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MAGNETOTRANSPORT STUDY OF MBE GROWN $Pb_{1-x}Eu_xSe$ EPILAYERS*

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Hall effect and electron conductivity investigations of MBE grown epilayers of $Pb_{1-x}Eu_xSe$ ($0 \leq x \leq 0.06$) as a function of temperature and magnetic field are reported. The strong Hall coefficient dependence on the magnetic field was found for p-type samples grown with Se excess. The possible origins of this effect are discussed.

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Rare earth monochalcogenides suit particularly well as constituents of alloys with IV–VI compounds when the widening of the energy gap is desired. They share the rock salt structure with IV–VI compounds and they have similar crystallographic lattice constants. Because their band gaps are much larger than those of IV–VI compounds even a moderate addition of a rare earth monochalcogenide substantially increases the band gap of a resulting mixed crystal. Among rare earth elements Eu is the most stable in 2^+ valence state. Moreover, it has a small diffusion coefficient which enables obtaining abrupt heterojunctions. These properties caused that lead chalcogenides mixed crystals containing europium have found wide applications as confinement layers and active layers in infrared diode lasers and as barriers in quantum well structures [1].

While optical and magnetooptical properties of $Pb_{1-x}Eu_xSe$ were rather extensively studied (see e.g. [2–4]) transport properties are relatively poorly known. In this paper we present the study of p- and n-type $Pb_{1-x}Eu_xSe$ ($0 \leq x \leq 0.06$) epilayers. The investigated layers were grown by molecular beam epitaxy (MBE) on (111) BaF_2 substrates. Thicknesses of layers varied between 2.5 and 5.5 μm. Measurements of dependencies of the electron conductivity σ and the Hall coefficient R_H (at $B = 1$ T) on temperature were performed in a continuous flow cryostat at the temperature range 2–300 K. High field measurements were per-

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TABLE

Carrier concentration p $(1/eR_H)$ and Hall mobility μ in $Pb_{1-x}Eu_xSe$ at various temperatures. Carrier concentration is given in cm^{-3}, mobility in $cm^2\ V^{-1}\ s^{-1}$. The Hall coefficient, R_H, was determined at magnetic field 1 T.

Symbol /type	Eu content	4.2 K		77.4 K		300 K	
		p	μ	p	μ	p	μ
1197-2/n	0.060[a]	1.3×10^{19}	1100	1.2×10^{19}	830	1.1×10^{19}	300
1201/p	0.054[b]	1.2×10^{19}	690	8.9×10^{18}	580	2.3×10^{18}	240
1217-4/p	0.000	5.5×10^{16}	59300	5.2×10^{16}	11200	2.1×10^{17}	335
1180-2/p	0.017	5.2×10^{16}	19000	6.6×10^{16}	5900	2.3×10^{17}	290
1181-1/p	0.024	5.8×10^{16}	7700	8.1×10^{16}	2800	2.9×10^{17}	210
1183-2/p	0.050	5.6×10^{16}	2100	5.0×10^{16}	1280	8.3×10^{16}	130

[a]additionally Bi doped; [b]additionally Ag doped

formed in 13 T superconducting magnet at 5 to 10 different temperatures from the range 1.8 to 270 K. The list of investigated samples is presented in Table.

Samples from the investigated set may be divided into two groups: heavily doped n-type and p-type samples and selenium enriched p-type samples. The temperature dependencies of the carrier concentration and the conductivity of the heavily doped n-type and p-type samples are different. The carrier concentration, derived from the Hall data, in the n-type sample remains practically constant at about 1.3×10^{19} cm^{-3}, while in the p-type sample starting from 1.2×10^{19} cm^{-3} decreases fivefold with the temperature rising from 4 to 300 K. The p-type sample exhibits pronounced Shubnikov–de Haas oscillations (see Fig. 1). At the magnetic field about 10 T the spin split oscillation is observed. A lack of any visible dependence of the position of the spin split oscillation on temperature indicates that the hole–Eu ion exchange interaction in $Pb_{1-x}Eu_xSe$ mixed crystals is very weak. This result is in agreement with the magnetooptical data [2] which show that the interaction in question is about one order of magnitude weaker than the Mn ion–hole interaction in $Pb_{1-x}Mn_xTe$, and two orders of magnitude smaller than that observed in II–VI compounds with Mn.

Interesting properties revealed the group of samples enriched with Se. Figure 2a shows the dependence of the hole concentration on the temperature for three such samples. With the increasing Eu content the character of the curves changes exhibiting in the middle range of temperatures a feature increasing with increasing x. Our computer simulation shows that similar shapes may be generated numerically when the presence of an acceptor level in the vicinity of the valence band edge is assumed.

The Hall mobility is a rapid function of the Eu content. For example, for $x = 0.017$ the mobility is lowered 3 times in comparison to that in the layer of undoped PbSe with comparable carrier concentration (cf. Table). Among reasons leading to the mobility suppressing a rapid increase in the energy gap with the growing Eu content may be distinguished. As a result, the effective mass of holes increases. Additionally, in the mixed crystals the alloy scattering is expected.

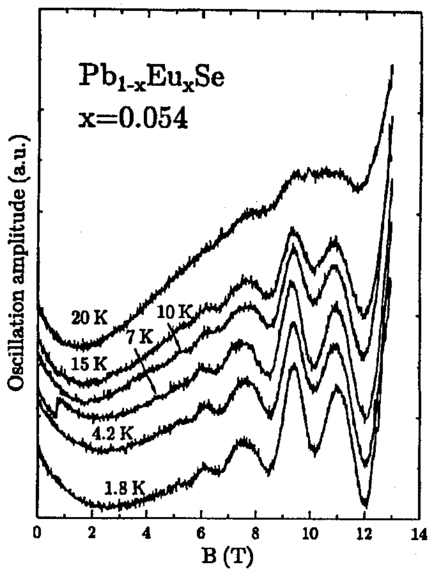

Fig. 1. Shubnikov–de Haas oscillations in the $Pb_{1-x}Eu_xSe$ epilayer, $x = 0.054$, at various temperatures.

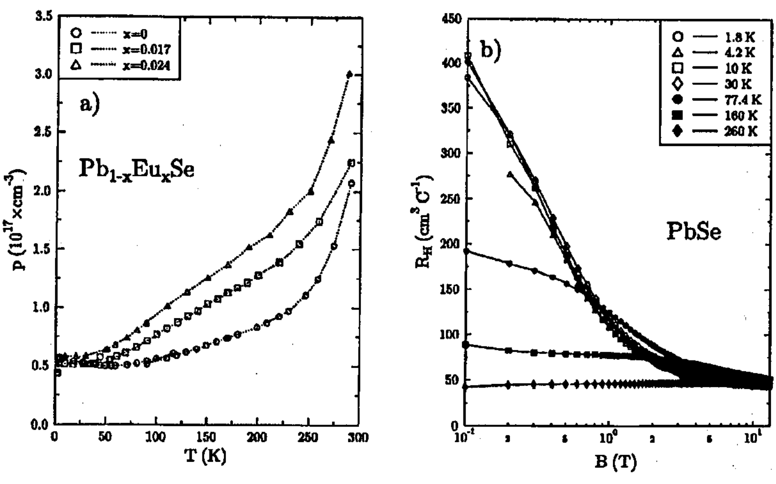

Fig. 2. (a) The temperature dependence of the hole concentration determined at $B = 1$ T in $Pb_{1-x}Eu_xSe$ epilayers. (b) Hall coefficient vs. magnetic field B for the p-type PbSe epilayer.

Magnetoconductivity and Hall coefficient data obtained for p-type samples with the small carrier concentration $p \approx 5 \times 10^{16}$ cm^{-3} (see Table) exhibit strong temperature and magnetic field dependencies. In $Pb_{1-x}Eu_xSe$, $x = 0.05$, the value of R_H diminishes more than twice in low temperatures when magnetic field rises to 13 T, but the effects are even more pronounced for samples containing less europium. In particular, a significant decrease in the Hall coefficient R_H with an increasing magnetic field may be observed for sample 1217-4 containing no Eu (see Fig. 2b). The effect is the strongest at low temperatures. The drop of R_H at $T = 1.8$ K for the sample shown in Fig. 2b equals almost an order of magnitude. For the same sample even at 160 K the 30% change of R_H is observed. Because the effect does not disappear even at the room temperature an immediate conclusion may be drawn. A value of the Hall coefficient is of practical importance only when it is considered together with the value of the magnetic field in which it has been measured.

The dependence of R_H on magnetic field obtained in our experiment resembles the situation when a conductivity is given by two types of carriers, in our case they would be holes, with different mobilities.

Searching for an explanation of this behavior, it should be noted that PbSe and $Pb_{1-x}Eu_xSe$ are many-valley semiconductors possessing four equivalent extrema at the L points of the Brillouin zone. The differences in lattice parameters of BaF_2 and $Pb_{1-x}Eu_xSe$ make a $Pb_{1-x}Eu_xSe$ layer elastically strained. The strain lifts the degeneracy and slightly shifts the valley with the main axis parallel to [111] with respect to the three obliquely oriented valleys (cf. [5, 6]). As a result, the carrier transfer between the different valleys takes place exerting an influence on the entire current carriers transport.

The fact that the Hall coefficient changes with the temperature even at the lowest temperatures may evidence that $Pb_{1-x}Eu_xSe$ epilayers, having metallic properties, approach to the metal–insulator transition. A similar picture was observed in PbTe epilayers on the metallic side of the metal–insulator transition [7].

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