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Semiconducting chalcogenide multilayers: structure and superconductivity

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Abstract

Superconducting properties study, X-ray diffractometry and TEM investigations of the structure have been carried out on rather exotic superconducting multilayers consisting only of semiconducting materials (chalcogenides of Pb, Sn and rare-earth elements). Superconductivity is discovered in a new combination of semiconductors PbSe/EuS. It is shown that essential features of the multilayers structure determining the appearance of superconductivity are the perfect single crystallinity of entire sample and regular grids of misfit dislocations on the interfaces between two semiconductors. The segregation of free Pb observed in some cases does not correlate with appearance of superconductivity. The possibility of dislocation-induced superconductivity is discussed. © 2000 Published by Elsevier Science B.V. All rights reserved.

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Among a large variety of different superconducting superlattices (SL) the special place belongs to the semiconducting superconducting SLs consisting of semiconductors $A^{IV}B^{VI}$. Two SLs of this type, PbTe/PbS and PbTe/SnTe, are known for a long time [1,2]. Recently, the novel superconducting semiconducting SLs (PbTe/PbSe; PbS/PbSe; PbTe/YbS; PbTe/EuS) with the transition temperature T_c of 3–6 K have been discovered [3]. Appearance of superconductivity in these SLs looks rather fascinating because it is inherent only to the multilayered systems, while the individual materials constituting SLs are not superconductors. The single chalcogenide thin films do not reveal superconductivity too. The suggestions explaining the origin of this phenomenon in semiconducting SLs are rather controversial [1–3]. In this situation, when origin of superconductivity itself demands clear explanation, the structural study of SLs become of the major importance.

SLs were grown epitaxially on (0 0 1) face of KCl single crystals. The PbTe/PbS SLs preparation is described in Ref. [4]. Other SLs were prepared in the same way. In some cases (0 0 0 1) face of mica was used as a substrate. The thicknesses of both constituting layers in SLs were, as a rule, 100 nm.

Here we report on the discovery of one additional new member (PbSe/EuS with $T_c = 2.5$ K) in a class of semiconducting SLs (Fig. 1).

The transmission electron microscopy (TEM) and X-ray diffractometry (XRD) were the main tools of the SL structural investigations. An evidence is obtained that SLs prepared on KCl are perfect single crystals. At the measurements in the θ–θ scanning mode for all compounds in SLs and for substrate only the lines of $(h\,0\,0)$ type are present. The data of other special scan mode, allowing to get the reflections from the crystal planes with different $(h\,k\,l)$ values, testify that all crystallographic directions in substrate and in SL components coincide. The SLs prepared on mica consist of blocks with two different orientations ([1 0 0] and [1 1 1] texture). The

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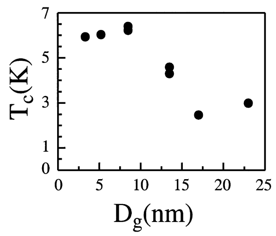

Fig. 1.

stability of the semiconducting SLs is rather low. The main reason of the SL degradation is a mechanical destruction which is due to the elastic stresses. In some cases the partial decomposition of the Pb-containing compounds occurs, and the lines characteristic for polycrystalline Pb appear. In the combination PbTe/PbS the weak Pb lines appear after a several month aging. The lines corresponding to the free Pb have never been seen on PbTe/YbS samples. There is no correlation between the presence of free Pb in the SLs and appearance of superconductivity. Thus, the origin of superconductivity in semiconducting SLs hardly may be attributed to the Pb segregation. Important results were obtained by TEM method. For all SLs condensed on KCl the regular grids of the misfit dislocations are observed which are located on the interfaces between two semiconductors. The grid periods obtained experimentally agree well with ones calculated according to formula $D_g = |\boldsymbol{b}_e|/f$ ($\boldsymbol{b}_e$ is the Burgers vector of misfit dislocation, the misfit $f = 2(a_1 - a_2)/(a_1 + a_2)$ is determined by the difference in the lattice parameter a of two compounds). The SLs prepared on the mica have island-type dislocation grids covering only small part of the interfaces. The same is true for thin-layer SLs with the thicknesses only a little exceeding the critical one for forming of the misfit dislocations.

The comparison of all data shows that the dislocations, saturating all interfaces, may be regarded as a phenomenon related to superconductivity. The full superconducting transitions are observed only when dislocation grids are continuous. In a case of the disconnected islands of the dislocation grids, only the partial transitions take place. When the density of dislocations diminishes, the T_c diminishes as well. This is seen in the figure where the T_c as a function of the dislocation grid period D_g is shown. There is additional experimental fact attracting attention to the dislocations as to a factor essential for superconductivity. From the study of critical magnetic fields and dimensional crossover on PbTe/PbS SLs it became clear that the superconducting layers are confined to the interfaces [4]. Presence of dislocations is not only condition necessary for superconductivity. The SLs consisting of two wide-gap semiconductors do not reveal superconductivity [3]. The narrow-gap semiconductor should be present to supply the electrons which may form the Cooper pairs. The data obtained allow one to suggest that the dislocation-induced change in electronic and elastic properties in the interface areas may by responsible for the appearance of superconductivity in semiconducting SLs.

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