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RESEARCH

Normal Metal–Insulator–Superconductor Aharonov-Bohm Interferometer

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Abstract
When a non-equilibrium excitation (a non-paired electron) is injected into a superconductor, it can travel fairly large distance before forming an equilibrium Copper pair. Here, we fabricated and experimentally studied electron transport in a solid-state analogue of a two-slit optical interferometer: T-shaped normal metal electrode (copper) — dielectric tunnel layer (aluminum oxide) — superconducting fork (aluminum). If the perimeter of the interferometer loop is sufficiently small, the phase of the non-equilibrium quasiparticle wave function is preserved and can be adjusted utilizing the Aharonov-Bohm effect. The coherent contribution manifests itself as non-monotonic dependence of the tunnel current on perpendicular magnetic field.

Keywords Non-equilibrium superconductivity · Normal metal–insulator–superconductor tunnel junction · Coherent electron current

1 Introduction

Rapid development of technology has already brought the level of nanoelectronic circuit integration to the limit, when the Joule heat dissipation becomes a serious problem. One of the possible and rather radical solutions is the utilization of superconducting elements with zero heat generation. At the same moment, it is clear that realistic nanoelectronic devices can be composed of various materials: not only superconductors. Given the permanent trend towards miniaturization, boundary phenomena at interfaces of such hybrid devices might become very important. In the extreme case of ultra-small electronic system, the entire hybrid structure can be considered as an 'interface'.

The topic of non-equilibrium superconductivity emerged at the early 70th of the previous century [1–3]. One of the key questions is the relaxation of non-paired electrons being the excitations of the equilibrium superconducting state represented by Copper pairs. Pioneering experiments [4, 5] performed on sandwich-type structures discovered that characteristic relaxation lengths tend to infinity at the critical temperature of a superconductor T_c. Theory considerations [3, 6, 7] predict the complicated interplay of various contributions responsible for non-equilibrium quasiparticle relaxation. In particular, one can define, at least, two mechanisms: *charge imbalance* and *energy imbalance* characterized by corresponding length scales λ_Q and λ_E. In later experiments enabling spatial resolution of the relaxation process [8–13], it was found that in superconducting aluminum at low temperatures ($T << T_c$) $\lambda_Q \approx 5$ µm and $\lambda_E \approx 40$ µm. These values are very large compared to other characteristic scales relevant for transport properties in typical aluminum thin film nanostructures: mean free path $l \approx 40$ nm and dirty limit superconducting coherence length $\xi \approx 100$ nm. Hence, at sufficiently low temperatures $T \ll T_c$, the relaxation of non-equilibrium quasiparticles in superconducting aluminum occurs extremely slowly and these excitations travel extremely large distances before forming equilibrium Cooper pairs.

It is reasonable to assume that on a certain scale $\lambda_\varphi \leq \min\{\lambda_Q, \lambda_E\}$ the phase of the wave function φ of these unpaired electrons with energies above the superconducting gap can be preserved and, accordingly, the coherent component of the electric current of such quasiparticles

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can be observed. Testing this hypothesis is the main objective of this work.

2 Results and Discussion

We fabricated a set of nanostructures consisting of a superconducting (S) fork overlapped by a normal metal (N) through a tunnel barrier (I). The depicted NIS structure can be considered as a solid-state analogue of a two-slit optical interferometer (Fig. 1a). When the distance $w = |AB|$ between the arms of the interferometer is less than the dephasing length of a normal electron $w < l_{\varphi}$, one can consider that the same electron tunnels into the superconductor through the two contacts at points A and B. Being injected from the normal metal at a bias voltage higher than the superconductor energy gap $V > \Delta/e$, such an electron forms a non-equilibrium excitation inside the superconductor. If the length of the fork arms is smaller than the quasiparticle phase breaking length $L + w/2 < \lambda_{\phi}$ one may detect the interference of these quasiparticles.

In a conventional light interferometer, the interference pattern is usually adjusted by variation of the optical path $|AO'|$ and/or $|BO'|$. In our case, the tunnel current $I(V > \Delta/e)$ represents the quasiparticle transport. To detect the coherent component, one should adjust the phase difference of electron wave function along the two paths OAO' and OBO': e.g., by utilizing the magnetic Aharonov–Bohm effect [14]. When a perpendicular magnetic field **B** is applied, constructive interference will occur subject to Bohr–Sommerfeld quantization condition:

$$\oint_{O'AOBO'} Pdl = \oint_{O'AOBO'} eAdl = e \oiint_{S_{O'AOBO'}} rotAdS = e \oiint_{S_{O'AOBO'}} BdS = e\Phi = nh$$

where P is canonic momentum, e is electron charge, A is vector potential of magnetic field B, Φ is magnetic flux through the contour, h is Plank's constant, $n = 0,1,2\ldots$ is an integer. Hence, the variation of magnetic flux Φ is expected to non-monotonously (periodically?) alter the quasiparticle current at a fixed bias above the gap $I(V = \text{const} > \Delta/e, \Phi)$.

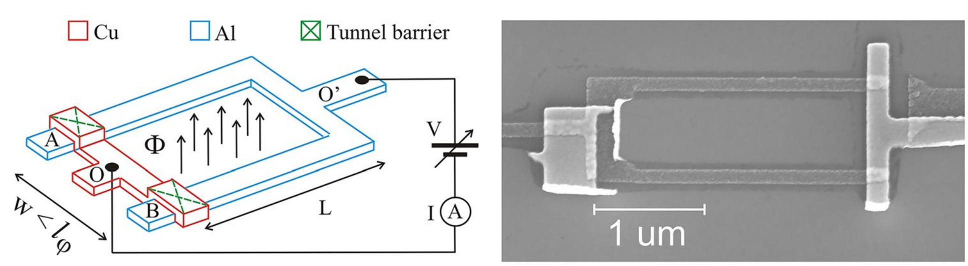
Lift-off electron beam lithography and directional vacuum deposition were used to fabricate the NIS interferometers (Fig. 1b). The thickness of the copper 'injector' was about 50 nm, aluminum — 30 nm, line width ~ 100 nm. The tunnel barrier was formed by oxidizing the lower layer of aluminum in the airlock chamber at a pressure of ~ 1 mbar for ~ 2 min. The typical value of the tunnel resistance of a Cu-AlOx-Al contact with the area ~ 100 nm * 100 nm was about 10 kOhm.

Electron transport was studied in several NIS structures (Fig. 1b) at ultra-low temperatures $T \sim 10$ mK $<< T_c$(Al film) ~ 1.4 K. To optimize the signal-to-noise ratio, the multi-stage RLC filters were used [15] separating the cryogenic measuring circuit from room temperature laboratory electronics. The I-V characteristics $I(V, T = const < T_c)$ revealed dependencies typical for tunnel NIS structures based on aluminum (S) with the energy gap $\Delta/e \approx 210$ µV (Fig. 2).

To test our hypothesis of coherent quasiparticle transport, perpendicular magnetic field **B** was applied and the $I(V = \text{const} \geq \Delta/e, T = const << T_c, B)$ dependencies were measured. The corresponding data (Fig. 3) demonstrates the central maximum at magnetic field -1 mT $\leq B \leq +1$ mT followed by some non-monotonous behavior at higher fields. So far, we do not have a satisfactory theory model to compare our data with. Just extrapolating the text-book Fraunhofer expression for intensity of a two-slit diffraction pattern to our problem, one comes to simple expression:

$$I = I_0 \left(\frac{\sin(\alpha)}{\alpha} \frac{\sin(2\beta)}{\sin(\beta)} \right)^2 \quad (1)$$

where $\alpha = b(\pi\Phi/\Phi_0)$, $\beta = d(\pi\Phi/\Phi_0)$ and $\Phi_0 = h/e$ is the magnetic flux quantum. In optics, parameters b and d correspond to the width and period of a two-slit grading. Comparison of experimental data (Fig. 3, symbols) with these naïve expectations (Fig. 3, dashed line) reveals some qualitative agreement, although the pronounced periodic structure with secondary maxima is not clearly resolved.



(a) (b)

Fig. 1 **a** Schematic diagram of a NIS interferometer. **b** Image of a typical nanostructure obtained by scanning electron microscope. One can notice the parasitic shadows being the result of lift-off lithography followed by multi-angle metal deposition

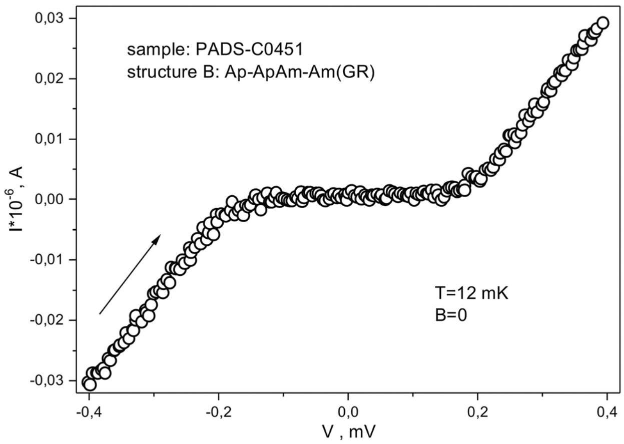


Fig. 2 Typical current-voltage characteristic I(V, T = *const*, B = 0) of a NIS interferometer at temperature T = 12 mK and zero magnetic field B = 0. The arrow indicates the direction of data recording

So far, we mainly studied structures with rather small perimeter (hence, area) of the interferometer loop (Fig. 1b). As the quasiparticle dephasing length λ_φ is not known, we have started from structures with the smallest dimensions. However, the smaller the area of the loop, the larger is the magnetic field producing one flux quantum Φ_0. The higher the magnetic field, the stronger is the suppression of superconducting energy gap Δ. Presumably, the monotonous increase of current I at magnetic field $|B|$ above ± 1 mT at a given voltage bias *V* in Fig. 3 is the impact of this trivial

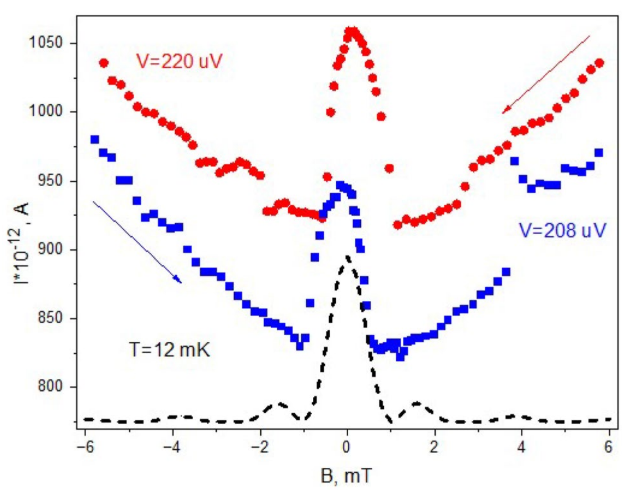


Fig. 3 Examples of I(V = *const*, T = *const* << T_c, B) dependencies for the NIS interferometer, measured at temperature T = 12 mK at two fixed values of the quasiparticle injection voltage V = 208 μV and 220 μV close to the gap edge Δ/e ≈ 210 μV. The arrows indicate the direction of magnetic field sweep. The dimensions of the NIS interferometer nominally are *w* = 0.7 μm and *L* = 1.2 μm. The dashed curve is the guide for the eyes representing the expression (1) with the best fit achieved at d ≈ 1.2b

effect. We hope that experiments with larger areas of the interferometer (e.g., smaller required fields) loop should diminish this undesired contribution.

The comparison of the experimental central maxima width with Fraunhofer formula indicates that the periodicity is set by Φ_0, rather than half of the single electron flux quantum $\Phi_0/2$. Half flux quantum periodicity has been observed in normal metal non-single-connected structures of mesoscopic dimensions [16]. The effect has been explained by interference of electrons with time reversal trajectories [17]. In normal metals, Φ_0 periodicity has been observed in extremely small rings [18]. With the lack of an adequate theory, one cannot exclude that somehow Cooper pair charge 2e might be involved, contributing to Little-Parks effect [19]. It should be noted that very similar geometry NIS structures have been studied earlier [20]. However, in that experiment, the sub-gap currents at a bias V → 0 have been of primary interest and the corresponding phenomena have been explained by coherent interference of Cooper pairs from nearly time-reversed states [21]. We believe that the physics in our experiments involving injection of non-equilibrium quasiparticles at energies eV ≥ Δ is different. Further experiments and theory development are required.

3 Conclusion

We fabricated and experimentally studied electron transport in a solid-state analogue of a two-slit optical interferometer: T-shaped normal metal electrode (copper) — dielectric tunnel layer (aluminum oxide) — superconducting fork (aluminum). The non-monotonous I (V = *const*, T = *const* << T_c, B) dependencies can be interpreted as the manifestation of an arguably new effect: the coherent transport of non-equilibrium quasiparticles injected from the normal metal into the superconductor. The topic needs further studies. However, already at this initial stage, it can be stated that some interesting physical phenomena occur in doubly connected small NIS systems.

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Author Contributions K. Yu. A. conceived the idea of the experiment; K. Yu. A. and G-W. D. analyzed data and composed manuscript; K. Yu. A, A. S. G and D.L.S. performed experiments; E. Ph.P., A.M.C., M.A.M fabricated the structures; M. A. T. designed the structures and fabrication sequence. All authors reviewed the manuscript.

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Data Availability No datasets were generated or analysed during the current study.

Declarations

Competing Interests The authors declare no competing interests.

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