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Ultrathin superconducting NbRe microstrips with hysteretic voltage-current characteristic

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Ultrathin microstrips based on polycrystalline NbRe films were investigated in order to preliminarily test the suitability of this material for the realization of superconducting single-photon detectors. The voltage-current characteristics measured on these samples show clear hysteresis. This is a fundamental ingredient for investigating single-photon detection as well as single vortex fluctuation phenomena in 2D NbRe-based devices.

Keywords: superconducting detectors, ultrathin superconducting strips.

The field of superconducting single-photon detectors (SSPDs) demands for devices with improving performances especially at the communication-relevant wavelength $\lambda = 1550$ nm [1]. The main key properties which characterize their operation, such as efficiency, dark counts rate, time jitter, and recovery time, apart from the device design, are all affected by the intrinsic parameters of the superconducting material on which they are based [2–5]. Moreover, a key feature required for the superconductor constituting the SSPD is that it should have a hysteretic voltage-current [$V(I)$] characteristic. Indeed, this feature allows the SSPD to amplify the tiny effect of the absorption of a single photon to a macroscopic measurable effect, that can be used also in more elaborate SSPD designs based on parallel strips, as well as in superconducting current pulse discriminators [2,6–10]. For reliable devices high efficiency requires low superconducting gap, Δ (or critical temperature, T_c), but large critical current density, J_c, and resistivity, ρ. On the contrary, minimization of the dark counts rate and time jitter demand for high values of Δ. Many other metrics affect the performance of a SSPD, such as the homogeneity and crystallinity of the superconducting material. While the uniformity of the wire constituting the detector is mandatory, wires with large grains may present more constrictions but better values for recovery time and time jitter [3]. SSPDs based on amorphous materials were used as an alternative to NbN or NbTiN, due to their higher resistivity and uniformity, along with their higher efficiency in the infrared frequency range, with the drawback, however, of working at much lower temperature [1]. However, very recent works demonstrate that there is room for improvement also for the devices based on amorphous superconductors [11]. From all these considerations it follows that the above mentioned requirements are often contradictory, and also the recent debate about the choice between amorphous and crystalline materials is still open. Indeed, the problem of improving the detector performance is by far more complex, and it is closely linked to the detection mechanisms responsible of their operation, which still present many open issues.

In a previous paper $Nb_{0.18}Re_{0.82}$ (hereafter NbRe) was suggested as promising candidate for the realization of fast SSPD [12]. In fact, it offers in principle the opportunity of accessing the spectral range useful for quantum communication, which is hardly doable with NbN-based devices, with the further advantage of larger expected hot-spot dimensions for the same incident photon energy. Furthermore, compared to amorphous superconductors recently proposed at these scopes, it is characterized by extremely reduced quasiparticle relaxation rates, almost an order of magnitude shorter than the ones of high performing NbN wires [12]. Moreover, its polycrystalline structure with small crystallites and disorder-dominated transport properties [13] make this material an alternative between other well-known Nb-based and amorphous materials.

In this paper the superconducting properties of micrometric strips of NbRe ultrathin films, 5-nm-thick, are presented. This thickness is comparable with the value of the coherence length estimated for this material from upper critical field measurements, namely $\xi = 4.8$ nm [13]. While the request on the reduced film thickness is standard for SSPD design [5], the choice of patterning the films in strips of micrometric width was inspired by the recent results presented in Refs. 14–17. Here it was claimed that, under the appropriate conditions, even a wide dirty superconducting bridge is able to detect a single infrared or optical photon. Among the needed requirements are the uniformity in the electrical current flow, which the low crystallinity of NbRe should fulfill, a large $C_e/C_{\rm ph}$ ratio, as reported in Refs. 12, 18, as well as critical current values which should reach at least 0.7 J_{dp}, where J_{dp} is the depairing current density. In particular, here the focus is on the $V(I)$ characteristics and on the estimation of some of the main figures of merit for a possible device based on this material. Finally, possible further experiments on NbRe nanostrips are indicated. This work represents a preliminary step to evaluate the possible application of NbRe in the field of SSPDs.

5-nm-thick NbRe films were deposited by dc magnetron sputtering on Si(100) substrates in a UHV system at room temperature, as previously described [13]. The superconducting properties of the nanowires were characterized by resistivity and $V(I)$ measurements, by using a low noise electronic set-up. Optical lithography and reactive ion etching (RIE) were used to pattern the microsized strips with a length $L = 400$ μm and width w from 2 to 5 μm. The geometry of the analyzed strips are not optimized for photoresponse experiments, since this work is intended to investigate the behavior of the NbRe $V(I)$ characteristics at this reduced thickness, as a first test for the feasibility of a NbRe-based wide area detector. In the design of the real device the geometry of the wires will be optimized in order to fulfill at the same time both requirements of large active areas and wire uniformity with no constrictions. Future experiments will indeed focus on the study of microbridges 2 μm wide and with L of the order of tens of μm, in agreement with Refs. 14–16. In the inset of Fig. 1 a scanning electron microscope (SEM) image of the strips realized on the same chip are shown. The samples have increasing width from right to left and are labeled as w2…w5, where the number indicates the strip width in μm. As it can be inferred from the picture, the points where the strip width changes are right-angled and this may have an influence on the critical current due to current-crowding effect [19]. The measured current density can be expressed as $J_c = R\,J_{c,\rm uniform}$, where $J_{c,\rm uniform}$ is the critical current density of an infinitely long wire with optimized corners and the coefficient R depends on the geometry under study [19,20]. Therefore, in the case of the geometry of

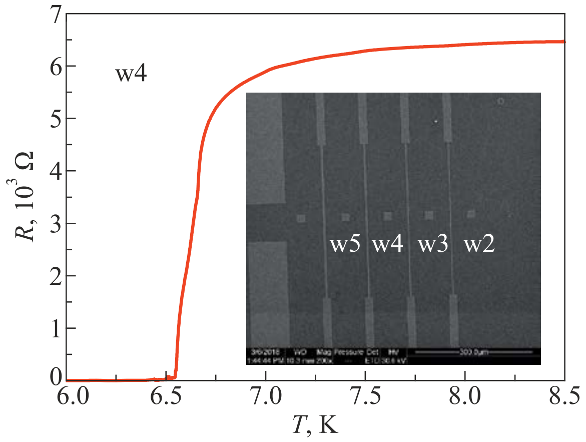

Fig. 1. $R(T)$ for the NbRe strip 5 nm thick and 4 μm wide (strip w4). Inset: SEM image of the micrometric strips based on 5-nm-thick NbRe film. The distance between the contact probes L is fixed at 400 μm, while w = 2, 3, 4, 5 μm from right to left (see labels).

the sample w4, in the framework of the Ginzburg–Landau model, a reduction of the critical current due to the crowding effect of about $R \approx (\xi/w)^{1/3} \approx 0.1$ is expected [19,20]. However, it is worth noticing that it was experimentally verified that by following this model the critical current reduction is often significantly overestimated [20,21]. It is also evident that, since the critical current reduction can have detrimental effects on the performance of superconducting wires working as single photon detectors, great care must be paid in the design of the final wires constituting the NbRe-based devices.

The resistive transition, $R(T)$ of a representative NbRe strip with $w = 4$ μm (w4) is reported in Fig. 1. The superconducting critical temperature was defined as the temperature at which the resistance is half of the one measured at $T = 10$ K ($T_c \equiv T_c^{50\%}$), that is $T_c = 6.65$ K. From the $R(T)$ curve the value of the normal state resistivity, ρ_n, can also be obtained, namely $\rho_n = 33\ \mu\Omega\cdot$cm.

In Fig. 2 the $V(I)$ characteristics acquired at $T = 4.2$ K on the strips with w = 2 and 4 μm (w2 and w4, respectively) are shown. As the bias current is increased from zero, a sudden transition to a dissipative state is observed at the so-called switching current I_s, as indicated by a thick arrow in the graph for sample w4 at $I_{s,\rm w4} = 0.127$ mA. This current corresponds to a nominal current density $J_{s,\rm w4} = 6.35\cdot 10^9$ A/m^2, which is very close to the value estimated for thicker bridges [12]. Interestingly, as the current is decreased the strip remains normal, until I is reduced below the so-called retrapping current, I_r, namely $I_{r,\rm w4} = 0.065$ mA for sample w4 (see thin arrow), which corresponds to $J_{s,\rm w4} = 3.25\cdot 10^9$ A/m^2.

This hysteresis of about 0.06 mA is highlighted in the inset of Fig. 2, where for the sake of the clarity arrows are added to to indicate the bias current sweep direction. Contrary to what was observed in the voltage–current characteristic of thin and wider NbRe bridges [12,13], where the

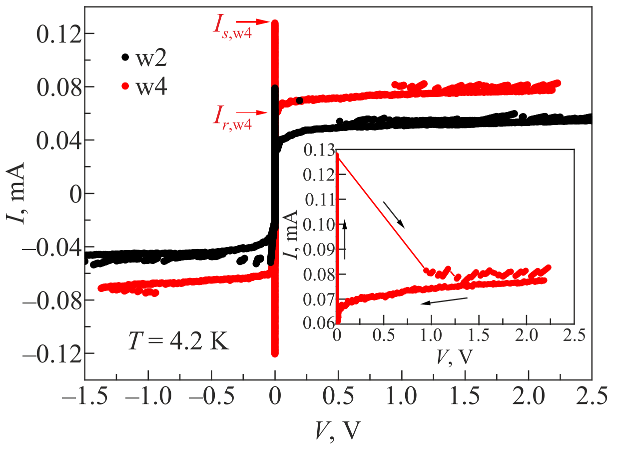

Fig. 2. (Color online) Voltage-current characteristic of the strips w2 and w4 measured at T = 4.2 K. The thick (thin) arrow indicates the switching ($I_{s,\mathrm{w4}}$) [re-trapping ($I_{r,\mathrm{w4}}$)] current for the strip w4. Inset: the region of the $V(I)$ curve of the strip w4 between $I_{s,\mathrm{w4}}$ and $I_{r,\mathrm{w4}}$ is enlarged for the sake of clarity in order to better show its hysteretic behavior.

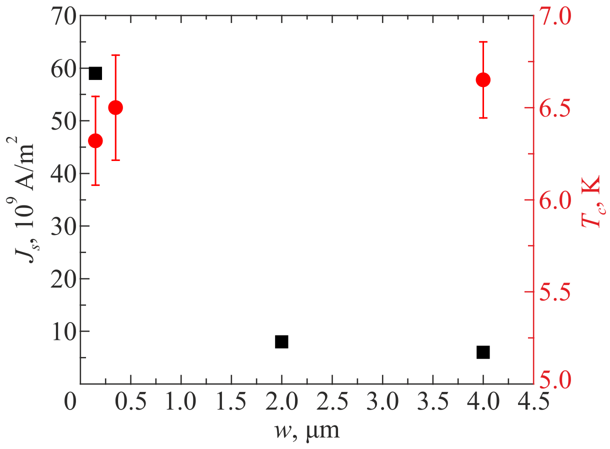

Fig. 3. Left (right) scale: dependence of the switching current density (superconducting critical temperature) as a function of the strip width. The error bars associated to J_s are smaller than the data symbols.

switch at I_s occurs from a finite voltage in the measured strips, here the switch at I_s happens at zero voltage.

The dependence of the switching current density, J_s, on the strip width is reported in Fig. 3 (left scale) and compared with the one measured on a different samples (c2) obtained from one micrometric bridge of the same batch by electron beam lithography (EBL) and RIE. The strip c2 has $w = 150$ nm and width L = 2.5 μm and was fabricated during the optimization of the process of scaling of the samples for future experiments. The critical current increases by reducing w. However, it is not possible to extract any clear dependence since the geometry of the sample c2 is different compared with the design of samples w2 and w4. First, for c2 the strip is by far shorter and narrower than for w2 and w4, and this may result in a better uniformity of the current distribution. Furthermore, c2 has rounded bends from the bridge to the contact pads and this contribute to minimizing current crowding effects. All these produce a significant enhancement of $J_{s,\mathrm{c2}} = \, = 5.9 \cdot 10^{10}$ A/m^2 with respect to both $J_{s,\mathrm{w2}}$ and $J_{s,\mathrm{w4}}$. The width reduction has less influence on the critical temperature of the strips, as it can be inferred from the $T_c(w)$ dependence reported in Fig. 3 (rigth scale). It results that T_c is almost constant within the experimental error, which was evaluated as half of the transition width (defined as $\Delta T_c = T_c^{90\%} - T_c^{10\%}$). Interestingly, the critical temperature is rather high, well above the liquid helium temperature, despite the reduced film thickness. This confirms that the NbRe superconducting properties are quite robust also regarding the patterning, since nanometric strips underwent two lithography processes.

Finally, it is useful to discuss about the values obtained for the switching current density, since J_s is a crucial parameter for the high detection efficiency of a SSPD. In particular one can compare those numbers with the expected value of J_{dp}, which is the intrinsic critical current the material can support. The values of the depairing current at $T = 0$ was evaluated according to $J_{dp}(0) = = (8\pi^2\sqrt{2\pi}/21\zeta(3)e)\sqrt{(k_B T_c)^3/\hbar v_F \rho(\rho l)}$ [22], here only microscopic experimental parameters are present and ζ is the Riemann function, by following the same procedure reported in Ref. 12. It results that $J_{dp}(0) \approx 2 \cdot 10^{11}$ A/m^2 in accordance with [12]. The comparison between J_{dp} with the measured critical current density values, and in particular the ratio J_s / J_{dp} at T = 4.2 K (reduced $t = T/T_c = 0.63$), can be obtained by profiting of the universal form of $(J_{dp}(t)/J_{dp}(0))^{2/3}$ vs t given by the theory of Kupriyanov and Lukichev via numerical solution [23]. At T = 4.2 K it is $J_{s,\mathrm{w4}}/J_{dp} = 0.2$, while $J_{s,\mathrm{c2}}/J_{dp} \approx 1$. This result is not unexpected since if on one hand J_{dp} represents an intrinsic property of the material, on the other it can be by far larger than the critical current density measured on wide bridges. Indeed, J_{dp} can be reached only if the current distribution is uniform over the width of the bridge, w, and if dissipation due to Joule heating is minimized [24,25]. The first requirement imposes constraints on the values of w, which must be smaller than both ξ and the penetration depth, as well as on the sample geometry (such as rounded bends), while biasing the strips with short current pulses reduces Joule heating. On the contrary, the hysteretic shape of our $V(I)$ curves, measured in a dc mode, is the fingerprint of the presence of an hot-spot in the superconducting strip [26,27], and assures a clear bistable switching from the superconducting to the dissipative state, which is crucial for the operation of the strip as a SSPD [28]. Moreover, the hysteresis also gives the opportunity to investigate single vortex fluctuation phenomena in 2D NbRe-based strips which are relevant for study of dark count mechanisms [29,30] as well as the physical nature of the switching phenomenon [31,32]. The importance of this work is twofold. First, it may shed a light on the nature of detection mechanism in this material [5,28], and equally important, it may indicate the optimal temperature of operation of the NbRe-based device [32]. Both these information are crucial for the design of a SSPD.

In conclusion, ultrathin microstrips of NbRe films were realized and electrically characterized by resistivity and $V(I)$ measurements. Reasonable values of both T_c and J_c were obtained. Equally important, the $V(I)$ curves show a clear hysteretic behavior. All these encouraging preliminary results deserve deeper investigation, in view of the possible realization of NbRe-based devices. In particular, future work will focus on the optimization of the strip dimensions and design, to increase the value of the critical current and fulfill the constraint reported in Ref. 14.

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Ультратонкі надпровідні мікросмуги NbRe з гистерезисною вольт-амперною характеристикою

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Ультратонкі мікросмуги, виготовлені з полікристалічних плівок NbRe, досліджуються для попередньої оцінки придатності цього матеріалу для створення надпровідних детекторів одиничних фотонів. Вольт-амперна характеристика даних зразків проявляє виражений гістерезис, що є фундаментальним інгредієнтом для дослідження однофотонної детекції, а також одновихрових флуктуаційних явищ у двовимірних пристроях на основі NbRe.

Ключові слова: надпровідникові детектори, надтонкі надпровідні смуги.

Ультратонкие сверхпроводящие микрополоски NbRe с гистерезисной вольт-амперной характеристикой

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Ультратонкие микрополоски, изготовленные из поликристаллических пленок NbRe, исследуются для предварительной оценки пригодности этого материала для создания сверхпроводящих детекторов одиночных фотонов. Вольт-амперная характеристика данных образцов проявляет выраженный гистерезис, что является фундаментальным ингредиентом для исследования однофотонной детекции, а также одновихревых флуктуационных явлений в двумерных устройствах на основе NbRe.

Ключевые слова: сверхпроводящие детекторы, сверхтонкие сверхпроводящие полосы.