Direct measurement of the electron-phonon relaxation rate in thin copper films

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We have used normal metal-insulator-superconductor (NIS) tunnel junction pairs, known as SINIS structures, for ultrasensitive thermometry at sub-Kelvin temperatures. With the help of these thermometers, we have developed an ac-technique to measure the electron-phonon (e-p) scattering rate directly, without any other material or geometry dependent parameters, based on overheating the electron gas. The technique is based on Joule heating the electrons in the frequency range DC-10 MHz, and measuring the electron temperature in DC. Because of the nonlinearity of the electron-phonon coupling with respect to temperature, even the DC response will be affected, when the heating frequency reaches the natural cut-off determined by the e-p scattering rate. Results on thin Cu films show a $T^4$ behavior for the scattering rate, in agreement with indirect measurement of similar samples and numerical modeling of the non-linear response.

1 Introduction

Interaction between conduction electrons and thermal phonons is elementary for many processes and phenomena at low temperatures, and better measurements of the scattering rate need to be developed to characterise these processes accurately. Most earlier data was taken at DC, where sample parameters have to be taken into account before one can obtain the strength of the e-p interaction from a fitting parameter [1, 2, 3, 4]. It would therefore be quite benefitial if one could measure the e-p scattering rate $1/\tau_{e-p}$ directly without any fitting parameters and as a function of any external parameter. Some steps towards this direction have already been taken with a RF-based technique [5].

Here we report a technique, which measures the e-p scattering rate directly without any fitting parameters and without the need of more complex RF circuitry. The rate is read directly from a cut-off frequency seen in the non-linear response of the DC electron temperature, measured with the help of NIS tunnel junctions at sub-Kelvin temperatures.

In the disordered limit $ql << 1$, where $q$ is wavevector of the dominant thermal phonons and $l$ is the electron mean free path, theory predicts that the electron-phonon scattering rate from acoustic phonons is $1/\tau_{e-p} = \alpha T_e^4$ [6, 7], where $\alpha$ is a sample parameter and $T_e$ the electron temperature. In contrast, in the pure limit temperature dependence $1/\tau_{e-p} = \alpha'/T_e^3$ is expected [8].

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2 Experimental techniques

Our sample geometry is nearly identical to the one reported for DC measurements [4, 9], schematic of the sample and the measurement circuit is depicted in Fig. 1(a). The sample used in this work has two Cu normal metal islands of length $\sim 500\mu$m, width 300nm, and thickness 45nm, on oxidized Si substrate. The islands were separated by a distance of $2\mu$m. The two aluminum wires going up in Fig. 1(a) from each island were separated from Cu by a thin oxide layer, forming normal metal-insulator-superconductor (NIS) tunnel junctions in the overlap area. NIS junctions (SINIS structure) were used to measure the electron temperature of the Cu islands. Two aluminum wires going down from the lower Cu line were in metallic contact with the island, forming normal metal-superconductor (NS) junctions. These provided good electrical contact to the Cu, but the heat leak through them is negligible due to Andreev reflection, thus providing uniform heating power for the Cu wire. Heat leak through the tunnel junctions was also estimated to be at least an order of magnitude smaller than the cooling by electron-phonon coupling.

SINIS thermometers were calibrated against a Ruthenium Oxide thermometer attached to the sample stage. The SINIS thermometers were current biased, and temperature of the cryostat (base temperature 60 mK) was changed slowly to keep the sample in thermal equilibrium with the sample stage, while the voltages of the SINIS thermometers were measured. There was a small discrepancy with the measured calibration curve and the corresponding BCS theory result at the lowest temperatures, but it can be explained by extra noise coming from the measurement circuitry to the sample [4, 9].

The experiment then proceeds by heating the electrons of the lower wire via the NS junctions with an ac-voltage. The frequency of the heating signal was changed step by step, and the voltages of both SINIS structures were measured simultaneously. The upper Cu island in Fig. 1(a) could be used to measure the phonon temperature [4, 9], whereas the lower SINIS measured the heated electron temperature. We took many frequency sweeps with the same ac-voltage amplitude, and averaged the data to reduce the noise. The amplitude of the ac-voltage was then changed to obtain a different average electron temperature. A typical sweep consisted of 300-500 frequency points between 0.1Hz-5MHz. The five representative sweeps shown in Fig. 1(b) are an average of approximately 20 frequency sweeps each. Overheating is clearly seen in the high frequency range between 10kHz-1MHz for all the sweeps shown, which can be understood by the numerical modeling discussed below.
3 Numerical modeling

To fully understand the effect of ac heating at a signal frequency $\omega$ on the electron temperature $T_e$, we need to solve the full differential equation governing the heat flow:

$$T_e \frac{dT_e}{dt} = -A(T_e^n - T_p^n) + P'[1 - \cos(2\omega t)],$$

where we have defined $A = \Sigma' / \gamma$ and $P' = P_{ac}/(2\gamma \Omega)$, where $\Sigma'$ is the sample constant in the electron-phonon interaction power $P = \Sigma' \Omega(T_e^n - T_p^n)$, $\Omega$ is the sample volume, $\gamma$ is the Sommerfeld constant and $P_{ac}$ is the amplitude of the ac power. Since $\Sigma'$ also depends linearly on $\gamma$, we point out that the temperature relaxation rate does not depend on the heat capacity at all, and is only dependent on the electron-phonon scattering rate.

We have integrated Eq. (1) numerically for exponents $n = 5, 6$, corresponding to $1/\tau_{e-p} = \alpha T_{e}^m$, $m = 3, 4$. From the $T_e(t)$ curve, the steady state average electron temperature has been determined as a function of $\omega$, with varying ratio of ac heating $P_{ac}$ to DC heating power $\Sigma' \Omega T_p^n$, and with realistic sample parameters. Fig. 2(a) shows the obtained results for four different power ratios in the case $n = 6$ (the impure limit). As can be seen, the average $T_e$ develops a clear step up at some cut-off frequency, and this frequency moves up as a function of $T_e$. To be able to define this cut-off unequivocally, we analyse the data further by taking the logarithmic derivative with respect to $\omega$, shown in Fig. 2(b). The log-derivative develops a clear peak, whose position we will use as the definition of the cut-off frequency $\omega_c$. In addition, the log-derivative shows quite clearly the effect of the strength of the non-linearity: the larger the relative ac power (top curve largest), the more non-symmetric the peak is.

If one plots $\omega_c$ vs. the low-frequency limit of $T_e$, one obtains the plot shown in Fig. 3(a), where both cases $n = 5$ and $n = 6$ are shown. It is quite clear that $\omega_c$ follows the right temperature dependence expected for a cut-off determined by the e-p scattering rate only, as long as the nonlinearity is not too severe (the lowest temperatures deviate a bit in this case). Therefore, we can state with confidence that the analysis scheme outlined above will be a direct measurement of the e-p scattering rate without any fitting parameters.

Fig. 2 (a) Simulated average electron temperature. (b) Logarithmic derivative of the simulation data.
4 Experimental results

Figure 3(b) shows the experimental data analyzed as outlined above, with the maxima of the log-derivatives of the measured data vs. the low-frequency limit of $T_e$. The best two parameter fit $f_e = a T^n$ gives $n = 3.7$. However, the scatter in the data is still a bit high, and to make a more qualitative analysis, we also compare the integer powers $n = 3$ and $n = 4$. As can be seen, the dashed line corresponding to power $T^4$ fits to data much better than the one corresponding to $T^3$. This temperature dependence is in agreement with the DC measurements in the disordered regime [4, 9]. From the $T^4$ fit we get $\Sigma' = 1.0 \times 10^{10} \text{W/Km}^3$, using a literature value $\gamma = 0.69 \text{mJmol}^{-2} K^2$ for copper, again in agreement with our DC data. One should keep in mind, however, that the numerical value of $\Sigma'$ is strongly dependent on the sample disorder. In fact, we have seen in other, very similar samples that the value of $\Sigma'$ can be almost an order of magnitude smaller.

5 Conclusions

We have presented a method to measure the electron-phonon scattering rate directly without the need to know any material or geometry dependent sample parameters. The measurements can be performed at DC, greatly simplifying the electronics, due to the non-linearity of the e-p interaction. Our initial experimental results agree with the DC data for Cu thin films in the disordered limit.

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References

[1] M.L. Roukes and M.R. Freeman and R.S. Germain and R.C. Richardson and M.B. Ketchen, Phys. Rev. Lett. 55, 422 (1985).
[2] F. C. Wellstood, C. Urbina, and J. Clarke, Phys. Rev. B 49, 5942 (1994).
[3] M. Kanskar and M. N. Wybourne, Phys. Rev. Lett. 73, 2123 (1994).
[4] I.J. Maasilta, J.T. Karvonen, J.M. Kivioja and L.J. Taskinen, unpublished, cond-mat/0311031.
[5] D. R. Schmidt, C. S. Yung, and A. N. Cleland, Phys. Rev. B 69, 140301(R) (2004).
[6] A. Schmid, Z. Phys. 259, 421 (1973).
[7] A. Sergeev and V. Mitin, Phys. Rev. B 61, 6041 (2000); Europhys. Lett., 51, 641 (2000).
[8] V. F. Gantmakher, Rep. Prog. Phys. 37, 317 (1974).
[9] J. T. Karvonen, L. J. Taskinen and I. J. Maasilta, in these proceedings.