NbN HEB for THz Radiation: Technological Issues and Proximity Effect

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Abstract*— Superconducting phonon-cooled hot-electron bolometer (HEB) detectors are complex multi-layer devices consisting of an ultra-thin superconducting film (mostly NbN) and a thick normal metal layer. We present results on the development of NbN ultra-thin film technology and the systematic study of superconducting and transport properties of NbN bridge-structures with different thickness (4 – 10 nm) and width (0.1 – 10 μm). The NbN films are deposited onto heated Si substrate by magnetron sputtering of Nb target in the reactive gas mixture of argon and nitrogen. A critical temperature of about 9.5 K is reached for NbN films with a thickness between 5 and 6 nm. Twofold increase of the film thickness increases the critical temperature to 12 K. Reducing the bridge width below 0.5 μm leads to a decrease in its critical temperature that is similar to the effect of the film thickness. The model of intrinsic proximity effect in ultra-thin films explains fairly well the degradation of superconductivity in NbN bridges with the decrease of either film thickness or bridge width. Moreover, the proximity effect theory agrees well with experimental data on the critical temperature variations in NbN/Au bi-layers with different thickness of the Au layer. We have shown that an 18 nm thick buffer layer of NbN under much thicker Au layer is sufficient to ensure a bi-layer critical temperature of 8.5 K that is close to the critical temperature of 5 nm thick HEB devices. Presented results demonstrate challenges of further developing HEB detectors for THz spectral range.

I. Introduction

The hot-electron bolometer detectors and mixers are widely used devices with low noise level and high detection speed that make them suitable for operation in the THz spectral range. In spite of the more than two decades development history their performance still has to be improved to meet requirements of particular applications in astronomy, spectroscopy, imaging and security. Further optimization of these complex multi-layer devices can only be done with the deep understanding of properties of each layer, their mutual influence, and interrelation between layer properties and technology. Typical phonon cooled HEB device consist of at least four layers (from bottom to top):

- Substrate is usually made of Si owing to its transparency for THz radiation, low price, well developed micro-machining technique and prospective ease of integration
- Ultra-thin NbN film, which is a key element of the device, should have a thickness equal or less than 5 nm and should therefore be deposited onto the heated substrate
- Buffer layer of some getter material is required to improve electrical and mechanical contact between NbN film and a planar THz antenna
- A few hundred nanometer thick Au layer from which the antenna is made.

In this multi-layer structure we have to consider three interfaces, each of them is important to assure proper operation of the HEB device. Transparency of the interface between Si substrate and NbN film for phonons is the major factor determining the efficiency of device cooling and hence the speed of the HEB detector or the intermediate frequency (IF) bandwidth of the HEB mixer [1]. The quality of the substrate surface substantially contributes to the interface transparency and also determines the superconducting and crystalline properties of the ultra-thin NbN film [2].

Gold layer is usually deposited *ex-situ* on top of the NbN film. With this technique one can not avoid contamination of the surface of the NbN film, which results in worsening of both Au adhesion to NbN and the electrical contact between them. Weak adhesion results in mechanical instability and shortens the life time of the device. Worse electrical contact introduces extra resistance in the AC and DC current path from the antenna to the HEB [3]. These problems are partly compensated by deposition of a thin buffer layer from a getter material on top of NbN film *in-situ* with gold layer. Further improvement of electrical quality of this interface can be achieved by *in-situ* pre-cleaning of the surface of the NbN film before deposition of the buffer layer [4]. Reduction of the noise temperature of NbN HEB mixers due to pre-cleaning of the NbN surface has been recently observed.

In spite of *in-situ* deposition, the interface between buffer and gold layers should be taken into consideration in the course of optimizing HEB performance. RF properties of the antenna structure are also dependent on the quality of this interface that makes a significant contribution to the overall performance of the HEB device. Because of the difference between crystalline lattices of the buffer and the gold layer this interface cannot be a priory considered to be ideal with 100% transparency for electrons.

Optimizing multi-layer structure of HEB devices we have also to keep in mind that we put in "good" contact a thick normal-metal layer and an ultra-thin superconducting NbN film with a thickness close to the coherence length in this material. In such proximity system superconductivity in the NbN film under the metal layer will be effectively depressed or even completely destroyed. Similarly, the proximity effect between the HEB and the antenna terminals decreases the superconducting order parameter in the HEB itself [5]. The HEB is a rectangle from ultra-thin NbN film which has the width of several micrometers and the length of a few hundred nanometers defined by the distance between antenna terminals. For proper operation the critical temperature of this rectangle should be at least two times higher than the ambient temperature of the HEB device, which is usually close to 4.2 K. In this longitudinal proximity system a hot-spot has a high probability to appear in the vicinity of normal contacts, where it has less mobility and where both the spot formation and dynamics are almost unpredictable and non-reproducible.

Usually good getter materials like Ti or Cr are used to create a buffer layer for further deposition of gold. Both materials are normal metals at typical operation temperatures of NbN HEB devices, which is about the liquid helium temperature. It has been suggested [4] to use superconducting Nb and NbTiN layers as buffer layers in order to weaken the proximity effect and to support superconductivity in NbN films.

The sensitivity of the bolometer can be enhanced by reducing its volume. This means possible reduction of all three dimensions of the HEB: the thickness of NbN film, the width and the length of the HEB rectangle. This is not only a technological challenge that is a big issue by itself. The dimensions become comparable with characteristic lengths in superconductor (the film thickness is already about the coherence length in NbN film) that might result in different quantum effects in these mesoscopic devices.

In this paper we present results on the systematic study of the three aspects directly affecting the performance of the sophisticated system that is the phonon cooled NbN HEB detector for THz radiation. We shall start with technology and the analysis of superconducting properties of NbN films with different thicknesses deposited on Si substrate. Then we analyze the superconducting transition temperature and the density of the critical current in NbN bridges with different width and thickness. We shall consider the influence of only two dimensions, thickness and width, on superconducting properties of HEB devices. The effect of the bridge length has to be analyzed accounting for the proximity effect between the bridge and the normal-metal contacts that requires knowledge on the transparency of their interface for Cooper pairs and quasiparticles. These problems are out of the scope of the present paper. Finally, we present properties of superconducting/normal metal (NbN/Au) bi-layers with different Au thickness which model the antenna structure of HEB devices. In both cases, for NbN/Au bi-layers and for NbN bridges, analysis will be done using the proximity effect theory.

II. NbN Thin-Film Technology and Characterization

The NbN films were deposited on 10×10 mm^2 two-side polished single-crystalline (100) oriented Si substrates which were fabricated by the floating-zone method. The base pressure in the deposition chamber was created by a turbomolecular pump. It was about 2×10^{-7} mbar at the ambient temperature. To deposit of NbN films the substrates were directly placed on the surface of a heater without any thermo-conducting glue. During deposition the temperature of the heater was kept at 750 °C. The pressure in the chamber rose with the increase of the heater temperature and reached a value of about 10^{-6} mbar. Before deposition a two inch diameter Nb target was cleaned by sputtering the target surface layer in pure Ar atmosphere at a pressure $P_{Ar} \approx 3\times10^{-3}$ mbar. A flow of nitrogen gas was then added resulting in a N_2 partial pressure $P_{N2} \approx 6\times10^{-4}$ mbar. After stabilization of a discharge voltage the shutter was opened to deposit an NbN film onto the substrate with a deposition rate approximately 0.2 nm/sec. We varied deposition times from 18 to 40 s. After cooling the heater down to the ambient temperature, the substrate with the deposited film was taken out of the chamber. The thickness of the films was estimated using ellipsometry and crosschecked by means of the high resolution transmission electron microscopy [2] that was performed on the NbN films deposited under the same nominal conditions.

Right after deposition the temperature dependence of the film resistance $R(T)$ was measured in the temperature range from 4.2 K up to the room temperature by the standard four-probe technique. The films show negative dependence $R(T)$, i.e. an increase of the resistance with the decrease of temperature. At temperatures ≈ 20 - 30 K the resistance reaches the maximum, which is a factor of 1.2 - 1.4 larger than the resistance measured at room temperature. Below the maximum the resistance gradually decreases until the superconducting transition is reached. The width ΔT of the transition, which was defined as the temperature difference between the states with 10% and 90 % of the resistance just above the superconducting transition, varied from ≈ 1 K for thickest films with $d \approx 9$ nm and to ≈ 2 K for thinnest films ($d < 4$ nm). The thickness dependence of the zero resistance critical temperature, which was measured using a Si-diode temperature sensor with an accuracy of ± 0.5 K [6], is shown in Fig. 1. The T_C value increases with the thickness and does not show clear saturation even at largest values of *d*.

The critical temperature of our NbN film on Si is lower than the T_C value ≈ 17 K of bulk samples. Reduction of T_C in thin superconducting films was experimentally observed [7] -[9] and described in terms of the intrinsic proximity effect theory which was first suggested by Cooper [10] and generalized by Fominov and Feigel'man [11]. In the framework of this theory the NbN film is considered as a superconductor (S) sandwiched between

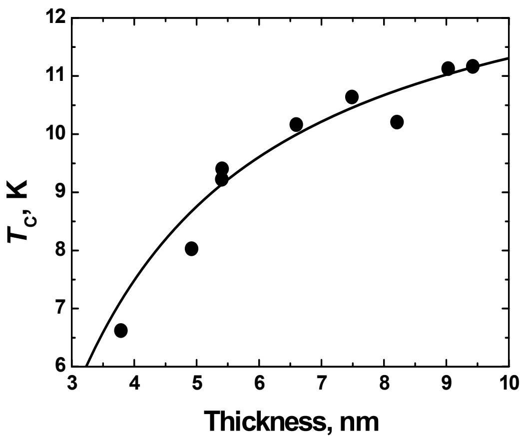

Fig. 1 Dependence of the zero-resistance critical temperature of NbN films on their thickness. The solid line is the best fit according to equation (1).

two normal-metal (N) layers. The superconductivity is destroyed in the surface layer of the film and in the layer near the interface between the film and the substrate. In such three-layer NSN system, the superconductivity of the central part of the film is depressed and the measured T_C of the whole structure is lower than in the superconducting film without normal layers. According to [11] T_C of a NSN structure can be estimated from

$$\ln\frac{T_C^0}{T_C}=\frac{\tau_N}{\tau_S+\tau_N}\left[\psi\left(\frac{1}{2}+\frac{(\tau_S+\tau_N)\hbar}{k_BT_C\tau_S\tau_N}\right)-\psi\left(\frac{1}{2}\right)-\ln\sqrt{1+\left(\frac{\tau_S+\tau_N}{\tau_S\tau_N\omega_D}\right)^2}\right],$$

(1)

where $\psi(x)$ denotes the digamma function, T_C^0 is the critical temperature of a pure superconductor, ω_D is the Debye frequency of the superconducting material, k_B and $\hbar$ are the Boltzmann and Planck constants. The τ_S and τ_N quantities for the NSN three-layer system are

$$\tau_S=\pi\frac{d_S}{V_S}\rho_{\text{int}},\quad \tau_N=2\pi\frac{V_Nd_N}{V_S^2}\rho_{\text{int}}$$

(2)

with $d_{S,N}$, $V_{S,N}$ being the thickness and the Fermi velocity of the S and N layers, correspondingly, and ρ_{int} is the dimensionless resistivity of the SN interface.

Superconductivity in surface and interface layers of the NbN films is destroyed due to formation of niobium monoxide, which is a normal metal above 1.38 K [12]. Following the theoretical approach [10], [11] and assuming that the superconductivity inside the films is of the same strength as in bulk NbN, we estimate for our NbN film the effective thickness d_N of surface and interface layers with destroyed superconductivity. Calculations were made assuming ideal interfaces between superconducting and non-superconducting parts of NbN film, i.e. in the Cooper's limit $\rho_{int}\rightarrow 0$ (the transparency of the interface approaches unity). We obtained $d_N \approx 0.6$ nm using the Debye temperature $\Theta_D = 300$ K, and the critical

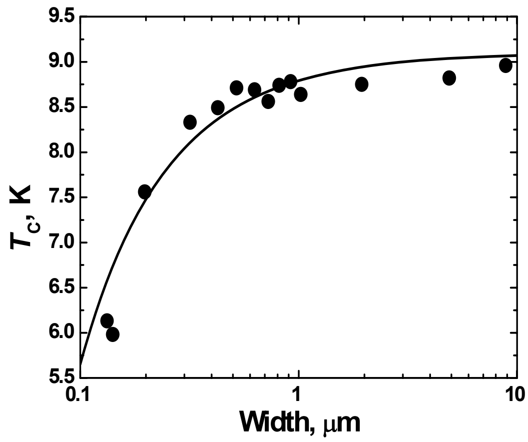

Fig. 2 Dependence of the zero resistance critical temperature of NbN thin-film bridges on their width. The thickness of NbN film is about 5.5 nm. The solid line is the best fit according to equation (1).

temperature of infinitely thick film $T_C^0 = 13.8$ K which provided the best fit of our experimental data (Fig.1) with equation (1). Thus the effective superconducting thickness of our films is about 1.2 nm smaller than the physical/geometrical one. The value of T_C^0 is lower than critical temperature reported for bulk NbN. There are several possible reasons for the reduction of the T_C^0 value. One of them is a deviation of the composition of the deposited material from the optimal one that results in weakening of the superconductivity in the film. Nano-crystallite structure of the deposited NbN films [2] can be also considered as a cause of lower T_C^0. It has been shown in [13], [14] that the critical temperature of NbN films with different thickness (up to several hundreds nanometer) depends on the diameter of grains, which is determined by the deposition conditions. Nevertheless, the T_C^0 value of NbN films studied in this paper is higher than the transition temperature of infinitely thick NbN films, which we have earlier deposited onto substrates kept at room temperature during deposition [15].

III. Single Bridge Structure: Fabrication and Characterization

Typical dimensions of the HEB rectangle are 1 – 2 μm (width) times 0.1 – 0.3 μm (length) that is required to match the impedance of the detector to the impedance of the antenna. Improvement of the detector sensitivity will require further shrinking of all dimensions keeping the value of the normal state resistance constant. An influence of the film thickness on the superconducting transition temperature was analysed in the previous section. Experimental observation of the dependence of T_C on the width of the NbN rectangle has been made on single bridge structures in the four probe configuration. The NbN films were patterned using a combination of electron-beam lithography to form a centre part of a sample and photolithography to form large contact pads. The image created in the photo- or the electron-beam resist was transferred into NbN film using ion milling technique. The width of bridges was varied from about 100 nm up to 10 μm. The actual width of each bridge was measured after patterning by SEM imaging.

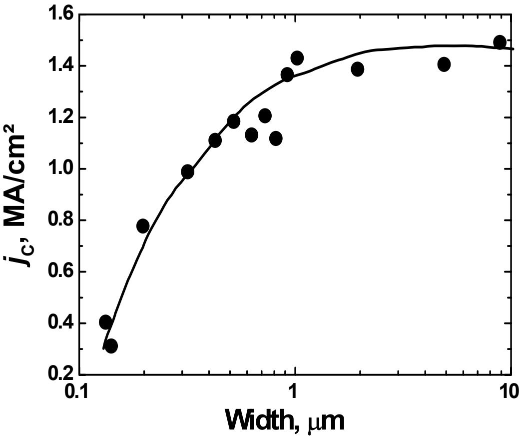

Fig. 3 Dependence of the nominal density of the critical current at $T = 4.2$ K on the bridge width. Bridges were made from the NbN film with a thickness of ≈ 5.5 nm. The solid line is to guide the eye.

The temperature dependencies of the resistance were measured on all bridges. Typical dependence of the zero resistance critical temperature on the width of NbN bridges is shown in Fig. 2. Reduction of the bridge width results in the significant decrease of T_C for bridges with a width smaller than half a micrometer. For wider bridges the T_C value is almost independent on the width. The small variation of T_C in this range might be due to spatial non-homogeneity of the film.

To describe reduction of the transition temperature T_C in narrow bridges, we suggest that the edges of each bridge were mechanically damaged by Ar ions during patterning of the film. The damaged areas oxidised later on after the bridges had been exposed to air. We speculate that these damaged edges became normal. We further consider the bridge as a planar NSN structure and apply to our experimental data on T_C the same approach as we used in order to describe the dependence of the superconducting transition temperature on the film thickness. The results of the fitting of the T_C dependence on the bridge width (W) are shown in Fig. 2 by the solid line. We used the only one fitting parameter W_N (instead of d_N in Eq. 2), which is the effective width of a normal strip running along both edges of the bridge. The value of T_C^0, which has been used for evaluation of $T_C(W)$ by means of equation (1), is equal to the value of T_C on plateau of the $T_C(W)$ dependence. We found $W_N \approx 15$ nm for NbN bridges made from the film with the thickness 5.5 nm.

The reduction of the bridge width and damage of the edges also influence the current carrying ability of the NbN thin film structures. Figure 3 shows the dependence of the nominal value of the critical current density $j_C = I_C(4.2\ \text{K})/(W\,d)$ on the bridge width that was evaluated from the current voltage characteristic measured at $T = 4.2$ K. The critical current value I_C was defined as the current corresponding to the full switching of the structure from the superconducting to the resistive state. The value of $j_C(4.2\ \text{K})$ is almost constant for bridges with a width larger than about 1 μm and decreases by a factor of 4 for the smallest width (≈ 0.12 μm). There are at least two factors resulting in such strong decrease of j_C value. The first one is T_C of the bridge, which decreases with the width (see Fig. 2). The difference in the transition temperature between micrometer wide and 120 nm wide bridges amounts at 3 K. The second reason is a real superconducting width of the bridge, which is smaller than the geometric width measured by SEM. Both factors are not accounted in the estimations of j_C. This has been purposely done in order to get a feeling about directly measured transport properties of NbN bridges, which were fabricated by the above described technology.

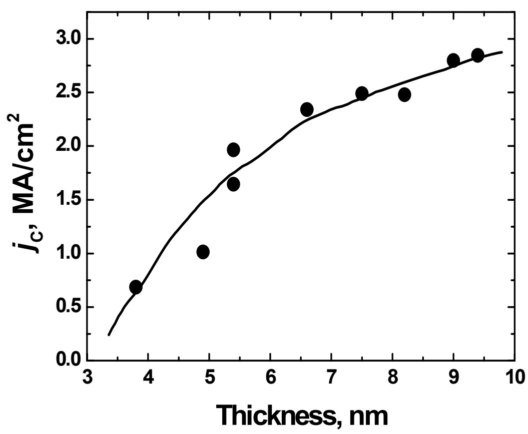

Fig. 4 Dependence of the nominal density of the critical current at 4.2 K on the thickness of the NbN film. The measurements were performed on bridges with a width larger than 1 μm. The solid line is to guide the eye.

The value of the critical current density on the plateau of its dependence on the width, i.e. the critical current density in micrometer wide bridges, was taken as the characteristic j_C value for unpatterned films. With this characteristic value we have found the dependence of the density of the critical current at 4.2 K on the thickness of NbN films deposited on Si substrates. The data are shown in Fig. 4. The j_C value gradually increases with the thickness. The rate of the increase weakens at larger thicknesses similar to the dependence of the critical temperature on the film thickness (see Fig. 1).

IV. Artificial Proximity Effect in NbN/Au Bi-Layer Systems.

Antenna structure for THz HEB mixers is usually made using lift-off technique. This limits the technological freedom via unavoidable *ex-situ* gold deposition at low temperatures that is required in order to avoid overbaking of the resist. Thus the only way to realise good enough mechanical and electrical contact between the gold layer and the contaminated surface of the NbN film is to deposit *in-situ* a buffer layer of any getter material. Usually used Ti and Cr are normal metal at operation temperatures of NbN HEB devices. Therefore, improving electrical contact immediately results in strong depression of superconductivity in underlying areas of the ultra-thin NbN film. Further reduction of RF losses at the interface between the superconductor and the antenna and, consequently, lower noise figure of the mixer can be reached via *in-situ* pre-cleaning of the NbN surface before

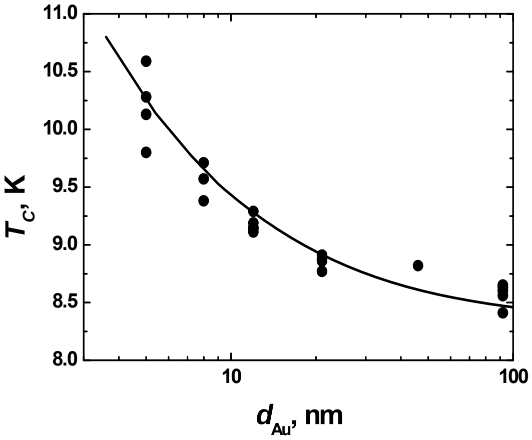

Fig. 5 Dependence of the zero-resistance critical temperature of the NbN/Au bi-layer structure on the thickness of the gold layer. The thickness of NbN film is 18 nm. The solid line is the best fit by means of Eq. (1).

deposition of the antenna [4]. However, the more transparent interface will result in stronger depression of the superconductivity in the NbN film.

To avoid this side effect, a superconducting material can be used as a buffer layer instead of the normal-metal getter. Criteria for choosing such material are high intrinsic critical temperature, low resistivity, good getter properties for small layer thickness and finally the T_C value of the bi-layer (buffer/Au), which should be about the critical temperature of the NbN film used for the device fabrication. It is hard to fulfil simultaneously all requirements since they are contradicting each other. It is well known that superconductors are usually bad metals and higher T_C generally means larger resistivity. If we consider the pair of Nb and NbN (both are reasonable candidates for NbN based HEB) the first material will be the winner as a getter and due to its lower resistivity in comparison to NbN. However, niobium nitride can be a better choice since it has higher T_C value for the same thickness of the buffer layer [15]. Another advantage of the NbN buffer is that it will be deposited onto the same material and will most likely have better superconducting and crystalline properties and make better interface to the underlying NbN film.

The NbN and gold layers were deposited *in-situ* on Si substrate kept at ambient temperature. DC magnetron sputtering was used for deposition of both layers. First Nb was reactively sputtered in argon/nitrogen atmosphere, then the gold film was deposited in pure Ar. Figure 5 shows the dependence of the transition temperature of NbN/Au bi-layers with 18 nm thick NbN layer on the thickness of the gold layer. The superconducting transition temperature of the 18 nm thick NbN film without gold was about 12 K. Subsequent deposition of the gold layer with approximately the same thickness resulted in about 3 K decrease in the T_C value of the bi-layer system. The increase of the thickness of the gold layer up to several hundred nanometers caused further decrease in the bi-layer T_C that levelled off at about 8.5 K and did not depend any more on the thickness of the gold layer. This value of the bi-layer transition temperature is only 0.5 – 1 K less than T_C of 5 to 6 nm thick NbN films which we used in the fabrication of THz HEB mixers [16]. The experimental dependence of the bi-layer T_C on the thickness of the gold layer agrees well with the result of the proximity effect theory [11], which is shown by the solid line in Fig. 5. The best fit was reached for the value of the interface resistivity ρ_{int} = 17 and T_C^0 = 12.8 K.

This T_C^0 value is larger than the transition temperature of bare NbN films with the same thickness. The possible reason can be the difference in the strength of the intrinsic and the artificial proximity effects. Nominally the strength is characterised by the value of ρ_{int}, which is much smaller in the case of the intrinsic proximity effect. In the case of bare NbN films, exposing the film to normal air after deposition contaminates the surface layer and makes it either “normal” or weakly superconducting. The interface between the “normal” surface layer and the superconducting core part of the film is almost ideal with $\rho_{int} \rightarrow 0$, that is demonstrated by very good agreement between experimental results and the theory for $T_C(d)$ dependence of bare NbN film (see Fig. 1). There are two remarkable differences between NbN/Au bi-layers and the intrinsic proximity effect in bare NbN films. One is that the interface transparency between NbN and Au is not perfect due to the difference in material (electron and phonon) properties of NbN and Au. This mismatch reduces mutual influence of the normal metal and the superconducting layer (weaker proximity effect). Another difference is that the surface of NbN layer was *in-situ* passivated by gold and hence was not contaminated/oxidized. The above arguments suggest that the effective transition temperature of a gold covered NbN layer might be larger than T_C of a bare NbN film that has a surface layer with destroyed superconductivity.

Conclusion

Systematic study of three objects forming together a phonon cooled HEB detector for THz frequencies – an ultra-thin NbN film on Si substrate, a narrow bridge made from such film, and a NbN/Au superconducting/normal metal bi-layer - has shown the strong influence of intrinsic and artificial proximity effects on their superconducting and transport properties. The following effects have been found experimentally and explained invoking the theory of the proximity effect. (i) Reduction of the film thickness, which is required to improve sensitivity and to increase speed of HEB detectors, is limited due to suppression of superconductivity in thinner films. A decrease in T_C worsens also the electron transport properties of NbN thin-film structures and hence the performance of the detector. (ii) Reducing the width of the NbN thin-film bridge below approximately 0.5 μm leads to further suppression of T_C. Structural damage of the bridge edges, which occurs in the patterning process, destroys superconductivity in narrow strips along the bridge edges. The NbN bridge can be considered as a superconducting core surrounded by non-superconducting, normal shell. Consequently, superconductivity in the core of the bridge is depressed due to proximity between the core and the normal shell. (iii) Superconducting buffer layer under the antenna structure of HEB detectors has to be thick enough to make the T_C of the entire bi-layer system with 200 - 300 nm thick gold comparable to the transition temperature of the NbN ultra-thin film. We have found that the optimal thickness of the NbN buffer layer deposited at ambient temperature should be about 20 nm which allows one to reach $T_C \approx 9$ K of the NbN/Au bi-layer.

The optimal thickness of the NbN buffer layer is 2 to 4 times larger than the thickness of commonly used Ti buffer layers while the resistivity of NbN is larger than the resistivity of Ti. Therefore, this way of improving AC superconducting properties of the device may increase RF losses since currents flow from the antenna through the buffer layer to the HEB made from ultra-thin NbN film. However, we believe that further optimisation of the room temperature deposition of NbN buffer layers aimed at the enhancing superconductivity and/or decreasing resistivity will improve performance of the phonon cooled NbN HEB detectors.

More complicated consequences of the proximity effect in a three-layer structure (ultra-thin NbN/ buffer NbN/ Au), which is closer to real THz HEB devices, has to be further investigated. The influence of the thickness and the material of the buffer layer on superconducting properties of the entire system containing normal metal contact pads and short superconducting bridge between them have to be studied in detail. The main criteria for the development and optimisation of technology of multi-layer structures are lower noise temperature and wider IF bandwidth of HEB THz mixers. Another important requirement coming from applications is the stability of HEB devices in time that includes mechanical rigidity and a low degradation rate of superconducting and transport properties and the sensitivity.

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