

## Role of Phonon Dimensionality on Electron-Phonon Scattering Rates

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Electron-heating measurements were carried out to measure the electron-phonon scattering rates in CuCr thin films. We examined free-standing and supported films whose thickness and width span lengths comparable to the mean thermal-phonon wavelength. The measured scattering rate was proportional to  $T^2$  from 0.5 to 10 K, independent of sample configuration. We observe that the quantization of the phonon spectrum required by sample dimensions has no effect on the temperature dependence of the electron-phonon scattering rate.

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The measurement of the electron-phonon scattering rate ( $\tau_{ep}^{-1}$ ) in thin metal films has received a great deal of attention in recent years [1-3]. A variety of results have been obtained for the temperature dependence of  $\tau_{ep}^{-1}$ , ranging from  $T^{1.4}$  to  $T^{3.7}$ , in both electron-heating and weak localization magnetoresistance measurements [4,5].

The first of two hypotheses used to explain the range in power laws is a correction to the  $T^3$  dependence expected for clean three-dimensional films due to disorder [6,7]. The impurity scattering in disordered metals modifies  $\tau_{ep}^{-1}$  to the form  $\tau_{ep}^{-1} \propto (T^3/\Theta_D^3)B(T)$ , where  $\Theta_D$  is the Debye temperature.  $B(T)$  introduces the effect of disorder. Its temperature dependence is determined by the parameter  $ql$ , where  $q$  is the mean thermal phonon wave vector and  $l$  is the conduction electron mean free path. In the limit that  $\Theta_D/T \gg 1$  and  $ql \ll 1$ ,  $\tau_{ep}^{-1} \propto T^4$ . In the clean limit,  $\Theta_D/T \gg 1$  and  $ql \gg 1$ , the temperature dependence remains  $\tau_{ep}^{-1} \propto T^3$ .

An additional modification to the scattering rate may be required if the phonon spectrum is affected by the finite film thickness [1,3,8]. Many experiments have been carried out (for films on substrates) in the regime where the mean thermal phonon wavelength ( $\lambda_T$ ) is greater than the film thickness,  $d$  [1-3]. If the acoustic mismatch between the film and substrate is large, then the quantization of the phonon spectrum in the direction perpendicular to the film may be significant. In this case the phonon distribution at low temperature resembles a 2D spectrum leading to a weakened temperature dependence of  $\tau_{ep}^{-1}$ . However, no experiment has been performed that systematically explores the role of phonon dimensionality on the electron-phonon scattering rate.

We have performed an experiment designed to examine the effect of the quantization of the phonon spectrum on the electron-phonon scattering rate in thin CuCr films. A 2D phonon spectrum can be realized at low temperature by removing the supporting substrate from the back of the film (a free-standing film), thus separating the effect of coupling across a film-substrate interface from the intrinsic behavior of the metal film. Electron-heating measurements on free-standing and supported metal structures allowed the determination of the electron energy relaxation rate for sample dimensions and temperatures

which require that the phonon dimensionality change within the metal films.

Films prepared for this experiment were deposited by thermal evaporation from a single CuCr source onto a silicon nitride film grown on a silicon wafer. All features were defined by electron lithography and photolithography using a liftoff process which allowed fabrication of films of thickness between 9.8 and 98.0 nm and widths between 35.0 and 2000 nm. Free-standing and supported structures were deposited simultaneously on the same substrate [9]. The film thickness was measured with a crystal thickness monitor.

The conduction electrons in a thin metal film can be out of equilibrium with the metal lattice for moderate current densities at low temperatures if the electron-phonon scattering rate, which determines the rate of heat flow out of the electron gas, is smaller than the elastic scattering rate [10,11]. The temperature difference between electrons (at temperature  $T_e$ ) and phonons (at temperature  $T_p$ ) is

$$T_e - T_p = \tau_{ep} E^2 / \rho C_e, \quad (1)$$

where  $E$  is the applied field,  $\rho$  the electrical resistivity, and  $C_e$  the electronic heat capacity [10-12]. This expression should hold in the low-field regime where  $eEl_e < k_B T_p$ ; here  $e$  is the electron charge and  $l_e$  is the inelastic scattering length [10]. We define the thermal resistance  $R_{ep} = (T_e - T_p) / \dot{Q} = \tau_{ep} / C_e V$  ( $V$  is the sample volume and  $\dot{Q}$  is the applied power) for comparison to other thermal resistances in this system [10,12].

Electron thermometry must be established for a successful measurement of  $R_{ep}$ . We chose to use the resistance anomaly associated with the Kondo effect as an electron thermometer [13]. Since the Kondo contribution to the resistivity is dependent only on the electron distribution at the Fermi surface [14], the electrical resistance will yield the effective electron temperature [15]. The Kondo resistance anomaly of a CuCr film can be as large as a few percent of the residual resistivity for moderate Cr concentration [16], allowing the electron temperature to be determined accurately as a function of heating power. The electron gas temperature is defined in equilibrium where the electron energy has a Fermi distribu-

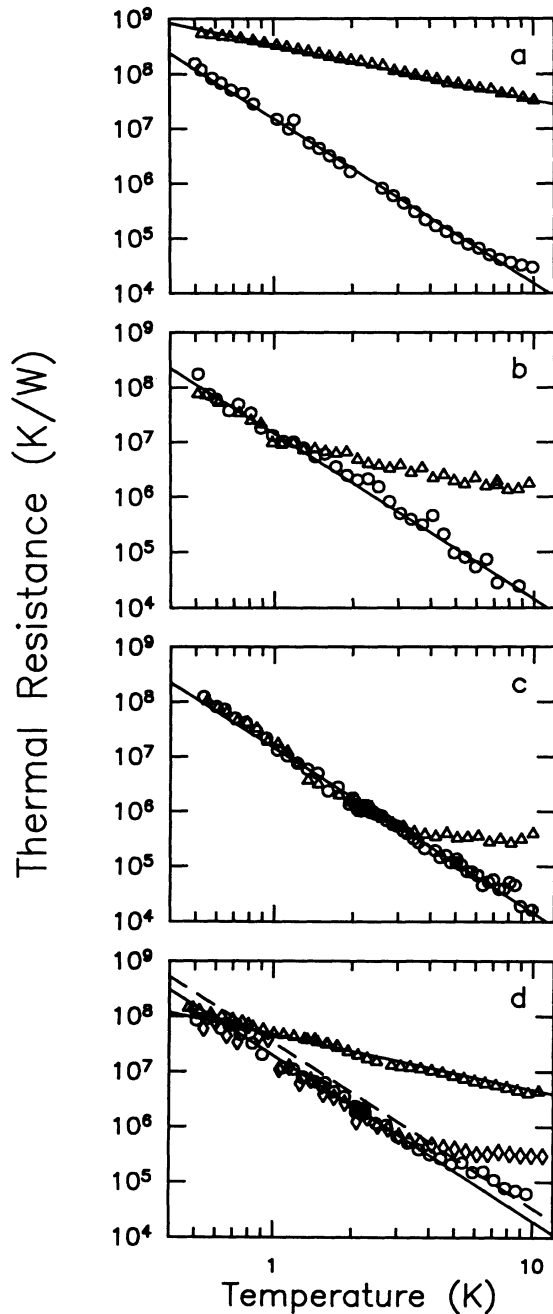


FIG. 1. The thermal resistance for heat transport out of the electron gas for supported and free-standing films. (a)–(c) refer to a  $20.0\text{ nm} \times 2.0\text{ }\mu\text{m} \times 100\text{ }\mu\text{m}$ , 2000 ppm Cr in Cu supported ( $\circ$ ) and free-standing ( $\Delta$ ) film. (a) In vacuum: The lines are a  $1.52 \times 10^7 T^{-3}$  fit to the supported film and a  $3.33 \times 10^8 T^{-1}$  fit to the free-standing film. (b) 3 to 4 monolayers of  $^4\text{He}$  deposited onto both films: The line is a  $1.42 \times 10^7 T^{-3}$  fit for the thermal resistance. (c) In 3 atm  $^4\text{He}$ : The line is the same as in (b). (d) Data for five parallel  $98.0\text{ nm} \times 0.16\text{ }\mu\text{m} \times 50\text{ }\mu\text{m}$ , 1000 ppm Cr in Cu supported ( $\circ$ ) and free-standing films ( $\diamond$ ) in 3 atm  $^4\text{He}$ , and a free-standing film in vacuum ( $\Delta$ ). The solid lines are a  $4.72 \times 10^7 T^{-1}$  fit for the free-standing film in vacuum and a  $2.51 \times 10^7 T^{-3}$  fit for the

tion. In the nonequilibrium situation of a heating experiment, the electron distribution will not necessarily resemble a Fermi distribution at an elevated temperature. However, calculations by Arai [17] and by Sarker *et al.* [18] show that this is indeed the case.

The thermal resistance between 0.5 and 10 K was measured by determining  $T_e$  from the electrical resistance as a function of dc heating current. An ac bridge with an excitation frequency of 17 Hz and amplitude small enough to generate negligible heating was used to measure  $\rho$ . The differential resistance was integrated to find the static resistance from which  $T_e$  can be determined by comparison to the calibration at zero dc electric field. The electron temperature was raised by no more than 10% above ambient, minimizing effects of a nonequilibrium phonon distribution.

The first set of samples consisted of two 20.0-nm-thick films each  $2.0\text{ }\mu\text{m}$  wide and  $100\text{ }\mu\text{m}$  long. One film was supported by a 140-nm-thick silicon nitride film on a silicon wafer, while the other was free standing. These films have  $k_F l = 140$ , with resistivities differing by only 4%. The total thermal resistance  $R_{th}$  of these films is shown in Fig. 1(a).  $R_{th}$  of the supported film is best fitted with a  $T^{-3}$  dependence. The free-standing film has a much higher thermal resistance, fitted with  $T^{-1}$  that results from conduction of heat by electrons along the length of the film. The electron-heat conduction in such a small metallic structure is much larger than the phonon conductivity [19,20].

A  $^4\text{He}$  film, about 3 or 4 monolayers thick, was deposited onto the surfaces of the films. Below 1 K, the helium will consist of a  $\sim 2$ -monolayer-thick, solidlike film and a  $\sim 1$ -monolayer superfluid film. The helium thickness can be estimated from the Kosterlitz-Thouless transition temperature of the films [21,22] which was manifested in the heating curves. This case is shown in Fig. 1(b), where  $R_{th}$  of the free-standing film changes dramatically when the helium is added. The phonons can now couple to the helium film, which has a high thermal conductivity below the Kosterlitz-Thouless transition. The thermal resistance of the free-standing and supported films is now similar up to about 1 K. Above 1 K, the thermal resistance of the helium becomes the main bottleneck for heat transport. Upon pressurizing the cell to 3 atm  $^3\text{He}$  [Fig. 1(c)], we found  $R_{th}$  of the two films to be similar up to  $\approx 3$  K, where the thermal resistance of the helium dominates.

We can determine the dominant contributions to the thermal resistance of the free-standing and supported films described in the preceding two paragraphs. In gen-

supported film. At high temperatures the data for the supported film fall on the dashed line representing the data for the evacuated cell (not shown) due to the higher thermal resistance through the  $^4\text{He}$ .

eral,  $R_{th}$  can be written as

$$R_{th}^{-1} = R_{ee}^{-1} + \frac{1}{R_{ep} + (R_{bd}^{-1} + R_K^{-1})^{-1}}, \quad (2)$$

where  $R_{bd}$  is the boundary resistance between phonons in the metal and the substrate,  $R_K$  the Kapitza resistance between phonons in the metal and the helium, and  $R_{ee}$  the thermal resistance associated with the electron thermal conductivity. From Fig. 1,  $R_{ee}^{-1}$  is small and so the first term can be neglected in all cases except that of the free-standing film in vacuum. For the supported film in vacuum,  $R_{th} = R_{ep} + R_{bd}$ . With  $^4\text{He}$  present we find that below  $\sim 3$  K the thermal resistances of the free-standing and supported samples are equivalent. Since there is no film-substrate interface for the free-standing film,  $R_{bd}$  is infinite and  $R_{th}$  reduces to  $R_{ep} + R_K$ . The supported film's thermal resistance is nearly unchanged by the addition of helium. The thermal resistance of the free-standing film in helium is nearly identical to that of the supported film in vacuum:  $R_{ep} + R_K \approx R_{ep} + R_{bd}$ . It is now evident that  $R_{ep}$  dominates. If, for example,  $R_{bd}$  were much larger than  $R_{ep}$ , then it follows that  $R_K \approx R_{bd}$ . Consequently, we would expect that the thermal resistance of the supported film,  $R_{th} = (R_{bd}^{-1} + R_K^{-1})^{-1}$ , should be substantially lower after the addition of helium. This is contrary to our experiment. A calculation supports the conclusion that  $R_{ep}$  dominates and we find that  $R_{bd}$  contributes about  $(25 \pm 10)\%$  of the thermal resistance for this film thickness [23]. Since the data very closely follow a  $T^{-3}$  power law over the entire temperature range, we conclude, from Eq. (1), that  $\tau_{ep} \approx (4.2 \pm 0.5 \text{ K}^2) T^{-2}$  ns.

The fact that the scattering rate is not affected by the film-substrate condition (whether the film is supported or free standing) implies either that the phonon spectrum in both films resembles a 2D spectrum or that the  $T^2$  dependence is intrinsic to the film and not affected by the dimensionality of the phonon spectrum. We present arguments as to why the latter is correct. The mean thermal phonon wavelength in copper ( $\lambda_T$ ) can be estimated as  $\lambda_T = hc/2k_B T$ , where  $c$  is the speed of sound. Since  $c$  in copper is 4760 m/s (longitudinal) and 2325 m/s (transverse),  $\lambda_T$  falls in the range  $55.5 \text{ nm}/T \leq \lambda_T \leq 114 \text{ nm}/T$  with  $T$  in kelvin. Thus, below a few degrees,  $\lambda_T$  is greater than the thickness of the free-standing metal film plus helium [Fig. 1(b)], ensuring a 2D phonon spectrum. We conclude that  $\tau_{ep}^{-1}$  for a Cu film on a silicon-nitride/silicon substrate has the same temperature dependence and magnitude as a film with a 2D phonon spectrum. If the phonon spectrum were 2D in both the free-standing and supported films, we would expect the scattering rate to cross over to a higher power law at a few degrees. We observe no evidence for such a crossover and conclude that the  $T^2$  dependence represents processes intrinsic to the films.

In an attempt to induce a 3D phonon spectrum we measured  $R_{th}$  of five parallel 98 nm thick,  $0.16 \mu\text{m}$  wide,

$50 \mu\text{m}$  long, 1000 ppm Cr in Cu films in both free-standing and supported configurations [Fig. 1(d)]. For this set of films,  $k_{Fl} = 500$ , and the resistivities differ by 10%. The power law is similar to the 20.0-nm-thick sample and  $R_{bd}$  is a larger fraction of the thermal resistance of this film. If  $R_{bd}$  had been dominant in the 20-nm-thick films, the thermal resistance in the 98-nm-thick films would have been 5 times larger due to the smaller contact area (compared to the 70% increase observed). The thermal resistance of the supported film decreases by  $\sim 35(\pm 5)\%$  when the cell is pressurized with 3 atm of  $^4\text{He}$ . We observed no evidence for a change in either the magnitude or temperature dependence of  $\tau_{ep}^{-1}$  from the rate measured in the 20.0-nm-thick films despite the  $5\times$  increase in film thickness. If the modification of the phonon spectrum were responsible for the  $T^2$  dependence of  $\tau_{ep}^{-1}$  in the 20-nm-thick films, we would expect that the power law would increase for the 98-nm films since  $d > \lambda_T$ . Again, the lack of any crossover implies processes intrinsic to the film.

To further explore the possible phonon dimensionality effect on  $\tau_{ep}^{-1}$ , we measured the thermal resistance of thin, narrow wires of the same material as in Figs. 1(a)–1(c). Figure 2 presents  $R_{th}$  of two parallel 35.0 nm wide, 20.0 nm thick,  $50.0 \mu\text{m}$  long, 2000 ppm Cr in Cu wires on a silicon-nitride/silicon substrate with  $k_{Fl} = 104$ . These data are best fitted with  $\tau_{ep} = (3.1 \pm 0.5 \text{ K}^2) T^{-2}$  ns, and have the same ratio of  $R_{bd}$  to  $R_{ep}$  as the previous 20.0-nm-thick films. The temperature dependence of  $\tau_{ep}^{-1}$  is unaffected by decreasing the film width. In this sample the thickness as well as the width will be less than  $\lambda_T$  below 2 K. It is clear that the modification of the pho-

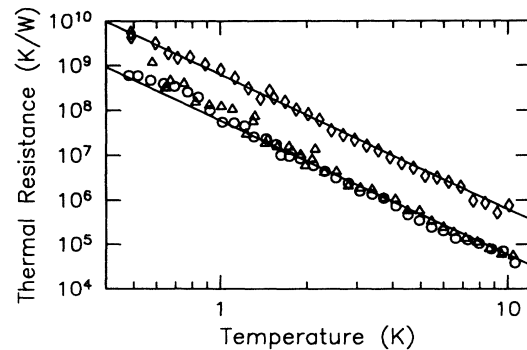


FIG. 2. The thermal resistance for a  $20.0 \text{ nm} \times 35.0 \text{ nm} \times 50 \mu\text{m}$ , 2000 ppm Cr in Cu supported wire in vacuum ( $\diamond$ ). The line is a  $6.25 \times 10^8 T^{-3}$  fit to the thermal resistance. We observe the same temperature dependence and magnitude for the electron-phonon scattering rate as in the wide film ( $2 \mu\text{m}$ ) case. Also presented are the thermal resistance for two  $9.8 \text{ nm} \times 2.0 \mu\text{m} \times 50 \mu\text{m}$ , 2000 ppm Cr in Cu films, one on a silicon substrate ( $\circ$ ), and the other on a 140-nm-thick silicon nitride film grown on a silicon substrate ( $\triangle$ ). The line is a  $7.87 \times 10^7 T^{-3}$  fit to the thermal resistance. No evidence is seen for a contribution to the thermal resistance from the nitride layer.

non spectrum is *not* responsible for the  $T^2$  dependence of  $\tau_{ep}^{-1}$ ; the reduction of the film width does not cause a corresponding change in the temperature dependence.

Finally, we investigated the effect of the nature of the substrate material on the thermal resistance. In Fig. 2, we present  $R_{th}$  of two 9.8-nm-thick CuCr films, one film on a silicon nitride film/silicon substrate and one film on a clean silicon substrate. The two data sets are identical within experimental uncertainty. We see a change ( $\leq 10\%$ ) when  $^4\text{He}$  is added to the system and conclude that the 120-nm-thick glassy nitride layer between the silicon and the metal film has no significant effect on  $R_{th}$  in this system. These 9.8-nm films extend the thickness range to a factor of 10 over which  $\tau_{ep}$  is essentially independent of  $d$ . A comparison of  $\tau_{ep}$  measured at different film thickness is instructive. The scattering times measured for the 98.0-, 20.0-, and 9.8-nm-thick films are between  $(3.1 \text{ K}^2)T^{-2}$  and  $(4.7 \text{ K}^2)T^{-2}$  ns.

Rammer and Schmid [6] calculate the function  $B(T)$  for various values of the parameter  $ql$  in the limit  $\Theta_D \gg T$ . In our films,  $ql$  varies from 0.1 in the thinnest films at 0.5 K to 21 in the thickest at 10 K ( $0.3 \leq ql \leq 5.8$  in the 20.0-nm films) for longitudinal phonons and  $\Theta_D/T$  ranges from 630 to 31.5 over the temperatures studied. These values of  $ql$  lie between the limits set in the introductory paragraph. Consequently,  $B(T)$  should exhibit a functional form between  $T^0$  and  $T^1$ , leading to a  $\tau_{ep}^{-1} \propto T^p$ , with  $3 < p < 4$ . This description will not fit our data. We find that  $\tau_{ep}^{-1} \propto T^2$  independent of phonon dimensionality and  $ql$ . It is the view of Al'tshuler *et al.* [1] that there is no experiment which has indicated the existence of a new mechanism of energy (or phase) relaxation that would account for  $\tau_{ep}^{-1} \propto T^2$ . They suggest that it is sufficient to take into account the particular film geometry, the electron mean free path, the structure of the film, and the phonon dimensionality. It is our view that other features may need to be included, such as phonon surface states and grain size, to understand the temperature dependence of the electron-phonon scattering rate.

In summary, we have measured electron-phonon scattering rates in thin CuCr films for free-standing as well as supported structures. The geometry of the films was varied in order to search for a change in the temperature dependence due to phonon quantization. The technique allowed us to characterize contributions to the thermal resistance from the electron conductivity, the acoustic mismatch at the interface, and electron-phonon processes. No evidence that the phonon dimensionality has an effect on  $\tau_{ep}^{-1}$  was found. The measured temperature dependence of the scattering rate cannot be explained within the theory of Rammer and Schmid. The absence of a dimensional dependence is unexpected and suggests that the theory of electron-phonon scattering may not be complete. Evidently more experimental and theoretical work is needed to understand the specifics of electron-phonon scattering in thin films.

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