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Dimensional Transition in the Fluctuation Conductivity of Pb/Ge Superconducting Multilayers.

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Abstract. – We have observed a two- to three-dimensional transition in the normal-state fluctuation conductivity of Pb/Ge superconducting multilayers. This transition, also characterized by changes in the temperature dependence of critical fields, exhibits a clear-cut signature in the fluctuation conductivity in good agreement with the theoretical calculation in two and three dimensions.

Dimensional transitions in the critical fields of superconducting multilayers and intercalated dichalcogenides have received considerable attention for a number of years [1, 2]. The temperature, thickness, diffusion constant and density of states dependence of critical fields have all been exhaustively studied experimentally and found to be in good agreement with theoretical calculations [1, 2]. However, the observation of dimensional transitions in other physical properties has been restricted to changes in the zero field fluctuation conductivity as a function of temperature in Nb/Ge multilayers [3] and of fluctuation diamagnetism above T_c in Nb/Si multilayers [4]. We present here the observation of a two- (2D) to three- (3D) dimensional transition in the normal-state fluctuation conductivity of Pb/Ge multilayers. We believe that this is the first time that a dimensional transition is observed in the fluctuation conductivity which is related to a parallel magnetic field. At this time, only limited calculations exist considering paramagnetic effects of a parallel field for layered superconductors with purely 2D superconducting layers [5].

Pb/Ge multilayers were prepared in a UHV molecular beam epitaxy (MBE) system equipped with two electron beam guns, at pressures better than 10^{-8} Torr during evaporation [6]. Evaporation rates were controlled using a quadrupole mass spectrometer in feedback mode, at typical rates of 5 Å/s for Pb and 2 Å/s for Ge. Multilayer samples consisting of 10 bilayers were evaporated onto liquid-nitrogen–cooled oxidized silicon and sapphire substrates, to assure uniform Pb layer growth. The thickness of the layers was cross-checked with quartz crystal oscillators, thickness profilometry and X-ray diffraction. Since X-ray diffraction experiments give no real space information, structural models have to be developed to compare the calculated diffracted intensity with the experiment. A kinematical model of the multilayered structure, including continuous Gaussian thickness fluctuations of the amorphous Ge layer and discrete Gaussian thickness fluctuations of the crystalline Pb layer, indicates that the interfacial roughness is of the order of a few Å [7].

Standard four-point resistivity patterns were defined photolithographically using a lift-off technique. Low-temperature measurements were performed in fields up to 7 Tesla and in the temperature range of $(1.5 \div 10)$ K with a stability of a few mK. All resistive transitions discussed in this paper were measured in a field that was applied parallel to the multilayer surface and had a width smaller than 0.01 K. The critical field H_{c2} was defined as the midpoint of the transition. Other definitions, however, do not change the conclusions presented here.

The temperature dependence of the parallel critical field of a layered superconductor has a distinct signature of its dimensionality and has been exhaustively studied for a number of years [1, 2]. Typically, an anisotropic three-dimensional superconductor ($t > \xi_\perp, \xi_\parallel$) has a linear temperature dependence of $H_{c2\parallel}$ given by

$$H_{c2\parallel}(T) = \frac{\Phi_0}{2\pi} \frac{1}{\xi_\parallel(T)\, \xi_\perp(T)} \tag{1}$$

with $\xi_\parallel(T)$, $\xi_\perp(T) \propto (T_c - T)^{-1/2}$, where Φ_0 is the superconducting flux quantum, t is the superconducting layer thickness, $\xi_\parallel(T)$ and $\xi_\perp(T)$ are the temperature-dependent parallel and perpendicular coherence lengths, respectively. A two-dimensional superconductor ($t < \xi_\parallel$) however exhibits a square-root temperature dependence given by

$$H_{c2\parallel}(T) = \frac{\Phi_0}{2\pi} \frac{\sqrt{12}}{t} \frac{1}{\xi_\parallel(T)}\,. \tag{2}$$

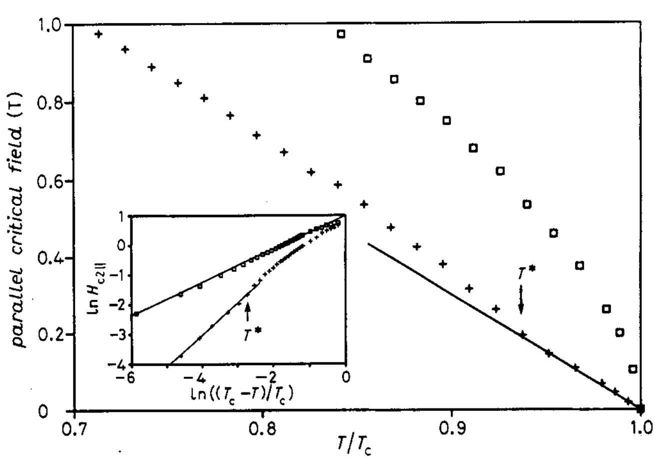

Fig. 1. – Parallel critical field *vs.* reduced temperature for a Pb(220 Å)/Ge(25 Å) (+) and a Pb(220 Å)/Ge(50 Å) (□) multilayer. The solid line emphasizes the linear temperature dependence of $H_{c2\parallel}$ close to T_c of the Pb(220 Å)/Ge(25 Å) multilayer. The inset shows $\ln H_{c2\parallel}$ (in Tesla units) *vs.* $\ln((T_c - T)/T_c)$. The solid lines are a linear fit for the Pb(220 Å)/Ge(50 Å) multilayer (□), with a slope 0.56, and a linear fit to the 3D region of the Pb(220 Å)/Ge(25 Å) multilayer (+), with a slope 1.06.

A multilayer, composed of alternating 2D superconducting layers and nonsuperconducting layers, will have a 2D or 3D behavior depending on the strength of the coupling. As seen in fig. 1 for a Pb(220 Å)/Ge(50 Å) multilayer (open squares), we have a 2D behavior when the Ge layer is thick enough. The inset in fig. 1 shows $\ln H_{c2\parallel}$ *vs.* $\ln((T_c - T)/T_c)$. A linear fit to the data of the Pb(220 Å)/Ge(50 Å) multilayer yields a slope 0.56, indicating its two-dimensional nature. From the measured perpendicular critical field $H_{c2\perp}(T) = \Phi_0/2\pi\xi_\parallel^2(T)$, which is linear in temperature, we can extract $\xi_\parallel(T=0) \simeq 286$ Å. This value confirms the 2D nature of the individual Pb films ($t < \xi_\parallel$). Since the multilayer behaves as a 2D system, we can use eq. (2) to deduce an effective layer thickness. This yields $t = 150$ Å, approximately equal to the Pb layer thickness. Since this effective thickness, which can be correlated with an effective perpendicular coherence length, is smaller than Λ, the multilayer periodicity ($\Lambda = 270$ Å), there is no coupling between the Pb layers.

Decreasing the Ge thickness allows a dimensional transition to be observed in the temperature dependence of $H_{c2\parallel}$, as shown in fig. 1 for the Pb(220 Å)/Ge(25 Å) multilayer (crosses). Close to T_c, $H_{c2\parallel}$ is linear in temperature. A linear fit to $\ln H_{c2\parallel}$ *vs.* $\ln((T_c - T)/T_c)$ indeed yields a slope 1.06 close to T_c (inset). In this 3D anisotropic region, $\xi_\perp/\xi_\parallel$ $(= H_{c2\perp}/H_{c2\parallel}) \simeq 0.14$ and $\xi_\perp(T) > \Lambda$. At T^*, where $\xi_\perp \simeq 0.7\Lambda$, a dimensional transition occurs for the Pb(220 Å)/Ge(25 Å) multilayer towards the 2D, square-root–like temperature dependence of $H_{c2\parallel}$. At low temperatures, as seen in the inset, $H_{c2\parallel}$ of the Pb(220 Å)/Ge(25 Å) multilayer coincides with the critical field of the 2D Pb(220 Å)/Ge(50 Å) multilayer.

The temperature dependence of the fluctuation conductivity above T_c has been predicted by Aslamazov and Larkin [8, 9] to depend on the dimensionality of the system. In 3D the fluctuation conductivity is given by

$$\sigma_{\mathrm{fl}}^{3\mathrm{D}} = \frac{e^2}{32\hbar\xi(0)}\varepsilon^{-1/2}, \tag{3}$$

whereas in 2D

$$\sigma_{\mathrm{fl}}^{2\mathrm{D}} = \frac{e^2}{16\hbar t}\varepsilon^{-1} \tag{4}$$

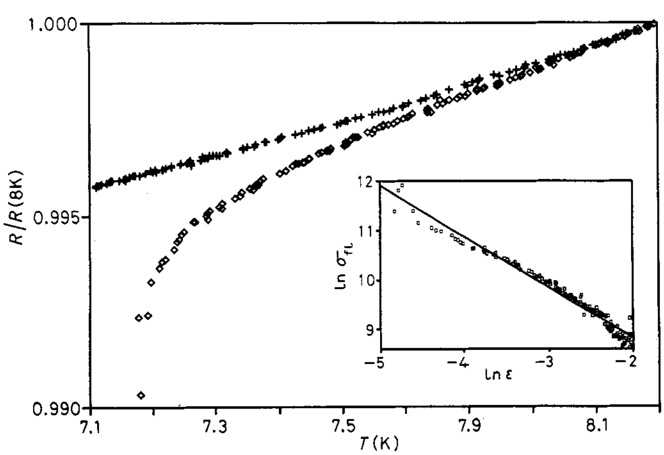

Fig. 2. – Zero field resistive transition of the Pb(220 Å)/Ge(50 Å) multilayer (◇), compared with the normal-state resistance, measured in a 1 T perpendicular field (+). The inset shows $\ln \sigma_{\mathrm{fl}}$ *vs.* $\ln \varepsilon$. The solid line is a linear fit to the data.

with $\varepsilon = (T - T_c)/T_c$. Further theoretical refinements change the detailed numerical values but do not affect the temperature dependence in a major way [9].

In fig. 2 a comparison of the resistivity in zero field (open squares) and a perpendicular field of 1 Tesla (crosses), above $H_{c2\perp}$, for the 2D Pb(220 Å)/Ge(50 Å) multilayer shows the presence of an extra fluctuation conductivity in zero field below $\simeq 8$ K. A logarithmic plot of the extra conductivity *vs.* temperature (see inset fig. 2) confirms the 2D nature of the fluctuation conductivity (*i.e.* linear dependence on ε^{-1}) as given by

$$\ln \sigma_{\mathrm{fl}} = 6.76 - 1.03 \ln \varepsilon$$

with the constant close to the theoretically given value in eq. (4) ($\ln(e^2/16\hbar t) = 6.53$). Variations of the value of T_c by 0.1 K do not change the slope appreciably but result however in more than a doubling of the χ^2 value. In addition we found that the Maki-Thompson correction term is negligible [10, 11].

We expect the fluctuation behavior to be different for the Pb(220 Å)/Ge(25 Å) multilayer. Figure 1 defines the resistive transition from the superconducting to the normal state in the presence of a parallel magnetic field. This resistive transition will have a 2D or 3D character depending on the position of the transition point on this curve. If the transition point is in the 3D linear region (above T^*), we expect 3D superconducting fluctuations to occur. However, in the 2D parabolic part of the phase boundary, we expect 2D fluctuations. A parallel magnetic field simply allows us to move along the phase boundary.

Figure 3 compares the resistive transition in an applied parallel magnetic field $H_{\parallel} = 0.07$ T and $H_{\parallel} = 0.4$ T, with the normal-state resistance, measured in a 1 T perpendicular field. For $H_{\parallel} = 0.07$ T, the transition point is located in the 3D part of fig. 1, whereas $H_{\parallel} = 0.4$ T moves the transition point to the 2D region. Figure 4 shows the logarithm of the extracted fluctuation conductivity *vs.* $\ln \varepsilon$ in the two cases. A least-square fit to the data gives $\ln \sigma_{\mathrm{fl}} = 8.26 - 0.47 \ln \varepsilon$ for the linear part of the curve in the $H_{\parallel} = 0.07$ T case, and yields $\ln \sigma_{\mathrm{fl}} = 7.50 - 1.09 \ln \varepsilon$ when $H_{\parallel} = 0.4$ T. The change in slope from about 1/2 to 1 when applying a larger magnetic field clearly indicates a change in dimensionality. The prefactor is somewhat larger than expected theoretically ($\ln(e^2/32\hbar\xi_{\parallel}(0)) = 5.58$,

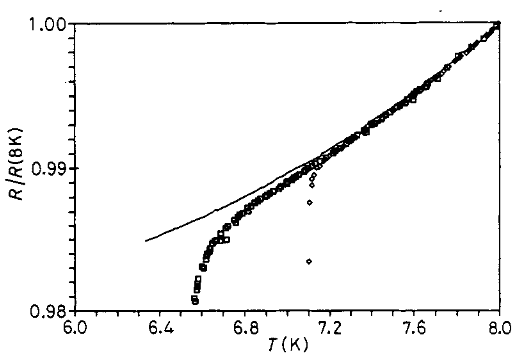

Fig. 3.

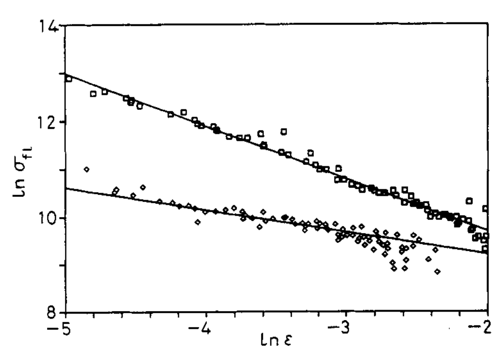

Fig. 4.

Fig. 3. – Resistive transitions of the Pb(220 Å)/Ge(25 Å) multilayer in the 3D region (with $H_{\parallel} = 0.07$ T (◇)), and in the 2D region (with $H_{\parallel} = 0.4$ T (□)). The solid line is the normal-state resistance, measured in a 1 T perpendicular field.

Fig. 4. – $\ln \sigma_{\mathrm{fl}}$ *vs.* $\ln \varepsilon$ for the resistive transitions of the Pb(220 Å)/Ge(25 Å) multilayer, shown in fig. 3. The solid lines are linear fits to the data and have a slope − 1.09 when $H_{\parallel} = 0.4$ T (□) and a slope − 0.47 when $H_{\parallel} = 0.07$ T (◇).

$\ln(e^2/16\hbar t) = 6.53$), but the presence of a parallel magnetic field is known [9-11] to leave the temperature dependence of σ_{fl} unaltered, with $\varepsilon = (T - T_c(H)/T_c(H))$, and an increased prefactor. We also found that all normal magnetoresistive effects are expected and found to be much smaller than the fluctuation conductivities reported here.

In summary, we have shown experimental evidence for a 3D to 2D transition in the fluctuation conductivity of layered superconductors, clearly indicating the decoupling role of the magnetic field. This experiment stimulates theoretical calculations of the magnetic-field dependence of superconducting fluctuations of quasi-2D superconductors.

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