Localization of order parameter on network of mismatch dislocations of PbTe–PbS superconducting superlattices

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Structural features associated with two types of dimensional transitions have been detected for the first time on the temperature and angular dependence of the upper critical field, $H_{c2}(T,\theta)$ (θ is the angle between the magnetic field and the plane of the supperlattice), and on that of the critical current, $I_c(T)$, for model samples of layered superconductors. These structural features are evidence of a localization of the order parameter.

The temperature dependence of the upper critical field parallel to the layers in layered compounds in the superlattices, $H_{c2}^{\parallel}(T)$, shows evidence of a 3D–2D dimensional crossover upon the localization of the superconductivity in the layers with the higher critical properties.[1] For metal superlattices with layers differing markedly in diffusion coefficient, the theory of Ref. 2 predicts an additional slope change on the temperature dependence of the longitudinal ($H_{c2}^{\parallel}$) and transverse ($H_{c2}^{\perp}$) magnetic fields in the 2D region, associated with a displacement of the superconducting nucleating region toward the layers with the higher value of H_{c2}. This effect has been observed in Nb–Ti and Nb–Ta superlattices.[3,4] A recent study of the angular dependence $H_{c2}(\theta)$ of superconducting superlattices revealed the conditions under which structural features can appear on the temperature dependence of the parameter $\varphi(T) = (1/H_2)\times(dH_{c2}/d\theta)|_{\theta=>0}$ (θ is the angle between the magnetic field and the plane of the superlattice).[5] The discovery of high T_c superconductivity has stimulated more-active research on the properties of superconducting superlattices, as models of layered superconductors.[1,6,7]

In the present letter we report the first observation of oscillations on the temperature dependence of the parameter $\varphi(T)$ of PbTe–PbS superconducting superlattices,[6,7] as predicted in Ref. 5. We are also reporting data on the appearance of some new structural features on the $H_{c2}^{\parallel}(T)$, $H_{c2}^{\perp}(T)$ and $I_c(T)$ curves in the 2D region.

The samples were prepared in an oil-free vacuum of 10 Pa under the conditions described in Refs. 6 and 7. Under these conditions, ordered networks of mismatch dislocations form at the interfaces of the PbTe and PbS layers. These dislocations are responsible for the appearance of superconductivity, which is not observed in single PbTe or PbS monolayers.[6,7] The period of the superlattice, $D = d_{\text{PbTe}} + d_{\text{PbS}}$, was varied over the interval 21–71 nm; the number of periods was $N \leqslant 10$ (the PbTe and PbS layers were of approximately the same thickness). The field H_{c2} was determined at the resistance level $0.5R_n$, where R_n is the residual resistance at $T > T_c$ [a determin-

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ation of H_{c2} at some other level of R_n would cause no qualitative change in the shape of the $H_{c2}(T)$ curves]. A preliminary study revealed that the highest values, $T_c = 5.5$ K, are exhibited by superlattices with D on the order of 35 nm and that the minimum structural unit for which a superconductivity with T_c up to 5.3 K is observed is a three-layer PbS–PbTe–PbS sandwich (with two interfaces). In a two-layer PbS–PbTe sandwich (a single interface), there is no superconductivity at $T_c > 1.5$ K, although electron microscopy reveals that the structure of the interface (the quality of the network of mismatch dislocations) and that of the layers are not different from the structure of the three-layer sandwich. This result confirms the suggestion by Dzyaloshinskiĭ and Kats[8] that the long-range order is suppressed in a 2D layer because of quantum fluctuations in the phase of the wave function and that this long-range order is restored even when there is a slight interaction of at least two such layers. With increasing N, the T_c of the superlattices increases, but it becomes essentially constant at $N > 10$. The critical temperature decreases as D is increased or reduced from 35 nm.

Figures 1(a) and 1(b) show $H^{\parallel}_{c2}(t)$ and $H^{\perp}_{c2}(t)$ $(t = T/T_c)$ for superlattices with $N = 10$ and various values of D (curves 1–4) and also for a three-layer sandwich (curve 5). The residual conductance of sample 4 is higher than that of sample 1 by a factor of 2.5, and the corresponding value of T_c is higher by a factor of 1.8, because of the better properties of the layers of the semiconductors making up the superlattices.

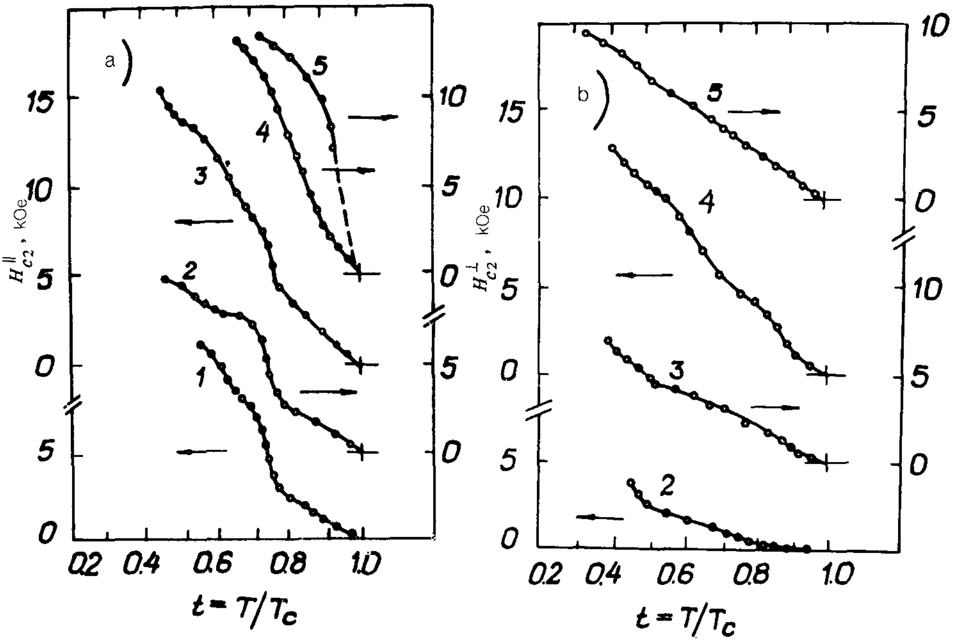

FIG. 1. Temperature dependence of (a) the longitudinal upper critical field $H^{\parallel}_{c2}$ and (b) the transverse upper critical field $H^{\perp}_{c2}$ of PbTe-PbS superlattices with various periods: 1—35 nm, $T_c = 3$ K; 2—71 nm, $T_c = 3.3$ K; 3—31 nm, $T_c = 4.5$ K; 4—35 nm, $T_c = 5.5$ K; 5—three-layer PbS-PbTe-PbS sandwich (17-18-17) nm, $T_c = 5.3$ K.

Note that near T_c the curves of $H_{c2}(t)$ are essentially linear; the slope of the curves, $dH_{c2}(t)/dt$, changes sharply and goes through extrema near $t = 0.9, 0.8, 0.7, 0.6$, and 0.5. The first sharp bend in $H_{c2}(t)$ for the superlattice corresponds to a transition from a 3D region to a 2D region, in the course of which the coherence length $\xi^{\perp}(T)$ becomes smaller than D, and the order parameter localizes in the semiconductor layers with the high critical properties (the PbTe layers primarily determine the conductance of the superlattices[7]). For the three-layer sandwich (curve 5), we see only the 2D behavior at $T < T_c$.

For all superlattices studied, the value of $\xi^{\perp}$ at the 3D–2D transition is in the interval 14–20 nm. This result is evidence that the superconducting nucleating region is localized in a layer of roughly the same scale in a magnetic field. Estimates of the thickness of the superconducting layer on the basis of the Tinkham formula[9] for a thin film also yield values of 10–15 nm near the transition. A superlattice with a larger period may be thought of as consisting, in a sense, of a set of three regions: "insulating" layers of PbS, regions of PbTe with an induced superconductivity, and a highly deformed layer of thickness d near the network of mismatch dislocations. This layer is responsible for the appearance of the superconductivity.[7] At $2d > d_{\mathrm{PbTe}}$ the strain fields of the network of mismatch dislocations overlap greatly, and the PbTe layer, bracketed by two networks of mismatch dislocations, may be thought of as a single superconducting layer which is interacting with neighboring PbTe layers through PbS interlayers by virtue of a proximity effect. We would expect the optimum values of T_c to be exhibited by the superlattices with $d_{\mathrm{PbTe}} \sim 2d_s \sim 17$ nm, and this is what is found experimentally.

Additional information about the nature of the localization of the order parameter was extracted from measurements of $H_{c2}(\theta)$ at various temperatures. It turned out that at small values of θ, satisfying the condition $\sin\theta/\cos^2\theta < HD/2\pi\Phi_0$ ($\Phi_0 = \mathrm{c}\hbar/2e$), the dependence $H_{c2}(\theta)$ in the $2D$ region, beyond the linear regions of the $H_{c2}(T)$ curves, can be described well by a modified version of the Tinkham formula,[9] which differs from the usual version for a thin film in a renormalization of the perpendicular critical field: $\widetilde{H}^{\perp}_{c2} H^{\perp}_{c2} (\widetilde{T}_c - T)/(T_c - T)$ (the Glazman formula[10]). The temperatures $\widetilde{T}_c$ calculated from the $H_{c2}(\theta)$ curves agree well with the temperatures of the 3D–2D crossover on the curve of $H^{\parallel}_{c2}(T)$, and the parameter $\varphi(T)$ exhibits the oscillations [Fig. 2(a)] predicted in Ref. 5.

The temperature dependence of the critical current, $I_c(T)$ (we measured the current which caused the appearance of a voltage of $10\,\mu V$ across the potential terminals), also reflects these anomalies in the $H_{c2}(T)$ behavior [Fig. 2(b)].

The series of structural features on the curves of $H_{c2}(T)$, $\varphi(T)$, and $I_c(T)$ in the 2D region apparently reflect corresponding anomalies on the temperature dependence of the superconducting energy gap and that of the differential resistance of these superlattices at low temperatures.[7] We believe that these structural features are associated with the circumstance that as the magnetic field is increased, and the temperature lowered, in the 2D region there is a localization of the order parameter, first in the PbTe layers and then in the neighborhood of the dislocation networks at the interface between the PbTe and PbS layers. These events are followed by a localization at the nodes of the dislocation network. In view of the quasi-2D nature of high-T_c supercon-

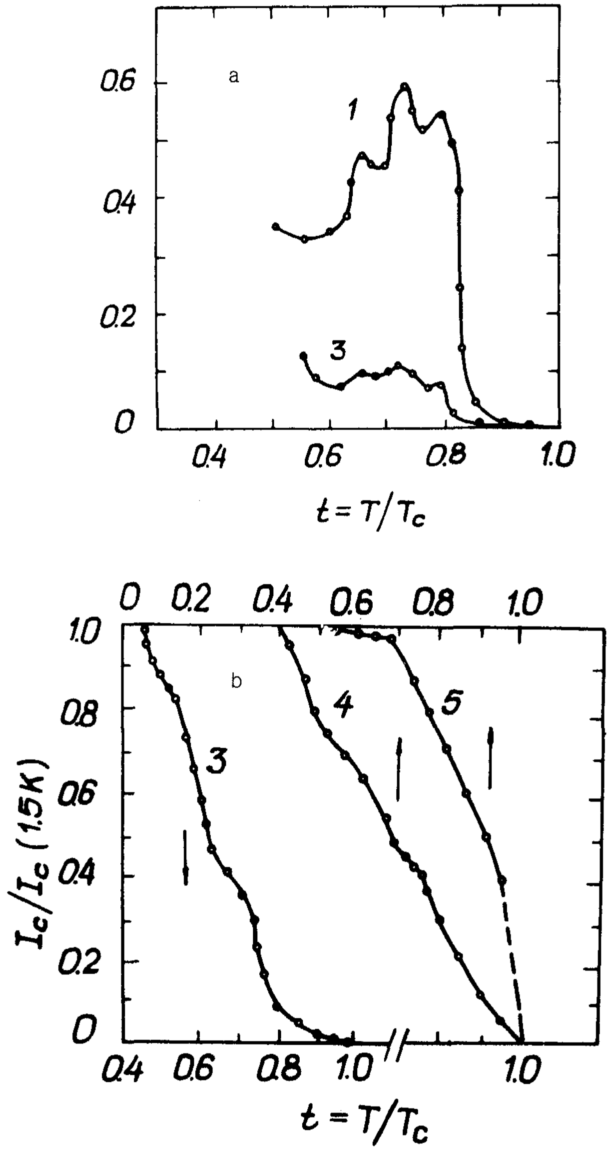

FIG. 2. Temperature dependence of (a) the parameter $\varphi(T) = (1/H_{c2}) \times (dH_{c2}/d\theta)|_{\theta \to 0}$ and (b) the critical field I_c of PbTe–PbS superlattices (the samples are numbered in accordance with the Fig. 1 caption).

ductivity, one might predict that anomalous structural features similar to those which we have observed will be found on the curves of $H_{c2}(T,\theta)$. Such features have already been seen in a study of $I_c(T)$ in the same regions of the parameter t (Refs. 11 and 12).

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