Highly Sensitive Superconducting Quantum-Interference Proximity Transistor

Alberto Ronzani, Carles Altimiras,[*] and Francesco Giazotto
NEST, Istituto Nanoscienze-CNR and Scuola Normale Superiore, I-56127 Pisa, Italy

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We report the design and implementation of a high-performance superconducting quantum-interference proximity transistor based on aluminum-copper technology. With the adoption of a thin and short copper nanowire, we demonstrate full phase-driven modulation of the proximity-induced minigap in the normal-metal density of states. Under optimal bias, we record unprecedentedly high flux-to-voltage (up to 3 mV/Φ_0) and flux-to-current (exceeding 100 nA/Φ_0) transfer function values at subkelvin temperatures, where Φ_0 is the flux quantum. The best magnetic-flux resolution (as low as $500\mathrm{n}\Phi_0/\sqrt{\mathrm{Hz}}$ at 240 mK being limited by the room-temperature preamplification stage) is reached under fixed current bias. These figures of merit combined with ultralow power dissipation and micrometer-size dimensions make this mesoscopic interferometer attractive for low-temperature applications such as the investigation of the magnetization of small spin populations.

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I. INTRODUCTION

The superconducting quantum-interference proximity transistor [1] (SQUIPT) is a two-terminal device based on a tunnel junction between a superconducting "probe" electrode and a normal-metal wire inserted in a superconducting loop; see Fig. 1(a). Because of the proximity effect [2], the clean electric contact between the normal and the superconducting metal leads to the appearance of a phase-dependent minigap in the electronic density of states (DOS) of the normal metal [3]. Yet, once proximized, the latter establishes a weak coupling [4] between the superconducting electrodes in contact with it so that the whole superconductor–normal-metal–superconductor (SNS) complex operates as a Josephson junction [5]. An external magnetic field threading the loop, therefore, modulates the amplitude of the minigap by establishing a definite phase difference across the Josephson junction as a consequence of flux quantization in the closed superconducting ring [6,7].

SNS weak links offer the possibility to realize superconducting couplings unachievable by Josephson tunnel junctions, for instance, by providing nonsinusoidal current-phase relation in the short-junction length limit [5] or achieving a π state by driving the weak link into nonequilibrium conditions [8]. In SQUIPTs, the SNS weak link is exploited so that the electronic DOS of the metallic wire is modulated [3,9,10] by externally driving the magnetic flux. Therefore, SQUIPTs can be considered as magnetic analogs of semiconductor field-effect transistors and can be exploited as sensitive magnetic-flux sensors. Being based on mesoscopic quantum effects, they bear technological similarities with single-electron transistors used as charge sensors [11]: They require being operated at subkelvin temperatures and are characterized by moderately high output impedances limiting their bandwidth unless radio-frequency matching techniques are used [12]. Despite these limitations, they are well worth the effort since their performance in terms of flux sensitivity and power dissipation has no technological counterpart. For instance, ultimate magnetic-flux resolution values as low as $1\mathrm{n}\Phi_0/\sqrt{\mathrm{Hz}}$ below 1 K (where $\Phi_0 = h/2e \simeq 2.067 \times 10^{-15}$ Wb is the flux quantum) have been predicted for SQUIPTs based on large energy-gap superconducting materials such as vanadium [13]. This makes them attractive for low-temperature applications such as the investigation of the magnetization of small spin populations.

Here we report the realization and characterization of a SQUIPT based on the Al-Cu technology, which shows record flux-to-voltage transfer function values (up to $\simeq 3$ mV/Φ_0), leading to a magnetic-flux resolution $\Phi_N \simeq 500\mathrm{n}\Phi_0/\sqrt{\mathrm{Hz}}$ at 240 mK in the near-dc frequency range and being limited by the voltage noise of the room-temperature preamplification stage.

The earliest proof-of-concept realization [1] of a SQUIPT describes a device based on a copper wire of length $L = 1.5$ μm proximized by a thin aluminum loop spanning a surface of approximately 120 $\mu\mathrm{m}^2$. These figures result in the SNS junction being in the long diffusive limit (i.e., $L \gg \xi_0$, where ξ_0 is the coherence length) entailing modest minigap modulation amplitudes (approximately equal to 10 μeV) under optimal current bias. In subsequent attempts aiming at increasing the response of the device up to its predicted intrinsic limits [13], the length of the N wire has been reduced to bring the SNS junction in the short regime, where the amplitude of the proximized minigap can approach that of the "parent" superconductor. These devices [14] succeed in achieving wider induced minigap values

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[*] carles.altimiras@sns.it

(approximately equal to 130 μeV) but suffer from hysteresis stemming from self-induced magnetic screening caused by the high critical current magnitude typical of short metallic weak links. This shortcoming has recently been lifted by reducing the cross section of the copper wire while keeping it in the short-junction limit ($L \approx 250$ nm), therefore, allowing one to reach a sizeable magnetic-flux responsivity with an estimated 50-μeV minigap modulation amplitude, i.e., approximately equal to 36% of the full induced minigap width deduced from the differential conductance measurements [15].

The cause for incomplete minigap modulation lies in a nonideal phase bias of the weak link. In the limit of negligible magnetic screening originating from the geometric self-inductance of the loop, the effective phase difference imposed to the weak link by flux quantization is affected by the competition between the kinetic inductance of the superconducting loop and that of the weak link (respectively, $\mathcal{L}^S$ and $\mathcal{L}^{\mathrm{WL}}$). A complete phase bias corresponding to high phase gradient developed across the Cu nanowire is only possible in the limit $\mathcal{L}^S/\mathcal{L}^{\mathrm{WL}} \ll 1$ [3]. The difficulty in achieving this regime originates from the short-junction nature of the weak links which, apart from the aforementioned high critical current values, also show at low temperature a nonsinusoidal current-phase relationship $I^{\mathrm{WL}}(\phi)$. Both effects [5,16] suppress the magnitude of $\mathcal{L}^{\mathrm{WL}} = (\Phi_0/2\pi)(\partial I^{\mathrm{WL}}/\partial\phi)^{-1}$ as the value of the phase difference ϕ approaches π, where the sharpest response is expected [13]. In the present SQUIPT, we show that a complete phase bias can be achieved in a junction approaching the short limit by realizing a copper wire having a nanoscale cross section (thus, maximizing $\mathcal{L}^{\mathrm{WL}}$) while at the same time having a compact superconducting aluminum loop characterized by low normal-state resistance (therefore, minimizing both the kinetic and geometric components of $\mathcal{L}^S$). As a consequence of the full minigap modulation in the proximized weak link, we obtain record magnetic-flux responsivity figures, both in current- and voltage-biased setups.

II. FABRICATION

Figure 1(b) shows the scanning electron micrograph of a typical SQUIPT device fabricated by standard electron-beam lithography on a suspended bilayer resist mask [17] (1000-nm copolymer–, 100-nm polymethyl-methacrylate) on top of an oxidized silicon substrate. An initial 15-nm-thick Al layer is deposited at 40° via electron-beam evaporation in ultrahigh vacuum conditions ($\simeq 10^{-9}$ Torr) and subsequently exposed to a pure O_2 atmosphere (37 mTorr for 300 s) to obtain the tunnel probe electrode. The normal-metal nanowire is realized by evaporating a 25-nm-thick Cu layer at 20°. Finally, a 150-nm-thick Al film in clean contact with the latter layer is deposited at zero angle to implement the superconducting loop designed to have an internal diameter $\simeq 1.7$ μm. The device core [see Fig. 1(c)] shows an interelectrode spacing $L \simeq 140$ nm, while the copper nanowire is 30 nm wide and overlaps the lateral superconducting electrodes for $\simeq 400$ nm per side. The width of the tunnel probe electrode is $\simeq 60$ nm. Based on previous measurement on Cu nanowires of similar cross section [18], we estimate the ratio $L/\xi_0 = L\sqrt{\Delta_r/\hbar D_{\mathrm{Cu}}} \approx 1.1$, which confirms the frame of the intermediate–short-junction regime. Above, $\Delta_r \simeq 185$ μeV is the energy gap in the superconducting ring and $D_{\mathrm{Cu}} \simeq 55$ cm^2/s is the diffusion coefficient for our Cu nanowire. The yield of such simple fabrication scheme is about 20% being mostly limited by the mechanical stability of the suspended polymethyl-methacrylate mask defining the loop.

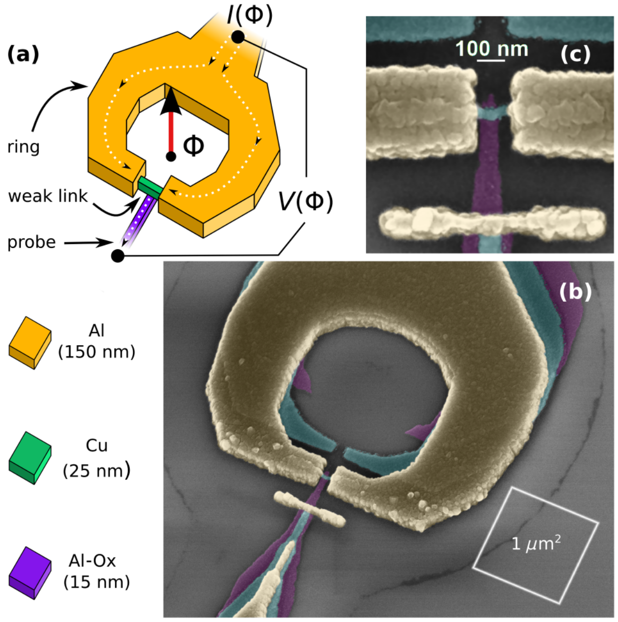

FIG. 1. (a) Functional schematic of a SQUIPT device realized by tilted evaporation of metallic thin films through a suspended resist mask defined by electron-beam lithography. The first evaporation (purple layer) consists in 15 nm of aluminum (Al), subsequently oxidized to form an AlOx tunnel barrier. The second evaporation (green layer) consists in 25 nm of copper (Cu) realizing the normal-metal nanowire. Finally, 150 nm of Al (dark yellow) are evaporated to form the superconducting loop (having inner diameter $\simeq 1.7$ μm) as well as the electrodes in clean electric contact with the Cu film. In the schematic, Φ is the magnetic flux linked to the superconducting loop; $I(\Phi)$ and $V(\Phi)$ are, respectively, the current flowing through and the voltage difference across the device. (b) Tilted scanning electron micrograph showing the complete SQUIPT loop. (c) Scanning electron micrograph centered on the Cu nanowire region. The interelectrode spacing is $\simeq 140$ nm; the width of the nanowire is $\simeq 30$ nm. The tunnel probe is $\simeq 60$ nm wide at the interface with the Cu weak link.

III. CHARACTERIZATION

The SQUIPT magnetoelectric characterization is performed in a filtered ^{3}He cryostat for several temperatures in the range 0.24–0.85 K. The current response under voltage bias is measured in a two-wire configuration with a commercial current preamplifier (DL Instruments model 1211) as a function of the magnetic flux generated by a magnetic field applied orthogonally to the plane of the substrate. The current response shows periodicity with respect to the applied magnetic field density with period $B_0 = \Phi_0/A_{\mathrm{eff}} \approx 6.2$ G, where $A_{\mathrm{eff}} \approx 3.3\ \mu\mathrm{m}^2$ is consistent with the area enclosed by the ring of the SQUIPT.

Figure 2(a) shows the current-vs-voltage $I(V_{\mathrm{bias}})$ characteristics recorded at the base temperature ($T = 240$ mK) for selected equally spaced values of the applied magnetic flux ranging from $\Phi = 0$ to $\Phi = \Phi_0/2$. At zero flux (fully open minigap), the characteristic shows a behavior resembling that of a tunnel junction between superconductors with different energy gaps. By increasing the magnetic field, the minigap closes until the characteristic is similar to that of a normal-metal–insulator–semiconductor junction at $\Phi = \Phi_0/2$. From these data, we estimate the 15-nm-thick aluminum probe to be characterized by a superconducting gap $\Delta_{\mathrm{pr}} \approx 235\ \mu$eV and a tunnel resistance $R_T \approx 55$ kΩ. The curves are consistent with a maximum minigap amplitude $\varepsilon_g(\Phi = 0) \approx 145\ \mu$eV, a value which corresponds approximately to 78% of the energy gap in the superconducting ring. Figure 2(b) shows the theoretical Bardeen-Cooper-Schrieffer (BCS)-like profile [19] of the DOS in the probe junction $\rho_{\mathrm{pr}}(E) = |\mathrm{Re}(\frac{E+i\gamma}{\sqrt{(E+i\gamma)^2-\Delta_{\mathrm{pr}}^2}})|$ where $\gamma/\Delta_{\mathrm{pr}} = 10^{-3}$ accounts for energy smearing due to the finite quasiparticle lifetime [20,21]. The panels in Fig. 2(c) show the theoretical DOS in the weak link $\bar{\rho}_{\mathrm{WL}}(E)$, spatially averaged over the probe width. The latter DOS is obtained by solving numerically the 1D Usadel equations [22,23] with parameters $L/\xi_0 = 1.1$, $\Delta_r = 185\ \mu$eV and assuming perfect interface transmissivity between the ring and the wire, for $\Phi = \{0, 0.25, 0.5\}\Phi_0$.

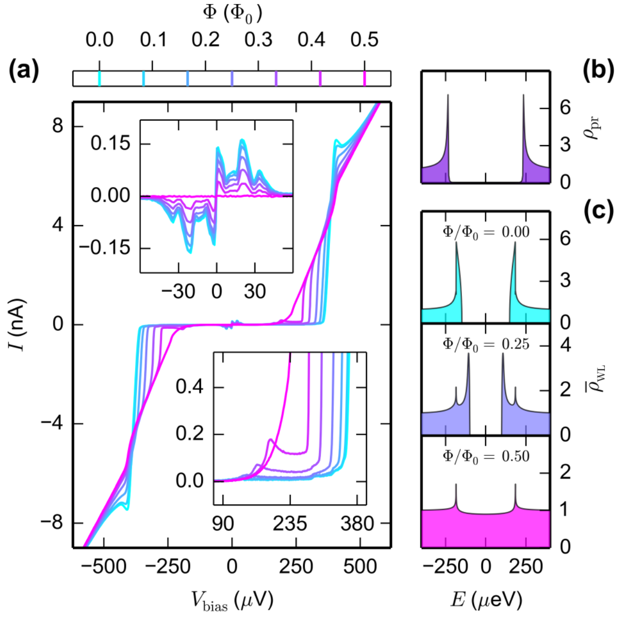

FIG. 2. (a) SQUIPT current-vs-voltage characteristics recorded at 240 mK for seven equally spaced magnetic-flux values ranging from $\Phi = 0$ to $\Phi = \Phi_0/2$. The upper inset shows a magnification of the low-voltage bias range, where weak phase-dependent supercurrent features appear at fixed voltage values. The lower inset shows a magnification of the onset of quasiparticle conduction, where the voltage dependence of the current can be nonmonotonic as a consequence of thermally activated transport. This is particularly evident (at finite temperature) when the minigap starts to be suppressed by the magnetic flux. (b) Theoretical BCS density of states $\rho_{\mathrm{pr}}(E)$ of the superconducting probe ($\Delta_{\mathrm{pr}} = 235\ \mu$eV). (c) Theoretical local density of states $\bar{\rho}_{\mathrm{WL}}(E)$ in the proximized weak link averaged over the probe width for three different values of the applied magnetic flux. $\bar{\rho}_{\mathrm{WL}}(E)$ was obtained by the numerical solution of the 1D Usadel equations assuming $L = 1.1\xi_0$ and full transparency at the interfaces.

The upper inset of Fig. 2(a) shows a magnified view of the flux-dependent features appearing at low bias. The latter can be attributed to a weak Josephson coupling between the proximized nanowire and the probe electrode, and their complete suppression at $\Phi = \Phi_0/2$ is a further indication of the full modulation of the minigap. A close inspection of the current-vs-voltage characteristics in Fig. 2(a) indicates that the measured current modulation is able to reach peak-to-peak amplitudes as large as 4 nA. On the other hand, when biased at fixed current, the amplitude of the corresponding voltage modulation approaches ε_g/e.

The lower inset in Fig. 2(a) shows a blowup of the characteristics at the onset of quasiparticle conduction. Here the current is nonmonotonic as a consequence of the appreciable thermal population of the quasiparticle states in the proximized nanowire resulting in additional conduction when $V_{\mathrm{bias}} = [\Delta_{\mathrm{pr}} - \varepsilon_g(\Phi)]/e$. This bias configuration shifts the chemical potentials of the tunnel junction electrodes so that the singularity in the empty DOS of the probe electrode is energetically aligned to the thermally excited quasiparticles in the copper nanowire. In the following, we adopt the term "singularity-matching peak" to refer to this particular transport feature, in analogy to S_1IS_2 systems [24]. The tunnel resistance value obtained in the fabrication process is compatible with the optimal input load impedance of both voltage and current preamplifiers. In the following, we consider both voltage-biased and current-biased setups.

Current-vs-flux (i.e., at fixed voltage bias) response figures are obtained by numerical differentiation with respect to the magnetic flux of the $I(\Phi, V_{\mathrm{bias}})$ characteristics [Fig. 3(a)] at fixed V_{bias}. Figure 3(b) shows the absolute value of the base-temperature flux-to-current transfer function $|\partial I(V_{\mathrm{bias}}, \Phi)/\partial\Phi|$ as a color map. In this context, the transfer function map indicates sharp response (due to the abrupt onset of quasiparticle conduction) reaching values as high as 108 nA/Φ_0, over a wide range of the bias parameters in both flux $\Phi \in [0.35\text{–}0.45\Phi_0]$ and voltage bias $V_{\mathrm{bias}} \in [275\text{–}310\ \mu\mathrm{V}]$. This high sensitivity

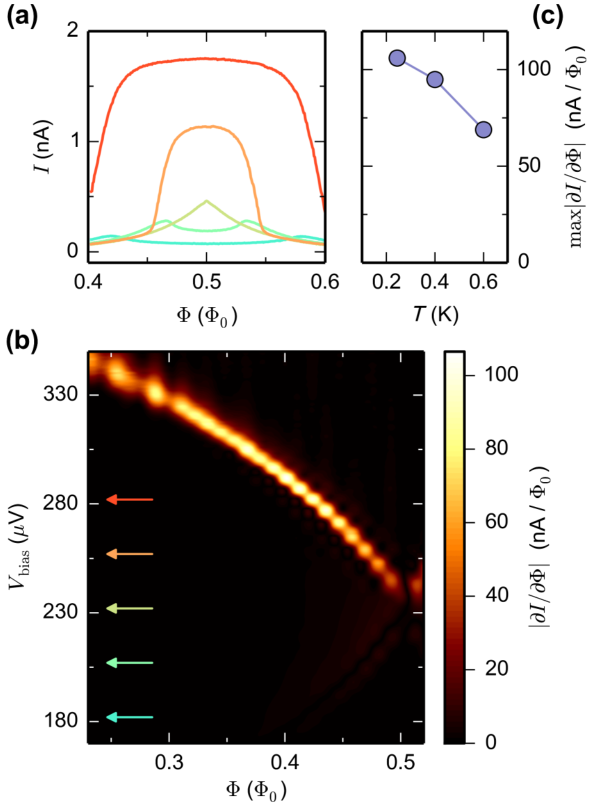

FIG. 3. (a) Current-vs-flux characteristics measured at 240 mK for fixed voltage bias (from bottom to top, $V_{\rm bias} = 182$, 212, 232, 252, 282 μV). (b) Color plot of the absolute value of the flux-to-current transfer function ($|\partial I/\partial\Phi|$ vs $V_{\rm bias}$ and Φ) obtained by numerical differentiation of the $I(\Phi)$ curves measured at 240 mK. Arrows indicate in corresponding colors the voltage bias values for the characteristics plotted in panel (a). (c) Temperature dependence of the maximum absolute value of the flux-to-current transfer function.

(approximately 4 times higher than the best-performing devices so far [15]) originates from both a lower tunnel probe resistance and a full modulation of the minigap. In addition, the maximum flux-to-current responsivity level is only moderately suppressed by increasing the temperature (see Fig. 3).

Voltage-vs-flux characteristics recorded at 240 mK for a few selected values of the current bias in the vicinity of the maximal response ($I_{\rm bias} = 435$ pA, $\Phi \simeq 0.5\Phi_0$) are shown in Fig. 4(a). The absolute value of the relative flux-to-voltage transfer function is plotted as a color map in Fig. 4(d). At low current bias, the nonmonotonicity of the current-vs-voltage characteristics [see the bottom inset of Fig. 2(a)] results in bistable voltage configurations giving rise to hysteretic behavior and limiting the useful bias range for a SQUIPT used as a linear sensor. The nonmonotonicity originating from the singularity-matching peak can, in principle, be limited by lowering the electron temperature beyond the base temperature of our cryostat. This can be achieved by using dilution refrigerators but also with the adoption of integrated on-chip electronic coolers [25,26] relying on the same fabrication technique. On the other side, the supercurrent peaks give rise to a similar electric bistability [see Fig. 2(a), top inset] and are expected to increase in magnitude at lower temperatures (when not countered by lower transparency of the tunnel barrier) and will ultimately limit the current bias range available for linear response.

Notably, the electric bistability provided by the singularity-matching peak could, instead, be exploited for operating the SQUIPT as a threshold detector. In this configuration, the flux is applied in close vicinity of a switching point [e.g., $I_{\rm bias} = 335$ pA and $\Phi = 0.48\Phi_0$ in Fig. 4(d)] so that flux variations crossing the threshold given by the switching point yield a voltage step response (whose amplitude may be approximately equal to 50 μV) within a time scale corresponding to the relaxation time of the measurement setup. Such scheme can be useful for sampling the probability distribution function of a noisy magnetic-flux source.

We now discuss the SQUIPT sensitivity when operated as a linear flux sensor. Inspection of the flux-to-voltage transfer function [shown as a color map in Fig. 4(d)] reveals that the current-biased setup allows for a high responsivity (approximately equal to 1 mV$/\Phi_0$) over a rather broad flux and current bias range, with a peak value of approximately 3 mV$/\Phi_0$ located at $\Phi = 0.495\Phi_0$ and $I_{\rm bias} = 435$ pA. This working point lies just outside of the hysteretic region [marked with magenta lines in Fig. 4(d)], and it is, thus, a suitable point for linear operation of the detector.

While compatible with earlier results [15], such a high value of the voltage transfer function may seem surprising. Indeed, the detailed theoretical investigation of the SQUIPT performance in the short-junction limit (where analytic calculations can be performed) carried in Ref. [13] predicted maximal transfer functions of about $3.1\Delta_r/e\Phi_0$ around $\Phi = 0.5\Phi_0$, which can be traced back to the flux dependence of the minigap. Extrapolating this limit to our moderately short SNS junction, i.e., assuming the same scaling but replacing Δ_r with the measured minigap $\epsilon_g = 145$ μeV, one would expect a response of about 450 μeV$/\Phi_0$, which is 6 times smaller than the maximum value obtained in the experiment. The reason for the observed higher response stems from the contribution of the singularity-matching peak ignored in Ref. [13], which bends the nonhysteretic $V(\Phi, I_{\rm bias})$ characteristics in the vicinity of $\Phi_0/2$ and $V = \Delta_{\rm pr}/e$ resulting in a sharper voltage response. This feature can be easily reproduced by using a simplified model which holds in the short-junction limit as described in Ref. [13], with the replacement $\Delta_r \leftrightarrow \epsilon_g$.

Figure 4(c) presents a contour plot of the $I(\Phi, V_{\rm bias})$ data set obtained with the above theoretical model in the vicinity of $eV_{\rm bias} = \Delta_{\rm pr} = 235$ μeV and $\Phi/\Phi_0 = 0.5$ at $T = 240$ mK. The white lines correspond to calculated

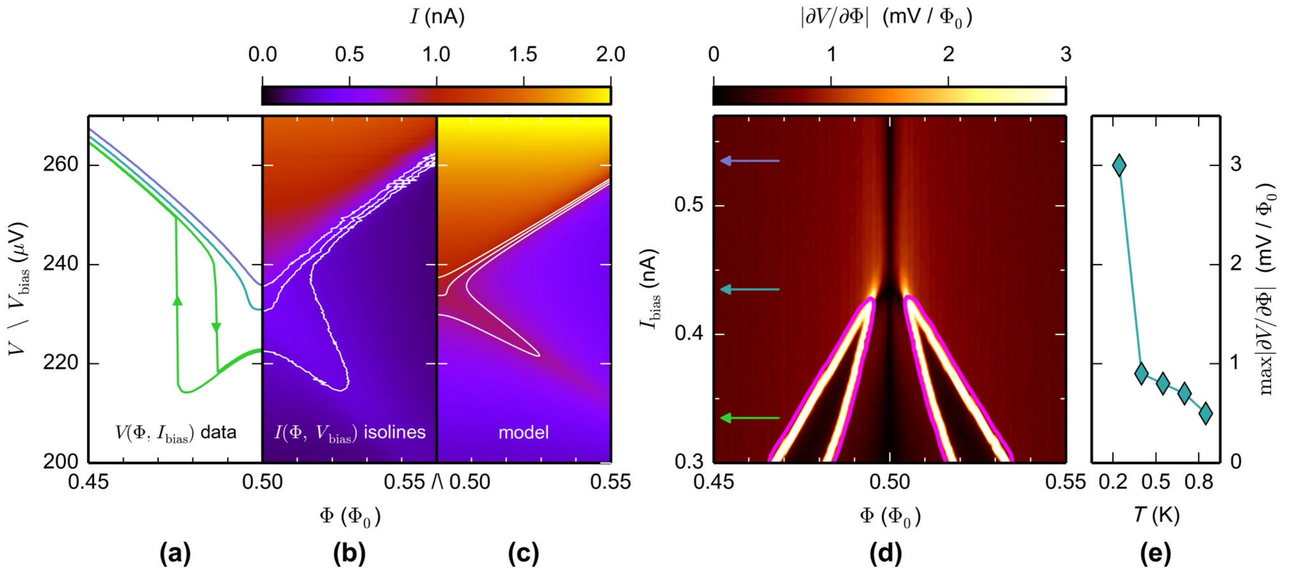

FIG. 4. (a) Voltage-vs-flux characteristics measured at 240 mK for fixed current bias (from bottom to top, $I_{\mathrm{bias}} = 335, 435, 535$ pA). (b) Color plot showing the measured $I(V_{\mathrm{bias}}, \Phi)$ data set; the current isolines match the characteristics shown in panel (a). The reentrant shape of the lowest current isoline is at the origin of the hysteresis displayed in the corresponding $V(\Phi, I_{\mathrm{bias}})$ characteristic [green trace in panel (a)]. (c) Color plot of the theoretical current vs V_{bias} and Φ calculated for a SQUIPT device based on a weak link in the short regime. (d) Color plot of the absolute flux-to-voltage transfer function ($|\partial V/\partial\Phi|$ vs V_{bias} and Φ) obtained by numerical differentiation of $V(\Phi)$ curves measured at 240 mK. Hysteresis originating from the nonmonotonicity of the current-vs-voltage characteristics [see lower inset of Fig. 2(a)] can be appreciated for $I_{\mathrm{bias}} < 435$ pA. The associated switching events are marked by green arrows in panel (a). Magenta lines mark the hysteretic regions in the color map. Arrows indicate in corresponding colors the current bias values for the characteristics plotted in panel (a). (e) Temperature dependence of the maximum absolute value of the flux-to-voltage transfer function.

current isolines, which strongly resemble those observed in the actual measured $I(\Phi, V_{\mathrm{bias}})$ characteristics [see Fig. 4(b)]. Although rather idealized, the model provides a satisfactory reproduction of the physical mechanism underlying the observed high responsivity. Furthermore, a close match between the measured $V(\Phi, I_{\mathrm{bias}})$ response curves and the current isolines can be appreciated in the juxtaposition of Figs. 4(a) and 4(b), therefore, corroborating the identification of the physical origin of the high flux-to-voltage responsivity we observe.

In particular, three regimes can be recognized depending on the magnitude of the quasiparticle current. The low-current regime [corresponding to the green trace and arrow in Figs. 4(a) and 4(d)] is characterized by hysteresis originating from the singularity-matching peak bistability, which is evident in the reentrant shape of the low-current isolines in Figs. 4(b) and 4(c). Conversely, in the high-current limit [exemplified by the blue trace and arrow in Figs. 4(a) and 4(d)], no hysteresis can be found, but the magnetic-flux responsivity is only moderate. The optimal regime for sensitivity [represented by the cyan trace and arrow in Figs. 4(a) and 4(d)] emerges in the smooth transition between the two above-mentioned limits. This latter regime features the highest value of the flux-to-voltage transfer function but no hysteresis.

The temperature dependence of the maximum value of the transfer function is displayed in Fig. 4(e). The substantial enhancement observed at lower temperature is due to the abrupt character of the thermal suppression of the singularity-matching peak appearing in the current-vs-voltage characteristics, which allows us to access the optimal current-bias range required for the sharpest voltage response.

Our device is designed to show that high transfer function values can be obtained in SQUIPTs based on Al-Cu technology. The intermediate value of the impedance of the device ($R_T = 55$ kΩ), allows sensitive operation of the interferometer in both voltage-biased and current-biased setups. However, given the significant capacitive load present in the filtered lines of our refrigerator setup, the current-biased measurement scheme shows better performance, thanks to the superior common-mode noise rejection properties of differential voltage preamplification.

Figure 5 shows an assessment of the noise performance of the SQUIPT as a magnetic-flux sensor obtained at 240 mK by measuring the power spectral density (PSD) of voltage fluctuations recorded at the output of battery-powered differential voltage preamplifiers (NF Corporation model LI-75A). Two identical preamplification units are connected to the two independent analog-to-digital converter (ADC) channels of a spectrum analyzer (HP model 89410A), which computes the PSD of each channel as well

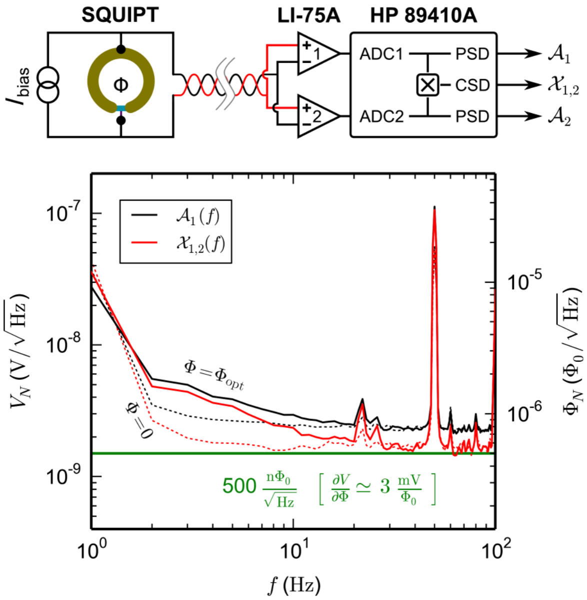

FIG. 5. Noise-level measurement in a current bias mode at 240 mK. The schematic displayed on top summarizes the measurement setup, in which the signal from the SQUIPT is split and fed symmetrically into two battery-powered differential voltage preamplifiers (NF Corporation model LI-75A). The outputs from the preamplifiers are independently sampled by two analog-to-digital converters (ADC) in a digital spectrum analyzer (HP model 89410A), which computes the power spectral density (PSD, $\mathcal{A}_i$, black traces) for each ADC channel as well as the cross spectral density (CSD, $\mathcal{X}_{1,2}$, red traces) between the two. The resulting data are expressed in voltage noise referred to the input of the preamplifiers (V_N, in V/$\sqrt{\text{Hz}}$ units). Continuous lines indicate traces recorded at optimal current and flux bias, where the transfer function is maximal (3 mV/Φ_0). The right vertical axis shows the values for the magnetic-flux resolution (Φ_N) under these conditions. The 500n$\Phi_0/\sqrt{\text{Hz}}$ white-noise level is shown as a green horizontal line. Dotted lines indicate control traces recorded with optimal current bias at $\Phi = 0$ (zero transfer function and comparable differential resistance).

as the cross-correlated spectral density (CSD) between the two. The latter quantifies the amount of noise, which shows as correlated in the two ADC channels, and sets an upper limit to the estimate of the intrinsic noise figures for the measurement setup. The SQUIPT device is operated in the current-bias mode with $I_{\text{bias}} = 435$ pA. The spectral densities (both PSD and CSD) are expressed in amplitude units (V_N, in V/$\sqrt{\text{Hz}}$); the expected bandwidth of the measurement setup ($\simeq$ 20 Hz when tuned for high sensitivity) is here limited by the significant capacitance of the filtered measurement lines ($\simeq$ 90 nF).

The continuous-line traces in Fig. 5 are acquired with the device tuned for maximum sensitivity ($|\partial V/\partial\Phi|_{\text{max}} = 3$ mV/Φ_0 and $\Phi_{\text{opt}} = 0.495\Phi_0$). In these conditions, besides some spurious noise peaks, the input-referred white-noise level for the preamplifiers (black trace) approaches the nominal limit for this model (2 nV/$\sqrt{\text{Hz}}$), while the cross-correlated white-noise level (red trace) reaches values as low as 1.5 nV$\sqrt{\text{Hz}}$. Control traces shown in Fig. 5 as dotted lines are acquired with $I_{\text{bias}} = 435$ pA but zero magnetic flux (and, hence, zero transfer function, yet similar output differential resistance). They differ from the maximum-sensitivity traces for the absence in the 2–20 Hz frequency range of a 1/f slope whose level (assuming a field-to-voltage coefficient $A_{\text{eff}}|\partial V/\partial\Phi|_{\text{max}} \simeq$ 4.8 V/T) is consistent with the expected magnetic low-frequency noise found in unshielded rooms in an urban environment (typically in the 0.1–1 nT/$\sqrt{\text{Hz}}$ range at 10 Hz [27]).

The white-noise floor displayed in the CSD traces is significantly lower than the corresponding levels from the single-channel PSD, meaning that the room-temperature preamplification stage is here limiting the noise performance of the measurement setup. The cross-correlated voltage white-noise floor sets an upper limit to the magnetic-flux resolution achievable by our measurement setup,

$$\Phi_N = \frac{V_N}{|\partial V/\partial\Phi|} \simeq 500\text{n}\Phi_0/\sqrt{\text{Hz}}.$$

In spite of the relatively simple measurement equipment used, this noise figure is already comparable with state-of-the-art SNS superconducting quantum interference device (SQUID) interferometers equipped with custom cryogenic preamplification readout systems [28,29].

IV. OUTLOOK

Significant improvement in terms of magnetic-flux resolution will be possible with the adoption of a cryogenic preamplification to reduce the measurement noise down to 0.3 nV/$\sqrt{\text{Hz}}$ [30]: Assuming noise figures still dominate by the readout [13], we can expect a fivefold increase in flux sensitivity making the present SQUIPT technology comparable to the 50n$\Phi_0/\sqrt{\text{Hz}}$ resolution obtained in state-of-the-art nanoSQUIDs based on lead [31]. Another path is to exploit wide-gap superconductors [18,32,33] (such as vanadium or niobium) as proximizing elements to boost the responsivity figures. The choice of the above-mentioned wide-gap superconductors is also a prerequisite for withstanding the sizeable magnetic field that would be necessary for pushing the spin resolution in nanoscale-loop SQUIPTs beyond the current state-of-the-art level [31]. In this respect, under optimal coupling [34], we estimate the spin resolution of our SQUIPT $S_N = r\Phi_N/\pi\mu_0\mu_B \approx 24\mu_B/\sqrt{\text{Hz}}$, where r is the SQUIPT effective radius, μ_0 is the vacuum permeability, and μ_B is the Bohr magneton.

In summary, we present a SQUIPT device implemented with a fabrication protocol based on the mature Al-Cu technology, whose design successfully resolves the limit of the incomplete phase-driven modulation of the proximity-induced minigap. The reduced spatial extent of our SQUIPT geometry (in the micrometer range) combined with ultralow power (approximately equal to 100 fW) suggests the study of the magnetic degrees of freedom of small spin populations as a possible application for this mesoscopic interferometer. We conclude by emphasizing that the improvement in performance achieved in just four years after the initial SQUIPT proof-of-concept demonstration put this device class already on par with the 50-year-old SQUID technology [27,35].

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