PHYSICAL REVIEW B VOLUME 48, NUMBER 7 15 AUGUST 1993-I

Electron-electron scattering in metal-insulator-metal sandwiches

N. Giordano and N. R. Dilley
Department of Physics, Purdue University, West Lafayette, Indiana 47907-1396
(Received 19 February 1993)

We have studied weak localization and electron-electron interaction effects in samples consisting of two thin metal films separated by an insulating layer of SiO. When the SiO thickness was less than about 200 Å, the electron-electron scattering rate was enhanced with respect to that found in isolated, i.e., well-separated, films. This suggests that in the sandwich structures, electrons in one metal film are able to "communicate" with, i.e., scatter from, electrons in the other film across distances of order 200 Å, and that this process enhances the phase-breaking rate.

I. INTRODUCTION

In the past decade there has been increasing interest in the behavior of electronic systems of reduced dimensionality.[1–5] The properties of effectively one- and two-dimensional, and also "zero"-dimensional, i.e., mesoscopic, systems have been studied extensively, and many novel effects have been revealed. Given the behavior of these "isolated" systems, it is natural to consider what happens when two such systems are brought near, but not in "contact" with, each other. This problem has been studied in systems involving both metal films,[6–8] and semiconductors[9–11] (see also the general theoretical work in Refs. 12 and 13). While some of the predicted effects have been observed in semiconductor structures, the situation with regards to metal-film-based systems is, as will be discussed below, not as clear. In the present work we have studied how the electrons in two metal films interact with each other when the films are separated by distances as small as ~ 30 Å. Our results suggest that when this separation is less than about 200 Å, there is a significant amount of scattering of electrons in one layer by those in the other layer. Our experiments thus provide direct information on the range of the electron-electron interaction in a metal.

II. THEORY AND BACKGROUND

It is well established that the effects of electron-electron interactions are enhanced by disorder, especially in systems of reduced dimensionality,[1–3] such as thin metal films.[4,14] These interactions are manifest in two ways. First, there is a direct contribution to the conductance which has the form[1–3]

$$\Delta G_{\square,ee} = \frac{e^2}{2\pi^2\hbar}(1-F)\ln(T) \; , \qquad (1)$$

where $G_\square$ is the sheet conductance, T is the temperature, and F is a screening factor whose value is typically small (≈ 0.1) for metal films. Second, electron-electron scattering is enhanced with respect to that found in pure systems, with a scattering rate (for phase breaking) given by[3]

$$\tau_{ee}^{-1} = \frac{k_B e^2 T \ln\left(\pi\hbar G_\square/e^2\right)}{2\pi\hbar^2 G_\square} \; . \qquad (2)$$

An important feature of (2) is that the scattering rate varies approximately inversely with $G_\square$ (the logarithmic factor has only a small effect). Hence if a metal film is made thicker, thereby increasing $G_\square$, the scattering rate is decreased.

According to the theory, a very important feature of electron-electron interactions in disordered systems is the greatly increased range of the Coulomb interaction, as compared to that found in pure systems. Dynamical screening, i.e., screening at the frequencies relevant for electron-electron interaction effects, is predicted to be much less efficient in a disordered system;[1–3] this is a result of the diffusive motion of the electrons, as compared to the ballistic motion found in pure systems. Several experiments have sought to observe the range of this screening directly. Bergmann and Wei[6,7] studied multilayer samples consisting of two or more thin metal films separated by insulating layers. They found that when the insulating layers were thicker than a few atomic spacings, the contribution of electron-electron interactions to $G_\square$ for each of the films in the multilayer was not affected by the presence of the other, nearby metal layers. This result was surprising, since a calculation by Bergmann and Wei[6,7] predicts that when metal layers are spaced closer than ≈ 10 μm, they should (at temperatures below about 10 K) "assist" each other in the screening process, thereby reducing substantially the electron-electron contribution to $\Delta G_\square$. Studies of superconducting films separated by very thin normal layers[8] also found no evidence for any change in the screening.

In this paper we present the results of an experiment that is essentially similar to that of Bergmann and Wei, but with one important difference; we have also studied the rate of phase breaking due to electron-electron scattering.[15] Our results imply that this rate is enhanced in sandwich structures when the metal films are separated by less than about 200 Å, suggesting that the effective range of the Coulomb interaction, at least as far as phase-breaking scattering is concerned, is of this order.

0163-1829/93/48(7)/4675(4)/$06.00 ©1993 The American Physical Society

III. EXPERIMENTAL METHOD

The samples were sandwich structures consisting of two thin metal films separated by a layer of SiO. For most of the samples the metal films were Sb; these were prepared by thermal evaporation, and usually had a thickness of ≈ 210 Å, although in a few cases somewhat thicker films were employed. A few sandwiches, in which both of the metal layers were evaporated Au films ≈ 140 Å thick, were also studied. The SiO was deposited using an "oven"-type evaporation cell,[16] and its thickness was varied from 30–2000 Å. The three layers, e.g., Sb, SiO, and Sb, were deposited sequentially within the span of a few minutes without breaking vacuum, during which time the pressure was typically below 1×10^{-6} Torr. Under such conditions there could easily be an extra contribution to the insulating layer from contamination, etc.; the thickness of such a contribution is not known. This three-layer sandwich was patterned into a long strip using conventional photolithography, and the conductance of the entire structure was measured, i.e., of all three layers in parallel. In separate tests, it was found that the SiO layers were generally free of pinholes for areas of order 1 cm^2 (the area of the samples used in the magnetoresistance measurements) when the SiO thickness was greater than about 300 Å. Pinholes were manifest by a finite resistance across the SiO layer. Assuming a cross section of atomic dimensions, the value of the resistance through the pinholes implied that there were of order 10 pinholes for samples with our smallest SiO thicknesses. We would expect that a pinhole would modify the behavior only within a phase-breaking length of its location; thus the amount of the sample affected by pinholes should be completely negligible.

The experiments consisted of measurements of the contribution of electron-electron interactions to the conductance and the electron phase-breaking rate. Weak localization (WL) makes a contribution to the conductance which, in the absence of a magnetic field, is similar in magnitude, but opposite in sign, to (1).[17,4,14] A moderate field suppresses WL, leaving only the electron-electron interaction part (1), so to obtain the latter we simply measured the conductance as a function of T in a fixed field of $H = 10^4$ Oe applied perpendicular to the plane of the sample. The phase-breaking length was obtained from measurements of the low-field ($H \leq 1000$ Oe, again perpendicular to the sample plane) magnetoconductance, which is due entirely to WL.[4,14] This yields the phase-breaking length $L_\phi \equiv \sqrt{D\tau_\phi}$, where D is the electron diffusion constant and τ_ϕ is the phase-breaking time. This measurement is sensitive to the total phase-breaking rate, which will in general have contributions from electron-phonon and magnetic scattering, in addition to electron-electron scattering. By employing Sb films with relatively low values of $G_\square$ we were able to enhance the importance of electron-electron scattering [see (2)], so that it was generally dominant.

For all of the sandwich samples, the sheet conductances of the two metal layers were made as closely matched as possible; they generally differed by less than 10%. In addition, for the majority of the samples, the thickness of the Sb layers was held fixed at ≈ 210 Å ($G_\square \approx 0.015\ \Omega^{-1}$), and only the SiO thickness was varied. In each batch we also made "incomplete" sandwiches; that is, samples consisting of only the "bottom" Sb film coated with SiO, and samples of just the "top" Sb film. Their properties were studied for comparison with those of the sandwiches. We found that the behavior of an Sb film coated with SiO was the *same* as that of an uncoated Sb film; i.e., the SiO layer alone did *not* significantly affect the behavior of an adjacent Sb film.

IV. RESULTS

For all samples the variation of the resistance with $H = 10^4$ Oe was logarithmic over the entire range studied, 1.4–4.2 K. Fitting these results to the form (1) we extracted the factor $A_{ee} \equiv \Delta G/(e^2/2\pi^2\hbar)$, where here ΔG is the change of the conductance normalized for one decade (base e) of temperature; if (1) is applicable, then $A_{ee} = (1 - F)$. Results for A_{ee} are shown in Fig. 1 as a function of $G_\square$. For isolated films our results are consistent with $(1 - F) \approx 0.90$ (the lower dashed line in Fig. 1), which is the value expected from previous work.[3,4,6] For the sandwiches A_{ee} is seen to be distinctly different; it is consistent (to within the uncertainties) with a value twice that found for the isolated films. If the two films of a sandwich were to behave as one "unit" with respect to electron-electron interactions, then the conductance change should be given by (1). On the other hand, if they behave independently, then *both* films should change by this amount, and the total change in the conductance of the sandwich will be *twice* as large as predicted by (1). As can be seen from Fig. 1, our results imply the latter; i.e., that the two films in a sandwich behave *independently* as far as the electron-electron contribution to the conductance is concerned. This result is in good accord with the experiments of Bergmann and Wei. We

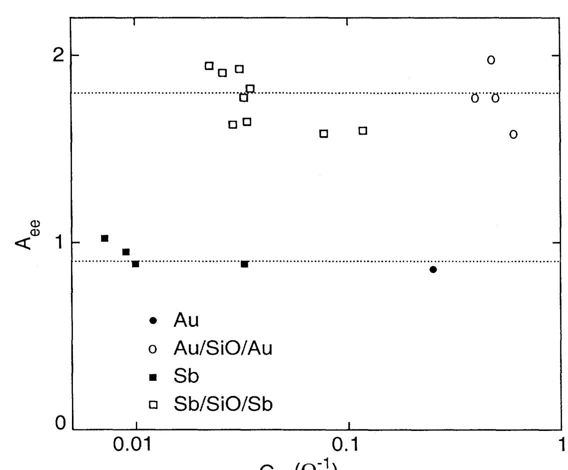

FIG. 1. A_{ee} as a function of $G_\square$ for films of Sb and Au, and sandwiches of Sb/SiO/Sb and Au/SiO/Au. The lower dashed line shows the value expected for isolated films $A_{ee} = (1 - F) = 0.90$, while the upper dashed line shows a value twice as large, $A_{ee} = 1.80$.

also note that the behavior of A_{ee} for the sandwiches was independent of the thickness of the SiO layer, d_{SiO}, i.e., the scatter about the upper dashed line in Fig. 1 does not appear to be correlated with d_{SiO}.[18]

Figure 2 shows results for L_ϕ as a function of T for two sandwich samples, along with results for two isolated films prepared at the same time, i.e., in the same evaporations, as the sandwiches.[19] It is seen that the phase-breaking length of the sandwich sample with $d_{\text{SiO}} = 400$ Å is essentially the same as that found for the films.[20] However, the sandwich with the thinner SiO layer ($d_{\text{SiO}} = 73$ Å) exhibits a significantly smaller value of L_ϕ, i.e., a larger scattering rate. This is clear evidence of an interaction between electrons in the two Sb layers.

We should note that the magnetoconductance is a sensitive function of both L_ϕ and $G_\square$. For the analysis involving the sandwich samples, it was necessary to use the value of $G_\square$ of the films composing the sandwich (i.e., half the value of the sandwich conductance). This indicates that the films behave independently as far as weak localization is concerned.

The behavior as a function of SiO thickness is shown in Fig. 3, where we plot $L_\phi(\text{sandwich})/L_\phi(\text{film})$, as a function of d_{SiO}. Here we have used the values of $L_\phi(\text{film})$ measured for each batch, although the values were approximately the same for all batches (see Fig. 2). We see from Fig. 3 that the sandwich behavior crosses over from an "independent" film regime $[L_\phi(\text{sandwich})/L_\phi(\text{film}) = 1]$ when $d_{\text{SiO}} \gtrsim 200$ Å, to an "interacting" film regime $[L_\phi(\text{sandwich})/L_\phi(\text{film}) < 1]$, when $d_{\text{SiO}} \lesssim 200$ Å. It is interesting to note that this crossover occurs when the thickness of the insulating layer is approximately equal to that of the individual Sb layers.

At this point we should mention another effect which could conceivably (but turns out not to) be important, namely the effect of tunneling through the SiO layer. Bergmann and Wei[21,22] have shown that the magnetoconductance is altered when the time required to tunnel through the insulator, τ_T, is small compared to τ_ϕ. We have found that with the appropriate choice of τ_T, the magnetoconductance data for a sandwich can be made to fit the theoretical form which includes tunneling effects, using the value of L_ϕ found for isolated films. One might then suppose that the effect we have interpreted as enhanced phase breaking in Figs. 2 and 3 is simply due to tunneling. However, further analysis shows this not to be the case. First, the tunneling time required for such an interpretation is strongly temperature dependent, increasing significantly at low temperatures. This behavior is in contrast to that expected for tunneling; τ_T in that case should be temperature independent. Second, experiments with much thicker Sb films, and also with Au films, showed no change of L_ϕ relative to that found with isolated films, even when $d_{\text{SiO}} \leq 50$ Å. This is presumably because the phase breaking in these cases is dominated by electron-phonon scattering, so that changes in the electron-electron rate (which is here much weaker) have no significant effect on L_ϕ.

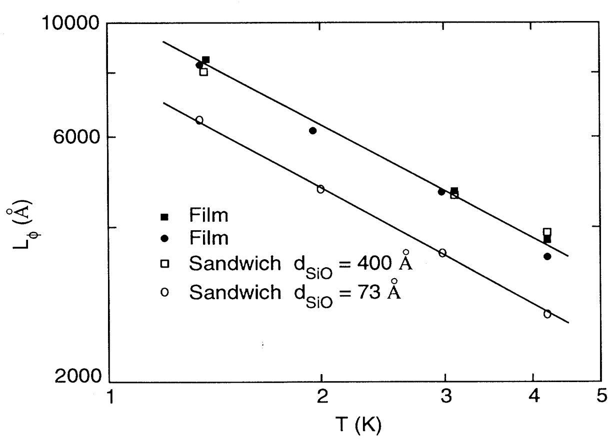

FIG. 2. Variation of L_ϕ with T for two Sb/SiO/Sb sandwiches, with $d_{\text{SiO}} = 400$ Å and $d_{\text{SiO}} = 73$ Å, as indicated. Also shown for comparison are the results for isolated films from each batch. The lines are guides to the eye.

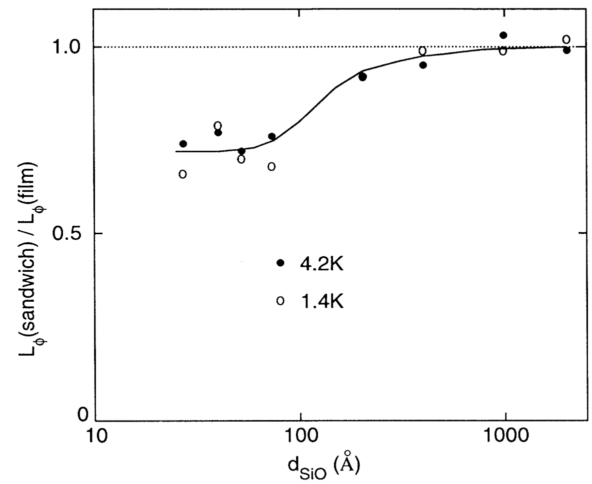

FIG. 3. $L_\phi(\text{sandwich})/L_\phi(\text{film})$ as a function of d_{SiO} for $T = 4.2$ K (•) and $T = 1.4$ K (∘). The solid curve is a guide to the eye.

V. DISCUSSION

From Fig. 3 we see that the phase-breaking length in the sandwiches with the thinnest insulating layers is reduced by ≈30% when compared to that found in isolated films. This may be explained, at least qualitatively, if one assumes that with two nearby Sb films the number of electrons available for scattering is twice as large as with a single film, thus doubling the phase-breaking rate. However, while this simple argument is consistent with the results in Fig. 3, the general question of the crossover behavior as a function of d_{SiO} is, in our view, still open. In particular, the theory predicts that making a film thicker, and thus increasing $G_\square$, should make the electron-electron scattering rate *smaller* [see (2)], which is opposite to the enhancement we have found. In a general sense, there are (at least) two competing effects which contribute to τ_{ee}^{-1} in the sandwiches. (1) The fact that there are more electrons to scatter from as compared to a single, isolated film; this could increase τ_{ee}^{-1}. (2) If the electrons in the two films of a sandwich can interact significantly, this may alter the strength of the screened Coulomb interaction, thereby affecting τ_{ee}^{-1}. The theory, Eq. (2), implies that this will reduce the scattering rate. Without a quantitative calculation, it does not appear possible to say which of these effects will be most important. Our results seem to suggest, perhaps surprisingly, that the former can dominate.

In summary, we have observed an enhancement of the electron-electron scattering rate in sandwich structures consisting of two metal films separated by a thin insulating layer. We interpret this enhancement as due to the scattering of electrons in one metal film by electrons in the other film, and our results provide a semiquantitative measure of the range of this interaction. At the same time, measurements of the electron-electron interaction contribution to the conductance in the same samples indicate that the two films behave independently as far as this effect is concerned, even when the phase breaking is strongly enhanced. It is a bit puzzling, and also intriguing, that one measure of the strength of electron-electron interactions, the phase-breaking length (Figs. 2 and 3), clearly shows that the interactions are effectively enhanced in the sandwich samples, while a second such measure, the "direct" contribution to the conductance (Fig. 1), shows no enhancement.

We should also mention that our experiment is in some respects similar to recent work on electron-electron scattering between electron gases separated by insulating layers in semiconductor heterostructures.[9-11] An important difference between those experiments and ours is that they are sensitive to the momentum transferred by electron-electron scattering, while we are probing the phase breaking. It also seems possible that our observations may be connected with the recent theoretical work of Rojo and Mahan,[12] but the precise relationship is not clear to us at present. Finally, we would like to note that our experimental approach appears to provide a new way to probe, in a fairly direct manner, the length scale involved in electron-electron interactions, and perhaps other electron-scattering processes.

We thank M. A. Blachly and P. F. Muzikar for helpful discussions, and constructive comments on the manuscript. This work was supported by the National Science Foundation through Grant No. DMR-8915574.

---

[1]B. L. Al'tshuler, A. G. Aronov, D. E. Khmel'nitskii, and A. I. Larkin, in *Quantum Theory of Solids*, edited by I. M. Lifshitz (Mir, Moscow, 1982), p. 130.

[2]P. A. Lee and T. V. Ramakrishnan, Rev. Mod. Phys. **57**, 287 (1985).

[3]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), p. 1.

[4]G. Bergmann, Phys. Rep. **107**, 1 (1984).

[5]*Mesoscopic Phenomena in Solids,* edited by B. L. Al'tshuler, R. A. Webb, and P. A. Lee (Elsevier, Amsterdam, 1991).

[6]G. Bergmann and W. Wei, Solid State Commun. **71**, 1011 (1989).

[7]G. Bergmann, Physica B **169**, 231 (1991).

[8]N. Missert and M. R. Beasley, Phys. Rev. Lett. **63**, 672 (1989).

[9]P. M. Solomon, P. J. Price, D. J. Frank, and D. C. La Tulipe, Phys. Rev. Lett. **63**, 2508 (1989).

[10]B. Laikhtman and P. M. Solomon, Phys. Rev. B **41**, 9921 (1990).

[11]See, for example, T. J. Gramila, J. P. Eisenstein, A. H. MacDonald, L. N. Pfeiffer, and K. W. West, Phys. Rev. Lett. **66**, 1216 (1991).

[12]R. Rojo and G. D. Mahan, Phys. Rev. Lett. **68**, 2074 (1992).

[13]J.-M. Duan and S. Yip, Phys. Rev. Lett. **70**, 3647 (1993).

[14]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.

[15]In the experiments in Refs. 6 and 7 the phase breaking appeared to be dominated by electron-phonon scattering.

[16]Type SO-22 evaporation source, from R. D. Mathis Co., Long Beach, CA.

[17]The contribution of weak localization to the conductance for both Sb and Au is positive, since the spin-orbit scattering is strong in both materials (Refs. 1 and 4).

[18]The theoretical calculation of Refs. 6 and 7 predicts that for the samples considered in Fig. 1, $d_{\rm SiO}$ is sufficiently small that A_{ee} should be equal to $(1-F)$, which is clearly at odds with our results.

[19]The theoretical form used to fit the magnetoconductance is the same as that described in Ref. 4. The theoretically predicted electron-electron phase-breaking time (2) yields L_ϕ = 5100 Å at 4.2 K and 8500 Å at 1.4 K, assuming $G_\Box = (70\ \Omega)^{-1}$ (typical for our Sb films) and $D = 20\ \text{cm}^2/\text{s}$ as obtained from previous work with similar Sb films [J. Liu and N. Giordano, Phys. Rev. B **39**, 9894 (1989)]. The phase-breaking time predicted for electron-electron scattering is thus in good agreement with our results for isolated films.

[20]The temperature dependence of L_ϕ is approximately $T^{-1/2}$, for our 210-Å Sb films, as expected for electron-electron scattering (2). A stronger temperature dependence would be expected (and is found) in the thicker Sb films and in the Au films, where we believe that electron-phonon scattering dominates (Refs. 4 and 14).

[21]G. Bergmann, Phys. Rev. B **39**, 11 280 (1989).

[22]W. Wei and G. Bergmann, Phys. Rev. B **40**, 3364 (1989).