Anisotropic Magnetoconductance in Quench-Condensed Ultrathin Beryllium Films

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Near the superconductor-insulator (S-I) transition, quench-condensed ultrathin Be films show a large magnetoconductance which is highly anisotropic in the direction of the applied field. Film conductance can drop as much as seven orders of magnitude in a weak perpendicular field (≤1 T), but is insensitive to a parallel field in the same field range. We believe that this negative magnetoconductance is due to the field de-phasing of the superconducting pair wavefunction. This idea enables us to extract the finite superconducting phase coherence length, $L_\phi$, in nearly superconducting films. Our data indicates that this local phase coherence persists even in highly insulating films in the vicinity of the S-I transition.

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The superconductor-insulator (S-I) transition remains a controversial subject after nearly two decades of intense research. Experimental systems have generally been grouped into two seemingly different categories, displaying somewhat different features. These are granular versus uniform films. In apparently granular films, the transition temperature, $T_c$, and the energy gap, $\Delta$, for the individual grains are essentially constant throughout the S-I transition [2]. It is well established that superconductivity is destroyed by the breakdown of long-range phase coherence between the grains [2]. Granular films tend to lose their zero resistance state at a normal state sheet resistance, $R_N$, that is not seen in granular films until $R_N \gg R_Q$. Films considered to be uniformly disordered, such as quench-condensed Bi/Ge and Pb/Ge films [4], amorphous InO$_x$ films [5], and a-MoGe films [6], undergo a much sharper S-I transition. On the superconducting side, $T_c$ decreases with decreasing film thickness, approaching zero at the S-I transition. Tunneling experiments have suggested [7] that in Bi/Ge and Pb/Ge films the superconducting gap, $\Delta$, decreases with decreasing film thickness until the pair wavefunction, $\Delta^{1/2} e^{i\phi}$, with $\phi$ being the phase of the order parameter, vanishes and the film becomes insulating. These results suggest that the S-I transition is driven by the vanishing of the superconducting gap. In the alternative "dirty-boson" model [8], superconductivity is suppressed by phase fluctuations, and the Cooper pairs persist even on the insulating side of the transition. In recent years, the "dirty-boson" model has been applied nearly exclusively to explain the scaling analyses of film resistance in the disorder-driven and field-driven S-I transitions in uniform films [9,10,11], although the existence of Cooper pairs in the insulating states of these films has yet to be demonstrated. The "dirty-boson" model is, in fact, expected to describe best the S-I transition in granular films, since the amplitude of the order parameter is well defined on both side of the S-I transition in granular films.

The key concept of the "dirty-boson" model is that phase fluctuations drive a continuous S-I transition. Thus, in the vicinity of the S-I transition, there should exist a finite superconducting phase coherence length, $L_\phi$, even on the insulating side of the transition. This $L_\phi$ should scale with the correlation length of the transition and should diverge approaching the transition. In this Letter, we report on magnetoconductance (MC) measurements in the vicinity of the S-I transition in quench-condensed ultrathin Be films. As we argue below, this MC study provides the first direct measurement of $L_\phi$ in insulating films. We have observed that, for a given insulating film, $L_\phi$ drops as temperature is lowered. This underscores the competition between localization and superconductivity. Approaching the superconducting state with increasing film thickness, we have found $L_\phi$ to grow drastically.

Our ultrathin Be films were quench-condensed onto bare glass substrates which were held near 20 K during the evaporations. We chose Be mainly for two reasons. First, earlier studies have suggested [11] that quench-condensed Be films are nearly amorphous. Scanning force microscopy studies of our Be films, after warming up to room temperature, have found no observable granular structure down to 1 nm. This indicates that the length scale of disorder in these Be films must be much smaller than the typical grain size in apparently granular films. Second, Be has a very weak spin-orbit coupling [12]. As a result, a magnetic field applied parallel to the film plane, $H_\parallel$, couples to electron spin only and it does not couple to the orbital motion of the electrons. However, a perpendicular field, $H_\perp$, couples to both. Thus the MC
can be highly anisotropic in the direction of the applied field. In our Be films, the MC is negative and varies as much as seven orders of magnitude in weak $H_\perp$ up to 1 T, but it is insensitive to $H_\parallel$ in the same field regime. The low-field MC in our films is thus clearly an orbital effect. We, therefore, believe that this negative and highly anisotropic MC provides a direct measurement of the superconducting phase coherence length, $L_\phi$, as was suggested by Barber and Dynes [13] in a MC study of superconducting granular Pb films. This method can eventually be used to measure the divergence of $L_\phi$ as films cross the S-I transition with varying film thickness.

It should be pointed out that the length scale of the disorder in films considered uniformly disordered is still not understood. Even if microscopy techniques fail to reveal any granular structure, there still can exist metallic clusters, which can support superconductivity and which are connected electrically by relatively narrow and insulating or metallic links. For example, the Ge underlayer in Bi/Ge and Pb/Ge films may produce tunneling channels connecting the superconducting clusters. Recently, Kapitulnik and collaborators [8] have proposed that, near the S-I transition in a-MoGe, there exist both insulating and superconducting puddles, with transport being dominated by tunneling or hopping between them. Presumably, the typical size of the superconducting puddles grows approaching the S-I transition and eventually become the longest length scale of the system. Another example is the InO$_x$ films studied by Hebard et al. [4], which are believed to be amorphous, yet they display the quasireentrant behavior of granular films. Thus it is not clear as to what are the fundamental differences between the S-I transitions observed in uniform and granular films, other than that the different morphologies may lead to different universality classes of the transitions.

The details regarding our quench-condensation apparatus, a rotating sample stage, as well as 4-terminal dc I-V measurements from which the film sheet resistance, $R_{\parallel}$, was obtained, have been described elsewhere [4]. In Fig. 1, we show the temperature dependence of $R_{\parallel}$ for one film section deposited on a bare glass substrate following successive deposition steps to increase film thickness. The film changed its behavior from insulating to superconducting when $R_{\parallel}$ at 20 K was reduced to below 10 k$\Omega$/\square with increasing thickness. Film #10 in Fig. 1, which was superconducting with a $T_c \sim 6$ K, had a critical field $H_c$ above the 10-T field our magnet could reach at 4.2 K. Thus the $H_c$ is not far below the spin-paramagnetic limit [15], which we estimated [4] to be $\sqrt{2}\Delta/g\mu_B \approx 11.2$ T, where $g \approx 2$ is the Landé g-factor, $\mu_B$ is the Bohr magneton, and $\Delta = 0.92$ mV is the superconducting gap for Film #10. Early studies [14] estimated that the critical field was 18 $\sim$ 20 T in quench-condensed Be films of $T_c = 8 \sim 10$ K, suggesting that these films were highly disordered with a very short penetration depth. The data in Fig. 1 do show the quasireentrant behavior, such as in Film #7, which is typically seen in granular films. However, this quasireentrance is seen in a range of $R_N$ that is much narrower than in the case of typical granular films [13]. In addition, the $T_c$ of these Be films appears to increase significantly with increasing film thickness, which is typically seen in uniform films. Thus these Be films show certain properties of both uniform and granular films.

In Fig. 2(a), we show the MC measured in $H_\perp$ at a

![Graph](image1.png)

**FIG. 1.** Selected curves of $R_{\parallel}$ versus temperature measured on one film area following a series of deposition steps to increase film thickness. Curves from top to bottom are labeled as Film #1 to Film #10, respectively. The thickness for these films changed from 4.6 Å to 15.5 Å.

![Graph](image2.png)

**FIG. 2.** (a): MC measured in $H_\perp$. Up-triangles and down-triangles are measured on Film #6 at 1.5 K and 1.0 K, respectively. MC was not measured on this film below 1.0 K because the film was too resistive. Circles are from Film #7 at 100 mK. Crosses are from Film #8 at 100 mK. (b): Comparison of MC data in $H_\parallel$ (filled and open circles) and $H_\perp$ (filled and open triangles) at 100 mK on a log-log scale. Filled symbols are for Film #8. Open symbols are for Film #7. The data in $H_\perp$ are copied from (a). The arrows indicate the crossover fields, $H^*$, at which film conductance starts dropping with increasing field.
number of temperatures. In the low-field regime below 1 T, the MC is negative and varies as much as seven orders of magnitude. This can not be due to weak-localization [7], which should lead to a positive and relatively small MC in weak spin-orbit materials such as Be. In H⊥, film conductance was found to be insensitive to the field below 1 T, as shown in Fig. 2(b). Such highly anisotropic behavior indicates that the MC in H⊥ is an orbital effect. We believe that this negative MC in the low H⊥ regime arises as the superconducting phase coherence is suppressed when H⊥ exceeds the crossover value H* that produces one flux quanta, Φ0 = h/2e, in a coherent area, or when L⊥2H⊥ ~ Φ0. Determining this crossover field H* when the conductance drops from its zero-field value, thus provides a measurement of Lφ. A few years ago, Barber and Dynes [1] made this argument to calculate Lφ in the descending resistance tail of superconducting granular Pb films, showing that for a superconducting film Lφ increases with decreasing temperature. In our non-superconducting films #7 and #8, the data plotted on a logarithmic field scale in Fig. 2(b) show that, at 100 mK, H* was near 0.002 T for Film #8 and 0.1 T for Film #7, as indicate by the arrows in Fig. 2(b). This translates into a coherence length, Lφ, at 100 mK of about 1.0 µm for Film #8 and 0.14 µm for Film #7. We therefore see a growing Lφ as the films approach the superconducting state with increasing thickness. We note that the drop in conductance at high H||, seen in Fig. 2(b), is likely due to the suppression of the amplitude of the superconducting order parameter as the H|| approaches the spin-paramagnetic limit.

Not only did we observe Lφ to vary with film thickness, but it varied with temperature as well. In the temperature range in which R|| decreases with decreasing temperature, we observed that the MC peak was sharper at lower temperatures, indicating an increasing Lφ with decreasing temperature. Such behavior is identical to that observed by Barber and Dynes [1]. It is due to the suppression of thermal fluctuations with lowering temperature. However, we have also observed, for the first time, that the MC peak is broader at lower temperatures in the quasireentrant regime where R|| increases with decreasing temperature, as we show in Fig. 3 (a). Such behavior is seen in all quasireentrant films similar to Film #7. Using the crossover field values, H*, obtained from the data in Fig. 3 (a), we find a reduction of Lφ with decreasing temperature in this temperature range, as shown in Fig. 3 (b). We believe that this observation demonstrates the suppression of the superconducting phase coherence as localization effects are enhanced at lower temperatures.

The above proposal that the MC probes the superconducting phase coherence is further supported by the nonlinear I-V curves we have measured near the S-I transition. Insulating and nearly superconducting films near the S-I transition each has a distinct type of I-V curve [3].

In the low bias regime, the I-V curves of nearly superconducting films show the supercurrent-type behavior: the I-V curves have a downward curvature; while the I-V curves of insulating films show the Coulomb-blockade-like behavior: the I-V curves have an upward curvature. The supercurrent-type behavior indicates the existence of a small supercurrent associated with local supercon-
conducting regions. There have been observations that the I-V curves evolve from the Coulomb-blockade-type to the supercurrent-type as the films cross the transition from the insulating side. We have seen the same type of behavior in our films. We have also observed that, in nearly superconducting films, the I-V curves changed from the supercurrent-type to the Coulomb-blockade-type as the conductance of the films is suppressed by a weak H \(_{\perp}\), as shown in the inset in the top-left corner of Fig. 4. This is therefore additional evidence that the application of H \(_{\perp}\) suppresses the superconducting fluctuations.

This negative MC and supercurrent-type I-V persisted even in much more insulating films such as Film #6, which did not show any quasireentrant behavior. In this case, the supercurrent-type I-V could only be observed in a narrow temperature range between 0.8 ~ 1.2 K. In the main part of Fig. 4, we plot the I-V curves measured at 1.05 K on Film #6, for a number of perpendicular field values. Although the effect was much weaker in Film #6 than in less insulating films #7 and #8, we can see clearly that, below a bias voltage of 15 mV, the curvature of the I-V curves changes from downward to upward with an increasing perpendicular field. However, as shown on a higher bias scale in the inset in the low-right corner of Fig. 4, the I-V curves always show an upward curvature regardless of the magnetic field, indicating the insulating nature of Film #6. Thus although Films #6 was very insulating, there still existed a finite LA, which resulted in an observable supercurrent-type I-V in zero-field at temperatures not so low that the effect is completely suppressed by localization.

In conclusion, we have directly observed for the first time the finite superconducting phase coherence length LAF on the insulating side of the S-I transition. Our quench-condensed Be films show both the quasireentrant behavior of granular films and the varying Tc usually seen in uniformly disordered films. Scanning force microscopy studies have shown that the length scale of disorder is much shorter in these Be films than that of apparently granular films. The MC is negative, large, and highly anisotropic in the direction of the field. Our results demonstrate that this MC gives a direct probe of the length scale associated with the S-I transition. In nearly insulating films, LAF is observed to decrease with decreasing temperature, highlighting the competition between localization and superconductivity. With increasing film thickness, we expect LAF to grow and to diverge as the films eventually develop a global superconducting phase with zero resistance.

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