Ferromagnetic insulator-based superconducting junctions as efficient temperature-to-frequency converters

F. Giazotto,1,a P. Solinas,2 A. Braggio,2 and F. S. Bergeret3,b

1) NEST Istituto Nanoscienze-CNR and Scuola Normale Superiore, I-56127 Pisa, Italy
2) SPIN-CNR, Via Dodecaneso 33, 16146 Genova, Italy
3) Centro de Física de Materiales (CFM-MPC), Centro Mixto CSIC-UPV/EHU, Manuel de Lardizabal 4, E-20018 San Sebastián, Spain
4) Donostia International Physics Center (DIPC), Manuel de Lardizabal 5, E-20018 San Sebastián, Spain

We propose and analyze a temperature-to-frequency converter based on a normal metal-ferromagnetic insulator-superconductor (NFIS) junction embedded in a superconducting loop which contains a superconducting quantum interference device (SQUID). By setting a temperature difference across the NFIS junction a thermovoltage will be generated across the circuit if the SQUID is in the resistive regime. This thermovoltage depends on both the magnitude and sign of the temperature difference, and will generate radiation at the Josephson frequency. In Eu-based FIs joined with superconducting Al the structure is in principle capable to generate frequencies up to ~ 120GHz, and transfer functions up to 200GHz/K at around ~ 1K. Yet, if operated as electron thermometer, the device may provide temperature noise better than 35nK Hz−1/2 thereby being potentially attractive for radiation sensing applications.

It has been suggested recently that the spin-splitting induced in a superconductor (S) placed in contact with a ferromagnetic insulator (FI) can be exploited in different kinds of spin caloritronic devices such as heat valves12 or thermoelectric elements3,4. They can be used as building blocks in phase-coherent thermoelectric transistors5, and for the creation of magnetic fields induced by a temperature gradient in Josephson junctions (JJs) due to the thermophase effect6. Yet, NFIS junctions have been proposed as well for efficient electron cooling of a normal metal7.

Here we propose a prototype structure based on the FIS building block acting as an efficient temperature-to-frequency converter that can be used, for example, for sensitive electron thermometry as well as for radiation sensing applications8–12. Our device consists of a normal metal-ferromagnetic insulator-superconductor (NFIS) junction, denoted here as the thermoelectric element (TE), which is connected, via the superconducting wires S1, to a dc superconducting quantum interference device (SQUID), as shown in Fig. 1(a). A temperature difference localized between the N and S side of TE induces thermoelectricity4. By properly tuning the magnetic flux (Φ) piercing the SQUID one can set the latter to operate in two regimes: i) Peltier regime, where the SQUID is in the Josephson regime, and a circulating thermocurrent is generated. This regime can be probed by an inductive measurement of the current. ii) Seebeck regime where the SQUID is in the resistive regime thereby allowing the generation of a Seebeck thermovoltage (V) across the TE element. In what follows we focus on the latter regime in which the generated thermovoltage will induce an ac-Josephson effect with oscillatory supercurrent at frequency ν = |V|/Φ014, where Φ0 ≃ 2.067 × 10−15 Wb is the flux quantum. The frequency ν can be measured with great accuracy providing accurate information about temperature difference across the TE.

It is instructive to start with the description of the TE. We assume the S layer to be thinner than the superconducting coherence length ξ0, so that the exchange field (hexc) induced in S by FI is spatially homogeneous15. In such a case the superconductor density of the states (DoSs) is given by the sum of the densities for spin-up and spin-down quasiparticles, N↑↓(E) = (1/2)Re[(E ± hexc)/√((E ± hexc)² − ∆²)]. Here η(ηS, ηc) is the pairing potential that depends both on temperature ηT in S and ηc,hexc, and it is computed self-consistently in a standard way15,16. We are interested in the current through the NFIS junction which is given by

\[ I_{TE} = \frac{1}{eR_T} \int_{-\infty}^{\infty} dE \left[ N_+ + P N_- \right] \left[ f_N(V, T_N) - f_S(T_S) \right] . \]

Here RT is the normal-state resistance of the tunneling junction and N± = (N↑ ± N↓). We assume thermalization on both the S and the N layer neglecting any deviation of the distribution functions from their equilibrium form13: fN(V, T_N) = [1 + exp(E/k_BT_N)]−1 and fS(T_S) = [1 + exp[(E + eV)/k_BT_S]]−1. Here TN and TS are the temperature in the N layer, −e is the electron charge and k_B is the Boltzmann constant. The role of the FI layer is twofold: it acts as a spin filter with polarization P17 and correspondly it is at the origin of the spin-split DoSs in the S layer. These two features have been experimentally demonstrated18–23. Finally, according to Eq. (1), even in the absence of a voltage bias across the junction a finite current I_{TE} can flow provided T_N ≠ T_S, as demonstrated in Ref.4.

Before analyzing the role of a temperature bias across TE, we first determine the current-voltage characteristics (IVCs) and differential conductance G of the NFIS junction. We set a low temperature, T_N = T_S = 0.01T_c, where T_c = Δ_0/(1.76k_B) is the critical temperature of the superconductor, and Δ_0 is the zero-temperature, zero-exchange field energy-gap. The results obtained from Eq. (1) are summarized if Fig. 1. Panels (b) and (c) show the IVC and G, respectively, for a polarization of the barrier P = 50% and different values of the spin-splitting exchange field h_{exc}. In panel (b) one clearly sees the deviation of the IVCs from those of a NIS junction where I

Electronic mail: francesco.giazotto@sns.it
Electronic mail: sebastian_bergeret@ehu.es
stands for a conventional insulator. For finite values of $h_{\text{exc}}$ there is a sizeable subgap current [see Fig. 1(b)] as a consequence of the spin-splitting of the DoSs in the S electrode. This splitting manifests itself in the differential conductance $G$ [see Fig. 1(c)], where the coherent peaks, usually appearing at $V = \pm \Delta/e$, are now split in four peaks appearing at $V = (\pm \Delta \pm h_{\text{exc}})/e$. The asymmetry in the height of the coherent peaks stems from the spin polarization $P$ of the FI barrier [see Figs. 1(d,e)] where we set $h_{\text{exc}} = 0.4\Delta_0$ and the curves are calculated for different values of $P$. Therefore from IVCs one can estimate both the polarization of the barrier and the spin-splitting induced into S.

We now assume a finite temperature difference between the electrodes, $\delta T = T_S - T_N$, and re-calculate the IVCs from Eq. (1) for $h_{\text{exc}} = 0.4\Delta_0$ and $P = 0.9$. The results are shown in Figs. 2(a) and 2(b), where we keep one of the electrodes at temperature $0.01T_c$ and change the other electrode temperature. The curves in Fig. 2(a,b) reveal two main properties of the IVC. First, the IVC strongly depends on the amplitude of the temperature difference $\delta T$: the larger the temperature difference, the larger is the current at low voltages. In the case that the S electrode is heated [see Fig. 2(a)], this trend is limited by the reduced critical temperature $T_S < T_c$ of the superconductor originating from the presence of a finite $h_{\text{exc}}$ which suppresses the $\Delta(T, h_{\text{exc}})$ calculated self-consistently. When $T_S \rightarrow T_c^*$, the TE goes into the normal state with ohmic characteristic [red curve in Fig. 2(a)]. There is another interesting feature of the IVCs: they strongly depend on the sign of $\delta T$. For the same value of $|\delta T|$, the current at $V = 0$ is larger when the N electrode is colder than the S one, i.e., when $\delta T > 0$. In other words, the thermoelectric effect in the TE depends on the sign of the temperature difference.

If the TE is placed in an open-circuit configuration, i.e., no charge current flows through the junction ($I_{\text{TE}} = 0$), then a voltage $V_0$ develops across for $\delta T \neq 0$. The value of $V_0$ can be obtained from Eq. (1) by setting the r.h.s. equal to zero. The results for $V_0$ are shown in the two lower panels of Fig. 2. Specifically, panel 2(c) shows the dependence of $V_0$ on $T_S$ for different values of $h_{\text{exc}}$, $P = 0.9$ and $T_N = 0.01T_c$. The increase of $T_S$, from $T_S = T_N$, leads first to an enhancement of $V_0$. Then, a further increase of $T_S$ leads to the sup-

FIG. 1. (a) Scheme of the temperature-to-frequency converter based on a normal metal-ferromagnetic insulator-superconductor (NFIS) junction. The latter is shown in the blow-up as stacked layers of different materials. $T_S$ and $T_N$ denote the temperature in S and N, respectively, $I_{\text{TE}}$ is the thermocurrent circulating in the circuit, and $V$ is the thermovoltage developed across the thermoelectric element (TE). $S_1$ is a superconductor contacted to both ends of the TE which realizes the DC SQUID, and $\Phi$ is an external magnetic flux piercing the interferometer. The SIS$1$ junction is an additional Josephson element present in the circuit. (b) Current vs voltage ($I_{\text{TE}} - V$) characteristics of the TE element calculated at $T_S = T_N = 0.1T_c$, $P = 0.5$ and for a few values of $h_{\text{exc}}$. (c) Differential conductance vs voltage ($G - V$) characteristics of TE calculated for the same parameters as in panel (b). (d) $I_{\text{TE}} - V$ and (e) $G - V$ characteristics of TE calculated at $T_S = T_N = 0.1T_c$, $h_{\text{exc}} = 0.4\Delta_0$ and for a few values of $P$. $\Delta_0 = 1.764k_BT_c$ is the zero-temperature, zero-exchange field superconducting gap, $T_c$ denotes the critical temperature, and $R_T$ is the normal-state resistance of TE.
FIG. 3. (a) Frequency $v$ vs $T_S$ calculated for a few values of $h_{exc}$ at $T_N = 0.01 T_c$. (b) $v$ vs $T_N$ at $T_S = 0.01 T_c$ calculated for the same $h_{exc}$ values as in panel (a). (c) and (d) show the transfer function $\tau$ of panel (a) and (b), respectively, calculated for the same values of $h_{exc}$. In all these calculations we set $P = 0.98$, $R_T/R_J = 0.1$, and $T_c = 3K$.

pression of the superconducting energy gap. This explains the suppression of $V_0$ at large $T_S$ until it vanishes when superconductivity is fully destroyed. We note that $V_0$ reaches zero continuously owing to the fact that we have chosen values of $h_{exc}$ for which the superconducting-normal state transition is of the second order. A different temperature behavior of $V_0$ is obtained when $S$ is kept at low temperature $T_S = 0.01T_c$ and $T_N$ is varied, as shown in Fig. 2(d). In particular, besides the obvious change of sign, $V_0$ grows monotonically by increasing $T_N$ until it reaches an asymptotic value. In contrast to the $V_0(T_N)$ dependence shown in Fig. 2(c), heating of the N electrode does not affect the superconducting gap $\Delta$, and therefore $V_0$ is not suppressed by increasing $T_N$. It is also important to stress that the curves $V_0(T_N)$ depends strongly on the polarization $P$ of the barrier [see Fig. 2(d)]. In particular, the larger $P$ the larger is the thermovoltage $V_0(T_N)$ developed across the TE. By contrast, the $V_0(T_S)$ amplitude turns out to be almost unaffected by the value of $P$. The different behaviors with respect to the sign of $\delta T$ allow one to reconstruct both the amplitude and direction of the thermal gradient in the TE element even without directly addressing the sign of $V_0$. This further information could be eventually exploited to reconstruct the spatial position of a heating event, thereby opening interesting possibilities to build detector-like devices.

Having analyzed the electronic transport in the TE we now focus on the temperature-to-frequency conversion process. This conversion is achieved with the device sketched in Fig. 1(a). The TE is connected via two superconducting arms $S_1$ to a dc-SQUID formed by two identical JJs. We assume to place a tunnel barrier between $S$ and $S_1$ to isolate the S element ensuring its description as a thermally homogeneous superconductor with a spin-split DoSs, reducing any influence of $S_1$ arms and therefore, guaranteeing that the current through the TE is described by Eq. (1). Superconductors $S$ and $S_1$ are Josephson coupled through the barrier and no additional voltage drop will occur. Furthermore, we assume the NS$_1$ junction to be a clean metallic contact, thereby contributing negligibly to the total resistance of the system but, for simplicity, we disregard the proximity effect induced into the N layer by the nearby superconductor $S_1$. The electric current through the SQUID $(I_{SQUID})$ depends both on the voltage $V$ and on the magnetic flux $\Phi$ piercing the loop. Within the RSI model (neglecting the loop inductance) the current is given by$^{14}$ $I_{SQUID} = (2/R_J) \sqrt{V^2 + [I_R \cos(\pi \Phi/\Phi_0)]^2}$, where $I_R$ and $L$ are the shunting resistance and the Josephson critical current of each junction of the SQUID, respectively. Thus, if one applies a magnetic flux such that $\Phi/\Phi_0 = 1/2 \pm n$, where $n$ is an integer, the SQUID is operated in the resistive regime with an ohmic IVC. $I_{SQUID} = 2V/R_J$. In this case there is a time oscillating current through the interferometer with a frequency equal to the Josephson frequency, $\nu = |V|/\Phi_0$. As discussed above, the value of $V$ depends on the temperature difference $\delta T$ across the TE, and therefore the frequency emitted by the SQUID is a measure of $\delta T$. In order to quantify the temperature-to-frequency conversion effect, one has to determine the voltage $V$ developed for any given $\delta T$ imposed across the TE which satisfies the following equation

$$I_{TE}(V, T_S, T_N, h_{exc}, P) + 2V/R_J = 0,$$

where $I_{TE}$ is defined in Eq. (1). The solution to the above equation is given by the point in which the dashed line in Figs. 2(a) and 2(b) intersects the IVCs.

Before analyzing the exact solution of Eq. (2), we discuss the linear response regime of the TE analyzed first in Refs. $^{3,4}$. In this regime the voltage $V$ and the temperature difference $\delta T \ll T \equiv (T_S + T_N)/2$ across the NFIS junction are small so that the current through the TE is given by $I_{TE} \approx \sigma V + P\alpha \delta T/T$, where $\sigma = (1/R_T) \int_{-\infty}^{\infty} dE \Sigma_{N}[4k_BT \cosh^2(E/2k_BT)]^{-1}$ is the electric conductance, and $\alpha$ is thermoelectric coefficient$^d$ defined as $\alpha = (1/eR_T) \int_{-\infty}^{\infty} dE \Sigma_{N}[4k_BT \cosh^2(E/2k_BT)]^{-1}$. By imposing the condition (2) we obtain the voltage $(V_{lin})$ across the SQUID within the linear response $V_{lin} = -P\alpha R_J \delta T/[T(R_J \sigma + 2)]$. It is obvious that $|V_{lin}|$, and therefore the frequency, does not depend on the sign of $\delta T$. As we show below, this symmetric behavior of $\nu(\delta T)$ only holds in the linear response regime, i.e., for small values of $\delta T$. Furthermore, from the expression for $V_{lin}$, it clearly follows that the larger the polarization $P$ the larger the achievable frequency $\nu$, and that large $R_J$ values allow to maximize the achievable voltage drop across the structure. In the limit of open-circuit configuration, i.e., for $R_J \rightarrow \infty$, we get $V_{lin} \approx -P\alpha \delta T/(\sigma T)$. The situation drastically changes if one goes beyond the linear response. The results for the non-linear regime are summarized in Fig. 3. Panels 3(a) and 3(b) show the frequency generated by the SQUID, for positive and negative $\delta T$, respectively. We have assumed a spin-filter efficiency $P = 0.98$ which is representative for EuO or EuS barriers$^{24}$, a superconductor with $T_c = 3K$ which would be implementable with ultra-thin Al films$^{19-22}$, and $R_T/R_J = 0.1$. If $T_N$ is
kept at 0.01\(T_c\), the maximum frequency is achieved around \(h_{\text{exc}} \approx 0.2\Delta_0\) for \(T_S \approx 0.75T_c\), and obtains values as large as \(\sim 120\text{GHz}\). By contrast, if \(T_S\) is kept at low temperature, \(\nu\) increases monotonically by increasing both \(T_N\) and/or \(h_{\text{exc}}\) but reaches smaller frequencies than in the previous case. A relevant figure of merit of the structure is represented by the temperature-frequency transfer function \(\tau\), defined as \(\tau = \partial \nu / \partial T\). Figures 3(c) and 3(d) display the transfer functions corresponding to panels (a) and (b), respectively. In particular, \(\tau\) exceeding 200GHz/K around \(T_S \sim 1\text{K}\) can be achieved for \(h_{\text{exc}} = 0.5\Delta_0\) by heating \(S\), while \(\tau\) up to \(\sim 55\text{GHz/K}\) can be achieved with the same values by heating \(N\).

We now turn on addressing the noise performance of the temperature-frequency conversion operation when operating the NFIS junction as an electron thermometer\(^2\). We identify the main source of noise in the current shot noise generated in the TE\(^{26}\),

\[
\delta T = \left(2 / R_T \right) \int \text{d}E \left| \mathcal{N}_e + \mathcal{P}_N \right| \left| \mathcal{N}(V,T_N,T_S) \right|
\]

where \(\mathcal{N}(E,V,T_N,T_S) = f_N(V,T_N,T_S)\left[1 - f_S(T_S)\right] + f_S(T_S)\left[1 - f_N(V,T_N)\right]\) and the bias \(V\) is given by the solution of (2).

The bias fluctuations are generated from the current noise via the load resistance seen from the TE, i.e., the parallel of SQUID resistance \(R_{T/2}\) and the TE resistance \(R_T\). Note that the differential resistance \(R_T = \partial \nu / \partial V_{\text{TE}}\) is calculated over the solutions of Eq. (2). The important quantity is represented by the frequency noise spectral density \((S_\nu)\), which can be expressed as \(S_\nu = S_V|2\Phi_0|\) where \(\Phi = R_T R_f / (2R_d R_f)\) describes the total load resistance as seen by TE. Finally, the intrinsic temperature noise (temperature sensitivity) per unit bandwidth of the thermometer \((s_T\nu)\) is related to the frequency noise spectral density as \(s_T\nu = \sqrt{S_V}(|\tau|^{-1})\).

Figure 4(a) and (b) show the calculated square root of the frequency noise spectral density \(S^1/2\) for positive and negative \(\delta T\), respectively, calculated for the same parameters as in Fig. 3, and for \(R_T = 1 \Omega\). In particular, for positive \(\delta T\), the noise spectrum \(S^1/2\) shows a non-monotonic behavior with a maximum at intermediate temperatures, and suppression at higher \(\delta T\). By contrast, for \(\delta T < 0\) the noise spectrum grows monotonically, and it is less influenced by \(h_{\text{exc}}\).

The behavior of \(s_T\) for positive and negative \(\delta T\) is displayed in Fig. 4(c) and (d), respectively. At small \(|\delta T|\) we can see the noise sensitivity in the linear regime, which is independent of the sign of \(\delta T\). By increasing \(|\delta T|\) the growth of \(S^1/2\) [Figs. 4(a) and (b)] is advantageously compensated by the enhancement of \(|\tau|\) [see Fig. 3(c) and (d)]. When the maximum of \(|\tau|\) is reached the best noise figure is roughly reached. The best performance of \(s_T \sim 35\text{nKHz}^{-1}\) is obtained around 1K for \(h_{\text{exc}} = 0.5\Delta_0\). After the minimum of \(s_T\) the nonlinear behavior will dominate. For \(\delta T > 0\) we see the peak of the divergence of \(|\tau|^{-1}\), i.e., the annihilation of the transfer function, as shown in Fig. 3(c). Differently, for \(\delta T < 0\) one observes a smooth increase of \(s_T\) determined by the progressive reduction of the transfer function [see Fig. 3(d)]. We conclude by noting that the best noise performance is obtained in the nonlinear regime for \(|\delta T| \lesssim 1\text{K}\) where \(s_T\) is almost independent of the sign of \(\delta T\). Therefore, the non-linearities that are useful to measure the temperature difference in the TE are important as well to maximize the temperature sensitivity.

In summary, we have theoretically investigated a temperature-to-frequency converter based on a normal metal-ferromagnetic insulator-superconductor (NFIS) thermoelectric element integrated with a SQUID. In particular, we have shown that with suitable structural material parameters the device allows for the generation of Josephson radiation at a frequency that depends on both the amplitude and sign of the temperature difference across the NFIS junction. Frequencies up to \(\sim 120\text{GHz}\) and large transfer functions (i.e., up to 200GHz/K) around \(\sim 1 - 2\text{K}\) can be obtained in a structure achievable with prototype Fls such as EuS or EuO providing \(P\) up to \(\sim 98\%\) in combination with superconducting Al thin films. If operated as a thermometer, the device is capable to provide intrinsic temperature noise down to \(\sim 35\text{kHz}^{-1/2}\) around 1K for a sufficiently large \(h_{\text{exc}}\). The proposed structure has the potential for the realization of effective on-demand on-chip temperature-frequency converters as well as sensitive electron thermometers or radiation sensors easily integrable with current superconducting electronics.

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