Integrated cryogenic resistors formed from NbN thin film under ion beam irradiation

B A Gurovich1, B V Goncharov1, M M Dementyeva1, K E Prikhodko1,2, L V Kutuzov1, D A Komarov1 and A G Domantovsky1

1National Research Centre «Kurchatov Institute», 123182 Moscow, Russia
2National Research Nuclear University (MEPhI), 115409 Moscow, Russia
goncharov_bv@nrcki.ru

Abstract. Niobium nitride ultrathin films were synthesized by cathode sputtering technique. The cryogenic resistors built in the superconducting nanowire were formed using the radiation technology developed in National Research Centre "Kurchatov Institute". This technique was based on the transformation of NbN superconducting film to a normal state (at 4.2K) under the composite ion beam irradiation through the resistive mask. The formation of the cryogenic resistors in the broad range of values was demonstrated.

1. Introduction

The traditional "lift-off" method of creation of the resistive elements integrated into the superconducting line from Ti-Au has a number of disadvantages: rather big sizes of elements, a large number of technological operations, and also essential difficulties of such method when forming elements of the nanometre sizes.

In National Research Centre "Kurchatov Institute" the new method of functional nanoelements creation under ion beam irradiation was developed for different applications [1,2].

The essence of a method consists of composite ion beam irradiation of thin NbN films. The irradiation leads to a controlled change in the chemical composition and a modification of the niobium nitride electrical properties. The change in the properties occurs due to the replacement of part of the nitrogen atoms by oxygen atoms. The advantages of using this approach are: a small number of required technological operations and a possibility of formation of small integrated elements (with sizes <100 nm). Moreover, this method allows forming different types of passive functional elements (resistors and capacities) by varying radiation dose, beam composition, and the geometry sizes of irradiated region.

2. Materials and experimental methods

Thin NbN films (5 nm), obtained by cathode sputtering on SiO2 substrates, were used to create the cryogenic resistors. Formation of structures for electrical measurements was performed by electron lithography and plasma-chemical etching [3]. NbN films were modified by the composite ion beam irradiation of H+ and OH+ ions [3,4]. Ions were extracted from RF plasma discharge by applying a square pulse alternating voltage bias to the holder with samples. The value of the negative voltage part of square bias was in the range from 0.1 to 4 keV to get more uniform distribution of oxygen ions to the depth of the film. To minimize the charging effect during irradiation, the electrons were extracted from the plasma discharge. Every high voltage square negative pulse was followed by the low voltage square
positive pulse (+100 V). The typical frequency of high voltage bias was about 100 kHz. The ratio of the concentration of OH ions to protons in the supplied gas mixture was controlled by measuring the partial pressures of the components (water vapor and hydrogen, respectively), and in our case it was $C = 1.2 \times 10^{-3}$ [2,3]. Composite irradiation damage rate (for nitrogen) was calculated by means of the SRIM [5], and in our case was $2.25 \times 10^{-2}$ dpa/s.

The samples of “micro-bridge” type, obtained by a photolithography method with metal contacts, were used to study a dose dependence of sheet resistance at room temperature and at a temperature of liquid helium. These samples were used for analysis of the temperature dependences of electrical resistance. The geometry sizes of “micro-bridges” were 20x20 $\mu$m$^2$ (Fig. 1).

Measurements of temperature dependences of resistance of the irradiated samples were performed in a temperature interval from 4.2 to 300 K at direct measuring current 100 nA.

We have created cryogenic passive nanoelements (resistors) using thin (5 nm) superconducting films of NbN. Normal state of the film for forming cryogenic resistors was created due to modification of NbN atomic composition under composite ion beam irradiation. Irradiated elements showed resistive properties at working liquid helium temperature (4.2 K) due to transition of an initial superconducting NbN film to a new state, which was characterized by metallic conductivity.

The irradiation conditions to modify the superconducting NbN to metallic NbNO were found in Ref. [6]. The analysis of the ion irradiation dose dependencies [6] (Fig. 2) showed that at radiation doses <1.8 d.p.a., the material kept its superconducting properties at temperatures over 4.2 K, and at doses higher than 8 d.p.a., electrical properties began approaching dielectric ones. Thus, the optimum range of doses for a composite ion beam irradiation was about 1.8-8 d.p.a. on nitrogen. Using the data on dose dependences of films [6] of NbN irradiated with the composite ion beam irradiation, we formed the resistive elements (resistors) integrated into the superconducting nanowire. Advantages of this approach were: a possibility to form cryogenic resistors with the broad range of values (by varying only 2 parameters: a dose of radiation and geometry of the irradiated area), and a possibility to produce

![Figure 1](image1.png)

**Figure 1.** Scheme of the functional nanoelement – “resistor” (top view): (a) the scheme of the chip with macroscopic electric contacts; (b) the scheme of a functional nanoelement.

![Figure 2](image2.png)

**Figure 2.** Temperature dependences of samples’ resistance after composite ion beam irradiation to various doses of radiation (a) dependence of $R_{300K}$ and $R_{4.2K}$ on a radiation dose (b) [6].
integrated resistors for active devices (the cryogenic switches, SNSPD, PNDs, etc.). Resistive element can be integrated into the superconducting current line during one technological process with active devices. The final resistance $R$ will be defined by the expression:

$$R = \frac{R_{sq}L}{W},$$

where $R$ – final value of resistance, $R_{sq}$ – sheet resistance of NbN after modification, $L$ – length, and $W$ – width of irradiated area.

3. Results and discussion

Using the described method and expression (1), resistors of different topology and values were formed. Scanning electron microscopy images of different types of geometry are shown in Figure 3.

To get high resistance values, a large number of squares was required. The topology "meander" (Fig. 3b) was used for this purpose. It was also possible to create different types of connecting elements to the scheme: in series (Fig. 3a) and in parallel (Fig. 3c).

Resistors integrated into the superconductive current line were made using the above mentioned radiation technique. The formed values of resistor were in the range of 2°Ohm-6°MOhm (Fig. 4). The dose of irradiation was ~2°d.p.a. (on nitrogen) and a corresponding sheet resistance was 850 Ohm/sq. Resistors were measured at a temperature of liquid helium by a "four-contact" method. Figure 4 shows that when a dose of irradiation is close to the lower bound of optimum range (1.8-8°d.p.a. on nitrogen), the resistors below 100°Ohms have a wide scatter of values. It was due to the difficulties to form open areas in the mask with a very small ratio of $L/W \approx 0.01$. At the same time, during the irradiation process, the edges of the open mask areas changed their shape and dimensions. As a result, the final irradiated region of the material had a different geometry than the initial one.

The lack of stability of mask shape and size could be overcome by the selection of optimum parameters of radiation, using more stable to composite ion beam irradiation protective mask material, and also by optimization of the topology of elements. Work in these directions will be continued.

Figure 3. The resistors of different topologies created using the SDA method: (a) built in current line by "straight line," (b) "meander," (c) three built-in superconducting current line resistors of different face values.
Figure 4. Dependence of the experimentally formed resistive elements on a number of squares (for a ~2°d.p.a. on nitrogen dose of irradiation and 850°Ohm/sq sheet resistance).

4. Conclusion
The cryogenic resistors, integrated into the superconducting nanowire, of different values (2°Ohm-6°MOhm) were made. It was shown that the composite ion beam irradiation was a new technique to form a nanoscale functional resistive elements in NbN thin films. The main advantage of this approach was that resistors integrated into the superconducting nanowire gave a chance to avoid additional sputtering on “lift-off” technology.

Integrated resistors can be used when forming nano-dimensional cryogenic devices of different functions – for example, cryogenic logical switches or cryogenic counters of single photons and in other cryoelectronic devices.

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