Optimization of the process of obtaining superconducting bilayer films based on niobium nitride and gold for the manufacture of a superconducting single-photon detector

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Abstract. We have manufactured a number of bilayer structures based on niobium nitride and gold with different deposition parameters for NbN-Au films (Table 1). We measured the characteristics of superconducting niobium nitride films both with the top layer of gold and without gold. On the basis of the measured characteristics of the films, the optimal parameters of the deposition of NbN-Au bilayer films were chosen for the further formation of a superconducting single-photon detector.

1 Introduction

To date, a superconducting single-photon detector are highly efficient detectors and promising for various research areas [3]. They have as wide scientific applications as well as commercial [4]. Optimizing the operation of detectors and improving the efficiency of their detection is an important task. The studies of the detectors allow us to study both the detection mechanisms and make assumptions that will improve and increase the efficiency of detection and improve other characteristics of the detector as a whole.

To implement many practical tasks in the field of superconducting nanotechnology it is necessary to manufacture superconducting films with characteristics that satisfy the conditions of homogeneity while maintaining the necessary superconducting parameters, such as the critical transition temperature \( T_c \), transition width \( \Delta T_c \), surface resistance at room temperature \( R_s \), metallicity coefficient \( K \) and critical current \( I_c \). Optimization of these characteristics is possible changing the parameters of the processes for producing superconducting films [2].

D. Yu. Vodolazov and others, in their work [1], suggest that adding a thin layer of normal metal to a superconductor significantly increases its superconducting properties due to the proximity effect, which will favorably affect the manufacture of two-layer superconducting structures and will increase their detection efficiency.

In our work, we try to verify the validity of the author's assumptions [1]. At the same time, we want to optimize the manufacturing parameters of superconducting structures based on NbN-Au bilayer.

2 Fabrication

We have manufactured ultrathin superconducting bilayer films based on niobium nitride (NbN) and gold (Au) with different thicknesses. The structures were made on two types of substrates: monocrystalline silicon (Si) 500 um thick and sapphire one-sided polishing (Sp) 300 um thick. This fabrication was carried out under different deposition conditions for films (NbN) and (Au) by magnetron reactive sputtering at direct current in stabilization mode using the LEYBOLD HERAEUS Z400 unit (Table 1).

The characteristics of manufactured films such as the critical transition temperature to the superconducting state \( T_c \), the transition width \( \Delta T_c \), surface resistance at room temperature \( R_s \) and the metallicity coefficient \( K \) of films NbN-Au bilayer and films NbN with strained a layer of gold (Au) (Table 1). These measurements will help us in further research and optimization of the
manufacturing parameters of future superconducting structures. Further optimization of ultrathin film production processes will be carried out to achieve the maximum critical current ($I_c$).

To study the characteristics of ultrathin films based on them, structures in the form of meanders consisting of niobium nitride and gold (NbN-Au) bilayer will be made. Ti-Au bilayer plating will be deposited to form contact pads.

### 3 Experimental results and obtained data

Table-1. The parameters of the deposition of superconducting bilayer films (NbN-Au) by magnetron reactive sputtering at direct current in stabilization mode using the LEYBOLD HERAEUS Z400 unit.

| №   | Sub. | Film | $T$,°C | $T$, sec | $R_s$, $\Omega$/sq. | $T_c$,K | $\Delta T_c$,K | K   |
|-----|------|------|--------|----------|---------------------|--------|----------------|-----|
| 2315 | Si   | NbN  | 400    | 7"       | 464                 | 9,94   | 0,35           | 0,76|
| 2317 | Si   | NbN  | 400    | 7"       | 496                 | 9,35   | 0,4            | 0,76|
|      |      | Au   | 200    | 10"      | 9,0-12,0            | 9,5    | 0,33           | 1,14|
| 2320 | Si   | NbN  | 400    | 7"       | 620                 | 7,75   | 0,6            | 0,75|
|      |      | Au   | 200    | 10"      | 11                  | 8,6    | 0,73           | 2,8 |
| 2335 | Sp   | NbN  | 400    | 6"       | 550                 | 8,38   | 0,73           | 0,6 |
|      |      | Au   | 200    | 10"      | 5,8                 | 7,94; 6,9 | 0,4; 0,14  | 1,54|
| 2336 | Sp   | NbN  | Cold   | 6"       | 1050                | 5,34   | 0,68           | 0,66|
|      |      | Au   | 10"    | 7,8      | 5,23; 5 -           | 1,07; 2 - | 0,71; 2 - | 1,16|
| 2337 | Sp   | NbN  | 400    | 6"       | 380                 | -      | -              | 0,92|
|      |      | Au   | 200    | 15"      | 3,4                 | -      | -              | 1,7 |
| 2338 | Sp   | NbN  | 400    | 6"       | 860                 | 6,87   | 0,6            | 0,63|
|      |      | Au   | 200    | 15"      | 2,5                 | 7,18; 6,2 | 1,02; 0,14 | 1,55|
| 2339 | Sp   | NbN  | 400    | 6"       | 454                 | 8,88   | 0,42           | 0,82|
|      |      | Au   | Cold   | 10"      | 6,2                 | 7,82; 7,18 | 0,74; 0,13 | 1,31|

To characterize the fabricated structures, the dependence of the resistance of bilayer structures on temperature was measured. The measurements were carried out at helium temperatures. By the nature of the dependence, the presence (Fig.1 (b)) or the absence (Fig.1 (a)) of the proximity effect for the manufactured bilayer films was determined. Varying the film deposition parameters it is possible to detect the proximity effect for some of the structures that will further allow to produce superconducting single-photon detectors based on bilayer. The proximity effect is observed when sputtering a small thickness of niobium nitride (5nm) and gold (10nm), but it was found that when
sputtering gold in a working chamber heated to 200 °C, defects were formed on the gold (Fig.2 (a)). But for films with a deposited layer of gold without heating the working chamber, a poor morphology was not detected, but there was also no proximity effect (Fig. 2 (b)).

Figure 1. (a, b). a) Dependence of resistance on temperature for NbN-Au films (Sp substrate) without proximity effect; b) Dependence of resistance on temperature for NbN-Au films (Sp substrate) with proximity effect.

Figure 2. (a, b). a) SEM image of the surface area of the NbN-Au film (Sp substrate) with defects; b) SEM image of the surface area of the NbN-Au film (Sp substrate) without defects.

4 Conclusion
A series of bilayer structures based on niobium nitride and gold were fabricated with different deposition parameters for NbN-Au films and the characteristics of superconducting films of niobium nitride with both the top layer of gold and without gold were measured. For some fabricated structures, a proximity effect was discovered. In the future, these structures will be studied in order to experimentally confirm the assumptions of the authors of the article [1]. Also, further optimization of the processes for obtaining ultrathin films will be carried out to achieve the maximum critical current (Ic) and to manufacture of superconducting single-photon detectors based on bilayer.

Acknowledgments
M Davydchenko acknowledge support by the Russian Science Foundation (Of the Agreement No. 17-72-30036 dated 02.08.2017).

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