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SOFTENING OF THE FLUX LINE LATTICE IN Ge/Pb MULTILAYERS

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ABSTRACT

We measured the critical current density J_c of artificially grown Ge/Pb multilayers as a function of the magnetic field $H_\perp$ applied perpendicular to the layers. In these layered structures $J_c(H_\perp)$ rapidly drops to a pronounced minimum at a field $H_\perp^*$, then increases through a broad maximum and finally decays to zero at $H_{c2\perp}$. The systematic evolution of this minimum as a function of temperature, layer thickness and pinning strength allows us to conclude that this peculiar behavior is due to a thermally driven softening of the flux line lattice which can be related either to a magnetic decoupling or a melting of the vortex structure.

INTRODUCTION

One of the most intriguing properties of the high T_c superconductors is the presence of a new phase boundary below $H_{c2}(T)$ in the H-T diagram [1]. To explain the origin of this phase boundary, above which the magnetization is reversible, several new models have been proposed based on a quasi de Almeida - Thouless line [2], vortex depinning by thermal fluctuations [3], or melting of the flux line lattice [4]. Within the melting models an additional reentrant vortex fluid phase at much lower fields was also predicted.

Many of the theoretical ideas rely on the layered nature of high T_c superconductors and describe the Flux Line Lattice (FLL) as a superposition of two-dimensional pancake vortices. This stirred a renewed interest in the properties of the FLL in artificially layered low T_c superconductors. In the latter systems it is possible to vary not only the superconductor layer thicknesses and properties, but also the interlayer coupling and hence also the anisotropy, making the artificial multilayers attractive candidates for providing valuable information about the FLL behavior and structure.

In this paper we report on an anomalous dependence on the perpendicular field $H_\perp$ of the critical current density J_c for artificially grown Ge/Pb superlattices. The J_c behavior is strongly dependent on the multilayered nature of the material, interlayer spacing, pinning strength and temperature, and can be explained in terms of a softening of the FLL. The anomalous behavior points towards the existence at low fields ($H_\perp \gtrsim H_{c1\perp}$) of a possible new phase boundary in the H-T plane. The origin of this boundary can be related either to a magnetic decoupling or to a melting of the FLL.

EXPERIMENTAL

The multilayered $[Ge/Pb]_n Ge$ structures, where n denotes the number of bilayers and the final Ge film is a 500 Å protective layer, were grown onto liquid nitrogen cooled SiO_2 substrates using a Molecular Beam Epitaxy system with electron beam guns controlled by a mass spectrometer. Since the Ge-Pb system does not form any intermetallic compound, layered structures with sharp interfaces can be grown, as confirmed by extensive X-ray diffraction studies [5].

A commercial SQUID system (Quantum Design) was used to measure the magnetic hysteresis loops from which $J_c(H_\perp)$ was estimated using Bean's model. In order to determine the absolute J_c values, several samples were patterned by combining lift-off techniques and electron beam lithography. From the measured I-V curves, J_c was determined using a 4.4 μV/cm criterion and using the total Pb cross sectional area of the multilayer. The shape and the position of the minimum in the critical current extracted from the magnetization experiments are in excellent agreement with the transport data.

RESULTS AND DISCUSSION

Fig. 1 shows the resistively measured J_c at T=4.2 K for a single Pb film (i.e. a Ge(60 Å)/Pb(140 Å)/Ge(500 Å) sandwich) and for two $[Ge(60\ Å)/Pb(140\ Å)]_n$ multilayers with n=5 and n=10. An increasing number of Ge/Pb bilayers clearly induces a pronounced minimum in the $J_c(H_\perp)$ curve at a field $H^*_\perp$. This field is not only thickness but also temperature dependent as shown in Fig. 2 where J_c, obtained from transport measurements and normalized by J_c(50 G) (the lowest measured field in this case), is plotted as a function of $H_\perp$ for a $[Ge(60\ Å)/Pb(140\ Å)]_{10}$ multilayer. At sufficiently low temperatures ($T < 2$ K) the minimum in the $J_c(H_\perp)$ curve disappears as shown in Fig. 3 for a $[Ge(50\ Å)/Pb(140\ Å)]_5$ multilayer. We note that similar effects on the $J_c(H_\perp)$ behavior were observed in the magnetization measurements of much thicker $[Ge/Pb]_{50}$ multilayers, indicating that this peculiar behavior is not an artefact caused by the measuring technique.

We also investigated the effect of the pinning strength on $J_c(H_\perp)$ by adding Bi to the Pb layers. The results are shown in Fig. 4 where we plot $J_c(H_\perp)$ at T=4.2 K measured resistively for a $[Ge(50\ Å)/Pb(100\ Å)]_{10}$ and a $[Ge(50\ Å)/Pb_{0.85}Bi_{0.15}(100\ Å)]_{10}$ multilayer. The increase in pinning strength suppresses the minimum in $J_c(H_\perp)$.

Our experimental results clearly indicate not only that the field $H^*_\perp$ at which the minimum occurs is a function of temperature but also that the increasing pinning and decreasing temperature play a similar role for the disappearance of the minimum. We conclude that any matching effect between the FLL and the array of pinning centers within the individual Pb layers is to be ruled out as a possible mechanism for the development of the non-monotonous shape of $J_c(H_\perp)$ and that thermal fluctuations play a relevant role. We therefore argue that the minimum in $J_c(H_\perp)$ is probably due to a thermally driven softening of the FLL, indicating that at $H^*_\perp$ the vortex lattice goes through a structural transition. Two different mechanisms may lead to this softening: a) a magnetic coupling/decoupling transition which transforms the 3D FLL at low fields ($H_\perp < H^*_\perp$) into a system of stacked 2D pancake vortex lattices in each Pb layer; b) a melting of the 3D FLL due to an exponential decay of the vortex-vortex interaction at low fields rendering the FLL highly unstable to thermal fluctuations. In Fig. 5 we summarize our experimental findings in an H-T phase diagram where the full line through the $H^*_\perp$ data points is only a guide to the eye. The inset shows a more detailed view of $H_{c2\perp}$ as a function of temperature. We point out that the variation of $H^*_\perp(T)$ has been qualitatively predicted within the framework of a melting model [4]. Whether there really occurs a phase transition or not is not clear at this moment and further experiments are in progress to elucidate the exact mechanism responsible for the observed $J_c(H_\perp)$ behavior.

In conclusion, we have shown that the critical current density $J_c(H_\perp)$ in Ge/Pb multilayers exhibits an anomalous field and temperature dependence. This anomaly gives rise to a new line at low fields in the H-T phase diagram, indicating the existence of a possible new phase transition in the structure of the FLL at low perpendicular applied fields.

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FIGURE CAPTIONS

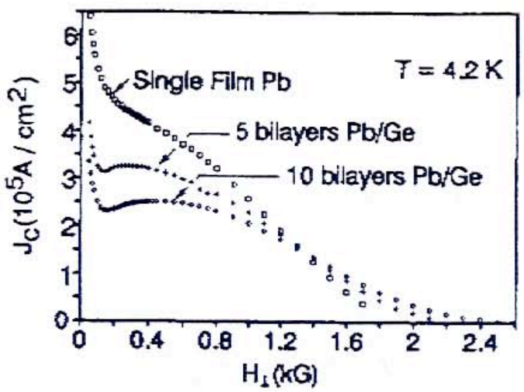
Fig. 1 $J_c(H_\perp)$ for a single Pb film and two [Ge/Pb] multilayers

Fig. 2 $J_c(H_\perp)$ for a multilayer at various temperatures

Fig. 3 Comparison between high and low temperature behavior

Fig. 4 Effect of pinning strength on $J_c(H_\perp)$

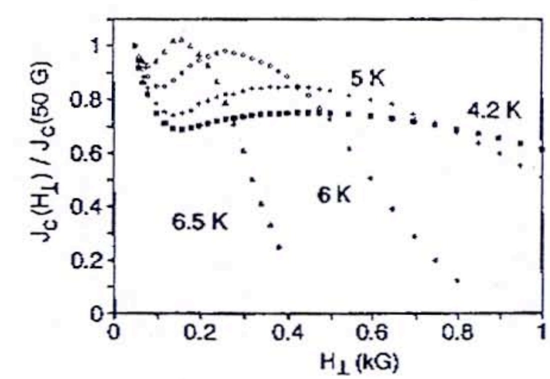
Fig. 5 The H-T phase diagram. The inset shows $H_{c2\perp}(T)$



Single Film Pb
T = 4.2 K
5 bilayers Pb/Ge
10 bilayers Pb/Ge
Jc(10^5A / cm2)
H⊥(kG)
0
1
2
3
4
5
6
0
0.4
0.8
1.2
1.6
2
2.4

Fig. 1

Fig. 2



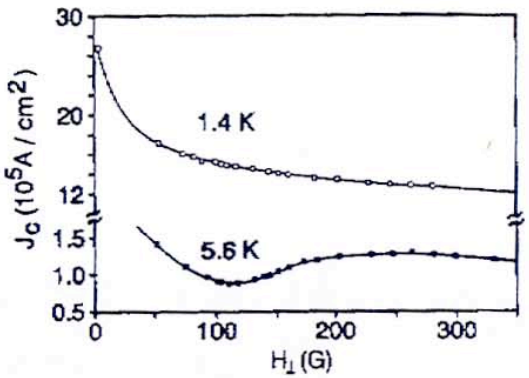


Fig. 3

Fig. 4

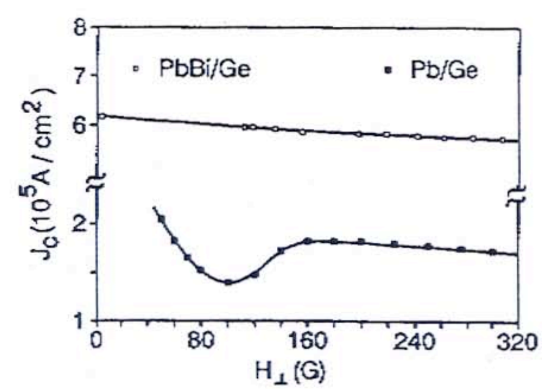


Fig. 5