Thermoelectric single-photon detection through superconducting tunnel junctions

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Abstract

Bipolar thermoelectricity in tunnel junctions between superconductors of different energy gap has been recently predicted and experimentally demonstrated. This effect showed thermovoltages up to ± 150 μV at milliKelvin temperatures. Thus, superconducting tunnel junctions can be exploited to realize a passive single-photon thermoelectric detector $\boldsymbol{TED}$ operating in the broadband range 15 GHz - 50 PHz. In particular, this detector is expected to show a signal-to-noise ratio of about 15 down to $\nu = \boldsymbol{50}$ GHz and a operating window of more than 4 decades. Therefore, the $\boldsymbol{TED}$ might find applications in quantum computing, telecommunications, optoelectronics, spectroscopy and astro-particle physics.

Keywords: thermoelectric detector, single-photon, superconducting tunnel junctions, quantum technology

1 Introduction

Superconducting detectors represent the state-of-the-art to reveal single-photons of frequency lower than 1 THz for their high efficiency and energy resolution [1]. Woefully, the noise and overheating introduced by the active readout signal are usually detrimental for their detection performance and limit the number of operating low-temperature
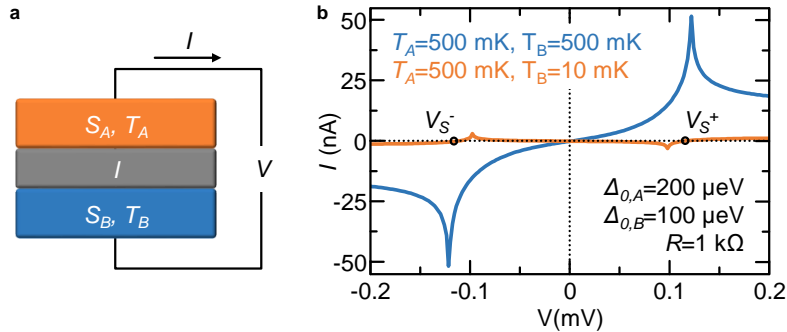
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Fig. 1 **a** Scheme of a S_AIS_B tunnel junction where the voltage drop V and the quasiparticle current I are indicated. **b** *IV* characteristics of a S_AIS_B junction with $\Delta_{0,A} = 200$ µeV, $\Delta_{0,B} = 100$ µeV, $R = 1$ kΩ calculated for $T_A = T_B = 500$ mK (turquoise) and $T_A = 500$ mK, $T_B = 10$ mK (orange).

devices in an array. A possible solution is provided by passive superconducting thermoelectric detectors TEDs generating electrical signals after the photon absorption. Indeed, hybrid superconductor/ferromagnet TEDs have been proposed [2] thanks to the predicted, but still not experimentally realized, thermoelectricity by extrinsic particle-hole (PH) symmetry breaking induced by spin splitting and filtering [3]. Here, we show an alternative route to generate thermoelectric TE signals in simple tunnel junctions made of different superconductors by spontaneous PH symmetry breaking and to exploit these phenomena to implement a single-photon TED operating to frequencies down to a few tens of GHz.

2 Thermoelectricity in S_AIS_B tunnel junctions

2.1 Theory

We study the properties of a S_AIS_B tunnel junction with completely suppressed Josephson coupling, where S_A and S_B are the two Bardeen-Cooper-Schrieffer (BCS) superconductors of zero-temperature energy gaps obeying to $\Delta_{0,A} > \Delta_{0,B}$ and I is the insulating barrier [see Fig. 1(a)]. A smeared PH-symmetric BCS density of states $N_i(\epsilon) = |\Re[(\epsilon + i\Gamma_i)/\sqrt{(\epsilon + i\Gamma_i)^2 - \Delta_i(T_i)^2}]|$ (with $i = A, B$ and Γ_i the Dynes broadening parameter [4]) is assumed for the two leads. Thus, the quasiparticle current flowing in the systems reads

$$I = \frac{1}{eR}\int_{-\infty}^{+\infty} d\epsilon N_A(\epsilon) N_B(\epsilon + eV)[f(\epsilon, T_A) - f(\epsilon + eV, T_B)], \qquad (1)$$

where e is the electron charge, R is the junction normal-state resistance, V is the voltage drop, and $f(\epsilon, T_i) = [1 + \exp(\epsilon/k_B T_i)]^{-1}$ (with $i = A, B$ and k_B the Boltzmann constant) are the quasiparticle Fermi distributions. At the thermal equilibrium ($T_A = T_B$), Eq. 1 provides the conventional dissipative behavior, as shown by the turquoise curve in Fig 1b. In the presence of a sufficient temperature gradient ($T_A > T_B$), the current flows against the voltage bias, that is the systems shows *absolute negative* conductance (ANC) [5, 6]. As a consequence, the S_AIS_B tunnel junction
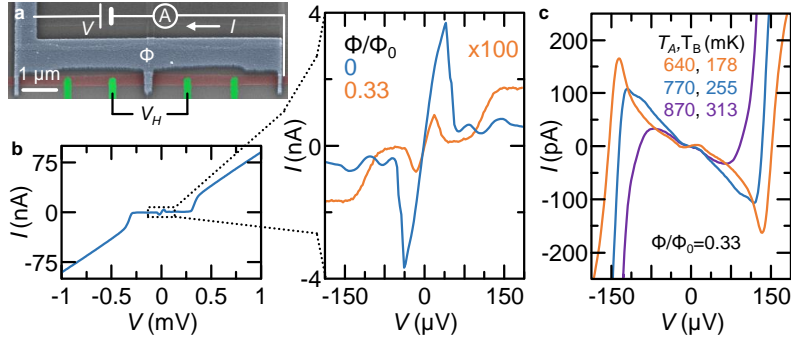
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Fig. 2 **a** False-color SEM picture of double-loop SQUID (S_A is red and S_B is blue) implementing the TE element and equipped with local tunnel heaters (green). The voltage generator V, the current I, the heater bias V_H and the magnetic flux Φ are indicated. **b** IV characteristics of the SQUID measured at $T_A = T_B = 30$ mK for $\Phi = 0$ (blue) and $\Phi = 0.33\Phi_0$ (orange). **c** Thermoelectric IV characteristics recorded at different temperature gradients.

is a TE generator [7, 8]. In addition, the IV characteristic is *antisymmetric* with V thus entailing the peculiar *bipolar* thermoelectricity, as depicted in Fig 1b. Finally, the Seebeck voltages (V_S^+ and V_S^-) are predicted to be comparable to the value of the matching peak, that is $[\Delta_A(T_A) - \Delta_B(T_B)]/e \sim |V_S^\pm|$ [7].

2.2 Experiments

Recently, the basic example of a bipolar TE element was realized in the form of a double-loop superconducting quantum interference device (SQUID) [9, 10], where S_A (red, Al $\Delta_{0,A} = 220~\mu$eV) is coupled to S_B (blue, Al/Cu bilayer $\Delta_{0,B} = 80~\mu$eV) through three insulating aluminum oxide tunnel junctions (see Fig. 2a). Furthermore, S_A is also equipped with several superconducting tunnel heaters (green, Al $\Delta_{0,H} = 200~\mu$eV) to increase T_A. In this setup, the Josephson coupling can be tuned by the external magnetic flux (Φ), as shown by the 2-probe IV characteristics recorded at $T_A = T_B = 30$ mK (see Fig. 2b). In particular, at $\Phi = 0.33\Phi_0$ the double-loop SQUID permits to suppress the supercurrent down to 0.175% of its maximum value. Thus, to experimentally demonstrate the predicted TE effect [7], the SQUID was flux biased at $\Phi = 0.33\Phi_0$ (the Josephson coupling can be practically neglected [11]) at a bath temperature of 30 mK, while T_A was increased by injecting a power (P_H) in S_A. The power injection causes also the increase of T_B, since heat diffuses through the SQUID junctions, but a thermal gradient $\delta T = T_A - T_B$ is established [12]. Within these conditions, the IV characteristics show ANC for both polarities of V at a *given* temperature profile (see Fig. 2c) in agreement with the theoretical behavior [7]. Differently from conventional thermoelectricity, $|V_s|$ monotonically decreases with increasing temperature bias [12, 13]. Finally, the maximum Seebeck coefficient ($\mathcal{S} = V_S/\delta T$) is $\sim \pm 300~\mu$V/K, that is near to the maximum theoretically achievable within the exploited architecture [7, 8].
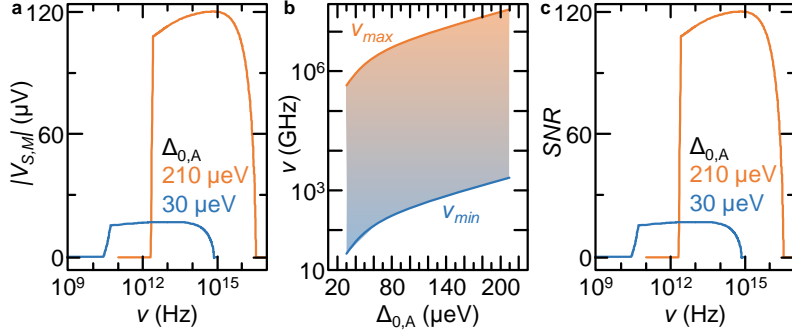
Fig. 3   **a** $|V_{S,M}|$ versus ν calculated for $\Delta_{0,A1} = 210\ \mu$eV (orange) and $\Delta_{0,A2} = 30\ \mu$eV (blue). **b** Minimum (ν_{min}, blue) and maximum (ν_{max}, orange) operating frequency of the TED versus $\Delta_{0,A}$. **c** SNR versus ν calculated for $\Delta_{0,A1} = 210\ \mu$eV (orange) and $\Delta_{0,A2} = 30\ \mu$eV (blue).

3 Single-photon superconducting TED

The single-photon TED [14] exploits the S_AIS_B tunnel junction presented in Sec. 2 with $\Delta_{0,B}/\Delta_{0,A} = 0.5$. Since this system provides two thermovoltages of same absolute value ($|V_S^+| = |V_S^-|$), we will consider only the positive solution $V_S = V_S^+$. After absorbing a photon of energy $h\nu$ (with h the Planck constant), S_A reaches a maximum temperature $T_{A,M}$ given by [15]

$$\int_{T_A = T_{bath}}^{T_{A,M}(\nu)} C_e(T)\mathrm{d}T = h\nu, \tag{2}$$

where T_{bath} is the bath temperature and $C_e(T) = T\frac{\mathrm{d}}{\mathrm{d}T}\mathcal{S}_A(T)$ is the electronic thermal capacity of S_A. The of S_A is computed as [16]

$$\mathcal{S}_A(T) = -2\mathcal{V}_A\mathcal{N}_{F,A}k_B \int_{-\infty}^{\infty} \mathrm{d}\epsilon N_A(\epsilon, T)f(\epsilon, T)\ln[f(\epsilon, T)], \tag{3}$$

where $\mathcal{V}_A$ and $\mathcal{N}_{F,A}$ are the volume and the density of states at the Fermi energy of S_A, respectively. Thus, the open circuit thermovoltage $V_{S,M}$ originated by the photon absorption can be computed by solving Eq. 1 for $T_{A,M}(\nu)$ given by Eq. 2 and $T_B = T_{bath}$. We evaluated the detector output signal by considering two different zero-temperature energy gaps for S_A, that is $\Delta_{0,A1} = 210\ \mu$eV and $\Delta_{0,A2} = 30\ \mu$eV, and a volume $\mathcal{V}_A = 2.5 \times 10^{-19}\ \mathrm{m}^3$ (see Fig. 3a). As expected, the TED output signal lowers by decreasing $\Delta_{0,A}$. However, $V_{S,M}$ is almost constant with ν. Contrarily, the detector becomes sensitive to a few tens of GHz single-photons for low gap superconductors. The operating frequency window of the TED stays almost constant for different values of the superconducting energy gap, as shown in Fig. 3b. The detector signal-to-noise ratio SNR provides the strength of the output signal relative to the noise. The SNR our TED is given by $SNR[T_{A,M}(\nu)] = V_{S,M}[T_{A,M}(\nu)]/(S_V\sqrt{\omega})$, where $\omega = 1$ MHz is the measurement bandwidth and $S_V = 1\ \mathrm{nV}/\sqrt{\mathrm{Hz}}$ is the system voltage noise spectral density. Indeed, we assume noise provided by the voltage pre-amplifier only, since the

TED is operated in the idle state in the absence of external signals. A TED of gap $\Delta_{0,A2} = 30\ \mu$eV is expected to show $SNR \sim 15$ for almost the entire operation window (down to ~ 50 GHz) when operated at $T_{bath} = 10$ mK (see Fig. 3c). Since it is directly linked to $V_{S,M}$, the SNR is directly to the superconducting energy gap of S$_A$.

4 Conclusions and perspectives

In this paper, we envisioned with a concrete proposal the possibility of sizeable thermoelectricity in superconducting tunnel junctions induced by non-equilibrium spontaneous symmetry breaking mechanism [7, 8]. The double-loop SQUID showed bipolar thermovoltages up to $\pm 150\ \mu$V corresponding to a Seebeck coefficient of $\pm 300\ \mu$V/K [12, 13]. This effect was exploited to theoretically implement a passive single-photon TED [14] operating in a wide range of frequencies down to a few tens of GHz. In particular, the TED is predicted to show a $SNR \sim 15$ for 50 GHz single-photons. To this scope, the TED could be couple to a twins-slot antenna by an impedance matched coplanar waveguide, similarly to SIS detectors that show a relatively high normal-state resistance. [17] This broadband TED could find practical applications both in quantum technologies, such as telecommunications, optoelectronics and qubits, and in basic science, such as axions search, astronomy and THz spectroscopy. Finally, bipolar thermoelectricity in superconducting tunnel junctions can find immediate applications in various fields of superconducting quantum technologies, such as a heat engine producing power on a generic load and a persistent TE memory cell written or erased by current injection [11].

Declarations

The authors have no relevant financial or non-financial interests to disclose.

References

[1] Semenov, A.D., Gol'tsman, G.N., Sobolewski, R.: Hot-electron effect in superconductors and its applications for radiation sensors. Supercond. Sci. Technol. **15**, 1 (2002)

[2] Heikkilä, T.T., Ojajärvi, R., Maasilta, I.J., Strambini, E., Giazotto, F., Bergeret, F.S.: Thermoelectric radiation detector based on superconductor-ferromagnet systems. Phys. Rev. Appl. **10**, 034053 (2018)

[3] Ozaeta, A., Virtanen, P., Bergeret, F.S., Heikkilä, T.T.: Predicted very large thermoelectric effect in ferromagnet-superconductor junctions in the presence of a spin-splitting magnetic field. Phys. Rev. Lett. **112**, 057001 (2014)

[4] Dynes, R.C., Garno, J.P., Hertel, G.B., Orlando, T.P.: Tunneling study of superconductivity near the metal-insulator transition. Phys. Rev. Lett. **53**, 2437 (1984)

[5] Aronov, A.G., Spivak, B.Z.: Photoeffect in a josephson junction. JETP Lett. **22**, 101 (1975)

[6] Gershenzon, M.E., Falei, M.I.: Absolute negative resistance of a tunnel contact between superconductors with a nonequilibrium quasiparticle distribution function. JETP Lett. **44**, 682 (1986)

[7] Marchegiani, G., Braggio, A., Giazotto, F.: Nonlinear thermoelectricity with electron-hole symmetric systems. Phys. Rev. Lett. **124**, 106801 (2020)

[8] Marchegiani, G., Braggio, A., Giazotto, F.: Superconducting nonlinear thermoelectric heat engine. Phys. Rev. B **101**, 214509 (2020)

[9] Kemppinen, A., Manninen, A.J., Möttönen, M., Vartiainen, J.J., Peltonen, J.T., Pekola, J.P.: Suppression of the critical current of a balanced superconducting quantum interference device. Appl. Phys. Lett. **92**, 052110 (2008)

[10] Fornieri, A., Blanc, C., Bosisio, R., D'Ambrosio, S., Giazotto, F.: Nanoscale phase engineering of thermal transport with a josephson heat modulator. Nat. Nanotechnol. **11**, 258 (2016)

[11] Marchegiani, G., Braggio, A., Giazotto, F.: Phase-tunable thermoelectricity in a josephson junction. Phys. Rev. Res. **2**, 043091 (2020)

[12] Germanese, G., Paolucci, F., Marchegiani, G., Braggio, A., Giazotto, F.: Bipolar thermoelectric josephson engine. Nat. Nanotechnol. **17**, 1084 (2022)

[13] Germanese, G., Paolucci, F., Marchegiani, G., Braggio, A., Giazotto, F.: Phase-control of bipolar thermoelectricity in josephson tunnel junctions. Phys. Rev. Applied **19**, 014074 (2023)

[14] Paolucci, F., Germanese, G., Braggio, A., Giazotto, F.: A highly sensitive broadband superconducting thermoelectric single-photon detector. Appl. Phys. Lett. **122**, 173503 (2023)

[15] Moseley, S.H., Mather, J.C., McCammon, D.: Thermal detectors as x–ray spectrometers. J. Appl. Phys. **56**, 1257 (1984)

[16] Rabani, H., Taddei, F., Bourgeois, O., Fazio, R., Giazotto, F.: Phase-dependent electronic specific heat of mesoscopic josephson junction. Phys. Rev. B **78**, 012503

(2008)

[17] Ezawa, H., Matsuo, H., Ukibe, M., Fujii, G., Shiki, S.: Studies on terahertz photon counting detectors with low-leakage sis junctions. J. Low Temp. Phys. **194**, 426–432 (2019)