

Resolving quantum Cooper-pair tunneling in graphene Josephson junctions under near-infrared illumination

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We report the observation of discrete supercurrent suppression steps arising from quantum Cooper-pair tunneling in superconductor-graphene-superconductor (SGS) Josephson junctions under near-infrared illumination. This quantum phenomenon remains robust against variations in photon energy, optical power, bath temperature, and dc bias. The nearly identical step spacing observed in SGS Josephson junctions with different graphene channel lengths indicates the dominant role of the superconductor-graphene interface in governing Cooper-pair transport. In contrast, the discrete steps vanish in the negative differential resistance regime, where quasiparticle transport dominates, confirming their microscopic Cooper-pair tunneling origin.

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I. INTRODUCTION

Cooper-pair tunneling underpins the Josephson effect, yet its microscopic signatures remain largely elusive in conventional Josephson junctions. In typical junctions, the supercurrent arises from collective tunneling governed by the macroscopic phase difference between the superconducting electrodes, which is conjugate to the junction charge. The discrete nature of charge transfer becomes experimentally accessible only in the strong Coulomb blockade regime, where the charging energy $E_C = e^2/2C$ (with C the junction capacitance) significantly exceeds the Josephson energy $E_J = \hbar I_c/2e$ (with I_c the critical current) [1,2].

Superconductor-graphene-superconductor (SGS) Josephson junctions provide a distinct and versatile platform for exploring quantum transport. In these hybrid devices, proximity-induced superconductivity emerges through phase-coherent Andreev reflection of quasiparticles at the graphene-superconductor interfaces [3,4]. Unlike conventional junctions, the supercurrent in SGS devices is mediated by a small number of Andreev-bound-state channels, and the macroscopic supercurrent depends sensitively on the occupation of these microscopic transport channels [5]. This occupation can be strongly influenced by nonequilibrium perturbations, such as photon-induced quasiparticle excitations in the su-

perconducting electrodes, which can lead to reductions in the supercurrent.

Prior studies of SGS Josephson junctions under photon irradiation, spanning microwave to optical regimes [6–9], focused on distinct observables or operated under different conditions. Microwave experiments primarily investigated bolometric responses, where SGS Josephson junctions entered a resistive state and electrothermal feedback dominated, strongly perturbing the Josephson coupling. Optical-irradiation studies emphasized single-photon detection, examining voltage development or switching statistics. In all these cases, any microscopic discreteness associated with coherent Cooper-pair transport was effectively averaged out.

In contrast, the present work investigates SGS Josephson junctions in a well-defined bias window just below the switching current, where the junction remains in the superconducting state and the response is dictated by coherent Josephson dynamics mediated by Andreev-bound-state channels. By directly monitoring supercurrent variations under photon irradiation and employing a low-noise dc superconducting quantum interference device (SQUID)-based current readout, we achieve continuous, time-resolved measurements of supercurrent with sub-0.1 μA resolution on nanosecond timescales. This sensitivity enables the observation of individual suppression events corresponding to Andreev-mediated Cooper-pair tunneling cycles, which are inaccessible using conventional techniques.

Here, we report the observation of discrete supercurrent suppression steps in SGS Josephson junctions under near-infrared (NIR) illumination. This supercurrent suppression occurs in nearly uniform increments, independent of photon energy, illumination power, bath temperature, or dc bias. Remarkably, the step spacing remains invariant with respect to the graphene channel length, indicating that the transport mechanism is determined by interface processes rather than

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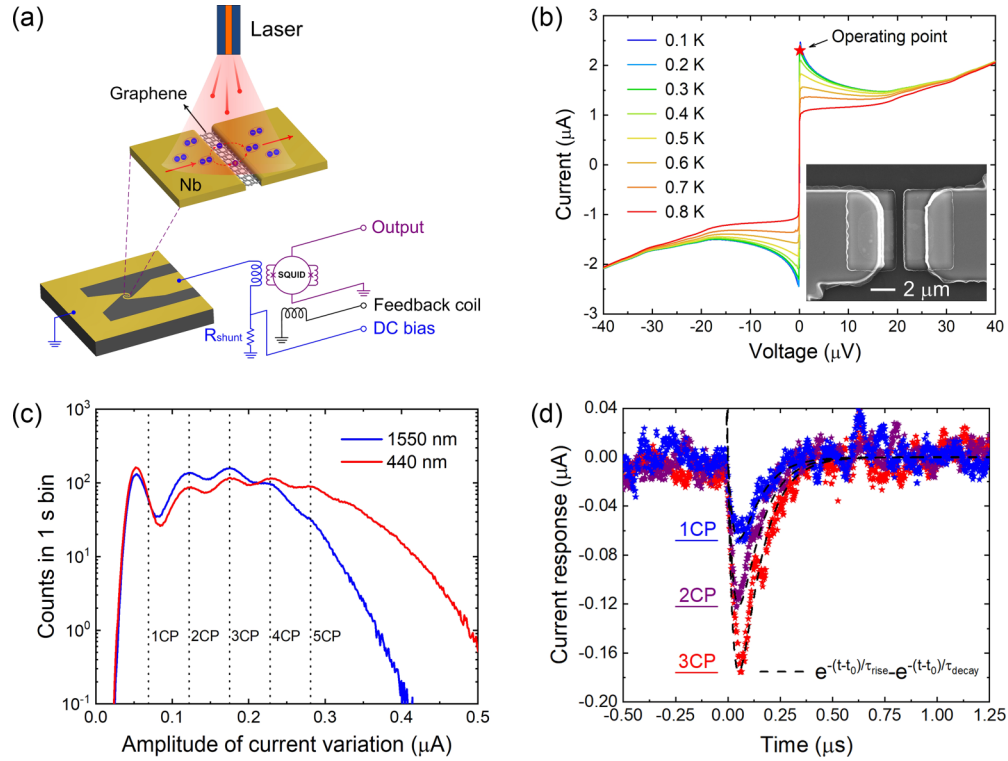


FIG. 1. Quantized Cooper-pair tunneling in an SGS Josephson junction. (a) Schematic of an SGS Josephson junction consisting of a graphene microbridge contacted by two Nb electrodes, without electrostatic gating. Incident NIR photons are predominantly absorbed in the Nb electrodes, leading to suppression of the Josephson supercurrent. (b) I - V characteristics of the SGS Josephson junction with a 0.5- μm graphene microbridge, measured from 0.1 to 0.8 K. Inset shows the SEM of the SGS Josephson junction. (c) Histogram of photon-induced supercurrent reductions under 1550 and 440 nm illumination. Discrete steps are labeled in units of Cooper pairs (CP), indicating quantized current reduction. The junction is biased at $I_{\text{dc}} = 2.4 \mu\text{A}$, just below its switching point, as marked by the star in panel (b). (d) Representative current traces under 1550 nm illumination, showing suppression of one, two, and three Cooper-pair tunneling cycles. Dashed lines are fits to a double-exponential model, capturing the rise and decay dynamics of the supercurrent variation.

bulk graphene properties. These results suggest that Andreev processes at the superconductor-graphene interfaces define characteristic transport cycles and associated timescales for Cooper-pair tunneling. Furthermore, the discrete steps vanish in the negative differential resistance (NDR) regime, where quasiparticle transport dominates, providing strong evidence that the observed quantization arises from coherent Cooper-pair tunneling.

II. SGS JOSEPHSON JUNCTION

We probe quantum Cooper-pair tunneling dynamics in SGS Josephson junctions by monitoring the suppression of Josephson supercurrent under NIR illumination, as illustrated in Fig. 1(a). The junction consists of a hydrogen-intercalated bilayer graphene (BLG) microbridge epitaxially grown on semi-insulating silicon carbide (SiC) substrate [10,11] and contacted by superconducting niobium (Nb) electrodes with lateral dimensions of $4 \mu\text{m} \times 6.6 \mu\text{m}$. Two SGS Josephson junctions were studied, both with a channel width of $4 \mu\text{m}$ and lengths of 0.5 and 0.16 μm , respectively. The quasi-free-standing BLG, obtained via hydrogen intercalation of epitaxial monolayer graphene, exhibits reduced substrate-induced scattering and enhanced carrier mobility [12], thus providing an optimal platform for exploring SGS Josephson

phenomena. The carrier density and mobility of the intercalated BLG, measured using the Van der Pauw method, are $n = 1.6 \times 10^{13} \text{ cm}^{-2}$ and $\mu = 2440 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$, respectively. These parameters correspond to a mean free path $l_e = 114 \text{ nm}$, calculated from $l_e = h\mu(n/\pi)^{0.5}/2e$ [13]. Since l_e is shorter than the channel lengths, the SGS Josephson junctions are in the diffusive transport regime [5]. Moreover, both junctions function without electrostatic gating, relying solely on the intrinsic doping of the graphene layer.

The SGS Josephson junctions are enclosed in a copper-shielded housing and cooled to a bath temperature of $T_{\text{bath}} = 0.1 \text{ K}$ in a dilution refrigerator. The junction current is measured using a low-noise dc SQUID. The junction is connected in series with a 6-nH coil inductively coupled to the SQUID and in parallel with a 0.196Ω shunt resistor, while a tunable dc source provides the bias current. In the superconducting state, the bias current flows through the SGS channel, whereas in the resistive state the much larger junction resistance diverts the current through the shunt resistor, enforcing a quasi-constant-voltage bias. The SQUID operates in flux-locked-loop mode [14] with a gain of $1.3 \times 10^5 \text{ V/A}$ and an effective bandwidth of 12.5 MHz, well below ac Josephson frequencies. The feedback coil maintains the SQUID within its linear operating regime throughout the measurement.

NIR light is delivered to the SGS Josephson junctions through a single-mode fiber (core diameter $10.4\text{ }\mu\text{m}$) with its end positioned about $100\text{ }\mu\text{m}$ above the junction, yielding an estimated beam diameter of $11.4\text{ }\mu\text{m}$ at the junction plane. Electromagnetic simulations considering the device geometry estimate coupling efficiencies of 0.24 for the Nb electrodes and 0.01 for the $0.5\text{-}\mu\text{m}$ -long graphene channel. Separately, the intrinsic absorption of the materials is 2.4% for 100-nm -thick Nb and 1.3% for BLG [15]. Taken together, these estimates indicate that photon absorption occurs predominantly in the superconducting Nb electrodes. Upon NIR irradiation, time-resolved current responses of the SGS Josephson junctions are recorded with a high-speed digital oscilloscope, allowing direct observation of photon-induced variations in the Josephson supercurrent and quantitative analysis of switching dynamics.

Figure 1(b) shows the measured I - V characteristics of the SGS Josephson junction with a $0.5\text{-}\mu\text{m}$ graphene channel. In the superconducting state, the applied current flows as a dissipationless Josephson supercurrent. As the bias increases, the junction undergoes a stochastic transition to the resistive state at the switching current I_c , which typically underestimates the intrinsic critical current due to thermal and quantum fluctuations [16,17]. In the resistive regime, the parallel shunt resistor R_{shunt} enforces a quasi-constant-voltage bias, producing a region of negative differential resistance. At higher bias, Joule heating drives the junction into the normal state with a resistance $R_n \approx 30\text{ }\Omega$.

To quantify the energy scales of the junction, we estimate the Thouless energy as $E_{\text{Th}} = \hbar D/L^2$ in the diffusive regime [5], with diffusion constant $D = 0.5v_F l_e = 0.14\text{ m}^2/\text{s}$ and Fermi velocity $v_F = 2.5 \times 10^6\text{ m/s}$. The latter follows from $v_F = \hbar(\pi n)^{0.5}/m^*$ [18], where $m^* \approx 0.033m_e$ denotes the effective electron mass in bilayer graphene and m_e is the free-electron mass [19]. For the $0.5\text{-}\mu\text{m}$ channel, this yields $E_{\text{Th}} = 375\text{ }\mu\text{eV}$, much smaller than the Nb superconducting gap $\Delta_{\text{Nb}} \sim 1.32\text{ meV}$ (derived from $T_c = 8.7\text{ K}$), confirming that the $0.5\text{-}\mu\text{m}$ junction operates in the long-junction regime. In contrast, the $0.16\text{-}\mu\text{m}$ channel has a higher Thouless energy, comparable to or exceeding Δ_{Nb} , indicating a crossover to the short-junction regime.

The measured switching current of the $0.5\text{-}\mu\text{m}$ SGS Josephson junction is $I_c = 2.68\text{ }\mu\text{A}$, corresponding to a characteristic energy scale $eI_c R_n \approx 80.4\text{ }\mu\text{eV}$, significantly lower than the theoretical upper bound of $10.8E_{\text{Th}}$ for long diffusive junctions [20,21]. This suppression is attributed to incomplete interfacial transparency at the superconductor-graphene interface [22,23], highlighting the crucial role of interface quality in determining proximity-induced superconductivity and Andreev transport.

III. QUANTIZED SUPERCURRENT SUPPRESSION

We next investigate the influence of NIR illumination on the Josephson supercurrent and the dynamics of Cooper-pair tunneling in the SGS Josephson junction. Experiments were performed on the $0.5\text{-}\mu\text{m}$ SGS Josephson junction biased at $I_{\text{dc}} = 2.4\text{ }\mu\text{A}$, just below the switching threshold. In this regime, the entire bias current flows through the junction. Incident NIR photons, with energies well above twice the Nb

superconducting gap, break Cooper pairs in the electrodes, leading to a reduction of the Josephson supercurrent. The resulting redistribution of current in the bias circuit induces a transient voltage across the SQUID input coil through its self-inductance, expressed as $V = L_{\text{in}} \times dI/dt$, where $L_{\text{in}} = 6\text{ nH}$ denotes the nominal input inductance. Supercurrent variations of the junction under illumination at 1550 and 440 nm were recorded and statistically analyzed, yielding the histogram of current variation amplitudes shown in Fig. 1(c). Strikingly, the supercurrent variations appear as discrete, evenly spaced steps, which are insensitive to photon wavelength or energy. These quantized steps differ fundamentally from those associated with coherent quantum phase slips [24], in which step heights scale with the frequency of an external microwave drive. Instead, we attribute the observed quantization to the intrinsic dynamics of Cooper-pair tunneling in the SGS Josephson junction. In this system, a Cooper pair traverses the graphene channel as a coherent superposition of an electronlike quasiparticle and a holelike quasiparticle propagating in opposite directions [3,4]. Absorption of NIR photons in the superconducting Nb electrodes reduces the Cooper-pair density, thereby suppressing Cooper-pair tunneling, and each suppressed Cooper-pair tunneling cycle gives rise to a discrete current reduction of $\Delta I_s = 2e/\tau_t$. Experimentally, the current step size is measured to be $\Delta I_s = 0.053\text{ }\mu\text{A}$, corresponding to a tunneling time of $\tau_t = 6\text{ ps}$, which reflects both the interface traversal time and the dwell time within the graphene microbridge. We note that the peak associated with suppression of single Cooper-pair tunneling is partially obscured by a zero-centered feature near $0.05\text{ }\mu\text{A}$, primarily originating from baseline fluctuations in the readout electronics.

Figure 1(d) shows typical current traces under 1550 nm photon illumination, corresponding to the suppression of one, two, and three Cooper-pair tunneling cycles in the junction. Their temporal evolution is well captured by a double-exponential model [25,26]

$$\Delta I(t) = -\Delta I_m \left(e^{-\frac{t-t_0}{\tau_{\text{decay}}}} - e^{-\frac{t-t_0}{\tau_{\text{rise}}}} \right), \quad (1)$$

where ΔI_m denotes the response amplitude and t_0 marks the onset of NIR photon absorption. The rise time, $\tau_{\text{rise}} \approx 30\text{ ns}$, is determined by the electrical time constant $L_{\text{in}}/R_{\text{shunt}}$, while the decay time, $\tau_{\text{decay}} \approx 100\text{ ns}$, primarily reflects the quasiparticle recombination time τ_{qp} in the Nb electrodes. This recombination time depends on temperature and follows [27,28]

$$\frac{1}{\tau_{\text{qp}}} = \left(\frac{1}{\tau_0} \right) \left(\frac{2\Delta}{k_B T_c} \right)^{2.5} \left(\frac{\pi T}{T_c} \right)^{0.5} e^{-\frac{\Delta}{k_B T}}, \quad (2)$$

where $\tau_0 \approx 0.149\text{ ns}$ is a material-specific prefactor for Nb [29]. The experimentally extracted value, $\tau_{\text{qp}} = 100\text{ ns}$, corresponds to an effective temperature ratio $T/T_c = 0.187$, much higher than the bath temperature ratio $T_{\text{bath}}/T_c = 0.011$ ($T_{\text{bath}} = 0.1\text{ K}$). Notably, τ_{qp} remains nearly unchanged up to 0.5 K . This discrepancy indicates a saturation of quasiparticle recombination at ultralow temperatures, likely due to disorder-enhanced scattering processes [30,31].

To confirm the quantum origin of the discrete steps, we performed statistical measurements of the Josephson supercurrent under varied experimental conditions (illumination

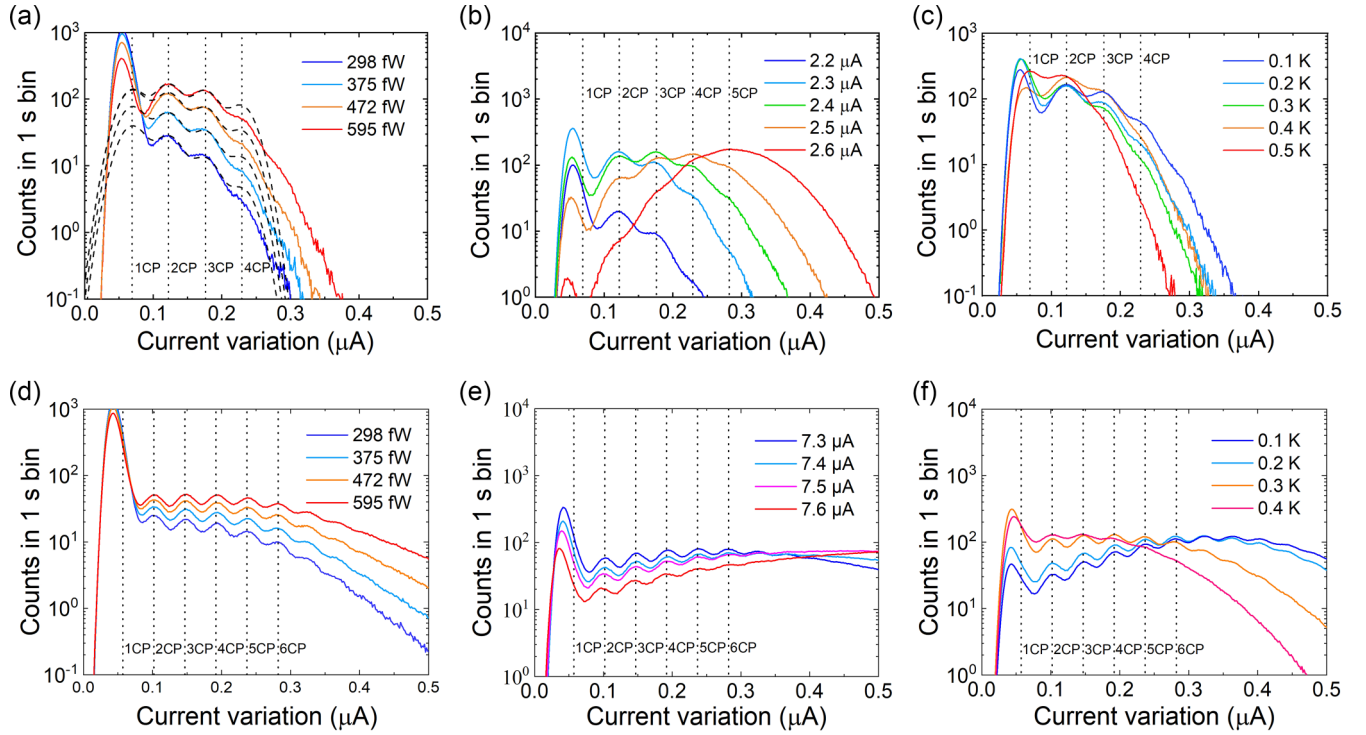


FIG. 2. Statistical measurements of supercurrent variations in two SGS Josephson junctions under varied experimental conditions, including illumination power, dc bias current, and bath temperature. Panels (a)–(c) correspond to the 0.5- μm Josephson junction. (a) Histograms of supercurrent variations under different 1550 nm illumination powers at $I_{\text{dc}} = 2.4 \mu\text{A}$ and $T_{\text{bath}} = 0.1 \text{ K}$. Each peak corresponds to a discrete number of suppressed Cooper-pair tunneling cycles. Dashed lines indicate Gaussian fits to individual peaks, with the overall distribution following Poissonian statistics. (b) Dependence of supercurrent variations on the dc bias current under 749 fW illumination at $T_{\text{bath}} = 0.1 \text{ K}$. (c) Supercurrent variations at different bath temperatures under the same illumination. Panels (d)–(f) correspond to the 0.16- μm Josephson junction, which has a normal resistance of about 10Ω and a switching current I_c of approximately $7.65 \mu\text{A}$. This junction also exhibits discrete supercurrent steps with a nearly constant interval of $0.045 \mu\text{A}$, independent of the varied experimental conditions. The uniform step spacing demonstrates the quantized and robust nature of Cooper-pair tunneling.

power, dc bias current, and bath temperature). In all cases, the supercurrent still exhibits discrete reductions with a fixed step spacing of $\Delta I_s = 0.053 \mu\text{A}$, confirming robust quantization. As shown in Fig. 2(a), increasing the illumination power leads to a higher average number of current response events, with the power calibrated outside the dilution cooler. The measured histograms are well fitted by a Poisson-weighted sum of Gaussian peaks [32,33]

$$P(A) = \sum_{i=0}^n \frac{\mu_p^i}{i!} e^{-\mu_p} \frac{1}{\sqrt{2\pi}\sigma^2} e^{-\frac{(A-A_i)^2}{2\sigma^2}}, \quad (3)$$

where μ_p is the mean number of current response events, $\sigma = 0.019 \mu\text{A}$ is the standard deviation of each Gaussian peak, and A_i denotes the current amplitude corresponding to i tunneling events. The Gaussian peak width is fundamentally set by generation-recombination noise of quasiparticles in Nb electrodes [31,34] and SQUID readout noise.

Figure 2(b) shows the dependence of current response counts on the dc bias at $T_{\text{bath}} = 0.1 \text{ K}$ under 749 fW 1550-nm illumination. The observed trend reflects a trade-off between enhanced photon sensitivity and increased susceptibility to thermally induced noise near the switching current. At lower bias, the SGS Josephson junction remains robustly superconducting, yielding weak photon-induced responses, whereas

at higher bias, dark counts become more likely, reducing detection fidelity. Figure 2(c) demonstrates discrete supercurrent steps persist up to 0.5 K . In this regime, the condition $E_{\text{Th}} > k_B T_{\text{bath}}$ is satisfied, ensuring that quantum transport in the junction is preserved despite thermal excitation of quasiparticles.

Measurements on the shorter 0.16- μm junction also reveal discrete supercurrent steps, with a step interval of $\sim 0.045 \mu\text{A}$ [Figs. 2(d)–2(f)], comparable to that of the longer junction. Although one might expect a larger step interval due to reduced dwell time in graphene, the nearly identical spacing indicates that the Cooper-pair tunneling time is governed by traversal process across the superconductor-graphene interfaces rather than by the dwell time within the graphene channel. In simple terms, the traversal time is given by $\hbar/(\Delta_{\text{Nb}} T_{\text{SG}})$, where T_{SG} is the interface transmission. Given $\tau_t = 6 \text{ ps}$, we estimate $T_{\text{SG}} = 0.17$, which further explains the substantial suppression of the characteristic energy $eI_c R_n$ relative to the theoretical value.

IV. ABSENCE OF QUANTIZATION IN THE RESISTIVE REGIME

The preceding analysis addresses the operation of the SGS Josephson junction in its superconducting state, where

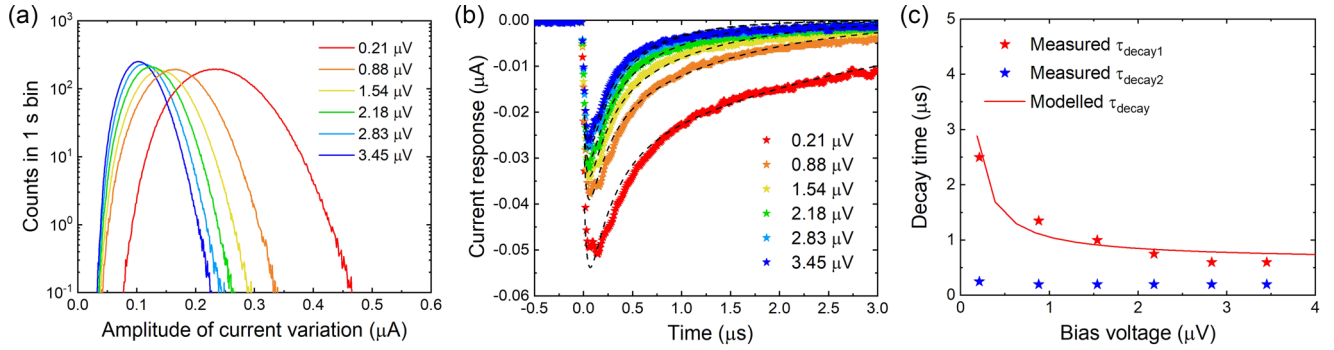


FIG. 3. Current response characteristics of the SGS Josephson junction with a 0.5- μm graphene channel in the NDR regime. (a) Histograms of current variations under 595 fW illumination at different bias voltages. The absence of discrete steps reflects the predominance of dissipative quasiparticle transport rather than coherent Cooper-pair tunneling. (b) Time-resolved current traces under 150 fW illumination at different bias voltages, fitted with a dual-exponential decay model to capture the temporal response dynamics. (c) Comparison of experimentally extracted decay constants with theoretical predictions from a bolometric model incorporating electrothermal feedback.

discrete reductions of the supercurrent under NIR illumination provide compelling evidence of quantum Cooper-pair tunneling. To further substantiate this interpretation, we examine the NDR regime, in which the Josephson coupling is suppressed and transport is dominated by quasiparticles. Figure 3(a) presents a histogram of current variations at various bias voltages. Unlike in the supercurrent regime, the discrete supercurrent steps are absent in the NDR regime. This absence is attributed to the predominance of quasiparticle current, whose dissipative dynamics differ fundamentally from those of Cooper-pair tunneling. At a representative bias of $V_0 = 1 \mu\text{V}$ and $I_0 = 2.2 \mu\text{A}$, corresponding to an effective resistance of 0.45Ω , the junction behaves as an equivalent normal graphene channel of length $L_n = 11 \text{ nm}$. The associated quasiparticle drift time, estimated as $\tau_D = L_n^2/(\mu \times V_0) = 50 \text{ ns}$, far exceeds the characteristic tunneling time. This disparity in timescales precludes the resolution of discrete current steps in the NDR regime.

The presence of normal current in this regime also gives rise to bolometric effects. NIR photon absorption in the Nb electrodes increases the junction resistance. Under constant voltage bias, this resistance increase reduces the Joule heating power, thereby inducing negative electrothermal feedback [35]. Figure 3(b) shows time-resolved current traces at various bias voltages. Analysis of these current transients reveals two distinct decay times, denoted τ_{decay1} and τ_{decay2} , each associated with distinct physical processes. The decay time τ_{decay1} exhibits a strong dependence on bias voltage, as illustrated in Fig. 3(c), and is attributed to electron-phonon interactions in graphene, consistent with previous studies on SGS bolometers [7–9]. Within a bolometric framework that incorporates electrothermal feedback [35], τ_{decay1} is modeled as

$$\tau_{\text{decay}} = \tau_0 \frac{Z_0 R + R_L}{2R Z_0 + R_L}, \quad (4)$$

where $\tau_0 = C_e/G$ is the intrinsic thermal time constant in the absence of electrothermal feedback, with C_e and G denoting the electronic heat capacity and electron-phonon thermal conductance of graphene, respectively. Here, $Z_0 = dV/dI$ is

the dynamic impedance extracted from the junction's I-V characteristics, and R_L is the load resistance determined by the shunt resistance R_{shunt} . The intrinsic time constant τ_0 , estimated to be $1.5 \mu\text{s}$, is comparable to the measured τ_{decay1} , and the model shows excellent agreement with the experimental data. In contrast, τ_{decay2} exhibits negligible bias dependence, suggesting it likely originates from quasiparticle recombination processes in the superconducting Nb electrodes.

V. CONCLUSION

We have demonstrated a robust quantized suppression of the Josephson supercurrent in SGS Josephson junctions under NIR illumination. The observed discrete supercurrent response originates from Andreev-mediated Cooper-pair tunneling cycles and is insensitive to photon energy, optical power, bath temperature, and dc bias. Notably, the nearly length-independent suppression quantum indicates that the underlying transport mechanism is governed by interface processes rather than by graphene channel properties. These observations imply that Andreev processes at the superconductor-graphene interfaces impose a characteristic timescale for Cooper-pair tunneling. By systematically comparing the superconducting regime with the dissipative transport NDR regime, we further demonstrate that the observed quantization is intrinsic to coherent Cooper-pair tunneling mediated by interface Andreev processes.

Taken together, these results establish SGS Josephson junctions as an experimentally accessible platform for investigating coherent Cooper-pair transport under nonequilibrium conditions. The capability to resolve discrete supercurrent suppression events enables systematic studies of nonequilibrium Andreev-bound-state dynamics, quantitative determination of interface-controlled Cooper-pair tunneling times, and the deliberate engineering of SGS Josephson junctions for broader applications, including photon detectors [6–9], superconducting quantum interference and amplification devices [36–38], and scalable coherent quantum circuits [39,40].

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

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