IL NUOVO CIMENTO **47 C** (2024) 270
DOI 10.1393/ncc/i2024-24270-1

Communications: SIF Congress 2023

Exploring NbRe for superconducting microstrip single photon detectors: Fabrication and resistance behaviour

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received 25 January 2024

Summary. — The superconducting nanostrip single photon detectors based on NbN exhibit unmatched performance at 1550 nm compared to the InGaAs single photon avalanche photodiodes at the same wavelength. However, they still have limitations in terms of active area and maximum detectable wavelength. Recently, single photon detectors based on superconducting microstrip in new materials have been very promising, as they could cover large areas and detect photons even in the mid infrared, extending the possibilities of use of this category of devices. The experiments point out that the role of vortices is crucial, accrediting the vortex-assisted detection mechanisms. According to the latter, a free vortex may be induced by photon absorption or appear as a result of a fluctuation and can give rise to a normal domain, responsible of a voltage pulse recording. Therefore, it is important to study the devices physical characteristics related to the vortices and their evidence in the material. In this work, we present the fabrication and the study of microstrips based on NbRe. We studied the resistance behaviour as the temperature decreases in order to investigate its superconducting properties according to the theoretical models based on the presence of vortices.

1. – Introduction

Many applications, such as quantum communication and computation, rely on single photon based technologies [1]. The most common detectors, Si single photon avalanche photodiodes (SPADs), have a restricted range of wavelengths that they can detect, because their efficiency decreases above 1 μm, leading to a lower signal-to-noise ratio [2]. InGaAs SPADs can sense single photons up to 1.7 μm, but they are affected by more noise. Conversely, Superconducting Nanostrip Single Photon Detectors (SNSPDs) made of superconducting materials like NbN, exhibit excellent performance at the telecom wavelength of 1550 nm. Indeed, they can detect single photons with near unit efficiency, and they have low dark count rate and fast time resolution [1]. Besides the standard meandered geometry, SNSPDs can also have spiral or fractal shapes to ensure polarization insensitivity [3], series of parallel strip blocks to enlarge the sensitive area without increasing the kinetic inductance and hence the recovery time [4], or interleaved independent strips for photon number resolution and short recovery time [5]. Micrometric strips can also work as single photon detectors and they can cover the same area as an SNSPD with lower impact on the recovery time [6]. However, the photon detection and dark counts mechanisms in these micrometric devices are still under investigation.

According to the model developed by Semenov *et al.* [7], a region of reduced superconductivity, known as hot-spot, emerges when a photon is absorbed. The diameter of this region typically ranges from 50 nm to 100 nm and causes the current to divert to its boundaries [8, 9]. This results in a local increase of the current density which, if it overcomes its critical value, switches the strip to the resistive state [7]. For a long time, the detection of single photons was thought to be possible only for superconducting strips with a width similar to the size of the hot-spot induced by photons. However, a later theoretical model, developed by Vodolazov [10], predicts that a wide strip can also detect single photons if it is biased at a current close to the depairing current. According to this model, the detection process depends on whether the hot-spot is located at the strip edge or in the strip center and involves vortex entry or vortex-antivortex pairs. A vortex penetrates the region of reduced superconductivity and traverses the strip when the hot-spot is close to the edge. On the other hand, when the hot-spot is in the center of the strip, a vortex and an antivortex emerge in it and move across the strip in opposite directions. Then, the dissipative vortex motion leaded by the Lorentz force, due to the high bias current, gives rise to a normal conducting domain [11, 12].

The photon detection in superconducting microstrip was indeed achieved [6]. According to the experiments, the vortices have a key role, supporting the idea of a vortex-assisted detection mechanism [13-15]. Hence, the investigation of the physical properties of the devices that are related to the vortices and their manifestation in the material is crucial. A first possibility is studying the behaviour of the resistance R as function of the temperature T by using well known models in literature such as Berezinskii-Kosterlitz-Thouless (BKT) theory [16, 17]. According to the latter, in bidimensional superconductors there is a transition temperature T_{BKT} above which the dissipation due to free vortices cause the resistance to be higher than zero [18].

In this work, we fabricated micrometric devices using optical lithography techniques, which are faster and cheaper than the electron beam lithography that is usually used for nanofabrication [19]. The devices are based on NbRe microstrips, which may open new possibilities for applications to mid infrared wavelengths, as it has been shown that they can detect single photons at least up to 1550 nm [20, 21]. We manufactured, besides single strips, a series of three pairs of parallel strips to increase the active area, and we investigated the resistance behaviour as a function of the temperature according to the vortices effect.

2. – Fabrication

We used DC magnetron sputtering in ultra-high vacuum (pressure around 10^{-8} mbar) to deposit 5 nm of NbRe ($Nb_{0.15}Re_{0.85}$) on Si/SiO_x substrate at room temperature. To prevent oxidation, we added a 2 nm Al layer on the NbRe surface employing the same deposition technique. We patterned the sample by optical lithography with a microprinter and argon ion etching.

We fabricated three devices, respectively a single strip wide 0.9 μm (device A), a single strip wide 1.5 μm (device B), and a series of three pairs of parallel strips (device C), whose widths range from 1.2 μm to 1.4 μm and then are comparable. Their images, taken by an optical microscope, are reported in fig. 1. It is worthy to note that the blocks at the sides of the device portrayed in in fig. 1(c) ensure the uniformity of all the strips during the fabrication process.

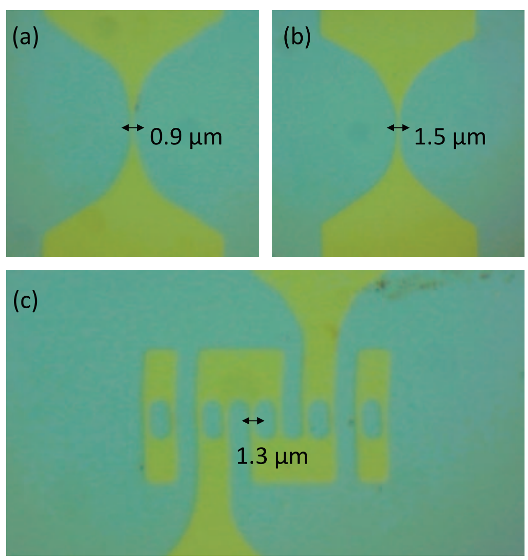

Fig. 1. – Micrometric devices under investigation: the single strip A (a), the single strip B (b), and the series of three pairs of parallel strips C (c).

TABLE I. – *Fabricated strips and their geometrical characteristics.*

Device	Geometry	Width [μm]	Length [μm]	Thickness [nm]
A	Single strip	0.9	5	5
B	Single strip	1.5	7.5	5
C	Series of three pairs	1.2–1.4	7.5	5

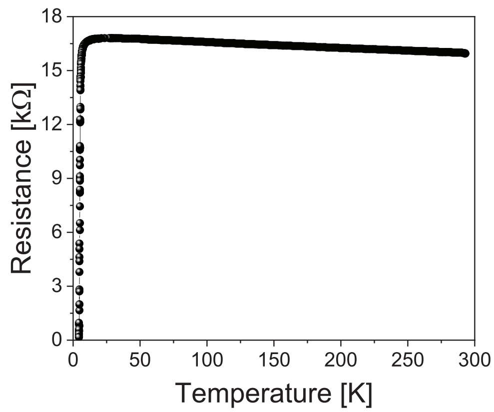

Fig. 2. – Resistance of device B from room temperature to 4.2 K.

3. – Resistance analysis

We mounted the sample with the microstrips on a cryogenic insert and placed it in the cryostat. We performed electric transport measurements using four-probe technique in helium vapours lowering the temperature gradually until it reached the liquid of temperature 4.2 K. The temperature was measured by a calibrated thermometer.

We measured the resistance of each device as its temperature decreases. In fig. 2 we report the resistance of device B as its temperature decreases from room temperature down to liquid helium one. The graph shows that a NbRe strip has the same property as dirty metals because of which it has a small rise in resistance when T decreases [22].

In fig. 3 we report the behaviour of the resistance at low temperatures, where the transition from normal conducting state to superconducting state occurs. It is worthy to note that, although it sharply decreases, R does not reach zero in the considered temperature range, but it is still of the order of magnitude of 100 Ω.

Indeed, as discussed as in [23], we can consider our devices as bidimensional superconductors. Therefore, according to BKT theory [16, 17], in addition to the critical temperature T_c, above which the strip is in the normal conducting state, there is another transition temperature T_{BKT}. When the temperature is below the latter, vortices and antivortices are all coupled. In this condition the resistance of the strip is strictly zero, as the bounded vortices and antivortices are not free to move and then there is no dissipation [18]. However, if the temperature overcomes T_{BKT}, a portion of the pairs is dissociated. Therefore, in addition to non-dissipating coupled vortices, there are also free ones which can move under the effect of the Lorentz force caused by the bias current. This effect appears as a non-zero resistance. In particular, the resistance as a function of the temperature, ranging from T_{BKT} and T_c, can be expressed as [18]

$$R(T) = a \exp\left(-2\sqrt{b\frac{T_c - T}{T - T_{BKT}}}\right), \tag{1}$$

where a is the resistance at the critical temperature and b quantifies the effect of the vortices on the resistance [18]. A fitting procedure according to (1) was performed for all the devices under investigation. The results are reported in table II.

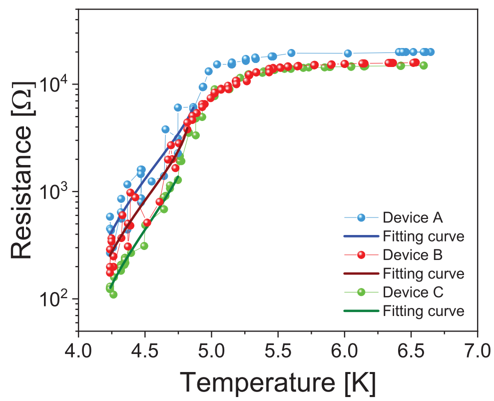

Fig. 3. – Resistance at low temperature and fitting curve for devices A (blue), B (red) and C (green).

The values of critical temperature are consistent and the same applies to T_{BKT} and b, which depends on the material. Conversely, a also depends on the geometry, and then it is different. It is worthy to note that T_{BKT} is lower than liquid helium temperature, and then we needed to reach lower temperatures in order to observe zero resistance. However, the agreement of these properties for different devices on the same chip is the result of a successful fabrication procedure, which guarantees a uniform outcome.

4. – Conclusion

Superconducting microstrip single photon detectors represent an appealing possibility to extend the applicability of SNSPDs to experiments where a large area and fast timing performance are required. The detection mechanism in these devices is not fully understood yet, but it seems clear that vortices play a crucial role in it. Therefore, it is of great interest to study the devices characteristics related to them. In this work, we have studied the superconducting properties of the strips with different geometries (single strips and a series of three pairs of parallel strips) according to the BKT theory, which predicts the existence of an additional transition, below the critical temperature, due to vortices. We measured the resistance behaviour as a function of the temperature, and we obtained that this transition temperature in our case is 3.7 K. The agreement with the trend expected by the BKT theory highlights the presence of vortices in the NbRe devices. Moreover, the values obtained in the three considered devices are consistent

Table II. – *Fitting results on each device.*

Device	a [kΩ]	b	T_c [K]	T_{BKT} [K]
A	10	2	4.9	3.7
B	5	2	4.8	3.7
C	4	3	4.8	3.7

and, besides showing the uniformity of the fabrication, define the minimum temperature below which the resistance is zero and hence these strips can work as photon detectors.

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This research was supported by the QUANCOM Project 225521 (MUR PON Ricerca e Innovazione No. 2014–2020 ARS01_00734).

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