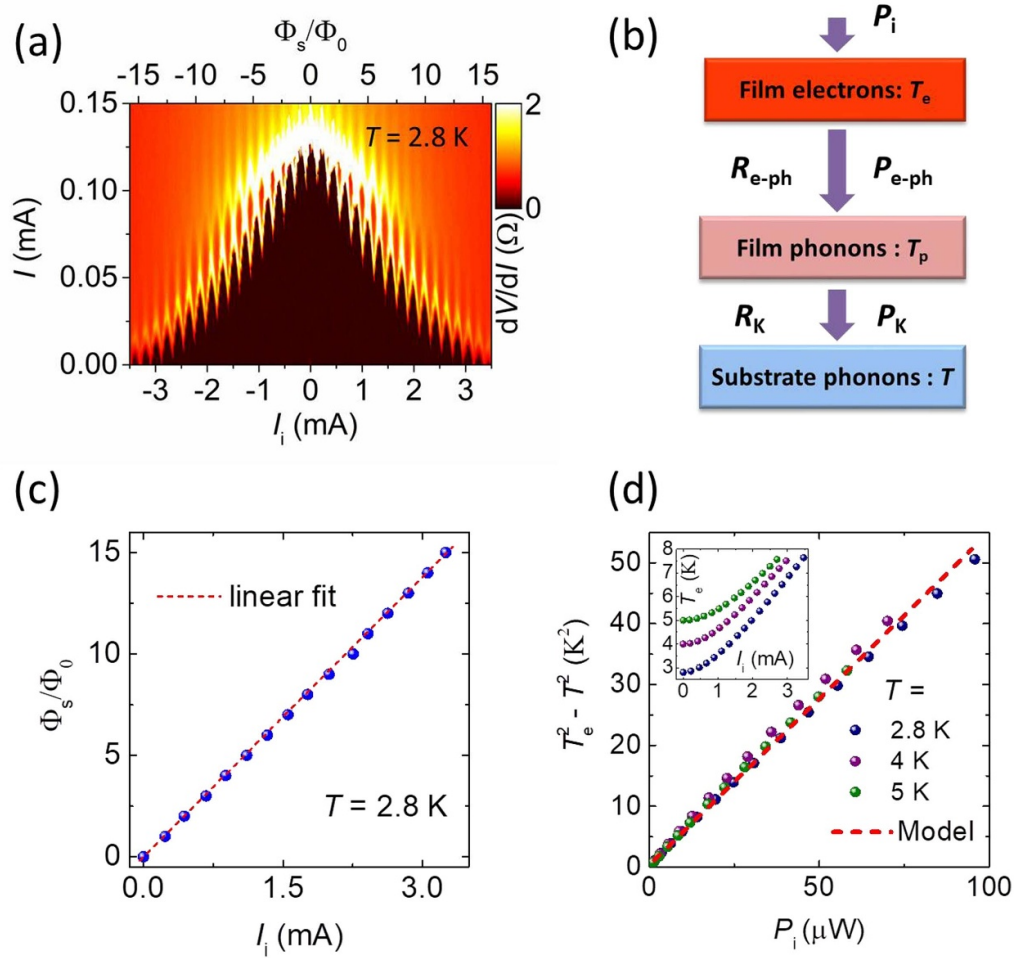


Figure 3. Current injection in the device. (a) Color-scale representation of a differential resistance (dV/dI) map measured at a bath temperature of 2.8 K as a function of the injection current (I_i), normalized magnetic flux (Φ_s/Φ_0), and the bias current (I). A current offset is eliminated for clarity. (b) The thermal model schematic for the power flow for the metal film on a substrate. (c) Extracted normalized magnetic flux (Φ_s/Φ_0) as a function of the injection current (I_i) shows a linear behavior. (d) The relation between the value of $T_e^2 - T^2$ and injection power P_i at different bath temperatures (circles) in comparison with the numerical model (dashed line). Inset shows the I_i dependence of electronic temperature T_e for different bath temperatures.

The periodic oscillations arise due to the phase difference $\Delta\delta$ changing with the I_i across the device [32, 33]:

$$\Delta\delta = \frac{2\pi}{\Phi_0} (\Phi_e + \Phi_s) \quad (3)$$

where $\Phi_s = L_1 I_1 - L_2 I_2 + L_i I_i$ is the flux generated by the bias current and injection current (cf figure 1(b)). L_1 , L_2 , I_1 , and L_i are the left and right inductance, the injection current and its effective inductance, respectively. Hence, the periodic critical current peaks in figure 3(a) is caused by the quantization of the self magnetic flux $\Phi_s = n\Phi_0$, where n is an integer. As a result, we are able to *in situ* control the phase difference $\Delta\delta$ of the SQUID with an injection current I_i . We extracted the oscillation peaks as a function of injection current (I_i) depicted in figure 3(c), exhibiting a linear relationship between the I_i and Φ_s/Φ_0 . The effective inductance $L_i \sim 9.3$ pH is obtained from the slope $\Delta\Phi_s/\Delta I_i$. We note here that the effective inductance L_i has both the geometric contribution and the

kinetic contribution [34, 35]. However, the L_i is smaller than the SQUID inductance L in our experiment, which could be attributed to the different way of injection current flowing the loop.

The complete suppression of the critical current I_c with injection current I_i , shown in figure 3(a), is expected to be the elevation of electronic temperature T_e in our device by hot-electrons. As illustrated in figure 3(b), when we apply a power P_i to the metal film, the heat power will be transferred to the phonons in the metal through the electron–phonon interaction. Then the power of phonons will flow to the substrate via the metal film/substrate Kapitza boundary resistance R_K , causing the device effective temperature T_e to rise until it reaches a steady-state value [36]. In the case of high substrate temperature (typically, $T > 1$ K), the interaction between the electrons and the phonons in metal is small, and the power is proportional to the square of substrate temperature ($P_i \propto T^2$) [24, 37]. At low temperature (typically, $T < 1$ K), the thermal resistance R_{e-ph} is greatly increased while the Kapitza

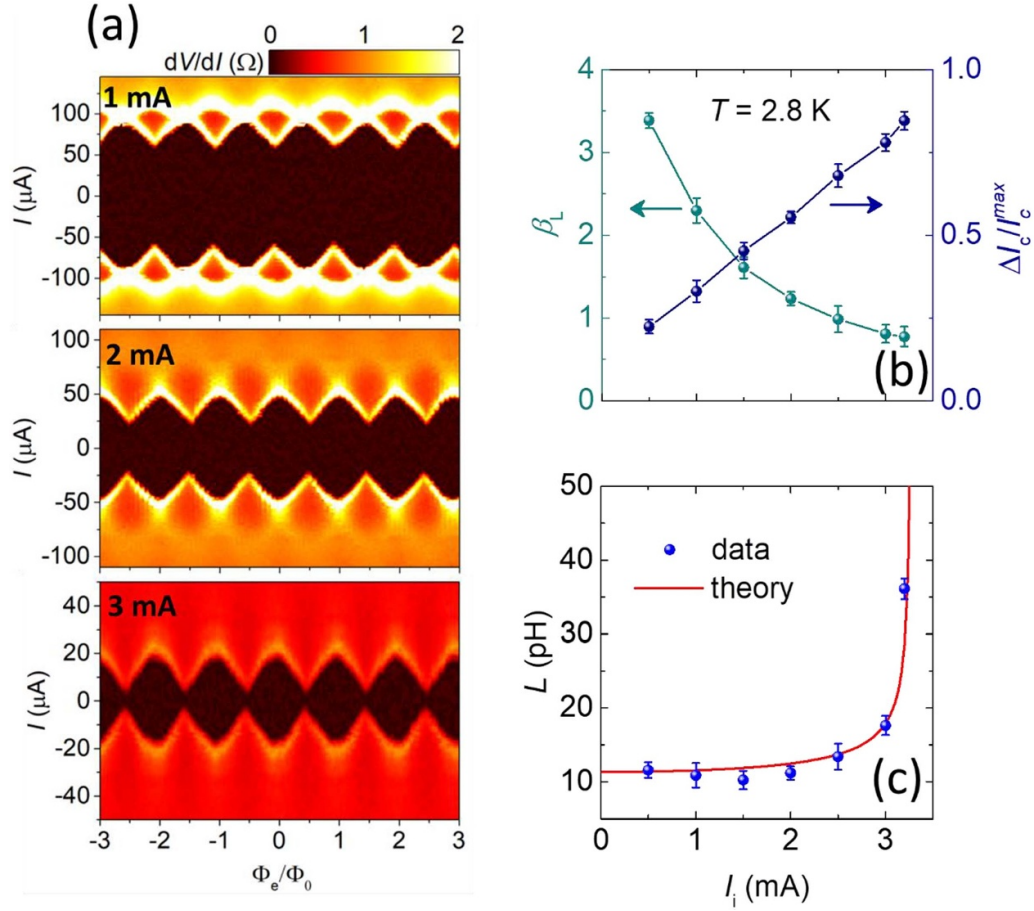


Figure 4. Modulation depth and inductance controlled by I_i . (a) Color maps of differential resistance (dV/dI) as a function of current I and normalized flux (Φ_e/Φ_0) for different values of injection current I_i at $T = 2.8$ K. (b) Extracted flux modulation depth ($\Delta I_c/I_c^{\max}$) and screening parameters (β_L) versus the injection current (I_i). (c) Variation of SQUID inductance L with injection current I_i at 2.8 K. The blue circles and the red line are the measured data and theoretical calculations, respectively. Error bars calculated from the different $I_c^{\max}$ and $I_c^{\min}$ values in the range of $\Phi_e = n\Phi_0 \sim (n + 1)\Phi_0$, where $n = 0, \pm 1, \pm 2$.

resistance R_K is negligible, and the power is proportional to the fifth power of temperature ($P_i \propto T^5$) [38]. A quantitative description of this effect in our device is too complex to analyze due to the complicated structure. Nonetheless, we developed a general and useful model in the thermal steady state:

$$P_i = I_i^2 R_i = \begin{cases} \eta(T_e^n - T_p^n) & (T < 1 \text{ K}, n \sim 5) \\ \alpha L_0 (T_e^n - T^n) & (T > 1 \text{ K}, n \sim 2) \end{cases} \quad (4)$$

where the P_i is the injection power, $R_i \sim 8 \Omega$ is the resistance of TiO_x leads, T is the bath temperature, T_e is the effective electronic temperature in metal films, T_p is the film phonon temperature, $\eta = \Sigma V$ is the parameter for $T < 1$ K, Σ is a material-dependent constant [36] (about $2 \text{ GW m}^{-3} \text{ K}^5$), V is the metal volume, $L_0 = 2.44 \times 10^{-8} \text{ W K}^{-2}$ is the Lorentz number, and α is the fitting parameter in our device. The difference in the two temperature ranges is attributed to the electron–phonon interaction playing a significant role at low temperatures (i.e. below ~ 1 K).

The value T_e can be determined by comparing the I_c peaks as a function of I_i in figure 3(a) with the temperature calibration I_c vs T . The converted $T_e(I_i)$ relations are displayed in the inset of figure 3(d) for different bath temperatures of 2.8 K, 4 K, and 5 K. Note that our experimental data are obtained at the temperature higher than 1 K, the $T > 1$ K case in equation (4) can nicely describe the observed behavior by using the fitting parameter $\alpha = 74.2$ (see the dashed red line in figure 3(d)). Our linear approximation shows good agreement of our model with the experimental data at the three bath temperatures. We also provide data for another two devices to ensure the reproducibility of the model (supplementary materials (available online at stacks.iop.org/SUST/34/125012/mmedia)). We find that the above model can excellently describe the multi-port devices measured at 2.8 K, and the fitting parameters are dependent on the loop geometry. We believe that the operating temperature in our multi-port SQUID also covers temperatures below 2.8 K. However, the working principle of the device at the temperature below 1 K might be different. The current injection in our device, which can be explained by a simple yet effective model, demonstrates the practical applicability

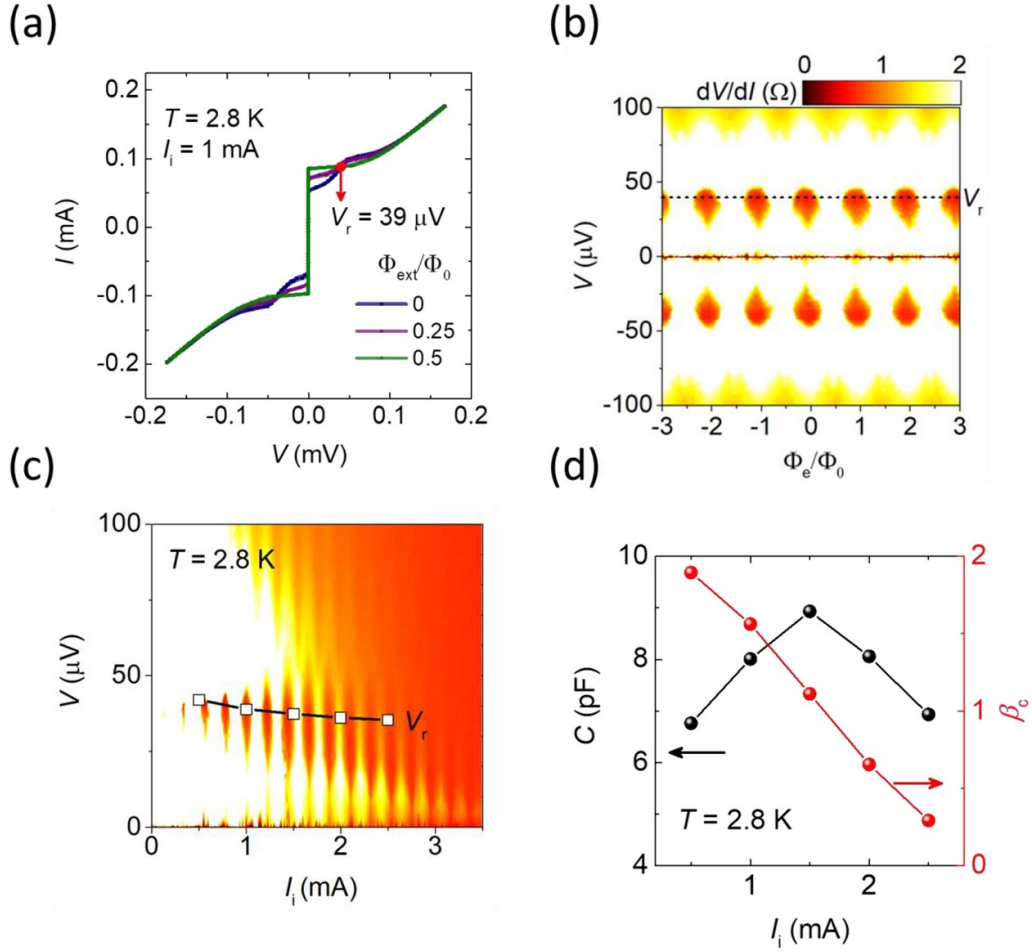


Figure 5. Resonances and capacitance. (a) IVCs taken at different Φ_e/Φ_0 values with applied injection current $I_i = 1$ mA, the red arrow indicates the voltage resonance point V_r . (b) Differential resistance (dV/dI) as a function of voltage V and normalized flux (Φ_e/Φ_0). The black dashed line indicates the voltage resonance point V_r . (c) Differential resistance (dV/dI) as a function of voltage (V) and injection current (I_i). The open symbols indicate the I_i dependence of V_r . (d) Calculated capacitance C and Stewart-McCumber parameter β_c as a function of I_i .

for analyzing multi-port superconducting devices that are difficult to model otherwise.

We now turn to analyze the critical current modulations of the SQUID under an externally applied magnetic flux with increasing I_i . Figure 4(a) shows the color-plots of differential resistance (dV/dI) vs current (I) and normalized magnetic flux (Φ_e/Φ_0) for selected injection currents. It is evident that the critical current modulation depth $\Delta I_c/I_c^{\max}$ increases by increasing I_i . Figure 4(b) shows the relation between the extracted $\Delta I_c/I_c^{\max}$ value and injection current I_i , giving us the screening parameter β_L as a function of I_i . We observe an increase of $\Delta I_c/I_c^{\max}$ and a decrease of β_L value on increasing the I_i for our device. To give more insight into the behaviors under external magnetic fluxes, the I_i dependence of the inductance L of our SQUID loop is calculated from the formula $\beta_L = 2\pi I_c L/\Phi_0$. As observed in figure 4(c), the I_i dependence of the L values shows an exponential growth trend. The change of the kinetic inductance L_k in the superconducting electrodes may be responsible for such behavior [28, 39]. Here, we expect the effective temperature to also have a substantial effect on L_k , i.e. $L_k = \mu_0 \lambda(T_e)^2 l/wt$. For the

I_i dependence of the loop conductance, we use the two-fluid model for London penetration depth to fit our experimental data [40]:

$$\lambda(T_e) = \lambda(0) \frac{1}{\sqrt{1 - (T_e/T_c)^2}} \quad (5)$$

where the T_e is the electronic temperature caused by I_i , $T_c = 8.3$ K is the critical temperature of the electrodes. We, therefore, fit the observed SQUID inductance behavior using equations (2) and (5). As shown in figure 4(c), the agreement between data (blue dot) and theoretical calculations (red line) is excellent using $L_g = 7.7$ pH. Our data indicate that the electronic temperature is spatially homogeneous throughout the SQUID. We demonstrate an alternative method to manipulate the kinetic inductance L_k *in situ* by injecting currents into the SQUID through barriers.

We next characterize the junction capacitance C as well as the Stewart-McCumber parameter β_c by analyzing the resonance voltage steps in the IVCs. Our Nb/TiO_x/Nb Josephson junctions are in essence of the SNIS type, so it is hard to

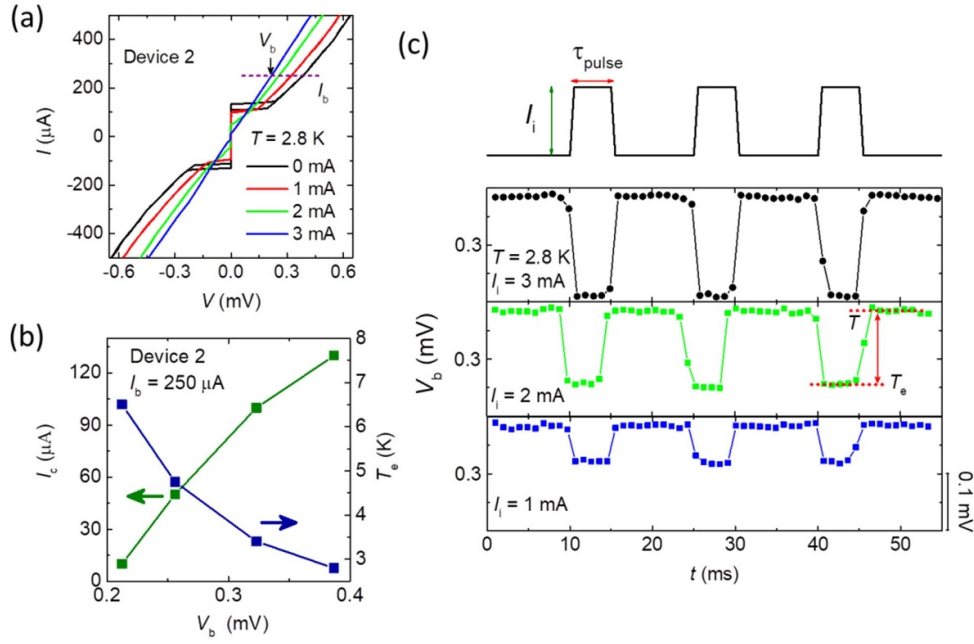


Figure 6. Injection current pulse measurement of device 2. (a) Current–voltage curves of device 2 for injection currents of 0, 1, 2, and 3 mA at 2.8 K. The bias current I_b and measured voltage V_b are marked by the purple dashed line and black arrow respectively. (b) The measured voltage V_b as a function of critical current I_c and electronic temperature T_e with $I_b = 250$ μ A. (c) The black line is the waveform of the injection current pulse train with the pulse interval of $\tau_{\text{pulse}} = 5$ ms. The black, green, and blue dotted lines are the voltage response to the pulse with different I_i amplitudes. The top and the bottom of the voltage response are the T and T_e , respectively.

estimate the standard capacitance since we do not know the relative permittivity ϵ_r and thickness of the insulating layer. The resonant voltage points V_r , excited by the ac Josephson effect due to the junction capacitance C and loop inductance L , can be utilized to precisely determine the capacitance C in the junctions [41, 42]. Figure 5(a) shows the resonance voltage steps at $I_i = 1$ mA with different external magnetic fluxes. The position of the resonant point $V_r = 39$ μ V can be determined by the concentration of the IVCs. The magnetic flux dependence of the resonant steps can be more clearly seen in the color plot of the differential resistance (dV/dI) as a function of voltage (V) and external magnetic flux (Φ_e/Φ_0), shown in figure 5(b).

The oscillation of the amplitude of the resonant steps is expected for the previous report [43, 44]. The resonant position here is marked by the dashed black line, which plays a crucial role in the capacitance estimation of the junctions. The equation:

$$V_r = \frac{\Phi_0}{2\pi\sqrt{LC}} \quad (6)$$

is used for determining the capacitance of the junctions [42]. The junctions capacitance $C = 7.98$ pF can be calculated at the injection current of 1 mA.

To investigate the validity of our mathematical approximations, we extracted the voltage resonant points V_r from the IVCs under external magnetic flux at different I_i . For clarity, the resonant voltage V_r positions are marked on the color map of the differential resistance (dV/dI) as a function of V and I_i ,

as shown in figure 5(c). We observed that the resonant voltage V_r gradually decreased by increasing I_i .

This behavior is mainly caused by the SQUID inductance L as discussed in figure 4(c). The dependence of the C on the I_i is plotted in figure 5(d). The capacitance C of the junction and the error bar σ in C can be described by:

$$C = \sum \frac{C(I_i)}{n} \quad (7)$$

$$\sigma = \sqrt{\frac{\sum (C(I_i) - C)^2}{n}} \quad (8)$$

where $n = 5$ is the number of measured points. We determined the value $C = 7.74$ pF as the average of five data with the error $\sigma = 0.89$ pF. The result indicates that the resonance measurement enables the valid estimation of the junctions' capacitance. We also discussed the specific capacitance $C_s = C/s$ in the junctions, where s is the total area of the two Josephson junctions. The specific capacitance value $C_s = 155$ fF μm^{-2} and the error 18 fF μm^{-2} in C_s are calculated in our TiO_x Josephson junctions using $s = 50$ μm^2 , a value which is very close to the AlO_x tunneling junctions [41]. In addition, the capacitance allows for the determination of the Stewart-McCumber parameter $\beta_c = 2\pi I_c R^2 C / \Phi_0$. Figure 5(d) shows the calculated β_c value as a function of I_i , which is clearly decreasing by increasing I_i .

Finally, we investigated the working speed of changing the parameters in the multi-port device. The operating speed

has been demonstrated in the superconducting nanobridge and proximity Josephson junctions [45, 46], which is measured by analyzing the switching current distributions. In our device, we find a straightforward method to describe the operating speed. Figure 6(a) shows the current–voltage curves with different injection currents of device 2. When the bias current I_b is larger than the device critical current I_c , the measured voltage V_b will reduce with the increase of injection current I_i . The recorded voltage V_b will give rise to the value of I_c and hence T_e simultaneously, as shown in figure 6(b). We attribute this phenomenon to the MAR process, in which case the gap voltage of the device will be reduced by the injection currents [22]. This technique allows us to describe the operating speed of the device by simply measuring the voltage V_b with a bias current I_b . In figure 6(c), we send a rectangular injection current pulse ($\tau_{\text{pulse}} = 5$ ms) from the additional ports and record the SQUID voltage V_b simultaneously with a sampling rate of 1 ms. Figure 6(c) shows the rectangular voltage response with different injection current pulse amplitude. Here, the electronic temperature changing speed $v_T = (T_e - T)/\Delta t \approx 3.7$ mK/ μ s is obtained at 2.8 K where $T_e = 6.5$ K ($I_i = 3$ mA) and $\Delta t = 1$ ms (restricted to the measurement). The measurement technique presented in our device can be used to easily determine the working speed of superconducting thermometry. Due to the limited resolution of our measurement setup, the speed reported here is expected to be much lower than the extreme operating speed.

On the other hand, we estimate the presumed speed of changing T_e in the device. As described in [47], the electronic temperature changing speed v_T in the metal can be expressed as:

$$v_T = \frac{\Delta T_e}{\Delta t} = \frac{P_i}{C_e} \quad (9)$$

where $\Delta T_e = T_e - T$ is the temperature variation in metal films, P_i is the injection power, $C_e = \gamma V T_e$ is the heat capacity of the metal film, and $\gamma = 71$ J K⁻² m⁻³ is the Sommerfeld constant [47]. Using $T = 2.8$ K and $T_e = 3$ K, we obtain the theoretical T_e changing speed $v_T = 93.8$ mK ns⁻¹. Thus, we expect the maximum operation frequencies of the device to be in the subgigahertz range by taking the thermal relaxation into account, which is quite promising to conduct further investigations.

4. Discussion

In this paper, we have fabricated a multi-port SQUID with two Nb/TiO_x/Nb junctions allowing to inject in-plane currents along the TiO_x layer. We demonstrate the control of the amplitude and phase difference of supercurrent of the SQUID via the injection current I_i . The observed experimental data of I_c suppression and oscillations vs I_i has been explained by the changes of the self magnetic flux Φ_s and the effective electronic temperature T_e . A simple model containing only one fitting parameter can nicely linearize our observations. In addition, the injection currents allow us to *in situ*

manipulate the parameters such as the kinetic inductance L_k , the screening parameters β_L , and the Stewart-McCumber parameter β_c . We have also obtained the specific capacitance value $C_s \sim 155$ fF μm^{-2} with the error of 18 fF μm^{-2} in our Nb/TiO_x/Nb junctions by taking the kinetic inductance into account. We expect that the current injection of our devices allows for a fast and reliable modulation of SQUID parameters, which is undoubtedly much more rapid than changing the bath temperature. Our results also demonstrate that the elevated electronic temperature induced by current injection through the TiO_x barrier is homogeneous throughout the SQUID.

From the practical point of view, the ability to locally probe and manipulate the specific SQUID parameters provides us with more possibilities in the applications of superconducting devices. For instance, the opportunity to locally control the supercurrent and phase difference may yield significant implications in phase superconducting qubits, and in superconducting electronics to implement phase-controllable caloritronics [48], superconducting transistors [21], and rapid single flux quantum logic [49]. Furthermore, the *in situ* manipulation of the kinetic inductance could be of significance for the realization of tunable sensitive magnetometry [50, 51] and parametric amplification [52]. In addition to the possible applications mentioned above, our work may also provide another investigative angle for understanding the nonequilibrium phenomena in multi-terminal SNS Josephson junctions [53].

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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