Progress in High Temperature Superconductivity – Vol. 32

Proceedings of the International Conference on

HIGH TEMPERATURE SUPERCONDUCTIVITY AND LOCALIZATION PHENOMENA

Moscow, USSR 11 – 17 May 1991

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DIMENSIONAL CROSSOVER IN Pb/Ge SUPERCONDUCTING MULTILAYERS

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ABSTRACT

We have observed the transition from two dimensional (2D) single film behavior towards coupled 2D or 3D behavior (depending upon the total thickness of the multilayer) in the temperature dependence of the parallel critical field $Hc_{2//}$ of superconducting Pb/Ge multilayers. Measurements of the fluctuation conductivity above the critical temperature T_c confirm this type of crossover.

1.Introduction

Artificially prepared superconducting multilayers, which have different characteristic length scales (thickness, coherence length...), offer an ideal testing ground for the study of dimensional phenomena and dimensional crossovers of physical properties.[1]

In this paper we focus on the dimensional and coupling effects which can be shown by measuring the temperature dependence of the critical magnetic fields Hc_2 and the fluctuation conductivity of Pb/Ge multilayers. The thin superconducting Pb layers of a Pb/Ge multilayer will be coupled or decoupled depending on the ratio of the multilayer period Λ and the perpendicular cohence length. For thick Ge layers, the thin superconducting Pb layers will be decoupled and the properties of the multilayer (critical magnetic field, fluctuations) will be that of a 2D superconductor while for thin Ge layers, the Pb layers will be coupled. When the superconducting layers are coupled, the pertinent length is the total thickness of the multilayer. If this total thickness is smaller than the parallel coherence length, the multilayer will have a 2D coupled behavior. In the other case, the behavior of the multilayer will be 3D. We have measured the upper critical magnetic field of Pb/Ge multilayers in the two cases of 10 bilayers and two bilayers. The aim of this paper is to study these 3D-2D or 2D-2D crossovers. The detail of the fabrication of the multilayers have been described elsewhere[2].

2.Critical parallel magnetic fields

The parallel critical magnetic field $Hc_{2//}$ of an anisotropic three dimensional (3D) superconductor (thickness t greater than the parallel $\xi_{//}$ and the perpendicular $\xi_{\perp}$ coherence length) has a temperature dependence given by

$$Hc_{2//}(T) = \Phi_0 / (2\pi\, \xi_{//}(T)\xi_{\perp}(T)) \qquad (1)$$

where Φ_0 is the superconducting flux quantum. Since $\xi_{//}(T)$ and $\xi_{\perp}(T)$ are proportional to $(T_c - T)^{-1/2}$, this temperature dependence is linear.

A 2D superconductor ($t < \xi_{//}$) however exhibits a square root temperature dependence given by :

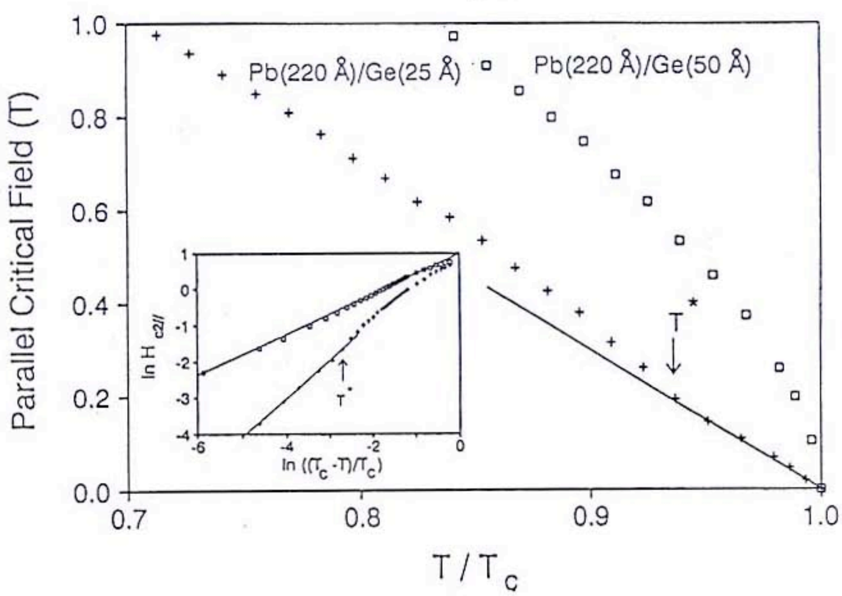
$$Hc_{2//}(T) = \Phi_0\, (12)^{1/2} / (2\pi\, t.\xi_{//}(T)) \qquad (2)$$

2.1. Multilayers with 10 bilayers

When the Ge is thick enough to decouple the Pb superconducting films, the parallel critical field of Pb(220A°)/Ge(50A°) multilayers displays a square root temperature dependence as shown fig 1 indicating a 2D decoupled behavior. The inset of fig 1 shows $\ln Hc_{2//}$ versus $\ln((T_c-T)/T_c)$. A linear fit to the data of the Pb (220A°)/ Ge (50A°) multilayer yields a slope of 0,56 indicating its 2D behavior. From the measured perpendicular critical field $Hc_{2\perp}(T) = \Phi_0 / (2\pi\, \xi_{//}^2(T))$, which is linear in temperature, we can extract $\xi_{//}(T=0) = 286$ A°. This value confirms the 2D nature of the individual Pb films ($t < \xi_{//}$). Using eq (2) we deduce an effective layer thickness t = 150 A° . Since t is smaller than Λ= 270 A°, the multilayer periodicity, there is no coupling between the Pb layers.

Decreasing the Ge thickness allows a dimensional transition to be observed in the temperature dependence of $Hc_{2//}$, as shown in fig 1 for the Pb (220A°) / Ge (25A°) multilayer. Close to T_c, $Hc_{2//}(T)$ is linear in temperature. A linear fit to $\ln Hc_{2//}$ versus $\ln(T_c-T/T_c)$ indeed yields a slope 1,06 close to T_c. (inset). In this 3D anisotropic region, $\xi_{\perp}/\xi_{//} = (Hc_{2\perp}/Hc_{2//})$ is constant and equal to 0,14. At T*, where $\xi_{\perp} \simeq 0{,}7\,\Lambda$, a dimensional transition occurs for the Pb (220A°)/ Ge (25A°) multilayer towards the 2D square root like temperature dependence of $Hc_{2//}$. At low temperatures, as seen in the inset, $Hc_{2//}$ of the Pb(220A°)/Ge(25A°) multilayer coincides with the critical field of the 2D Pb(220A°) / Ge(50A°) multilayer

Fig. 1

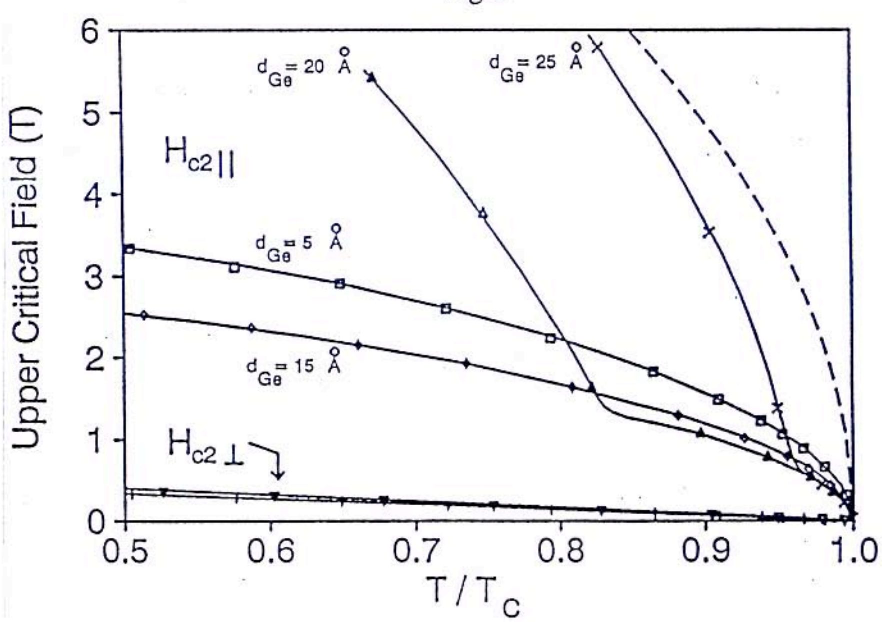


2.2. Multilayers with two bilayers

We have also investigated the upper parallel critical field of Pb/Ge multilayers with a total thickness smaller than the parallel coherence length in order to have always a two dimensional superconducting behavior. To obtain this condition, we have decreased both the number of bilayers (2 bilayers) and the thickness of the films (d_{Pb} = 70A°).

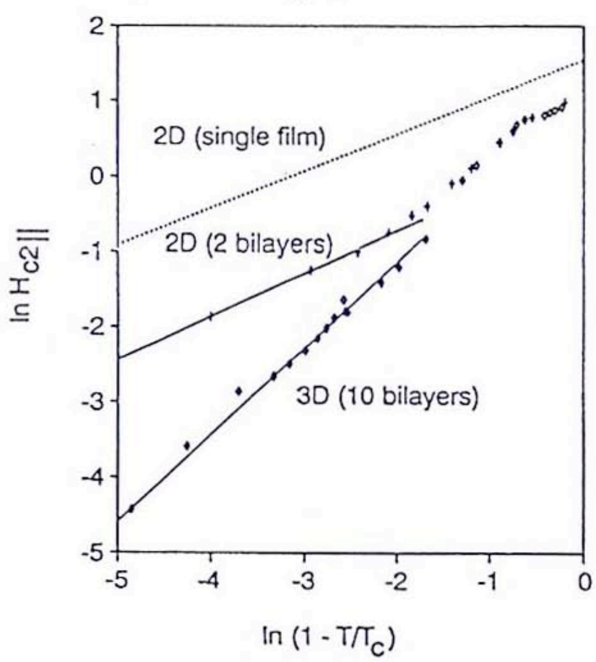
Fig 2 shows the upper critical fields parallel ($Hc_{2//}$) and perpendicular ($Hc_{2\perp}$) to the layers as a function of the reduced temperature T/T_c for a set of Pb/Ge multilayers with d_{Pb} = 70 A° and different d_{Ge}. In the case of small Ge thickness (d_{Ge}= 5 to 15A°), the multilayers are coupled and still have a 2D temperature dependence of $Hc_{2//}$ but with a different amplitude. For sufficiently large Ge thickness (d_{Ge}= 20 to 25A°), the weak interlayer coupling induces a 2D single film behavior at lower temperature. The temperature dependence of $Hc_{2\perp}$ is linear as expected and does not change appreciably with the Ge thickness. From the measured perpendicular critical field we extract the parallel coherence length $\xi_{//}(T=0)$ = 220 A° for all samples. Since $\xi_{//} > d_{Pb}$, the individual films are 2D. Since $\xi_{//}$ is also larger than the sum of the two Pb/Ge bilayer thicknesses ($\xi_{//} > 2\Lambda$) we also expect a 2D behavior for the coupled multilayer. The 2D nature of a superconductor is revealed by expression (2) where t is the effective thickness. As shown in fig. 2 , $Hc_{2//}$ is proportional to (T_c -T$)^{1/2}$ for the multilayer with d_{Ge}= 5A°. The effective superconducting layer thickness t_{eff} = 130 A° as calculated from eq.(2) is approximately equal to 2 Λ = 150 A° indicating that the two Pb layers are coupled through the Ge layer. Since 2 Λ is smaller than $\xi_{//}(0)$, the coupled multilayer behaves as a 2D superconductor. Increasing the Ge thickness initially leads to a decrease of $Hc_{2//}$ for d_{Ge}= 15A°, until for d_{Ge}= 20A° a remarkable upturn of $Hc_{2//}$ occurs at lower temperature. This enhancement indicates a crossover from the parallel critical field of the 2D coupled multilayer close to T_c, to the parallel critical field of a 2D, 70 A° Pb film at lower temperature. It should be noted that $Hc_{2//}$ of the d_{Ge}= 20 A° and the d_{Ge}= 25 A° multilayers has a 2D square root like temperature dependence below as well as above the crossover temperature. This 2D-2D crossover is characterized by a transition from a 2D single film behavior towards a 2D coupled behavior[3]. A further increase of d_{Ge} drives the critical field towards the measured $Hc_{2//}$ value of a 70 A° Pb film sandwiched between two Ge layers (dashed line in fig.2)

Fig.2



The role of the number of bilayers in the problem of dimensionality can be demonstrated when we analyse the temperature dependence of $Hc_{2//}$ for multilayers with a different total thickness. Figure 3 shows ln $Hc_{2//}$ vs ln $(1 - T/T_c)$ for two multilayers with the same Ge thickness (d_{Ge}= 20 A°) and the same Pb thickness (d_{Pb}= 140 A°) but a different number of bilayers. For a Pb (140A°) /Ge (20A°) multilayer with only two bilayers $Hc_{2//}$ α $(1 - T/T_c)^{0.57}$ close to T_c indicating the 2D nature. Since the superconducting effective layer thickness (t_{eff}= 250 A°) is of the same magnitude as the multilayer thickness (2Λ = 320 A°), the two Pb layers are coupled. At lower temperature decoupling occurs and the critical field tends towards the $Hc_{2//}$ of the single 140 A° Pb film (dotted line in fig3). On the other hand, the temperature dependence of $Hc_{2//}$ of a Pb (140 A°)/ Ge (20A°) multilayer with ten bilayers is completely different. At low temperature, the behavior is identical to the decoupled Pb(140 A°)/ Ge (20A°) two bilayer sample. When coupling occurs (close to T_c), $Hc_{2//}$ α $(1 - T/T_c)^{1.15}$ indicating that the coupled ten-bilayer multilayer displays a 3D behavior. The different dimensionality for the coupled ten-bilayer multilayer compared to the coupled two-bilayer multilayer, confirms the importance of the total thickness to determine the effective dimensionality of the system.

Fig. 3



3. Fluctuations

3.1. Multilayers with ten bilayers

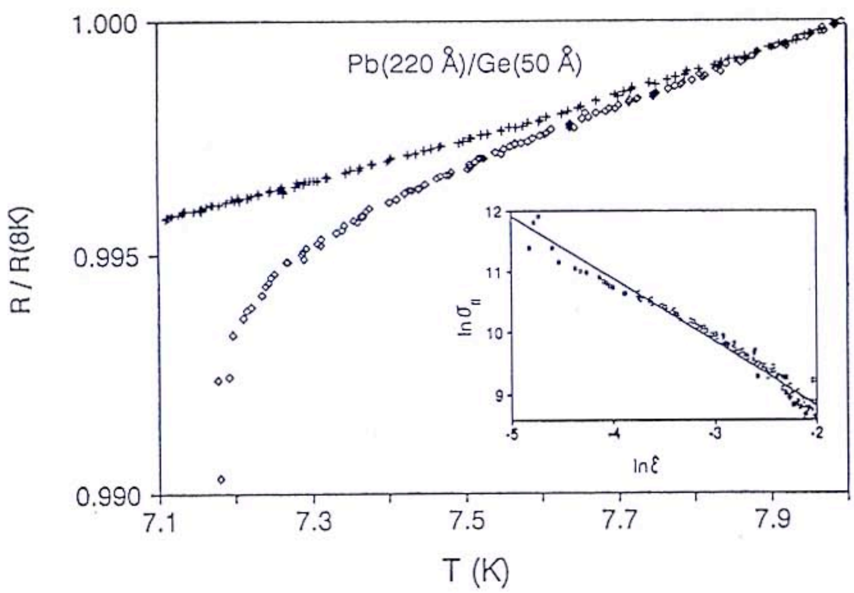
The temperature dependence of the fluctuation conductivity above T_c has been predicted by Aslamazov and Larkin to depend on the dimensionality of the system. In 3D the fluctuation conductivity is given by :

$\sigma_{fl}^{3D} = e^2\ \varepsilon^{-1/2} / (32\hbar\ \xi(0))$ whereas in 2D

$\sigma_{fl}^{2D} = e^2\ \varepsilon^{-1}/(16\,\hbar.t)$ with $\varepsilon = (T - T_c)/ T_c$.

In Figure 4 a comparison of the resistance (normalized to its value at 8 K) in zero field (open squares) and a perpendicular field of 1 Tesla (crosses) above $Hc_{2\perp}$ for the 2D Pb (220A°)/ Ge (50A°) multilayer shows the presence of an extra fluctuation conductivity in zero field above T_c up to 8 K. A logarithmic plot of the extra conductivity versus temperature (inset fig 4) confirms the 2D nature of the fluctuation conductivity (linear dependence on ε^{-1}) as given by $\ln \sigma_{fl} = 6.76 - 1.03 \ln \varepsilon$ (solid line) with the constant close to the theoretically given value $\ln (e^2/16\hbar.t) = 6.53$

Fig.4



We expect the fluctuation behavior to be different for the Pb(220A°)/Ge(25A°) multilayer. Fig. 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.

Fig 5 compares the resistive transition in an applied parallel magnetic field $H_{//}$ = 0.07 T and $H_{//}$ = 0.8 T, with the normal state resistance, measured in a 1T perpendicular field. For $H_{//}$ = 0.07 T, the transition point is located in the 3D part of Fig 1,whereas $H_{//}$ = 0.8 T moves the transition point to the 2D region.

Fig. 6 shows the logarithm of the extracted fluctuation conductivity versus ln ε in the two cases. A least square fit to the data gives $\ln \sigma_{fl} = 7.426 - 0.56 \ln \varepsilon$ for the linear part of the curve in the $H_{//}$ = 0.07 T, and yields $\ln \sigma_{fl} = 8.94 - 1.03 \ln \varepsilon$ when $H_{//}$ = 0.8 T. The change in slope from about 1/2 to 1 when applying a larger magnetic field clearly indicates a change in dimensionality.

Fig.5

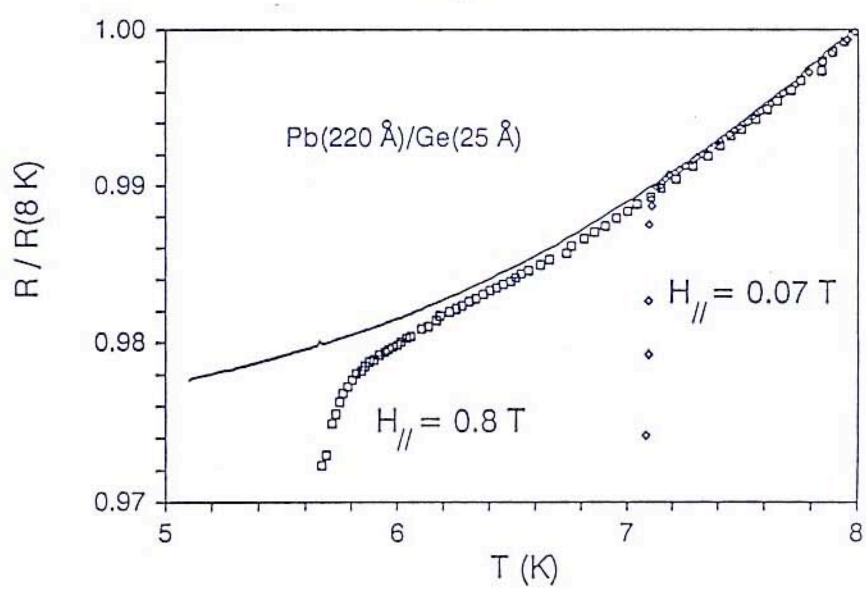
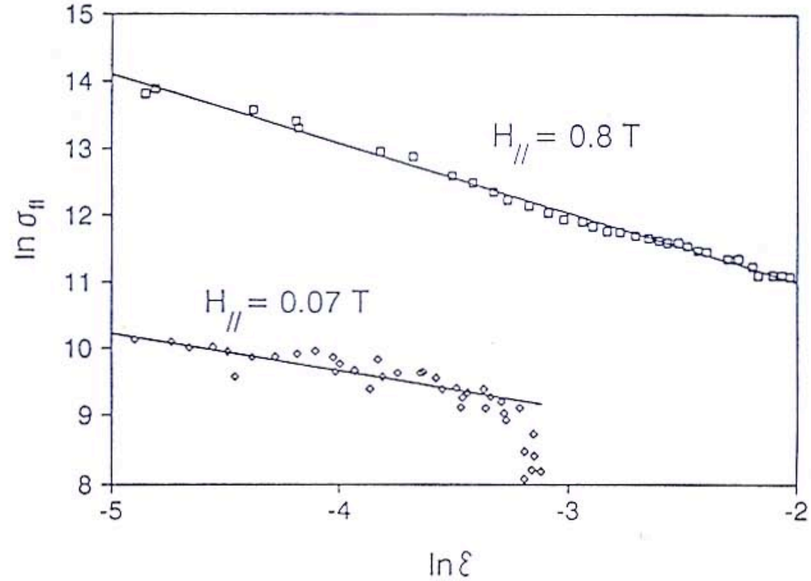


Fig.6



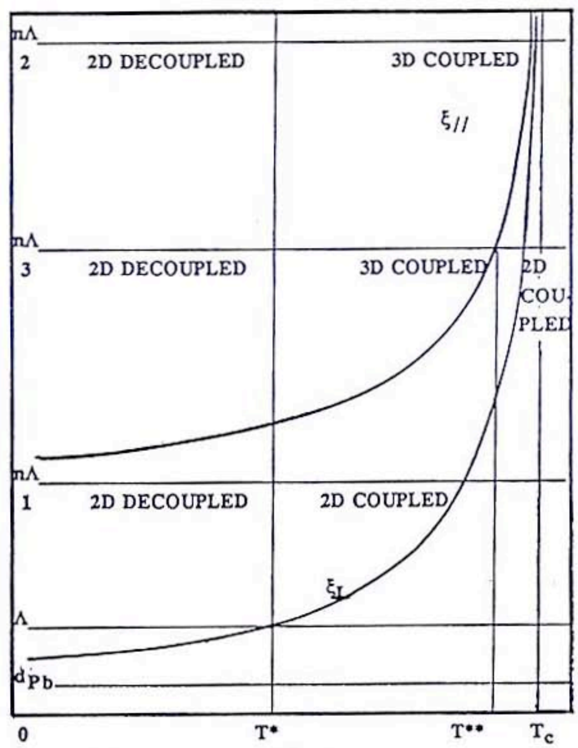
3.2. Multilayers with two bilayers

Similarly, we expect the resistive transition from the superconducting to the normal state for a two-bilayer multilayer in the presence of a parallel magnetic field, to show a 2D fluctuation behavior in both the coupled and decoupled region of the $Hc_{2//}$ (T) phase diagram. We measured σ_{fl} for a Pb (80A°)/ Ge (25A°) multilayer with two bilayers in the presence of a parallel field $H_{//}$ = 0.3 T (coupled region) and $H_{//}$ = 3 T (decoupled region). In both cases, the slope of ln σ_{fl} versus ln ε is approximately -1 indicating that this system is always 2D.

4. Conclusion

The temperature dependent properties of a multilayered system consisting of N two dimensional superconducting layers of Pb ($d_{Pb} < \xi_{//}$) separated by layers of Ge will have different dimensionality (Figure 7). At temperatures below T*, the multilayers are decoupled and as the Pb layers are thin they are 2D. At temperatures above T*, the layers are coupled and two possibility can occur: the structure can be 2D coupled or 3D coupled. Increasing the temperature from low temperatures to T_c, the properties will present a crossover from a 2D decoupled to a 2D coupled system in the case of total

Fig.7



thickness n Λ (line 1) smaller than the parallel coherence length. In the other case (line 2) of thick multilayer we will have a crossover from a 2D decoupled to a 3D coupled superconducting behavior. There is an other possibility (line 3) for an intermediate thickness of the multilayer. This case has not yet been reported . It is a crossover from a 2D decoupled to a 3D coupled structure at a temperature T* and then becoming 2D coupled at T** near the critical temperature. This case will be investigated in the near future.

5. References

1.For a recent review see for instance I.K.Schuller, J.Guimpel and Y. Bruynseraede. *Mat. Res. Soc. Bull..* XV, 29, (1990).

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