Electron-phonon interaction in thin copper and gold films

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We have studied the electron-phonon (e-p) interaction in thin Cu and Au films at sub-Kelvin temperatures with the help of the hot electron effect, using symmetric normal metal-insulator-superconductor tunnel junction pairs as thermometers. By Joule heating the electron gas and measuring the electron and the lattice temperatures simultaneously, we show that the electron-phonon scattering rate follows a $T^4$ temperature dependence in both metals. The result is in accordance with the theory of e-p scattering in disordered films with vibrating boundaries and impurities, in contrast to the $T^3$-law expected for pure samples, and $T^2$-law for static disorder.

1 Introduction

Interaction between conduction electrons and thermal phonons is elementary for many processes and phenomena at low temperatures, but there are still only few experimental studies supporting the theory for typical disordered metals. Several earlier results indicated that both in ordered and disordered films the electron-phonon scattering rate follows power law $1/\tau_{e-p} \propto T^3$ [1, 2, 3, 4], and thus the heating power from electrons to phonons is of the form $P = \Sigma \Omega (T_e^5 - T_p^5)$, where $\Sigma$ is a material dependent parameter, $\Omega$ the volume of the sample, $T_e$ the electron temperature and $T_p$ the phonon temperature. However, according to the theory this result is possible only for pure samples in the limit $ql >> 1$, where $q$ is the wavevector of the dominant thermal phonons and $l$ the electron mean free path, coupling to longitudinal phonons only.

In disordered metals, where $ql << 1$, theory predicts that the scattering rate from vibrating disorder is $1/\tau_{e-p} \propto T^4$ [5] so that the heating power is

$$P = \Sigma' \Omega (T_e^6 - T_p^6),$$

when electrons are expected to couple dominantly to transverse acoustical phonons [6]. This result has not been widely confirmed, and in fact we are not aware of any observation of it in standard normal metal films like Cu, Au, Ag, etc. Some evidence exists for strongly disordered ($l \sim 1$nm) Ti and Hf films [7] and Si SOI wafers [8].

Recently we have observed the theoretically expected $T^4$ dependence for e-p scattering rate in evaporated copper [9] and gold films. We have measured the rate at which electrons in a normal metal wire overheat, when DC power is applied to it. Overheating rate was determined directly by measuring the electron and phonon temperatures with help of SINIS-thermometers.

2 Experimental techniques and samples

We have measured several Cu samples with a range of film thicknesses and thus a range of $l$, as reported earlier [9]. Here we concentrate on comparing the data of one of those Cu samples with new data from a Au

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sample. To assess the quality of metal films and to determine the electron mean free path \( l \), we measured the sample resistivities \( \rho \) at 4.2 K and at room temperature in a four-probe configuration, and determined \( l \) for the sub-Kelvin range from the 4.2 K data. Now we can estimate the critical phonon temperatures \( T_{c}^{ql=1} \) corresponding to \( ql = 1 \) by \( T_{c}^{ql=1} = (\hbar c_{t})/(2.82 k_{B}l) \), where \( c_{t} \) is the transverse sound velocity (\( c^{Cu}_{t} = 2300 \) m/s and \( c^{Au}_{t} = 1200 \) m/s).

All measured samples have two normal metal wires of length \( \sim 500 \) µm and width \( \sim 300 \) nm on thermally oxidized Si substrate, separated by a distance 2 µm. The normal metal wires were connected to the measurement circuit by superconducting Al leads as shown in the SEM image (a). Two pairs of current biased leads in both wires are SINIS tunnel junctions for measuring the electron temperature of the wire. The junctions connecting the lower wire to a voltage source are NS-junctions for heating the normal metal. For low enough heating voltages the NS-junctions are biased within the superconducting gap \( \Delta \) of the leads, and Andreev reflection can take place. This makes the NS-junctions perfect thermal insulators despite being electrically conducting, and thus it is possible to Joule heat the normal metal uniformly through the NS-junctions.

![SEM image of a sample](image1.png)

**Fig. 1** (a) An SEM image of a sample. (b) Schematic of the sample and the measurement circuit.

All the measurements were performed by current biasing the two SINIS thermometers and measuring their DC voltages simultaneously in a dilution refrigerator with a base temperature 60 mK. The thermometers were calibrated by varying the bath temperature of the refrigerator very slowly, while measuring the temperature of the sample stage with a calibrated Ruthenium Oxide thermometer.

Figure 2 shows an example of a calibration measurement. It is evident that the agreement between measured calibration curve and corresponding theoretical curve calculated numerically from the BCS theory is good except at the very lowest temperatures. This deviation could arise by two major mechanisms: (i) a component of leakage or noise current affects the measurement, and (ii) the electrons overheat at the low-\( T \) range. We have ruled out (i) by directly measuring the responsivities \( dV/dP \) of the SINIS-thermometers as a function of \( I \) using a lock-in amplifier (fig. 2 inset), and setting the bias current such that we see the expected behavior from BCS theory (\( dV/dP \) decreasing vs. \( I \)). Mechanism (ii), overheating by noise power \( P_{\text{noise}} \), is an obvious explanation since we have seen that filtering the lines clearly improves the situation. Overheating can be modelled with the help of theory for e-p scattering and the Kapitza resistance and the model fits the data perfectly. Thus, the thermometers are calibrated correctly by reading \( T_{e} \) from the BCS-theory curve.

| sample | \( t \) (nm) | RRR | \( \rho \) (\( \mu \Omega \cdot \text{cm} \)) | \( l \) (nm) | \( T_{c}^{ql=1} \) (K) |
|--------|-------------|-----|-----------------|-------|-----------------|
| Cu     | 35          | 1.8 | 3.06            | 21.4  | 0.29            |
| Au     | 40          | 2.3 | 1.94            | 43.0  | 0.08            |

Table 1 Parameters of measured Cu and Au samples. \( \rho \) is the value measured at 4.2 K, \( T_{c}^{ql=1} \) is for transverse modes.
3 Results

In our experiment we applied slowly ramping DC voltage to Joule heating the lower wire through NS-junctions and determined heating power by measuring the current and voltage directly in a 4-wire configuration at $T_{\text{bath}} = 60 \text{ mK}$. Simultaneously we measured the electron temperatures in both wires by SINIS-thermometers.

In Fig. 3 (a) we plot the electron temperatures in both wires vs $P$ obtained from several sweeps for both samples. As can be seen, the temperatures of both wires rise when heating power is increased. This means that the second wire is heated indirectly by phonons, since there is no direct electrical contact between the wires. Therefore, there must be mechanism in the substrate to backscatter hot phonons generated in the lower wire. Most likely this scattering take place in the oxide layer and/or at the interface between the oxide and the substrate. Looking at Fig. 3(a), above a few pW this phonon heating clearly dominates the signal over the noise heating in the upper, non-Joule heated wire (labelled $T_p$). Thus we can identify this as the phonon temperature $T_p$, since all the power absorbed from the phonons has to be re-emitted back into the substrate. Moreover, since the two wires are separated only by $\sim 2 \mu m$, much shorter than lateral mean free path of phonons in SiO $[10]$, the same $T_p$ is seen by the lower wire also. The conclusion is that we can simultaneously measure the electron and phonon temperatures of the heated wire.

Looking back at Fig. 3(a) we can see that for both samples $T_e$ and $T_p$ scale as $(P/A)^{1/6}$. Since the approximation $T_e^6 >> T_p^6$ holds for both samples, we can conclude from the behaviour of $T_e$ alone that equation (1) is valid, and e-p scattering is mediated by vibrating disorder. However, empirically the relation $T_c^6/T_p^6 = \text{const}$ also holds for both samples, which explains why in the data of Fig. 3(a) $P \propto T_p^6$ also. The physical reason for this empirical observation is not clear.

In figures 3 (b-d) we also plot $T_e^n - T_p^n$ vs applied Joule heating power $P$ when $n = 4, 5, 6$ in linear scale, which is strictly the only correct way to plot the data without approximations. It can be clearly seen from Fig. 3(b) that $n = 4$ does not fit the data. This means that Kapitza resistance or e-p scattering by static impurities is not in a dominant role. Also the expected theory for pure samples, $n = 5$, does not fit the data according to the curve shown in Fig. 3(c). However from Fig. 3(d) we can see that $n = 6$ gives straight line for both samples and thus evidence for the validity of equation (1). From the linear fits through the origin we get $\Sigma' = 2.4 \times 10^{10} \text{W/K}^6 \text{m}^3$ for the Copper sample and $\Sigma' = 7.5 \times 10^{10} \text{W/K}^6 \text{m}^3$ for the Gold sample. It should be stressed that in the disordered regime $\Sigma'$ is not only a material dependent parameter but depends directly on the level of disorder through $l$ [6]. For comparisons between different measurements, therefore, both $\Sigma'$ and $l$ need to be quoted. Also, it is unclear at the moment why the Au sample follows the disorder theory, although it has $ql > 1$ if calculated for transverse modes (Table 1). For longitudinal modes it is still in the $ql < 1$ limit.

![Fig. 2](image)

**Fig. 2** Calibration for the SINIS junction in Au sample connected to the lower wire in Fig. 1. The junction is biased at $I = 60 \text{ pA}$ according to responsivity $dV/dP$ measurement shown in the inset.
Fig. 3 (a) The temperature $T_e$ and $T_p$ vs heating power $P$ in log-log scale. Dashed lines are $T = (P/A)^{1/6}$. In the Figs. (b), (c) and (d) $T_e^n - T_p^n$ vs $P$ with $n = 4, 5, 6$ is plotted. Dashed lines are one parameter fits through the origin.

4 Conclusions

We have for the first time obtained clear evidence that the electron-phonon scattering rate scales with temperature as $1/\tau_{e-p} \propto T^4$ in disordered evaporated Cu and Au thin films. This power law corresponds to electrons scattering from phonons mediated by disorder vibrating together with the phonon mode. In contrast, e-p scattering in the presence of static disorder leads to $1/\tau_{e-p} \propto T^2$, a result that has been confirmed in several materials and samples [11].

We stress that the theoretical result $1/\tau_{e-p} \propto T^4$ is valid for a simple metal with $qI < 1$ and little nonvibrating disorder, and with 3D phonons coupled to electrons by the deformation potential. We believe most earlier experiments do not satisfy all these conditions.

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References

[1] V.F. Gantmakher, Rep. Prog. Phys. 37, 317 (1974).
[2] M.L. Roukes et al., Phys. Rev. Lett. 55, 422 (1985).
[3] F. C. Wellstood, C. Urbina, and J. Clarke, Phys. Rev. B 49, 5942 (1994).
[4] M. Kanskar and M. N. Wybourne, Phys. Rev. Lett. 73, 2123 (1994).
[5] A. Schmid, Z. Phys. 259, 317 (1985).
[6] A. Sergeev and V. Mitin, Phys. Rev. B 61, 6041 (2000); Europhys. Lett., 51, 641 (2002).
[7] M.E. Gershenson, D. Dong, T. Sato, B.S. Karasik and A.V. Sergeev, App. Phys. Lett. 79, 2049 (2001).
[8] P. Kivinen et al., J. Appl. Phys. 94, 3201 (2003).
[9] I.J. Maasilta, J.T. Karvonen, J.M. Kivioja and L.J. Taskinen, unpublished, cond-mat/0311031.
[10] E.T. Swartz and R.O. Pohl, Rev. Mod. Phys 61, 605 (1989).
[11] J.J. Lin and J.P. Bird, J. Phys. Condens Matter 14, R501 (2002).