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Hall mobility of charge carriers in films of $(PbX)_{1-x}(Sm_2X_3)_x$ semiconductors formed on porous silicon

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Abstract. Presented paper is devoted to studying the methods to prepare epitaxial films of $(PbX)_{1-x}(Sm_2X_3)_x$ (X – S, Se, Te; x = 0.04) semiconductors and to examine the Hall mobility of charge carriers in these films. It is revealed that the derived dependences $\mu_H(T)$ for the samples on values of the exponential coefficient $\nu = 1.7\text{-}2.8$ testify the temperature course of mobility in the majority of samples and can be explained via the dispersion of acoustic oscillations in the lattice and presence of a temperature dependence on the effective mass.

Keywords: chalcogenide film, porous silicon, Hall mobility, polycrystalline semiconductor films.

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1. Introduction

The transition to silicon substrates [1] is considered as one of promising directions in production of infrared detectors based on $A^{IV}B^{VI}$ semiconductors. The silicon clarity in the infrared spectral range makes the integration of photosensitive structures from the substrate side possible. This fact provides integration of photosensitive structures in composition of unique monolithic circuit produced using silicon technology. This approach allows providing the collection and processing of information because of transformation and amplifying circuits formed in a silicon substrate [2]. However, the direct growth of lead chalcogenide films and solid solutions on its base on the silicon is related with some difficulties. The most important of them is big disagreement between crystal lattice parameters. The comparative information about semiconductor lattice parameters $(PbX)_{1-x}(Sm_2X_3)_x$ and silicon is given in Table 1.

The low quality of grown films of lead chalcogenides pronounces itself as inadequate adhesion, polycrystallinity, appearance of microcrack grid [2] and is the consequence of this disagreement. The use of buffer layers is the way out of this situation. The transition layers suitable for growth of lead chalcogenides (BaF_2 (CaF_2, SiF_2), YbS) [1] or porous silicon [3] can be used for qualitative growth of $(PbX)_{1-x}(Sm_2X_3)_x$ films on silicon. Rather high growth temperature (400-750 and 900-950 °C, correspondingly) is the growth lack of buffer layers on the base of fluorides of II group and rare-earth chalcogenides. The formation method of buffer layers on the base of silicon semiconductors is the low-temperature one, and it is compatible technological processes in microelectronics. Besides, if in the first two cases the transition layers are the dielectric ones, then the use of silicon semiconductors allows varying of the specific resistance value in wide limits. That's why studying the possibility of lead chalcogenide epitaxial growth on porous silicon with different pore morphology and wide interval of specific resistance is an actual one.

Table 1. The lattice parameters and widths of semiconductor forbidden bands $(PbX)_{1-x}(Sm_2X_3)_x$ and silicon.

Material	Lattice parameter, Å	Width of the forbidden band, eV (300 K)
Si	5.43	1.1
$(PbX)_{0.96}(Sm_2S_3)_{0.04}$	5.91	0.44
$(PbSe)_{0.96}(Sm_2Se_3)_{0.04}$	6.15	0.34
$(PbTe)_{0.96}(Sm_2Te_3)_{0.04}$	6.40	0.35

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Table 2. Preparation of $(PbX)_{1-x}(Sm_2X_3)_x$ $(X - S, Se, Te; x = 0.04)$ films on porous silicon and their properties.

Orientation	Porosity of buffer layer	Film composition	Covering method	Crystalline orientation
(111)	Mesoporous	$(PbS)_{0.96}(Sm_2S_3)_{0.04}$	MBE, T_s = 450 °C	Polycrystalline orientation (100), (110), (311)
(100)	Mesoporous	$(PbSe)_{0.96}(Sm_2Se_3)_{0.04}$	MBE, T_s = 350°C	
(100)	Macroporous	$(PbTe)_{0.96}(Sm_2Te_3)_{0.04}$	MBE, T_s = 400°C	
(111)	Microporous	$(PbS)_{0.997}(Sm_2S_3)_{0.003}$	MBE, T_s = 450°C	

The semiconductor films of the $(PbX)_{1-x}(Sm_2X_3)_x$ (X – S, Se, Te; $x = 0.04$) system were used as investigation objects.

The aim of this work is to investigate the Hall mobility of charge carriers in the prepared films of the $(PbX)_{1-x}(Sm_2X_3)_x$ (X – S, Se, Te; x = 0.04) system.

2. Experimental

The silicon wafers with crystalline orientations (111) and (100) were used as initial substrates. The thickness of buffer porous layer was 3 up to 20 µm. The porosity value did not exceed 20 %. The method of molecular-beam epitaxy (MBE) was used to deposite lead chalcogenide films. The substrate temperature (T_s) was varied within the interval 350-450 °C. The thickness of grown films $(PbX)_{1-x}(Sm_2X_3)_x$ was 1.5-2.5 µm.

The film structural perfectness was analyzed by the methods of X-ray diffractometry. The buffer layer of porous silicon at the definite conditions is able to lead to formation of qualitative axially textured films of lead chalcogenides with high adhesion to substrate. The obtained polycrystalline films of (100), (110), (311) orientations don't contain pores, microcracks and endure multiple heat cycling 350 – 80 – 350 K. The heat cycling mode was chosen by analogy to the heat cycling mode for lead chalcogenides recommended in [7].

The investigations of Hall coefficient and specific conductance of semiconductor films $(PbX)_{1-x}(Sm_2X_3)_x$ (X – S, Se, Te; x = 0.04) were carried out.

The curves of temperature dependences for the Hall coefficient, specific conductance for this film are shown in Fig. 1.

The temperature dependence of the Hall mobility in $(PbX)_{1-x}(Sm_2X_3)_x$ $(X - S, Se, Te; x = 0.04)$ films (Fig. 2) was constructed being based on data for the Hall coefficient and specific conductance.

3. Results and discussion

The character of R_H temperature dependences for $(PbX)_{1-x}(Sm_2X_3)_x$ samples of different compositions has the similar form: the increase of R_H with temperature is observed within the temperature range 77 to 150 K, R_H gradually decreases with following temperature increase and the ratio R_{300}/R_{100} is ~1.22-1.41 (Fig. 1a). The sample No. 3 $(x = 0.0030; R_{300}/R_{100} \approx 1)$ is the exclusion. This dependence of the Hall coefficient on temperature reminds the similar dependence at x = 0.001-0.016 for bulk samples of solid solutions in the $(PbS)_{1-x}(Sm_2S_3)_x$ system. The Hall coefficient in semiconductor films $(PbX)_{1-x}(Sm_2X_3)_x$ is one order larger than that in bulk samples of solid solutions in the given systems.

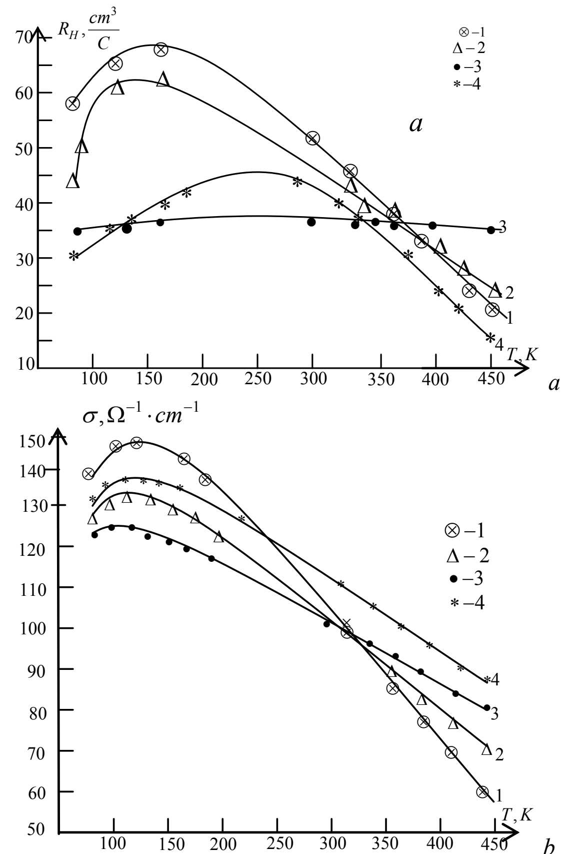

Fig. 1. Temperature dependences of the Hall coefficient (*a*) and the specific conductance (*b*) in $(PbX)_{1-x}(Sm_2X_3)_x$ films: 1 – $(PbS)_{0.96}(Sm_2S_3)_{0.04}$; 2 – $(PbSe)_{0.96}(Sm_2Se_3)_{0.04}$; 3 – $(PbS)_{0.997}(Sm_2S_3)_{0.003}$; 4 – $(PbTe)_{0.96}(Sm_2Te_3)_{0.04}$.

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The temperature dependence of the sample conductivity σ $(PbX)_{1-x}(Sm_2X_3)_x$ system is given in Fig. 1b. The sample electrical conduction monotonically increases a little within the temperature range 100-150 K, and further, it decreases with temperature increase (Fig. 1b) that is typical for semiconductors with degenerate gas of current carriers. The presence of clearly expressed σ increase region in the temperature range 80 to 160 K is a peculiar feature of σ(*T*) dependences.

The values of the power coefficient ν = 1.7-2.8 obtained from the dependences $\mu_H(T)$ evidence that temperature variations of the mobility in majority of samples can't be explained only by dispersion on lattice acoustic vibrations, as it is observed in lead chalcogenides. The higher ν values observable in $(PbX)_{1-x}(Sm_2X_3)_x$ can be related with the presence of temperature dependences of the effective mass, since it is considered as an established fact that the dispersion on acoustic phonons is the main dispersion mechanism of charge carriers in lead chalcogenides at mean and high temperatures. From the data obtained in the given work, it is seen that the tendency to decrease the power coefficient is observed in S-Se-Te series.

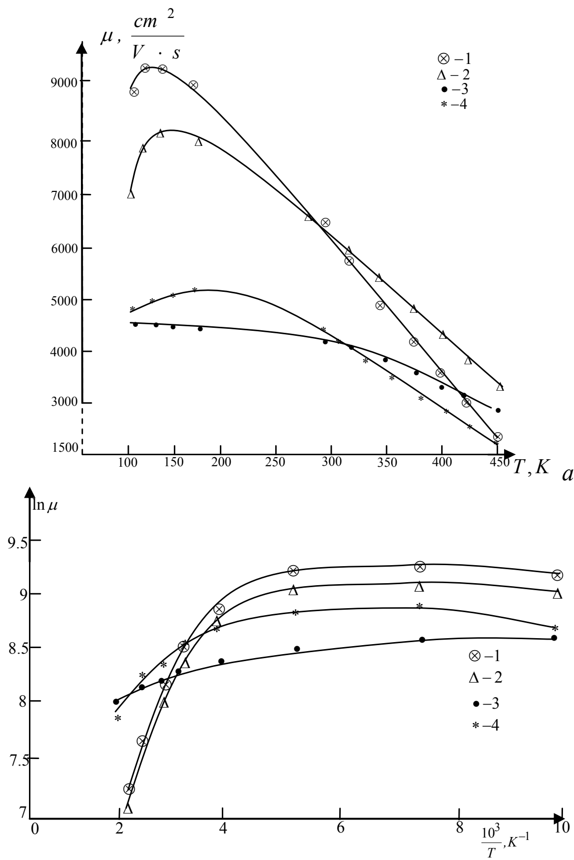

Fig. 2. Dependence of the Hall mobility of charge carriers (*a*) and inverse dependence of the sample Hall mobility (*b*) on temperature. $(PbX)_{1-x}(Sm_2X_3)_x$: 1 – $(PbS)_{0.96}(Sm_2S_3)_{0.04}$; 2 – $(PbSe)_{0.96}(Sm_2Se_3)_{0.04}$; 3 – $(PbS)_{0.997}(Sm_2S_3)_{0.003}$; 4 – $(PbTe)_{0.96}(Sm_2Te_3)_{0.04}$.

Table 3.

Composition	Activation energy ΔE_a, eV
$(PbS)_{0.96}(Sm_2S_3)_{0.04}$	0.32
$(PbSe)_{0.96}(Sm_2Se_3)_{0.04}$	0.27
$(PbTe)_{0.96}(Sm_2Te_3)_{0.04}$	0.28

The activation character of charge carrier mobility within the range 80 to 150 K can be related with the presence of energy barriers caused by the formation of thin oxide interlayers on the boundaries of separate grains [4].

The inversion of thermoelectromotive force sign in fine-dispersed samples PbS with electron conduction was explained by the authors of the work [4] by formation of acceptor levels in the grain near-surface layer as a result of oxygen adsorption. According to the work [5], for the layer consisting of well conducting crystallites surrounded by thin insulating interlayers, R_H is determined by the charge carrier concentration in crystallites, and μ_H is related with the carrier mobility μ_{H0} in crystallites and height of the energy barrier ΔE_a by the following relation:

$$\mu_H = \mu_{H0}\, e^{-\Delta E_a/kT} .$$

The increased charge carrier energy in the temperature range 200-240 K becomes sufficient for overcoming the energy barriers formed by interlayers on grain boundaries, and μ_H begins to decrease with temperature increase. The values of activation energy of charge carriers in the samples defined using the $\ln\mu \sim 1000/T$ dependence are illustrated in Table 3.

In all the cases, one can note the strong decrease in the Hall mobility for the S-Se-Te series, which is connected with growth in the rate of crystal lattice defectiveness and increase of electron scattering. The authors of the work [6], also observing the significant decrease in the PbS mobility with introduction of impurities, noted the fact of strong failure in the periodical lattice potential. Taking into account all mentioned above, we made the following conclusion: Sm action in semiconductor films $(PbX)_{1-x}(Sm_2X_3)_x$ cannot be considered as a small disturbance in contrast to other isovalent solid solutions.

4. Conclusion

The polycrystalline semiconductor films firstly obtained on the buffer layer of porous silicon for the $(PbX)_{1-x}(Sm_2X_3)_x$ system have crystalline orientations (100), (110), (311). The pores and microcracks are absent in the films.

It is established that the Hall coefficient in the films of $(PbX)_{1-x}(Sm_2X_3)_x$ system exceeds by one order the same parameter in bulk samples of the given system.

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The temperature dependence of specific conductance has the character typical for semiconductors with degenerate current carriers. The Hall mobility of current carriers has the activation character within the temperature range 80 to 150 K. The values $\nu = 1.7\text{-}2.8$ indicate the fact that the dependence of effective mass on temperature is added to the main dispersion mechanism related with acoustic phonons.

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