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THE STRUCTURE AND GALVANOMAGNETIC PROPERTIES OF THE PLANAR EPITAXIAL SUPERLATTICES OF LEAD CHALCOGENIDES*

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The crystal structure and galvanomagnetic properties of superlattices (SL) of lead chalcogenides with and without misfit dislocation grids at the layer interfaces have been investigated. The SLs with misfit dislocation grids exhibit superconductivity and 3*D*-2*D* crossover in temperature and angle dependences of the second critical magnetic field. The oscillating dependence of critical current on the parallel magnetic field has been detected in the region of 2*D* behaviour.

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Interest to the superlattices (SL) of $A^{IV}B^{VI}$ compounds is motivated both by the peculiarities of an electron energy spectrum of two-dimensional semiconductor systems and by the potentialities of creation of novel infrared photodetectors and sources on their base. The quantum-size effects at a photoluminescence spectrum of SLs of lead chalcogenides grown on BaF_2 was observed [1]. The SL of lead chalcogenides with regular misfit dislocation (MD) grids at layer interfaces is a new type of semiconductor SL with almost unknown galvanomagnetic properties.

The lead chalcogenides are narrow-gap semiconductors which exhibit superconductivity at the critical temperature $T_c < 2.0$ K under high pressure or when heavily doped with Tl [2]. Epitaxial films of such chalcogenides are extremely adaptable to technological processing and can serve as convenient models for high-temperature superconductors (HTSC) being their structural analogs: the lead atoms are located in the centres of octahedrons of eight chalcogen atoms like the copper atoms are in the centres of octahedrons of eight oxygen atoms in $Ba_2Cu_3O_7$. The layered nature of HTSC can be modeled easily

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by means of SLs of epitaxial thin layers deposited sequentially one upon the other in oil-free vacuum 10^{-5} Pa. By choosing a pair chalcogenides and by varying their layer thickness it is possible to create both homogeneous elastic strains due to pseudomorphism of layers and nonhomogeneous elastic strains of MDs at the layer interfaces [3]. The periodical square grids of edge MDs with a period of 13 nm (PbSe-PbS), 8.6 nm (PbTe-PbSe) or 5.2 nm (PbS-PbTe) in the SLs grown on (OOI)KCl model two-dimensional structure features of HTSC, which are presumably responsible for the initiation of superconductivity (SC). To clear up the role of the structural features in the explanation of SC the SLs of PbTe-PbS, PbTe-PbSe and PbS-PbSe were synthesized on the surface of (OOI)KCl where the lead chalcogenides grow in a layer-by-layer mode (by Frank van der Merwe mechanism) and on (III)BaF_2 where the growth occurs by the Volmer-Weber island mechanism without the formation of MDs at the interfaces of multilayer structures. The periodicity and the regularity of SLs were checked on the basis of satellite reflections on X-ray diffraction patterns. The error in the determination of layer thicknesses was not worse than 0.1 nm. The control single-layer films with thicknesses equal to the total thicknesses of all the corresponding layers of SL were also grown for comparison with SLs. In studies of the temperature dependence of electrical conductivity $\sigma(T)$ the superconducting transitions at $T < 6.0$ K were observed only in the SLs on (OOI)KCl in contrast with the analogous SLs on (III)BaF_2 and the control single-layer films of lead chalcogenides [3]. Single-layer and multilayer films of lead chalcogenides tend to metal-dielectric transitions observed for HTSCs [3]. Further evidences in favour of superconductivity are the following: 1) the absence of Hall voltage U_H for SL samples in weak magnetic fields $H < H_{c1}$, H_P where H_{c1} is the first critical magnetic field; H_P is the magnetic field of break loose of pinning of magnetic whirls; 2) the existence of a "frozen-in" magnetic flux B_f at $H = 0$ and $T < T_{c1}$, when the sample was cooled down at $H \neq 0$ ($H > H_{c1}$(T); 3) the appearance of hysteretic electrodynamic effects observed during measuring magnetoresistance in perpendicular $\Delta R^{\perp}(H)$ and parallel $\Delta R''(H)$ magnetic fields (Fig. 1b and Fig. 1c, respectively) at $H > H_{c1}$. From the observation of the relaxation of B_f the value $\sigma_{SC} > 10^{15}$ ohm^{-1} cm^{-1} at $T < T_c$ was estimated. In studies of the temperature dependences of magnetoresistance hysteretic effects it was possible to evaluate a dependence $H_{c1}(T)$. It was found that the highest values of $T_c = 5.5$ –4.3 K were exhibited by the SLs of PbTe–PbS/(OOI)KCl with a period $D = 35$ nm. T_c depended on value D and number N of the periods of SL. SC appeared at $N = 1.5$ (a three-layer film with two interfaces). T_c grew with an increase of N being saturated at $N \geqslant 10$ and lowered both with an increase and a decrease of D relatively to its optimum value $D = 35$ nm. The average Hall concentration of electrons in such SLs was $n_H = (1\text{–}5) \cdot 10^{11}$ cm^{-3}, while their mobility did not exceed 300–600 cm^2/(v · s). It should be noted that the value of σ of these SLs near SC transition was similar to the value $\sigma = (1\text{–}4) \cdot 10^3$ ohm^{-1} cm^{-1} of HTSCs. The observed decrease in T_c with an increase in the electron mobility may evidence in favour of the existence of SC resonance scattering effects like those revealed in p-PbTe doped with Te [2]. Earlier from the analysis of the temperature dependences of second critical magnetic field $H_{c2}(T)$ with regard to its anisotropy relative to the SL plane it was supposed that SC in the SLs of the lead chalcogenides had quasi-two-dimensional nature [3, 4]. The temperature dependences of $H_{c2}^{\parallel}(T)$ of SLs

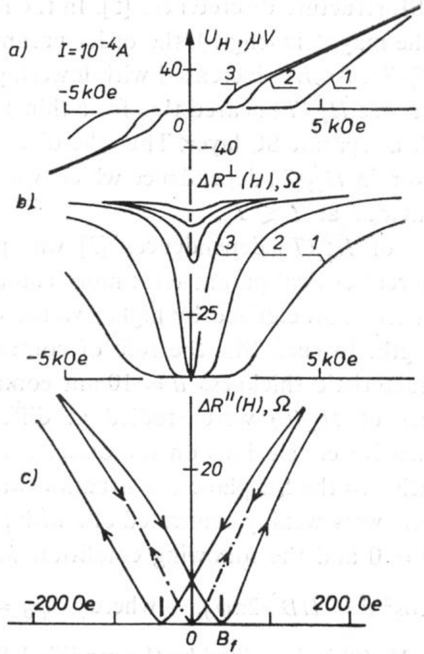

Fig. 1. The field dependence of Hall voltage U_H (a), perpendicular $\Delta R^{\perp}$ (b) and parallel $\Delta R^{\parallel}$ (c) magnetoresistance of a superlattice grown on (001)KCl. Curves *1*, *2* and *3* are measured at 3.8, 2.9 and 1.8 K, respectively

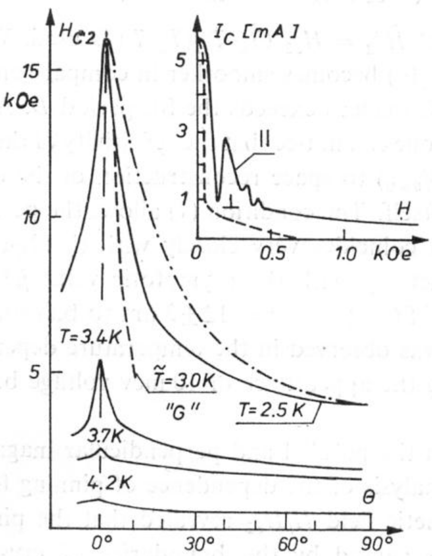

Fig. 2. The dependence of second critical field H_{c2} on angle between the magnetic field direction and the superlattice plane. Number of periods $N = 10$; layer thicknesses: PbS — 16 nm and PbTe — 15 nm. The field dependence of the critical current on the parallel and perpendicular magnetic field for the same superlattice is shown on the inset

were determined from the SL structure discreteness [5]. In the region of small H ($L_H > D$, where $L_H = (c\hbar/eH)^{1/2}$ is the magnetic length), the order parameter changed weakly from layer to layer and $H_{c2}^{\parallel} \sim (T_c - T)$. As $H_{c2}^{\parallel}$ increased with lowering T the relation D/L_H grew and the temperature dependence $H_{c2}^{\parallel}(T)$ neared that for a thin film $H_{c2}^{\parallel} \sim (T_c - T)^{1/2}$, when a nucleus was located inside a separate SC layer. Thus the discreteness of the SL structure resulted in 3D–2D crossover in $H_{c2}^{\parallel}(T)$ dependence which was absent in the three-layer system with pure 2D behaviour at $T \lesssim T_c$.

The positive curvature of $H_{c2}^{\perp}(T)$ dependences [3] was presumably caused by the presence of layers with different critical parameters: more contaminated layers with lower T_c due to 2D fluctuations were characterized by higher values of $\partial H_{c2}^{\perp}/\partial T$ in consequence of smaller electron-free length. In such SLs the role of contaminated layers was played by 2D planes with a characteristic thickness $d = 10$ nm containing the MD grids.

The angle dependences of $H_{c2}(\theta)$ were studied at different temperatures $T < T_c$ (Fig. 2) for more comprehensive conclusions on the discreteness of the SC properties of SLs. At small angles θ relative to the SL plane the situation was still 2D, when SC nuclei in the neighbouring SC layers were weakly connected one with another across a SL normal layer like in the case of $\theta = 0$ and the following condition was satisfied

$$\sin\theta/\cos^2\theta \leqslant HD^2/2\pi\phi_0, \quad \text{where} \quad \phi_0 = \mathrm{ch}/2e. \tag{1}$$

In this case the dependence $H_{c2}(\theta)$ is described by the modified Tinkham formula (Glazman formula [5])

$$\left(\frac{H_c \cos\theta}{H_{c2}^{\parallel}(T)}\right)^2 + \frac{H_c \sin\theta}{H_{c2}^{\perp}(T)} \cdot \frac{T_c - T}{\tilde{T}_c - T} = 1, \tag{2}$$

where new normalization of $\tilde{H}_{c2}^{\perp} = H_{c2}^{\perp}\,(\tilde{T}_c - T)/(T_c - T)$ is used. When the condition (1) is violated the dependence $H_{c2}(\theta)$ becomes smoother in comparison with the region of small θ because the size of the SC nucleus exceeds the SL period D. All these features are seen distinctly in Fig. 2 in which one can notice that the sensitivity of the temperature dependence of parameter $\beta = (\partial H_{c2}/\partial\theta/_{\theta=0})$ to space reconstruction of the order parameter is larger than the sensitivity of H_{c2} itself. The condition (1) allows the period of SL to be estimated as $D = 31 \pm 1.0$ nm, which coincides very closely with the X-ray data for this sample. The comparison of parameter β with the asymptotic value $\beta^* = (3\phi_0/\pi d^{*2})$ of theory [5] enables the thickness of SC layers $d^* = 12 \pm 3$ nm to be estimated for these SLs.

Analogous crossover was observed in the temperature dependence of critical current of SLs (the current causing the appearance of 10 mcv voltage between potential contacts was measured).

The behaviour of I_c in the parallel and perpendicular magnetic field was not trivial (see the inset in Fig. 2). Analysis of the dependence of pinning force $F_p \sim |\vec{I}_c \times \vec{H}|$ on the value of the reduced magnetic field H/H_{c2} revealed that the pinning of a perpendicular magnetic field ($\vec{H} \perp \vec{I}$) was caused by the boundaries of crystal fragments with size 200–300 nm and a dislocation density 10^9 cm^{-2}. The estimate of distances between the magnetic whirls in the field $H^{\perp}$ corresponding to maximum F_p was in accordance with this assumption.

Oscillating behaviour of $I_c(H)$ at $T = 1.7\,\mathrm{K}$ and $\vec{H} \parallel \vec{I}$ was connected with the pearance of an ordered whirl lattice commensurable with the SL period (presumably, agnetic whirls have nonabrikosov's nature).

Thus the results of this paper evidence that superconductivity of SLs based on lead halcogenides has two-dimensional character with weak bonds between superconducting layers and occurs as a result of the presence of square grids of MDs at interfaces. High T_c of such SLs in comparison with traditional semiconductors, the existence of quasi-two-dimensional layered structure of a perovskite type and low electron concentration $n_x = 10^{19}\ \mathrm{cm}^{-3}$ make possible the appearance of noncommon mechanisms of SC discussed actively recently in connection with high temperature superconductivity.

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