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Electrical characterization of superconducting single-photon detectors

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Superconducting meanders of NbN thin films have applications as single-photon detectors with high sensitivity in the infrared region. We report here a detailed analysis of the electrical characteristics of such meanders, by studying structures where each wire of the meander is separately contacted. The effect of heating on the superconducting-normal transition of adjacent stripes is evidenced. Moreover, the analysis of the switching current distribution of each wire highlights the high-critical current uniformity achieved by our meander process. © 2007 American Institute of Physics.

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I. INTRODUCTION

High counting-rate detectors capable of sensing single photons in the infrared region are needed for several applications in different fields; among them there are high-bandwidth interplanetary communications,¹ test of high-speed semiconductor circuits,² and quantum key distribution.³ Superconducting single photon detectors (SSPDs) are nanoscale photonic devices that can fulfill these requirements.

The sensing mechanism of the device, suitable for this purpose, is based on the combination of the superconducting properties and of the submicrometric width of a wire.⁴ The device is biased below, but very close, its critical current, where due to superconductivity the voltage across the device is zero. When a single photon is adsorbed in the wire, a normal “hot spot” is created.⁵ This normal region, of about 20 nm size for 850 nm wavelength photons, forces the current to flow in the lateral remaining part of the wire. Due to the small width of the wire, about 100 nm, in this region the current exceeds the critical current of the material: A superconducting to normal transition takes place so that in a time of the order of 10 ps the whole region near the hot-spot becomes normal and a voltage pulse is generated. The SSPD reset mechanism is due to the low impedance of the electromagnetic environment. As the superconducting film is very thin (<10 nm), the normal part of the SSPD has a high resistance, about 400 Ω /sq. During the transition the device follows a properly designed load line and reaches a metastable region; the bias current is diverted from the active part of the device to the 50 Ω coaxial transmission line and the 50 Ω load, so that the power dissipated in the device is not enough to sustain a stable resistive region. The device is self reset to its superconducting state and is able to detect a new photon.

A meander geometry is used to enhance the filling factor of the detection area and hence the detection efficiency of the device. The ultrathin superconducting film is patterned in a meander shape with submicrometer wide strips. SSPD detectors can reach high-detection efficiency of about 30% at 1.3 μm and low dark count rate ≤ 1 count/s. Operating frequencies up to 2 GHz have been also demonstrated at 2.3 K.^{6,7} However, although the intrinsic detection mechanism is very fast allowing picosecond response, the kinetic inductance of a standard designed SSPD determines the fall time of the response voltage transient and leads to nanosecond dead time.⁸ For practical application, higher-detection efficiencies are needed, while the capability of resolving also the energy of the incoming photons can make these devices useful also for other applications different from those mentioned above.

The meander geometry presents several challenges. On one hand, as a consequence of this photodetection mechanism, the wires of the device need to be narrow (about 100 nm) and must have very uniform linewidth so that each part of the meander has the same critical current.⁹ A small constriction along the meander would have a lower critical current limiting the maximum bias current of the device: In such a condition only the region near the constriction (much smaller than the full meander) is correctly biased and is really sensitive to the incoming radiation. On the other hand, the closely-packed wires of the meander may interact, e.g., by exchanging heat. Thermal effects on the current-voltage characteristics of the meander have not been investigated previously.

In this article, we address some of these issues by investigating the current-voltage characteristics of specially designed structures. In particular, by comparing the current-voltage (I - V) curves of meanders with very different filling factors, we evidence the role of thermal coupling between adjacent stripes in closely packed meanders. Moreover, by fabricating meanders where each wire is separately con-

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tacted, we measure the critical current distributions for the different wires and directly probe the linewidth homogeneity. These results provide physical insight into the working principle of meander-type SSPDs.

II. DEVICE FABRICATION

The material used for our SSPDs is an ultrathin film (thickness=10 nm) of NbN deposited by dc magnetron sputtering on top of a $10 \times 10 \text{ mm}^2$ MgO $\langle 100 \rangle$ substrate heated up at 400 °C. The sputtering process takes place in a gas mixture of Ar and N₂; the total pressure is $P_{\text{tot}}=3.4 \text{ mTorr}$ and the ratio between the nitrogen and the total pressure is 33%. The film obtained has a superficial roughness of 1.4 Å (rms) and a critical temperature T_c of 11.5 K.

The nanolithography step to fabricate SSPD detectors has been already described in Ref. 10. Here we recall the main steps of the process. Our electron beam lithography (EBL) system is equipped with a field emission gun and electrons accelerated at high voltage (100 kV). A two step process is used to fabricate the devices. For the first step a PMMA (Polymethyl Methacrylate, positive tone) electronic resist is spun on top of the NbN film and then exposed by EBL direct writing and developed. A 60 nm Ti/Au film is then e-gun deposited and lifted off to define the pads of the SSPDs and the markers needed to align the next lithography. The second EBL step directly writes the meander structure on the HSQ (hydrogen silsesquioxane, negative tone) electronic resist. A reactive ion etching (RIE), based on a CHF₃/SF₆ gas mixture, is used to transfer the pattern obtained onto the NbN film, removing all the unwanted material (not covered by the HSQ). Patterns and exposure doses have been accurately optimized.

The standard device is a $10 \times 10 \mu\text{m}^2$ area meander-type SSPD with a filling factor¹⁰ (the ratio of the area occupied by the superconducting meander to the device nominal area) up to 0.4. The width of the superconductive strips ranges from 50 to 200 nm. A 3×3 matrix of chips is realized on top of the MgO substrate. Several layouts with linewidths ranging from 50 to 200 nm, have been fabricated in order to get a characterization of the linewidth uniformity.

III. ELECTRICAL CHARACTERIZATION

As pointed out in the Introduction, one of the most important requirements of a SSPD is the spatial uniformity of the critical current along the whole length of the meander. A small constriction in the width can affect considerably the critical current of a stripe, without changing too much its normal resistance and hence the total resistance of the meander. For diagnostic purposes then, it is better to characterize the critical current than the resistances of the single parts of a meander. SSPDs designed to allow the electrical access to each stripe of the meander, as shown in Fig. 1 and schematically in the inset of Fig. 2, have been fabricated specifically for analyzing the distribution of the critical current in the various stripes of the meander.

FIG. 1. SEM micrographs of type A (a) and type B (b) SSPDs. The devices consist of five stripes, 100 nm wide and 10 μm long. All five stripes are electrically connected to external pads. The spacing between two adjacent lines is (a) 150 nm and (b) 1.5 μm . The other “dummy” stripes visible in (a) have been added to improve the dose uniformity over the whole device area.

A. *I-V* characteristics

The two SSPDs showed in Figs. 1(a) and 1(b), called structures A and B, respectively, have been electrically characterized. Both of them have 100 nm wide stripes but the stripe spacing is 150 nm in structure A and 1.5 μm , i.e., ten times larger, in structure B. The two meanders have been made of five stripes, each electrically connected to pads, with total normal resistance $R_n=132$ and 134 k Ω , respectively. By comparison, a standard SSPD with 41 stripes has a resistance of about 1.5–2 M Ω . Both *I-V* characteristics and switching current distributions have been acquired at 4.2 K in a rf shielded environment with all connection leads heavily filtered, because the noise can reduce considerably the critical current of a superconducting wire. To acquire the *I-V* characteristics of the SSPD we use a standard 10 V voltage generator in series with a $R_s=15 \text{ k}\Omega$ resistance and a PC-controlled acquisition board. The current that is flowing in the circuit is obtained by measuring the voltage drop across R_s by means of a low-noise voltage amplifier (PAR113) and the voltage is directly measured from the SSPD leads. The schematic view of the contacts is shown in the inset of Fig. 2(a).

Figures 2(a) and 2(b) shows the *I-V* characteristics of structures A and B, respectively, as measured by using L and R leads. Both structures have been fabricated on the same substrate. As it can be seen from the *I-V* characteristics,

FIG. 2. I - V curves measured at 4.2 K of a (a) type A and a (b) type B SSPD, obtained measuring the voltage drop using the contacts L and R. The schematic view of the SSPD wiring is showed in the inset.

when the meander is in the superconducting state the circuit is effectively current biased but as soon as the first stripe of the SSPD becomes normal (with a resistance of about 25 k Ω) the resistance of the meander becomes suddenly larger than R_s and the current drops. Each time a new stripe of the SSPD becomes normal, the current drops and it is possible to follow each different branch of the I - V curve, avoiding the simultaneous transition of the whole structure, this because at both ends of each stripe the linewidth is much larger, strongly increasing the local critical current allowing only the transition of each stripe at once. As shown in Fig. 2(b) by increasing the bias current from the critical current A, the I - V characteristics follow the letters in alphabetic order up to K through all the single branches B-C, D-E, F-G, H-I, and J-K. When the current starts to decrease, the characteristics follow a different path, from K to L, down to the supercurrent region. The hysterical behavior of the I - V curves is caused by the power dissipated in the meander while it is in the resistive regime.¹¹ When the current has followed all the resistive branches of the I - V 's, the power dissipated is high enough to keep the meander in its normal state even if the current is decreased because the local temperature is higher than the transition temperature. In this con-

FIG. 3. Typical I - V curve, measured at 4.2 K, of a single wire of the meander, 100 nm wide, and 10 μm long. The superconducting region is the zero voltage branch of the characteristics while the horizontal branch is the hot-spot plateau.

dition [K-L part of the characteristics of Fig. 2(b)] the current must be reduced to a value lower than the other branches to allow again the normal to superconducting transition. From Fig. 2(b) the first switching from the superconducting to the normal state [A of Fig. 2(b)] is always the one with the higher-critical current and all the other transitions take place at lower currents. Again to explain this behavior we have to invoke heating effects, because the critical current strongly depends on the temperature.

Heating effects can also explain the differences between the I - V characteristics of the two different types of meander. In a type B meander the stripes are 1.5 μm apart (while the width is the same of device A), so we expect a lower-thermal coupling between the stripes in the normal state and the others still in the superconducting state, less affecting their critical currents. This behavior is clearly shown comparing the I - V curve of Figs. 2(a) and 2(b): the first transition is the one with the largest critical current and all the other transitions take place at a lower current, but in case of type B, because of a larger thermal decoupling between stripes, this effect is lower.

B. Hot-spot plateau

Figures 3 and 4(b) show typical I - V characteristics of 10 μm long, 100 nm wide superconducting single stripe. When the device is voltage biased (Fig. 3), a transition occurs from the superconducting state (zero voltage branch of the I - V characteristics) to a current plateau called hot-spot plateau.¹¹ The current of this plateau (about 6 μA , in this case) generates by joule effect enough heat to sustain a normal spot balancing the heat diffusion out of this region. Increasing the voltage bias, the length of the normal region increases: As soon as the whole wire becomes normal, the I - V curve starts to follow a normal ohmic behavior. At this point the value of the resistance is a constant equal to the normal nanowire resistance.

FIG. 4. (Color online) (a) Scheme of the escape measurement experimental setup. (b) In the I - V curve of a single stripe of a meander the vertical dashed line shows the threshold voltage used for the voltage comparator. The horizontal dotted line shows the transition to the voltage state that takes place at the critical current in the case of current bias.

The hot-spot plateau characterization is important because it is connected to the working regime of the SSPD. The correct current bias point for single-photon detection is in the zero voltage state, slightly lower than the critical current. With this bias, when the transition takes place (due to the adsorption of a single photon), the device follows a properly designed load line and reaches a metastable region (and not the stable hot-spot plateau) generating a voltage drop.¹² This pulse is proportional to the difference between bias current and plateau current multiplied by the transmission line resistance (about $50\ \Omega$), say about $1\ \text{mV}$. The metastable region is that between the superconducting branch and the beginning of the hot-spot plateau. An accurate analysis of the critical current, of the hot-spot level and of the metastable region is necessary to correctly bias the SSPD.

C. Current switching distributions

To study in detail the homogeneity properties of each part of the meander we have measured the critical current of each wire not only by its I - V characteristics but also by using an escape-current-analysis technique. This technique is frequently used to study Josephson junctions, superconducting quantum interference devices (SQUIDs) and in general all phenomena correlated with an escape over a potential barrier.¹³ Here we use this technique in order to achieve a high-precision measurement of the critical current of each

FIG. 5. (Color online) Current switching distributions of the five stripes of types (a) A and (b) B SSPDs, measured at $4.2\ \text{K}$.

stripe of the meander. The schematic view of the experimental set up is shown in Fig. 4(a). The meander is current biased and the voltage across a single wire is sent to a voltage comparator. The voltage threshold value of the comparator [see dashed line in Fig. 4(b)] is set very close to the superconducting branch: in this way as soon as the transition takes place and the voltage starts to increase, the comparator sends a TTL (Transistor-Transistor Logic) pulse toward the acquisition board that acquires the current that is circulating in the nanowire at that time. As shown in Fig. 5, producing several times a switching event, a plot of the number of these switching events as a function of the current is obtained for each stripe of the meander, since each stripe was electrically contacted. From this analysis we can compare the critical current uniformity of a type A SSPD [Fig. 5(a)], with filling factor 0.4 and that of a type B SSPD [Fig. 5(b)], with filling factor 0.06. The critical current is about $20\ \mu\text{A}$ and is smaller than the critical current measured in Ref. 14 for similar devices, this because of a poorer quality of our NbN film. The results obtained show that in this particular case the critical current uniformity is about the same, 6% and 8.5% for types A and B, respectively. These values indicate a good control of the linewidth uniformity even when the filling factor is increased by a factor of 10. From the lithographic point of view, we would expect that the linewidth control can

be spoiled because of the local electron overdose due to the nearby exposed patterns: This proximity effect becomes more and more important when spacing between stripes decreases.⁹ The fact that the uniformity is quite similar in types A and B is an encouraging result and we think is related to the high-acceleration voltage (100 kV) of the electrons in our lithography system that allowed us to spread the backscattered electrons in a larger area decreasing; at the same time, the amplitude of the local spurious effect due to electron overdosing.

IV. CONCLUSION

In this article, the low-temperature characterization of the critical current of each part of the meander has been used to check the fabrication parameters and enhance reproducibility and yield. The hot-spot plateau has been used to test the quality of the device and to find the optimal bias parameters. The comparison of meanders with different filling factors shows that heating effects are important in explaining the full I - V characteristics of the devices. Moreover, we have shown that the study of the current switching distributions of the stripes of the meander is a powerful tool to investigate fabrication process reliability.

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