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（計畫名稱）

介觀及無序金屬中電子相位破壞時間之量測（III）

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中　華　民　國　92　年　4　月　24　日

## 一、研究計畫中英文摘要：

關鍵詞：奈米結構、介觀物理、量子傳輸

本計畫擬研究奈米結構及介觀系統中的量子傳輸現象，包括電傳輸性質和熱傳輸性質。在電傳輸性質方面，我們將進行奈米尺度（1-2 nm）之金屬-絕緣體複合物中的巨大霍耳效應、量子干涉、和電子退相位時間的量測與研究。在熱傳輸性質方面，我們將進行奈米尺度之金屬-絕緣體複合物中的熱電勢、和熱傳輸係數的量測與研究。這一部份的研究，是持續近年來我們與香港科技大學，以及美國密西根大學的合作研究。在介觀物理方面，我們將以量測低溫電子退相位時間為主，尤其著重在當溫度趨近於絕對零度時之電子退相位性質的探討上。我們的實驗目標在於釐清“一個微小電子系統如何與外界產生耦合，因之失去其量子相干特性、而回復到古典傳輸行為”的這一個基礎而重要的低維物理問題。因為奈米科技的許多課題，都與電子相位相干的概念密不可分。我們計畫進行的奈米結構及介觀系統的研究，必將相輔相成。

**Keywords:** nanostructures, mesoscopic physics, quantum transport

In this project, we propose to investigate both the electrical-transport and thermal-transport properties of nanostructures and mesoscopic systems at cryogenic temperatures. On electrical-transport properties, we plan to study the giant Hall effect, quantum-interference transport, and electron dephasing times in metal-insulator composites that possess metal (insulator) grains of order 1-2 nm in diameter. On thermal-transport properties, we propose to measure the thermoelectric powers and thermal conductances in nano-composites at low temperatures. Research efforts in this direction are highly desirable, since the issue of heat transport in nano and mesoscopic structures has not been much explored experimentally. In addition, we plan to investigate electron-dephasing time in metal and semiconductor mesoscopic structures down to sub-Kelvin regime. We wish to clarify the question of how a mesoscopic system may lose its quantum nature and recover Boltzmann-transport properties, in the presence of external dephasing processes at very low temperatures.

## 二、研究成果：

本計畫之執行成果已經發表了 3 篇專業期刊論文，列舉如下：

1. *Recent experimental studies of electron dephasing in metal and semiconductor mesoscopic structures*, J. J. Lin and J. P. Bird, J. Phys.: Condens. Matter **14**, R501 (2002).
2. *Effect of microstructures on the electron-phonon interaction in the disordered metals* $Pd_{60}Ag_{40}$, Y. L. Zhong, J. J. Lin, and L. Y. Kao, Phys. Rev. B **66**, 132202 (2002).
3. *Electron dephasing near zero temperature: an experimental review*, J. J. Lin, T. J. Li, and Y. L. Zhong, J. Phys. Soc. Jpn. **72**, 7 (2003), Supplement A. (An invited review)

# Effect of microstructure on the electron-phonon interaction in the disordered metals $Pd_{60}Ag_{40}$

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Using the weak-localization method, we have measured the electron-phonon scattering times $\tau_{ep}$ in $Pd_{60}Ag_{40}$ thick films prepared by dc- and rf-sputtering deposition techniques. In both series of samples, we find an anomalous $1/\tau_{ep} \propto T^2 l$ temperature and disorder dependence, where $l$ is the electron elastic mean free path. This anomalous behavior cannot be explained in terms of the current concepts for the electron-phonon interaction in impure conductors. Our result also reveals that the strength of the electron-phonon coupling is much stronger in the dc- than rf-sputtered films, suggesting that the electron-phonon interaction is not only sensitive to the total level of disorder, but is also sensitive to the microscopic quality of the disorder.

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## I. INTRODUCTION

The electron-phonon ($e$-ph) scattering time $\tau_{ep}$ is one of the most important physical quantities in metals and superconductors. For instance, it determines the dephasing (also called the phase-breaking or decoherence) time for the electron wave function, the cooling time for an electron gas, and the relaxation time for the order parameter in a superconductor. The $e$-ph scattering time also plays a crucial role in the development of novel mesoscopic devices such as sensitive low-temperature bolometers.[1] The $e$-ph scattering time in the presence of multiple (elastic) impurity scattering has been intensively calculated by several authors,[2–4] but the current understanding of the temperature and electron elastic mean free path, $l$, dependences of $\tau_{ep}$ is still incomplete. In particular, different temperature and disorder dependences of $\tau_{ep}$ have been reported, both theoretically and experimentally.[5,6] Recently, it was proposed that, in addition to the dependence on the total level of disorder, the $T$ and $l$ dependences of $\tau_{ep}$ might be fairly sensitive to the microscopic quality of the disorder.[7–9] It has also been conjectured that the contribution due to the umklapp process of impurity scattering may be important.[10]

In this work, we have fabricated two series of $Pd_{60}Ag_{40}$ thick films by dc-sputtering and rf-sputtering deposition techniques. The palladium-silver alloys are chosen because Pd and Ag form perfect fcc solid solutions through the alloy series.[11] Also, since the masses of the Pd and Ag atoms are quite similar, the vibrational spectrum of the lattice does not change significantly through the alloy series.[12] The low-field magnetoresistances of our films are measured at liquid-helium temperatures and are compared with the weak-localization theoretical predictions to extract the values of the $e$-ph scattering time. Our results for the temperature and electron mean free path dependences of $\tau_{ep}$ and their implications are described below.

## II. EXPERIMENTAL METHOD

Our films were prepared from a 99.995% pure $Pd_{60}Ag_{40}$ (hereafter referred to as PdAg) target. Two series of thick films were fabricated, one by the dc-sputtering and the other by rf-sputtering deposition technique. The films were deposited onto glass substrates held at room temperature. In both cases, a background pressure of $3\times10^{-6}$ torr was reached before an argon atmosphere of $3.8\times10^{-3}$ torr was introduced to initiate the deposition process. A same sputtering gun was used for these two deposition methods, but with the gun being connected to either a dc or a rf power supply. The distance between the sputtering target and the glass substrates was the same for both methods. The sputtering power was progressively adjusted to ''tune'' the deposition rate, which resulted in different amounts of disorder, i.e., the residual resistivities $\rho_0$ [$=\rho(10\ \mathrm{K})$], in the films. For the dc-sputtering (rf-sputtering) case, the deposition rate was varied from 30 to 230 (19 to 333) Å/min, and values of $\rho_0$ ranging from 281 to 183 (74 to 178) $\mu\Omega$ cm were obtained.

The sample structures of our films were carefully studied by performing the powder diffraction on an MAC MXP18 x-ray diffractometer. The x-ray power was 10 kW and the scanning speed was 6° per minute. In all cases, we found our samples to reveal very similar diffraction patterns, which clearly suggested that both the dc- and rf-sputtered films possessed the same fcc lattice structure characteristic as that of the PdAg alloys. Representative x-ray diffraction patterns for two dc- and two rf-sputtered films are shown in Fig. 1.

Most of our films had a thickness $t \gtrsim 4000$ Å. This thickness ensured that the weak-localization effects were three dimensional in our samples. It also ensured that the thermal phonons were unambiguously three dimensional; i.e., the wavelength of the most probable thermal phonons was always smaller than the film thickness at our measurement temperatures. This latter condition greatly eliminated any complications that might result from phonon confinement effects. (In reduced-dimensional systems, modifications to the phonon spectrum and the speed of sound might be significant, which could lead to nonstraightforward temperature and disorder behavior of $\tau_{ep}$.)

Our values of the diffusion constant $D$ were evaluated through the Einstein relation $\rho_0^{-1} = De^2N(0)/(1+\lambda)$, where $N(0)$ is the electronic density of states at the Fermi level and

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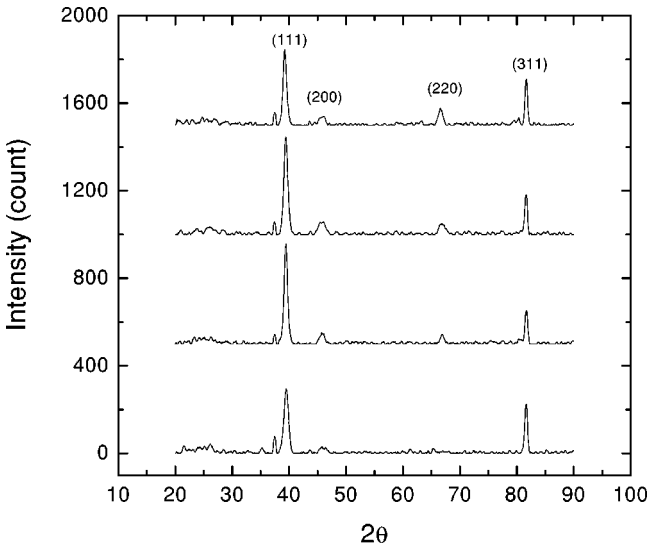


FIG. 1. X-ray diffraction patterns for two dc- (top two curves) and two rf- (bottom two curves) sputtered PdAg thick films. The sample resistivities $\rho(300\,\mathrm{K})$ from top down are 189, 82, 79, and 132 $\mu\Omega$ cm. The diffraction intensity shows an arbitrary unit.

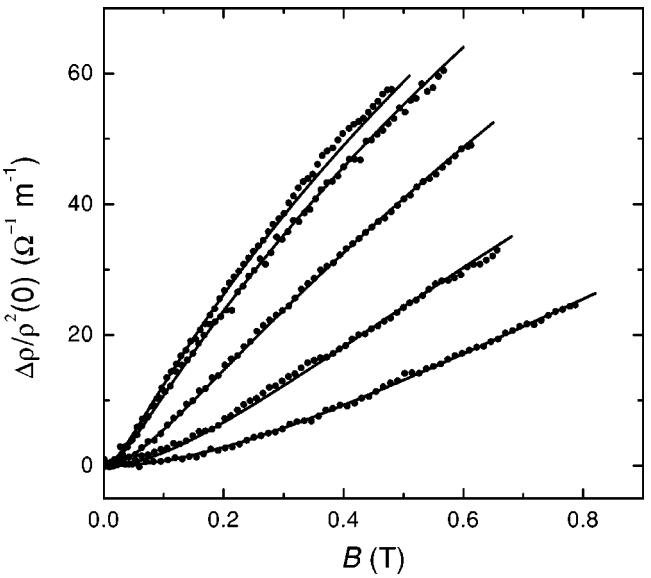


FIG. 2. Normalized magnetoresistivities as a function of magnetic field for the PdAg17 thick film at (from top down) 1.0, 3.0, 6.0, 9.0, and 14.0 K. The solid curves are the three-dimensional weak-localization theoretical predictions.

$\lambda$ is the $e$-ph mass enhancement factor. The values of $N(0)$ were calculated from the independently determined electronic specific heat: $\gamma T=\frac{1}{3}\pi^2 k_B^2 N(0)T$. For $Pd_{60}Ag_{40}$, $\lambda \simeq 0.43$ and $\gamma \simeq 3.3$ mJ/mol K$^2$.[11] Then, we obtained $D \approx (100/\rho_0)$ cm$^2$/s, where $\rho_0$ is in $\mu\Omega$ cm. Table I lists the values of the relevant parameters for our films studied in this work.

### III. RESULTS AND DISCUSSION

The normalized magnetoresistivities $\Delta\rho(B)/\rho^2(0) = [\rho(B)-\rho(0)]/\rho^2(0)$ for the PdAg17 thick film at several temperatures are plotted in Fig. 2. The symbols are the experimental data and the solid curves are the three-dimensional weak-localization theoretical predictions.[13] It is clearly seen that the weak-localization predictions can describe well our experimental data. Therefore, the electron dephasing time $\tau_\phi$, which is the key parameter in the weak-localization theory, can be reliably extracted. Since PdAg has a very strong spin-orbit scattering, $\tau_\phi$ is the *only* adjusting parameter in the comparison of the theory with experiment. (That the spin-orbit scattering is strong in PdAg is evident in the shape of the positive magnetoresistivity curves shown in Fig. 2.) The details of our data analysis procedure was discussed previously.[14]

In *three* dimensions, the total electron dephasing rate that governs the weak-localization effects is given by[13]

$$\frac{1}{\tau_\phi(T,l)} = \frac{1}{\tau_\phi^0(l)} + \frac{1}{\tau_{ep}(T,l)}, \tag{1}$$

TABLE I. Values of the relevant parameters for $Pd_{60}Ag_{40}$ thick films. The samples end with (without) a dagger denote films prepared by the dc- (rf-) sputtering deposition technique. $t$ is the film thickness. $\rho_0$ is the resistivity at 10 K. $D$ is the diffusion coefficient. The values of $k_F l = 3mD/\hbar$ are computed by assuming the free electron mass of $m$, where $k_F$ is the Fermi wave number. $\tau_\phi^0$ is the fitted electron dephasing time as $T \to 0$. $A_{ep}$ and $p$ are the fitted strength of $e$-ph coupling and effective exponent of temperature, respectively, in $1/\tau_{ep} = A_{ep}T^p$.

| Sample | $t$(Å) | $\rho_0$ ($\mu\Omega$ cm) | $D$ (cm$^2$/s) | $k_F l$ | $\tau_\phi^0$ ($10^{-10}$ s) | $A_{ep}$ ($10^8$ s$^{-1}$ K$^{-p}$) | $p$ |
|---|---|---|---|---|---|---|---|
| PdAg11† | 3900 | 281 | 0.36 | 0.93 | 2.8 | 1.5 | 2.3±0.1 |
| PdAg15† | 5100 | 235 | 0.43 | 1.1 | 1.1 | 2.4 | 1.9±0.2 |
| PdAg08† | 3900 | 224 | 0.45 | 1.2 | 6.7 | 2.0 | 2.4±0.1 |
| PdAg12† | 4800 | 183 | 0.55 | 1.4 | 3.7 | 2.8 | 2.2±0.1 |
| PdAg18 | 5000 | 178 | 0.56 | 1.5 | 4.3 | 0.40 | 2.4±0.1 |
| PdAg17 | 4500 | 101 | 0.99 | 2.6 | 1.6 | 2.2 | 2.2±0.1 |
| PdAg19 | 4000 | 98 | 1.0 | 2.6 | 1.6 | 2.9 | 2.3±0.1 |
| PdAg14 | 4100 | 90 | 1.1 | 2.9 | 1.1 | 2.5 | 2.2±0.2 |
| PdAg16 | 3300 | 74 | 1.3 | 3.5 | 0.97 | 3.6 | 2.2±0.1 |

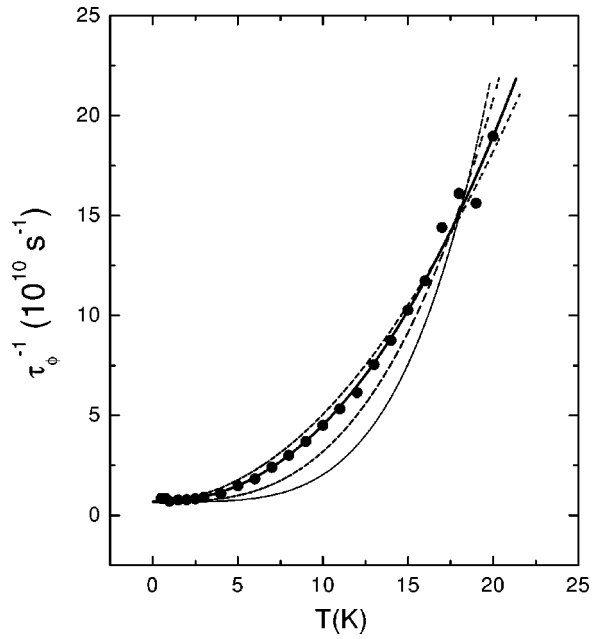


FIG. 3. Electron dephasing rate as a function of temperature for the PdAg17 thick film. The thick solid curve drawn through the data points is a least-squares fit to Eq. (1), using $p$ as a free parameter. The dotted, dashed, and thin solid curves are least-squares fits to Eq. (1) with $p$ fixed at 2, 3, and 4, respectively (see text).

where $\tau_\phi^0 = \tau_\phi(T \to 0)$ depends very weakly on temperature, if at all, and is called the saturated dephasing time. Whether $\tau_\phi^0$ should reach a finite or an infinite value as $T \to 0$ is currently under vigorous experimental and theoretical investigations.[6] At finite temperatures, the dominating inelastic electron process in three dimensions is solely due to the $e$-ph scattering, while the Nyquist electron-electron scattering is negligibly small.[6,15,16] Usually, one writes $1/\tau_{ep} = A_{ep}T^p$ over the limited temperature range accessible in a typical experiment, where $A_{ep}$ characterizes the strength of the $e$-ph coupling and $p$ is an effective exponent of temperature. According to current understanding, $p$ lies between 2 and 4.[2–4,9]

The extracted $\tau_\phi(T)$ between 0.5 and 20 K for each of our films is least-squares fitted to Eq. (1), and the fitted values of the relevant parameters ($\tau_\phi^0$, $A_{ep}$, and $p$) are listed in Table I. Figure 3 shows a plot of the variation of $1/\tau_\phi$ with temperature for the PdAg17 thick film. The symbols are the experimental data. The thick solid curve drawn through the data points is obtained with $\tau_\phi^0$, $A_{ep}$, and $p$ as free parameters. In this case, we obtain a temperature exponent $p = 2.2 \pm 0.1$. For comparison, we have also least-squares fitted the measured $1/\tau_\phi$ with Eq. (1), but with $p$ fixed at an integer value of either 2, 3, or 4 (while allowing $\tau_\phi^0$ and $A_{ep}$ to vary). The dotted, dashed, and thin solid curves in Fig. 3 plot the fitted results with $p = 2$, 3, and 4, respectively. It is clearly seen that our temperature dependence of $1/\tau_{ep}$ can be best described with an exponent $p$ equal or close to 2. In fact, we have found that the temperature behavior of $\tau_{ep}$ for all films listed in Table I is very similar; i.e., $1/\tau_{ep}$ demonstrates an *essentially quadratic* temperature dependence.

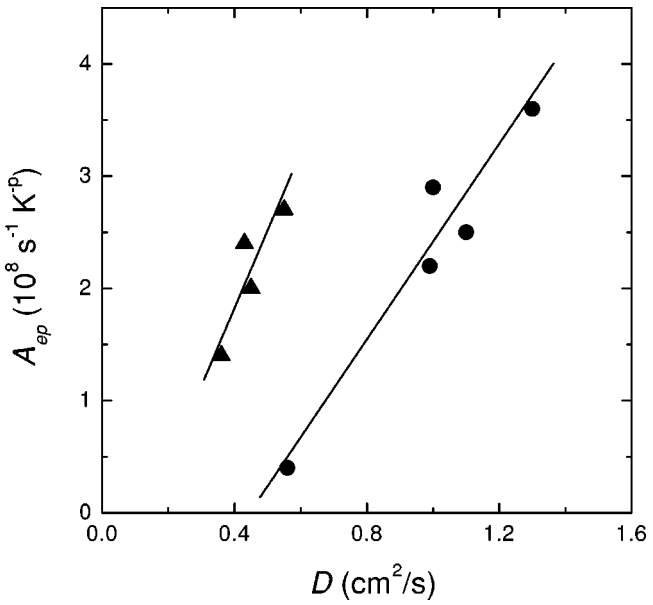


FIG. 4. The strength of $e$-ph coupling $A_{ep}$ as a function of diffusion constant for dc- (triangles) and rf- (circles) sputtered PdAg thick films. The straight lines drawn through the data points are guides to the eye.

Inspection of Table I indicates that, for either dc- or rf-sputtered films, the value of $A_{ep}$ decreases with increasing level of disorder ($\rho_0$) in the sample. Figure 4 plots the fitted $A_{ep}$ as a function of the diffusion constant. Clearly, ones sees that $A_{ep}$ varies *linearly* with $D$, implying that $1/\tau_{ep} \propto D \propto l$. It should be noted that, if we plot $1/\tau_{ep}$ as a function of the measured $\rho_0^{-1}$, we also observe a linear variation, i.e., $1/\tau_{ep} \propto \rho_0^{-1} \propto l$. Such a linearity of $A_{ep}$ with $l$ holds for *both* series of films. Quantitatively, however, the values of $A_{ep}$ (for a given disorder) for the dc- and rf-sputtered films are very different. For example, while the dc-sputtered PdAg12 and the rf-sputtered PdAg18 thick films have essentially the same $\rho_0$, their values of $A_{ep}$ differ by several times. Moreover, Fig. 4 reveals that the slope of the linearity is about a factor of 2 larger in the dc- than rf-sputtered films. Since the x-ray diffraction studies demonstrate that the crystal structures are quite similar for both series of films (Fig. 1), the differences in the values of $A_{ep}$ and the variation of $A_{ep}$ with $l$ strongly imply that the $e$-ph interaction must be very sensitive to the microstructures of the samples. The subtle difference in the microstructures in these two series of films may result from the different ways of sample preparation.

Taken together, Figs. 3 and 4 demonstrate that the $e$-ph scattering in PdAg possesses an *anomalous* temperature and disorder dependence of $1/\tau_{ep} \propto T^2 l$. This dependence is insensitive to the fabrication method. Such a $T^2 l$ behavior is totally unexpected, even qualitatively, in terms of the current theoretical concepts for the $e$-ph interaction in impure conductors. According to the ''orthodox'' $e$-ph interaction theory for disordered metals,[2–4] which assumes a coherent motion of impurity atoms with deformed lattice atoms at low temperatures, one should expect a $T^4 l$ dependence. Recently, it was speculated that, in real metals containing heavy (light) impurities and tough boundaries, the impurity and/or bound-

ary atoms might not move in phase with the lattice atoms.[7] The first calculations in consideration of this effect have been done by Sergeev and Mitin.[9] They found that even a small amount of ''static'' potential scatterers drastically changes the $e$-ph-impurity interference, and the relaxation rate is proportional to $T^2\mathcal{L}^{-1}$, where $\mathcal{L}$ is the electron mean free path with respect to the static impurities ($\mathcal{L}\gg l$). Experimentally, a $T^4$ temperature dependence has been observed very recently in disordered Hf and Ti thin films.[1] (A $T^4$ dependence had been previously observed in Bi thin films over a very limited temperature range of 0.6–1.2 K.[17]) However, to the best of the authors' knowledge, the combined $T^4l$ law has never been confirmed in real conductors thus far. On the other hand, a distinct $T^2l^{-1}$ dependence has been observed in $Ti_{1-x}Al_x$ (Ref. 7) and $Ti_{1-x}Sn_x$ (Ref. 8) alloys. Previously, a $T^2l$ dependence was independently found in AuPd *thick* films[15] ($t\gtrsim 4000$ Å), and Nb *thin* films[18] ($t\lesssim 200$ Å). In the present case of PdAg thick films, the masses of the Pd and Ag atoms are quite similar, and the films are three dimensional. Therefore, it is not clear how the Sergeev-Mitin theory evoking heavy (light) impurities and tough boundaries can apply to this case.

The criterion for the $e$-ph interaction to satisfy the dirty-limit condition is $q_Tl\ll 1$, where the wave number of the thermal phonons $q_T\approx k_BT/\hbar v_s$ and $v_s$ is the speed of sound. Taking $v_s\approx 2600$ m/s (Ref. 19) and $l\approx 2$–8 Å, we obtain $q_TT\approx(0.01$–$0.04)T$ for our PdAg thick films. The phase-breaking lengths $\sqrt{D\tau_\phi}$ in our films are calculated to be 690–1500 Å at 2 K. (The dephasing length essentially saturates below about 2 K.) This length scale justifies the use of three-dimensional weak-localization theory to describe our experimental magnetoresistivities.

## IV. CONCLUSION

We have measured the $e$-ph scattering time $\tau_{ep}$ in dc- and rf-sputtered PdAg thick films. In both series of films, we observe an anomalous $1/\tau_{ep}\propto T^2l$ temperature and disorder dependence. Moreover, the $e$-ph coupling is found to be much stronger in the dc- than rf-sputtered films. This observation strongly indicates that the $e$-ph interaction is not only sensitive to the total level of disorder, but is also sensitive to the microscopic quality of the disorder. These results pose a new theoretical challenge.

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# Electron dephasing near zero temperature: an experimental review

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The behavior of the electron dephasing time near zero temperature, $\tau_\phi^0$, has recently attracted vigorous attention. This renewed interest is primarily concerned with whether $\tau_\phi^0$ should reach a finite or an infinite value as $T \to 0$. While it is accepted that $\tau_\phi^0$ should diverge if there exists only electron-electron (electron-phonon) scattering, several recent measurements have found that $\tau_\phi^0$ depends only very weakly on temperature, if at all, when $T$ is sufficiently low. This article discusses the current experimental status of "the saturation problem", and concludes that the origin(s) for this widely observed saturation are still unresolved.

KEYWORDS: electron dephasing, saturation of dephasing time, mesoscopic structures, disordered metals, magnetic scattering, two-level systems, weak localization

## 1. Introduction

The electron dephasing time, $\tau_\phi$, is one of the most important quantities governing quantum-interference phenomena in mesoscopic structures. Recently, the behavior of the dephasing time near zero temperature, $\tau_\phi^0 = \tau_\phi(T \to 0)$, has attracted vigorous experimental[1–7] and theoretical[8–13] attention. One of the central themes of this renewed interest is concerned with whether $\tau_\phi^0$ should reach a finite or an infinite value as $T \to 0$. The connection of the $\tau_\phi^0$ behavior with fundamental condensed-matter physics problems, such as the validity of the Fermi-liquid picture,[14] the possibility of the occurrence of a quantum phase transition, the persistent current problem in metals,[15,16] and also the feasibility of quantum computing, has been intensively addressed.[17] Conventionally, it is accepted that $\tau_\phi^0$ should reach an infinite value in the presence of only Nyquist electron-electron (e-e) and electron-phonon (e-ph) scattering. However, several recent careful measurements, performed on metal and semiconductor mesoscopic structures, have revealed that $\tau_\phi^0$ depends only very weakly on temperature, if at all, when $T$ is sufficiently low. Until now, there is *no generally* accepted process of electron–low-energy-excitation interaction that can satisfactorily explain the widely observed saturation of $\tau_\phi^0$.

This article discusses existing proposals for the observed saturation of $\tau_\phi^0$ and surveys recent systematic efforts aimed at testing these proposals. We argue that recent measurements have extensively demonstrated electron heating, external microwave noise, and very dilute magnetic impurities *cannot* be the dominant source for the finite value of $\tau_\phi^0$ found in the experiments. We suggest that "the saturation problem" can be most unambiguously addressed using tailor-made samples covering a wide range of material properties. We also propose that three-dimensional (3D) mesoscopic structures can shed light on this issue.

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## 2. Extracting $\tau_\phi$ from magneto-transport measurements

In quantum-interference studies, the electron dephasing time $\tau_\phi$ is given by[18]

$$\frac{1}{\tau_\phi(T,\ell)} = \frac{1}{\tau_\phi^0(\ell)} + \frac{1}{\tau_{\rm i}(T,\ell)}\,, \qquad (1)$$

where $\ell$ is the electron elastic mean free path, $\tau_\phi^0$ is presumed to be independent of temperature, and $\tau_{\rm i}$ is the relevant inelastic electron scattering time(s) in question. The temperature dependence of $\tau_\phi$ is controlled entirely by the $T$ dependence of $\tau_{\rm i}$, while $\tau_\phi^0$ determined the value of the dephasing time in the limit of very low $T$. In three dimensions (3D), the e-ph scattering is the *sole*, dominating inelastic scattering[19,20] and $\tau_{\rm i}^{-1} \approx \tau_{ep}^{-1} \propto T^p$, with $2 \lesssim p \lesssim 4$. In lower dimensions, the Nyquist e-e scattering dominates[18] and, generally, $\tau_{\rm i}^{-1} \approx \tau_{ee}^{-1} \propto T^p$ at a few kelvins and lower, with $p = 2/3$ in one dimension (1D) and $p = 1$ in two dimensions (2D).

It is well established that *very reliable* values of $\tau_\phi$ in mesoscopic structures can now be extracted from magneto-transport measurements.[19] For example, Fig. 1 shows the variation of $\tau_\phi$ with $T$ for a thick and a thin Sb films obtained from weak-localization (WL) studies. One sees that, at the highest measurement temperatures, e-ph scattering dominates and $\tau_\phi$ reveals a strong $T$ dependence. In the thick film, $\tau_\phi^{-1} \approx \tau_{ep}^{-1}$ all the way down to about 2 K; while in the thin film, e-e scattering gradually becomes more important and, thus, $\tau_\phi^{-1} \approx \tau_{ee}^{-1}$ below about 5−6 K. *In both cases, a progressively weakened $T$ dependence is observed at the lowest measurement temperatures.* We notice that (i) the overlap of the values of $\tau_{ep}$ for the two films at high measurement temperatures, and (ii) the crossover of $\tau_\phi$ to e-e scattering in the thin film (but not in the thick film!) at lower temperatures, provide a convincing consistency check for the experimental $\tau_\phi$ inferred from WL studies.

Figure 2 shows the variation of $\tau_\phi$ with temperature for a DC- and a RF-sputtered $Pd_{60}Ag_{40}$ thick films ob-

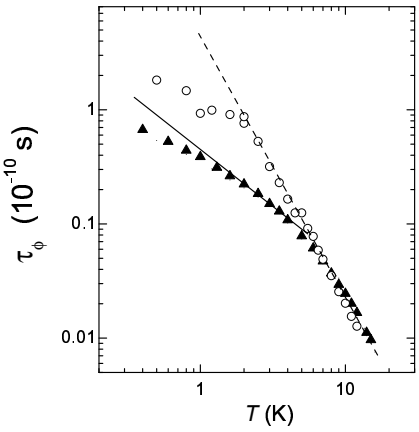


Fig. 1. Variation of $\tau_\phi$ with temperature for a 3000-Å (circles) and a 175-Å (triangles) thick Sb films. The thick and thin films have resistivities $\rho(10\,\mathrm{K}) = 1320$ and 1920 $\mu\Omega$ cm, respectively. The dashed line is a guide to the eye and the solid line is drawn proportional to $T^{-1}$.

tained from WL studies. These two thick films are 3D and have a similar level of disorder. Notice that they assumes a similar value of $\tau_\phi^0$ as $T \to 0$, independent of the different fabrication methods. This observation provides an alternative convincing consistency check for the experimental $\tau_\phi$ extracted. (See further discussion below.)

## 3. Electron heating and related effects

Of the prominent interest on this subject is "the saturation problem", i.e., a finite experimental value of $\tau_\phi^0$ extracted as $T \to 0$. In particular, in the WL studies, the saturation of $\tau_\phi^0$ is inferred from the low-field magnetoresistance, which does not increase as fast as expected with decreasing $T$.[4,19] For instance, Natelson *et al.*[4] found, in wide AuPd wires, that the magnetoresistance changed by less than 40% even when the temperature was significantly decreased from 4.2 down to 0.08 K. On the other hand, it should be noted that the temperature insensitive magnetoresistance at low $T$ is found in a $T$ regime where the electron gas is *in thermal equilibrium* with the lattice, i.e. the weak dependence is *not* caused by electron heating (due to either the measurement current or external noise). This assertion is clearly confirmed by the observation of a continuous resistance rise with decreasing temperature down to the lowest temperatures in each measurement.[1,3,4,21] (The resistance rise can generally be ascribed to e-e interaction effects in metal samples.[18,22]) This assertion is also confirmed in other quantum-interference studies. For example, Bird *et al.*[23] have extracted estimates for the dephasing length, $L_\phi = \sqrt{D\tau_\phi}$, where $D$ is the diffusion constant, in quasi-ballistic GaAs/AlGaAs quantum wires from the amplitude of the universal conductance fluctuations. They found that $L_\phi$ remained independent of $T$ below 1 K, even though the amplitude of the fluctuations themselves increased by a factor of 4 over the same range.*

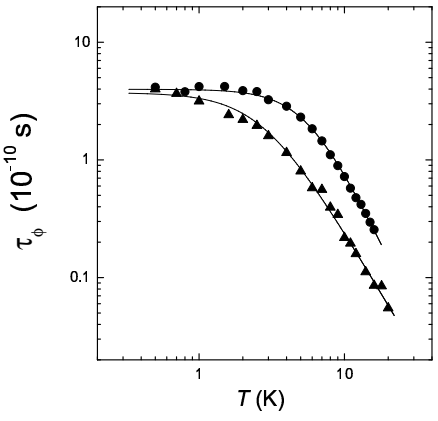


Fig. 2. Variation of $\tau_\phi$ with temperature for a DC- (triangles) and a RF-sputtered (circles) $Pd_{60}Ag_{40}$ thick films. The two films have $\rho(10\,\mathrm{K}) = 180$ $\mu\Omega$ cm. The solid curves are guides to the eye.

*Microwave-noise dephasing.* Altshuler *et al.*[24] have considered the electron dephasing by non-equilibrium high-frequency electromagnetic noise. They have argued that the microwave noise can already be large enough to cause dephasing, while still too small to cause significant Joule heating of the conduction electrons.[8,20] Careful experimental measurements have recently been designed to test these predictions. These experiments[7,25,26] explicitly demonstrated that direct dephasing due to radiation could *not* be the cause of the widely observed saturation. More precisely, Webb *et al.*[25] and Huibers *et al.*[7] found that there was heating by the high-frequency noise, before it affected dephasing, i.e. electron heating *preceded* dephasing by high-frequency noise. Burke *et al.*[26] have very recently investigated the effect of externally applied *broadband* Nyquist noise on the intrinsic dephasing rate of electrons in 2D GaAs/AlGaAs heterojunctions at low temperatures. They also found *no major* change in the measured $\tau_\phi$ even when their sample was subject to *large-amplitude*, externally-applied, voltage fluctuations. (At the same time, heating was unimportant in their measurements.) These measurements, therefore, strongly suggests that the effect of microwave noise on electron dephasing and heating requires further theoretical clarification.

## 4. Magnetic impurities: spin-spin scattering

Over the years, the saturation behavior of $\tau_\phi^0$ has often been ascribed to a finite spin-spin scattering rate, due to the presence of a tiny amount of magnetic impurities in the sample. Such a finite scattering rate will eventually dominate over the relevant inelastic scattering in the limit of sufficiently low $T$, Eq. (1). This idea of magnetic-scattering-induced dephasing immediately became widely accepted since the discovery of WL effects two decades ago.[27] In addition to many early studies that often attributed the observed finite value of $\tau_\phi^0$ to spin-spin scattering, there are some recent studies that also argue in favor of the role of magnetic impurities.

* The $T$ dependence of the fluctuations in this case is understood to result *solely* from the corresponding variation of the thermal diffusion length $L_T = \sqrt{D\hbar/k_BT}$.[23]

Especially, the Saclay-MSU group[2)] has measured both the energy exchange rate between quasiparticles and the dephasing time of quasiparticles in several Cu, Ag, and Au narrow wires. They found in one Ag wire and one Au wire that $\tau_\phi$ varies as $T^{-2/3}$ down to 40 mK. (The $T^{-2/3}$ variation is expected from 1D Nyquist e-e scattering.[18,22)]) Comparing these two complementary measurements, they concluded that a saturation of $\tau_\phi$ occurs only in wires that contain a small amount of magnetic impurities. In those wires where they found no anomalous energy exchange, they also found *no* sign of saturation in $\tau_\phi^0$. The Saclay-MSU group experimental results have triggered several theoretical studies[12,28,29)] of the inference of one-channel and two-channel Kondo effects on the energy-relaxation and dephasing rates. We notice that the metal wires studied by the Saclay-MSU group are relatively "clean", namely, their wires have a diffusion constant $D \approx 100-200$ cm$^2$/s.

*Proposal for non-magnetic origin.* In sharp contrast to the conclusion reached by the Saclay-MSU group discussed just above, Mohanty *et al.*[1)] have tested and argued for a *non-magnetic* origin for the finite value of $\tau_\phi^0$. Mohanty *et al.* first studied a series of very pure Au wires, finding that there was always a saturation of $\tau_\phi^0$. From these measurements, they realized that both the value of $\tau_\phi^0$ and the onset temperature of saturation could be tuned by adjusting the sample parameters such as the wire length, resistance, and diffusion constant. To explore this idea, Webb *et al.*[25,30)] reported further measurements on several carefully fabricated Au wires and films, whose onset temperature of saturation was indeed pushed down to unattainable temperatures ($\ll 40$ mK). Webb *et al.* also noticed that a finite value of $\tau_\phi^0$ is also often observed in semiconductor mesoscopic structures. Since such structures are thought to contain only the smallest concentration of magnetic impurities, they concluded that the widely observed saturation must be universal, and *cannot* be simply due to magnetic scattering. (They suggested that the saturation of $\tau_\phi^0$ is intrinsic and is a signature of the breakdown of the independent single-electron picture in mesoscopic systems as $T \to 0$.)

The contradicting conclusion of the Saclay-MSU group and Webb *et al.* illustrates well the subtlety and complexity of "the saturation problem". First, it is *not* a trivial experimental task to unambiguously determine the influence of magnetic scattering on $\tau_\phi^0$, because the level of magnetic contamination is probably so low that it cannot be readily detected with state-of-the-art material-analysis techniques. Secondly, since there are no known physical properties that are more sensitive to spin-flip scattering than the dephasing process, the problem of whether there is a tiny amount of magnetic contamination in the sample, thus, cannot be readily verified with other complimentary measurements. Moreover, the situation becomes even more serious when *lower-dimensional* systems are considered. In the case of low-dimensional structures, surface effects due to interfaces, substrates, and paramagnetic oxidation[31)] are likely to be non-negligible. Then, it is not straightforward to ascribe the observed saturation behavior of $\tau_\phi^0$ to either intrinsic material properties or surface effects.

## 5. Systematic measurements and the importance of three-dimensional systems

To resolve the underlying physics of $\tau_\phi^0$, the usual experimental approach of measuring the inelastic electron processes via temperature-dependent magnetoresistance studies is not very useful. In the case of inelastic scattering, the microscopic physics of the relevant electron–low-energy-excitation interactions is extracted through the measured variation of the scattering time with $T$. However, in the case of $\tau_\phi^0$, there is only a very weak, or no, $T$ dependence involved. It is then desirable to seek variations of $\tau_\phi^0$ with the material characteristics of the samples, such as the amount of disorder,[3)] the sample geometry,[4)] the effect of annealing,[32,33)] and the effect of the microscopic quality of disorder.[5,19)] Systematic information about the influence of sample properties on $\tau_\phi^0$ should shed light on the origins of the zero-$T$ dephasing mechanism.

As discussed above, an explanation for the saturation behavior of $\tau_\phi^0$ based on magnetic scattering cannot be easily discerned experimentally. This experimental difficulty results in several groups insisting on the presence of magnetic impurities in the sample as the origin of saturation. In our opinion, this problem may be resolved by studying a series of samples covering a *sufficiently wide* range of sample properties. For instance, Lin and Giordano[32)] have performed systematic measurements of $\tau_\phi^0$ on a number of as-sputtered and annealed AuPd thin films with varying sheet resistance $R_\square$. They found a $\tau_\phi^0$ increasing with decreasing $R_\square$, which led them to conclude that magnetic scattering could *not* be the mechanism responsible. They suggested that the strength of the impurity scattering which is responsible for $\tau_\phi^0$ could be very sensitive to the *metallurgical properties* of the films, which are in turn a function of both thickness and annealing, etc. Since two-level systems (TLS) are closely associated with the presence of dynamical defects in the microstructures in the sample, their observation of a sensitive, metallurgical-property, influence on $\tau_\phi^0$ has recently inspired several theoretical studies of the interaction between conduction electrons and TLS.[10,11)]

### *5.1 Three-dimensional polycrystalline metals*

Lin and Kao[3)] have recently studied the electron dephasing times $\tau_\phi$ in numerous 3D *polycrystalline* disordered metals. Their samples were made of various materials, using various fabrication techniques (see the caption to Fig. 3). Since one of the major issues in this direction of research is to study whether there might exist a universal saturation behavior of $\tau_\phi^0$, the use of many kinds of samples with distinct characteristics is highly desirable. Any behavior of $\tau_\phi^0$ common to all these materials, if found, should bear important information on the nature of the zero-$T$ dephasing. Regardless of the very different preparation and measurement conditions, the authors found in numerous metals that there is a saturation of $\tau_\phi$ at sufficiently low $T$. Most surprisingly, they found that their experimental $\tau_\phi^0$ varied with the

diffusion constant with a simple power law as

$$\tau_\phi^0 \propto D^{-\alpha}, \quad \alpha \gtrsim 1 \tag{2}$$

where $\alpha$ is *close to* or *slightly larger* than 1.

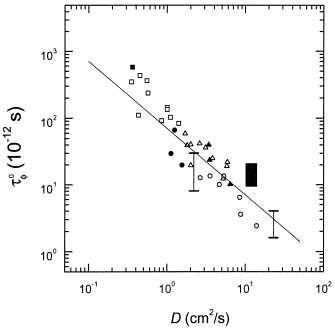


Fig. 3. Variation of $\tau_\phi^0$ with diffusion constant for 3D polycrystalline metals: dc sputtered $Au_{50}Pd_{50}$ (circles), dc/RF sputtered $Pd_{60}Ag_{40}$ (squares), dc sputtered Sb (triangles), thermal-flash evaporated $Au_xAl$ (solid triangles), thermal-flash evaporated $Sc_{85}Ag_{15}$ (solid squares), and arc-melted $V_{100-x}Al_x$ (solid circles). The two vertical bars represent the $\tau_\phi^0$ measured in AuPd thin films in Ref.[32] The shaded area represents the $\tau_\phi^0$ measured in AuPd wires and films in Ref.[4] (Notice that these AuPd films and wires have short electron mean free paths and are 3D with regard to the Boltzmann transport.) The solid line is drawn proportional to $D^{-1}$ and is a guide to the eye.

Figure 3 shows the variation of $\tau_\phi^0$ with $D$ measured by Lin and Kao. This figure indicates that the values of $\tau_\phi^0$ for all samples fall essentially on a universal dependence. Particularly, it reveals that, regardless of the distinct material characteristics (e.g., electronic structure) of the various samples, all that matters in determining the value of $\tau_\phi^0$ is $D$. (Figure 2 is a straight manifestation of this observation.) This observation of $\tau_\phi^0 \propto D^{-\alpha}$, with $\alpha \gtrsim 1$, is totally unexpected. This result implies that the functional form of $\tau_\phi^0$ on disorder may be universal for a given dimensionality and a given kind of sample structure, while it may *not* be universal over different dimensionalities and different sample (e.g., polycrystalline, amorphous or well-textured semiconductor) structures. On the contrary, it is often conjectured that $\tau_\phi^0$ should increase with *reducing* disorder, *at least* in lower dimensions.[1,21] Until now, it is *not* known exactly how differently $\tau_\phi^0$ should behave in different dimensionalities and in different sample structures. This observation may also suggest that the saturation behavior of $\tau_\phi^0$ can be very different between "clean" and "dirty" metals. For comparison, the diffusion constant considered in Fig. 3 is typically 1 to 2 orders of magnitude smaller than that in the metal wires studied by the Saclay-MSU group[2] and Mohanty *et al.*[1,25] On the other hand, the diffusion constant in the AuPd wires and films studied by Natelson *et al.*[4] is similar to that considered in Fig. 3. Consequently, Natelson *et al.* obtained corresponding values of $\tau_\phi$ very close to that shown in Fig. 3.

The result of Fig. 3 argues against the role of magnetic scattering as the dominant dephasing process in 3D polycrystalline metals as $T \to 0$. This is asserted since the numerous samples considered in Fig. 3 were made from very different high-purity sources, using very different fabrication techniques. It is hard to conceive that spin-flip scattering due to "unintentional" magnetic contamination could have caused the "systematic" variation given by Eq. (2). If magnetic scattering were responsible for the measured $\tau_\phi^0$ in Fig. 3, then the unintentional magnetic impurity concentration, $n_m$, must vary *randomly* from sample to sample, and hence one should expect a *random* $\tau_\phi^0$ ($\propto n_m^{-1}$), independent of disorder. Besides, any spin-spin scattering that might result from surface effects (substrates, paramagnetic surface oxidation, etc.) should be largely minimized in these 3D samples. Therefore, the result of Fig. 3 *cannot* be simply explained in terms of magnetic scattering.

The observation of Fig. 3 is still not understood. Nevertheless, this result unambiguously indicates that the saturation of $\tau_\phi^0$ in this case is certainly *not* due to microwave noises, because microwave-noise dephasing should result in a $\tau_\phi^0 \propto D^{-1/3}$ dependence in 3D.[24]

### *5.2 Effect of annealing: 3D polycrystalline metals*

The effect of annealing on 3D polycrystalline metals has been studied very recently. Lin *et al.*[33] have performed systematic measurements of $\tau_\phi$ on several series of *as-sputtered* and subsequently *annealed* AuPd and Sb thick films. Such controlled annealing measurements† are crucial for testing theoretical models of dephasing that invoke the role of magnetic scattering and dynamical defects. Figure 4(a) shows a plot of the variation of $\tau_\phi$ with $T$ for one of their as-prepared and subsequently annealed AuPd thick film. This figure clearly indicates that $\tau_\phi$ is increased by annealing. At first glance, it appears that this observation is easily explained. Suppose that annealing results in the rearrangement of lattice atoms and a relaxation of grain boundaries, thereby making the film less disordered. Because TLS are closely associated with defects in the microstructures, their number concentration, $n_{\rm TLS}$, is therefore reduced by annealing. Assuming that dynamical defects are effective scatterers as $T \to 0$, one can then understand Fig. 4(a) in terms of a TLS picture, i.e. $\tau_\phi^0 \propto n_{\rm TLS}^{-1}$. However, it is impossible to perform a quantitative comparison of the experiment with TLS theories.[10,11] The difficulties lie in the facts that (i) the number concentration $n_{\rm TLS}$ in a particular sample is unknown, (ii) the strength of coupling between conduction electrons and a TLS is poorly understood, and (iii) the dynamical properties of real defects (impurities, grain boundaries, etc.) are even less clear. Moreover, further measurements of Lin *et al.* indicate that the nature of low-$T$ dephasing in polycrystalline metals is not so straightforward. They found that the effect of annealing on $\tau_\phi$ is distinctly different in samples having much higher resistivities.

In addition to the study of Fig. 4(a), Lin *et al.*[33] have also carried out measurements on AuPd thick films containing much higher levels of disorder. Surprisingly, they discovered that annealing has a *negligible* effect on $\tau_\phi$ in *strongly* disordered AuPd thick films. Figure 4(b) shows

† We notice that annealing experiment may not be performed on metallic glasses, because thermal annealing can cause crystallization of amorphous samples.

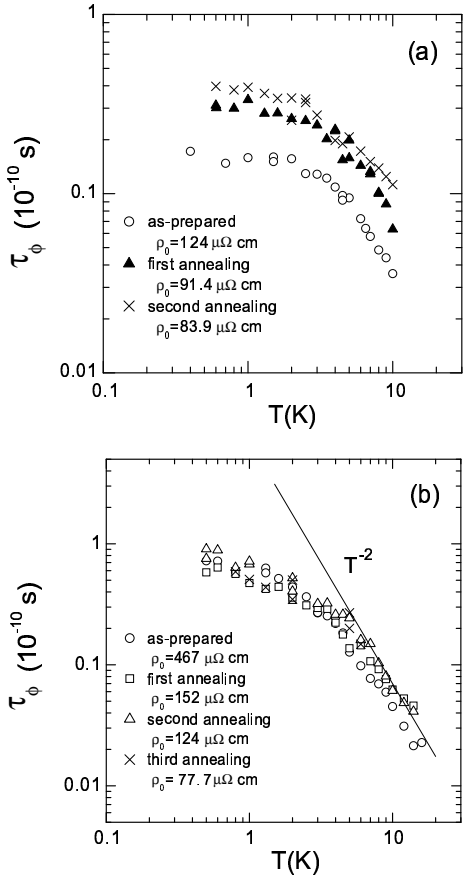


Fig. 4. Variation of $\tau_\phi$ with temperature for (a) a 'moderately' disordered, and (b) a 'strongly' disordered, AuPd thick films before and after annealing. The solid line in (b) is a guide to the eye. These figures were taken from Ref.[33)]

the variation of $\tau_\phi$ with temperature for a strongly disordered AuPd thick film. This figure demonstrates that the values of $\tau_\phi$ for the as-prepared and annealed samples are essentially the same, even though the resistance is changed by the annealing by a factor of more than 6. The absence of an appreciable annealing effect in this case implies that, in addition to the usual TLS addressed above, strongly disordered films also contain other defects that cannot be readily cured by annealing. This ineffectiveness of thermal annealing may suggest that there are two kinds of TLS. On the other hand, it may suggest that, despite a large effort in this direction, no real defects of any nature have dynamical properties which can explain the saturation of $\tau_\phi^0$ found in the experiments.[10)] Inspection of the large discrepancy in Figs. 4(a) and 4(b) strongly indicates that low-$T$ dephasing is very sensitive to the microstructures in the samples.

We return to the issue of magnetic scattering. The result of Figs. 4(a) and 4(b) indicates that magnetic scattering should play a subdominant role, if any, in inducing the saturation of $\tau_\phi^0$. The reasons are given as follows. (i) Suppose that there is a low level of magnetic contamination in the as-sputtered film. Upon annealing, the magnetic impurity concentration $n_m$ should be left unchanged. If the original saturation in the as-sputtered sample is caused by spin-spin scattering, one should then expect the same value of $\tau_\phi^0$ ($\propto n_m^{-1}$) after annealing. However, the result of Fig. 4(a) indicates an increased $\tau_\phi^0$ with annealing, which is in disagreement with this assumption. (ii) Blachly and Giordano[34)] have found that the Kondo effect is very *sensitive* to disorder, namely that increasing disorder suppresses the Kondo effect. Along these lines, if the original saturation of $\tau_\phi^0$ found in Fig. 4(b) were really due to magnetic scattering, one should then argue that annealing that suppresses disorder should enhance the Kondo effect. Therefore, a decreased $\tau_\phi^0$ should be expected with annealing. Since the measured $\tau_\phi^0$ does not change, even when the sample resistivity is reduced by a factor of more than 6 by annealing, Fig. 4(b) thus cannot be reconciled with a magnetic-scattering scenario. This picture of a suppressed Kondo effect with increasing disorder is also incompatible with the result for the moderately disordered film considered in Fig. 4(a), where an increased, instead of a decreased, $\tau_\phi^0$ is found after annealing. In short, systematic annealing measurements in both thin[32)] and thick[33)] films *cannot* be reconciled with magnetic scattering being responsible for the saturation of $\tau_\phi^0$ at low temperatures.

### *5.3 The importance of three-dimensional structures*

It is worth noting that the saturation problem can be better addressed in 3D, rather than lower-dimensional, structures. This is because of the increased contrast between the saturation and the strong dependence of $\tau_{\rm i}(T)$ in 3D. As discussed in §2, the inelastic electron scattering rate $\tau_{\rm i}^{-1} \approx \tau_{ep}^{-1} \propto T^p$, with $p \gtrsim 2$ in 3D. Such a $T$ variation is much stronger than the dominating $p = 2/3$ in 1D and the $p = 1$ in 2D. For example, inspection of the solid line, which is drawn proportional to $T^{-2}$, in Fig. 4(b) clearly reveals that the measured $\tau_\phi^0$ at 0.5 K is *already more than one order of magnitude* lower than would be extrapolated from the measured $\tau_{ep}$ at a few degrees Kelvin. Obviously, such a large discrepancy cannot simply be ascribed to experimental uncertainty. (The increasing contrast between the saturation and the dependence of $\tau_{\rm i}(T)$ with increasing sample dimensionality is already directly manifested in Fig. 1.) There is another advantage of using 3D structures in the studies of $\tau_\phi^0$. Compared with the fabrication of narrow wires, the preparation of 3D samples usually does not require sophisticated lithographic processing, thereby greatly minimizing any (magnetic) contamination that might eventually act like a spin-flipper as $T \to 0$.

## 6. Conclusion

Over the years, the advances in our understanding of quantum-interference effects have made feasible systematic and quantitative measurements of $\tau_\phi$ ($\tau_\phi^0$). Despite extensive efforts in theoretical calculations and experimental measurements of $\tau_\phi^0$, our current understanding of the microscopic origins for the zero-$T$ dephasing in *real* conductors is still incomplete. Experimentally, carefully designed low-$T$ magneto-transport measurements employing tailor-made structures, with sample specifics varying over a wide range of disorder and dimensional-

ity, would be highly desirable to help with discerning the underlying physics of $\tau_\phi^0$. In addition to the systematic studies on high-disorder 3D polycrystalline metals,[3,33] combined measurements of the electron energy exchange rate, dephasing rate, and Aharonov-Bohm oscillations in the presence of a high magnetic field will shed light on this issue.[2] Thus far, systematic measurements have ruled out electron heating, microwave noise, and magnetic scattering as the dominant source for the saturation behavior of $\tau_\phi^0$ observed in the experiments.

In addition to the case of disordered metals in the diffusive regime, a saturation of $\tau_\phi^0$ has also been observed in semiconductor, diffusive and quasi-ballistic, quantum wires, and ballistic dots.[19] In many regards, the features of this saturation appear reminiscent of that found in dirty metal wires. The saturated value of $\tau_\phi^0$ is typically of similar order in semiconductor wires and dots, and is also of comparable magnitude to that found in studies of dirty metal wires and films. The characteristic temperature for onset of the saturation also varies widely in these structures—again reminiscent of the behavior found in dirty mesoscopic systems. It is intriguing, and deserves serious investigation, why semiconductor quantum structures and dirty metals reveal similar saturation behavior of $\tau_\phi^0$.

Another important issue revealed in a number of studies is a sensitivity of the electron dephasing to the microscopic quality of disorder. For instance, Ovadyahu[5] has measured $\tau_\phi$ at low temperatures in diffusive $In_2O_{3-x}$ and $In_2O_{3-x}$:Au thin films. He found that, although the Au doping is only $\lesssim 3\%$ in $In_2O_{3-x}$:Au thin films, the behavior of the dephasing time in these two materials could be *significantly different*. Bird and co-workers[35] have studied semiconductor quantum dots and found that their $\tau_\phi$ can show significant dot-to-dot variations, in samples realized in materials with similar mobilities. These measurements reflect a critical sensitivity of the dephasing processes to disorder. These experiments clearly suggest that $\tau_\phi^0$ is not only dependent on the *total* level of disorder, but are also very sensitive to the microscopic *quality* of the disorder. This can be particularly crucial for mesoscopic devices, whose disorder profile is know to be highly sample specific. This is a key point that needs to be taken into consideration in future theories of electron dephasing times.

## Acknowledgements

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