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† 八十六年度及以前的一般國科會專題計畫(不含產學合作研究計畫)亦可選擇適用，惟較特殊的計畫如國科會規劃案等，請先洽得國科會各學術處同意。

一、中文摘要

本計畫研究無序系統中之電子相位破壞時間，尤其是電子-聲子散射時間對溫度和電子彈性平均自由徑的函數關係。我們利用對弱局域效應所引致之低溫磁阻的高精密度量測，從實驗上決定出銻（Sb）中的電子-聲子散射時間。我們的實驗結果，將可以促進物理學家對電子相位破壞機制的瞭解。

(See attached report.)

關鍵詞：無序金屬、電子相位破壞時間、弱局域效應

Abstract

We have measured the electron-phonon scattering times in disordered conductors. The temperature and electron mean free path dependence of the electron-phonon scattering times are determined from low-temperature weak-localization studies of bulk, i.e., three-dimensional Sb films.

Keywords: disordered metals, electron dephasing times, weak localization

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

Abstract--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.

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. 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 $1/\tau_{ep}$ in a series of thick Sb films which have $ql \approx 0.2\,T$, 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]
\begin{equation}
\frac{1}{\tau_\phi (T)} = \frac{1}{\tau_0} + \frac{1}{\tau_{\rm i}(T)} \approx \frac{1}{\tau_0} + \frac{1}{\tau_{ep} (T)} \approx \frac{1}{\tau_0} + AT^p\,,
\end{equation}
where τ_0 is a constant (the zero-temperature dephasing time) currently being under much debate \cite{Alei99}. 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 $1/\tau_{\rm i} \approx 1/\tau_{ep} \approx AT^p$ in Eq. (1), where A characterizes the strength of the electron-phonon interaction,

and p is the effective exponent of temperature.

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 $\rm \AA$/min in order to ``tune" the amount of disorder, i.e., the residual resistivity ρ_0 [= ρ(10\,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 ρ(300 K)/ρ_0 were in the range 0.90$-$0.94. The films deposited were all 3000$\pm$300 $\rm\AA$ 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 [9], where ρ_0 is in $\mu \Omega$ cm.

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 magnetoresistances. 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].

For our thick Sb films, the average sound velocity $v_{\rm s} \approx$ 2000 m/s [11]. Then, $ql \approx (k_BT/\hbar v_{\rm s})l \approx$ (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$) between the clean limit ($q\ell \gg 1$) and dirty limit ($q\ell \ll 1$) at our temperatures of measurement.

Recently, the theory for electron-phonon interaction in disordered metals has been re-examined in the literature. 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 non-monotonic dependence on T and l. For the case of semimetal Sb in the intermediate regime of disorder, their 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 [9,11,12]) 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 $ql \ll 1$ [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 $\rm\AA$ 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 ($\approx$ 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 $1/\tau_{\rm i} = BT^{p'} + CT^{3/2}$, 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 $1/\tau_{\rm i}$ 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.

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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