Enhance of the superconducting properties of the NbN/Au bilayer bridges

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Abstract. We experimentally demonstrate strong temperature dependence of the critical current of the superconducting 600-nm-wide and 5-μm-long bridge made of NbN/Au bilayer. The result is achieved due to the proximity effect realized between the highly disordered superconducting NbN layer and low resistive normal-metal Au layer.

1. Introduction
The operation of the Superconducting Single-Photon Detector (SSPD) \cite{1} is based on the transition of a small portion of the superconducting strip of niobium nitride (NbN) to the resistive state upon photon absorption \cite{2}. The strip is biased by the current, so the transition of its part to the resistive state is accompanied by a voltage pulse that can be detected. For a long time, it was thought that the detector would operate in single-photon mode if the width of the superconducting strip was in the range of 100 nm (which is comparable with the size of hot-spot produced by the photon).

Single photon detection by superconducting NbN strips of micron width \cite{3} demonstrate that in a practical single-photon detector made of several-micron-wide NbN strip the critical current must be close to Ginsburg-Landau depairing current. To achieve this, the superconducting strip must be of high homogeneity with the minimum of geometric constrictions. This goal is a technological challenge, as superconductor with high normal state resistance has a spatially fluctuating superconducting energy gap and the critical current in it is usually determined by a weak point. As a result, the measured critical current is much lower than the depairing current.

A promising approach can be a usage of a bilayer consisting of highly disordered (with high normal state resistivity) superconductor (S) and a good (low resistive) normal metal (N) films. An increase of critical current was theoretically predicted and experimentally demonstrated in NbN/Ag and NbN/Al bilayers \cite{4}. The authors explain the increase of the critical current in the SN layer compared to a single S-layer by the fact that injected supercurrent is redistributed in such a way that the largest part of the current flows via the N-film without dissipation due to proximity effect. Besides, their results demonstrate that proximity induced superconductivity in N-film is weakly sensitive to local inhomogeneities of the superconductor, therefore there are no requirements for high quality of the superconducting film.

2. Experimental results and methods
In this work, several batches of two-layer structures are made as bridges (straight strips) of different widths, with the ratio of the resistivities of the superconductor and the normal metal approximately equal to 100, as suggested in reference \cite{4}. In the manufacture of the films, a single-side-polished sapphire substrate (Al\textsubscript{2}O\textsubscript{3}) is chosen. Niobium nitride (NbN) as a superconductor and gold (Au) as a normal metal were chosen as bilayer materials.
The NbN and Au films are deposited by DC reactive magnetron sputtering. The NbN film is produced by sputtering in argon and nitrogen atmosphere, while Au film is deposited in argon only. To obtain films with different ratios of sheet resistivities, the film thickness is controlled the deposition time. The thickness of a film is estimated by the deposition rate (determined in the calibration process of thick film deposition) and deposition time.

The film sheet resistance at $T = 300K$, $R_s(300)$, is measured by a four-point-in-line probe technique using a commercial wafer probe. The magnetron sputtering of bilayer films is performed on two pieces of wafer simultaneously. On one of them, the sheet resistance of Au is measured. The other one is subjected to chemical etching of Au, and then the sheet resistance of NbN is measured. For patterning we selected the film with the ratio of resistivities equal to 80 (among all fabricated films it is the closest to 100, our target value). The samples are made in the form of straight strips, as in figure 1(b). The width of the strips varies from 100 nm to several microns, and the length from several microns to a couple of tens of microns.

Next, the surface of the selected bilayer film is scanned using an atomic force microscope (AFM), and the resulting image is shown in figure 1(a). The granular structure of the surface of gold is clearly visible in the image. In addition to this scan, a photograph of the sensitive area of the structure is taken using an electron microscope figure 1(b). In this case, it is a bridge 600 nm wide and 5 microns long. In addition, the granular surface of gold is also traced here.

The thickness of the superconducting and normal layers is about 1.6$\xi$ and 3.8$\xi$ (coherence length $\sim 6.5$ nm), respectively. The sheet resistance of a bilayer is 2 Ohms per square. The sheet resistance of NbN layer is 575 Ohms per square. In accordance with [5], the ends of the bridges are rounded in order to avoid the effect of the current crowding, which can lead to a decrease in the critical current.

The temperature dependences of the bilayer’s resistance are measured to obtain $T_c$. A piece of film, from which gold was previously etched, is also used as a comparison with the bilayer and to monitoring the properties of the superconducting layer. Figure 2(a) shows the temperature dependence of the sheet resistance ($R_s$) normalized to $R_s(20)$, the sheet resistance at 20 K. The blue and red dots correspond to the two-layer and single-layer film, respectively. Two normal-to-superconductor transitions are clearly visible for the bilayer. The transition at lower temperature of 6.25–6.45 K is caused by the proximity effect. The transition in the range of 9–10 K corresponds to the transition of NbN where proximity effect does not exist. It is worth noting that according to the ratio of resistances, approximately 80% of the film exhibit the proximity effect. The temperature transition of the NbN film (red dots) is also observed in the range from 9 to 10 K. In an ideal two-layer structure, the temperature transition would completely fall to the 6.35 K region. In the above case, these 20% of the temperature transition are associated with the inhomogeneity of the two-layer structure, that is, in some places of the film either poor gold contact with the superconductor or the gold is completely absent (in this case, it was shown above the surface of the NbN/Au bilayer granular figure 1).

We selected a bridge 600 nm wide and 5 microns long and performed a series of measurements of its critical current ($I_c$) at different temperatures. Figure 2(b) shows the temperature dependence of the $I_c$ normalized to depairing current ($I_{dep}$) at 0 K. The black solid line is the theoretical curve calculated for the reference NbN film by the Barden formula [6]:

$$I_{dep}(T) = I_{dep}(0) \times \left[1 - \left(\frac{T}{T_c}\right)^2\right]^{3/2},$$

$$I_{dep}(0) = \frac{0.74 + w + \Delta(0)\pi}{e\hbar \gamma(h/\pi)^2} R_s,$$

where $w$ is the width of the sample, $\Delta(0)$ is the superconducting energy gap at zero temperature, $e$ is electron charge, $R_s$ is sheet resistance (575 $\Omega$), $D$ is diffusion coefficient which we take 0.34 cm$^2$/s. The red dots correspond to the to the usual NbN bridge with a width and length that matches the one selected from the bilayer batch. One can observe a similarity with the theoretical curve and a slight subsidence in relation to it. This is due to the fact that in conventional NbN SSPDs the critical current is less than the depairing current. The blue dots correspond to a bilayer NbN/Au bridge of the selected length and width. Note that this dependence is not trivial for a bilayer and, at a temperature $T/T_c=0.6$ a noticeable
increase of $I_c$ is observed with respect to $I_{dep}$. Moreover, at a temperature $T/T_c=0.2$, $I_c$ reaches its climax and exceeds $I_{dep}$ for a single-layer NbN structure by a factor of 3.

**Figure 1.** (a) The AFM image of the NbN/Au film with its granular structure. (b) The SEM image of the sample which is NbN/Au 600-nm-wide and 5-μm-long bridge and the zoomed-in surface of the Au layer.

**Figure 2.** (a) Temperature dependence of the sheet resistance $R_s$ normalized to the sheet resistance at 20K temperature $R_s(20K)$ for NbN/Au bilayer (blue) and reference single NbN layer (red). (b) Temperature dependence of the critical current $I_c$ normalized to the depairing current at 0 K temperature $I_{dep}(0)$ for the NbN/Au bridge (blue), reference NbN film (red) and theoretical dependence $I_{dep}(T)$ (black).

### 3. Conclusion

The fabrication process of bilayer structures is successfully tested. Although the obtained bilayer superconducting structures are not ideal, and two superconducting temperature transitions are observed in which the majority of the transition falls on the bilayer part confirming the presence of the proximity effect, a dramatic increase in critical current with the temperature reduction is observed. Due to induced superconductivity, in bilayer structures, critical current exceeds the depairing current of a single layer by almost three times. The experimental results on are in agreement with the Vodolazov work [4].

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