Sensitive Superconducting Calorimeters for Dark Matter Search

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Abstract: The composition of dark matter is one of the puzzling topics in astrophysics. Since, the existence of axions would fill this gap of knowledge, several experiments for the search of axions have been designed in the last twenty years. Among all the others, light shining through walls experiments promise to push the exclusion limits to lower energies. To this end, effort is put for the development of single-photon detectors operating at frequencies < 100 Ghz. Here, we review recent advancements in superconducting single-photon detection. In particular, we present two sensors based on one-dimensional Josephson junctions with the capability to be in situ tuned by simple current bias: the nanoscale transition edge sensor (nano-TES) and the Josephson escape sensor (JES). These two sensors seem to be the perfect candidates for the realization of microwave light shining through walls (LSW) experiments, since they show unprecedented frequency resolutions of about 100 GHz and 2 GHz for the nano-TES and JES, respectively.

Keywords: axion; single-photon detectors; superconducting detectors

1. Introduction

Axions and weakly interacting massive particles (WIMPs) are expected to be possible components of the cold dark matter. Furthermore, axions and axion-like particles (ALPs) are proposed to solve the charge-conjugation parity (CP) problem in quantum chromodynamics (QCD) by means of the Peccei-Quinn mechanism [1–3]. Up to now, the experimental searches focusing on axions or ALPS produced null results with corresponding excluded regions in the coupling constant (g) versus mass parameter space shown in Fig. 1(a). Two classes of experiments are performed: astrophysical experiments observing astrophysical phenomena or attempting to detect cosmic axions, and laboratory-based experiments which aim to demonstrate the existence of axions in strictly controlled settings [4].

The observation of solar axions is strongly affected by the limits of the solar models. Indeed, the coupling of low-mass weakly interacting particles produced in the sun with normal matter is bounded by the observations of stellar lifetimes and energy loss rates. Solar models together with measurement of neutrino fluxes imply limits on the magnitude of the coupling constant to g ≤ 7 × 10−10 GeV−1. In addition, the presence of ALPs created by the Primakoff process [5,6], that is photon-axion conversion in an external magnetic field, would alter stellar-evolution. Thus, many exclusion limits on the axion mass have been argued. Instead of using stellar energy losses to infer the axion exclusion limits, the flux of axions created by the sun can be detected through an axion helioscope, such as CAST [7] and IAXO [8] experiments. These experiments constantly point at the sun by means of a tracking system aiming to convert the solar axions into detectable X-ray photons through Primakoff effect. Instead, in microwave cavity experiments, such as ADMX [11] and QUAX [10], galactic halo axions may be detected by their resonant conversion into a quasi-monochromatic microwave signal in a high-quality-factor electromagnetic
cavity permeated by a strong static magnetic field. The resonance frequency of the cavity is tuned to equalize the total axion energy. Interestingly, only these experiments are able to probe part of the QCD Peccei-Quinn region.

Light shining through walls (LSW) experiments, such as ALPS [11] and STAX [12], are fully in-laboratory searching techniques. The general concept of a LSW experiment is shown in Fig. 1(b). A laser beam is sent through a long magnet, allowing for the coherent photon-axion conversion due to the Primakoff effect. The wall acts as a photon barrier, thus blocking the laser beam, while allowing the axion to pass through (since its interaction with massive matter is negligibly small). A second magnet placed after the wall causes the photon-axion back conversion. Since both conversions are very rare (depending on $g^4$), very intense sources are necessary. The highest luminosity photon sources currently available are the gyrotrons, that operate typically below the THz region, with a maximum power of 1 MW at about 100 GHz. In this spectral region, single-photon detection is extremely difficult. In fact, LSW experiments at the microwave have been proposed [12] but not realized yet.

To implement microwave LSW experiments, the key ingredient is thus the development of new ultrasensitive single-photon detectors operating at unprecedented low frequencies $f \leq 100$ GHz [13,14]. Nowadays, state of the art detectors for astrophysics are mainly based on transition edge sensors (TESs) [15,16] and kinetic inductance detectors (KIDs) [17–19]. A strong reduction of the thermal exchanges in the sensing elements is fundamental to push single-photon detection to lower bounds. To this end, miniaturization and Josephson effect [20] have been exploited [21–24].

Recently, two microwave single-photon detectors, nanoscale transition edge sensors (nano-TES) [25] and the Josephson escape sensor (JES) [26], have been designed by employing a one-dimensional fully superconducting Josephson junction (1DJ) as radiation absorber. The nano-TES and the JES point towards unprecedented frequency resolutions of about 2 GHZ thus enabling the possibility to implement LSW experiments. In addition, the sensitivity of these sensors can be in situ tuned by simple current biasing.

This paper reviews these sensors by covering their theoretical and experimental properties. In particular, Section 2 presents the theoretical description of the 1DJs, while Sec. 3 shows their experimental electronic and thermal transport properties. Section 4 introduces the operation principles of the nano-TES and JES detectors. Section 5 presents the detection performance of the nano-TES and the JES. Section 6 presents the experimental methods used for the sensors characterization. Finally, Sec. 7 resumes the results and opens to new applications for the nano-TES and the JES detectors.

2. Theoretical modelling of a one-dimensional fully superconducting Josephson junction

A Josephson junction (JJ) is a structure where the possibility of a superconductor to carry a dissipationless current is strongly suppressed. Typically, the discontinuity of the supercurrent flow is realized by interrupting the superconductor by means of a weak link. A weak link can consist of a thin insulating barrier forming a superconductor/insulator/superconductor SIS-JJ, a short section of normal metal creating superconductor/normal metal/superconductor SNS-JJ, a physical constriction in the superconductor producing an SsS-JJ (known as Dayem bridge), or a short section of lower energy gap superconductor realizing a SS’S-JJ. Here, we focus on the one-dimensional version of a SS’S-JJ where the two superconducting lateral electrodes (S) are separated by a one-dimensional wire (A) made of a different superconductor. In addition, both the thickness ($t$) and width ($w$) of $A$ are smaller than the London penetration depth ($\lambda_{L,A}$) and the Cooper pairs coherence length ($\xi_A$). The one-dimensionality ensures constant superconducting wave function and homogeneous supercurrent density along the wire cross section, and uniform penetration of $A$ by an out-of-plane magnetic field. In the following, we will name such a structure as 1DJ for simplicity. The general structure of a 1DJ is shown in Fig. 2(a).
**Figure 1.** Laboratory axion search. (a) Photon-axion coupling ($g$) versus axion mass, where axions origins are indicated. The diagonal band shows the parameter space consistent with the quantum chromodynamics (QCD) axion from the Peccei-Quinn theory. The grey area depicts the operating range of the detectors presented in this review. (a) Conceptual representation of a light-shining-through-wall (LSW) experiment. A laser (violet) feeds photons in a Fabry-Perot cavity immersed in a constant magnetic field. An axion is generated by the conversion of a photon through Primakoff effect and passes through the wall (grey). The axions converts back in a photon of same energy in the second magnetic field area and is revealed by a single-photon detector (red).

**Figure 2.** Structure and transport properties of a 1DJ. (a) Top: Scheme of the structure a 1DJ. Two superconducting electrodes ($S$, blue) are separated by a weak link composed of a superconducting wire ($A$, bronze). The width ($w$) and the thickness ($t$) of $A$ are indicated. The two superconducting energy gaps follow $\Delta_A \ll \Delta_S$. The current ($I$) flowing along the 1DJ is shown. Bottom: RSJ model of a 1DJ where $I$ is the bias current, $J$ is the junction and $R_N$ is the shunt resistor. (b) Tilted washboard potential of a 1DJ calculated for different values of $I$. The energy barrier for the escape of the phase particle from the WP ($\delta U$) decreases by rising the bias current, thus the probability of the transition of the 1DJ to the normal-state increases with $I$. The phase particle in the WP is indicated. (c) Energy barrier ($\delta U$) normalized with respect to the zero-temperature Josephson energy ($E_{J,0}$) calculated by varying the critical current (top) and the bias current (bottom), respectively. (d) temperature dependence of the normalized resistance ($R/R_N$) calculated for selected values of $I$. $R_N$ is the normal-state resistance of the 1DJ. (e) Temperature derivative of the resistance ($dT / dT$) calculated for the same values of $I$ in panel (d).
The behavior of the 1DJ can be described by means of the overdamped resistively shunted junction (RSJ) model [27], where the JJ is shunted by its normal-state resistance [see Fig. 2(a)]. Here, the bias current \( I \) dependence on the stochastic phase difference \( \varphi(t) \) over the junction reads

\[
\frac{2e}{h} \frac{\dot{\varphi}(t)}{R_N} + I_C \sin \varphi(t) = I + \delta I_{th}(t),
\]

where \( e \) is the electron charge, \( h \) is the reduced Planck constant, \( R_N \) is the wire normal-state resistance, while \( I_C \) is its critical current. The normal-state resistance of the 1DJ acts as shunt resistor providing a thermal noise contribution to the flowing current given by \( \langle \delta I_{th}(t) \delta I_{th}(t') \rangle = \frac{k_B T}{R_N} \delta(t - t') \), where \( k_B \) is the Boltzmann constant and \( T \) is the temperature. The transition to the normal-state of a JJ or a superconducting nano-wire is usually attributed \( 2\pi \) quasiparticle phase-slips [27,28], because a full phase rotation entails to pass through \( I_C = 0 \). Within the RSJ model, the phase slip is represented as the motion of a phase particle in a tilted washboard potential (WP) under the presence of friction forces. The WP can be written

\[
U(\varphi) = -\frac{h I}{2e} \varphi - \delta U \cos \varphi,
\]

where \( \delta U(I, E_J) \) is the escape energy for the phase particle. We note that, the only parameter dependent on the JJ geometry is \( \delta U(I, E_J) \). For a 1DJ, it takes the form [29]

\[
\delta U(I, E_J) \sim 2E_J (1 - 1/I_C)^{5/4} = \frac{\Phi_0 I_C}{\pi} (1 - 1/I_C)^{5/4}.
\]

Equations 2 and 3 show that both bias current and Josephson energy \((E_J = \Phi_0 I_C/2\pi, \Phi_0 \approx 2.067 \times 10^{-15} \text{ Wb} \) the flux quantum) define the WP. In particular, \( \delta U \) is suppressed by lowering the Josephson energy and rising the bias current. The latter also produces the tilting of the WP, as shown in Fig. 2(b). It is interesting to quantitatively compare the effects of I and \( E_J \) on the WP. To this end, we substituted the Josephson energy with the critical current in Eq. 3. Without current bias \((I = 0) \), the barrier depends linearly on the critical current. Instead, it lowers faster by increasing the bias current, since \( \delta U \sim I_C^{-5/4} \). The comparison between the two methods to suppress the energy barrier is shown in Fig. 2(c). Thus, the current bias is the most efficient method to control the supercurrent flowing in a 1DJ.

The normal-state resistance of a 1DJ is very low. Therefore, it can be described by means of the overdamped junction limit of the RSJ model. In this approximation, the temperature dependence of the voltage drop build across a 1DJ can be written [30]

\[
V(I, E_J, T) = R_N \left[ I - I_{C,0} \operatorname{Im} \frac{\mathcal{I}_{1-iz} \left( \frac{E_J}{k_B T} \right)}{\mathcal{I}_{-iz} \left( \frac{E_J}{k_B T} \right)} \right],
\]

where \( I_{C,0} \) is the junction zero-temperature critical current, \( \mathcal{I}_{\mu}(x) \) is the modified Bessel function with imaginary argument \( \mu \), and the imaginary argument takes the form \( z = \frac{E_J}{k_B T} \frac{1}{I_C} \). Therefore, \( V \) strongly depends on \( I_C \) (thus \( E_J \)) and \( I \). The current derivative of the voltage drop calculated at different values of temperature provides the \( R(T) \) characteristics

\[
R(I, E_J, T) = \frac{dV(I, E_J, T)}{dI}.
\]

By solving Eq. 5 for different values of \( I \), we can evaluate the impact of the bias current on the resistance versus temperature characteristics of a 1DJ. In particular, Fig. 2(d) highlights that the
temperature of the superconducting-to-resistive state transition of the JJ decreases by rising $I$. Furthermore, high values of bias current have a second important effect on the $R(T)$: the temperature width of the transition narrows. The temperature derivative of $R(T)$ confirms the positive impact the current bias on the transition width, as shown by Fig. 2(e). This behavior is related to the decrease of $\delta U$ and to the current induced tilting of the WP (providing a preferred direction of the phase-slips).

Two different temperatures related to the superconductor-to-normal-state transition can be defined, as shown in Fig. 3(a). On the one hand, the effective critical temperature ($T_C$) is the temperature corresponding to half of the normal-state resistance $[R(T_C) = R_N/2]$. On the other hand, the escape temperature ($T_e$) is the maximum value of temperature providing a zero resistance of the 1DJ $[R(T_e) = 0]$. The bias current has a strong influence on both $T_C$ and $T_e$, as shown in Fig. 3(b). In particular, the effective critical temperature decreases much faster than the escape temperature by rising $I$, thus providing $T_C \sim T_e$ for $I \to I_C$.

This behavior highlights once more the narrowing of the superconducting-to-normal-state transition from increasing bias current.

3. Experimental demonstration of a 1DJ

This section is devoted to the experimental demonstration of bias current tuning of the $R$ versus $T$ characteristics of a 1DJ. In particular, Sec. 3.1 aims to proof that the structure under study is one-dimensional, while Sec. 3.2 will show the tuning of the superconducting-to-normal phase transition by varying $I$.

3.1. Density of states and one-dimensionality

A typical 1DJ is realized in the form of a 1.5 $\mu$m-long ($l$), 100 nm-wide ($w$) and 25 nm-thick ($t$) Al/Cu bilayer nanowire-like active region sandwiched between the two Al electrodes. The detailed fabrication procedure is described in Sec. 6. To ensure that the JJ is one-dimensional ($\xi_A > t, w$ and $\lambda_{L,A} > t, w$), a full spectral characterization of $A$ is necessary. To this end, the test device is equipped with two additional Al tunnel probes, as shown by the false-color scanning electron micrograph (SEM) in Fig. 4(a). The $IV$ tunnel characteristics of $A$ are performed by applying a voltage ($V$) and measuring the current ($I$) flowing between one lateral electrode and a tunnel probe. The experimental set-up is described in detail in Sec. 6.

The energy gap of a superconductor is temperature independent up to $T \sim 0.4T_C$ thus implying $\Delta(T) = \Delta_0$, with $\Delta_0$ its zero-temperature value [27]. Since aluminum thin films typically show a $T_C \geq 1.2$ K [31], the superconducting gap of the aluminum probes is temperature independent up to at least 500 mK. In this temperature range the energy gap of the nanowire is strongly temperature dependent, since the inverse proximity effect weakens its superconducting properties (it is a superconductor/normal metal...
The Cooper limit has two requirements: negligible contact resistance between the two layers and thickness properties of the Al/Cu bilayer. As a consequence, this experimental set-up can be employed to study the superconducting properties of A. In particular, the zero-temperature energy gap ($\Delta_{0,A}$) will be helpful to demonstrate the one-dimensionality of the nanowire.

To obtain $\Delta_{0,A}$, the IV characteristics were measured at base temperature ($T = 20$ mK) and well above the expected critical temperature of A but below $0.4T_{C,A}$ ($T = 250$ mK), as shown in Fig. 4(b). At the base temperature, both A and P are in the superconducting state. Therefore, the voltage bias needs to reach $V = \pm(\Delta_{A,0} + \Delta_{P,0})/e$ (with $\Delta_{A,P}$ the zero-temperature gap in the Al probe) to switch to the normal-state [32]. On the contrary, at $T_{bath} = 250$ mK the nanowire is in the normal-state thus the transition occurs at $V = \pm\Delta_{P,0}/e$. The resulting zero-temperature energy gap of the Al probe is $\Delta_{0,P} \approx 200$ $\mu$eV [see the blow in Fig. 4(c)], therefore indicating a critical temperature $T_{C,P} = \Delta_{P,0}/(1.764k_B) \approx 1.3$ K. Furthermore, the difference between the curves recorded at 20 mK and 250 mK provides $\Delta_{A,0} \approx 23$ $\mu$eV thus indicating a critical temperature $T_{C,A} \approx 150$ mK.

A 1DJ requires that the intrinsic superconducting properties of the nanowire are uniform and dominate over the proximity effect induced by the lateral banks. The latter could induce an energy gap in a non-superconducting Al/Cu bilayer given by $E_g \approx 3hD_A/I^2 \approx 5$ $\mu$eV [33], where $D_A$ is the diffusion constant of the active region. The latter can be calculated as $D_A = (t_{Al}D_{Al} + t_{Cu}D_{Cu})/(t_{Al} + t_{Cu}) \approx 5.6 \times 10^{-3}$ m$^2$/s, where $t_{Al} = 10.5$ nm and $D_{Al} = 2.25 \times 10^{-3}$ m$^2$/s$^{-1}$ are the thickness and the diffusion constant of the Al thin film, respectively, while $t_{Cu} = 15$ nm and $D_{Cu} = 8 \times 10^{-3}$ m$^2$/s$^{-1}$ are the thickness and the diffusion constant of the Cu layer, respectively. Since $E_g \sim 0.25\Delta_{A,0}$, the superconducting properties of A are dominated by the Al/Cu bilayer.

If the Al/Cu bilayer lies in the Cooper limit [34,35], it can be considered a uniform superconductor. The Cooper limit has two requirements: negligible contact resistance between the two layers and thickness of each layer lower than its coherence length. Since its large surface area, the Al/Cu interface resistance is negligibly small with comparison to the nanowire normal-state resistance, thus fulfilling the first requirement. In addition, the superconducting Al film fulfils $\xi_{Al} = \sqrt{hD_{Al}/\Delta_{Al}} \approx 80$ nm $\gg t_{Al} = 10.5$ nm, where $\Delta_{Al} \approx 200$ $\mu$eV is its measured superconducting energy gap. At the same time, the Cu layer obeys to $\xi_{Cu} = \sqrt{hD_{Cu}/(2\pi k_B T)} \approx 255$ nm $\gg t_{Cu} = 15$ nm, where $k_B$ is the Boltzmann constant and $T = 150$ mK is chosen in the worst possible working scenario. Therefore, the second condition is fulfilled, too. We can conclude that the Al/Cu bilayer respects the Cooper limit and A can be considered as formed from a single superconducting material.

**Figure 4. Measurement of the density of states in a 1DJ.** (a) False-color scanning electron micrograph of a device used to measure the DOS of a 1DJ. The 1DJ is made of an Al/Cu bilayer nanowire (yellow) interrupting two Al electrodes (blue). The Al probes (red) allow to perform tunnel spectroscopy. To this end a voltage ($V$) is applied between A and one probe while recording the current ($I$). (b) Tunneling current ($I$) as a function of voltage ($V$) characteristics recorded at $T_{bath} = 20$ mK (blue) and $T_{bath} = 250$ mK (yellow). (c) Zoom of the IV characteristics in correspondence of the transition to the normal-state. It is possible to extract $\Delta_{A,0} \approx 23$ $\mu$eV and $\Delta_{P,0} \approx 200$ $\mu$eV as the crossing between the black dotted lines and $I = 0$. 
We can now discuss the one-dimensionality of $A$. In particular, the superconducting coherence length in $A$ is given by $\xi_A = \sqrt{\hbar / [(t_{\text{Al}}N_{\text{Al}} + t_{\text{Cu}}N_{\text{Cu}})R_Ne^2\Delta_{A,0}]} \approx 220$ nm, where $R_N = 80$ $\Omega$ is the nanowire normal-state resistance, $N_{\text{Al}} = 2.15 \times 10^{47}$ $J^{-1}m^{-3}$ and $N_{\text{Cu}} = 1.56 \times 10^{47}$ $J^{-1}m^{-3}$ are the density of states at the Fermi level of Al and Cu, respectively. Since the Cooper pairs coherence length in $A$ is much larger than its thickness ($\xi_A \gg t = t_{\text{Al}} + t_{\text{Cu}} = 25.5$ nm), the pairing potential of the bilayer is constant along the $z$ axis. Furthermore, the active region is one-dimensional with respect to the superconducting coherence length, since $\xi_A \gg w = 100$ nm. In addition, the London penetration depth for the magnetic field of $A$ takes the form $\lambda_{L,A} = \sqrt{h \omega t_A R_N} / (\pi \mu_0 \Delta_{A,0}) \approx 970$ nm, where $\mu_0$ is the magnetic permeability of vacuum. Therefore, the nanowire is 1D with respect to the London penetration depth, since $\lambda_{L,A} \gg t, w$.

Concluding, the Al/Cu bilayer embedded between two Al electrodes forms a 1DJ. Therefore, this structure can be used to investigate the impact of $I$ on the $R(T)$ characteristics.

### 3.2. Current control of the $R$ vs $T$

To investigate the impact of the bias current on the transport properties of a 1DJ, the resistance $R$ vs temperature characteristics were obtained by conventional four-wire low-frequency lock-in technique by varying the excitation current amplitude from 15 nA to 370 nA. The current was generated by applying a voltage ($V_{ac}$) to a load resistor ($R_L$) of impedance larger than the device resistance ($R_L = 100$ k$\Omega \gg R_N \approx 77$ $\Omega$), as shown in Fig. 5(a). For the details regarding the device fabrication and experimental set-up see Sec. 6.

The magnetic field generated at the wire surface by the maximum employed bias current is $B_{I,\text{max}} = \mu_0 I_{\text{max}} / (2\pi t) \approx 4.7$ $\mu$T, where $I_{\text{max}} = 370$ nA and $\mu_0$ is the vacuum magnetic permeability. This value is
orders of magnitude lower than the critical magnetic field of $A$ that was measured to be about 21 mT [26]. So, the self-generated magnetic field does not affect the properties of the 1DJ.

The resistance versus temperature characteristics shift towards low temperatures by rising the current from $\sim 3\%$ and $\sim 65\%$ of $I_{C,0}$. In addition, the $R(T)$ characteristics preserve the same shape up to the largest bias currents. The use of an AC bias allowed to resolve the $R$ vs $T$ characteristics near the critical temperature. In fact, values of DC bias higher than the retrapping current [36] ($I_R$, that is the switching current from the resistive to the dissipationless state) would cause the sudden transition of the device resistance to $R_N$. Instead, the AC bias has always a part of the period lower than $I_R$ thus enabling the precise measurement of the entire $R(T)$ traces.

The electronic temperature of the nanowire ($T_A$) at the middle of the phase transition under current injection does not coincide with $T_{bath}$ since Joule dissipation (for $R \neq 0$) causes the quasiparticles overheating in $A$ yielding $T_A > T_{bath}$ [32]. Therefore, from the $R$ vs $T$ curves we can only specify the current-dependent escape temperature [$T_e(I)$]. The values of $T_e$ are shown in Fig. 5(c) as a function of $I/I_C$ for two different samples. The escape temperature is monotonically reduced by rising the bias current with a minimum value $\sim 20$ mK for $I = 370$ nA, that is $\sim 15\%$ of the intrinsic critical temperature of the active region, $T_C^i \sim 130$ mK.

The superconducting-to-normal-state transition ($\delta T_C$) narrows in temperature by increasing the current injection, as depicted in Fig. 5(d). In particular, $\delta T_C$ is suppressed by a factor of 4 at the largest bias current. We stress that this behavior is in full agreement with the theoretical behavior of a 1DJ shown in Sec. 2. Therefore, in the following we will focus on the detection properties of a 1DJ.

4. Operation principle of the nano-TES and JES

The 1DJ was employed to design two single-photon detectors operating in the GHz band: the nanoscale transition edge sensor (nano-TES) [25] and the Josephson escape sensor (JES) [26]. These sensors take advantage of the strong resistance variation of the superconducting nanowire while transitioning to the normal-state, such as in a conventional TES [15]. Differently from the TES, the sensitivity of the nano-TES and the JES can be in situ controlled, since the resistance versus temperature characteristics of a 1DJ can be tuned by varying the bias current. As a consequence, the 1DJ serves as the active region of

![Figure 6. General thermal and electrical model of the nano-TES and JES. (a) Schematic representation of a typical biasing circuit for the nano-TES and JES. The parallel connection of the sensor (of variable resistance $R$) and the shunt resistor ($R_S$) is biased by the current $I_{Bias}$. The role of $R_S$ is to limit the Joule overheating of $A$ when transitioning to the normal-state. The variations of the current ($I$) flowing through the sensing element are measured thank to the inductance $L$. For instance, an inductively-coupled SQUID amplifier could serve as read-out element. (b) Thermal model of the nano-sensors where the main thermal exchange channels are shown. $P_{in}$ is the power coming from the incoming radiation, $P_{e-ph}$ is the heat exchanged between electrons in the active region (yellow) at $T_A$ and lattice phonons (grey) at $T_{bath}$, while $P_{A-B}$ is the heat current flowing towards the superconducting electrodes (blue) residing at $T_{bath}$.](image-url)
these sensors. The main difference between the nano-TES and the JES is the operating temperature. Indeed, the nano-TES operates at $T_c$, i.e., at the middle of the superconductor-to-normal-state transition [see Fig. 3(a)], while the JES operates at $T_e$, i.e., deeply in the superconducting state. Notably, these temperatures can be very different at large bias currents [see Fig. 3(b)].

For both sensors, the absorption of radiation provokes an increase of the electronic temperature in the superconducting nanowire ($T_A$) thus driving its transition to the normal-state. The latter would generate Joule heating in the active region when biased with a constant current with consequent thermal instability. To solve this issue, the the nano-TES and the JES could be biased with the circuitry shown in Fig 6(a).

The shunt resistor ($R_S$) limits the current ($I$) flowing through the sensor ($R$) when the $A$ undergoes the superconducting-to-normal-state transition. This is called negative electrothermal feedback (NEFT) [15]. For the nano-TES, the sensor is biased at $T_C$ ($R = R_N/2$), therefore the condition for the shunting resistor reads $R_S = IR_N / [2(I_{Bias} - I)]$, where $I_{Bias}$ is the current provided by the generator. For the JES, the device is operated at $T_e$, i.e., at $R = 0$, and the role of $R_S$ is to limit the current flow through the sensing element below $I_R$. This happens for $R_S \leq R_N I_R / I_{bias}$ and brings $A$ quickly back to the superconducting state after radiation absorption. Therefore, the sensor always operates in the superconducting state. For both the nano-TES and the JES, the variations of $I$, due radiation absorption, can be measured via a conventional SQUID amplifier coupled to the inductance $L$ [25].

The ability of a superconducting sensor to resolve a single-photon depends on their ability to convert the power of the incoming radiation into a change of electronic temperature in the active region. The latter is related to the predominant thermal exchange mechanisms occurring in $A$. Figure 6(b) shows the thermal model describing the active region of both the nano-TES and the JES, where $P_{in}$ is the power associated to the external radiation, $P_{e-ph}$ is the heat exchange with lattice phonons, and $P_{A-B}$ represents the energy out-diffusion for the active region to the lateral leads. When the critical temperature of the lateral electrodes ($T_{C,B}$) is much higher than operating temperature ($T_C$ for the nano-TES and $T_e$ for the JES), they behave as energy filters, the so-called Andreev mirrors [37], thus ensuring perfect thermal insulation of $A$ ($P_{A-B} \rightarrow 0$). Within this condition, $P_{e-ph}$ is the predominant thermal relaxation channel in the active region. See Ref. [25] for the application limits of this assumption.

For the nano-TES, the active region operated almost in the normal-state (at $R_N/2$). Therefore, the electron-phonon coupling of a normal-metal diffusive thin film can be employed [15,32]

$$P_{e-ph,n} = \Sigma_A V_A \left( T_A^5 - T_{bath}^5 \right), \quad (6)$$

where $V_A$ is the volume of $A$, while $\Sigma_A$ is its electron-phonon coupling constant. The resulting thermal conductance for the active region of a nano-TES ($G_{th,nano-TES}$) can be calculated through the temperature derivative of the electron-phonon energy relaxation [15]

$$G_{th,nano-TES} = \frac{dP_{e-ph,n}}{dT_A} = 5 \Sigma_A V_A T_A^4. \quad (7)$$

Differently, the JES operates deeply in the superconducting state at $T_e$ with $A$. Therefore, at very low temperatures the electron-phonon heat exchange is exponentially suppressed with respect to the normal-state [38]

$$P_{e-ph,s} \propto P_{e-ph,n} \exp \left[ -\Delta_A / (k_B T_A) \right], \quad (8)$$

where $\Delta_A$ is the superconducting energy gap in $A$. The thermal conductance of the active region of a JES (operating in the superconducting state) takes the form [39]
where the first term refers to the electron-phonon scattering, while the second term stems from the recombination processes. In Eq. 9, \( \zeta(5) \) is the Riemann zeta function, \( \bar{\Delta} = \Delta_A/k_B T \) is the normalized energy gap of \( A \), \( \bar{\Delta} = \Delta/k_B T \) represents exchange field (0 in this case), \( f_1(x) = \sum_{n=0}^{3} C_n x^n \) with \( C_0 \approx 440, C_1 \approx 500, C_2 \approx 1400, C_3 \approx 4700 \), and \( f_2(x) = \sum_{n=0}^{2} B_n x^n \) with \( B_0 = 64, B_1 = 144, B_2 = 258 \). We note that the thermal conductance for a JES is exponentially damped compared to the nano-TES, due to the operation in the superconducting state. Thus, we expect the JES to be extremely more sensitive than a nano-TES operating at the same temperature.

5. Single-photon detection performance of the nano-TES and the JES.

Microwave LSW experiments for axions search require single-photon detectors of frequency resolution on the order of a few GHz. In the next sections, we will show all the theoretical relations describing the sensing properties of a nano-TES and a JES single-photon detector and the performance deduced from the experimental data.

5.1. Modelling of the nano-TES

In order to determine the performances of a sensor in single-photon detection, the frequency resolution is the most used figure of merit, since it defines the lowest energy that the detector can reveal. For a nano-TES, it can be written [15]

\[
\delta \nu_{\text{TES}} = \frac{2.36 \bar{\nu}}{\hbar} \sqrt{\frac{4}{\alpha} \sqrt{\frac{n}{2} k_B T_C C_{e,\text{nano-TES}}}},
\]

where \( \hbar \) is the Planck constant, \( \alpha = \frac{dR}{dT} \) is the electrothermal parameter accounting for sharpness of the phase transition from the superconducting to the normal-state [15], \( n = 5 \) is the electron-phonon coupling exponent for a pure metal and \( C_{e,\text{TES}} \) is the electron heat capacitance. It is interesting to note the strongly dependence on \( \alpha \) value which determines the NETF mechanism [15].

Since the nano-TES operates at the critical temperature, the electron heat capacitance of the active region is written [32]

\[
C_{e,\text{nano-TES}} = \gamma_A V_A T_C,
\]

where \( \gamma_A \) is the Sommerfeld coefficient of \( A \).

The time response of the detector defines the speed of the read-out electronics necessary to correctly reveal the incoming single-photon. By considering the circuitry implementing the NETF [see Fig. 6(b)], the pulse recovery time takes the form [15]

\[
\tau_{\text{eff}} = \frac{\tau_{\text{nano-TES}}}{1 + \frac{\alpha}{n}},
\]

where \( \tau_{\text{nano-TES}} \) is the intrinsic recovery time of \( A \). The latter can be calculated by solving the time dependent energy balance equation that takes into account all the exchange mechanisms after radiation absorption [32]. The re-thermalization of the quasiparticles to the equilibrium depends exponentially on
time with a time constant ($\tau_{\text{nano-TES}}$) given by the ratio between the thermal capacitance and the thermal conductance of $A$

$$\tau_{\text{nano-TES}} = \frac{C_{e,\text{nano-TES}}}{G_{th,\text{nano-TES}}}. \quad (13)$$

Since $a \gg n$, the pulse recovery time is much shorter than the intrinsic time constant of $A$ ($\tau_{\text{eff}} \ll \tau_{\text{nano-TES}}$). Therefore, the overheating into the active region is decreased by the NETF, thus compensating for the initial temperature variation and avoiding the dissipation through the substrate.

5.2. Modelling of the JES

Since the current injection does not change the energy gap of the active region ($\Delta_A \sim \text{const}$), only the effective critical temperature of $A$ changes with $I$, while the intrinsic values of critical temperature ($T_{iC}$) is unaffected. As a consequence, being at $T_c(I)$, the JES operates deeply in the superconducting state, thus ensuring high sensitivity (the thermalization is exponentially suppressed by the energy gap, see Eqs. 8 and 9).

The frequency resolution of a JES ($\delta\nu_{\text{JES}}$) can be calculated from [24]

$$\delta\nu_{\text{JES}} = \frac{4}{h} \sqrt{2 \ln 2 k_B T_c^2 C_{e,JES}}. \quad (14)$$

The electron heat capacitance needs to be calculated at the current-dependent escape temperature [$T_e(I)$], thus in the superconducting state, and takes the form

$$C_{e,JES} = T_A V_A T_e \Theta_{Damp} = C_{e,\text{nano-TES}} \Theta_{Damp}, \quad (15)$$

where the electronic heat capacitance is given by

$$C_e = 1.34 T_A \left( \frac{\Delta_A}{k_B T_e} \right)^{-3/2} e^{-\Delta_A/k_B T_e}. \quad (16)$$

Furthermore, $\Theta_{Damp}$ is the low temperature exponential suppression with respect to the normal metal value, and it takes the form [40]

$$\Theta_{Damp} = \frac{C_e}{1.34 T_A T_e}. \quad (17)$$

Since the JES does not operate at the middle of the superconducting-to-normal-state transition, the JES speed does not depend on the electrothermal parameter. Indeed, it is given by the relaxation half-time ($\tau_{1/2}$), which reads [24]

$$\tau_{1/2} = \tau_{JES} \ln 2, \quad (18)$$

where $\tau_{JES}$ is the JES intrinsic thermal time constant. The latter is calculated by substituting the JES parameters in Eq. 13, thus considering $C_{e,JES}$ and $G_{th,JES}$ in deep superconducting operation.

5.3. Deduced experimental performance

In this section, we show the sensing performance deduced for two different 1DJs (samples 1 and 2 of Fig. 5) operated both as nano-TES and JES.

Table 1 resumes the figures of merit calculated in case of nano-TES operation. The intrinsic relaxation time of the active region is limited by $G_{th,\text{nano-TES}}$ to a few microseconds for both devices ($\tau_1 \simeq 6 \mu s$ and $\tau_2 \simeq 5 \mu s$). On the one hand, the electron heat capacitance is $C_{e,\text{nano-TES}} = 4 \times 10^{-20} \text{ J/K}$ and
the thermal conductance takes value $G_{th,nano-TES_1} = 6.7 \times 10^{-15}$ W/K for sample 1. On the other hand, $C_{c,nano-TES_2} = 4.2 \times 10^{-20}$ J/K and $G_{th,nano-TES_2} = 9.3 \times 10^{-15}$ W/K for sample 2. The thermal response of the nano-TES full detector is strongly damped from the electrothermal parameter. Consequently, $\tau_{eff}$ is from one to two orders of magnitude smaller than the thermal response time ($\tau_{eff} \ll \tau$). In particular, the detector response time is $\tau_{eff,1} = 0.01 \mu s$ and $\tau_{eff,2} = 0.2 \mu s$ for sample 1 and sample 2, respectively. The frequency resolution depends on the electrothermal parameter ($\alpha^{-1/2}$), too. Therefore, the two nano-TESs show different values of $\delta \nu$. In particular, $\delta \nu_1 \simeq 100$ GHz ($\delta E_1 \simeq 0.4$ meV) for sample 1 and $\delta \nu_2 \simeq 540$ GHz ($\delta E_2 \simeq 2$ meV) for sample 2 were calculated. Accordingly, the resolving power ($v/\delta \nu$) reaches values larger than 1 for $v \geq 100$ GHz for sample 1.

The performance in the JES operation are expected to strongly depend on he bias current. Indeed, Fig. 7(a) emphasizes the variations over 3 orders of magnitude of $\delta \nu_{JES}$ on $I$. The best frequency resolution is $\sim 2$ GHz at 370 nA. This value would enable the detection of single-photons at unprecedented low energies. The disrupting sensitivity is highlighted by the resolving power ($v/\delta \nu_{JES}$). Figure 7(b) shows $v/\delta \nu_{JES}$ calculated as a function of the frequency of the incident photons. In particular, $v/\delta \nu_{JES}$ can reach $\sim 80$ at 100 GHz and $\sim 240$ at 300 GHz for 370 nA.

The dependence of the JES time constant ($\tau_{1/2}$) on $I$ is shown in Fig. 7(c). In particular, $\tau_{1/2}$ monotonically increases by rising $I$, and varies between $\sim 1 \mu s$ at low current amplitude and $\sim 100$ ms at 370 nA. Notably, these values are orders of magnitude larger than that of nano-TESs. As a consequence, the read-out of single photons with the JES allows to employ slower and thus cheaper electronics.

Concluding, both the nano-TES and the JES show frequency resolutions enabling the search of axions through LSW experiments in the microwave frequency band. In particular, the JES allow to perform experiments in a wide range of energies down to about 8 $\mu$eV. Furthermore, the slow response time of the JES would simplify the read-out circuitry involved in the experiment.

6. Materials and Methods

6.1. Fabrication procedure

All the devices presented in this review were fabricated by electron-beam lithography (EBL) and 3-angles shadow evaporation through a suspended resist maske onto a silicon wafer covered with 300-nm-thick SiO$_2$ thermally grown on an intrinsic silicon wafer. To obtain the resist suspended mask, a bilayer composed of a 950-nm-thick MMA(8.5)MMA layer and a PMMA (A4, 950k) film of thickness of about 300 nm was spin-coated on the substrate. The ratio between the electron irradiation doses to make the resists soluble is $DOSE_{MMA} : DOSE_{PMMA} \simeq 1 : 4$. The evaporations were performed in an ultra-high vacuum electron-beam evaporator with a base pressure of about $10^{-11}$ Torr by keeping the target substrate at room temperature. First, 13-nm-thick Al layer was evaporated at an angle of $-40^\circ$. Second, the film was then oxidized by exposition to 200 mTorr of O$_2$ for 5 minutes to obtain the tunnel probes of the device devoted to the spectral and the thermal measurements. Third, the Al/Cu bilayer ($t_{Al} = 10.5$ nm and

| Sample | $T_c$ (mK) | $\tau$ ($\mu s$) | $\tau_{eff}$ ($\mu s$) | $\delta \nu$ (GHz) | $v/\delta \nu$ (100 GHz, 300 GHz) |
|--------|------------|-----------------|------------------------|------------------|--------------------------------|
| 1      | 128        | 6               | 0.01                   | 100              | 1 (3)                          |
| 2      | 139        | 5               | 0.2                    | 540              | 0.18 (0.55)                     |

Table 1. Main figures of merit deduced for the nano-TES. The time constant $\tau$, the pulse recovery time $\tau_{eff}$, the frequency resolution $\delta \nu$, and the resolving power $v/\delta \nu$ (at 100 and 300 GHz) are reported for two fabricated nano-TESs.
\( t_{Cu} = 15 \text{ nm} \) forming the superconducting nanowire is evaporated at an angle of 0\(^\circ\). Fourth, a second 40-nm-thick Al film was evaporated at an angle of +40\(^\circ\) to obtain the lateral electrodes completing the 1DJ. The angle resolution of each evaporation was \( \sim 1^\circ \). The average film thickness can be controlled during the evaporation process with the precision of 0.1 nm at the evaporation rate of about 1.5 angstrom/s.

6.2. Measurement setups

The electronic and the spectral characterizations presented in this review were performed at cryogenic temperatures in a \( ^3\text{He} - ^4\text{He} \) dilution refrigerator equipped with RC low-pass filters (cut-off frequency of about 800 Hz). The lowest electronic temperature obtained was 20 mK.

The bias current tuning of the transport properties of the 1DJ is realized by standard lock-in technique. The AC current bias is produced by applying a voltage \( V_{ac} \) at a frequency 13.33 Hz to a load resistance \( R_L = 100 \text{ k} \Omega \) \((R_L \gg R_N)\) in order to obtain a bias current independent from the resistance of the 1DJ. The voltage drop \( V \) the device is measured as a function of \( T_{bath} \) via a voltage pre-amplifier connected to a lock-in amplifier. The use of a pre-amplifier allows to decrease the noise in the measurement. The control of the transport properties of the 1DJ is thus performed by varying \( V_{ac} \).

The energy gap of the superconducting nanowire was determined by tunnel spectroscopy. To this end, a voltage was applied between one tunnel probe and one lateral electrode by means of a low noise DC source, while the flowing current was measured through a room temperature current pre-amplifier.

7. Conclusions

This paper reviewed two innovative hypersensitive superconducting radiation sensors: the nanoscale transition edge sensor (nano-TES) and the Josephson escape sensor (JES). Both devices are based on a one-dimensional Josephson junction (1DJ) with the capability to in situ fine tune their performance by simple current bias. The nano-TES and the JES have the potential to drive single-photon detection in the gigahertz band towards unexplored levels of sensitivity. In fact, the nano-TES shows a frequency resolution of about 100 GHz, while the JES is able to resolve single-photons down to 2 GHz. Therefore, these sensors are the perfect candidate for the implementation of light shining through walls (LSW) experiments for the search of axions operating at micro- and milli-electroVolt energies. Furthermore, the nano-TES and the JES could have countless applications in several fields of quantum technology where single-photon detection is a fundamental task, such as quantum computation [41] and quantum cryptography [42,43].
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