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Physica E 18 (2003) 21–22
PHYSICA E
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Response time of a thermometer based on normal metal–insulator–superconductor (NIS) tunnel junctions

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Abstract

We have measured the thermal response of a superconductor–normal metal–superconductor (SINIS) tunnel junction structure at substrate temperature ~ 60 mK by directly heating the electron system in the normal metal island. In our structure, we find the response time is determined by the electron–phonon coupling in the electron temperature range 300–600 mK. By using AC heating, the cut-off frequency caused by this response time has been measured, showing that SINIS structures operate as a thermometer up to a few MHz in this temperature range.

PACS: 73.23.−b; 68.60.Dv; 74.

Keywords: NIS tunnel junction; NS junction; Thermal relaxation time; Electron–phonon coupling

1. Introduction

Symmetric NIS tunnel junction pairs, known as SINIS structures, are known to have interesting applications in solid-state cooling and thermometry [1,2]. If one wants to use them as thermometers for radiation detector applications (bolometry), it is important to know also their frequency response. The goal of this study is to determine the natural bandwidth of a SINIS thermometer, i.e. to directly measure its response time. Since the cryostat used in this study can only be used to measure at low frequencies, we actually measure the DC response, but with an AC heating signal applied to the sample. Since the expected dominant cut-off mechanism, electron–phonon coupling, is a strongly non-linear function of temperature, a change in the DC response is expected as a function of the heating frequency.

Here, we have studied a sample with four NIS junctions and one NS junction connected by a common normal metal (Cu) island, whose lattice temperature ≈ 60 mK is assumed to be given by the cryostat temperature (Fig. 1). By applying the AC heating voltage between one of the superconducting electrodes (connected to a NIS junction) and the grounded Cu island, we can heat the electrons in the frequency range DC—2 MHz, and measure the temperature of the normal metal with a current biased SINIS tunnel junction pair. Direct grounding of the Cu island via the NS junction is used to prevent the heat current from going through the thermometer junctions at high frequencies.

2. Theory and results

In our case, the total cooling power of the Cu island can be described reasonable well as

$$\dot{Q} = \dot{Q}_{\text{el–ph}}(T_{\text{el}}) + \dot{Q}_{\text{NS}}(T_{\text{el}}), \tag{1}$$

where the two terms correspond to cooling by electron–phonon coupling and heat leak through the NS junction. In three-dimensions the electron–phonon cooling power can be written as $\dot{Q}_{\text{el–ph}}(T_{\text{el}}) = \Sigma\Omega(T_{\text{el}}^5 - T_{\text{ph}}^5)$ [3], where Σ is a material dependent parameter and Ω the volume of the Cu island. The heat transfer through the NS-junction is given by

$$\dot{Q}_{\text{NS}}(T_{\text{el}}) = \frac{2}{R_m e^2}\int_{-\infty}^{\infty} \varepsilon(f_{\text{N}} - f_{\text{S}})(1 - A - B)\,\text{d}\varepsilon, \tag{2}$$

where R_m is the normal state resistance of the junction and $f_{\text{N}}(T_{\text{el}})$ and $f_{\text{S}}(T_{\text{S}})$ are the Fermi functions in the normal metal and the superconducting lead [4]. $A(\varepsilon)$ and $B(\varepsilon)$ are coefficients of Andreev and normal reflections. In our

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1386-9477/03/\$ - see front matter
doi:10.1016/S1386-9477(02)00939-6

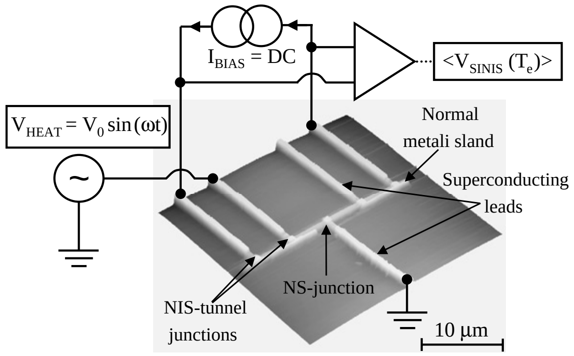

Fig. 1. An AFM image of a typical sample. The line in the middle is the Cu island and others are superconducting Al lines. Upper Al lines are connected to the Cu line with (NIS) tunnel junctions and the lower Al line is connected directly (NS junction). The sample was fabricated on a Si substrate by using electron beam lithography. The volume of the Cu island is Ω=(15 μm)×(450 nm)×(53 nm).

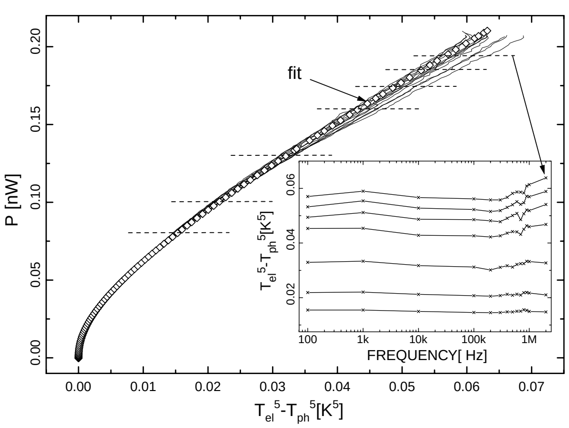

Fig. 2. Measured Cu island electronic temperature as a function of heating power with different frequencies at $T_{ph} \approx 60$ mK (lines). Diamonds are the theoretical fit to Eq. (3). Inset shows electronic temperature as a function of the heating frequency at seven different heating power levels indicated by the dashed lines in the main figure.

simplified model we assume that these coefficients are constant and can be incorporated into an effective normal state resistance $R_m^{\rm eff}$. By using Sommerfeld expansion for Eq. (2) and assuming that $T_S = T_{ph}$, the total heat flow from the Cu island can be approximated as

$$\dot{Q} = \Sigma\Omega(T_{el}^5 - T_{ph}^5) + \frac{1}{R_m^{\rm eff} e^2}\,\frac{\pi^2}{3}\,k_B^2(T_{el}^2 - T_{ph}^2). \tag{3}$$

Fig. 2 shows the measured normal metal electronic temperature as a function of the applied heating power with heating frequencies ranging from 100 up to 2 MHz, at substrate temperature $T_{ph} \approx 60$ mK. The highest heating frequency is limited by the bandwidth of the heating circuit. For the lowest heating frequency data (at 100 Hz), we fit the theoretical cooling power of Eq. (3) using two free parameters Σ and $R_m^{\rm eff}$. The best fit gives $\Sigma = 5.0$ (nW/K^5 μm^3) and $R_m^{\rm eff} = 80\ \Omega$. The value for Σ is consistent with literature [2]. Clearly, Eq. (3) fits the data well up to reasonably high frequencies of a few hundred kHz. Above that, the electron temperature starts to differ strongly from the low-frequency data, and deviate from the fitting model in the high heating power limit.

We suggest that this deviation is due to the thermal relaxation time between electrons and phonons. The thermal cut-off frequency has the form $f_c = 1/(2\tau) = (1/2\pi)(\partial\dot{Q}/\partial T_{el})(1/C_{el})$, where C_{el} is the electronic heat capacity of the Cu island. In Fig. 2 we see that above ~ 300 mK ($T_{el}^5 - T_{ph}^5 \approx 0.03$ K^5) electron–phonon coupling becomes the dominant cooling effect, so that in the high heating power limit the cut-off simplifies to $f_c = (5\Sigma/2\pi\gamma n)T_{el}^3$, where γ is the Sommerfeld constant and n is the number of Cu atoms. By using typical material parameters for Cu and the fitted value for Σ, we find that f_c is of the order of a few MHz in the temperature range 300–600 mK.

At temperatures below 300 mK the dominant cooling effect is the heat flow through the NS junction, which causes f_c to be independent of temperature and of the order of a few hundred kHz. Because of the much weaker temperature dependence of $\dot{Q}_{NS}$, it is possible that our measurement sensitivity is not high enough for observing the effect with smaller heating power.

Acknowledgements

This work is supported by the Academy of Finland. J.M.K. wishes to thank partial financial support by the Emil Aaltonen Foundation and the Finnish Cultural Foundation.

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