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Electron, thermal, and fluctuation transport in superconducting TiN and NbN microbridges

PhD Dissertation Summary

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General work description

At present, superconducting detectors such as superconducting nanowire single photon detectors (SNSPD), Transition Edge Sensors (TES), and hot electron bolometers (HEB) are the most sensitive infrared detectors. For example, SNSPDs have high sensitivity to infrared and photons, almost 100% detection efficiency [1—3] and hundreds of MHz counting rates [4], making them suitable for a wide range of applications [5]. However, to combine all these high characteristics in one device is a challenge, requiring not only technical achievements, but also a clear understanding of the physics underlying the theoretical description of single photon detection mechanisms. The problem of development a theory for superconducting detectors lies in the complex relationship between the resistive and thermal properties of a thin superconducting film in a highly nonequilibrium regime [6]. Understanding the detectoŕs response to radiation is complicated by the fact that the converted energy of absorbed photons in the film is associated with quasiparticle excitations, the phonon system, the Cooper pair condensate, and unpaired Berezinsky-Kosterlitz-Thouless (BKT) vortices.

The appearance of resistance in a superconductor can be explained by considering the transition of a normal conductor to a superconducting state. It is known that such a transition occurs continuously and is accompanied by fluctuations in the modulus and phase of the superconducting order parameter [7]. These fluctuations manifest themselves in various macroscopic properties [8] and, most importantly, in direct current resistance (R), although their dynamics is averaged over time and sample volume. When measuring resistance, fluctuations in the modulus of the superconducting order parameter cause excess conductivity at temperatures above the critical temperature, T_c, [9; 10], and its phase fluctuations lead to non-zero resistance below T_c [11—18]. Thus, the resistive transition (RT) is stretched over the width of the fluctuation region. It is also expected that the RT broadening effect will be stronger for smaller samples, which is determined by the ratio of the linear size of the sample to the superconducting coherence length ξ. However, many studies show a much stronger RT broadening, which is difficult to explain within existing theories [19]. Such discrepancies can be attributed to the influence of built-in inhomogeneity [20] or, as recent studies of low-dimensional superconductors suggest, to more fundamental effects such as the preformation of Cooper pairs above T_c [21; 22]. To better understand the mechanisms of fluctuations, one should go beyond measuring the time-averaged response and focus on the dynamics of fluctuations. A well-known tool is the use of noise measurements as a direct study of correlation time scales and the magnitude of fluctuation effects. Thus, in previous studies of spontaneous voltage or resistance fluctuations on the RT, various mechanisms were considered, such as the correlated motion of magnetic vortices [23], the stochastic motion of vortices over the BKT transition [24; 25], and electron temperature fluctuations [26; 27]. In such experiments, excess noise was measured at relatively low frequencies ($f < 100\,\mathrm{kHz}$), which is far beyond the frequency range of the Ginzburg-Landau (GL) correlation time τ_{GL}, which is responsible for thermodynamic fluctuations at superconducting phase transition [17]. It is noteworthy that the time divergence GL $\tau_{\mathrm{GL}} \propto |T - T_{\mathrm{c}}|^{-1}$ for $T \to T_{\mathrm{c}}$ has apparently never been observed experimentally. On the contrary, measurements of the fast relaxation dynamics, important for the time response of superconducting detectors [28—30], show that the resistance relaxation time τ_{R} at the resistive junction is related to inelastic energy relaxation processes [31—36]. The resistance relaxation time τ_{R} tends to diverge in the superconducting phase as T_{c} is approached from below, which is observed for superconductors with relatively narrow RT [31; 37; 38]. This behavior of τ_{R} is related to the renormalization of inelastic scattering in the limit of the superconducting gap tending to zero [39]. Description of the time response of superconducting detectors to radiation is not straightforward. For example, it was found that τ_{R} is described by the relaxation time of the radiation energy absorbed by electrons into phonons τ_{eph} and the time of escape of the ballistic phonon into the substrate τ_{esc}, which depends on the acoustic properties of the film-substrate interface. In real detectors, the phonon escape time τ_{esc} is much longer than the flight time of the ballistic phonon across the film d/v_{s} [35; 40—42], where d and v_{s} — film thickness and sound velocity, which has no unambiguous explanation today. In general, studies of the time scales that determine the spreading of the RT and the escape of phonons into the substrate are, unfortunately, extremely scarce and do not allow us to draw unambiguous conclusions [35].

Aim of this work is to study spontaneous voltage fluctuations in microbridges of titanium nitride and niobium nitride in the vicinity of the critical temperature of the superconducting transition and in the normal state in order to obtain information about the microscopic mechanisms responsible for the formation of a resistive transition and manifested in the response of low-temperature detectors.

To achieve this goal the following **objectives** were considered:

1. Techniques for measuring voltage noise with primary calibration of the signal by Johnson-Nyquist noise in a dilution cryostat and a helium Dewar at the Laboratory of Quantum Detectors at MSPU were implemented.
2. The transport properties and heat transfer of NbN and TiN microbridges were studied by noise thermometry in the normal state.
3. The bolometric voltage response at the resistive transition of the NbN detector in response to laser radiation is studied.
4. The spectrum of voltage fluctuations in the vicinity of a resistive transition in TiN microbridges was studied. It was found that the main mechanism responsible for the voltage fluctuations at the resistive junction is associated with spontaneous temperature fluctuations.
5. The effect of spontaneous temperature fluctuations and random magnetic disorder on the broadening of the resistive transition in TiN was studied.

Theoretical significance of the obtained results lies in receiving new information about the role of inelastic energy relaxation processes in the phenomenological theory of superconductivity. Such information is of critical importance for solving the fundamental question of the temporal and spatial scales of superconducting fluctuations. The results obtained could stimulate new interest in this direction.

From the side of **practical significance**, knowledge about the mechanisms of energy relaxation and suppression of superconductivity can be directly used to improve the characteristics of superconducting devices, in particular, to select the material of the substrate and the surface protective layer.

KEY RESULTS

The key results of the study and provisions for the defense can be summarized as follows:

1. The transport properties of epitaxial TiN films with a low level of disorder at low temperatures were studied. The effect of suppression

of the critical temperature with decreasing film thickness was found, which was explained by the presence of a small amount of built-in magnetic disorder on the surface of TiN films. A model was provided that consistently described the shift of the critical temperature due to magnetic disorder and smearing of the resistive transition by spatial fluctuations in the number of magnetic moments.

2. It was demonstrated that broadband resistance fluctuations at the superconducting resistive transition in TiN microbridges were associated with spontaneous fluctuations of the electron temperature. The latter in turn were due to the stochastic energy exchange between the electronic system and the thermal reservoir. It was shown that the correlation length and time of resistance fluctuations coincide with the time and length of inelastic energy relaxation and turned out to be much larger than the scales of the Ginzburg-Landau correlation length and time. A fundamental limit was proposed for the minimum smearing of the resistive transition in TiN microbridges, which was associated with temperature fluctuations.
3. The heat transfer of thin NbN microbridges on an amorphous substrate, including those suspended over a crystalline substrate, was studied using noise thermometry in the normal state. Due to the strong electron-phonon interaction in NbN, all remaining thermal bottlenecks in the film-substrate-sample holder system became revealed. It was demonstrated that, at temperatures above 10 K, in NbN microbridges deposited on amorphous dielectric substrates, heat transfer was determined by the thickness of the amorphous dielectric layer, and not by the thermal resistance of Kapitza. This phenomenon was explained in terms of the propagation of a special type of phonon excitations – diffusons.
4. The heat transfer in NbN microbridges of various thicknesses on a crystalline substrate was studied using noise thermometry in the normal state. It was demonstrated that, as the thickness of the NbN film increased, an additional thermal bottleneck arose due to the short phonon mean free path in NbN films. As a consequence, in the process of

energy relaxation, an electron temperature gradient appeared, directed towards the substrate.

Reliability of the obtained results is confirmed by their reproducibility on various experimental setups and by agreement with the results obtained by other authors, to the extent that such results exist.

Author's personal contribution is to carry out most of the experimental measurements given in this paper. The author took an active part in the interpretation and processing of the experimental results. These works were carried out by the author in the Laboratory of Quantum Detectors of the Moscow State Pedagogical University and in the Laboratory of Electron Kinetics of the Institute of Solid State Physics, Russian Academy of Sciences.

PUBLICATIONS AND APPROBATION OF RESEARCH

First-tier publications

[1] E.M. Baeva, M.V. Sidorova, A.A. Korneev, K.V. Smirnov, A.V. Divochy, P.V. Morozov, P.I. Zolotov, Yu.B. Vakhtomin, A.V. Semenov, T.M. Klapwijk, V.S. Khrapai, and G.N. Goltsman "Thermal Properties of NbN Single-Photon Detectors"// *Phys. Rev. Applied.* — 2018. — Dec. — v. 10, 6. — p. 064063. — DOI: 10.1103/PhysRevApplied.10.064063.

[2] E.M. Baeva, N.A. Titova, L. Veyrat, B. Sacépé, A.V. Semenov, G.N. Goltsman, A.I. Kardakova, and V.S. Khrapai "Thermal Relaxation in Metal Films Limited by Diffuson Lattice Excitations of Amorphous Substrates"// *Phys. Rev. Applied.* — 2021. — May. — v. 15, 5. — p. 054014. — DOI: 10.1103/PhysRevApplied.15. 054014.

[3] E.M. Baeva, N.A. Titova, A.I. Kardakova, S.U. Piatrusha, and V.S. Khrapai "Universal Bottleneck for Thermal Relaxation in Disordered Metallic Films"// *JETP Letters* . — 2020. — Jan. — v. 111, N 2. — p. 104—108. — DOI: 10.1134/s0021364020020034.

[4] N.A. Saveskul, N.A. Titova, E.M. Baeva, A.V. Semenov, A.V. Lubenchenko, S. Saha, H. Reddy, S.I. Bogdanov, E.E. Marinero, V.M. Shalaev, A. Boltasseva, V.S. Khrapai, A.I. Kardakova, and G.N. Goltsman "Superconductivity

Behavior in Epitaxial TiN Films Points to Surface Magnetic Disorder"// *Phys. Rev. Applied.* — 2019. — Nov. — v. 12, 5. — p. 054001. — DOI: 10.1103/PhysRevApplied.12. 054001.

Other publications

[5] E.M. Baeva, M.D. Soldatenkova, P.I. Zolotov, N.A. Titova, A. Triznova, A.I. Lomakin, A.I. Kardakova and G.N. Goltsman "Thermal relaxation in NbN films on crystalline substrates"// *IEEE Transactions on Applied Superconductivity* — 2022. — т. 32, № 4. — с. 1—5. — DOI: 10.1109/TASC.2022.3147135.

[6] E.M. Baeva, A.I. Kolbatova, N.A. Titova, S. Saha, A. Boltasseva, S. Bogdanov, V. Shalaev, A.V. Semenov, A. Levchenko, G.N. Goltsman, and V.S. Khrapai "T-fluctuations and dynamics of the resistive transition in thin superconducting films — 2022. — arXiv: 2202.06309.

[7] E.M. Baeva, A.I. Kolbatova, N.A. Titova, S. Saha, A. Boltasseva, S. Bogdanov, V. Shalaev, A.V. Semenov, G.N. Goltsman, and V.S. Khrapai "Resistance fluctuation spectroscopy of the superconducting transition in epitaxial TiN films — 2022. — arXiv: 2202.06310.

Conference presentations

The main results and conclusions of the study have been presented at international conferences, including: International Scientific Conference Superconducting Quantum Technologies (Moscow, Russia, 2018), 54th Rencontres de Moriond (La Thuile, Italy, 2019), Interaction between Radiation and Quantum matter (Moscow, Russia, 2019), XVIII School-conference for young scientists «Problems of solid state physics and high pressure physics» (Sochi, Russia, 2019), XXIV International Symposium «Nanophysics and Nanoelectronics» (Nizhny Novgorod, Russia, 2020), XXV International Symposium «Nanophysics and Nanoelectronics» (Nizhny Novgorod, Russia, 2021), 15th European Conference on Applied Superconductivity (Moscow, Russia, 2021), XXVI International Symposium «Nanophysics and Nanoelectronics» (Nizhny Novgorod, Russia, 2022).

CONTENTS

This dissertation contains an introduction, seven main chapters and a conclusion. The total length of dissertation is 140 pages with 32 figures and 4 tables. The reference list contains 197 items.

Chapter 1 provides information from experimental and theoretical works devoted to the study of noise in mesoscopic systems and the thermal model used to describe low-temperature detectors.

Chapter 2 provides general information about the exploited superconducting films and the procedure for preparing the studied samples, as well as describes the main experimental techniques and the processing of experimental data.

Chapter 3 is devoted to measurements of superconducting and transport properties of epitaxial TiN films. The obtained experimental data demonstrate the high structural quality of the films and the size effect as a function of the thickness of the film resistance. As the film thickness decreases, the critical temperature of the superconducting transition is suppressed. The data obtained are in reasonable agreement with the Abrikosov-Gorkov model, which describes the suppression of superconducting properties by magnetic disorder.

In **Chapter 4**, we study the superconducting fluctuations in TiN microbridges. First, the dependence of resistance on temperature is investigated. It is shown that the width of the resistive transition increases with decreasing sample width. Meanwhile, it remains much wider than the Ginzburg-Levanyuk number, and the conductivity in the vicinity of the critical temperature is not described by the Aslamazov-Larkin corrections. The study of spontaneous voltage fluctuations at a resistive transition demonstrates that superconducting fluctuations are caused by resistance modulation noise. The measured characteristic time of resistance fluctuations is described by the time of electron-phonon interaction and diffusion of electrons into the contacts. At the end of the chapter, it is shown that the minimum smearing of the resistive transition in TiN microbridges is determined by the length and time scales of the electron-phonon interaction and diffusion of electrons into contacts. The rest of broadening of the resistive transition can be explained by fluctuations in the number of surface magnetic moments.

In **Chapter 5**, we investigate the thermal transport of a superconducting single-photon NbN detector at the critical temperature of the superconducting transition. We study the response to modulated laser radiation via resistive thermometry, and obtain the temperature dependence of the thermal resistance of the detector. From this data, we estimate the ratio of the electronic and phonon heat capacities of NbN. This parameter is important for describing the operation of single-photon detectors.

In **Chapter 6**, we investigate the thermal transport in various films (NbN, InO_x, Au/Ni) deposited on a Si substrate with an amorphous SiO_2 layer (200-300 nm). It is shown that at temperatures above 10 K in metal microbridges deposited on SiO_2/Si substrate, the heat transfer is determined by the thickness of the SiO_2 layer, rather than by the thermal resistance of Kapitza.

Chapter 7 continues the study of thermal transport in NbN films, but from a slightly different perspective. We study NbN samples on crystalline Al_2O_3, GaN, and Si substrates above the critical temperature of the superconducting transition by noise thermometry. The data shows that the heat transfer on crystalline substrates has noticeably improved in comparison with the data obtained in the samples on SiO_2/Si substrate. In the NbN/Al_2O_3 samples, a regime, when with an increase in the thickness of the NbN film, a temperature gradient appears across the NbN film, is reached.

The conclusion contains the list of main results of this dissertation.

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2. Waveguide integrated superconducting single-photon detectors with high internal quantum efficiency at telecom wavelengths / O. Kahl [и др.] // Scientific Reports. — 2015. — Июнь. — Т. 5, № 1. — DOI: `10.1038/srep10941`.
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