Superconducting fluctuation effects in the resistive transition of amorphous bismuth films*

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(Received 1 March 1977)

Improved measurements were made of the temperature-dependent resistivity of amorphous Bi films in order to observe the effects of superconducting fluctuations. Measurements were made in the temperature range $T_c \leq T \leq 2.5T_c$ on films ranging from 500 to 5000 Å thick. Temperature resolution near T_c of 0.2 mK and precise resistance measurements at higher temperatures (1 part in 10^4) permitted a detailed comparison with theory. Films over 500 Å thick showed a temperature-dependent transition from thin-film (two-dimensional) behavior to bulk (three-dimensional) behavior in agreement with the predictions af Aslamzov and Larkin.

I. INTRODUCTION

During the past several years numerous studies have been made of superconducting fluctuation rounding of the resistive transition of thin-film superconductors.[1,2] The usual procedure in analyzing resistive transition data has been to perform a multiparameter least-squares fit to a theoretical prediction for the fluctuation conductivity. A difficulty with this procedure is that adjustment of the theoretical parameters will generally permit the Aslamazov-Larkin (AL) theory[3] or other[4-7] theories of the resistive transition to fit any smooth data over at least a portion of the transition region. Testardi *et al.*[8] have pointed out that a more critical test of proposed theories would be an experimental observation of the predicted change in the temperature dependence of the resistance corresponding to the transition between the two- and three-dimensional fluctuation regimes. Several investigators have attempted to study the two- to three-dimensional transition; however, in most cases there have been some doubts about the results. Testardi *et al.*[8] found only two-dimensional behavior in Pb films that were supposedly in the three-dimensional regime. Gittleman *et al.*[9] observed the $\tau^{-1/2}$ (where $\tau = \ln T/T_c$) temperature dependence predicted by the AL theory for fluctuations in the three-dimensional regime. However, their measurements on granular Al and Sn films did not show a two- to three-dimensional transition. Goldman *et al.*[10] believe they have observed the transition in $Nb_{0.88}Ti_{0.12}N$ films, however, their results were highly dependent on the method used to analyze the data. Inspection of their Fig. 1 suggests that the films they used were not uniform; furthermore, the films proved to have a temperature-dependent normal-state resistance which greatly complicated the data analysis. Sixl and Sanwald[11] claim to observe zero, one, two, and three-dimensional behavior in quench-condensed Al films, but their results do not show the two- to three-dimensional transition. In addition, Granqvist[12] has shown that their results can be interpreted as due to a thickness-dependent pair-breaking parameter. Finally, Johnson and Tsuei[13] have made measurements on a variety of bulk amorphous alloys. Very close to T_c they observe a $\tau^{-1/2}$ temperature dependence; however, they do not observe the transition to the two-dimensional regime, perhaps because of transition broadening due to statistical variations in alloy composition. The best observations of the two- to three-dimensional transition are Glover and Naugle's work[14] on ~3000 Å thick amorphous Bi films. However, additional measurements with higher accuracy and covering a larger range of film thicknesses offer the possibility of a more definitive test of proposed theories.

The measurements reported here were made on amorphous Bi films with work concentrated in the temperature range where mean-field theories such as the AL theory[3] are expected to apply. Film thicknesses ranged from 500 to 5000 Å. The measurements covered the temperature range $T_c \leq T \leq 2.5\ T_c$. Special attention has been given to a discussion of the analysis procedure.

II. THEORETICAL CONSIDERATIONS

Assuming that normal-state and fluctuation conductivity occur in parallel, the AL theory gives the following expression for the temperature-dependent resistance of a film of thickness D[3,15]:

$$\frac{R_0 - R(T)}{R(T)} = \frac{e^2}{16\hbar}\,\frac{1}{\sigma_0 D\tau}\,G(\tau) = \frac{\sigma'_{AL}}{\sigma_0}\,, \tag{1}$$

$$G(\tau) = \tfrac{1}{2}\{1 + D/\xi_T \coth D/\xi_T\}\,, \tag{2}$$

$$\xi_T = \eta/\tau^{1/2}\,, \tag{3}$$

where R_0 is the normal-state residual resistance, $R(T)$ is the temperature-dependent resistance of the film, σ'_{AL} is the fluctuation conductivity, σ_0

is the residual normal-state conductivity, $\tau = \ln T/T_c^{mf}$, and η is the Ginzburg-Landau coherence length constant. The notation T_c^{mf} is used to indicate that the transition temperature is to be considered a theoretical parameter; thus, the film resistance will not necessarily be zero at T_c^{mf}.

In the two-dimensional limit $D \ll \xi_T$, the AL theory becomes

$$\frac{R_0 - R(T)}{R(T)} = \tau_0^{AL}/\tau \,, \tag{4}$$

while in the three-dimensional limit $D \gg \xi_T$, the AL theory becomes

$$[R_0 - R(T)]/R(T) = \frac{\tau_0^{AL}}{2\tau^{1/2}} \frac{D}{\eta} \,, \tag{5}$$

where $\tau_0^{AL} = (e^2/16\hbar)R_{0\square}$ with $R_{0\square} = 1/\sigma_0 D$.

According to the AL theory, whether a sample exhibits two-dimensional or three-dimensional behavior depends only on the ratio of the sample thickness D to the Ginzburg-Landau coherence length ξ_T. Since ξ_T decreases with increasing temperature, the AL theory predicts a change from a τ^{-1} temperature dependence characteristic of two-dimensional fluctuations to a $\tau^{-1/2}$ dependence characteristic of three-dimensional fluctuations when the temperature is raised sufficiently far above T_c^{mf}.

To properly test the AL theory, measurements must be made on a single thin film in *both* the two-dimensional ($\xi_T \gg D$) and the three-dimensional ($\xi_T \ll D$) regimes. As Goldman *et al.*[10] emphasize, the measurements must be made on a well-characterized material and the analysis should be done in such a way as to avoid the problems inherent in multiparameter fits. Furthermore, measurements made on films of different thickness should all show comparable behavior with a systematic dependence on film thickness.

III. EXPERIMENTAL DETAILS

A schematic of the cryostat-evaporator used for the experiment is shown in Fig. 1. The vacuum in the vicinity of the sample was ~10^{-8} Torr. Z-cut, polished, crystalline quartz substrates were mounted on a substrate holder attached to the innermost liquid He tank. A germanium resistance thermometer was mounted on the rear of the substrate holder along with a small heater used to raise the temperature above 4.2 K. A mask mounted on the front of the substrate holder ~75 μm above the surface of the substrate was used to define the film geometry.

Three films were produced simultaneously by depositing Bi(Tl) onto the quartz substrate; during deposition the temperature of the substrate rose

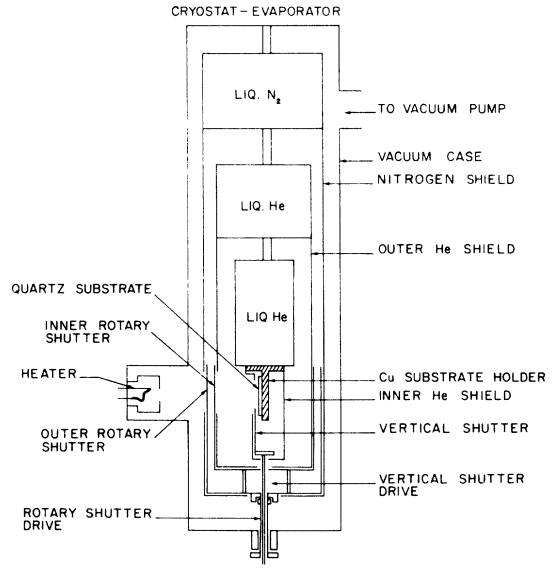

FIG. 1. Crystat evaporator. Bismuth evaporated from a crucible held in the heater was deposited on the quartz substrate which was held at cryogenic temperatures by the lower of the two helium reservoirs.

to between 7 and 10 K. The purpose of the Tl was to stabilize the amorphous phase[16,17] which otherwise tended to crystallize at ~12 K. With 3 at.% Tl the films were stable up to ~18 K; additional Tl raised the crystallization temperature as high as 100 K. The Bi(Tl) mixtures were prepared by the method described by Shier and Ginzberg.[18]

The Bi(Tl) mixtures were evaporated from a resistively heated Mo crucible with an 0.6-mm orifice. The crucible was located ~30 cm from the substrate. From geometrical considerations alone the thickness uniformity of the films is ~$\frac{1}{2}$%. The shadowed "edge" regions of the films are computed to be ~0.2 μm wide.

The temperature was determined with a germanium resistance thermometer calibrated by the National Bureau of Standards to an absolute accuracy of ±20 mK. The thermometer resistance was plotted on an X-Y recorder or read from a digital millivoltmeter. The film resistance was determined using a four-terminal potentiometric method. A mercury cell warmed to 40 °C supplied a current constant to ~1/50 000 per hour. The measurements were made with a current of 100 μA; reducing the current to 10 μA did not change the results within experimental error. The voltage drop across the film was plotted on an X-Y plotter in the temperature interval $T_c \leq T \lesssim T_c + 0.1$ K where the resistance changes rapidly with temperature. At higher temperatures the voltage drop was determined with a microvolt potentiometer with a resolution of 1 part in 10^4. A summary of the

TABLE I. Measurement errors.

	$T_c < T < T_c + 0.1$ K	$T > T_c + 0.1$ K
Film resistance	±0 .15% R_0	±0.004 Ω
Relative temperature	±0 .2 mK	±0.8 mK at ~6 K increasing to ±50 mK at ~18 K
Absolute temperature	±20 mK	±20 mK

errors involved in the measurements is given in Table I. Further discussion of the experimental details can be found elsewhere.[19]

IV. RESULTS AND ANALYSIS PROCEDURE

The data consists of resistance vs temperature measurements for thirteen amorphous Bi films.[19] The procedure adopted to analyze the data is outlined below. (i) The normal-state residual resistance R_0 was determined from the relation

$$R_0 \equiv 1.0025 R_{\max} \tag{6}$$

where $R_{\max}$ was the maximum value of resistance measured for the film being analyzed. Generally, $R_{\max}$ occurred at $T \simeq 12$ K (Fig. 2). (ii) Assuming that the AL theory correctly describes the data, and using the fact that close to T_c, $\ln T/T_c \simeq (T - T_c)/T_c$, Eq. (4) shows that a plot of $R(T)/[R_0 - R(T)]$ vs T will be linear with a slope equal to $(T_c^{mf}\tau_0)^{-1}$ and an extrapolated intercept at $T = T_c^{mf}$ (Fig. 3). The notation τ_0 indicates the experimentally determined value of the AL parameter τ_0^{AL}. The uncertainty in τ_0 and T_c^{mf} ranges from ±4% and ±0.4 mK, respectively for the thinnest films, to ±10% and ±0.2 mK for the thickest films. The dominant source of error in τ_0 and T_c^{mf} is the accuracy of the resistance measurement. Error in the determination of R_0 has an insignificant effect on the values of T_c^{mf} and τ_0. (iii) The film thickness D was determined from the relation

$$D = \rho_0 / R_{0\square} , \tag{7}$$

with $\rho_0 = 155$ μΩ cm.[20] The thickness of seven amorphous Bi + 3 at.% Tl films made in conjunction with this study was determined by the Tolansky method; the measured thickness agreed with those calculated from Eq. (7) to ±10%. (iv) After determining R_0, T_c^{mf}, τ_0, and D as described above, the Ginzburg-Landau coherence length constant η was determined by fitting Eq. (1) to the data at $\tau = 0.050$. This point was chosen because it is well into the three-dimensional fluctuation region for all but the thinnest films, yet it is still below the temperature at which variation in the normal-state resistance affects the measurements. The uncertainty in η is almost entirely due to uncertainty in the determination of R_0. A change in R_0 of 0.1% produces approximately a 15% change in η. For films over 1000 Å thick the uncertainty in η is estimated to be ±20%. Because finite thickness effects are smaller in the thinner films at $\tau = 0.050$, the uncertainty in η is correspondingly larger. For the three films which are less than 1000 Å thick the uncertainty in η is ~30%.

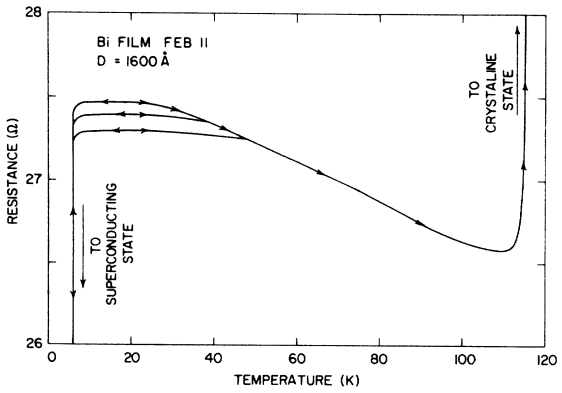

FIG. 2. Annealing curve of an amorphous bismuth film. The double-ended arrows (⟷) indicate "reversible" behavior. The single-ended arrows (→) indicate "irreversible" behavior.

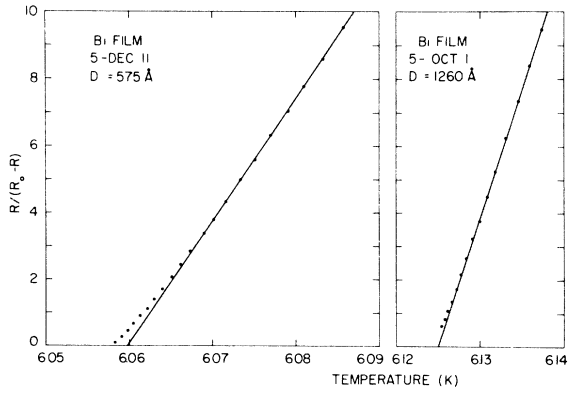

FIG. 3. $R/(R_0 - R)$ as a function of temperature for two amorphous Bi films. The straight line drawn through the data points was used to determine the transition temperature T_c^{mf} and the experimental transition width $\tau_0 T_c^{mf}$. Error bars are the size of the plotted points.

TABLE II. Experimental parameters determined from comparison with the Aslamazov-Larkin theory.

Film No.	$R_{0\square}(\Omega)$	$\frac{\tau_0}{R_{0\square}}(\Omega^{-1})$	T_c^{mf} (K)	η(Å)	D(Å)	$\frac{\text{Film length}}{\text{Film width}}$
1-Jun 24	32.335	1.66×10^{-5}	6.0449	86	480	5.38
2-Jun 24	32.342	1.66×10^{-5}	6.0452	86	480	5.54
1-Aug 23[a]	5.440	1.74×10^{-5}	6.1604	103	2850	5.38
2-Aug 23[a]	5.359	1.77×10^{-5}	6.1606	103	2890	5.54
1-Aug 31	9.636	1.65×10^{-5}	6.1443	99	1610	5.38
2-Aug 31	9.517	1.67×10^{-5}	6.1448	99	1630	5.54
1-Sep 10	8.166	1.66×10^{-5}	6.1391	101	1900	5.38
2-Sep 10	8.078	1.67×10^{-5}	6.1397	100	1920	5.54
5-Oct 1	12.357	1.68×10^{-5}	6.1251	99	1255	5.44
4-Oct 18	5.564	1.70×10^{-5}	6.1350	100	2785	5.14
5-Oct 18	5.563	1.70×10^{-5}	6.1343	98	2785	5.44
5-Dec 3[a]	3.119	1.78×10^{-5}	6.1643	99	4970	5.44
5-Dec 11	27.049	1.62×10^{-5}	6.0599	85	575	5.44

[a] Bi + 6 At. % Tl.

The data for several of the films is shown in Fig. 4. The values of $R_{0\square}$, $\tau_0/R_{0\square}$, T_c^{mf}, η and D are given in Table II for thirteen amorphous Bi films including those for which the data is plotted in Fig. 4.

V. NORMAL-STATE RESISTANCE

Since the fluctuation conductivity is so small at higher temperatures, it is important to have an accurate determination of the residual resistance R_0. For this reason, special attention was paid to the normal-state properties of the films.

In the vicinity of 12 K, the measured resistance was constant within experimental resolution ($\sim1\times10^{-4}$); at higher temperatures, the resistance exhibited a slow, *irreversible* decrease. Annealing the films at ~16 K made the normal-state resistance more nearly constant, but even after annealing a small *reversible* decrease still remained (Fig. 2). Korn *et al.*[21] have made a detailed study of the temperature dependence of the normal-state resistance in amorphous superconductors. Their measurements on amorphous Bi + 25 at. % Ag films are in agreement with the present measurements on amorphous Bi + 3 at. % Tl. Furthermore, their results show that the normal-state resistance varies *linearly* with temperature. This is in contrast with measurements made on thin polycrystalline Al films where the temperature dependence appears to be exponential.[22]

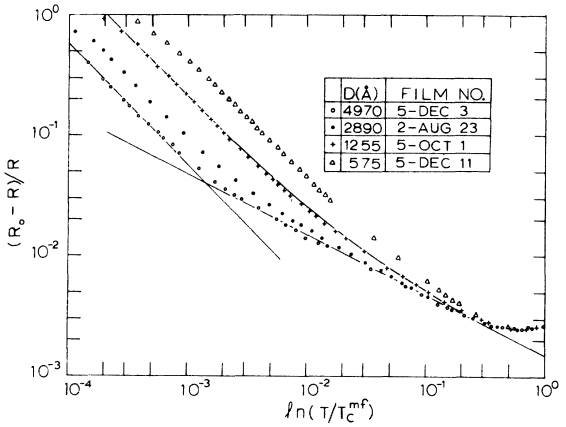

FIG. 4. Temperature dependence of the fluctuation conductivity. Data are plotted for four films; $R_{0\square}$, $\tau_0/R_{0\square}$, T_c^{mf} and η are given in Table II. The curved solid line was calculated from the AL theory with finite thickness corrections [Eq. (1)]. The two straight lines give the limiting two- ($\sigma'\alpha\tau^{-1}$) and three-dimensional ($\sigma'\alpha\tau^{-1/2}$) forms of the AL theory. Error bars are the size of the plotted points.

All films used in this study were annealed before any measurements were made. Several of the films were made with the composition Bi + 10 at. % Tl; these films could be annealed at ~100 K without crystallizing. After annealing, the normal-state resistance $R_n(T)$ could be represented by

$$R_n(T) = R_n(0)(1 - aT)\,, \tag{8}$$

where $a \simeq 10^{-4}K^{-1}$. Thus, over the range in which the data could be analyzed to determine the fluctuation conductivity (6 K $\leq T \leq$ 9 K) the *change* in $R_n(T)$ was negligible.

The primary difficulty in determining the residual resistance R_0 is due to the finite magnitude of the fluctuation conductivity at the highest temperatures at which measurements could be made without crystallizing the Bi + 3 at. % Tl films used in this study; thus, $R_{max} = R(12\text{ K})$ was less than $R_n(12\text{ K})$. The fluctuation conductivity can be estimated from Eq. (5) if η is known. Using $\eta \simeq 90$ Å

as determined from critical-field measurements on the films used in this study,[19] one can estimate that $\sigma'_{AL}(12\text{ K}) \simeq 2\times10^{-3}\sigma_n$; thus,

$$R_n(12\text{ K}) = R(12\text{ K})(1+\sigma'/\sigma_n) \simeq 1.0020R_{max}.$$

This is the basis for determining R_0 from the relation $R_0 = 1.0025R_{max}$. (The additional factor of 5×10^{-4} accounts for the increase in R_n, when going from 12 down to ~7 K.) The fact that this same procedure for determining R_0 gave consistent results for *all* the films studied is a strong reason for believing it to be valid.

VI. DISCUSSION

A. Temperature dependence of the fluctuation conductivity

The most noteworthy aspect of the present results is the definitive observation of the two- to three-dimensional transition predicted by the AL theory. Except perhaps for the thinnest films, each film exhibited a two-dimensional region ($\sigma' \alpha \tau^{-1}$) and, at higher temperatures, a three-dimensional region ($\sigma' \alpha \tau^{-1/2}$).

The results agree closely with Eq. (1) for $0.0003 \lesssim \ln T/T_c^{mf} \lesssim 0.3$. Deviations near T_c^{mf} are believed due to the expected breakdown of the AL theory in the critical fluctuation region.[23] Deviations at $T \gtrsim 2T_c$ are due to the previously discussed temperature dependence of the normal-state resistance. Small systematic differences between experiment and theory were observed in the vicinity of the two- to three-dimensional transition. These deviations most likely result from the idealized boundary conditions assumed in the derivation of Eq. (1).[15]

The experimentally determined temperature dependence in the three-dimensional region is dependent on the value used for R_0. For $R_0 = 1.0025\ R_{max}$, $\sigma'_{3D} \alpha \tau^{-n}$ where $n = 0.50 \pm 0.01$; increasing (decreasing) R_0 by 1×10^{-3} changes n to 0.44 (0.56). Larger changes in R_0 would not be consistent with the measurements of $R_n(T)$ discussed in Sec. V.

B. Experimental values of $\tau_0/R_{0\square}$

The AL theory predicts a universal value of $1.52\times10^{-5}\ \Omega^{-1}$ for $\tau_0/R_{0\square}$. The present results are 5% to 17% higher than this value. Figure 5 shows the experimental values for a number of amorphous Bi films. The largest error in the determination of $\tau_0/R_{0\square}$ as well as the greatest enhancement over the theoretical value occurs for thick films (small $R_{0\square}$). This is, to some extent, an artifact of the graphical procedure used to determine τ_0. Even discounting the highest values of $\tau_0/R_{0\square}$, the experimental values average about

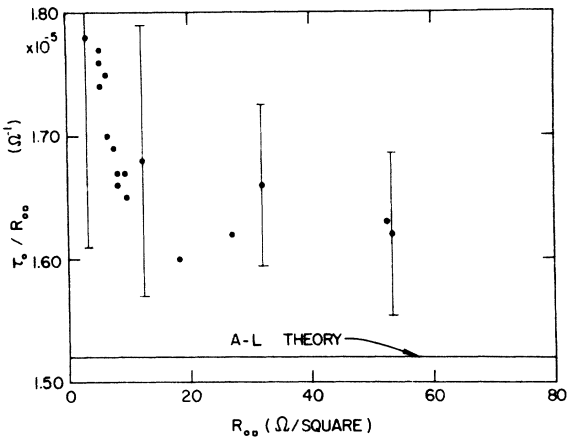

FIG. 5. Comparison of measured and theoretical values of the AL parameter $\tau_0/R_{0\square}$ for amorphous Bi films.

10% greater than the AL value. The enhancement of τ_0 could result from residual strains or inhomogeneities in the films. However, the uniformity and consistent characteristics of amorphous Bi films argue against this possibility. Another possibility is the strong coupling nature of amorphous Bi. Estimates of the effect of strong coupling on the fluctuations, however, predict a decrease rather than an enhancement of τ_0.[24,25] A final possibility has been suggested by Fulde and Maki[24] who predict that pair-breaking effects should enhance the value of τ_0. The presence of pair breaking in amorphous Bi is suggested by the apparent lack of a contribution from the Maki-Thompson term.[4,5]

C. Experimental values of η

Eliminating the results from the thinnest films, the η values determined by fitting the data to Eq. (1) were remarkably consistent, averaging approximately 100 Å. By way of comparison, Lejeune and Naugle[26] have determined η from the proximity effect between amorphous Bi and Fe, finding a value of 95 ± 6 Å. Bergman[27] has calculated a value of 70 Å from critical-field measurements on amorphous $Bi_{0.85}Tl_{0.15}$. The author has found a value of 90 Å from critical-field measurements on Bi + 3 at.% Tl.[19] A value of 72 ± 9 Å was determined by Glover[14] from measurements of the fluctuation conductivity in the presence of a perpendicular magnetic field.

D. Comparison with previous measurements on amorphous Bi

The present results are best compared with Glover and Naugle's[14] measurements on two amorphous Bi films for which they reported thicknesses of 2750 and 3200 Å, with $\tau_0/R_{0\square}$ equal to (1.46

$\pm 0.11) \times 10^{-5}\ \Omega^{-1}$ and $(1.43 \pm 0.11) \times 10^{-5}\ \Omega^{-1}$, respectively, and η equal to 86 ± 22 Å and 80 ± 20 Å, respectively. Using these values they found quantitative agreement with Eq. (1). In analyzing their data Glover and Naugle adjusted $R_{0\square}$, τ_0, and η so as to optimize the fit to Eq. (1) over the entire measurement range. This procedure differs substantially from the present method; however, the results obtained by the two analysis procedures agree within the combined errors.

E. Contribution from the Maki-Thompson fluctuation mechanism

It has been assumed in this paper that the Maki-Thompson fluctuation mechanism[4,5] does not contribute to the fluctuation conductivity in amorphous Bi. The reasons behind this assumption are discussed in detail elsewhere.[19] Briefly, they are as follows: (i) To fit the data requires $\delta > 1$ for the thinner films, where δ is Thompson's pair-breaking parameter.[5] (ii) Fitting the data to the Maki-Thompson theory results in $\eta \sim 300$ Å, which is far too large when compared with other determinations of η, all of which give values below ~100 Å.[14,19,26,27] (iii) Recent theoretical results have shown that the electron-phonon interaction rate is greatly enhanced in amorphous metals, leading to a suppression of the Maki-Thompson fluctuation mechanism.[28]

VII. SUMMARY

Measurements of the superconducting fluctuation contribution to the conductivity of amorphous Bi films gave results in agreement with the Aslamazov-Larkin (AL) theory[3] for temperatures in the range $0.0003 \lesssim \ln T/T_c \lesssim 0.30$. Films in the thickness range $500 \lesssim D \lesssim 5000$ Å agreed with the AL prediction for the temperature and thickness dependence of the fluctuation conductivity; all but the thinnest films clearly showed the change from two-dimensional to three-dimensional behavior predicted by the AL theory.

ACKNOWLEDGMENTS

The author is grateful to Dr. Rolfe E. Glover, III, for suggesting the research project on which the paper is based and to the faculty and staff of the University of Maryland Solid State group for their help in its completion, especially Dr. Victor Korenman for explaining theoretical details. The help of Dr. C. V. Briscoe, of the University of North Carolina, in the preparation of this paper is greatly appreciated.

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*Paper based in part on a thesis submitted by Peter J. Silverman in partial fulfillment of requirements for the degree of Doctor of Philosophy.

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[1]R. E. Glover, III, Phys. Lett. A 25, 542 (1967).
[2]R. A. Craven, G. A. Thomas, and R. D. Parks, Phys. Rev. B 7, 157 (1973). This paper contains a summary of many of the recent experimental results.
[3]L. G. Aslamazov and A. I. Larkin, Phys. Lett. A 26, 238 (1968).
[4]K. Maki, Prog. Theor. Phys. (Jpn.) 39, 897 (1968); 40, 193 (1968).
[5]R. Thompson, Phys. Rev. B 1, 327 (1970).
[6]B. Patton, Phys. Rev. Lett. 27, 1273 (1971).
[7]J. Keller and V. Korenman, Phys. Rev. Lett. 27, 1270 (1971).
[8]L. R. Testardi, W. A. Reed, P. C. Hohenberg, W. H. Haemmerle, and G. F. Brennert, Phys. Rev. 181, 800 (1969).
[9]J. I. Gittleman, R. W. Cohen, and J. J. Hanak, Phys. Lett. A 29, 56 (1969).
[10]A. M. Goldman, F. M. Schaer, L. E. Toth, and J. Zbasnik, Physica (Utr.) 55, 234 (1971).
[11]H. Sixl and W. Sanwald, Solid State Commun. 16, 603 (1975).
[12]C. G. Granqvist, Solid State Commun. 19, 913 (1976).
[13]W. L. Johnson and C. C. Tsuei, Phys. Rev. B 13, 4827 (1976).
[14]R. E. Glover, III, Physica 55, 3 (1971).
[15]A. Schmid, Z. Phys. 215, 210 (1968).
[16]W. Buckel and R. Hilsch, Z. Phys. 138, 109 (1954).
[17]W. Buckel, Z. Phys. 138, 136 (1954).
[18]J. Shier and D. Ginsberg, Phys. Rev. 147, 384 (1966).
[19]P. J. Silverman, University of Maryland Technical Report No. 73-053 (1972) (unpublished).
[20]D. G. Naugle, R. E. Glover, III, and W. Moorman, Physica (Utr.) 55, 250 (1971).
[21]D. Korn, W. Murer, and G. Zibold, Z. Phys. 260, 351 (1973).
[22]M. Strongin, J. Dickey, and J. Crow, Solid State Commun. 8, 1647 (1970).
[23]M. K. Chien and R. E. Glover, III, *Proceedings of the Thirteenth International Conference on Low Temperature Physics*, Vol. 3, edited by K. D. Timmerhaus, W. J. O'Sullivan, and E. F. Hammel (Plenum, New York, 1974), p. 649.
[24]P. Fulde and K. Maki, Phys. Kondens. Mater. 8, 371 (1969).
[25]S. Imai, Prog. Theor. Phys. 54, 624 (1975).
[26]J. D. Lejeune and D. G. Naugle, *Proceedings of the Fourteenth International Conference on Low Temperature Physics*, edited by M. Krusius and M. Vurio (North Holland, New York, 1976).
[27]G. Bergman, Phys. Rev. B 7, 4850 (1973).
[28]B. Keck and A. Schmid, Solid State Commun. 17, 799 (1975).