Observation of the superconducting proximity effect from kinetic-inductance measurements

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A method is described for observing the proximity effect in a thin-film-superconductor–normal-metal bilayer. The superconducting film must be thin compared to its penetration depth. The kinetic inductance of the superconducting film alone is then proportional to $\lambda^2(T)/d$. It is found that in a bilayer the temperature dependence of the kinetic inductance deviates significantly from this dependence at low temperatures. The kinetic inductance may be measured in a nondestructive manner using the two-coil mutual-inductance technique. Bilayers of NbN/Al and Nb/Cu have both exhibited the effect, whereas a bilayer in which the proximity coupling was purposefully suppressed had the same temperature dependence as the superconducting film alone. The effect is analyzed in terms of a spatially varying penetration depth through the film thickness, and the observations are found to be in qualitative agreement with the predictions of the model. A more exact fitting will require improved theoretical models for the proximity effect.

INTRODUCTION

Many of the proposed devices using high-T_c superconductors involve proximity coupling through a normal metal, typically Au or Ag.[1] It would be desirable to have a method to quantitatively characterize the induced condensation amplitude in the normal metal as a function of crystallographic orientation, processing techniques, etc., without fabricating the final device. We report here a technique for characterizing the proximity effect in a superconductor–normal-metal film bilayer that requires no processing. It is particularly applicable to superconductors with long penetration depth. To date the method has been successfully applied to well-characterized conventional superconductor–normal-metal bilayers (Nb/Cu and NbN/Al), but it should translate easily to other materials of current interest.

The essence of the technique consists of monitoring the temperature dependence of the kinetic inductance L_k of the bilayer. For a superconducting film of thickness d_s less than λ, the London penetration depth, we have $L_k=\mu_0\lambda^2/d_s$. The inverse of the kinetic inductance can be simply interpreted as proportional to the number of superconducting electrons per square cm in the film, since $\lambda^{-2}\sim n_s$, the density of superconducting electrons. In the case of a proximity bilayer, the key point is that while n_s is no longer constant through the film thickness, the kinetic inductance still depends only on the areal density of superconducting electrons: $L_k^{-1}\sim\int n_s dz$, where z is normal to the film surface. At low temperatures a significant contribution to this integral can come from the normal-metal region, where n_s is finite at the interface and decays over a length $\xi_N\sim T^{-1/2}$ into the normal region. The temperature dependence of the decay length leads to a distinctive signature in the temperature dependence of L_k that signals the presence of a strong proximity effect.

It should be noted that the present measurement explores a different regime than earlier ones where expulsion of magnetic fields in the normal metal was observed.[2,3] This previously observed "Meissner effect" in the normal metal involves a large drop in the vector potential across the film thickness. By contrast, the inverse proportionality of kinetic inductance to areal density of superconducting electrons is only correct if the vector potential is almost *unchanged* through the film thickness. Thus the method described here has a sensitivity to contributions from the normal film even when the proximity effect is too weak to produce a Meissner effect.

EXPERIMENT

To measure the kinetic inductance we use the two-coil scheme pioneered by Fiory *et al.*[4] A thin-film sample is positioned between two identical flat coils, oriented along a common axis. The mutual coupling between the coils is measured using a sufficiently small drive current to remain in a linear response regime. Various procedures have been outlined in the literature for relating the film impedance to the mutual coupling.[4,5] When the coupling is greatly reduced from its value with no film present, which is the case for all the data presented here, we are in the strong screening limit. It is shown in Ref. 4 that in this case the mutual inductance is proportional to the kinetic inductance of the film. Since it is the temperature dependence of L_k that is of interest here, no attempt has been made to determine the proportionality factor for our particular geometry.

It is instructive to consider a related geometry which we believe contains all the important physics of the two-coil planar system and for which analytical results are available: that of a cylindrical film with a solenoid drive coil outside and a receiving coil inside the cylinder. The general solution for the mutual inductance M in this case is[6]

$$M=M_0/[\coth(d_s/\lambda)+(R/2\lambda)\sinh(d_s/\lambda)] \ . \tag{1}$$

Here M_0 is the mutual inductance with no film present, and R is the radius of the cylinder. Since R is typically of macroscopic dimensions compared to λ, the second term in the denominator dominates. In the limit $d_s \ll \lambda$ we find

$$M \approx M_0(2\lambda^2/Rd_s) \ . \tag{2}$$

It is plausible that for the planar geometry R is replaced by an effective value that is of the order of the radius of the coils.

The effect of the normal-conducting electrons in a bilayer on the mutual coupling can be shown to be negligible: Invoking again the cylindrical geometry, a simple calculation shows that with a normal layer of thickness d_n, skin depth δ, Eq. (2) is generalized to

$$M \approx M_0/[1+R(d_s/2\lambda^2+id_n/\delta^2)] \ . \tag{3}$$

For realistic parameters the second term in the denominator is negligibly small.

In analyzing data of this sort it is important to be aware that, in practice, the measured mutual inductance includes a component that is independent of λ. This offset is best treated as an adjustable parameter. It arises from several sources: (1) Stray coupling in the cryostat wiring. Careful attention to shielding can reduce this in comparison to other terms. (2) Stray coupling between coils as a result of the finite size of the film sample. We assume that this coupling is independent of λ^2/d_s, and so may be treated as a fixed offset for a given sample. (3) When the film thickness is of the order of the penetration depth, a first-order expansion of Eq. (1) shows that the mutual inductance remains proportional to λ^2/d_s, but with an offset $-d_s/6$.

To test the ideas given above, we have used bilayer film samples of Nb/Cu and NbN/Al. In both cases the superconductor layer was quite thin, ≈ 500 Å, to ensure that the limit $d_n < \lambda$ applied. The normal-metal layers were significantly thicker. The samples were prepared in a UHV sputtering chamber that allowed sequential deposition of the superconductor and normal metal without breaking vacuum. The intention was to produce the cleanest interface possible. In the case of the NbN films, different crystallographic texturing could be obtained by varying the substrate and/or deposition conditions. We found no significant dependence of our results on orientation of the NbN. For both the NbN/Al and Nb/Cu samples, the normal metal could be removed chemically with presumably very little effect on the underlying superconductor. A third sample, NbN/AlO_x/Al, was prepared to examine the effect of a tunneling barrier at the interface. The oxidized Al layer was identical to the tunneling barriers used in Josephson junctions fabricated in the same apparatus.

RESULTS

We first consider the case of the bare superconducting films, obtained by removing the normal-metal layer. In this case it is reasonable to attempt to fit the data with the BCS London penetration length (defined as λ_{eff} by Tinkham[7]). This has no simple analytical form, and depends on mean free path as well as coupling strength. If we consider the tabulated calculations for the clean-limit, weak-coupling case,[8] λ_{eff} can be fitted rather well by a modified two-fluid expression of the form

$$\lambda_{\text{eff}}^2(t) \sim A/(1-t^4)-B \ , \tag{4}$$

where $t=T/T_c$. Calculated results for finite mean free path[9] or strong coupling[10] can also be fitted very well by an expression of the form (4). The main difference between these theoretical limits is in the value of B/A. The existence of a λ-independent offset of unknown magnitude in our data thus makes it difficult to distinguish between theoretical forms for λ_{eff}, since B/A is incorporated in the unknown offset in the mutual inductance. A similar point has been made by Hebard, Fiory, and Harshman[11] and we believe it applies to all measurements of λ except by muon spin rotation.

It is thus appropriate to fit our mutual-inductance data to the "modified two-fluid" expression (4), and we show in Fig. 1 that the fit for a NbN film from which the Al has been stripped is quite good. There are three fitting parameters, corresponding to A, B, and T_c.

Figure 2 shows the results for the same NbN film, but with the initial Al layer present. Evidently the mutual inductance cannot be fitted over the whole temperature range by (4). We will show that a fit to (4) near T_c is to be expected, and this is shown as a dotted line. The fitted T_c of the bilayer is lower than that of the superconductor alone by ≈ 0.4 K; this is a well-known result of the proximity effect.[2] The deviation of the mutual inductance from the two-fluid form at low temperatures is a much more pronounced result of the proximity effect, that has

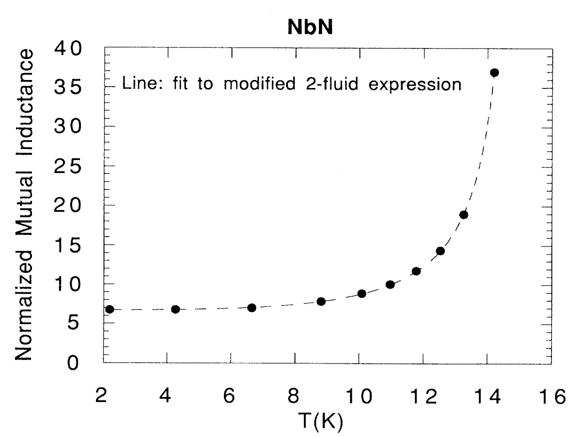

FIG. 1. Plot of the mutual inductance normalized to 0.1% of its value above T_c vs temperature for a NbN film. The film has an estimated thickness ~ 500 Å, sheet resistance $=48\ \Omega$ above T_c. The dashed line is a best fit to a dependence $\sim A/[1-(T/T_c)^4]-B$, giving $T_c = 15.11$ K.

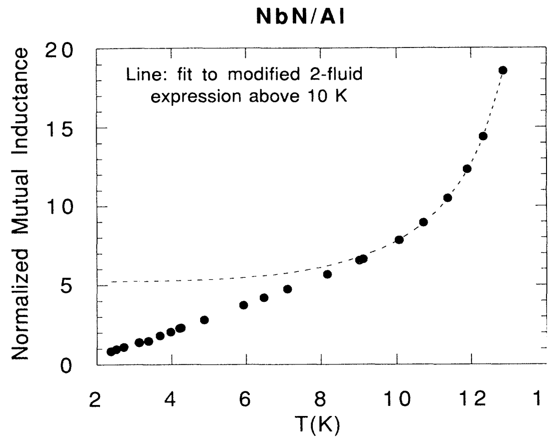

FIG. 2. Similar plot to Fig. 1 for the same NbN sample with 1100-Å Al overcoating (resistance ratio of the Al is 2.85). The dashed line is a fit of the same form restricted to temperatures ≥ 10 K, giving $T_c = 14.70$ K.

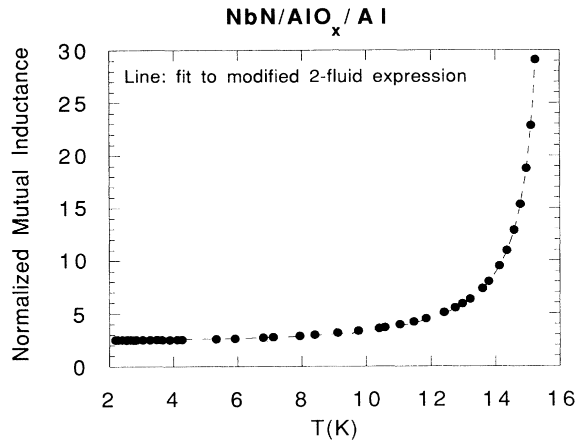

FIG. 4. Similar plot to Fig. 1, for a NbN/AlO$_x$/Al sample. The oxide layer was very thin, formed with a process that results in Josephson junctions when a superconducting counterelectrode is used. The Al thickness ≈ 2500 Å. The fit is of the same form as in Fig. 1 for the whole data set.

only now been observed.

One might wonder whether the low-temperature behavior seen in Fig. 2 is a consequence of an approach to the transition temperature of the Al. Our data for a Nb/Cu bilayer, shown in Fig. 3, reveal that this behavior is typical for any "good" normal metal: Again the low-temperature data for the bilayer drop well below the level extrapolated from the data near T_c. Superficially it appears that the effect of the normal-metal layer is not as pronounced as in the case of the NbN/Al system, but this is an artifact of plotting the raw mutual-inductance data. As we have shown, the areal density of superconducting electrons is proportional to M^{-1}. The extrapolated low-temperature values of M^{-1} (corresponding to the dashed lines in the figures) presumably reflects the superconducting electrons associated with the superconducting film alone, while the data values correspond to the total. Thus the difference between extrapolated and measured M^{-1} values is a measure of the strength of the proximity

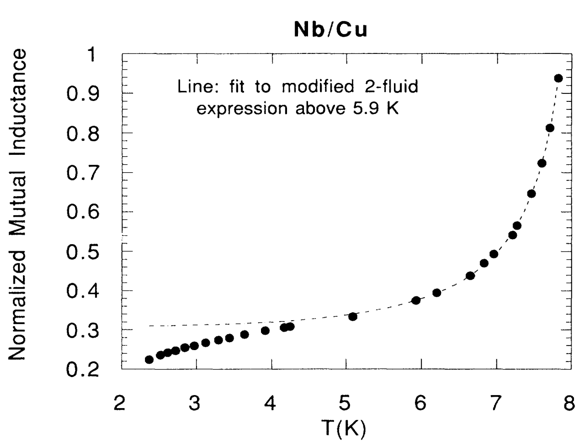

FIG. 3. Similar plot to Fig. 1, for a Nb/Cu bilayer. The thickness of the Nb and Cu are ≈ 550 Å and ~ 1.2 μm, respectively. The copper resistance ratio is ~ 36.

effect in the normal metal.[12] This turns out to be of comparable magnitude for both the NbN/Al and Nb/Cu cases. The contribution from the Nb in the latter case was almost 15 times greater than from the NbN, since its penetration depth is considerably smaller.

To verify that it is indeed the proximity effect that produces this dramatic result, we measured a similar bilayer which had a thin tunneling barrier of AlO$_x$ between the NbN and Al. This would be expected to have a much reduced proximity coupling into the Al.[13] Figure 4 shows that indeed this fits the modified two-fluid expression over the entire temperature range with no drop in the mutual inductance at low temperatures.

DISCUSSION

As mentioned in the Introduction, the presence of a proximity layer results in a superconducting condensation amplitude F that is not uniform through the film thickness. One can still define a local penetration depth, such that $\mu_0 J(x) = -A(x)/\lambda^2(x)$: $\lambda^{-2} = (\mu_0 \pi\sigma / hkT)(FV)^2$ near T_c in the case of a dirty superconductor,[14] where V is the electron-electron interaction potential. In the normal metal, a local penetration depth can be similarly defined:[2] $\lambda^{-2} = (\mu_0 \pi\sigma / hkT)(F/\pi N)^2$, where N is the density of states. It can be shown[15] that for a spatially varying λ, the kinetic inductance is inversely proportional to $\int \lambda^{-2}(x)dx$, as long as the vector potential does not change significantly through the film thickness. (In the case of constant λ, this is equivalent to the requirement $\lambda \gg d$.) Thus by integrating $(FV)^2$ on the superconducting side and $(F/\pi N)^2$ on the normal-metal side, we obtain terms proportional to the respective contributions to L_k^{-1}. In simplified terms, $(FV)^2$ and $(F/\pi N)^2$ are proportional to n_s in the two regions.

On the superconductor side, F obeys the well-known Ginsburg-Landau equations[2] with boundary condition

$dF/dx = -F/b$ at the S-N interface, where the extrapolation length b depends on properties of the normal metal. $F(x)$ must be calculated numerically in the superconducting side. In general, the S-N boundary condition has the effect of reducing F at the interface. On the normal side, $(F/\pi N) \sim \exp(-x/\xi_N)$, where $\xi_N^2 = (\hbar v_F 1/6\pi kT)$.

We have performed calculations of the temperature dependence of the superconductor and normal-metal contributions to L_k^{-1} with the above assumptions using various values for b and d_s that result in a $\sim 5\%$ reduction in the T_c of the bilayer. The general result is that both terms have a "modified two-fluid" temperature dependence near the transition. Thus, measurements near T_c cannot reveal the existence of a proximity effect, since the temperature dependence is the same as for a superconductor alone. Although there is no theoretical justification in formally extending these calculations to low temperatures, we find that when this is done the general features of our data are reproduced: L_k drops well below an extrapolation of the fit near T_c, and shows no signs of approaching a constant value at low temperatures. The physical interpretation is that in the normal metal the value of the condensation amplitude F at the interface is nearly constant at low temperatures, but the decay length ξ_N increases as $1/\sqrt{T}$.[16] Thus $\int F^2 dx$ (proportional to the normal-metal contribution to L_k^{-1}) will increase as $1\sqrt{T}$. In general, this temperature dependence should persist until either $\xi_N d_n \sim 1$ (which will cause L_k to stop changing) or field expulsion from the normal metal becomes important (which will result in a much more rapid drop in L_k with temperature).

Given the exceptional difficulty in performing exact calculations of the proximity effect even in the transition region,[17] the present measurement technique cannot hope to be other than being qualitative in revealing the strength of a proximity effect. Nevertheless, it could prove to be quite useful to demonstrate the very existence of a proximity effect and in optimizing processing procedures to enhance it.

CONCLUSIONS

In conclusion, we have shown experimentally that the existence of a proximity effect in a superconductor–normal-metal bilayer may have a profound effect on the kinetic inductance at low temperatures. To observe this effect, the superconductor thickness must be less than its penetration depth at low temperature, a condition that is easily achieved with the high-T_c materials. The normal-metal thickness should be greater than its coherence length at th lowest temperature explored to observe the maximum effect. For typical good metals and easily achievable temperatures this implies a thickness between 0.3 and 1.0 μm. The magnitude of the effect, namely the deviation of L_k from a modified two-fluid dependence at low temperatures, is proportional to the induced condensation amplitude. A quantitative theory for the low-temperature region is currently not available, although *ad hoc* extensions of existing theory for the region near the transition provide a reasonably qualitative explanation of observed results.

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