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Thermometers based on NIS junctions of temperature range 1.5−9.0 K

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The paper presents a study of structures based on tunnelling transitions of normal metal–insulator–superconductor (NIS) Al/AlO_x/Nb and Al/AlN/NbN, in which the role of superconductor is performed by niobium (Nb) or niobium nitride (NbN), which are able to operate as thermometers in the temperature range of 1.5−10 K. SNEAP (Selective Niobium Etching and Anodisation Process) technology was used to form tunnel transitions. The Rd/Rn(T) dependences of the test samples were obtained; the experimental data agree with the theoretical model. The values of fluctuation sensitivity of the order of $1\,\mu K/\sqrt{Hz}$ close to the theoretically expected values have been measured. Normal metal−insulator−superconductor (NIS) and superconductor−insulator−normal metal−insulator−superconductor (SINIS) structures made of Al and Nb or Al and NbN can be used as on-chip thermometers. Bolometers, electronic cooling systems and on-chip thermometers can be developed based on the studied structures, integrated directly into or placed next to the working structures for precise monitoring of thermal effects.

Keywords: tunnel junction, thermometer, normal metal−insulator−superconductor (NIS), chains of NIS contacts, SNEAP (Selective Niobium Etching and Anodisation Process), fluctuation sensitivity.

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Introduction

There are several fundamental ways to determine temperature. Gas [1,2], noise [3–5] and nuclear orientation [6] thermometers are successfully used as primary thermometers. However, their use in applied tasks is often limited. For instance, in the case of low temperatures, gases are liquefied, and the level of thermal noise is significantly reduced, which significantly affects the accuracy of calibration. In this regard, some secondary thermometers are more preferable. The advantageous parameters of secondary thermometers are a wide operating range with a simple and monotonous dependence on temperature, low self-heating, fast response and measurement time, ease of operation, and resistance to external parameters. So, in the temperature range from 1.5 to 10 K, calibrated semiconductor resistors [7] and other types of thermometers are widely used. These devices show an increase in resistance when the temperature drops, which makes them suitable for use over a wide temperature range. The study of NIS (normal metal−insulator−superconductor) structures as a thermometer is presented in this paper. The advantage of this device compared to the thermometers listed above is that it is an on-chip thermometer. The tunnel NIS-junctions studied in this paper can be placed in close proximity to the working element, which increases the accuracy of measurements.

Devices based on NIS junctions have been used in X-ray detectors [8], far-infrared bolometers [9, 10] and in electronic coolers at low temperatures [11]. NIS structures were used as a thermometer in [12]: the authors estimated the heating of the electron gas in the structure due to a change of the current-voltage characteristics (I-V) of the tunnel junction, even with a slight change in the electronic temperature. The authors noted that the method of measuring temperature using NIS junctions turned out to be more sensitive than methods for determining temperature based on the Shubnikov−de Haas effect. The article [13] discusses the principle of operation of NIS junctions as thermometers and provides methods for estimating the temperature at which the structure was located depending on the curvature of the measured I-V characteristics.

In addition, NIS thermometers can be used in combination with other nanoscale devices, such as single-electron transistors or superconducting quantum interference devices (SQUIDs), to create integrated temperature measurement and control systems in quantum computing, in quantum processors based on superconducting qubits, where temperature plays a key role in maintaining the superconducting state, NIS thermometers allow measuring the temperature in real time.

Thermometers based on the junction $Fe + Al/AlO_x/Al$ used in [14] indicated the presence or absence of heating of the metal absorber of the bolometer on hot electrons (receiver based on SNS (superconductor–normal metal–superconductor) structures) due to thermal noise or interference. The tunnel junctions produced in this study are supposed to be used in further studies to determine the substrate temperature when studying the response of a receiving element based on NIS junctions to external radiation, and to study the effect of electron cooling in a superconductor–insulator–normal metal–insulator–superconductor (SINIS) structures.

1. Theory

The NIS type junctions are based on the phenomenon of electron tunneling through a thin insulating layer between a normal metal and a superconductor. The probability of tunneling strongly depends on the temperature. The sensitivity of the junction to temperature is attributable to the fact that the fermionic distribution of electrons in the metal is blurred at the final temperature, and even small temperature changes lead to a noticeable change in the tunneling current due to the difference in the filling of electronic states on both sides of the junction. This makes it possible to use NIS structures for temperature measurements in the region below the critical temperature of the superconductor.

The dependence of the single-particle tunneling current on the voltage under conditions $T \ll T_c$, $V < \Delta/e$, where T_c is the critical temperature of the superconductor structure, [15] is described by the formula:

$$I(V, T) = \frac{1}{eRn}\sqrt{2\pi kT\Delta}\exp\left(-\frac{\Delta}{kT}\right)\sinh\left(\frac{eV}{kT}\right), \quad (1)$$

where T is the electron temperature of a normal metal, R_n is the asymptotic resistance of the tunnel junction and Δ is the energy gap of the superconductor. In standard aluminum-based NIS thermometers, the gap is assumed to be constant above a certain temperature (e.g., 300 mK), and T represents the electron temperature of the metal [15]. In the studied temperature range of 1.5–10 K, the gap in a superconductor cannot be considered constant and equal to the gap at zero temperature, which leads to strong discrepancies between theory and experiment above 3 K. Therefore, it is necessary to take into account the dependence of $\Delta(T)$ on the temperature of the superconductor Nb. The electron-phonon interaction in Al has not yet weakened, and the phonon system of a normal metal is connected to an electronic one. During measurements, we do not observe the effect of electron cooling, therefore, we believe that the temperature of the electronic system of a normal metal is equal to the temperature of a superconductor.

Differentiating the current strength (1) by voltage, we obtain an expression for the differential conductivity of the junction under conditions $T \ll T_c$, $U < \Delta/e$. The differential resistance of the tunnel junction is found from it:

$$R_d = \frac{dV}{dI} = R_n\sqrt{\frac{kT}{2\pi\Delta}}\exp\left(\frac{\Delta}{kT}\right)\cosh\left(\frac{eV}{kT}\right)^{-1}. \quad (2)$$

If $V = 0$ R_d will be the maximum

$$R_d(V = 0) = R_n\sqrt{\frac{kT}{2\pi\Delta}}\exp\left(\frac{\Delta}{kT}\right). \quad (3)$$

The differential resistance can be normalized to the asymptotic resistance at voltages well above the gap — R_n. This yields a dimensionless parameter, R_d/R_n, whose values at $V = 0$ depend solely on the temperature of the measured structure. This property allows NIS junctions to be used as thermometers. Moreover, the dependence $R_d/R_n(T)$ is universal for all structures with the same superconductor for cases where Δ does not depend on the thickness of the superconductor, and the parameter $R_d/R_n(V = 0, T)$ at a fixed temperature is the target for all structures made of the same material. Therefore, it serves as a quality parameter by which, in the absence of noise from the measuring system, leaks and overheating, it is possible to assess which of the tunnel junctions with different R_n is better made.

This paper presents the results of production and comparative analysis of tunnel junctions based on two different structures: $Al/AlO_x/Nb$ and Al/AlN/NbN. The key difference between them lies in the materials of the superconducting electrode (NbN with $T_c = 12.0$–15.0 K and $\Delta(T = 0) = 2.16$–3.05 mV or Nb with $T_c = 9.2$ K and $\Delta(T = 0) = 1.4$ mV), as well as in the transparency of the produced tunnel barrier. The transparency of the barrier in operation is not measured directly, but is estimated indirectly through the parameter R_nS, where R_n is the asymptotic resistance of the NIS junction, and S is the area of the tunnel junction. Theoretically, the value R_nS should remain constant for junctions made on the same substrate regardless of the geometric dimensions. The absence of significant fluctuations in this parameter indicates a high uniformity of the tunnel barrier. The estimates show that the AlN barrier is about 40 times more transparent than the AlO_x barrier (see Section 3, Table 1). The latter difference significantly affects the transport properties of the junctions, in particular, a significantly lower current flows through the structure with AlO_x compared to the structure with the AlN barrier under the same conditions.

Thus, structures based on Al/AlN/NbN junctions have a more transparent tunnel barrier, which is suitable for studying the effect of electron cooling, since the high transparency of AlN provides a greater current and efficient removal of hot electrons. And structures based on $Al/AlO_x/Nb$ are suitable for creating SINIS bolometers, since their less transparent barrier AlO_x minimizes the loss of received radiation power to superconducting electrodes, and most of the energy remains in the area of the absorber made of normal metal. This makes it possible to increase the detection efficiency of weak signals. Thus, the choice of barrier material (AlO_x or AlN) determines not only the amount of current through the junction, but also the possibilities of its functional use.

We took into account the dependence of the value of the superconductor gap Nb ($T_c = 9.2\,K$) on temperature (Fig. 1) and calculated the theoretically expected dependence of the parameter R_d/R_n $(V = 0)$ on temperature, taking into account $\Delta(T)$, and also compared it with the calculation of R_d/R_n $(V = 0)$ (Fig. 2), where we took the constant value of the superconducting gap $\Delta = \text{const}$, equal to $\Delta(\text{Nb})$ at $T = 4.2\,K$.

The theoretical dependence of the fluctuation sensitivity on the temperature of NIS structures with Nb superconductor and NbN superconductor was also calculated. The following formula was used for the calculation

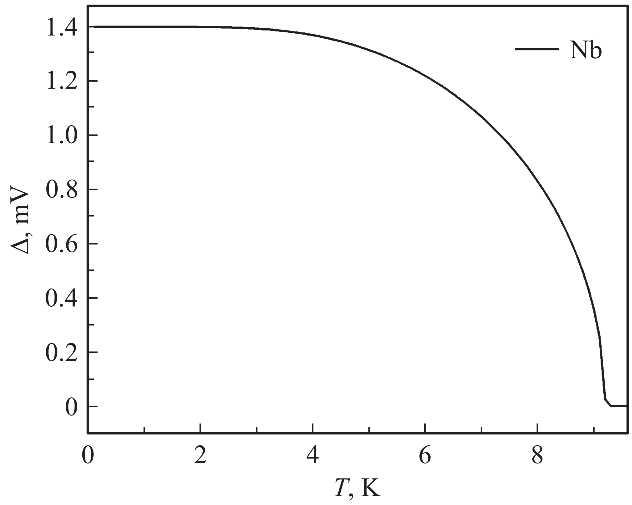

Figure 1. Dependence of the energy gap of the Nb superconductor on temperature.

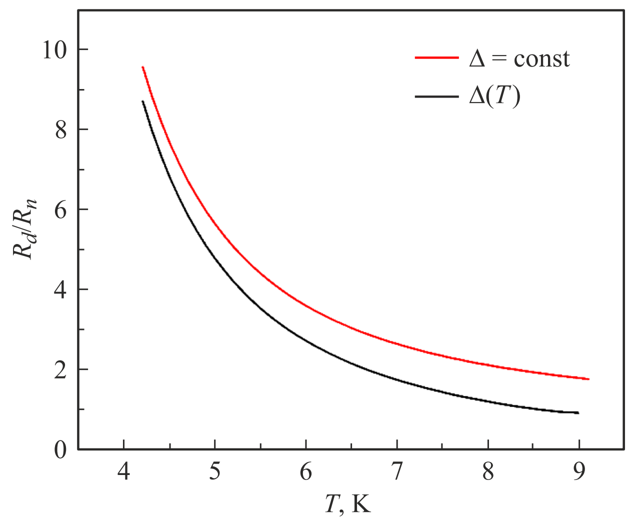

Figure 2. Dependence of $R_d/R_n(T)$ for a NIS type transition with Nb as a superconductor, taking into account the dependence of the gap size Δ on temperature (black curve) and without, where $\Delta = \text{const}$.

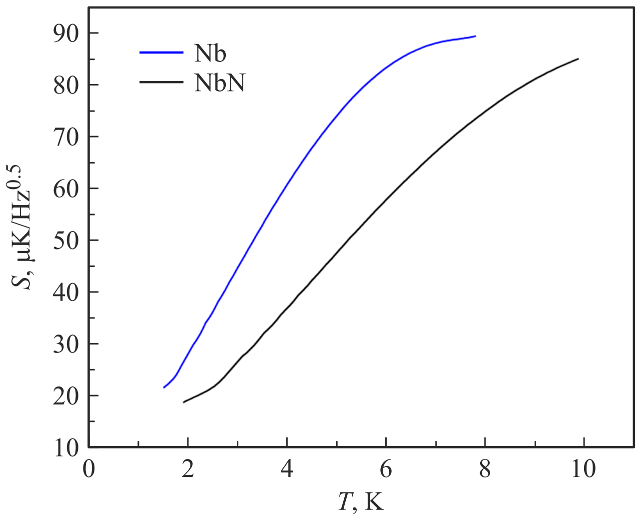

Figure 3. Theoretical dependence of the fluctuation sensitivity of NIS-type structures based on Nb (blue curve) and NbN (black curve) in the temperature range 2.7–10 K.

$$S = \frac{dT}{dV} N_{\text{amplifier}},$$

where dV/dT is the temperature sensitivity with respect to voltage, and the noise of the amplifier used, which operates at room temperature, $N_{\text{amplifier}}$ is the dominant noise source. This is because the shot noise $(\sim 10^{-11}\,V/\sqrt{\text{Hz}})$ and thermal noise $(\sim 10^{-10}\,V/\sqrt{\text{Hz}})$ were found to be lower than the amplifier's voltage noise $(\sim 10^{-9}\,V/\sqrt{\text{Hz}})$, as specified in the technical datasheet. Fig. 3 shows the dependencies $S(T)$ of structures based on Nb and NbN. Since the sensitivity of tunnel junctions significantly depends on their normal resistance R_n, experimentally measured values of this parameter were used to correctly compare the characteristics: 6.1 Ω for Al/AlN/NbN and 13.4 Ω for Al/AlO_x/Nbn structures. These real parameters of the samples formed the basis of the constructed theoretical dependencies.

It can be seen that the sensitivity depends linearly on the temperature in the range of $T < T_c/2$. This area can be considered the working temperature range of the sensitive structure, since in this area dS changes proportionally to dT.

Experimental data show that NbN-based structures exhibit a wider temperature range of linear sensitivity dependence compared to junctions containing Nb. This behavior is explained by the fact that the energy gap of NbN is $\Delta = 2.16–3.05\,mV$ (at the critical temperature $T_c = 12.0–15.0\,K$), which significantly exceeds the similar parameter for Nb ($\Delta = 1.4\,mV$ at $T_c = 9.2\,K$). This difference in superconducting characteristics leads to several important consequences. Firstly, the increased value of the NbN energy gap causes a higher ratio of R_d/R_n $(V = 0)$ at the same operating temperatures compared with Nb-containing structures. Secondly, the increase in the range of linearity of the temperature dependence $S(T)$ described above.

2. Manufacturing technology and measurement methods of NIS structures

The manufacturing technology of the studied samples is described in detail in [16]. Single NIS junctions were made, as well as SINIS structures: two consecutive junctions connected by a metal absorber.

100 nm of Al_2O_3 was deposited onto the silicon wafer using magnetron RF sputtering to prevent corrosion of the substrate during subsequent etching steps. The three-layer structure was formed in one vacuum cycle. The bottom layer of aluminum with a thickness of 100 nm is deposited by direct current magnetron sputtering in an argon plasma. The AlN barrier of the Al/AlN/NbN tunnel junction was formed by nitridization, i.e. nitrogen implantation into an aluminum film in a plasma discharge of a high-frequency magnetron on an aluminum target in a nitrogen atmosphere for 90 s. The AlO_x barrier of the Al/AlO_x/Nb structure was formed by thermal oxidation in pure oxygen at a constant pressure of 10 mbar for 10 min. After the tunnel barrier was formed, the top layer of NbN or Nb with a thickness of 80 nm was applied by DC (direct current) magnetron sputtering.

The area of tunnel junctions was determined by the method of contact photolithography, then the junctions were formed using selective niobium etching and anodization process (SNEAP). The insulation between the base and upper supply electrodes was provided by a SiO_2 layer applied by RF magnetron sputtering with a thickness of 200 nm. The technology of forming the upper niobium electrode from aluminum includes two sequential processes: contact photolithography and DC sputtering of metals. The contact pads were made of aluminum in the same way.

The I-V characteristics of single junctions were measured using a four-pin circuit in pairs of ^{4}He in the temperature range of 4.2–10.0 K using an immersion probe. An industrial thermometer 31Ц-08, located directly on the submersible probe, was used to determine the temperature. The probe position was set manually. Subsequently, a wait time of 1–3 min was observed for thermal relaxation and stabilization of the readings from the calibration thermometer, after which the I-V characteristic of the sample under study was measured. This technique ensured high reproducibility of the results and minimal effect of thermal instabilities on the measurement accuracy. Special attention was paid to the stabilization of the sample temperature, which is critically important for obtaining reliable data on the temperature dependence of tunnel junction parameters.

The I-V characteristics of SINIS structures in the temperature range of 2.4–10.0 K were measured in a Gifford–McMahon closed-cycle cryostat with an additional nitrogen jacket, operating temperature of 2.4 K. The sample in the holder was placed on the lower stage of the cryostat. A resistance thermometer R151K0N001 was installed on the same stage to determine the temperature of the stage. After the extremely low temperature was set in the cryostat, the compressor was turned off and the I-V characteristics of the samples was measured as the stage gradually warmed up.

Using the DAC ADC of the input–output board NI-6289, a symmetrical voltage in the range of -10–10 V was applied to the samples via switchable ballast resistances, thereby setting the value of the measuring current within 1 nA – 1 μA. The voltage across the structure during measurements was 0–1 mV with noise less than 1 μV, amplified 100 times by an operational amplifier with an ultra-low noise level and supplied to the analog input of the digital converter (ADC) of the board. The voltage noise of the amplifier (AD743) reaches $1.5 \cdot 10^{-9}\,\mathrm{V}/\sqrt{\mathrm{Hz}}$.

Table 1. Main parameters of NIS structures

Sample	d, μm	R_nS, $\Omega \cdot \mu m^2$	R_d/R_n ($V = 0$, $T = 4.2$ K)
Al/AlN/NbN	1.7	21.6	48.9
Al/AlO_x/Nb	4.2	800	8.4

3. Experimental results and discussions

The main characteristics and parameters of the created tunnel structures, including the differential resistance in the superconducting state R_d and the normal resistance of the junction R_n, as well as important derived characteristics, the junction quality parameter $R_d/R_n(V)$ and the transparency and uniformity parameter of the barrier R_nS, are determined as a result of the analysis of the I-V characteristics of test samples. The measurements of I-V characteristics allow obtaining the values of all these parameters, which are critically important for assessing the quality and performance characteristics of produced tunnel junctions.

Test samples with tunnel junctions Al/AlO_x/Nb and Al/AlN/NbN were produced using the technology described in Section 2. The main parameters of the produced structures are given in Table 1.

Figs. 4, 5 show the temperature dependences of the I-V characteristics of tunnel junctions in the range of 4.2–10 K, and at temperatures above critical.

The dependences of the differential resistance on the applied voltage were calculated for the measured curves and the ratio R_d/R_n $(V = 0)$ was found for each temperature point. For the Al/AlO_x/Nb structure parameter R_d/R_n $(V = 0,\ T = 4.2\,\mathrm{K}) = 8.4$ with expected 8.7; for the Al/AlN/NbN structure parameter $R_d/R_n = 48.9$ at zero voltage and temperature offset of liquid helium. The dependence $R_d/R_n(T)$ for the junction Al/AlO_x/Nb, as well as its comparison with the calculated one, is shown in Fig. 6. The data are in good agreement with the theoretical

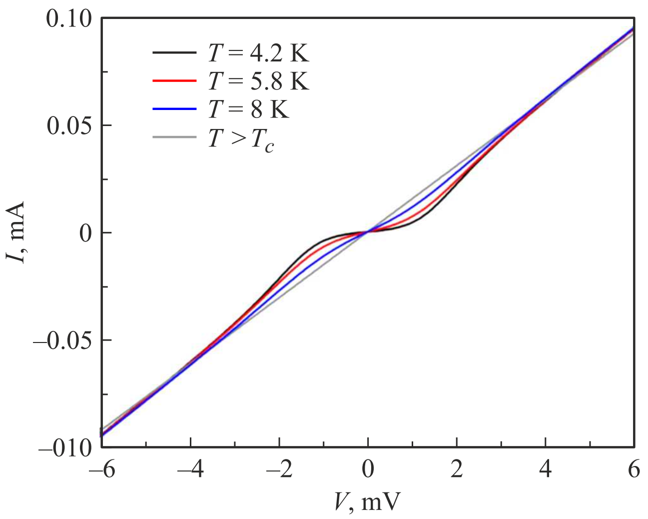

Figure 4. I-V characteristics of the Al/AlO$_x$/Nb junction at temperatures above (gray curve) and below (colored curves) critical.

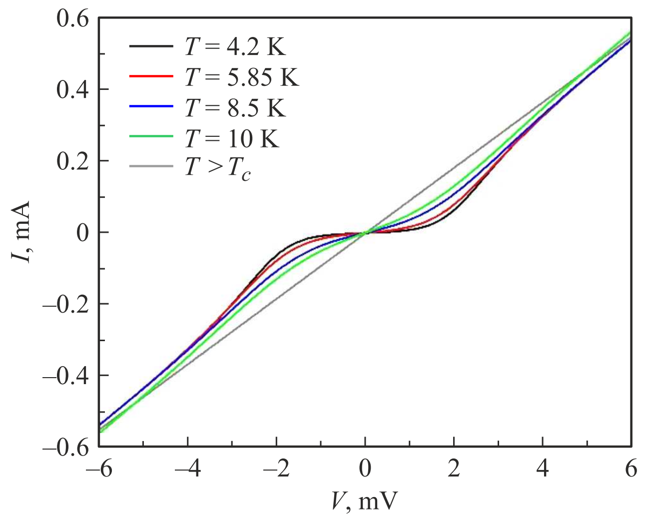

Figure 5. I-V characteristics of the Al/AlN/NbN junction at temperatures above (gray curve) and below (colored curves) critical.

model. The graph shows the results of thermometric measurements on different dates with squares and triangles (the numbers are signed on the legend). Several cycles of temperature measurements of the I-V characteristics test structure were carried out in the period between 05.09.24 and 01.11.24. It can be seen from the data that the nature of the dependence R_d/R_n $(V = 0,\ T)$ and the values of the parameter measured on different dates at the same temperatures coincide (for example, at points $T = 4.5$ K, $T = 8.0$ K, etc.), which indicates that the produced structures are resistant to thermal cycling. The values of the parameter $R_d/R_n(T)$ of the Al/AlN/NbN structure are shown in Fig. 7.

Fig. 8 shows the values of the obtained fluctuation sensitivities based on the measured data at temperature points corresponding to the region of theoretically linear dependence of sensitivity on temperature, and calculated curves $S(T)$. The graph shows that the experimental data show a linear relationship.

The values of the junction sensitivities do not reach the theoretical limits: we obtained the values of $61\,\mu\mathrm{K}/\sqrt{\mathrm{Hz}}$ for the Al/AlN/NbN junction with a possible fluctuation sensitivity of $39\,\mu\mathrm{K}/\sqrt{\mathrm{Hz}}$, sensitivity values of $80\,\mu\mathrm{K}/\sqrt{\mathrm{Hz}}$ were obtained for Al/AlO$_x$/Nb with possible fluctuation sensitivity of $64\,\mu\mathrm{K}/\sqrt{\mathrm{Hz}}$ at $T = 4.2$ K. Taking into account

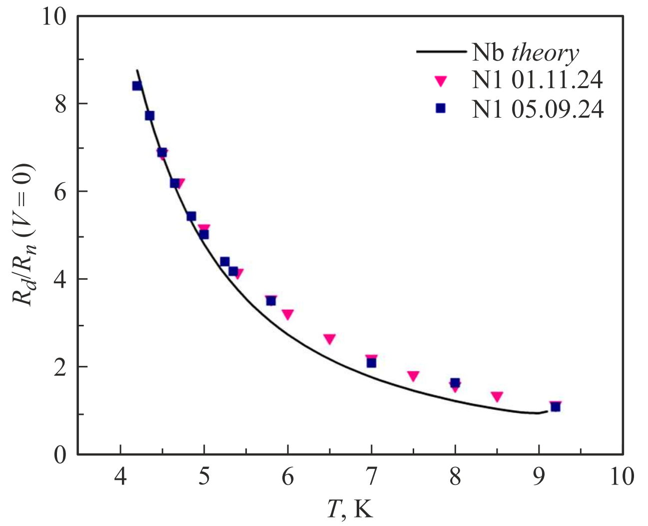

Figure 6. Dependency R_d/R_n $(V = 0,\ T)$ of NIS junction Al/AlO$_x$/Nb (squares and triangles for measurements on different dates) and theoretical dependence R_d/R_n $(V = 0,\ T, \Delta(T))$ — black curve.

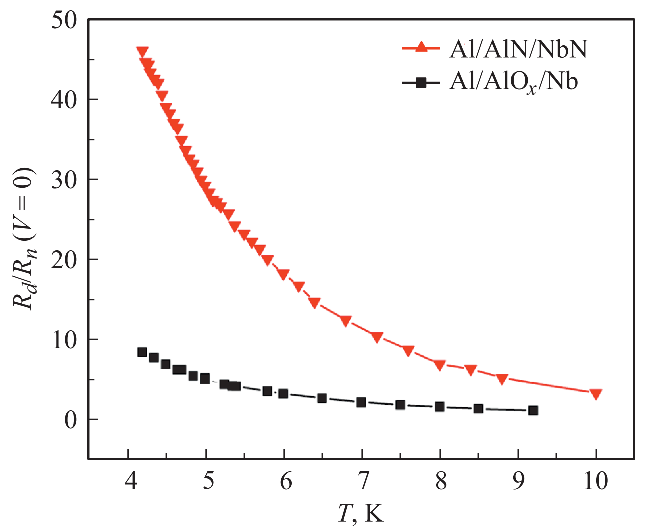

Figure 7. Dependencies R_d/R_n $(V = 0,\ T)$ of NIS of Al/AlO$_x$/Nb junctions (black rectangles) and SINIS structures NbN/AlN/Al/AlN/NbN (red triangles) at different temperatures in the range of 4.2–10.0 K.

the measurement errors, the experimental data still do not reach the theoretical ones, the discrepancy can be explained by several interrelated factors.

The key reason for the observed discrepancy is probably the imperfection of the measuring system. The actual noise characteristics of the amplifier used seem to exceed the parameters stated in the technical documentation. At the same time, parasitic thermal interference and insufficient efficiency of the filter elements of the measuring circuit have a significant impact. These factors together lead to a deterioration in the achievable sensitivity of structures.

A pattern is revealed upon closer examination that the degree of discrepancy between experiment and theory significantly depends on the type of the studied structure. The difference is about 25% for Al/AlO$_x$/Nb junctions, while this value reaches 57% for Al/AlN/NbN structures. The values of $S(T)$ are given in Table 2. Such a significant variation may be related to the peculiarities of the interaction of the measuring system with samples of different resistance, as well as the possible presence of additional noise sources unaccounted for in the model.

It is important to note that the measurement results may be influenced by other factors: imperfection of electromagnetic shielding, thermoelectric effects in the contact system. Each of these aspects contributes to the observed discrepancy between theoretical predictions and experimental data. It is necessary to carry out a set of measures for upgrading the measuring system to minimize these effects in the future. This includes a thorough check of the actual noise characteristics of the amplification path, enhanced electromagnetic shielding, and optimization of the supply voltage filtration system. Such improvements will make it possible to bring the experimental results closer to the theoretically predicted values.

Table 2. Sensitivity values of NIS structures

Sample	S ($T = 4.2$ K), μK/$\sqrt{\text{Hz}}$	Theory S ($T = 4.2$ K), μK/$\sqrt{\text{Hz}}$
Al/AlN/NbN	61	39
Al/AlO$_x$/Nb	80	64

Despite the identified discrepancies, the results obtained convincingly demonstrate the fundamental suitability of the developed structures for use as thermometers. Further work to eliminate the identified shortcomings of the measuring system opens up prospects for the full potential of these devices. Of particular importance is the fact that all measurements demonstrate good reproducibility, which confirms the reliability of the developed technology for manufacturing structures.

Fig. 9 shows the voltage differences of the I-V characteristics measured at two temperature points $T_1 = 4.2$ K and $T_2 = 6.9$ K, structures of Al/AlO$_x$/Nb and Al/AlN/NbN, respectively, the voltage differences for the theoretically calculated I-V characteristics are also shown (formula (1)) of NIS junctions with superconductor Nb and NbN. The graph shows the experimentally obtained sensitivities and expected values of S ($\Delta T = T_2 - T_1$), where $T_1 = 4.2$ K and $T_2 = 6.9$ K.

Based on the sensitivity values obtained, we can make an estimate of the NEP (noise equivalent power) of the receiving structure at the NIS junctions made from Nb and Al. For an aluminum absorber of standard size $1 \times 5 \times 0.03\,\mu\text{m} = 0.15\,\mu\text{m}^3$, the NEP will be equal to $3 \cdot 10^{-17}\,\text{W}/\sqrt{\text{Hz}}$ with the fluctuation sensitivity of the tunnel junction of $80\,\mu\text{K}/\sqrt{\text{Hz}}$, which is comparable to the results, obtained for aluminum bolometers at 0.3 K [17].

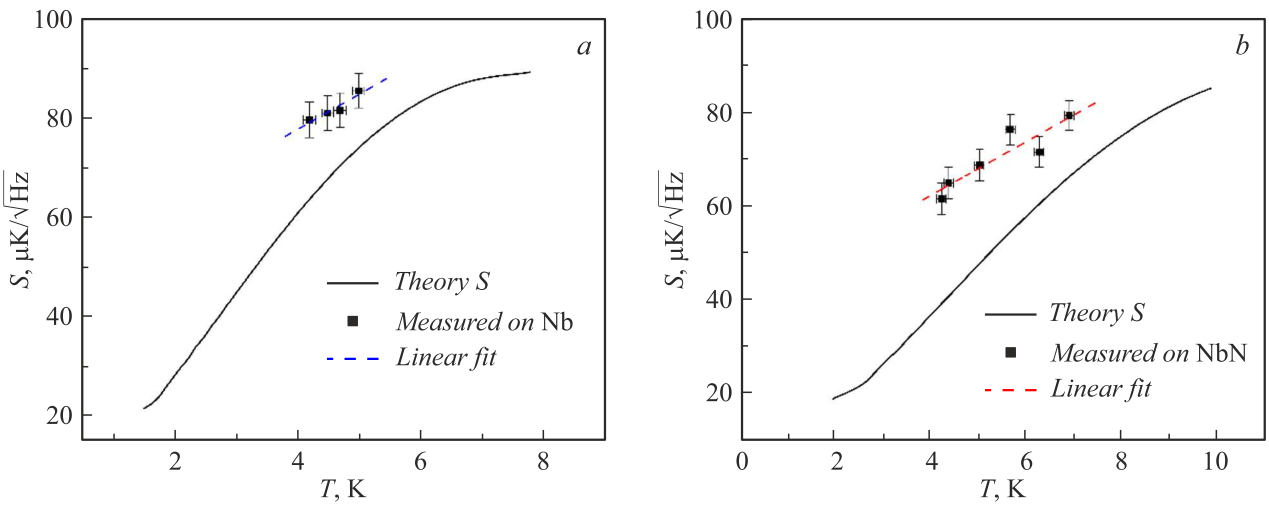

Figure 8. a — dependence of the fluctuation sensitivity of the Al/AlO transition$_x$/Nb on temperature, obtained from experimental data (dots), linear approximation (bar) and theoretically calculated curve (solid line); b — temperature dependence of the fluctuation sensitivity of the Al/AlN/NbN transition, obtained from experimental data (dots), linear approximation (bar) and theoretically calculated curve (solid line).

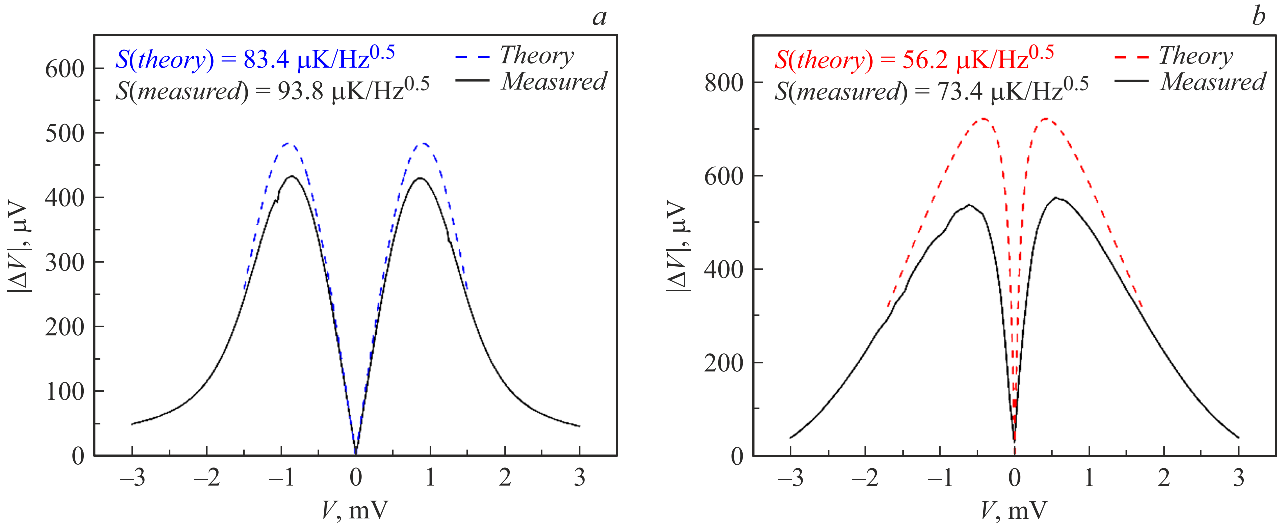

Figure 9. *a* — response of —delta $V|(V)$ to a temperature change from $T_1 = 4.2$ K to $T_2 = 6.9$ K of the Al/AlO_x/Nb junction, measured (black curve) and theoretically calculated (blue stroke); *b* — response —delta $V|(V)$ to temperature change from $T_1 = 4.2$ K to $T_2 = 6.9$ K of the Al/AlN/NbN junction, measured (black curve) and theoretically calculated (red stroke).

Thus, the values of the characteristic parameters of the studied structures will allow them to be used for radiation receivers in radio astronomy applications.

Conclusions

Structures of NIS and SINIS types designed for use as on-chip thermometers in the temperature range of 1.5–10 K have been developed, manufactured and experimentally studied. Experimental data have confirmed the exceptional stability of the characteristics of the developed structures under multiple thermal cycles, which makes them promising for practical use in cryogenic systems. The samples showed dependencies $R_d/R_n(T)$ close to the theoretically expected ones: for structures Al/AlO_x/NbR_d/R_n $(V = 0,\ T = 4.2\,\mathrm{K}) = 8.4$, for structures Al/AlN/NbN R_d/R_n $(V = 0,\ T = 4.2\,\mathrm{K}) = 49.8$. The values of fluctuation sensitivity were obtained: on structures Al/AlO_x/Nb S $(T = 4.2\,\mathrm{K}) = 80\,\mu\mathrm{K}/\sqrt{\mathrm{Hz}}$ with theoretically calculated $64\,\mu\mathrm{K}/\sqrt{\mathrm{Hz}}$, for structures Al/AlN/NbN$S(T = 4.2\,\mathrm{K}) = 61\,\mu\mathrm{K}/\sqrt{\mathrm{Hz}}$ with theoretically expected $39\,\mu\mathrm{K}/\sqrt{\mathrm{Hz}}$. The measured values of fluctuation sensitivity make it possible to use such structures as on-chip thermometers.

The prospects for the practical application of the developed structures include their integration into electronic cooling systems and use in the research of receiving elements based on NIS junctions based on niobium and aluminum. The results obtained are of considerable interest for the development of cryogenic electronics, opening up new possibilities for creating compact and reliable measuring systems capable of operating at helium temperatures. The demonstrated stability of the characteristics over multiple thermal cycles is of particular value, as this is critically important for practical applications in real cryogenic systems.

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Conflict of interest

The authors declare that they have no conflict of interest.

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