Electron-phonon scattering times in three-dimensional disordered Sb films

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We have measured the electron-phonon scattering times τ_{ep} in a series of three-dimensional Sb films having the characteristic of $ql \sim 1$, where q is the wave number of the thermal phonons, and l is the electron elastic mean free path. We observe that $1/\tau_{ep} \sim T^p$, with $p \approx 2.4$, in the temperature range 1–14 K. In addition, we find a very weak dependence of $1/\tau_{ep}$ on l. Our observations are compared with theoretical predictions for electron-phonon interactions in the presence of disorder and with previous experimental results in thin Sb films.

I. INTRODUCTION

The electron-phonon scattering time τ_{ep} in the presence of strong impurity scattering is an issue of long-standing interest. Theoretically, electron-phonon interaction in disordered metals has been studied for over two decades and widely varied results were obtained.[1–4] Recently, it is widely accepted that a consensus has finally been reached in theoretical efforts.[2–4] On the other hand, few experiments have successfully provided an overall consistency check for the various aspects of the theoretical predictions. For instance, apart from the dependence on the electron elastic mean free path l, the expected T^4 dependence of the electron-phonon scattering rate $1/\tau_{ep}$ in the dirty limit is (almost) unseen in experiments.[5] In fact, it is conjectured that most material systems previously studied are not yet strongly disordered enough for the electron-phonon interactions to strictly satisfy the dirty-limit criterion of $ql \ll 1$, where q is the wave number of the thermal phonons. Instead, most experiments reported in the literature possessed values of $ql \sim 1$, i.e., the electron-phonon interaction fell in the intermediate region between the clean limit ($ql \gg 1$) and dirty limit. It has been argued that the theory is in good agreement with experiment in this intermediate region.[6] In this work, we report our experimental results of $1/\tau_{ep}$ in a series of thick Sb films, which have $ql \approx 0.2T$, where T is in K. Our results are compared with the theoretical predictions for electron-phonon interactions in the presence of disorder and with previous experimental results in thin Sb films.

It is now well established that weak-localization studies can be very reliably used to extract the electron dephasing scattering times τ_ϕ in disordered metals. According to the theory, the weak-localization effects in disordered systems are essentially controlled by τ_ϕ given by[7]

$$\frac{1}{\tau_\phi(T)} = \frac{1}{\tau_0} + \frac{1}{\tau_i(T)} \approx \frac{1}{\tau_0} + \frac{1}{\tau_{ep}(T)} \approx \frac{1}{\tau_0} + AT^p, \qquad (1)$$

where τ_0 is a constant (the zero-temperature dephasing time) currently under much debate.[8] In the case of *three* dimensions, unlike the cases of reduced dimensions, electron-phonon scattering is the *sole*, significant inelastic process, while the small-energy-transfer (''quasielastic'') electron-electron scattering is not important.[3] Therefore, we have identified the inelastic scattering rate with the electron-phonon scattering rate and written $1/\tau_i \approx 1/\tau_{ep} \approx AT^p$ in Eq. (1), where A characterizes the strength of the electron-phonon interaction, and p is the effective exponent of temperature.

II. EXPERIMENTAL METHOD

Thick Sb films were prepared by dc sputtering deposition onto glass substrates held at room temperature. A background pressure of $\approx 8 \times 10^{-6}$ torr was achieved before the sputtering deposition was initiated, while an argon atmosphere of $\approx (4.5-5.0) \times 10^{-2}$ torr was maintained during the deposition process. The deposition rate was varied from about 11 to 60 Å /min in order to ''tune'' the amount of disorder, i.e., the residual resistivity $\rho_0 [= \rho(10\,\mathrm{K})]$ of the films. For our films used in the present work ρ_0 varied from about 700 to 2500 $\mu\Omega$ cm, and the resistivity ratios $\rho(300\,\mathrm{K})/\rho_0$ were in the range 0.90–0.94. The films deposited were all 3000±300 Å thick so that they were three dimensional with regard to weak localization effects. Also, the phonons participating in electron-phonon scattering in these films were three dimensional. The values of the electron diffusion constant for our films are $D \approx (4300/\rho_0)$ cm^2/s (Ref. 9), where ρ_0 is in $\mu\Omega$ cm.

III. RESULTS AND DISCUSSION

The magnetoresistances of our samples are measured in low magnetic fields and are then compared with three-dimensional weak localization theory[7] to extract the values of $1/\tau_\phi$. As expected, the three-dimensional weak localization theoretical predictions can well reproduce our measured

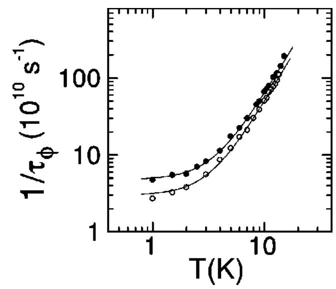

FIG. 1. The electron-dephasing rate $1/\tau_\phi$ as a function of temperature for two representative thick Sb films with $D \approx 3.8$ (●) and 2.6 cm^2/s (○). The solid curves are the theoretical predictions of Eq. (1).

magnetoresistances (not shown). Our experimental results of the electron dephasing rate $1/\tau_\phi$ as a function of T for two representative Sb films are plotted in Fig. 1. For each of our samples studied in this work, the measured $1/\tau_\phi$ are least-squares fitted to Eq. (1) with the strength of electron-phonon coupling A, the exponent of temperature p, and the zero-temperature dephasing time τ_0 as adjusting parameters. We find that Eq. (1) can well describe the experimental data of $1/\tau_\phi$ over our measuring temperatures of 1–14 K. Our best fitted value of p is *essentially the same* for the various films studied; we obtain the effective exponent of temperature $p \approx 2.4 \pm 0.2$. In addition, we observe that $1/\tau_{ep}$ for our thick films depends *very weakly* on the electron elastic mean free path l. Such l behavior is distinctly different from that in, e.g., the dirty-limit regime where $1/\tau_{ep}$ depends notably on disorder.[2,3,10]

Figure 2 shows the variation of $1/\tau_{ep}$ at a representative temperate of 10 K as a function of electron diffusion constant D ($\sim l$) for several thick Sb films. It is seen that the dephasing rate $1/\tau_{ep}(10\,\mathrm{K})$ changes only in the range $(4.7-6.5)\times 10^{11}$ s^{-1} as D increases by a factor ~ 3 from 2.0 to 5.8 cm^2/s (corresponding to l varying from 14 to 40 Å). That is, $1/\tau_{ep}$ depends very weakly on D or l. Our values of $1/\tau_{ep}$ are on the same order of magnitude with previous experimental values found in thin Sb films.[9]

For our thick Sb films, the average sound velocity $v_s \approx 2000$ m/s.[11] Then, $ql \approx (k_B T/\hbar v_s) l \approx (0.1-0.3)T$, where T is in K. That is, insofar as electron-phonon interaction is concerned, our thick films fall in the intermediate regime ($ql \sim 1$) between the clean limit ($ql \gg 1$) and dirty limit ($ql \ll 1$) at our temperatures of measurement.

Recently, the theory for electron-phonon interaction in disordered metals has been reexamined in the literature.

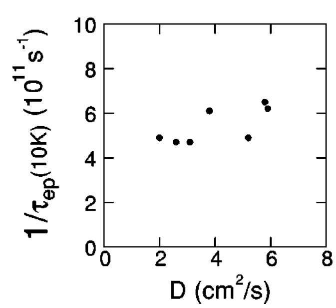

FIG. 2. The electron-phonon scattering rate $1/\tau_{ep}(10\,\mathrm{K})$ as a function of diffusion constant D for several thick Sb films.

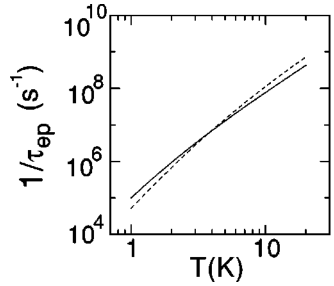

FIG. 3. Theoretical electron-phonon scattering rate $1/\tau_{ep}$ as a function of temperature for two representative thick Sb films with $l = 14$ (dashed line) and 40 Å (solid line). These two theoretical curves are evaluated using longitudinal speed of sound $v_{s,L} \approx 3400$ m/s, transverse speed of sound $v_{s,T} \approx 1400$ m/s, the Debye temperature $\theta_D \approx 210$ K, the Fermi wave number $k_F \approx 1.0 \times 10^9$ m^{-1}, the Fermi energy $E_F \approx 90$ meV, and the electronic density of states at the Fermi level $N(0) \approx 9.1 \times 10^{45}$ states/m^3 J.

Rammer and Schmid,[3] Reizer and Sergeyev,[2] and Belitz[4] have treated this problem by considering contributions from both the longitudinal and transverse phonons and predicted that interactions between electrons and transverse phonons dominate the inelastic scattering, resulting in a total $1/\tau_{ep}$ possessing a nonmonotonic dependence on T and l. For the case of semimetal Sb in the intermediate regime of disorder, their theoretical predictions of $1/\tau_{ep}$ as a function of T are plotted in Fig. 3 for two values of l: 14 (dashed curve) and 40 Å (solid curve). Figure 3 indicates that the theoretical $1/\tau_{ep}$ is fairly insensitive to disorder and has a nonsingle value of p (~ 2.5–3.3 for the case $l = 40$ Å, while ~ 2.7–3.6 for the case $l = 14$ Å, for example). Comparison of Figs. 2 and 3 reveals that the theoretical values of $1/\tau_{ep}$ are about 3 to 4 orders of magnitude lower than the experimental values. Such large discrepancies can by no means be removed even if the uncertainties in our values of the relevant parameters (taken from Refs. 9, 11 and 12) used in evaluating the theoretical curves are somewhat minimized. Thus, our experimental results are in disagreement with the theoretical predictions in the intermediate regime of $ql \sim 1$. Previously, we have already observed in a number of disordered metals that the theory is incomplete in the dirty-limit regime of $ql \ll 1$ (Ref. 10) (where the most noticeable discrepancy is that the theory predicts $1/\tau_{ep} \sim T^4$, while very frequently the experiment reveals $1/\tau_{ep} \sim T^2$).

Using heating measurements, Liu and Giordano[12] have previously obtained a *low* value of exponent of temperature $p \sim 1.4$ for $1/\tau_{ep}$ in numerous *thin* (50–900 Å thick) Sb films. They also reported that $1/\tau_{ep}$ was independent of disorder even when the sheet resistances of their films were changed by a factor of 10. Our observation of a very weak dependence of $1/\tau_{ep}$ on l is in line with their result. Their T dependence can be reconciled with ours if one considers that phonon confinement effect might be significant in their films. If the phonons behave effectively two dimensionally in their thin-film samples while three dimensionally in our thick-film samples, then it is straightforward for us to obtain a value of p (≈ 2.4) that is raised by an amount of 1.0 from its corresponding two-dimensional value of 1.4. Our observation, together with the independent observation of Liu and Giordano, strongly suggests the importance of the effect of phonon dimensionality in determining the temperature dependence of $1/\tau_{ep}$. Thus far, the role of the phonon confinement effect in determining the temperature behavior of $1/\tau_{ep}$ has been controversial and investigated by, e.g., comparing (constricted) supported and free-standing films.[13]

Finally, since we are concerned with three-dimensional samples in this work, the *only* relevant inelastic electron-scattering process is the electron-phonon scattering, while the quasielastic electron-electron scattering ($1/\tau_{ee} \sim T^{3/2}$ in three dimensions) is negligibly weak. Therefore, the exponent of temperature $p \approx 2.4$ we obtain should represent an intrinsic exponent for a $1/\tau_{ep} = AT^p$. In other words, it does not represent an effective exponent for some combined inelastic electron time of the form $1/\tau_{\mathrm{i}} = BT^{p'} + CT^{3/2}$, where B and C being constants, and p' being an exponent of temperature different from (larger than) p. (It is now well known that the quasielastic electron-electron scattering is only important in reduced dimensions; in such cases both electron-phonon scattering and quasielastic electron-electron scattering could both contribute to the resulting $1/\tau_{\mathrm{i}}$ at liquid-helium temperatures.) As just mentioned, our three-dimensional value of p can readily be reconciled with the two-dimensional value of p independently obtained by Liu and Giordano.[12] In their experiment p was obtained from electron heating measurements, instead of from the more standard magnetoresistance measurements, and thus should very directly reflect the role of electron-phonon interactions. This consistency with the result of Liu and Giordano is a strong support for the reliability of our experimental p for $1/\tau_{ep}$ in bulk Sb. To understand why the value of p is low in Sb, a realistic calculation of $1/\tau_{ep}$ for Sb, taking the electronic structure and phonon excitation spectrum of this particular semimetal into account, would be most welcome.

IV. CONCLUSION

We have measured the electron-phonon scattering times in disordered thick Sb films with $ql \sim 1$. Our results reveal that $1/\tau_{ep} \sim T^p$ with $p \approx 2.4$, and also that $1/\tau_{ep}$ depends very weakly on disorder. The values of our experimental $1/\tau_{ep}$ are a few orders of magnitude higher than the theoretical evaluations. On the other hand, our observation suggests the importance of the phonon confinement effect in determining the temperature dependence of $1/\tau_{ep}$.

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