Observation of spin-polarization effects in disordered metals

N. Giordano and M. A. Pennington
Department of Physics, Purdue University, West Lafayette, Indiana 47907
(Received 10 June 1991; revised manuscript received 23 December 1991)

We have studied the properties of submicrometer thin-film Au conductors that are in direct contact with relatively thick films of Fe. The magnetoresistance of these structures exhibits features that appear to be due to spin polarization of the conduction electrons in the Au, which is induced through their proximity to the Fe. The results imply that the length scale over which electrons maintain a "memory" of this polarization is of order 1 μm at a temperature of 4 K. This is much longer than both the elastic mean free path and the spin-orbit scattering length, but is of the order of the electron-phase-coherence length. Our results are in accord with recent theories.

I. INTRODUCTION

It is now well established that weak localization plays a central role in electrical conduction in disordered metals.[1–4] It has been studied extensively in recent years, and seems well understood. Indeed, weak localization is now widely used as a tool with which to study various electron-scattering processes. The magnetoresistance due to weak localization is a sensitive function of several different length scales, including the electron-phase-coherence length, L_ϕ, and the spin-orbit scattering length, L_{SO}. The phase coherence length is the (average) distance which an electron travels between scattering events which disrupt its phase memory. These are usually inelastic scattering events, but may also be due to spin-spin scattering, in which the conduction electron is scattered by a magnetic impurity. In spin-orbit scattering the spin of the conduction electron is altered due to the presence of spin-orbit coupling in the elastic-scattering potential.

Phase coherence plays an important role not only in weak localization but also in so-called mesoscopic systems.[5–7] These are systems whose dimensions are comparable to or smaller than L_ϕ. Many properties of mesoscopic systems cannot be understood in terms of ensemble averaging; rather, each sample must be treated as a unique "individual." For example, the magnetoresistance exhibits fluctuations which are independent of the size of the system, so long as it is smaller than L_ϕ. These are known as universal conductance fluctuations (UCF's), and when expressed in terms of conductance their magnitude is $\sim e^2/h$.

In this paper we report the experimental observation of spin-polarization effects in mesoscopic conductors. Using methods described in the next section we have fabricated Au "wires" which have cross sections of order $(300\ \text{Å})^2$, and lengths of $0.3-3$ μm. Both ends of the wire are continuous with a Au film, but the Au contact film on one end is coated with a thick layer of Fe. The Fe film is ferromagnetic and the conduction electrons in the Fe are thus spin polarized. While the electrons in the Au would normally be unpolarized, we expect that the polarization in the Fe must penetrate, to some extent, into the Au. As we will discuss in detail below, our results suggest that this is indeed the case. The length scale over which "memory" of the spin polarization extends into the Au appears to be of order L_ϕ, as expected on general grounds for mesoscopic systems.

II. THEORY AND BACKGROUND

We will rely on magnetoresistance measurements to obtain information about spin-polarization effects, so it is useful to discuss first the behavior one would expect to find in the absence of such polarization. For a "large" system, i.e., one that is macroscopic as opposed to mesoscopic, weak localization results in a pronounced magnetoresistance in relatively small magnetic fields.[1,2,4] In this paper we will be concerned with Au, which has a short spin-orbit scattering length in which case weak localization yields a positive magnetoresistance which is symmetric about $H = 0$. The functional form of the magnetoresistance has been calculated theoretically,[1,2,4] and observed in previous experiments.[1,8] For strong spin-orbit scattering the magnetoresistance is a function of essentially only one parameter, L_ϕ (aside from dependences on factors such as the cross-sectional area, or sheet resistance, etc., which can be easily and independently determined). Hence measurements of the magnetoresistance can be used to deduce L_ϕ in a fairly direct manner.

The detailed functional forms of the weak-localization magnetoresistance in one and two dimensions have been discussed amply elsewhere,[1,8,9] and need not be repeated here. We only note that the direction of the magnetic field can be of crucial importance. For example, in two dimensions one can view the weak localization magnetoresistance as arising from the phase shift experienced by electron waves which travel in opposite directions around a closed path which is threaded by a magnetic flux.[1] Thus the magnetic field must have a component perpendicular to the plane of the sample in order for there to be a nonzero magnetoresistance; an in-plane field will give rise to a magnetoresistance which is much smaller than that caused by a perpendicular field of the same size. In

contrast, for a one-dimensional system there will be a significant magnetoresistance for all directions of the field, although it will be largest when the field is perpendicular to the direction of current flow. This "directionality" of the magnetoresistance will be important in our analysis below.

In a mesoscopic system one has, in addition to the usual weak-localization magnetoresistance, the UCF fluctuations[10–13,5,7] described in the Introduction. At sufficiently low temperatures these fluctuations are of order $\Delta G \sim e^2/h$. It turns out that this is comparable to the size of the weak-localization magnetoresistance discussed above, and as a result, UCF's tend to obscure weak localization. Nevertheless, it is usually possible to observe, at least qualitatively, the weak-localization magnetoresistance even in mesoscopic samples. In addition, as the temperature is increased, L_ϕ, and also the thermal length, $L_T = \sqrt{D\hbar/k_BT}$, become comparable to or smaller than the sample dimensions, and the UCF's decrease in magnitude.[10–13,5,7]

While the weak-localization magnetoresistance generally remains visible even in the presence of UCF, the functional form of this magnetoresistance is different in a mesoscopic system as compared to a macroscopic one.[14,5,7] For a wire which is much shorter than L_ϕ (which is the geometry we have studied), the important (classical) electron "trajectories" will include ones in which the electrons diffuse into the leads a distance of order L_ϕ. As a result, the magnetoresistance of such a sample will reflect the properties of the leads as well as those of the sample. Indeed, if the sample length, L, is much less than L_ϕ the behavior will be completely determined by the leads. For the systems we have studied, i.e., a two-lead geometry in which the leads are thin films, this behavior will be two dimensional. When $L \sim L_\phi$ the detailed functional form of the magnetoresistance cannot be classified as simply one or two dimensional. The magnetoresistance for systems which are of order L_ϕ in length has been discussed extensively elsewhere,[14] and quantitative theoretical predictions are available for several different sample geometries, although apparently not for the one appropriate for our experiments. In any case, as will become clear below, our analysis will hinge largely on the *qualitative* features of the data, so the lack of quantitative theoretical predictions for the magnetoresistance for our particular sample geometry is not a serious drawback.

An interesting property of mesoscopic systems which will turn out to be very important in the present work concerns the symmetry of the resistance with respect to changes of the sign of the magnetic field. This became apparent as a result of four-lead measurements of the resistance.[15–17] It turns out that in this case for a normal, i.e., nonmagnetic, metal the resistance is *not* invariant under reversal of the direction of the magnetic field. However, it *is* invariant if the field reversal is accompanied by interchange of the current and voltage leads. For a two-lead measuring geometry like the one we have employed, there is no problem with reversing the leads (since they are already the same), so we expect $R(+H) = R(-H)$. However, in the more general case, i.e., in a magnetic system, this symmetry only applies if the magnetization of the system also changes sign with H. That is, one really has[17]

$$R(+H,+M) = R(-H,-M) , \tag{1}$$

where M is the magnetization.

The problem of spin-polarization effects in mesoscopic systems has been discussed theoretically in several recent papers.[18–20] Consider a system which has strong spin-orbit scattering, and thus has a short spin-orbit scattering length (as is the case in the Au systems we have studied) so that $L_{SO} \ll L_\phi$.[21] Hence, the spin direction of an electron will be "rotated" many times as it travels a distance L_ϕ.[1] These rotations will depend on the details of the scattering potential and hence will appear to be "random." However, a second electron which has the same initial polarization, and follows the same classical path as the first one, will experience the same sequence of scattering events, and will end up with the same final spin direction. In this way spin "memory" can be maintained over distances of order L_ϕ, which is much longer than L_{SO}. This has been demonstrated explicitly by several calculations, and schemes for observing this effect experimentally have been discussed.[18–20] Our sample geometry is, in fact, very similar to ones proposed by Zyuzin[18] and Zyuzin and Serota.[20]

Spin-polarization effects in pure metals (as opposed to the disordered case which is appropriate for the present experiments) have been the subject of a good deal of previous work. There have been extensive surface physics studies of the polarization of electrons emitted from solids[22] (i.e., through photoemission, etc.). This work does not appear to be directly relevant to our experiments, since the surface physics measurements are sensitive to electrons which are typically 1 eV or more above the Fermi level, while the electrons relevant to transport measurements are essentially right at the Fermi level.

We know of at least two different types of transport experiments which seem relevant to our work. The first is tunneling between a ferromagnet and a superconductor in a large magnetic field. In a series of experiments,[23–29] it has been shown that the tunneling conductance exhibits a series of peaks which arise from differences in the density of states for spin-up and spin-down electrons in both the ferromagnet and the superconductor. An analysis of the peak intensities yields the spin polarization of the tunneling electrons. The result for this polarization is in good agreement with theoretical calculations,[30] with a value of $\sim 44\%$ for Fe, the ferromagnet relevant for our work.

Another interesting set of experiments has been reported by Johnson and Silsbee,[31–34] who studied the transport of spin, and its coupling to charge transport. By using a ferromagnet in contact with a normal metal, they were able to generate and detect spin currents. Their work differs from ours in (at least) one important respect. Their measurements were sensitive to the *absolute* polarization, which will be disrupted by any scattering or interaction (i.e., with a magnetic field) which affects the spin direction. In contrast, as we will see

below, our experiments appear to be sensitive to "spin memory," in much the same way that weak localization is sensitive to "phase memory."

III. EXPERIMENTAL TECHNIQUE

The samples we have studied were fabricated using a step-edge method very similar to that described by Garfunkel and Weissman,[35,36] which is sketched in Fig. 1. Optical contact lithography together with lift-off is first used to deposit a Cr pattern on a glass substrate, Fig. 1(a). The precise shape of this pattern is not important; the only requirement is that it have a relatively long straight section. This structure is then ion milled at normal incidence with Ar^+, Fig. 1(a), which removes some of the glass (where it is exposed), along with some of the Cr. For the structures studied in this work, the glass was milled to a depth of typically 750 Å. The remaining Cr was then removed chemically, producing a substrate which contained a step. An $\sim$ 150 Å thick film of 99.999% pure Au was then evaporated onto the substrate at a 45° angle so as to coat the "vertical" edge of the step, Fig. 1(b). Just prior to this evaporation, the substrate was exposed to an O_2 glow discharge, to improve the adhesion of the Au film. The typical (low temperature) sheet resistance of this film was 4 Ω, corresponding to a resistivity of 6 $\mu\Omega$ cm, and an elastic mean free path of $\sim$ 50 Å. These numbers are appropriate for all of the samples (both one and two dimensional) considered below. Another stage of lithography was then performed. In this case the slide was exposed so that following development of the photoresist, half of the step was coated with photoresist, while the Au film on the other half remained exposed, as shown in Fig. 1(c). This pattern was projected onto the photoresist coated substrate with an optical microscope.[37] The key result of this step was to produce a photoresist edge which was perpendicular to the step in the substrate. Next a metal film (typically 500 – 2000 Å thick) of either Fe or Ag was evaporated at an angle so as to cast a "shadow" over the photoresist edge, Fig. 1(d). The result was a "slot" which separated the edge of the photoresist from the edge of the Fe (or Ag) film; in this slot the Au film was exposed. The width of the slot was determined by the thickness of the photoresist (which was approximately 5000 Å) and the evaporation angle, and varied from 3000 Å to 3 μm. The evaporated film of either Fe or Ag overcoated the underlying Au layer, and will be referred to as a Au/Fe (or Au/Ag) film in the following. The final step was to ion mill this structure, with direction of the Ar^+ beam coplanar with the slot, and at angle of 45° from normal incidence, such that the Au on the vertical edge of the step was protected, i.e., was in the shadow of the glass step.[36] This milling was used to remove all of the exposed Au, leaving behind a narrow Au "wire" which ran along the edge of the step. Following removal of the remaining photoresist, this short Au wire connected films of Au and either Au/Fe or Au/Ag, Fig. 1(e). The cross-sectional area of the wire depended on the milling time, and was in the range $\sim 150 \times 1200$ Å^2 to $\sim 150 \times 800$ Å^2.

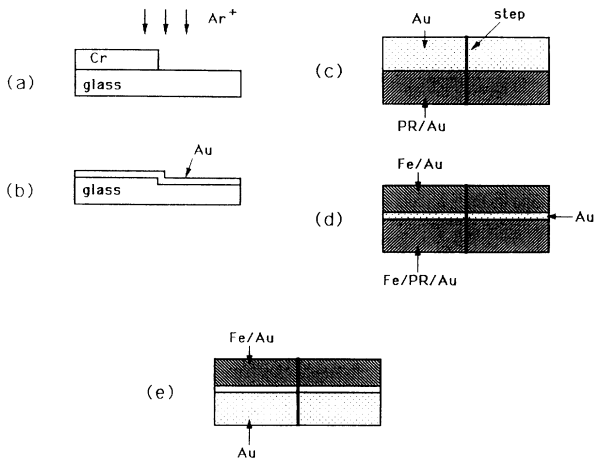

FIG. 1. Schematic description of the method used to make short "wires" in contact with different metals. PR denotes photoresist. The different steps are discussed in the text.

This method was used to produce small Au structures whose electrical resistance could be measured in a two-lead geometry. One of these leads was the Au film which was continuous at one end with the Au wire, while the other lead was a Au/Fe or Au/Ag film. As discussed in the Introduction, the samples with Au/Fe were expected to exhibit spin-polarization effects; the samples with Au/Ag were studied for comparison purposes.

Several other comparison samples were also examined. First, the magnetoresistance of Au films codeposited with the samples was studied to determine the phase breaking length of the two-dimensional Au. These samples were patterned using conventional photolithography and lift-off techniques, to make "meander" patterns typically 120 μm wide and 5 cm long. In addition, the phase breaking length in long ($\sim$50–100 μm) Au wires made using a step-edge method[36] [i.e., essentially just skipping steps (c) and (d) in Fig. 1] was measured. Finally, we also studied the magnetoresistance of Au/Fe films like those used for one of the contact pads in Fig. 1(d). These results will all be described in the following section.

The measurements were performed in a standard ^{4}He cryostat, in which the sample was mounted on a Cu block inside a vacuum can. The block was weakly coupled thermally to the ^{4}He bath, and the sample temperature could be varied from 1.3 to 10 K, or higher. A superconducting magnet provided a field for the magnetoresistance measurements. This field could be directed either perpendicular or parallel to the plane of the substrate. For the parallel measurements, the field was perpendicular to the direction of current flow.

The resistance measurements were carried out with a standard ac bridge setup, similar to that described elsewhere.[38] Using a ratio transformer, the resistance of the sample was compared to that of a reference sample. The resistance of the entire structure, including the Au wire and the contact pads, was typically 30–150 Ω.[39] With such a low resistance it was necessary to position the reference sample of the bridge at low temperatures, so as to eliminate the effects of lead resistance. The reference samples were thick Au films patterned to give a

resistance comparable to that of the sample. These reference films had sheet resistances of typically 0.1 Ω or less, so any changes of their resistance due to weak localization (or electron-electron interactions) were much smaller than the changes in the sample resistance, and could be neglected. The lock-in amplifier could, with suitable averaging, detect voltage changes less than 10^{-9} V, and the sample current was kept below 10^{-6} A. Measurements at higher currents demonstrated that the behavior described in this paper was independent of the measuring current.

IV. RESULTS

Magnetoresistance measurements were first performed on Au films codeposited with the samples, and on long Au wires fabricated as described above. In both cases, the magnetoresistance was well described by the predicted form appropriate for weak localization in two and one dimensions, respectively. Figure 2(a) shows the magnetoresistance of a long Au wire at several temperatures. The solid curves are fits to the predicted weak-localization magnetoresistance.[40] At each temperature there are two fitted parameters, the phase breaking length and the zero field resistance [the curves in Fig. 2(a) were all offset to give $\Delta R = 0$ at $H = 0$]. The cross-sectional area of the wire is also required to calculate the magnetoresistance, but it is known from independent measurements at room temperature, and is not a free parameter in the fits. The theory is seen to give an essentially perfect description of the results. The phase-coherence lengths obtained from these fits are shown in Fig. 2(b), where we also show L_ϕ derived from similar measurements for a Au film sample. From previous studies of electron inelastic-scattering in similar systems,[1,41,8,42] we expect that electron-phonon and electron-electron scattering could both be important. The scattering times for these process are characterized by temperature dependences of the form T^{-p}. For electron-phonon scattering $p \sim 2.5$, while for electron-electron scattering $p = 1$ in two dimensions and $p = \frac{2}{3}$ in one dimension. Since $L_\phi = \sqrt{D\tau_\phi}$, we would expect a simple power law $L_\phi \sim T^{-p/2}$ when only one scattering process is important.

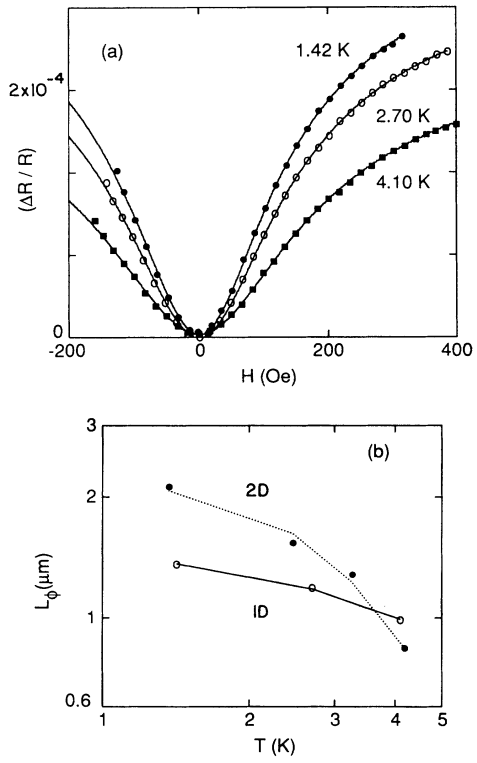

FIG. 2. (a) Magnetoresistance of a long Au wire at three different temperatures, as indicated. The cross-sectional area was $\sim 150 \times 1200$ Å^2, and the length of the sample was 75 μm. The solid curves are fits to the predicted weak-localization magnetoresistance in one dimension, with strong spin-orbit scattering (Refs. 4 and 9). (b) Phase-coherence length derived from data like that in (a), for one and two dimensions. The solid and dotted curves are guides to the eye.

While the amount of data is limited, it appears from Fig. 2(b) that in both cases the temperature dependence of L_ϕ cannot be described by a power law with a single value of p over the entire temperature range studied (a pure power-law behavior would yield a straight line). This suggests that both electron-phonon and electron-electron scattering are important, with the former dominating at high temperatures [with a higher value of p and thus a larger slope in Fig. 2(b)], while the latter dominates at low temperatures.[43] In addition, the absolute magnitudes of L_ϕ are also consistent with previous quantitative results, both theoretical and experimental, for these scattering rates.[42,44] Similar results were found for other one- and two-dimensional samples. It should be noted that the theory predicts that L_ϕ depends on the cross-sectional area in one-dimension (1D), and the sheet resistance (and hence film thickness) in 2D. We did not attempt to study the variation of L_ϕ with these parameters, as it was not important for the present study. As far as the present work is concerned, the key result of the magnetoresistance measurements described above is that L_ϕ is typically in the range 1-2 μm, which is comparable to or larger than our typical sample length.

Figure 3 shows results for the magnetoresistance of a 2.0-μm-long sample which had a Au/Ag film in contact at one end. Here we show results for both polarities of the field, and it is seen that to within the experimental uncertainties, the resistance is symmetric; i.e., $R(+H) = R(-H)$, as expected for a two-lead measurement. The scatter in the data is larger than in the results for the large samples, because the total voltage across the sample is much less for the short samples. Nevertheless, to within this scatter, $R(H)$ is independent of the sign of H. Near $H = 0$ the characteristic weak-localization "dip" is evident. There are, in addition, undulations in R which are due to universal conductance fluctuations. As a check on this interpretation one can estimate the predicted magnitude of the fluctuations in this case. If we begin by assuming that the sample can be treated as a single phase-coherent region (see, however, below), we expect ΔG to be of order e^2/h times

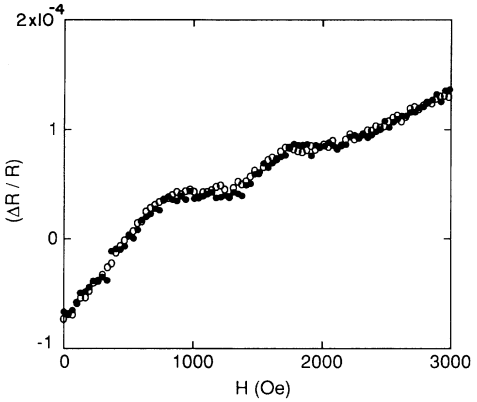

FIG. 3. Magnetoresistance of a Au wire with a Au/Ag contact film at one end. The wire was 2.0 μm long, T = 4.19 K, and the field was perpendicular to the plane of the substrate. The solid symbols are data taken with one polarity of H, while the open symbols are for the opposite polarity. In both cases, the results were independent of the direction in which H was swept. The zero of the vertical scale is arbitrary.

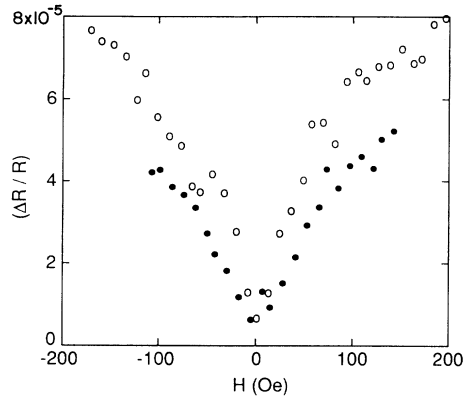

FIG. 4. Magnetoresistance for a Au wire with a Au/Ag contact film at one end. The wire was 0.6 μm long and the field was perpendicular to the plane of the substrate. The solid symbols are data taken at 4.20 K, while the open symbols were obtained at 1.34 K. In both cases, to within experimental error the results were independent of the direction in which H was swept. The two curves have been offset vertically for clarity. The zero of the vertical scale is arbitrary.

length of $L = 2$ μm and $D = 15$ cm^{2}s as estimated from the elastic mean free path given above, we find $T_c \sim 0.025$ K. The measurements in Fig. 3 were performed at 4.2 K, so the reduction factor due to energy averaging is ~0.08. We therefore expect the UCF fluctuations to be $\Delta G \sim 0.25e^2/h = 3 \times 10^{-6}$ mho. Converting this to resistance we have $\Delta R/R = 1.5 \times 10^{-4}$ (since for this sample $R \sim 50$ Ω), which is a little larger than the fluctuations observed in Fig. 3 which are several parts in 10^{-5}. However, the sample length in this case is about a factor of 2 larger than the phase breaking length [Fig. 2(b)] so we would expect an additional reduction of the UCF fluctuations due to subsystem averaging[13] by an amount of order $(L_\phi/L)^2 \sim 4$ which brings the theoretical predictions into very good agreement with the fluctuation magnitude obeseved in Fig. 3. It is also interesting to consider the field scale of the fluctuations. According to the theory[13] the field "correlation" scale for UCF should be $H_c A \sim (h/e)$ where A is the area of a phase-coherent region which is normal to the field. For the sample in Fig. 3, $A = L_\phi \times L_W$, where L_W is the width of the sample in the plane perpendicular to the field. Using $L_\phi = 1$ μm (see above) and $L_W = 1000$ Å as measured for this sample, we find $H_c = 800$ Oe, which is in good agreement with the results in Fig. 3. The general behavior seen here is thus in good agreement with the theory of UCF (Refs. 10–13) and with previous studies[5–7] of similar samples.

Figure 4 shows the magnetoresistance near $H = 0$ in more detail for another sample with a Au/Ag film at one end. We again see the characteristic weak-localization minimum at $H = 0$. The magnitude of the dip becomes larger as the temperature is reduced, and its width becomes smaller. This is caused by the increase of L_ϕ as T is lowered [compare with Fig. 2(a)]. In addition, we find again that to within the uncertainties the resistance is symmetric about $H = 0$, i.e., $R(+H) = R(-H)$, as expected for a nonmagnetic system.

We now consider samples in which a Au/Fe film served as one contact pad. Figure 5 shows results for a sample which was 0.5 μm long. The results seen here are characteristic of those found for all ten samples with a Au/Fe contact film which we have studied. First, there are fluctuations in the resistance which have a magnitude of several parts in 10^{-5}. The magnitude of these fluctuations is quite similar to that seen in Fig. 3, and as shown above this is consistent with UCF theory.[45] Second, the resistance is, especially at low fields, a sensitive function of the field direction and history. At high fields (above about 500 Oe in Fig. 5, although this field varied

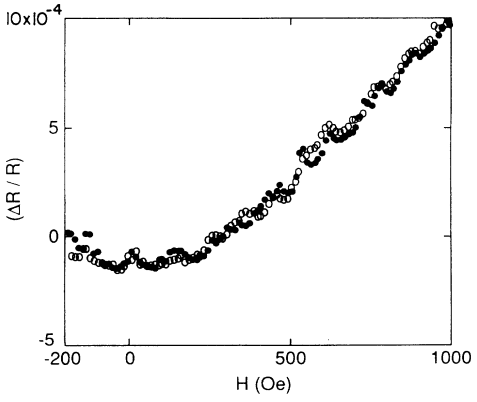

FIG. 5. Magnetoresistance for a Au wire with a Au/Fe contact film at one end. The wire was 0.5 μm long, the temperature was 4.20 K, and the field was perpendicular to the plane of the substrate. The solid symbols are data taken with one polarity of H, while the open symbols are for the opposite polarity. In both cases, the field was swept from "negative" towards "positive" fields. The zero of the vertical scale is arbitrary.

somewhat from sample to sample) the resistance and the associated fluctuations are the same for $\pm H$, and there is negligible hysteresis. However, as can be seen from Fig. 6, at lower fields the resistance is very different for $\pm H$ and is strongly hysteretic. In particular, we note that in general $R(+H) \neq R(-H)$, at low fields. This behavior, which is clearly suggestive of magnetic effects, was *never* observed in samples with Au/Ag contacts. Hence the proximity of the Fe clearly has a pronounced effect on the behavior.

A quantitative analysis of the results in Fig. 6 would require, at a minimum, knowledge of the direction of the magnetization, M, in the Fe film as a function of field. This direction will depend on many factors, such as imperfections in the film, the previous field history, etc., and is difficult to predict ahead of time. Presumably, the domain size is large compared to the width of the Au wire, so that a single magnetic domain is in contact with the end of the wire. This domain should be affected by changes in the magnetic field, and the existence of some hysteresis in low fields would not be surprising. Thus we expect that the direction of M in the Fe which is directly adjacent to the Au wire will depend on the field history. The results in Fig. 6 can then be understood qualitatively if we assume that the direction of M near $H = 0$ depends on the direction of H during the most recent excursion to "large" fields; here "large" means of the order of a few hundred Oe. Hence, when H was swept down from large positive fields the direction of M was presumably "positive," and this direction was evidently maintained for small negative fields. Similarly, for the sweep up from large negative fields M was presumably in the opposite direction. When H is restricted to relatively small fields, as in Fig. 6, we speculate that changing the sign of H does *not* change the direction of M. From (1) we would therefore expect $R(+H) \neq R(-H)$, as observed.

We believe that this is the correct qualitative explanation of the asymmetry and hysteresis seen in Fig. 6. However, this explanation leaves open the *microscopic* origin of these effects. There are two different microscopic mechanisms of which we are aware that we feel are plausible. (1) Electrons from the Fe will diffuse into the Au wire, since the two are in direct contact. These electrons will be spin polarized, since the polarization of electrons at the Fermi level in Fe is known from much previous work to be ~44%.[30] The direction of this polarization will depend on the direction of the magnetization in the portion of the Fe film which is adjacent to the Au wire. In Au the spin-orbit scattering is strong, so electrons with different polarizations will experience different scattering potentials,[1] thus changing the spin polarization of the electrons in the Au is essentially equivalent to "changing" the potential, i.e., "changing" the sample in the manner of universal conductance fluctuations. In accord with our understanding of UCF we expect that this will result in a conductance change which is comparable in magnitude to UCF fluctuations, and this is consistent with the observed size of the fluctuations in Fig. 6. (The magnitude of these fluctuations must, of course, depend in some way on the degree of spin polarization, but the UCF magnitude should provide an approximate upper bound.) We believe that this is the most likely microscopic explanation of the behavior we have observed. However, a second explanation is consistent with the results we have presented so far. (2) In a mesoscopic system the electrons maintain phase coherence over a distance of order L_ϕ (the value of L_ϕ in the Au/Fe film will be considered below). As discussed above, this coherence will not be limited to the "sample" proper, but will also extend out into the leads a distance L_ϕ. In our case this means that the electrons in the Au will diffuse into the Fe contact film, and hence the measured conductance will depend to some extent on what happens in the Fe.

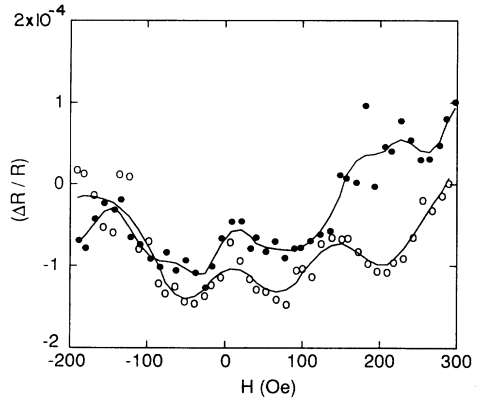

FIG. 6. Magnetoresistance for a Au wire with a Au/Fe contact film at one end. The wire was the same sample as in Fig. 5, the temperature was 4.20 K, and the field was perpendicular to the plane of the substrate. The open symbols are data taken by sweeping H from -200 to 300 Oe, while the closed symbols are for a sweep in the opposite direction. The solid curves are guides to the eye. The zero of the vertical scale is arbitrary.

We have conducted two measurements which we believe make it possible to distinguish between these two alternatives. First, we have measured the magnetoresistance of a film of Au overcoated with a layer of Fe. These films were chosen to be the same thicknesses as those used to make the Au/Fe contacts at the ends of our Au wires, so this measurement should yield direct information on the contribution of the contact to the overall behavior of the structure. Figure 7 shows the magnetoresistance for a Au/Fe film. It is seen that the magnitude of the magnetoresistance is relatively small, about an order of magnitude smaller than that seen in our Au wire samples. Fitting these results to weak-localization theory yields a qualitative value of the phase breaking length of $\sim$ 3000 Å. Moreover, this length is independent of temperature over the range we have studied, suggesting that the Fe produces strong spin-spin scattering (which is temperature independent), which dominates the phase breaking length. This also means that phase coherence does not extend very far into the Au/Fe film as compared with the phase-coherence length for electrons in the Au wire. It is also noteworthy that the results for the Au/Fe film are, to within the experimental scatter, *symmetric* with respect to the sign of H, and exhibit

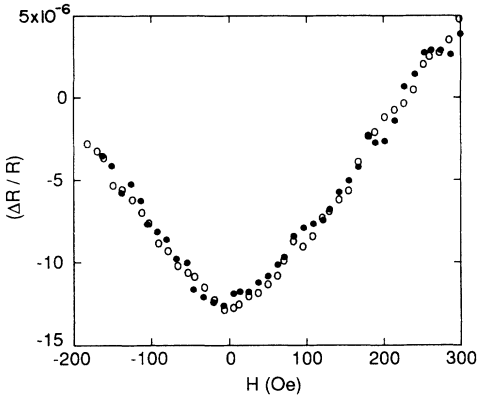

FIG. 7. Magnetoresistance of a Au/Fe film. The temperature was 4.26 K, and the field was perpendicular to the plane of the substrate. The solid symbols are data taken by sweeping H from -200 to 300 Oe, while the open symbols are for a sweep in the opposite direction. To within experimental, the results were independent of the direction the field was swept, in contrast to the results in Fig. 6. The zero of the vertical scale is arbitrary. The small fluctuations are due to the uncertainties in the measurements, and not UCF.

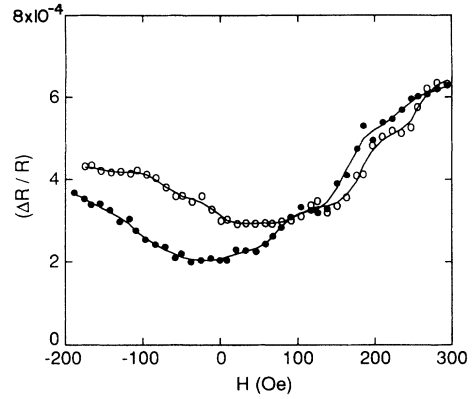

FIG. 8. Magnetoresistance for a Au wire with a Au/Fe contact film at one end. The wire had a length of 0.6 μm, the temperature was 4.22 K, and the field was *parallel* to the plane of the substrate. The open symbols are data taken by sweeping H from -200 to 300 Oe, while the closed symbols are for a sweep in the opposite direction. The solid curves are guides to the eye, and the zero of the vertical scale is arbitrary.

no hysteresis.[47,48] That this behavior is qualitatively so different from that seen in Figs. 5 and 6 strongly suggests that the behavior seen in Figs. 5 and 6 is not due to electron-phase-coherent effects in the Au/Fe contacts. Rather, we believe that they are due to processes which occur in the Au wire itself.

A second measurement supports this conclusion. We have studied the magnetoresistance of the Au wire structures with H directed in the plane of the substrate and perpendicular to the direction of current flow. Some typical results for this case are shown in Fig. 8, where we again see a pronounced asymmetry and hysteresis, which is very similar to that found with perpendicular fields (Fig. 6). If these effects were due to electron motion in the Au/Fe film (or in the Au film at the other end of the wire), the magnetoresistance should in this case be very small, since for parallel fields the flux through the classical electron trajectories is greatly reduced as compared to the situation with the field perpendicular to the plane.[46] For processes taking place in the Au wire itself, perpendicular and parallel fields should yield similar results since the flux is the same in the two cases because of the peculiar geometry of our samples. As can be seen from Fig. 1 (see also Refs. 36 and 35) our samples are essentially "wrapped around" the step in the substrate. The angle of the final milling [Fig. 1(e)] ensures that half of the sample cross section is on the "vertical" portion of the step, while the other half is on the "flat" portion of the substrate. That is, the sample has an "L" shaped cross section so that a magnetic field applied in the plane of the substrate and perpendicular to the direction of the current (as was the case in Fig. 8) will produce the same effective flux as far as weak localization and UCF are concerned as does a field perpendicular to the substrate. Hence, if the important physics is taking place in the Au

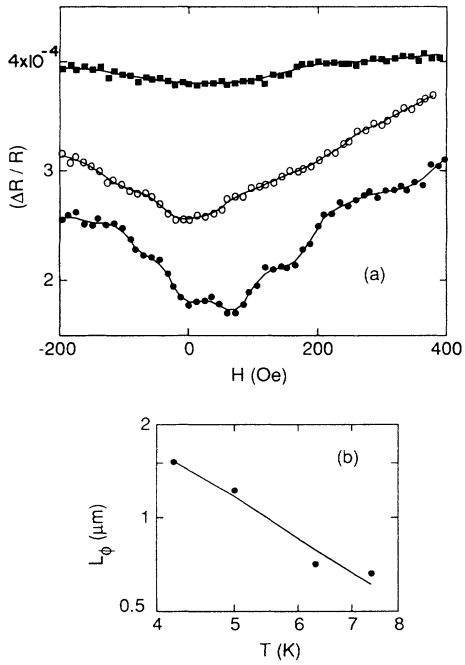

FIG. 9. (a) Magnetoresistance for a Au wire with a Au/Fe contact film at one end. The wire had a length of 1.5 μm, and the field was perpendicular to the plane of the substrate. The temperature was 4.20 K for the lower data set, 5.01 K for the middle set, and 6.32 K for the upper set. From repeated scans at each temperature, it was determined that essentially all of the fluctuations visible at 4.20 K were reproducible, the largest ones at 5.01 K were repeatable, while at 6.32 K the results were, to within experimental error, symmetric with no dependence on the direction in which the field was swept. The data shown here were all taken by sweeping H from -200 to 300 Oe, and the solid curves are guides to the eye. The solid curve is a guide to the eye, and the zero of the vertical scale is arbitrary. (b) *Qualitative* variation of the phase-coherence length, L_ϕ (see text), obtained from fits to data like that shown in (a).

wire as opposed to the contact films, then the measurements in Figs. 5 and 8 should yield similar results. The essential qualitative features of the data, the magnitude and the field scale of the fluctuations, are seen to be the same in the two cases.

Our results thus suggest that the asymmetry and hysteresis we observe is due to spin-polarization effects in the Au wires, and we believe that this polarization arises through the diffusion of polarized electrons from the Fe into the Au. As noted in Sec. II, theory predicts that the length scale for this spin "memory" is L_ϕ. In order to determine this length scale experimentally we have examined the asymmetry as a function of temperature. By changing T one varies L_ϕ, and thereby effectively changes the length of the sample, when measured in terms of L_ϕ. Some typical results are shown in Fig. 9(a). It is seen that as T is increased the asymmetry decreases markedly. At the highest temperatures in Fig. 9(a) the magnetoresistance is, to within the experimental error, symmetric; i.e., $R(+H) = R(-H)$. The magnitude of the weak-localization magnetoresistance is also seen to decrease rapidly as T is increased, implying that L_ϕ is becoming smaller. While the finite length of the sample together with the UCF fluctuations preclude a quantitative analysis,[14] we can nevertheless make qualitative fits of these results to the theoretical predictions for a long one-dimensional sample. These fits will admittedly not be quantitatively correct, but should give at least a qualitative estimate of the variation of L_ϕ; the results are shown in Fig. 9(b). One sees that the vanishing of the asymmetry occurs as L_ϕ is becoming significantly smaller than the sample length. A more quantitative analysis will have to await further theoretical calculations of the magnetoresistance in such complicated geometries, but these results clearly support an interpretation in terms of polarization diffusion[18–20] from the Fe into the Au.

V. SUMMARY AND CONCLUSIONS

We have studied mesoscopic Au wires which are in direct contact at one end with a ferromagnetic film. We have observed features in the magnetoresistance which indicate that spin-polarization effects are important. Furthermore, the experiments seem to suggest that the effects arise from processes inside the Au wires. An explanation in terms of the diffusion of spin polarization from the ferromagnet into the Au is in good qualitative agreement with our results. The sample geometry we have employed should prove useful for a number of other experiments in this area.

ACKNOWLEDGMENTS

We thank S. Santhanam and R. Serota for providing preprints of their work, M. Blachly and J. Liu for helpful discussions and assistance with the fabrication, and P. F. Muzikar for comments on the manuscript. This work was supported by the National Science Foundation through Grant No. DMR-8915574.

[1] G. Bergmann, Phys. Rep. **107**, 1 (1984).
[2] P. A. Lee and T. V. Ramakrishnan, Rev. Mod. Phys. **57**, 287 (1985).
[3] See, for example, *Localization 1990,* edited by K. A. Benedict and J. T. Chalker (Institute of Physics, Bristol, 1991).
[4] B. L. Al'tshuler, A. G. Aronov, D. E. Khmel'nitzkii, and A. I. Larkin, in *Quantum Theory of Solids,* edited by I. M. Lifshitz (Mir, Moscow, 1982).
[5] S. Washburn and R. A. Webb, Adv. Phys. **35**, 375 (1986).
[6] *Nanostructure Physics and Fabrication,* edited by M. A. Reed and W. P. Kirk (Academic, San Diego, 1989).
[7] *Mesoscopic Phenomena in Solids,* edited by B. L. Al'tshuler, R. A. Webb, and P. A. Lee (Elsevier, Amsterdam, 1991).
[8] C. Van Haesendonck, M. Gijs, and Y. Bruynseraede, in *Localization, Interaction, and Transport Phenomena,* edited by B. Kramer, G. Bergmann, and Y. Bruynseraede (Springer, Berlin, 1985), p. 221.
[9] D. E. Beutler and N. Giordano, Phys. Rev. B **38**, 8 (1988).
[10] B. L. Al'tshuler, Pis'ma Zh. Eksp. Teor. Fiz. **41**, 530 (1985) [JETP Lett. **41**, 648 (1985)].
[11] P. A. Lee and A. D. Stone, Phys. Rev. Lett. **55**, 1622 (1985).
[12] B. L. Al'tshuler and D. E. Khmel'nitzkii, Pis'ma Zh. Eksp. Teor. Fiz. **42**, 291 (1985) [JETP Lett. **42**, 359 (1985)].
[13] P. A. Lee, A. D. Stone, and H. Fukuyama, Phys. Rev. B **35**, 1039 (1987).
[14] V. Chandrasekhar, P. Santhanam, and D. E. Prober, Phys. Rev. B **44**, 11 203 (1991).
[15] A. D. Benoit, S. Washburn, C. P. Umbach, R. B. Laibowitz, and R. A. Webb, Phys. Rev. Lett. **57**, 1765 (1986).
[16] M. Büttiker, Phys. Rev. Lett. **57**, 1761 (1986).
[17] M. Büttiker, IBM J. **32**, 317 (1988).
[18] A. Yu. Zyuzin, Europhys. Lett. **12**, 529 (1990).
[19] Yu. V. Nazarov, Pis'ma Zh. Eksp. Teor. Fiz. **51**, 373 (1990) [JETP Lett. **51**, 426 (1990)].
[20] A. Yu. Zyuzin and R. A. Serota (unpublished).
[21] The spin-orbit scattering length in Au is very short. Previous work (Ref. 8) has found $L_{SO} \sim 300$ Å in Au films.
[22] M. Landolt, in *Polarized Electrons in Surface Physics,* edited by R. Feder (World Scientific, Singapore, 1985), p. 385.
[23] P. M. Tedrow and R. Meservey, Phys. Rev. Lett. **26**, 192 (1971).
[24] P. M. Tedrow and R. Meservey, Phys. Rev. B **7**, 318 (1973).
[25] J. S. Moodera, M. E. Taylor, and R. Meservey, Phys. Rev. B **40**, 11 980 (1989).
[26] Work on tunneling involving superconductors in contact with magnetic insulators (Refs. 27–29) is also of obvious interest in the context of the present work.
[27] P. M. Tedrow, J. E. Tkaczyk, and A. Kumar, Phys. Rev. Lett. **56**, 1746 (1986).
[28] P. M. Tedrow, J. E. Tkaczyk, and A. Kumar, J. Appl. Phys. **61**, 3368 (1987).
[29] J. S. Moodera, X. Hao, G. A. Gibson, and R. Meservey, Phys. Rev. Lett. **61**, 637 (1988).
[30] See, for example, M. B. Stearns, J. Magn. Magn. Mater. **5**, 167 (1977).
[31] M. Johnson and R. H. Silsbee, Phys. Rev. Lett. **55**, 1790

(1985).
[32] M. Johnson and R. H. Silsbee, Phys. Rev. B **37**, 5312 (1988); **37**, 5326 (1988).
[33] M. Johnson and R. H. Silsbee, Phys. Rev. B **39**, 8169 (1989).
[34] See also A. G. Aronov, Pis'ma Zh. Eksp. Teor. Fiz. **24**, 37 (1976) [JETP Lett. **24**, 32 (1976)].
[35] G. A. Garfunkel and M. B. Weissman, J. Vac. Sci. Technol. B **8**, 1087 (1990).
[36] See also D. E. Prober, M. D. Feuer, and N. Giordano, Appl. Phys. Lett. **37**, 94 (1980).
[37] D. W. Palmer and S. K. Decker, Rev. Sci. Instrum. **44**, 1621 (1973).
[38] N. Giordano and M. A. Pennington (unpublished).
[39] The spreading resistance was estimated to be approximately 50% of the total resistance of the structure. In any quantitative analysis of the magnetoresistance this contribution would have to be taken into account. However, in this paper we will draw our conclusions from the qualitative behavior, so such a correction will not be necessary. In the figures below R refers to the resistance of the entire structure, including the spreading resistance.
[40] The functional forms used to fit the magnetoresistance in both one and two dimensions are given in detail in Ref. 9.
[41] B. L. Al'tshuler and A. G. Aronov, in *Electron-Electron Interactions in Disordered Systems*, edited by A. L. Efros and M. Pollak (Elsevier, Amsterdam, 1985).
[42] D. Belitz and S. Das Sarma, Phys. Rev. B **36**, 7701 (1987).
[43] It is also possible that spin-spin scattering is important at the lowest temperatures. However, L_ϕ in the Au film [Fig. 2(b)] is still varying fairly rapidly with T at the lowest temperatures, suggesting that spin-spin scattering is not important.
[44] J. Liu and N. Giordano, Phys. Rev. B **43**, 3928 (1991).
[45] It is also interesting to note that the field scale of the fluctuations in Fig. 5 is somewhat smaller than that seen in Fig. 3. The reason for this is not completely clear, but is probably due to the fact that the sample in Fig. 5 was about a factor of 2 wider than that considered in Fig. 3. This would reduce the value of H_c by the same factor, which could explain the difference in the field scales. The sample in Fig. 5 was also a factor of 4 shorter, and this may also have affected H_c.
[46] We have verified that the parallel magnetoresistance in both the Au and Au/Fe films is very small (more than an order of magnitude smaller) compared to that found in perpendicular fields.
[47] The behavior found in the Au/Fe films seems to be consistent with previous studies of transport in Fe (Ref. 48). In particular, the magnetoresistance in bulk Fe in the low fields considered here is smaller than the weak-localization contribution.
[48] See, for example, A. Isin and R. V. Coleman, Phys. Rev. **142**, 372 (1966).

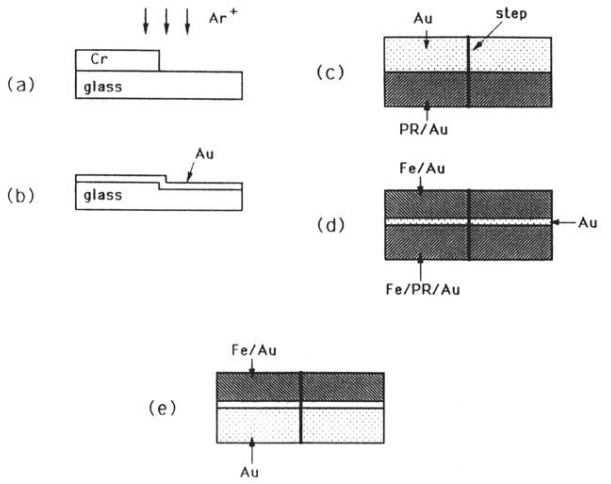

FIG. 1. Schematic description of the method used to make short "wires" in contact with different metals. PR denotes photoresist. The different steps are discussed in the text.