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Impact of Electron-Beam Radiation on Electrical Properties of $Pb_{1-x}Mn_xTe$ Epitaxial Films

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Abstract: It has been obtained $Pb_{1-x}Mn_xTe$ (x=0.04) epitaxial films on BaF_2 substrates at 10^{-4}Pa vacuum by molecular beam condensation method and studied the impact of electron-beam radiation on their electrical properties. From temperature dependence curves of electrical conductivity it has been determined that the electrical conductivity decreases with an increase of Mn concentration. İnfluence of electron flux $\Phi=2\cdot10^{15}$см$^{-2}$ (E=4.5MeV,) leads to a decrease of electrical conductivity due to the compensation of local level, further increase of radiation dose up to $\Phi=10^{16}$см$^{-2}$ increases the electrical conductivity. It has been investigated the impact of electron-beam radiation on VAC.

Keywords: Semimagnetic Semiconductor, Thin Film, Epitaxial Film, Substrate, VAC, Electrical Conductivity, Electron-Beam Radiation

1. Introduction

In last 20 years semimagnetic semiconductors (SMS) of lead chalcogenides ($Pb_{1-x}Mn_xS$, $Pb_{1-x}Mn_xSe$, $Pb_{1-x}Mn_xTe$) have been subject of intensive experimental and theoretical researches [1-5]. They attracted attention because of interaction between free carriers and Mn ions. In these semiconductors lead (Pb) atoms are partly replaced by transition element atoms - magnetic ions of manganese (Mn). By increasing of Mn concentration the band gap sharply increases and the lattice constant insignificantly decreases. Energy spectrum of charge carriers in magnetic field extraordinarily changes. It is possible to make devices on the basis of these materials controled by magnetic field and temperature.

Unlike II-VI qroup of SMS, $Pb_{1-x}Mn_xTe$ can be grown with higher concentration of free carriers. $Pb_{1-x}Mn_xTe$ thin films are promising materials for the devices used in infrared spectrum, because they possess high chemical stability, radiation resistance, high photosensitivity in IR spectral region [6-10].

Use of radiation-resistant materials in microelectronics, optoelectronics and spintronics is one of the actual issues. Though the physical properties of $Pb_{1-x}Mn_xTe$ epitaxial films have been sufficiently studied, the impact of ionizing rays on their physical properties has not been investigated. In this work we have investigated the impact of electron-beam radiation on electrical properties of $Pb_{1-x}Mn_xTe$ thin films. It has been investigated the impact of electron-beam radiation on current-voltage characteristics (VAC) and electrical conductivity of epitaxially grown $Pb_{1-x}Mn_xTe$ thin films

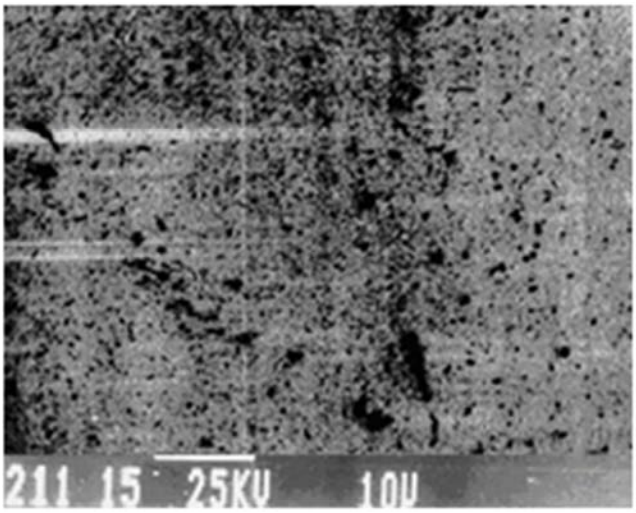
2. Experimental

$Pb_{1-x}Mn_xTe$ epitaxial films (x=0.04) has been obtained on BaF_2 substrates at 10^{-4}Pa vacuum by molecular beam condensation method. As a source it has been used pre-synthesized $Pb_{1-x}Mn_xSe$ (x=0.04) solid solutions The thickness of $Pb_{1-x}Mn_xTe$ (x=0.04) thin films was d=1µm.

Obtain of Pb1-xMnxTe epitaxial films on dielectric substrates BaF_2 have a scientific and practical importance. Thermal expansion coefficient (at 300K, $\alpha_{BaF_2}=1{,}8\cdot10^{-6}$ K^{-1}, $\alpha_{Pb_{1-x}Mn_xTe}=2{,}12\cdot10^{-6}$ K^{-1}) and crystal parameter of these substrates and solid solutions of $Pb_{1-x}Mn_xTe$ are close values (6.19A˚, 6.44A˚). This is allows to get epitaxial films with perfect crystal structure.

It is necessary use also substrate having a pure surface to obtain a structural perfect epitaxial films Therefore, freshly cleaved (111) surface of BaF2 single crystals was used as a substrate. Studies have shown that to obtain epitaxial films of higher structural quality during growing it is necessary to use the additional compensating source of Te. It was found that at the temperature of substrate Ts = 663÷673 K, at the temperature of additional source T_a=420÷430 K and condensation rate of υ_k = 8÷10Å/c we can obtain epitaxial films of n-type conductivity of 0,5÷1μm thickness, grown in the (111) plane parallel to the substrate. The increase of the substrate temperature and the rate of condensation lead to thickening of the films. Each value of the substrate temperature and the condensation rate corresponds to a certain thickness of the epitaxial film. This is called a critical thickness (dc). In the case of $d>d_c$, epitaxial growth is disturbed, and the film grows in different crystallographic directions. The crystal parameter is calculated on the basis of electron diffraction and X-ray diffraction curves which is equal to a= 6,445 Å. The half-width of the X-ray diffraction curves maximum of films is in the range W½ = 90÷100".

Crystal structure has been studied by X-ray diffraction method. Electron microscopic studies have shown that spots (Fig. 1) of black color are observed on the surface of the thin films. According to the literature data and our studies, these black spots appear as a result of oxidation process of excess lead atoms formed on the films during growth. In order to eliminate these black spots, and accordingly, to increase the structural perfection and mobility of charge carriers in the epitaxial films, an additional compensating Te source was used in the growth process. The temperature of additional source was in the range of 370÷460 K during the epitaxial growth. With increasing of additional source temperature above 430 K, the black spots disappear and surface of obtained epitaxial films get smoother, cleaner. At high speeds of condensation process in the result of partial decomposition of the solid solution, occurs evaporation of Te components. Because of increasing of amounts of metal - Pb atoms in the thin films, semiconductor has *n*-type conductivity. With increasing of additional source temperature T above 420 K, it take place inversion of type of the conductivity, i.e. *n*-type conductivity is replaced by a p-type conductivity. This is due to the filling of vacancies by Te atoms



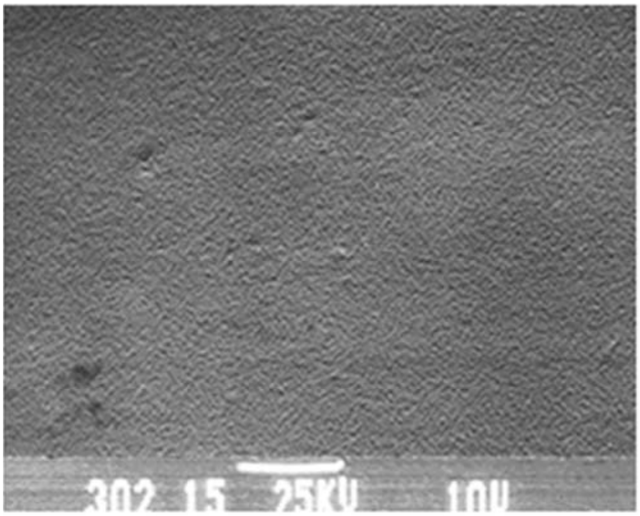


Fig. 1. *Electron microscopic patterns the surface of $Pb_{1-x}Mn_xTe$ (x=0,01) thin films a) before compensation by Te at $T_{noд}$≥680 K, b) after compensation by Te at T_{Te}=370-460 K.*

It is found that in the obtained thin films carrier concentration and carrier mobility respectively have the following value: $\mu_{n,p}$(77K)=(2,5÷3)·10^4cm^2/V·s, *n,p*(77K)=5·10^{16}÷1·10^{17}cm^{-3}. It is determined that the inversion of the conductivity type depends on compensating additional source temperature and condensation rate. With decreasing of the rate of condensation, the *n*-type carrier density decrease and there is an inversion of the conductivity, i.e. *n*-type conductivity is replaced by a *p*-type conductivity. By decreasing of condensation rate the partial split decreases, while volatile components existing in the system are replaced with acceptor atoms of oxygen and in the films arises *p*-type conductivity. On the other hand, with an increase in the substrate temperature increases the mobility of carriers. This growth is explained by an increase in the degree of crystallization of the obtained epitaxial films.

So, without breaking the vacuum, within the single technology process, on the BaF_2 substrates by the MBE method have been established the conditions of growing of structural perfect epitaxial films having n- and *p*- type conductivity.

For the study of the VAC of $Pb_{1-x}Mn_xTe$ (x = 0.04) epitaxial films, indium ohmic contacts of 1μm thickness were deposited on the samples. The electrodes were deposited on freshly cleaved face on the sides of the film having a smooth surface.

The samples were irradiated at room temperature in electron linear accelerator ELU-6 (E=5MeV, Φ≤7·10^{17}cm^{-2}). It have been studied VAC and temperature dependence of electrical conductivity of $Pb_{1-x}Mn_xTe$ (x=0.04) thin films before and after irradiation. Primarily to comparative analyses, CVC were measured before irradiation at various temperatures T = 80–210K. It has been observed in CVC linear part J ~ U corresponding to Ohm's law, J ~ U^2 quadratic part and I~U^3–U^4 part corresponding to rapid increase of current (Fig. 2).

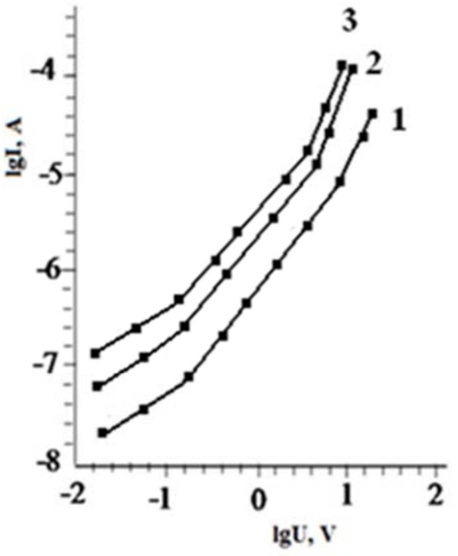


Fig. 2. CVC of $Pb_{1-x}Mn_xTe$ (x=0.04) thin film: 1) T =80 K; 2) T =155 K; 3) T =210 K.

The Fig. 2 show that the nature of dependencies have not changed, but there is a parallel shift of the curve in the direction of increasing the current over the entire investigated range of voltages with increasing temperature up to *T* = 210K.

After irradiation of $Pb_{1-x}Mn_xTe$ (x = 0.04) epitaxial films, it was observed on curves first ohmic part $I \sim U$, then quadratic part $I \sim U^2$, further cubic part $I \sim U^3$, the nature of dependency does not change (Fig. 3).

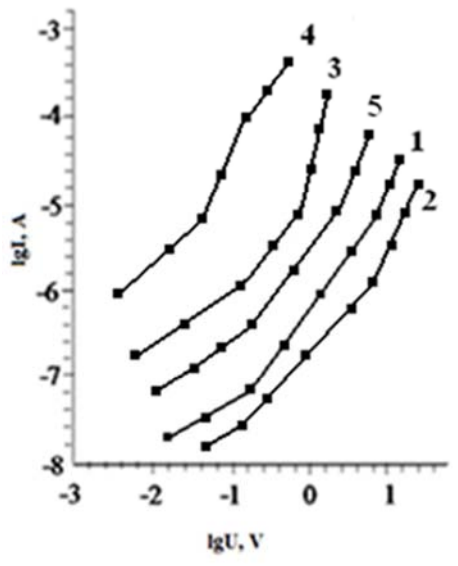


Fig. 3. CVC of $Pb_{1-x}Mn_xTe$ (x=0.04) thin film at T=80K 1) Φ =0; 2) Φ =10^{15}см$^{-2}$; 3) Φ = $5\cdot10^{15}$см$^{-2}$ 4) Φ = $2\cdot10^{16}$см$^{-2}$: 5) Φ =$7\cdot10^{17}$см$^{-2}$.

The current, value of which is determined by the concentration of charge carriers of the samples, increases with increasing of radiation dose. Further increasing of the radiation dose leads to the parallel shift in the direction of increasing the current over the entire investigated range of voltages. After irradiation of samples at higher doses, the quadratic part becomes cubic corresponding quadratic trapping part. At irradiation it is formed a number of deep levels in the band gap of $Pb_{1-x}Mn_xTe$ (x = 0.04) epitaxial films.

After irradiation of samples by electron beam Φ=10^{15}cm-^{2}, on the CVC is observed trapped quadratic part and a part of sharp rise, ohmic part is very small. In this case, the current value decreases as compared with unexposed films (Fig. 3, c. 2)

Irradiation of samples at higher doses Φ=$5\cdot10^{15}$cm^{-2}, the current value was increased, but the nature of the dependences didn't change. Ohmic region CVC is lengthened, quadratic part was reduced, after that followed a sharp rise (Fig. 3, c. 3).

With further increase of radiation dose up to Φ=$2\cdot10^{16}$sm^{-2}, current value was more than the others (Fig. 3 c. 4). It appeared nontrapped quadratic part. With a further increase of radiation dose up to the Φ=$7\cdot10^{17}$cm^{-2} current value was decreased (Fig. 3 c. 5), there was again trapped quadratic part.

The results show that irradiation of crystals up to Φ=10^{15}cm^{-2} dose leads of radiation defects to self-compensation and conductivity tends to own. At Φ=$5\cdot10^{15}$cm^{-2} radiation dose as a result of the decay of neutral complexes, conductivity of sample increases, and at Φ=$7\cdot10^{17}$cm^{-2} dose, current the value of which is determined by the concentration of charge carriers of the samples is reduced.

The electrical conductivity of the samples by heating was measured at E7-13A teraohmmeter before and after irradiation. The heating rate was 2K / min. In Fig. 4 shows the temperature dependence of electrical conductivity of $Pb_{1-x}Mn_xTe$ epitaxial films at different concentrations of Mn (x = 0 ÷ 0.05). It was defined from the curves that the nature of the conductivity dependency of the samples does not change. From temperature dependency curves of electrical conductivity it has been determined that the electric conductivity decreases with an increase of Mn concentration.

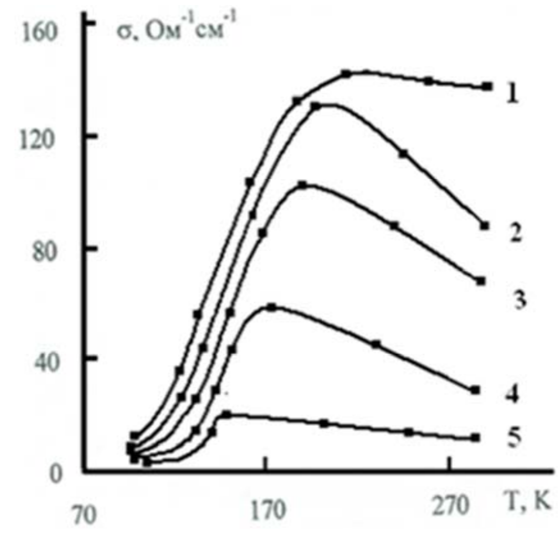


Fig. 4. Ttemperature dependence of electrical conductivity of $Pb_{1-x}Mn_xTe$ thin films: 1) x = 0. 2) x=0.01, 3) x=0.02, 4) x=0.04, 5) x=0.05.

Irradiation of crystals affects their electrical conductivity. Impact of electron flux at $\Phi=2\cdot10^{15}$см$^{-2}$ (E=4.5MeV) doses leads to a decrease in electric conductivity due to the compensation of local level. Fig.5 shows the temperature dependence of electrical conductivity of $Pb_{1-x}Mn_xTe$ after irradiation at doses $\Phi=2\cdot10^{15}$см$^{-2}$.

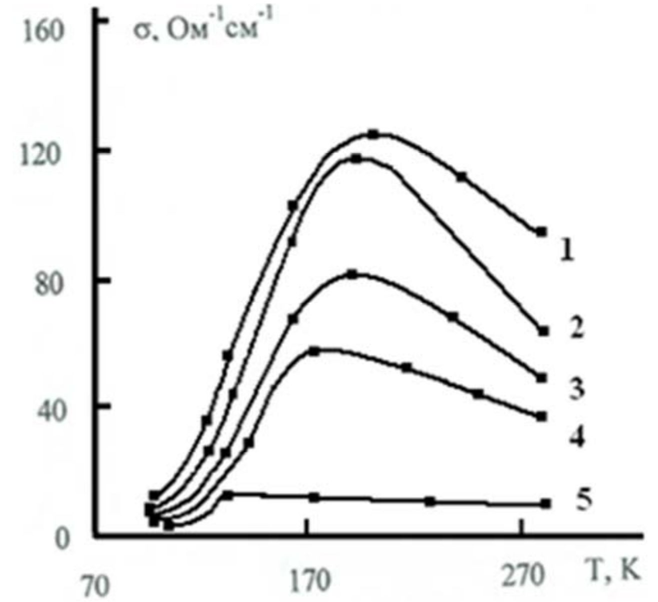


Fig. 5. *Ttemperature dependence of electrical conductivity of $Pb_{1-x}Mn_xTe$ thin films irradiated at $\Phi = 2\cdot10^{15}$см$^{-2}$: 1) x = 0. 2) x=0.01, 3) x=0.02, 4) x=0.04, 5) x=0.05.*

It is shown in Fig. 6 the temperature dependence of electrical conductivity of $Pb_{1-x}Mn_xTe$ before and after irradiation at doses $\Phi=2\cdot10^{15}$см$^{-2}$.

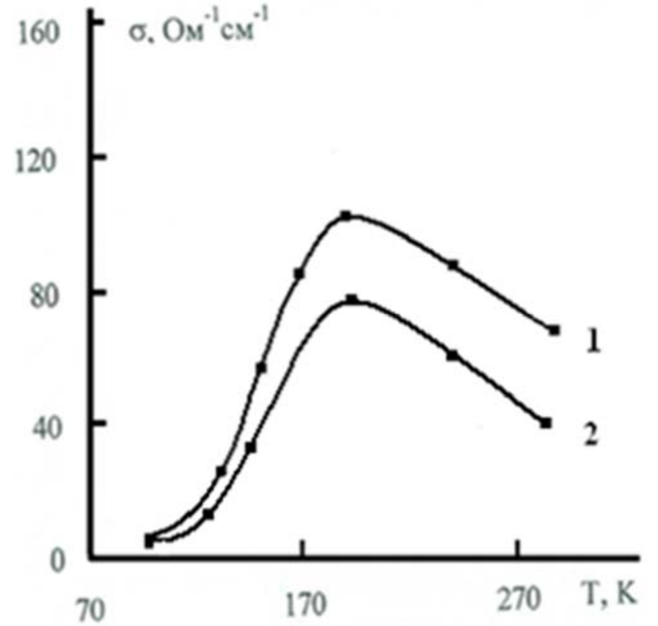


Fig. 6. *Ttemperature dependence of electrical conductivity of $Pb_{1-x}Mn_xTe$ (x=0.02) thin films 1) Φ =0; 2) $\Phi = 2\cdot10^{15}$см$^{-2}$.*

Further increase of radiation dose up to $\Phi=10^{16}$см$^{-2}$ increases the electrical conductivity (Fig. 7).

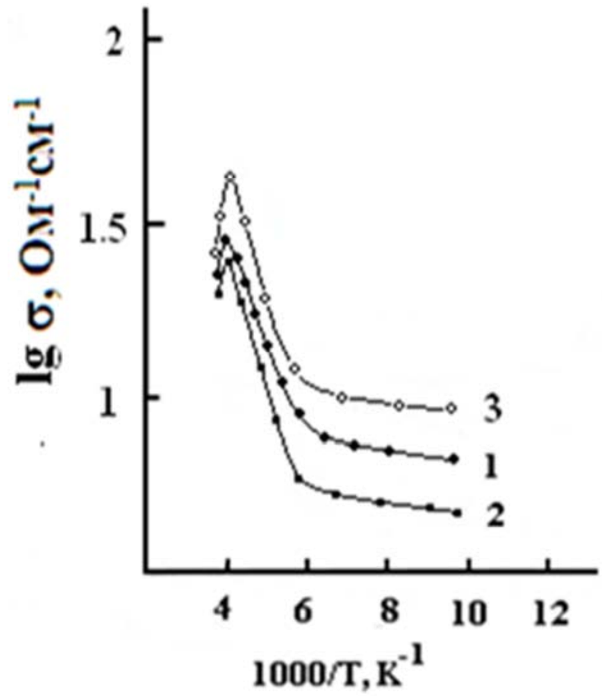


Fig. 7. *Ttemperature dependence of electrical conductivity of $Pb_{1-x}Mn_xTe$ (x=0.04) thin films irradiated at 1. Φ =0; 2. $\Phi = 2\cdot10^{15}$см^{2}; 3. $\Phi = 10^{16}$см$^{-2}$.*

3. Results

Without breaking the vacuum, within the single technology process, on the BaF_2 substrates by the MBE method have been established the conditions of growing of structural perfect epitaxial films having of *n*- and *p*- type conductivity. Getting films of *n*- and *p*-type conductivity opens up wide possibilities for their use in the manufacture of highly sensitive photodetectors operating in the infrared region of the spectrum and with high electrophysical parameters.

It has been determined that the electrical conductivity decreases with an increase of Mn concentration. Impact of electron flux $\Phi=2\cdot10^{15}$см^{2} (E=4.5MeV) leads to a decrease in electric conductivity due to the compensation of local level, further increase the radiation dose up to $\Phi=10^{16}$см$^{-2}$ increases the electrical conductivity.

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