Observation of a crossover of the inelastic electron scattering in $Sc_{100-x}Ag_x$ thick films

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We have made a series of thick Sc films doped with different amounts of Ag, which results in a systematic decrease in the resistivities, i.e., disorder, of the films. From measurements of the low-field magnetoresistances and comparison with three-dimensional weak-localization theoretical predictions, the electron dephasing times are extracted in every film. We find a crossover of the inelastic electron process from the critical electron-electron scattering to the electron-phonon scattering as the disorder decreases and the system progressively moves away from the Anderson localization.

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I. INTRODUCTION

Since the theoretical and experimental realization of weak localization, namely, the coherent backscattering effects in disordered conductors, the quantum-interference transport has been extensively investigated in mesoscopic structures.[1,2] It is now established that one of the key physical quantities governing all kinds of the quantum-interference transport phenomena (weak localization, universal conductance fluctuations, Aharonov-Bohm oscillations, etc.) is the electron dephasing time τ_φ. In fact, our understanding of the underlying physics and microscopic mechanisms of electron dephasing has advanced significantly over the last two decades.[3] In practice, the temperature and disorder dependences of τ_φ can be written as[2,3]

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

where l is the electron elastic mean free path, τ_φ^0 is presumed to be a temperature-independent constant, and τ_i is the relevant inelastic electron scattering time(s) in question. The problem whether τ_φ^0 should reach a finite or an infinite value as $T \rightarrow 0$ has been intensively studied very recently.[3] In this work, we shall focus our discussion on the second term, i.e., the temperature-dependent inelastic scattering time τ_i. In general, the inelastic scattering time can be effectively expressed as $1/\tau_i \propto T^p$ over the temperature range accessible for a typical experiment, where p is an exponent of temperature. The knowledge of the value of p is indispensable for identifying the responsible inelastic process (electron-electron scattering, electron-phonon scattering, etc.) in the mesoscopic conductors under study.

The inelastic electron scattering in reduced dimensions in the weakly disordered regime has been extensively studied and it is now understood that the Nyquist electron-electron interaction is responsible for the dephasing at low temperatures.[4] On the other hand, it is established that the inelastic electron scattering in three dimensions in the weakly disordered regime is due to the electron-phonon interaction.[5] Electron-phonon scattering times have been measured in many bulk metals and alloys.[3] What is much less studied is the inelastic electron process in three-dimensional conductors near the Anderson localization or the mobility edge. Under such latter circumstances, Belitz and Wysokinski[6] have proposed that the electron-electron scattering should be very sensitive to the critical, as opposed to diffusive, current dynamics, resulting in an electron-electron scattering rate dominating over the electron-phonon scattering rate in *three* dimensions. (In the present work, this Belitz-Wysokinski process will be referred to as the ''critical'' electron-electron scattering, so as to be distinguished from the more familiar quasielastic, Nyquist electron-electron scattering originally proposed by Altshuler, Aronov, and Khmelnitskii.[7]) Experimentally, the critical electron-electron scattering time τ_{EE} has been observed in several systems having *very low* values of electron diffusion constant D, including thick granular aluminum films,[8] doped semiconductors,[9] heavily doped conjugated polymers,[10] polycrystalline disordered Sc thick films,[11] and RuO_2 and IrO_2 thick films.[12] A very low value of D basically signifies that the conductor is not very far away from the mobility edge.

In all of those experiments just mentioned (except Ref. 8, see below), the critical electron-electron scattering time was observed, but the electron-phonon scattering time was not. This is mainly because that, in most three-dimensional conductors, it is extremely difficult to make the resistivities sufficiently high and vary over a wide range, while keeping the disorder microscopically homogeneous. Thus, most real experiments can only reveal either the critical electron-electron or the electron-phonon process, depending on the amount of randomness and the microscopic quality of disorder in the sample. In this work, using a single material system, namely, Ag doped Sc thick films, we are able to observe a crossover from the critical electron-electron scattering to the electron-phonon scattering. By controlling the amount of Ag addition, we gradually adjust the resistivities of the films, and hence move the films from being close to being away from the mobility edge. Our results are reported below.

TABLE I. Values of relevant parameters for several thick $Sc_{100-x}Ag_x$ films studied in this work. x is the actual composition determined by energy dispersive x-ray spectroscopy. t is the film thickness, D is the electron diffusion constant at 10 K, p is the *fitted* effective exponent of temperature in $1/\tau_i \propto T^p$, and τ_{so} is the spin-orbit scattering time. The resistivity ρ is in $\mu\Omega$ cm.

Film	x	t (Å)	ρ(300 K)	ρ(10 K)	D(cm^2/s)	p	τ_{so} (ps)
$Sc_{99}Ag_1$	1.1	5950	740	641	0.11	1.2 ± 0.1	48
$Sc_{97}Ag_3$	3.0	4900	400	348	0.20	1.1 ± 0.1	17
$Sc_{95}Ag_5$	3.7	5060	356	332	0.21	1.6 ± 0.2	4.1
$Sc_{90}Ag_{10}$	11.0	5170	273	250	0.28	1.8 ± 0.1	3.1
$Sc_{85}Ag_{15}$	15.7	5400	224	197	0.36	1.9 ± 0.1	2.7

II. EXPERIMENTAL METHODS

We have fabricated a series of thick (i.e., three-dimensional) $Sc_{100-x}Ag_x$ films with the *nominal* composition x ranging from 1 to 15. Appropriate amounts of Sc (99.99% pure) and Ag (99.995% pure) were first arc melted in a high-purity Ar atmosphere to form ingots of 2 to 3 g. Appropriate amounts of the ingots were then placed in a vacuum chamber to make thick film samples, using the standard thermal-flash deposition technique. A background pressure of 3×10^{-6} Torr was reached before the evaporation-deposition process was initiated. The films were deposited on glass substrates held at room temperature, and they were patterned into meanders of 0.46 mm wide and 18 mm long using a mechanical metal mask. The thickness of the films varied somewhat around 5000 Å. Table I lists the relevant parameters for our samples studied in this work.

The homogeneity of our $Sc_{100-x}Ag_x$ films for a given composition x was checked by both energy dispersive x-ray spectroscopy and resistivity ρ measurement. We found that, for films with $x\lesssim 15$, the measured values of x and ρ were similar for all the films made from the same batch with the same nominal composition. In addition, the resistivity decreased monotonically with increasing composition x (see Table I). For $x>15$, however, we found that the film resistivities were much less reproducible from batch to batch. Thus, we will focus our discussion on those films with $x\lesssim 15$ in this work.

The resistances and magnetoresistances of our films were measured by the standard four-probe technique at liquid-helium temperatures. Measurement temperatures down to 0.3 K were achieved using a ^{3}He fridge. A calibrated carbon glass thermometer was used for monitoring temperatures above 7 K, while a calibrated RuO_2 thermometer was used for monitoring temperatures below 7 K. In this work, we shall concentrate our discussion on the magnetoresistance data measured at various temperatures, from which the electron dephasing times are inferred. The measured magnetoresistance curves were fitted with three-dimensional weak-localization theoretical predictions[13,14] since our films were made sufficiently thick, as mentioned above. In addition, the phonons are three dimensional in our case. The absence of phonon confinement effects makes our extraction of the inelastic electron-phonon scattering time have a much higher degree of accuracy than that usually achieved in the studies of low-dimensional structures.[3,15] In the latter case, the electron-phonon interactions are often complicated by the film thickness, the substrate material, and the acoustic transparency of the film-substrate interface.

III. RESULTS AND DISCUSSIONS

Figure 1 shows the measured, normalized magnetoresistivities $\triangle\rho(B)/\rho^2(0)=[\rho(B)-\rho(0)]/\rho^2(0)$ (symbols) and the three-dimensional weak-localization theoretical predictions (solid curves) for a representative film $Sc_{85}Ag_{15}$, at three measuring temperatures as indicated in the caption to Fig. 1. The inset shows the $\triangle\rho(B)/\rho^2(0)$ for another film $Sc_{99}Ag_1$, at three measuring temperatures as indicated in the caption to Fig. 1. It is clearly seen that the theoretical predictions agree very well with the experimental data in low magnetic fields. The discrepancies in higher magnetic fields especially at low measuring temperatures are expected and are only drawn for reference.[16] The fitted values of the spin-

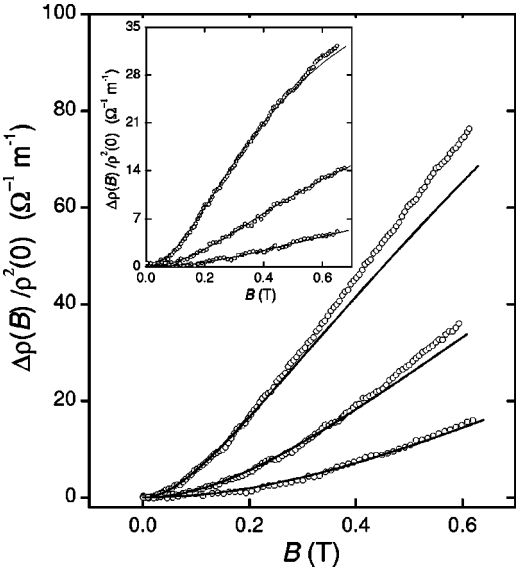

FIG. 1. Normalized magnetoresistivity as a function of magnetic field for the $Sc_{85}Ag_{15}$ thick film at (from top down) 3.0, 6.0, and 10.0 K, respectively. The symbols are the experimental results, and the solid curves are the three-dimensional weak-localization theoretical predictions. Inset: Normalized magnetoresistivity as a function of magnetic field for the $Sc_{99}Ag_1$ thick film at (from top down) 3.0, 6.0, and 10.0 K, respectively.

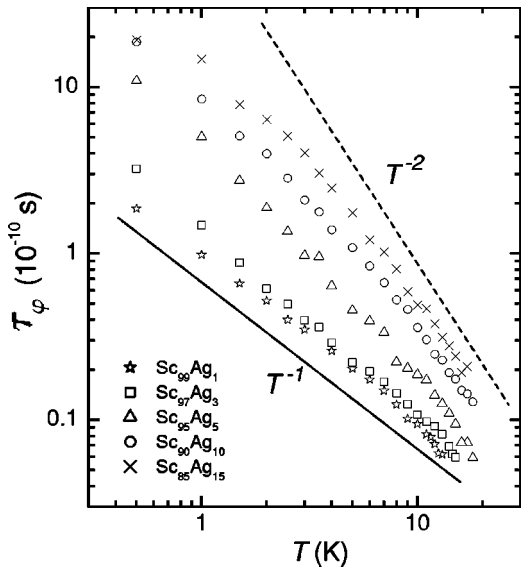

FIG. 2. Experimental electron dephasing time as a function of temperature for five $Sc_{100-x}Ag_x$ thick films. For clarity, the values of τ_φ have been scaled by multiplying a factor of 1, 1, 2, 3, and 4 for $Sc_{99}Ag_1$, $Sc_{97}Ag_3$, $Sc_{95}Ag_5$, $Sc_{90}Ag_{10}$, and $Sc_{85}Ag_{15}$, respectively. The solid line is drawn proportional to T^{-1}, and the dashed line is drawn proportional to T^{-2}. They are guides to the eye.

orbit scattering times τ_{SO}, also involved in the weak-localization theory, are listed in Table I. As expected, the magnitude of τ_{SO} decreases with increasing Ag addition, which can be readily attributed to the large atomic weight of Ag in comparison with that of relatively light Sc. This result provides a consistency check of our experimental method (samples fabrication and data analysis).

Figure 2 shows the extracted electron dephasing time τ_φ as a function of temperature for five $Sc_{100-x}Ag_x$ samples. For clarity, the values of τ_φ have been scaled by multiplying a factor of 1, 1, 2, 3, and 4 for $Sc_{99}Ag_1$, $Sc_{97}Ag_3$, $Sc_{95}Ag_5$, $Sc_{90}Ag_{10}$, and $Sc_{85}Ag_{15}$, respectively. The basic feature of this figure shows that the magnitude of τ_φ increases with decreasing temperature, indicating that inelastic processes are responsible for the electron dephasing, i.e., $1/\tau_\varphi \approx 1/\tau_i$ (at least at not too low temperatures[17]). Physically, the inelastic electron scattering time over the finite temperature range for a typical experiment is effectively given by $1/\tau_i \propto T^p$, where the exponent of temperature p is of order unity. Figure 2 shows the main result of this work, namely, the value of p increases systematically with increasing Ag concentration in these $Sc_{100-x}Ag_x$ thick films. With only 1% of Ag addition, the electron dephasing time reveals a fairly linear temperature dependence over the wide temperature range from 0.3 to above 10 K. This linear behavior of $\tau_\varphi(T)$ is extremely similar to that previously observed in pure Sc thick films.[11] In fact, the measured τ_φ in this sample basically overlaps the value of $\tau_\varphi \approx (1.3\times 10^{-10})T^{-1}$ s found in those pure Sc films[11] just mentioned. This observation provides a consistency check of our experimental method and data analysis.

As the Ag addition increases, one sees that the temperature behavior of τ_φ varies systematically. More precisely, the value of p increases with increasing Ag concentration. (Our fitted value of p for each sample is listed in Table I.) Inspection of Fig. 2 demonstrates that, from 1 up to 15 % of Ag addition, the temperature behavior of our experimental τ_φ evolves progressively from a linear dependence in $Sc_{99}Ag_1$ (our most resistive sample) to a more or less quadratic dependence in $Sc_{85}Ag_{15}$ (our least resistive sample). This systematic change in the temperature dependence of τ_φ is understood as follows.

In the $Sc_{99}Ag_1$ thick film, the linear temperature behavior of τ_φ can be successfully ascribed to the "critical" electron-electron scattering in *three-dimensional* conductors near the mobility edge.[6,12] This is due to the fact that the electron diffusion constant is extremely low (~ 0.1 cm^2/s) in $Sc_{99}Ag_1$, signifying that this film is much closer to the mobility edge than ordinary metals are. In contrast, $D > 1$ cm^2/s in ordinary (weakly disordered) metals. Therefore, the electron-electron interaction is very sensitive to the critical, as opposed to diffusive, current dynamics. According to Belitz and Wysokinski,[6] the inelastic electron-electron scattering rate $1/\tau_{EE}$ under such circumstances should possess a linear dependence on temperature and be independent of disorder. Indeed, besides a linear temperature dependence, a mean-free-path independence of $1/\tau_{EE}$ has previously been confirmed in experiments.[11,12] It should be noted that this $1/\tau_\varphi \approx 1/\tau_{EE} \propto T$ is not due to the *two-dimensional* Nyquist electron-electron scattering usually operating in *weakly disordered* thin metal films in which an exponent $p=1$ has been widely observed.[18]

In the $Sc_{85}Ag_{15}$ thick film, the film resistivity drops significantly from that in $Sc_{99}Ag_1$ (see Table I). As a consequence, one sees that the inelastic electron process illustrates a somewhat quadratic temperature dependence (Fig. 2). This quadratic temperature behavior of $1/\tau_\varphi$ can be understood in terms of the electron-phonon scattering in the presence of disorder, i.e., $1/\tau_\varphi \approx 1/\tau_{ep}$, where τ_{ep} is the electron-phonon scattering time. It has been established over the past two decades that the inelastic electron scattering in weakly disordered conductors is dominated by electron-phonon interaction in three dimensions,[5] while the inelastic scattering is dominated by the Nyquist electron-electron scattering in reduced dimensions.[4] Moreover, it is now clear (especially experimentally) that the electron-phonon scattering rate frequently changes from the T^3 dependence for the pure case to a T^2 dependence for the disordered case.[15,19–22] We believe this T^2 law for the electron-phonon scattering in impure conductors is exactly what is observed in the case of the $Sc_{85}Ag_{15}$ thick film. Quantitatively, the measured value of $\tau_\varphi(10\text{ K}) \approx \tau_{ep}(10\text{ K}) \approx 1\times 10^{-11}$ s in this sample is compatible with the electron-phonon scattering time ($\sim 10^{-10}-10^{-12}$ s at 10 K) measured in, e.g., TiAl alloys,[19,20] and AgPd (Ref. 21) and AuPd (Ref. 15) thick films. However, Fig. 2 indicates that a quadratic temperature dependence is not yet fully developed in this sample at our lowest measuring temperatures. We think that this is due to the fact that the $Sc_{85}Ag_{15}$ film is still too resistive for the electron-phonon scattering to fully dominate the total inelastic scattering rate. That is, the critical electron-electron scattering rate is probably not yet completely suppressed even in this sample. On the other hand, it may be possible that the

deviation from a T^2 law at low temperatures is a signature of the occurrence of a saturation in τ_φ as $T \rightarrow 0$.[3,17]

Between 1 and 15 % doping of Ag, the film resistivity decreases gradually with increasing amount of Ag concentration (see Table I). As a result, the effective exponent of temperature p in $1/\tau_\varphi$ increases systematically from 1 (i.e., $1/\tau_\varphi \approx 1/\tau_{EE}$) toward 2 (i.e., $1/\tau_\varphi \approx 1/\tau_{ep}$).

In conclusion, using a single material system with different levels of disorder, we demonstrate a crossover of the inelastic electron process from the ''critical'' electron-electron scattering to the electron-phonon scattering as the randomness of the system decreases, and the system moves away from the mobility edge. Previously, a similar crossover of the inelastic process has already been observed in a series of high-resistivity, thick granular aluminum films by Mui *et al.*,[8] where most of the resistivities are contributed from the grain boundaries while the metal grains might only be weakly disordered. However, pertinent theoretical understanding was unavailable then and their experimental result could not have been satisfactorily explained until recently.

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