Properties modification of superconducting single-photon detectors under irradiation low-energy ions

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Abstract

In this paper we present the results of using of combined irradiation techniques to superconducting nanomaterials for cryo device's creating for different applications.

It has been shown that low energy particles irradiation of superconducting functional devices such as single-photon detectors and Hot Electron Bolometer resulted to significant improvement of the operation characteristics. The sensitivity of superconducting single photon detectors was improved up to the maximum possible QE ~ 30% at a wavelength of 1.55 microns (as determined by the absorption coefficient of the ultrathin film). The red-limit of superconducting detectors was also increased almost two times and productivity of the samples was increased up to 90%. Noise equivalent power of Hot Electron Bolometer was significantly reduced and the receiver's sensitivity was increased in range 1-3 THz.

In our opinion low energy particle's irradiation of the superconducting single-photon detectors leads to effective reduction in the thickness of the functional ultrathin films without surface discontinuity that in the framework of the "hot spot" model leads to significant increasing of the quantum efficiency. The increasing of the productivity is due to the alignment of the natural inhomogeneity arising during fabrication of detectors. Apparently, the influence of irradiation on the noise equivalent power associated with a qualitative agreement with the sensitive element of bolometer with contacts pads (antenna) by partial metal implantation into superconducting ultrathin film (Andreev contacts).

Keywords: Superconductivity, irradiation technique, cryo devices, single photon detector, HEB

1. MAIN TEXT

It was found that irradiation of the single-photon superconducting NbN-detector (SSPD - Superconducting Single Photon Detector) leads to a change of its critical characteristics (decrease in the critical transition temperature T_c, the critical current I_c) and, in certain doses, to substantial increase in the quantum efficiency (QE) of the detector, and also to an increase in the red limit of the photosensitivity. The results are explained by the alignment distribution of structural inhomogeneities on the sensor detector area. We offer the qualitative model of supercurrent flow in superconducting nanostructures after low-energy ions irradiation process.

The SSPD is the most efficient photon counter, combining high single-photon sensitivity, low dark count, high counting rate and wide spectral range of photosensitivity. Such detectors are widely used in the study of biological objects, in large integrated circuits testing by contactless method PICA (Picosecond imaging circuit analysis) [1], the study of quantum dots emission and fluorescence of atoms and molecules [2]; quantum cryptography [3] and quantum optics [4]. In this paper we used the SSPD with sensitive element which is look like narrow strip of width ~ 100 nm and a total length of about 350 microns in the form of a meander with filling area 7 x 7 um^2 [5]. The detectors have the high performance: the superconducting critical current density of ~ 10 MA/cm^2, the critical temperature of the superconducting state of ~ 12 K. The detectors have operating temperature of 4.2 K.

The absorption principle of single photons in the detector strip leads to the formation of the resistive state and the appearance of a voltage pulse recorded using fast electronics [6]. According to the traditional "hot spot" model [7] after photon absorption in a narrow superconducting canal a local suppression of the order parameter (ξ) takes place in the vicinity of the area generated by excess quasiparticles ("hot spots") generated during the relaxation of the energy transferred by a photon in the electron subsystem. "Hot spot" size and areas with depressed order parameter (ξ) is usually substantially less than the width of the strip so the formation of such area does not cause resistivity. However, in the strip cross-section, in which there was a suppression of the order parameter (ξ), supercurrent redistributed in width and is gradually being replaced in the area, where the order parameter is not yet suppressed. The current density in the superconducting area increases and if it exceeds a critical value the resistance will take place in full cross sectional.

It is important to note that while the geometrical parameters and superconductor sensitive detector element (width of the strip surface resistivity (R_{sq}), critical temperature (T_c) and critical current (I_c)) show a good reproducibility and a small spread in the batch structures fabricated on single substrate. The probability of the photoresponse occurrence for the single photon absorption behaves randomly. According to accumulated statistics of structures parameters (total samples ~ 1000) was found to lack any correlation between the probability of occurrence of the photoresponse and the kinetic parameters of the films. The number of structures that demonstrate a high probability of the photoresponse for single photon, is sufficiently small. Thus, the structure share with the probability of occurrence of the photoresponse at a wavelength 1.26 microns is greater than 5%, is 5% from the total number of structures, and the proportion of structures with a probability of more than 25% - less than 1%. These data suggest that the dependence of the photoresponse probability at the absorption of a single photon of I_c, T_c, and R_{sq} is random.

The lack of correlation between the photoresponse probability and detector parameters suggests that the probability of such photoresponse in the structures can be determined by inhomogeneities affecting on the superconducting current flow along the strip due to inhomogeneities arising as a result of the fabrication process. The explanation of the probability of appearance of photoresponse by such irregularities was suggested previously [8].

It was assumed that the source of the inhomogeneities are fluctuations of the width of the structure along its length (direction of the bias current). However, as it turned out from the results of studies by atomic force microscopy, the constancy of the width of the strip is not worse than ~ 3 nm along its total length, which is much smaller than the estimate the size of the "hot spot." Therefore, the width of the structures inhomogeneity can not be accepted as a possible explanation of very high probability of the observed dispersion photon photoresponse. At the same time, lattice defects, disorders stoichiometry subnanometer defects edge strips etc. are uncontrolled parameters. All of these sources of inhomogeneity can lead to a change in the supercurrent density depending on the coordinates. The influence of such inhomogeneities in the framework of the model of "hot spot" can be described by introducing the dependence of I_c and T_c on the "current-carrying section» (S_o), varying along the strip. Neglecting for simplicity discuss irregularities in thickness (d), for the investigated structures with widths and lengths well above their thickness, we can confine ourselves to the two-dimensional picture of the overcurrent and, accordingly, having the local values of the superconductor gap between maximum and minimum S_o.

In this case, I_c and T_c of structure are determined in the areas with the lowest I_c and the smallest S_o, while the probability of single-photon response of whole structure is determined by the global distribution statistic of I_c along total length of the strip and to a first approximation, is determined by the ratio of the film area with large and small S_o.

Create free from inhomogeneities in structure, which would have the maximum quantum efficiency is hardly possible due to the small size of the strip and a very large length of the structure. A fabrication of ultrathin film with thickness d ~ 4-5 nm without discontinuities on a scale commensurate with the size of the studied nanostructures practically is impossible by any of the existing methods. Therefore, to solve problems of the detectors fabrication with reproducible quantum efficiency we decided to use the alternative approach. This method is to use a process step that allows to draw a veil over the initial uncontrolled inhomogeneities by big quantity of other controlled inhomogeneities distributed in structure as evenly as possible with the highest possible density.

As such a process step we propose a method of selectively changing the atomic composition under low energy irradiation ion beams, which has already demonstrated its ability to manage physical properties of metals and semiconductors [9, 10].

For small interaction of protons (or different ions) with the substance introduced by inhomogeneities in the crystal lattice, are distributed with equal probability by volume. The probability of distances between R_c violations subject to the Poisson distribution:

$W(R) = (R/R_c)\ e^{(R/R_c)^3}$

,where R_c=0.62 $N^{1/3}$, and N is the number of lattice violations which matches as homogeneous as possible distribution of defects.

We have studied dependences R_{sq}, T_c, I_c and QE of detectors versus dose proton irradiation. Characteristics of the samples - R_{sq}, T_c, I_c and QE were measured before and after proton irradiation with energies in the range of 1-3 keV with a certain dose, which ranged from 0.01 up to 2.25 d.p.a. (displacement per atom).

Measuring the quantum efficiency was carried out at a temperature of 4.2 K in the spectral range from 0.45 to 1.55 um (coupled with the core of the SMF-Single Mode Fiber) on structures with different QE, T_c, I_c and R_{sq}. In this case, all the samples before irradiation had a quantum efficiency of less than 1% (at a wavelength of 1.26 microns, and at operating temperature 4.2 K).

Electric bias was produced by low-noise stabilized current source. Voltage pulses (photoresponce) of detector amplified cascaded low-noise amplifiers and fixed by electronic counter. The total quantity of studied detectors was about ~ 100 pieces.

It was established that after proton irradiation detectors properties change as follows:

- SSPD resistance in the normal state is increased 2 - 3 times;
- T_c is reduced from 11 - 12 K up to 5 - 6 K (see Fig. 1), I_c is reduced to 5 times (see. Fig. 2a) compared with the initial value;
- QE at a given wavelength increases, sometimes to the theoretically expected maximum of 30% (which corresponds to absorption of the film at this thickness) (see. Fig. 2a), and is accompanied by photosensitivity range extension towards longer wavelengths;
  - The dark count per second of the detectors is not increases (see. Fig. 2b);
- The variation of I_c in batch is significantly reduced, providing a productivity to a level of 85-90%.

The Figure 1 shows the temperature dependences of the detector resistivity before and after proton irradiation. These dependences show that the resistance of detectors increases monotonically and T_c and I_c decrease monotonically with increasing of irradiation dose. In case of using high irradiation doses (greater than 2.5 d.p.a.) the superconducting properties are missing or the temperature of the superconducting transition becomes subhelium. The figure 2b shows a field curves QE(I_b) of sample which was repeatedly subjected to irradiation that led to various irradiation total dose. The QE and I_c was not changed at low doses (smaller that 0.05 d.p.a.).

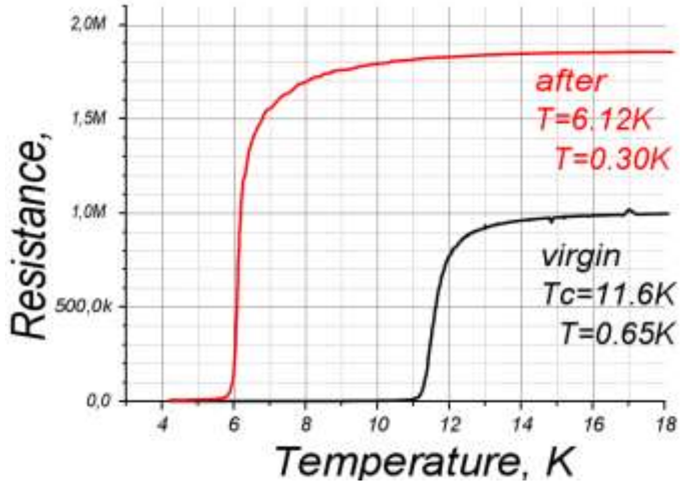
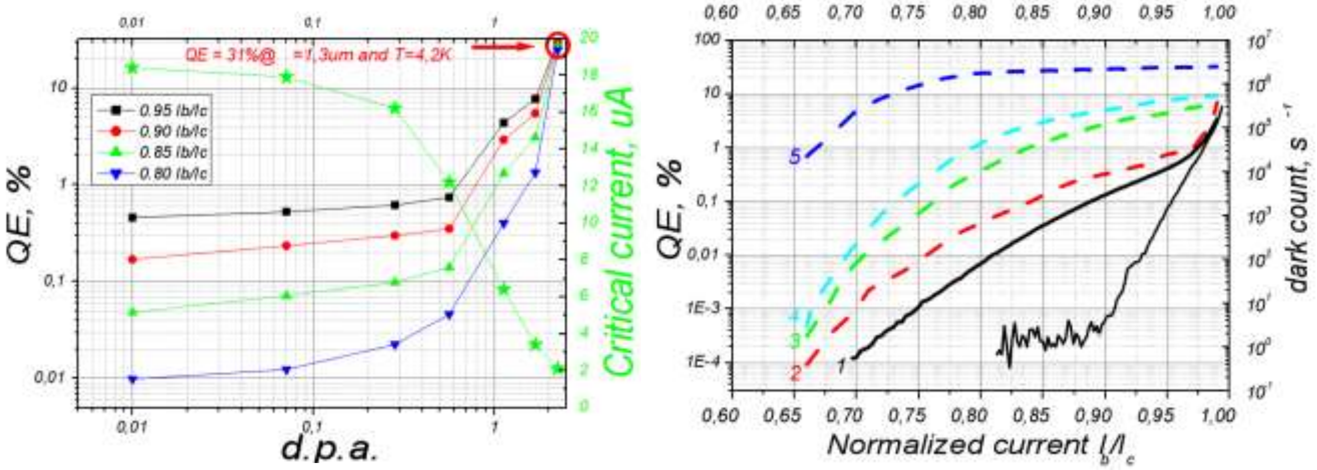


Fig. 1. Dependence of SSPD resistance versus temperature before and after proton irradiation (at optimal dose). The black curve – virgin (before irradiation) and the red curve – after irradiation (d.p.a. is 2.1)

At a certain dose of irradiation (below the "optimal dose") the maximum possible value of QE is 30% (see. Fig. 2a). Dependence QE(I_b) having its characteristic plateau at high bias currents (the curve 5 in figure 2b). This means, the detection efficiency along sensitivity element of SSPD is close to 1 [11]. The measurement of QE became technically impossible at doses greater than (to close 2.1 d.p.a.), as the operating current decreases to less than 1 uA and the detector response was lost in the noise amplifiers.

As it was shown in [10] the main mechanism responsible for materials properties modification under 1-3 keV ion irradiation was atomic displacement due to the elastic collisions of ions with light oxygen (O) and nitrogen (N) atoms with maximum transfer energy above the displacement threshold Ed. During this process, light atoms were displaced to the interstitial positions that was lead to the crystal lattice disorder and sometime amorphous phase formation. At the significant dose of irradiation the light atoms were removed from the film due to the selective removal of atoms (SRA) process [10].



a

b

Fig. 2. a) Dependence of QE and critical current versus displacement per atom (d.p.a.). **b)** Dependence of QE and dark count rate versus normalized current. The curves 1 (solid black), 2 (dash red), 3 (dash green), 4 (dash cyan), 5 (dash blue) correspond to doses 0, 0.6, 1.14, 1.7, 2.25 d.p.a., respectively

Another key factor responsible for the result of ion beam thin film modification was the chemical activity of the target atoms. For instance, if the heavy atoms (Nb) displayed high chemical activity to the oxygen atoms, the removal of oxygen atoms from the film was suppressed because of the high probability of reuptake process. As a result, during ion beam irradiation the part of niobium oxide phase was increased and the part of niobium nitride phase was decreased that influenced, together with above mentioned disordering, to the thin films superconductive properties.

The distribution morphology of the niobium oxide film in the original nitride after irradiation requires further study. Partly removal of a portion of the nitrogen atoms film amorphization and replacement of nitrogen atoms (atomic and in connection with niobium) on oxygen atoms should lead to decrease in the conductivity of films and to a homogeneous or a weakening of superconducting correlations in the film or the formation of a large number of individual centers in which the superconductivity is suppressed. This is possible due to the formation of crystallites non-superconducting phase of lower oxides (NbO, NbO_2) with dimensions of the order of the coherence length in the film NbN.

The observed effects (increasing quantum efficiency and range of photosensitivity to longer wavelengths) are explained in the framework of a hot spot model.

The current density (j) in the "hot spot" model is the microscopic size which directly determines the detection efficiency of photons in the detector. When this occurs the current density j in the given area strip after redistribution of the current due to the formation of a normal region with a suppressed gap (hot spot), is:

$j = j_b$ (w/d), where

j_b = Ib/w- displacement current density at a given place in the absence of stripes spots, d is diameter of the spot and depending on the coordinate along the strip, w is the width of the sense, in which supercurrent flows.

Probability of occurrence of the response to the absorbed photon increases with increasing j, and equal to 1 at $j = j_c$ (j_c - the critical current density, which can also depend on the coordinates). Therefore, the probability of detection of each site, and the quantum efficiency of the detector as a whole increases with the ratio d/w. In the case of a uniform reduction of the order of the photon energy at a fixed ratio of d/w is increased by increasing the spot size d. The decrease in average current-carrying strip width w due to the suppression of the order parameter in some centers also implies increase in the ratio d/w and a corresponding increase in the quantum efficiency.

The expanding of the spectral range is obtained in both mechanisms (the same as the average for the sample the ratio d/w is achieved at lower photon energies). It suffices to note to explain the decrease in the spread QE that for large values of d/w ratio significant proportion of the sample area has a unit probability of response to the absorbed photon, which is why QE saturates and ceases to depend on the statistics of the distribution d/w along the length of the sample.

Finally, the same considerations explain the appearance of a "plateau" in the dependence of the quantum efficiency on the wavelength and on the bias current of the detector.

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