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ABSTRACT

This study explores gate-controlled superconductivity in metallic superconductors by employing a top-gate architecture with a 15 nm monocrystalline h-BN as a gate dielectric. The transport properties under gate voltage can be elucidated by injecting high-energy electrons, following the Fowler–Nordheim electron field emission model. In contrast to conventional resistive Joule heating, high-energy electron injection with top-gating exhibits excellent power efficiency in suppressing superconductivity. A nearby superconducting bridge, which serves as a thermometer, indicates that our top-gate device can achieve good local control, well limited within a distance of 0.6 μm due to the very low top-gating power. These findings are essential for advancing efficient and highly integrated tunable superconducting electronic devices.

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The control of supercurrent has long been a central focus in applied superconductivity. Various strategies have been employed to regulate supercurrents.^{1–3} Notably, prior research has shown that supercurrents in superconductor nanobridges can be modulated through the application of hot-electron injection.^{3,4} As highlighted in Ref. 5, the implementation of superconducting thermal switches, utilizing current-induced heating in the resistor, has been explored. The transition to the normal state occurs when Joule heating phonons applied to the superconducting nanowire exceed twice the superconductor energy gap. This method can lead to excessive Joule heating in the devices, significantly impairing the performance of the superconducting circuit,⁶ prompting further investigation into heat transfer mechanisms,^{7–9} and thermal applications.^{10,11} Alternatively, semiconductor materials,¹² such as graphene^{13–15} and two-dimensional electron gases,^{16–18} are frequently incorporated into devices to enhance superconductivity through electric field effects. However, the integration of semiconductor materials may result in increased device losses¹⁹ and might not be universally applicable to all superconducting electronic systems.

Therefore, it is necessary to explore versatile and feasible approaches to achieve tunable superconductivity.

The prospect of adjusting the properties of metallic superconductors through field effect has been dismissed by several works.^{20,21} This exclusion is primarily attributed to the external electric field dissipating within a depth comparable to the Thomas–Fermi screening length, which is at the atomic scale.²² However, recent experiments have revealed that gate voltages can significantly influence the superconductivity of metallic nanobridges. This effect is achieved by applying a voltage bias to the gate near the nanodevices, primarily through methods such as the side gate,^{23–27} ionic liquid,²⁸ or the bottom and top gates with dielectric layers.^{29,30} This phenomenon was explained as the effect of a strong electrostatic field in subsequent reports.^{23–28} The most recent studies have demonstrated that the suppression of the critical current in metallic superconductors is closely tied to minuscule gate leakage currents induced by the emission of high-energy electrons under the influence of the electric field emission.^{29,31–34} Detailed investigations have shown that these high-energy electrons produce phonons by relaxing in the substrate, efficiently quenching the

superconductivity of the devices. This viewpoint has also been validated by measuring tunnel spectra to study the population of quasiparticles (QPs), directly observing the control process of QPs generated by field emission.^{33,35} This effect is found to be distinct from the conventional resistive Joule heating effect, which causes an increase in electronic temperature.^{3,31} In Ref. 23, utilizing a sapphire substrate and Ti nanowires, the power consumption is reduced to several picowatts. Conversely, Ref. 32 demonstrates that using the SiO₂ and Si substrates, the energy consumption of Ti superconductor switches increases to several nanowatts, and with niobium (Nb) nanowires, it can reach several hundred nanowatts. This variation in power consumption is intricately linked to various factors such as materials, substrate, and device dimensions, the operational working principle of these devices remains unclear to date, necessitating further studies and interpretation.

In this work, we investigate the transport characteristics of a top-gated Nb superconductor microbridge with the h-BN thin flakes as the gate dielectric and observe the suppression of critical current with increased leakage current between the gate and Nb microbridge. The gate current–voltage characteristic follows the Fowler–Nordheim field emission model, indicating that the leakage current of high-energy electrons is presumably responsible for the gating effect, which is consistent with previous works.^{33,34} Quenching the critical current by the gating or the resistive heater, we find that high-energy electron injection is significantly more efficient, nearly forty times lower than the power of resistive Joule heating. Consequently, our top-gate device achieves efficient local control, without observable heat effect on a superconducting bridge 0.6 μm away from it. These results provide practical methods for designing superconducting circuits with tunability and high integration.

The schematic of our device is shown in Figs. 1(a) and 1(b). The device fabrication process has been partly reported earlier.³⁶ For clarity, we briefly mention the main steps for device A. We used photolithography and sputtering techniques to define the bottom Nb with 15 nm (blue) on a sapphire substrate, which constituted an $18 \times 1 \mu\text{m}^2$ bottom microbridge, along with a $14 \times 1 \mu\text{m}^2$ superconducting thermometer 5 μm away from the gate. The excess parts were removed using a liftoff technique. Subsequently, we used the PDMS film to stack the h-BN dielectric layer [approximately 15 nm, as shown in the supplementary material, Fig. S1(c)] onto the Nb bottom microbridge via a dry transfer technique. Afterward, an additional 50-nm-thick Nb microbridge ($14 \times 3.5 \mu\text{m}^2$) is patterned and deposited on a heterostructure to serve as the top-gate electrode (green). The distances between the gate and the thermometer are 5 μm , 545 nm, and 1 μm in device A, device B, and device C, respectively. The optical microscope images are shown in the supplementary material.

It is noteworthy that, in our scenario, the Nb microbridge serves as an effective thermometer. The thermodynamic process of applying power to a metal involves electron–phonon interactions, leading to an elevated electronic temperature (T_e) within the metal. The critical current of superconductors is intrinsically temperature-dependent, rendering it a suitable gauge for electronic temperature variations and, consequently, monitoring the power consumption of the gate. Specifically, in prior research,³⁷ the critical current of a superconducting Nb nanowire was utilized as a thermometer to assess the local electronic temperature. In Fig. S5 of the supplementary material, we observed that the correlation between T_e and gate power can be precisely elucidated through the electron–phonon interactions process.

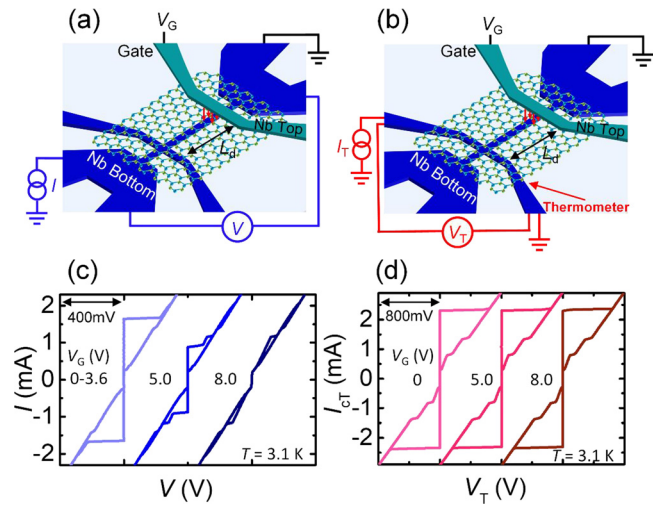


FIG. 1. Layout and basic characteristics of device A. (a) and (b) Measurement scheme using a four-probe method for the bottom microbridge or the superconducting thermometer. The width of the bottom microbridge and thermometer is 1 μm , and the top gate has a width of 3.5 μm . The separation distance between the gate electrode and the thermometer is denoted as L_d , which amounts to 5 μm . (c) The current I and voltage V characteristics of the bottom microbridge were measured at a temperature of $T = 3.1$ K, with gate voltage (V_G) values ranging from 0 to 3.6, 5.0, and 8.0 V. (d) The current I_T and voltage V_T characteristics of the thermometer measured at $T = 3.1$ K, with V_G values taken as 0, 5.0, and 8.0 V.

Therefore, we can rely on the critical current of the Nb microbridge as a dependable indicator of temperature variations, effectively utilizing it as a thermometer.

Figures 1(a) and 1(b) show the test wiring diagrams of the Nb bottom microbridge and superconducting thermometer using the standard four-probe method, respectively. The several current–voltage characteristics (IVCs) corresponding to the gate voltage applied to the Nb bottom microbridge and superconducting thermometer are shown in Figs. 1(c) and 1(d). The thermometer detects the temperature increase generated by the heat power diffusion resulting from the gate voltage V_G . As depicted in Fig. 1(c), at $V_G = 0$ V and $T = 3.1$ K, the Nb microbridge and the thermometer displayed hysteretic behaviors with critical currents of $I_c = 1.67$ mA for the Nb microbridge and $I_{cT} = 2.34$ mA for the thermometer, respectively. Notably, the application of gate voltage to the top electrode reveals that the superconducting properties of the bottom microbridge are suppressed when the gate voltage exceeds 3.6 V. Conversely, at a greater distance from the gate (5 μm), no significant changes were observed in the superconducting properties of the thermometer even when the gate voltage reached 8.0 V.

We first focus on the gating effect of the supercurrent in the microbridge. Figure 2(a) shows the I_c (blue dot line) and gate current I_G (green dot line) as a function of the V_G . The dependence of the supercurrent on the gate voltage exhibits a plateau until V_G falls below a threshold voltage V_{Gth} of approximately 3.6 V. Beyond this threshold, the supercurrent decreases, reaching zero at a critical gate voltage V_{GC} of around 8.5 V. I_G remains negligible until $|V_G|$ reaches the threshold voltage V_{Gth} , and starts to increase with the increase in the gate voltage.

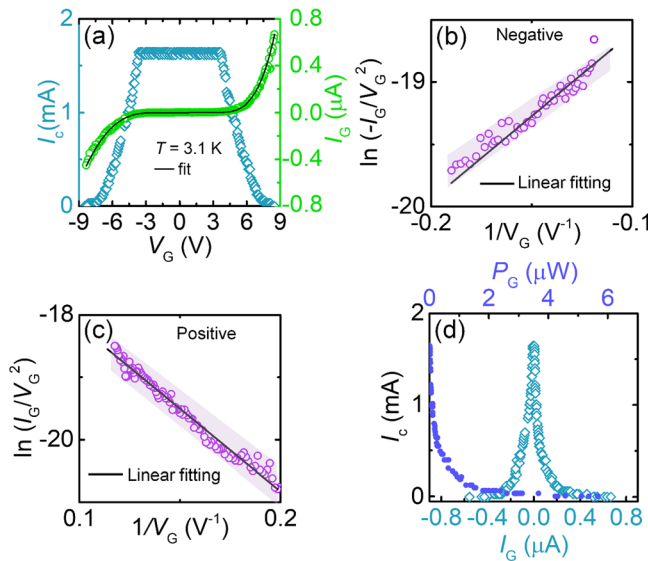


FIG. 2. High-energy electron injection in the bottom microbridge at a temperature of 3.1 K. (a) The dependence of critical current I_c (blue dot line) and gate current I_G (green dot line) on gate voltage V_G . A fitting result of the gate current I_G and gate voltage V_G was obtained with the Fowler–Nordheim electron field emission model (black curve). (b) and (c) The linear variation of $\ln(I_G/V_G^2)$ with $1/V_G$ for the negative and positive voltage. (d) The variation of critical current I_c with gate current I_G and gate power $P_G (= V_G I_G)$.

This observation verifies previous findings regarding the phenomenon in which electrons are emitted from the electrode into the medium due to the application of a high electric field.²⁹ This process occurs when the electric field intensity at the material's surface surpasses the work function, a phenomenon described by the Fowler–Nordheim (F-N) electron field emission model.^{38–40} In our experiment, we applied a maximum electric field strength of around 570 MV/m, in accordance with the F-N electron field emission model. In this context, we elucidate the I_G (V_G) relationship,

$$I_G = \alpha V_G^2 \exp\left(-\frac{\beta}{V_G}\right), \quad (1)$$

where α and β depend on our device's material properties and geometry. The experimental data for the I_G (V_G) curve is best fitted by Eq. (1) (solid black line), as depicted in Fig. 2(a). In this work, we assume the barrier width to be the thickness of the h-BN layer ($d \approx 15$ nm), and $m^*/m = 0.26$ for h-BN.^{40–42} The fitting parameters, $\alpha = 0.31 \pm 0.14$ $\mu\text{A}/\text{V}^2$ (0.035 ± 0.007 $\mu\text{A}/\text{V}^2$) and $\beta = 30 \pm 5$ V (14 ± 2 V), are obtained from the slope of each respective curve.^{39,42,43} These values yield a barrier height ϕ of approximately 0.69 eV (0.41 eV) for a positive (negative) bias. We further present $\ln(I_G/V_G^2)$ vs $1/V_G$ data for both negative and positive voltage sweeps, shown in Figs. 2(b) and 2(c). The evident linear dependence observed in these plots implies that electron tunneling through the h-BN can be best described by the F-N model. These results indicate that the critical current suppression due to the gate voltage can be attributed to high-energy electron field emission, in agreement with earlier works.^{29,31–34} Indeed, as depicted in Fig. 2(d), the supercurrent significantly reduces with the increase in

the gate current (I_G) and becomes completely quenched at approximately $I_G \sim 0.6$ μA .

To have a more comprehensive understanding of the high-energy electron field emission, we try to compare it with conventional resistance heating, with experimental configurations depicted in Figs. 3(a) and 3(b), respectively. Different from the gating method, we modulated the critical current with the resistive Joule power P_H by passing a heat current I_H directly through the Nb gate control line. Figure 3(c) shows that I_c can be suppressed when I_H exceeds the critical current of the gate electrode. As expected, the resistive Joule heating stemming from the normal state of the gate electrode is responsible for the quenching of the supercurrent.^{44–46}

Figure 3(d) compares the gate power and resistive heat power in terms of the suppression of the I_c . The gate power P_G is defined as $V_G I_G$, while the resistive heating power P_H is calculated as $I_H^2 R_H$, where R_H is the normal resistance measured from the I - V curves of the gate electrode. With an increase in P_H , I_c undergoes a sudden transition due to the switching from the superconducting state to the resistive state. Notably, to quench I_c , P_H should be several tens of times as high as P_G . Quantitatively, the power required to suppress I_c in our 1- μm -wide Nb microbridge completely is approximately 200 μW for the resistive heater, in contrast to the value of 5.67 μW with top-gating. Our research indicates that the procession of the gating effect suppresses the superconductivity, emphasizing a significant correlation between the suppression of critical current (I_c) and high-energy electron field emission. The high-energy electron injection offers a much more efficient method for modulating the critical current in a metallic superconductor.

We also examined the responses of the thermometer to both heating power and gate power. As illustrated in Fig. S2 of the supplementary material, we noted a close similarity in the power levels between the two approaches, with the quenching power of the thermometer critical current (I_{CT}) measuring approximately 1.5 mW.

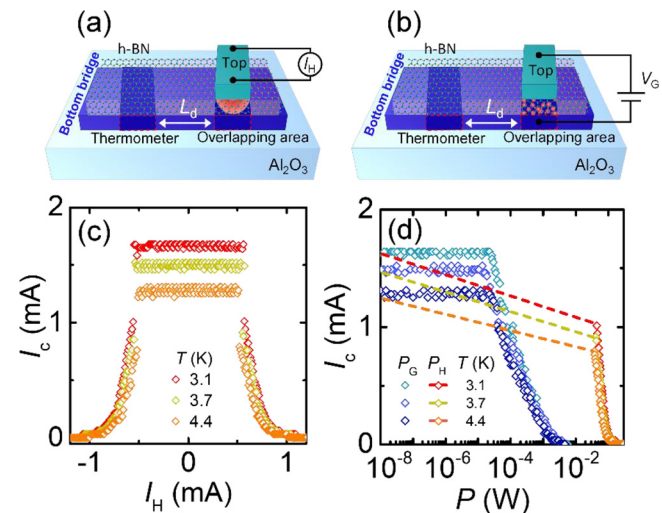


FIG. 3. Modulation of microbridge superconductivity for two heat configurations. (a) Schematics of device A for the voltage gating configuration. (b) Schematics of device A for the resistive heating configuration. (c) The dependence of the critical current on the heating current I_H for different temperatures. (d) Critical current I_c as a function of gate power (P_G), and heating power (P_H).

This observation may be ascribed to the monitoring accuracy of the Nb microbridge thermometer in our experimental setup, which we will delve into in the ensuing discussion.

To further substantiate our experimental findings, we conducted finite element method (FEM)-based electrothermal simulations. In our simulations, we utilized a resistive heater positioned at the intersection of the gate electrode and the bottom microbridge, aligning the heating area with the conditions of high-energy electron injection. The substrate temperature in the simulation is held at 3.1 K, and more comprehensive details can be found in Part 2 of the supplementary material. Figure 4(a) shows the color plot of the simulation results when an input power P_i of $5.67 \mu\text{W}$ is applied to the gate electrode. This value corresponds to the one in Fig. 3(d), where the experimentally observed suppression of I_c to zero is achieved through high-energy electron injection. In this scenario, the temperature increase in the cross-sectional area beneath the gate electrode is approximately 0.19 K. Obviously, it is not sufficient to cause suppression of the bottom superconducting microbridge, indicating the high efficiency of high-energy electrons.

In addition, as shown in Fig. 4(b), when the input power P_i is set to $200 \mu\text{W}$, the temperature below the gate electrode increases to approximately 6.41 K, very close to the critical temperature of niobium film $T_c \approx 6.7 \text{ K}$, and then I_c is almost suppressed. This aligns well with the experimental resistive Joule heating power P_H of $200 \mu\text{W}$ required for quenching the superconductivity, as shown in Fig. 3(d). The simulation results verified that resistive Joule heating is comparatively inefficient for low-temperature devices compared to high-energy electron injection.

The numerical results of the simulation are depicted in Figs. 4(c) and 4(d). We present the elevated temperature (ΔT) as a function of the distance from the gate (L) for various power values. It is evident that when the resistive heating power exceeds about $100 \mu\text{W}$, the

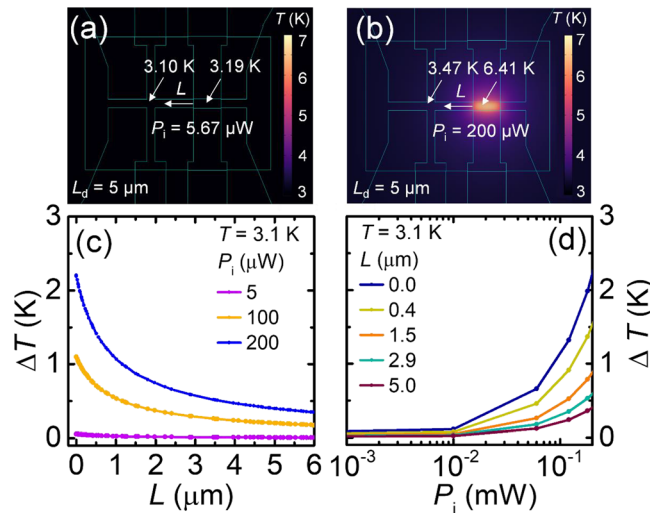


FIG. 4. Simulation results for device A. (a) Color-coded simulation result depicting the temperature distribution with an applied Joule heat power ($P_i = 5.67 \mu\text{W}$) and thermal diffusion length ($L_d = 5 \mu\text{m}$). (b) The applied Joule power P_i is $200 \mu\text{W}$. (c) The elevated temperature (ΔT) as a function of the L for different simulated applied power values P_i . (d) The elevated temperature (ΔT) is plotted against the applied Joule power P_i for different positions (L).

heating effect around the device becomes noticeable. We then explored the correlation between the temperature variation at different positions (L) and the applied Joule power. As seen in Fig. 4(d), the temperature starts to increase in the surrounding region only when the power exceeds $10 \mu\text{W}$, which is a considerably high threshold compared to high-energy electron injection. In other words, this simulation results suggest that the thermalization area associated with the high-energy electron injection would be minimized, owing to the higher power efficiency (or low gate power) in suppressing the superconductivity of the underneath area.

Finally, we designed the other sample, device B, with the L_d value of approximately 545 nm . The detailed sample characteristics are in Part 3 of the supplementary material. To explore the thermalization effect in the substrate resulting from high-energy electron injection, we measured the transport properties of the superconducting thermometer with gating. Figures 5(a) and 5(b) illustrate the variations in the critical current of the bottom microbridge and the thermometer of device A, respectively, with the application of gate power. The critical current of the bottom superconducting microbridge (I_c) decreases exponentially with increasing gate power. As expected, the top-gate control displays locality, with no significant change observed in the critical current of the superconducting thermometer at $5 \mu\text{m}$. Subsequently, we examine the behaviors of device B, as depicted in Figs. 5(c) and 5(d). The application of approximately $5 \mu\text{W}$ of high-energy electron power is sufficient to suppress the superconducting

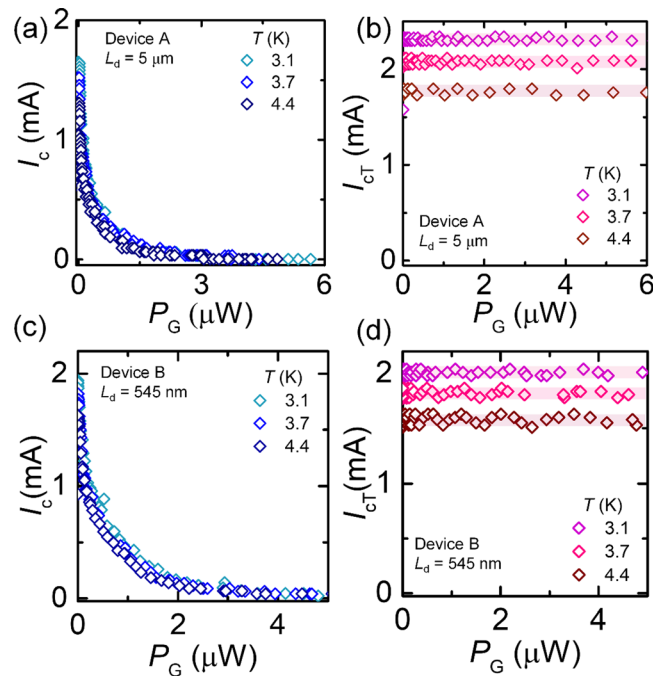


FIG. 5. Investigation into the localized impact of gating. (a) The critical current of the microbridge vs gate power at various temperatures for device A. (b) The relationship between the critical current of the thermometer and the gate power of device A at different temperatures. (c) Variation of the microbridge's critical current with gate power at different temperatures for device B. (d) The relationship between the critical current of the thermometer and the gate power of device B at various temperatures.

characteristics of the bottom microbridge, consistent with the observations in device A. However, the critical current of the thermometer (I_{CT}), located 545 nm away from the gating area, remains unaffected, as illustrated in Fig. 5(d). The findings suggest that high-energy electron injection is suitable for tuning the superconductivity locally. At least in our experiment, 0.6 μm is a safe distance.

To further explore the thermometer's sensitivity to power consumption, we analyzed the relationship between the critical current of the thermometer and the gate power, as illustrated in Fig. S6 of the supplementary material. Our findings suggest that the Nb microbridge thermometer demonstrates detectable sensitivity only when the power exceeds several tens of micro-watts. Notably, comparable sensitivity levels were observed at distances of 5 and 1 μm from the gate, as depicted in Fig. S6(b). This experiment suggests that the distance from the gate, within the range of 1–5 μm , may not be the primary factor influencing sensitivity. Instead, it highlights the dimensions of the thermometer as a critical parameter for sensitivity. Specifically, the minimum power required to quench the superconductivity of the entire microbridge, denoted as $P_r = I_c^2 R_N$, is related to the retrapping current (I_r) and the normal state resistance (R_N) of the Nb microbridge.³² For devices A and C, P_r values of approximately 9 and 10 μW were derived, consistent with the power levels observed in Fig. S6. As indicated in Ref. 29, if the dimensions of the thermometer can be reduced to the hundred-nanometer scale, the minimum sensing power could potentially be within the pico-watt range.

While the current device's thermometer may not be sensitive enough, the 0.6 μm distance for device B appears to be a safe distance. This is because the power required to suppress the critical current of the thermometer is significantly larger than the gate power needed to quench the bottom Nb microbridge. Consequently, the gate power, falling within the range of several hundred nanowatts, is unlikely to appreciably raise the electronic temperature of the adjacent superconductors. Furthermore, we emphasize that utilizing a superconductor wire thermometer to detect the gate power remains a valuable tool for scrutinizing the performance of metallic superconductor switches, warranting further investigation.

In conclusion, our study explored the modulation of superconducting properties in metallic Nb microbridges, employing a top-gate architecture with monocrystalline h-BN as the dielectric. The gate's current-voltage characteristic adhered to the Fowler-Nordheim model, demonstrating that the gating effect was attributed to the leakage current from the high-energy injection. Experimental and simulation results show that high-energy electron injection is significantly more effective, by several dozen times, in tuning the critical current than resistive heating. Therefore, top-gating is good for the local tuning of the superconducting devices. Our study presented here holds potential applications for designing integrated superconducting electronic devices and the control optimization of superconducting circuits such as Josephson junctions.

See the supplementary material for the detailed process of device preparation and measurement, data on device A, device B, and device C, as well as the Joule thermal power modulation.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Hongmei Du: Software (equal); Writing – original draft (equal). **Zuyu Xu:** Conceptualization (equal); Formal analysis (equal). **Ping Zhang:** Investigation (equal). **Dingding Li:** Methodology (equal). **Zihan Wei:** Validation (equal). **Zixi Wang:** Validation (equal). **Shoucheng Hou:** Investigation (equal). **Benwen Chen:** Data curation (equal). **Tao Liu:** Software (equal). **Ruxin Liu:** Resources (equal). **Yang-Yang Lyu:** Methodology (equal). **Hancong Sun:** Conceptualization (equal). **Yong-Lei Wang:** Validation (equal). **Huabing Wang:** Writing – review & editing (equal). **Peiheng Wu:** Funding acquisition (equal).

DATA AVAILABILITY

The data that support the findings of this study are available within the article and its supplementary material.

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