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Effect of heat dissipation on the current-voltage characteristics of ultrathin NbN nanowires

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Abstract. The nonlinear current-voltage characteristics of niobium nitride (NbN) nanowires have been studied experimentally at the vicinity of the resistive transition. We show that the nonlinear behavior of the current-voltage characteristics is in agreement with the thermal model considered the heat dissipation in NbN samples.

Keywords: superconductivity, superconducting transition, thermal activated phase-slips

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Материалы конференции
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Влияние эффекта разогрева на вольт-амперные характеристики в ультратонких нанопроводах NbN

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Аннотация. Экспериментально исследованы нелинейные вольт-амперные характеристики нанопроволок нитрида ниобия NbN в окрестности резистивного перехода. Показано, что нелинейное поведение вольт-амперных характеристик полностью согласуется с тепловой моделью релаксации тепла в NbN.

Ключевые слова: сверхпроводимость, сверхпроводящий переход, термические проскальзывания фазы

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Introduction

Superconducting NbN nanowires have attracted a lot of interest as elements of superconducting circuits, detectors, and high frequency devices [1]. For instance, single photon detectors based on long superconducting NbN nanowires (SNSPD) [2] are extensively used in optical and infrared quantum technologies due to their ultimately high response speed, high system detection efficiency, and low dark count level [3]. One of the key parameters of SNSPDs, the dark count rate, is associated with the thermal activated phase slips (TAPS) [4]. Meanwhile, signatures of TAPS are observed in the temperature dependences of resistance [5,6] and the current-voltage (IV) characteristics [7,6] of narrow NbN wires. However, as shown in [5] only a part of the IV curve at low bias can be described by the TAPS model, and the non-linearity of the IV curve at high bias appears to be of thermal origin. Effect of joule heating on IV curves of superconductors has been known for a long time [8-10], but at the same time such an interpretation of the IV curves is complicated by lack of an accurate information about heat dissipation in thin wires and by presence of electronic inhomogeneities due to strong disorder in NbN films.

In this paper we study the effect of joule heating on ultrathin NbN nanowires at the resistive transition. We measure the current-voltage characteristics at the low-temperature part of the resistive transition. The data is analyzed in terms of the TAPS anf thermal models. The latter model considers influence of heat dissipation on nonlinearities of the IV-curves in a one-dimensional (1D) NbN wire. As a key parameter for the thermal model, we take the Kapitza resistance [11], which has been measured via the noise thermometry above the superconducting transition. Our results show that the thermal model can adequately describe the nonlinearity of the IV curves at the resistive transition.

Materials and Methods

The measurements described in this paper are performed on NbN wires, patterned from ultrathin NbN film deposited by RF magnetron sputtering on r-cut sapphire (Al_2O_3) substrate. After deposition, NbN film is covered *in situ* by a 5-nm thick Si layer. The film has a thickness $d \approx 3.5$ nm, the critical temperature T_c of 10 K, and the normal-state resistivity ρ of 260 μΩ·cm. Finally, the film is patterned into two-contact bridges using the electron-beam lithography, the plasma-chemical etching and thermal evaporation of Ti/Au contact pads. The image of a representative sample obtained with the scanning electron microscope (SEM) is presented in (Fig. 1, *a*). The length L, the width w of samples A and B, and the normal-state resistance R at 20 K and at 300 K are listed in Table 1.

Table 1

Parameters of the studied NbN nanowires

	w, nm	L, μm	R_{300K}, kΩ	R_{20K}, kΩ	T_c, K
A	70	4	35	43.73	10.4
B	70	4	35.84	43.82	10.2

Measurements of the resistance, the current-voltage characteristics, and voltage fluctuations are performed using of a cryogenic ^{4}He dipstick. In this experiment, the bath temperature T_b is controlled by a position of the dipstick in the liquid ^{4}He dewar. Resistance measurements, shown schematically in (Fig. 1, *a*), are performed with the standard lock-in technique in a quasifour-probe configuration. The bias current is varied in the range of 1 – 10 nA at the modulation frequency of 8 Hz. The output AC voltage signal is amplified by a SR560 preamplifier and measured with a SR830 lock-in. The experimental setup is designed using stainless steel coaxial lines and low-pass resistor-capacitor filters. For each of the devices the current-voltage characteristics are measured at the current-biased regime. The output DC voltage signal is amplified by a SR560 preamplifier and measured with a Keysight 34461A multimeter.

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To determine the mechanism of heat dissipation in the studied samples, we measure the noise temperature T_N at the normal state above the superconducting transition using the noise thermometry [11]. Figure 1, *a* shows schematic of the experimental setup. Above T_c, the sample is biased with dc current I, and the excess current noise from the sample is passed through the resonance tank circuit at a central frequency of 46 MHz. The signal is amplified by a homemade low-temperature (LTamp) amplifier (with 6-dB gain and input current noise of 10^{-27} A^2/Hz) and room-temperature amplifiers and measured by a power detector. When calibrating a circuit with the Johnson-Nyquist noise, the current noise of the sample S_I can be extracted. Thus, T_N can be found using the Johnson-Nyquist relation $T_N = S_I R_d / 4k_B$, where Rd is the differential resistance of the sample, k_B is the Boltzmann constant. We assume that the length of NbN samples is much longer than the electron-phonon scattering length [12], which implies that an electron temperature T_e is uniform along the sample length. As a consequence, T_N can be considered equal to T_e.

Results and Discussion

To obtain information about heat dissipation in NbN wires, we measure the heat flow rate. Figure 1, *b* displays results of the noise thermometry performed at $T_b = 16$ K for two studied samples. The data, presented with symbols, follow a T_e^4 dependence on the normalized Joule power $P_2D = I^2R / A$, where $A = w \times L$ is the area of sample. The exponent $n = 4$ revealed in $P_2D(T_e)$ dependence indicates that the thermal relaxation is limited by the Kapitza resistance [11]. For further analysis, we fit the experimental data with expression $P_{2D} = \sum_{2D}\left(T_e^4 - T_b^4\right)$, considering $\sum_{2D}$, the two-dimensional cooling rate, as a fitting parameter (the black solid line in Figure 1, *b*). The obtained value of $\sum_{2D} 120WK^{-4}m^{-2}$ is close to results reported for NbN/Al_2O_3 interface in [13], however it is in 1.5 times smaller than $\sum_{2D}$ obtained in our previous work [11].

Next, we investigate the resistance of NbN samples at the vicinity of the resistive transition. A low-temperature tail of the resistance transition can be result of the TAPS contribution [5-6]. The resistivity caused by TAPS can be described in the framework of the Langer-Ambegaokar-McCumber-Halperin (LAMH) theory [14-15]:

$$R_{LAMH} = \frac{\pi\hbar}{2e^2} \frac{\hbar L}{\kappa_B T \xi(0) / \sqrt{T / T_C - 1}} \left(\frac{\Delta F}{\kappa_B T}\right)^{1/2} \frac{\pi\hbar}{8\kappa_B \left(T_C - T\right)} e^{-\Delta F / \kappa_B T}, \tag{1}$$

with the condensation energy

$$\Delta F = 0.83 \frac{\pi\hbar}{2e^2} \frac{1}{R_{20K}} \frac{L}{\xi(0)} k_B T_C \left(1 - \frac{T}{T_C}\right)^{3/2}. \tag{2}$$

Where ξ (0) is the Ginzburg-Landau coherence length. In the experiment, ξ (0) is determined using the relation ξ (0)2 = – ħ / 2eTc(dBc2(T)/dT) from the temperature dependency of the second critical magnetic field Bc2(T).

The LAMH model also predicts the finite voltage induced by TAPS, when the wire is biased with a current [14-15]:

$$V_{LAMH} = \frac{2e\kappa_B T}{\pi\hbar} R_{LAMH} \sinh \frac{\pi\hbar I}{2e\kappa_B T}. \tag{3}$$

In Figure 1, *b* we fit the temperature dependence of resistance (shown with the green symbols) by the TAPS model as $R = \left(R_{20K}^{-1} + R_{LAMH}^{-1}\right)^{-1}$. One can see that the temperature dependence of resistance can be partially described by the LAMH model. Low-temperature residual resistance which is not described by TAPS can be result of superconducting properties of leads. For the sample B we obtain the similar results (not shown). The fitting parameter T_c is listed in Table 1.

In Figure 2, *a* we compare the current-voltage (IV) curves measured at the vicinity of the resistive transition (Fig. 2, *b*) with the LAMH model. One can see that only the low-bias part of the IV curve can be described with the LAMH model. Note that the comparable fits can be obtained in the framework of the Golubev-Zaikin theory [16] (not shown here). Similar results for fitting the IV curves with the LAMH model have been obtained for NbN wires in [5]. The discrepancy of the LAMH model with the experimental data can be related to the effect of joule heating. It is well-known that the thermal effect, accompanied with inhomogeneity of superconducting properties, can lead to the nonlinearity of the current-voltage characteristics [8, 9] and fully describes the retrapping current [10,13].

To analyze the effect of joule heating on the IV curves at the resistive transition, we assume that the transition into superconducting state occurs by the formation of expanding superconducting domains. Here we neglect contributions of paraconductivity to broadening of the resistive transition and current conversion processes for simplicity. Similar to the thermal model reported in [9], we assume that electronic inhomogeneities and, hence, inhomogeneity of T_c along the length of the wire play a role.

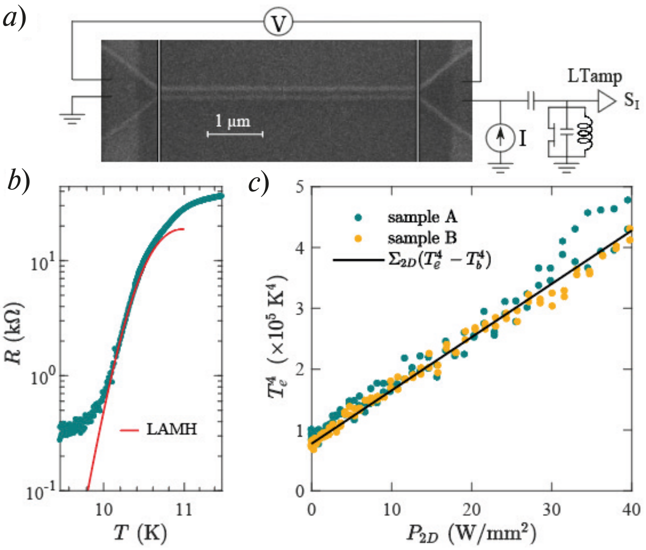

Fig. 1. SEM photo of a representative sample with a schematic sketch of the noise thermometry experiment (*a*); the temperature dependence of resistance for sample A on a logarithmic scale. The solid and dashed lines show the TAPS contribution to $R(T)$ derived from the LAMH theory (*b*); the measured electron temperature T_e is presented as a function of joule power P_2D for samples A and B. The data are presented on a linear scale. The solid line shows a fit with the expression $P_{2D} = \sum_{2D}\left(T_e^4 - T_b^4\right)$ with $\sum_{2D} = 120WK^{-4}m^{-2}$ (*c*)

To describe the experimental data we consider a one-dimensional (1D) model (see a schematic representation of the model in (Fig. 2, *a*), in which joule heating is dissipated in the normal-state parts of the wire under the constant bias current and at finite bath temperature T_b. In this straightforward model, we consider that a segment of the wire is in the normal state if the local electron temperature T_e exceeds the local T_c. We also assume that the electron T_e and the phonon T_{ph} temperatures are constant over the normal region and their values do not depend on the size of the normal region. In the one-dimensional model, the non-zero resistance state can be simply determined by the part of the normal regions ν_N. Thus, a decrease of the resistance with decreasing temperature is accompanied by a decrease of the portion of normal domains $\nu_N(T) = R(T) / R20\text{K}$. With the noise thermometry we found that the electronic temperature and the electronic heat flow rate in the studied NbN nanowires are controlled by phonons escape to the substrate, known as the Kapitza resistance. Thus the electronic heat flow rate due to heat dissipation in the normal segments of the wire can be determined as:

$$\frac{I^2 R_{20\text{к}} \nu_N}{A_N} = \sum_{2D}\left(T_e^4 - T_b^4\right). \tag{4}$$

Here the joule power is normalized on the net area of normal parts in the 1D wire, $A_N = \nu_N \times L \times w$. This simple equation provides the average electron temperature T_e of the normal regions under the bias current I. Then, one can find the total voltage drop on the normal parts of the wire as $V = I(\text{d}R(T) / \text{d}T)T_e$ using the average value of T_e. Figure 2 demonstrates the results of the thermal model with the solid blue lines. One can see that the simplified thermal model better describes the non-linearity of the IV curves than the TAPS model. These results indicate that, similarly to recent observations in TiN [8], NbTiN [9], MoGe [10] wires, the nonlinearity of the IV curves at the resistive transition in NbN wires can be associated with the heating effect.

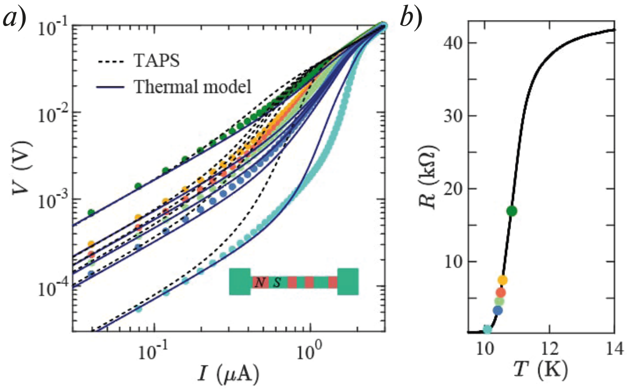

Fig. 2. The current–voltage characteristics of the NbN nanowire (sample A) at various bath temperatures on a log-log scale and a schematic representation of the model ("N" and "S" are superconducting and normal regions of the nanowire, respectively) (*a*); symbols show the experimental data measured at Tb marked by the same symbols at the resistive transition (panel (*b*)). The black dashed lines are fits by the LAMH theory (Eq. (3)). The blue solid lines demonstrate the results of the heating model discussed in the text

Conclusion

In conclusion, we have shown that the current-voltage characteristics measured at the superconducting resistive transition in NbN nanowires can be quantitatively described by the thermal model considered the heat dissipation in NbN samples.

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