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Cross-talk effects in superconductor–insulator–normal-metal trilayers

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We have observed a "cross-talk" effect in structures composed of two metal films, at least one of which is a superconductor, S, separated by a thin insulating layer. A current was passed through one film and the voltage induced in the other, V, was monitored. While V was negligibly small when film S was either normal or superconducting, V exhibited a peak in the immediate vicinity of the normal-to-superconducting transition. This effect was found to be nonreciprocal, as the *sign* of V depended on which film carried the current.

I. INTRODUCTION AND BACKGROUND

In this paper we report on what we believe to be a new effect in metal-insulator-metal trilayer structures. The type of structure we have studied is shown schematically in Fig. 1; the bottom metal layer (Al), was covered with a thin insulating layer (SiO), upon which another metal layer (usually Sb) was deposited. The insulating layer was completely free of electrical shorts. This made it possible to study the electrical properties of the two metal films separately, so as to investigate the nature of the coupling between them. In recent work we have described some interesting aspects of electron-electron scattering, and electron-electron interaction effects in these structures.[1,2] Here, we report an effect which concerns the voltage which is induced in one of the metal layers by the presence of a current in the other. This "cross-talk" effect appears at first sight to be related to the Coulomb drag which has been observed in similarly designed semiconductor heterostructures.[3–7] However, the effect we have observed appears *only* when one of the metal layers is a superconductor, and in that case is large *only* in the vicinity of the superconducting transition. These features are not expected for simple Coulomb drag.

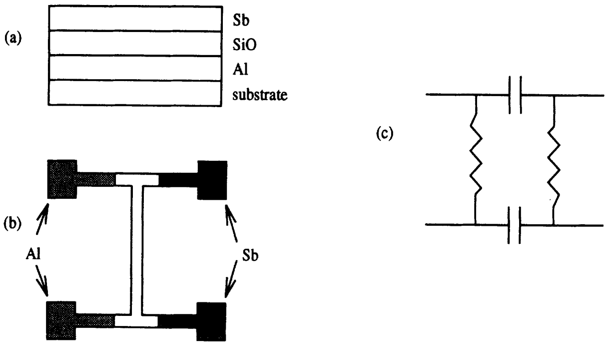

FIG. 1. (a) Cross-sectional view of a sample. The substrate was glass. (b) Top view of the sample geometry. The left-hand shaded region consisted of the Al film covered with SiO, while the right-hand shaded region was Sb on top of SiO. In the center region (which is unshaded) all three films, Al, SiO, and Sb [see (a)] were present. This arrangement made it possible to attach separate leads to the Al and Sb layers at the four corners. (c) Equivalent electrical circuit of a sample. The resistors represent the Al and Sb layers.

At present we have no model to explain our observations. However, it is interesting to note that they bear a strong resemblance to recent results in high-T_c superconductors. This resemblance and its possible implications will be discussed below.

II. EXPERIMENTAL METHOD

The sample geometry is sketched in Figs. 1(a) and 1(b). A layer of Al was first evaporated onto a glass substrate. This deposition was performed in the presence of O_2 so as to enhance the critical temperature of the Al, and thereby make it more convenient to study the behavior near and below T_c. The partial pressure of O_2 during the evaporation was typically 2×10^{-4} T (the evaporator pressure was 6×10^{-7} T or less before the O_2 was admitted), and the resulting T_c was generally in the range 1.8–2.0 K. Next an insulating layer of SiO was evaporated from an oven source, followed by an evaporation of either Sb (which is not superconducting) or Al (in this case there was no excess O_2 in the evaporator, and the critical temperature was below 1.3 K). The Al layers were typically 350 Å thick with a sheet resistance ranging from a few to $\sim 20\ \Omega$, while the Sb layer was typically ≈ 230 Å thick, and had a sheet resistance in the range 20–50 Ω. All of the results shown in this paper were obtained with samples in which the top layer was Sb, but similar results were found with a sample in which the top layer was Al in its normal state.

Since we wanted to make separate electrical measurements on the two metal layers, it was essential that the SiO layer contain *no* electrical shorts (i.e., pinholes) over the entire area of a sample, which was typically 1–10 mm^2. We found that if we deposited the SiO layer in two separate evaporations, with exposure to air before

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and after each evaporation, the resulting layer was usually free of pinholes;[8] this was not the case if the SiO layer was deposited in a single evaporation. Apparently this trick makes use of the fact that after exposure to air the nucleation sites for the second SiO evaporation are completely different from those of the first. The chance that a single pinhole extends throughout the entire SiO layer is thus much reduced. For all of the samples reported here the resistance across the SiO layer was greater than 30 MΩ at both room temperature and low temperatures.

While the insulating layer consisted mainly of SiO, there was also a contribution from the oxide on the bottom Al layer. From measurements of the capacitance[2] we found that the thickness of the Al oxide was approximately 40 Å, which is consistent with the expected thickness of a thermal oxide on Al. In all of our samples the thickness of the insulating layer was large enough that we expect tunneling through this combined layer of SiO and Al oxide to be completely negligible. Note that when we discuss our results below, we will often refer to the thickness of the SiO layer; we leave it to the reader to keep in mind the presence of the "extra" 40 Å of Al oxide.[9]

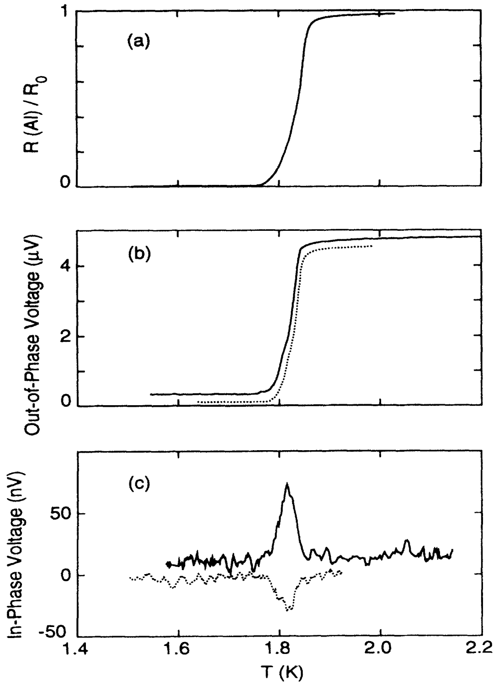

FIG. 2. Results for an Al/SiO/Sb sample with a SiO thickness of 400 Å. The measuring frequency was 5 Hz, the drive current was 7 μA (rms), and $H = 0$. (a) Resistance of the Al layer as a function of T normalized by the normal state resistance, R_0, which was 4 kΩ. (b) Out-of-phase detector signal as a function of T. The solid curve was obtained with the drive current applied to the Sb film, while for the dotted curve it was applied to the Al film. The very small "knee-like" feature in the solid curve just below the transition was due to instrumental noise. (c) In-phase detector signal as a function of T. The solid curve were obtained with the drive current applied to the Sb film, while for the dotted curve it was applied to the Al film.

The resulting Al/SiO/metal trilayers were patterned using photolithography and liftoff into a long, narrow strip, typically 1 cm × 150 μm, with two separate lead strips at each end, as shown in Fig. 2(b). By using a mechanical mask during the evaporations to selectively expose the contact areas (at the four corners of the sample), we were able to make separate electrical connections to the two metal layers using standard In-Sn solder together with silver paint.

The simplest approach to measuring cross-talk effects would be to apply a dc current to one film and measure the dc voltage induced in the other. However, given the maximum current which could be applied without significant sample heating, the induced voltages were typically of order 10^{-8} V, which is difficult to measure accurately with conventional dc techniques. We therefore employed an ac measurement method. An ac current was applied to one film and the voltage across the other was detected with a lock-in amplifier. In principle this is equivalent to the dc approach, but there is one important difference. With the ac method one must worry about the phase of the detector voltage relative to that of the drive current, I_{drive}. The component of V_{detector} which is in phase with the drive current is the signal in which we are interested; this assumes, of course, that the drive frequency is much lower than the characteristic frequency of the cross-talk mechanism, so that the cross-talk voltage will be in phase with the drive current. There will in general also be a component of V_{detector} which is 90° out of phase with respect to I_{drive}. Such an out-of-phase component will result from capacitive coupling between the drive and detector films, as one would expect from the very simple equivalent circuit sketched in Fig. 1(c). This out-of-phase component can be minimized by working at low frequencies, but there is a trade off with the desire for high voltage sensitivity. We found that at 5 Hz the capacitive coupling was manageably small, while the voltage sensitivity was still acceptable, so this frequency was used for most of the measurements. Results were also obtained at other frequencies in the range 0.5–500 Hz, and will be discussed below.

The measurements were carried out in a ^{4}He cryostat of standard design, which permitted a magnetic field to be applied perpendicular to the plane of the films. Studies of weak localization and electron-electron interaction effects in similar samples have been reported elsewhere.[1,2]

III. RESULTS

Figure 2 shows some typical results for an Al/SiO/Sb sample in which the SiO layer was 400 Å thick. Figure 2(a) shows the resistance of the Al layer as a function of temperature. The transition width is larger than one would expect from intrinsic effects, such as the Kosterlitz-Thouless transition,[10] but is in accord with that typically seen in similarly prepared films. This width is probably due to slight inhomogeneities in, for example, the O_2 concentration.

Figure 2(b) shows the cross-talk signal obtained when one measures the component of the detector voltage which is 90° out-of-phase with respect to the drive current. The solid curve shows the result when the drive current was imposed on the Sb film and the Al film was the detector, while the dotted curve was obtained with the current applied to the Al film and the voltage detected across the Sb. The curves are offset for clarity; in both cases the signal was zero (to within our uncertainties) well below T_c. In addition, the two out-of-phase signals were identical (again, to within our uncertainties) if the same drive current was used. We believe that this out-of-phase cross-talk signal was due to capacitive coupling between the drive and detector films. Using the equivalent circuit shown in Fig. 1(c) to calculate the cross-talk signal expected from capacitive coupling, one finds that the out-of-phase capacitive cross talk should be proportional to $\omega R(\mathrm{Al}) R(\mathrm{Sb})$, where ω is the drive frequency, $R(\mathrm{Al})$ is the resistance of the Al layer, and $R(\mathrm{Sb})$ is the resistance of the Sb layer. Hence, we expect this out-of-phase cross-talk signal to have the same functional form as the resistance of the Al [the resistance of the Sb was, on this scale, independent of T (Ref. 2)]. Comparing Figs. 2(a) and 2(b) we see that this was indeed the case. Moreover, this model predicts that the out-of-phase cross-talk signal should not depend on which film is used as the drive and which as the detector, which is again in accord with the results in Fig. 2(b). Finally, the absolute magnitude of the out-of-phase cross talk agrees well (to within a factor of 2 or better) with that expected from this simple calculation evaluated using the measured capacitance (300 pf) and resistances. We have also investigated the frequency dependence, and found that the out-of-phase cross-talk signal was proportional to the frequency in the range 0.5–500 Hz, again as expected from this equivalent circuit. The evidence is thus very strong that the out-of-phase cross talk is due simply to capacitive coupling.

Figure 2(c) shows results for the in-phase cross talk; this is the detector voltage which was in phase with the drive current. Here a positive cross-talk voltage corresponds to a signal with the same polarity as the drive current. Given the results for the out-of-phase signal, Fig. 2(b), it is tempting to also attribute the in-phase signal to capacitive coupling. However, it is readily seen that this cannot be the case for the following reasons. First, the in-phase capacitive cross talk calculated for the equivalent circuit in Fig. 1(c) is several orders of magnitude smaller than that observed in Fig. 2(c). Second, this calculation shows that the in-phase capacitive cross talk should vary as ω^2, but we found that the signal in Fig. 2(c) was independent of frequency. In spite of these results, one might still worry that the circuit model in Fig. 1(c) is too simple, and that a more sophisticated model, perhaps with distributed capacitances, etc., could account for the experimental results.[11] However, this can be ruled out for the following reason. All four-terminal networks consisting of only capacitors, resistors, and inductors (including mutual inductors) must obey the reciprocity theorem.[12] If a current is imposed on any two terminals of such a network, then the open circuit voltage across the other two terminals can be used to define a cross resistance, $V_{\mathrm{detector}}/I_{\mathrm{drive}}$. The reciprocity theorem states that if the current and voltage leads are interchanged, this cross resistance is *unchanged*, in both sign and magnitude. This is clearly *not* the case in Fig. 2(c), since the *sign* of the cross talk depends on which film carries the current. We emphasize that this violation of the reciprocity theorem does not violate any laws of physics; it simply means that the in-phase cross-talk signal cannot possibly be due to "classical" circuit effects. It is also interesting to compare the magnitudes of the in- and out-of-phase signals, Figs. 2(b) and 2(c). We see that in this case the out-of-phase signal was larger by an order of magnitude or more. This comparison depends on the measurement frequency since, as noted above, the out-of-phase signal was proportional to ω while the in-phase signal was frequency independent. Since we were primarily interested in the in-phase signal, which is the smaller one, this made low measuring frequencies (typically 5 Hz as in Fig. 2) desirable. Higher frequencies would have been more convenient, but they would have made it more difficult to isolate the desired in-phase signal. At 5 Hz our sensitivity was a few nV (for a bandwidth of about 1 Hz), as can be seen from Fig. 2.[13]

In Fig. 3 we consider the effect of a magnetic field applied perpendicular to the plane of the sample; here we show the resistive transition of the Al film [Fig. 3(a)] and the in-phase cross-talk signals [Fig. 3(b)], in a field of 500 Oe. This is the same sample considered in Fig. 2, so the values of T_c can be compared directly (T_c depends on the O_2 content in the Al film, and varied from sam-

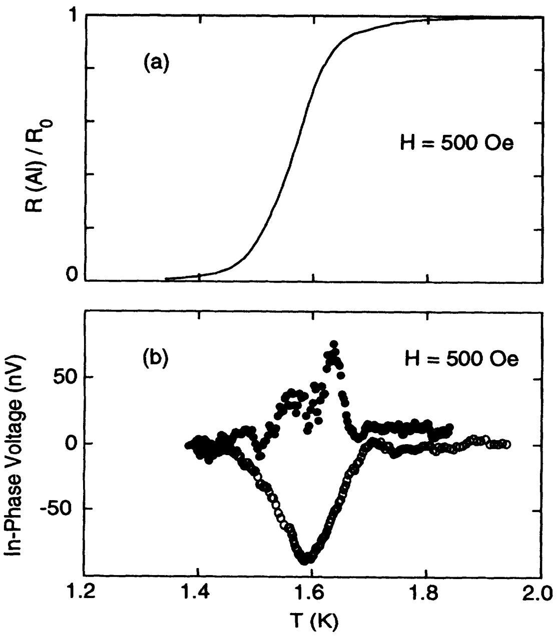

FIG. 3. Results for the same Al/SiO/Sb sample considered in Fig. 2, with $H = 500$ Oe. The measuring frequency was 5 Hz, and the drive current was 12 μA (rms). (a) Resistance of the Al layer as a function of T. (b) In-phase detector signal as a function of T. The solid symbols were obtained with the drive current applied to the Sb film, while for the open symbols it was applied to the Al film.

ple to sample). Figure 2(a) shows that, as expected, the field shifted T_c downward, and from Fig. 2(b) it is seen that the peaks in the in-phase cross-talk signal shifted in temperature by the same amount. This is further evidence that the cross-talk is intimately connected with the transition. The magnitude of the cross-talk was approximately the same with $H = 500$ Oe as with $H = 0$. However, the "line shape" with $H = 500$ Oe was not quite as narrow as in the zero-field case. This was especially evident for this sample when the Al film was used as the detector, as there appear to be two overlapping peaks in Fig. 3(b). We suspect that this was due to broadening from inhomogeneities (perhaps in the oxygen content) in the Al film, as such behavior was not observed in every sample. While they are not shown in Fig. 3, the out-of-phase cross-talk signals were again what one would expect from capacitive coupling, i.e., they had the same functional form as the resistive transition of the Al.

One of the most surprising results concerns the behavior as a function of drive current, which is shown in Fig. 4. This sample was similar to that considered in Figs. 2 and 3, except that the SiO thickness was 300 Å (similar behavior was observed in several other samples with different SiO thicknesses). The resistive transition of the Al film is shown in Fig. 4(a) for three different drive currents. At these current levels, the results for the resistance and the value T_c were essentially independent of the current. [At currents a factor of 2 higher than the largest value used in Fig. 4(a) the transition was observed to shift to lower temperatures by approximately 10 mK.] Results for the in-phase cross-talk are shown in Figs. 4(b) and 4(c), at approximately the drive current levels used in Fig. 4(a). In Fig. 4(b) the drive current was applied to the Sb film, and the cross-talk signal, i.e., the detector voltage, varied approximately linearly with the drive amplitude. However, when the drive current was applied to the Al film, Fig. 4(c), the cross-talk was definitely *not* a linear function of the drive. While we were only able to observe the cross-talk over a limited range of drive amplitude (without appreciably affecting T_c), it appears that in this case the detector voltage varied approximately as the square of the drive current. This occurred even though the current was sufficiently low that the resistive transition of the Al film [Fig. 4(a)] was not significantly affected by the current.

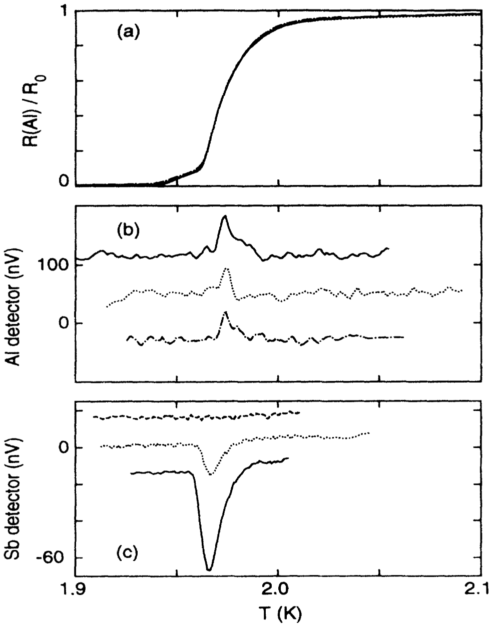

FIG. 4. Results for an Al/SiO/Sb sample at different drive currents; the SiO thickness was 300 Å, the measuring frequency was 5 Hz, and $H = 0$. (a) Resistance of the Al layer as a function of T. The resistance well above T_c was 9 kΩ. Solid curve: $I_{\rm drive} = 14\ \mu$A (rms). Dotted curve: 7 μA. Dot-dashed curve: 2 μA (this curve is nearly indistinguishable from the solid curve). (b) In-phase detector signal as a function of T, with the drive current applied to the Sb film. Solid curve: $I_{\rm drive} = 10\ \mu$A (rms). Dotted curve: 5 μA. Dot-dashed curve: 1.5 μA. (c) In-phase detector signal as a function of T, with the drive current applied to the Al film. Solid curve, $I_{\rm drive} = 14\ \mu$A (rms); dotted curve, 7 μA; dot-dashed curve, 2 μA.

IV. DISCUSSION

In the previous section we have presented the essential features of our cross-talk results. We have shown detailed results for two samples; several others, including one in which the Sb layer was replaced by Al,[14] exhibited quantitatively similar behavior. We will now discuss these results in the context of previous experiments and theories.

First, as is evident from the results shown above, we have been unable to observe any cross-talk signal when both of the metal layers are normal; we can therefore only place an upper limit on the "conventional," i.e., normal state, Coulomb drag. This upper limit, when expressed as the ratio of the detector film voltage to the drive film current, is of order 10^{-4} Ω for our sample geometry, which is approximately 2 orders of magnitude larger than the theoretically predicted value.[15] Thus, our null result for a drag effect above T_c is consistent with the theory, and with previous experiments (which were in agreement with those theories). The basic reason that the Coulomb drag is negligible in our case, as compared to semiconductor heterostructures, is that our screening lengths are much shorter.[16,17]

Yip and Duan[18] have recently predicted that when the detector film is part of a closed superconducting circuit a new drag effect will occur; this effect will thus only be present only when the detector film is superconducting. To within our resolution we observed no drag effect below T_c (see Figs. 2–4; we also have much more data below T_c which is not shown here). However, since our detector was not part of a closed superconducting circuit there is no contradiction with the theory.

It is also interesting to note that Muzikar[19] has shown that if one considers a Fermi liquid interacting with a superfluid, a supercurrent in the latter cannot induce a current in the Fermi liquid. While this calculation was performed with superfluid ^{3}He in mind, it should apply equally well to electronic systems. This prediction would appear to be at odds with our results, but there are several ways out of this apparent difficulty. First, our systems are effectively two dimensional, and Fermi liquid theory is known to be only marginal in this case. In addition, our drag effect is nonlinear when the drive current is imposed on the superconductor, while the calculation in Ref. 19 is presumably applicable only in the linear response regime.

The cross-talk effect we have observed exhibits several intriguing properties. First, its polarity depends on which film is used as the "detector." It is *positive* when the superconductor is used as the detector, which is the polarity predicted for the superconducting drag effect.[18] In contrast, the cross-talk signal is *negative* when the normal film is used as the detector, which is the polarity predicted (and observed) for the normal Coulomb drag,[6,7] and also predicted for the van der Waals drag.[17] Second, the cross talk is nonzero *only* in the vicinity of the superconducting transition. This would seem to be an important clue as to the origin of the cross talk, but so far we have not been able to devise a model which is even qualitatively consistent with our results. Nevertheless, we can make some speculations as to its origin.

One possibility is that vortices are somehow playing a role, since one expects there to be a (relatively) large concentration of free vortices in the vicinity of the superconducting transition.[10] The cross talk would then be a result of an interaction between these vortices and the current in the adjacent layer. However, the nature of this coupling is not clear. While our cross-talk effect was measured at a nonzero frequency, the results show that it is independent of frequency, and thus presumably present even at dc. One would not ordinarily expect the magnetic field associated with a dc current to cause vortices to move in a preferred direction, suggesting the possibility of a more subtle coupling mechanism.[20] With this in mind, it is interesting to note the recent work of Wan *et al.*,[21] involving $\mathrm{Bi_2Sr_2CaCu_2O_{8-y}}$, which is a layered superconductor in which the normal state conductivity within the *a*-*b* plane is a factor of $\approx 10^4$ higher than along the *c* direction. The highly anisotropic nature of conduction in this material was investigated by employing contacts on opposite *a*-*b* faces of a single crystal. Wan *et al.* measured the voltage induced on an *a*-*b* face when current was injected (and removed) through the *opposite* face; this arrangement is closely analogous with ours, since the very small *c*-axis conductivity plays the role of our insulating layer. Wan *et al.* found that the cross-talk voltage was zero well below T_c, fairly small above T_c, and exhibited a pronounced peak in the vicinity of T_c (see Fig. 4 in Ref. 21). They proposed that this peak is due to the interaction of thermally excited vortices in the *a*-*b* planes on opposite sides of the crystal. This behavior bears an extremely strong resemblance to our results, and suggests that they may have a common origin. If so, then the explanation of Wan *et al.* could not be correct, since their explanation requires superconductivity (i.e., the presence of vortices) in *both* layers, while in our case only one layer is superconducting. Nevertheless, the fact that the peak in V_{Al} occurs only in the vicinity of the Al transition is consistent with their suggestion that thermally excited vortices are involved, at least in one of the layers. If we are correct in supposing that our results and those of Ref. 21 arise from the same mechanism, this again raises the intriguing possibility of a new coupling mechanism between vortices and electronic currents in highly anisotropic systems. It also implies that our simple metal-insulator-metal trilayers may serve as model systems for the study of vortex dynamics, since their properties (i.e., sheet resistance, insulator thickness, etc.) can be conveniently tuned over wide ranges.

It is also conceivable that our cross-talk effect is due to some type of nonequilibrium superconducting effect which is enhanced by the proximity of T_c. While we can propose no specific mechanism, one could imagine various possibilities, such as the following. Coulomb drag between a normal current in the Sb layer and the quasiparticles in the Al might favor the production of a quasiparticle "current." This current would then be opposed by a supercurrent, etc. At present we cannot offer even a qualitative model based on such ideas, but we feel that it is an avenue which should be explored.

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[9] The fact that the capacitance measurements agree with the expected thickness of the SiO and Al oxide suggests that the insulating layer was fairly uniform. However, the possibility that some regions of this layer were somewhat

thinner than the nominal values quoted here cannot be ruled out.

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[11] One might also worry that perhaps the in-phase cross-talk signal in Fig. 2(c) is due to an error in the phase setting of the lock-in amplifier. Since the out-of-phase signal [Fig. 2(b)] is much larger than the in-phase signal, proper adjustment of the phase is crucial, and we therefore performed several tests of this adjustment. First, we checked the phase setting by comparing it against the phase of the drive current; we made this check often, and at many different temperatures (i.e., below, above, and in the transition region). Second, in measurements at frequencies as low as 0.5 Hz, we found that the in-phase signal was independent of frequency, while the magnitude of the out-of-phase signal varied linearly with frequency. Also, at 0.5 Hz the out-of-phase signal was less than an order of magnitude larger than the in-phase component, making the effects of a phase error much smaller than at higher frequencies. These tests indicate that the in-phase signal we have observed is not an artifact due to the ac measurement scheme.

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[13] When a lock-in amplifier (in our case it was a PAR model 126) is used to distinguish a small signal (our in-phase cross-talk signal) which is shifted in phase by 90° with respect to a much larger signal, it is important to check that the larger signal is not affecting the results in some way. We have therefore performed a number of tests to be certain that we were in fact measuring the two signals (in-phase and out-of-phase) properly. First, if the in-phase signal were due to an imperfect separation of the signals by the lock in, then it should be proportional to the size of the interfering signal, i.e., the magnitude of the out-of-phase signal. However, this was not the case, since as discussed above, the two signals had different frequency dependencies. Second, the ratio of the two signals was not always terribly large. For the data in Fig. 2 this ratio was of order 100, and for the measurements at 0.5 Hz (which were mentioned above) the ratio was only of order 10. These ratios (especially the latter) are not at all large by the standards of what a good lock-in can distinguish. Third, we did a number of tests of the lock-in and associated circuitry with resistive-capacitive networks (like the equivalent circuit sketched in Fig. 1) and these showed that there was no problem with distinguishing in-phase and out-of-phase signals with the magnitudes observed in these measurements.

[14] For the sample which had an Al film as the top layer, the top Al film was not deposited in an O_2 atmosphere, and had a T_c below 1.3 K.

[15] Our estimate of the Coulomb drag employed the theoretical relations given (Ref. 7) together with standard values of k_F, etc., for Sb. See J-P. Issi, Aust. J. Phys. **32**, 585 (1979); and the discussion in J. Liu and N. Giordano, Phys. Rev. B **39**, 9894 (1989).

[16] We also note that the van der Waals mechanism discussed in Ref. 17 predicts a temperature-independent drag which is about 2 orders of magnitude below our resolution.

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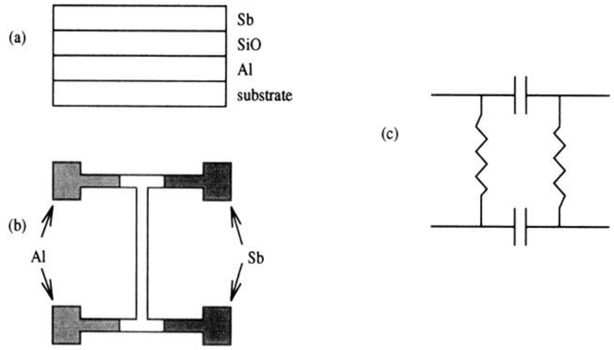

FIG. 1. (a) Cross-sectional view of a sample. The substrate was glass. (b) Top view of the sample geometry. The left-hand shaded region consisted of the Al film covered with SiO, while the right-hand shaded region was Sb on top of SiO. In the center region (which is unshaded) all three films, Al, SiO, and Sb [see (a)] were present. This arrangement made it possible to attach separate leads to the Al and Sb layers at the four corners. (c) Equivalent electrical circuit of a sample. The resistors represent the Al and Sb layers.