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Influence of the distance between evaporation source and substrate on formation of lead telluride (PbTe) nanostructures by vacuum thermal evaporation method

G. S. Amirbekova[a], Zh. K. Tolepov[a,*], N. Guseinov[a], M. A. Tulegenova[a],
T. Kuanyshbekov[b]
[a]Department of Physics and Technology, Al-Farabi Kazakh National University, Al-Farabi Avenue, 71, Almaty 050040 Kazakhstan
[b]National Scientific Laboratory of Collective Use S. Amonzholov East Kazakhstan University, 55 Kazakhstan str., Ust-Kamenogorsk 070002, Kazakhstan

Lead telluride nanostructures were obtained on silicon substrates by thermal evaporation in vacuum. Growth occurred at three different distances between the evaporation source and the substrate. The distances between the evaporator and the evaporation source were 5 cm; 7.5 cm and 10 cm. Structural characteristics were studied using XRD, SEM, EDX, AFM analyses. These methods provided information about the crystal structure, morphology, microstructure and elemental composition of the material. X-ray diffraction analysis showed that thin films of lead telluride obtained by thermal evaporation in vacuum have a cubic crystal structure. This experimental work was carried out to determine the effect of distance on the structure of lead telluride (PbTe). During the experiment, the optimal modes for the formation of lead telluride (PbTe) nanostructures were determined, which was equal to d = 10 cm. It was found that lead telluride (PbTe) nanostructures are formed at this distance.

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Keywords: Lead telluride, Thermal evaporation, Nanostructure, Substrate

1. Introduction

Lead telluride (PbTe) is a binary inorganic chemical compound of lead and tellurium that crystallizes in a NaCl-type cubic structure. It is used in the production of photoresistors, photodiodes, and lasers operating in the infrared region of the spectrum. This material is a semiconductor with a narrow band gap [1]. This means that it requires little energy to release an electron from the valence band to the conduction band. This property makes PbTe useful for various thermoelectric devices. Lead telluride (PbTe) has attracted much attention due to its potential applications in thermoelectric devices [2], infrared photodetectors [3], and diode lasers [4]. Infrared detectors can detect infrared radiation, which is a type of thermal radiation and is also used in thermoelectric generators to generate electricity from waste heat [5].

There are various methods for producing lead telluride, for example: The chemical deposition method is a simple and economical method, but can lead to the formation of inhomogeneous nanostructures [6]. The molecular beam epitaxy method allows the formation of high-quality nanostructures, but is an expensive and complex method [7]. The sol-gel method allows the formation of nanostructures with specified properties, but can lead to the formation of amorphous materials [8]. Research is currently underway to develop new methods for forming PbTe nanostructures with improved characteristics. The vacuum thermal evaporation method is one of the common methods for the formation of lead telluride (PbTe) nanostructures [9]. In this method, the PbTe starting material is evaporated in a vacuum and then condenses on a substrate to form nanostructures. To do this, PbTe is placed in a crucible, which is heated to a temperature sufficient to evaporate it [10-13]. PbTe atoms leave the crucible and move freely in a vacuum chamber and are transferred to the substrate, which is at a lower temperature, and condense on the substrate, forming nanostructures [14-18]. Vacuum pressure affects the growth rate of nanostructures, and the type of substrate affects the type and structure of nanostructures [19]. The

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[*] Corresponding author: mr.tolepov@mail.ru

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advantages of this method are that it is relatively simple and economical. It is possible to use this method to form nanostructures over large areas and adjust the process parameters to obtain the desired structures [20].

2. Materials and methods

An experimental study of the formation of PbTe nanostructures by the method of vacuum thermal evaporation was carried out to improve the technology of forming PbTe nanostructures by the method of vacuum thermal evaporation and to determine the optimal parameters. To do this, a pure silicon (Si) substrate was boiled in alcohol at 70°C and cleaned in an ultrasonic bath for 1 hour [21]. Subsequently, the prepared substrate and the evaporation source (PbTe) were placed in a vacuum chamber. The distance between the evaporation source and the substrate varied: 5 cm, 7.5 cm and 10 cm. The mass of the evaporation source was 1 g. The experiment was repeated several times for each distance. The results obtained were studied using XRD, SEM, EDX AFM analyses. To study the structural properties, a set of methods was used, including: scanning electron microscopy (SEM) - a method that provides information on the morphology of the surface of the material, its microstructure and distribution of elements. EDX analysis is a method that allows you to determine the elemental composition of a material. AFM is a powerful technique that can be used to obtain information about the nanoscale properties of materials. This information can be used to develop new materials and improve the performance of existing materials. X-ray diffraction (XRD) is a method that allows one to determine the crystal structure of a material, its phase composition, unit cell parameters and other characteristics. The combined use of these methods made it possible to obtain a complete picture of the structural properties of the material under study.

3. Results and discussion

Lead telluride (PbTe) is a promising material for various applications in optoelectronics, thermoelectricity and other fields. In this regard, studying methods for producing PbTe with specified characteristics is an urgent task. In this study, PbTe structures on silicon substrates were obtained by vacuum thermal evaporation. The distance between the substrate and the evaporation source varied in the range from 5 cm to 10 cm. PbTe structures were studied using scanning electron microscopy (SEM), atomic force microscopy (AFM) and X-ray diffraction (XRD). Figure-1 shows the SEM micrograph of PbTe nanomaterial. Top view SEM images of such PbTe films show a smooth and uniform texture compared to bulk PbTe films

This study investigated the effect of the distance between the substrate and the evaporation source on the structure of lead telluride. For this purpose, structures were formed at distances of 5 cm, 7.5 cm and 10 cm. At a distance of 5 cm, a thin PbTe film with a thickness of 102 nm without nanoparticles was formed. At a distance of 7.5 cm, the PbTe structure became rough and inhomogeneous. The nanoparticle size was 83 nm. At a distance of 10 cm, uniform PbTe nanoparticles with a size of 51 nm were obtained.

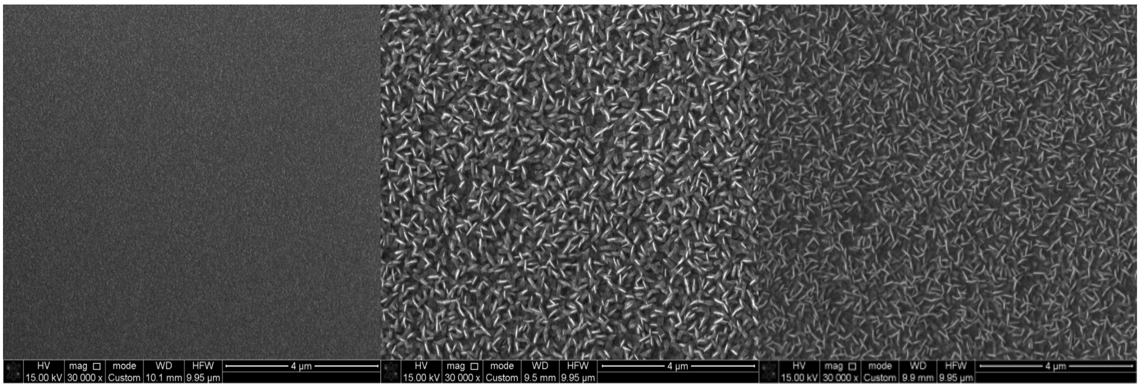
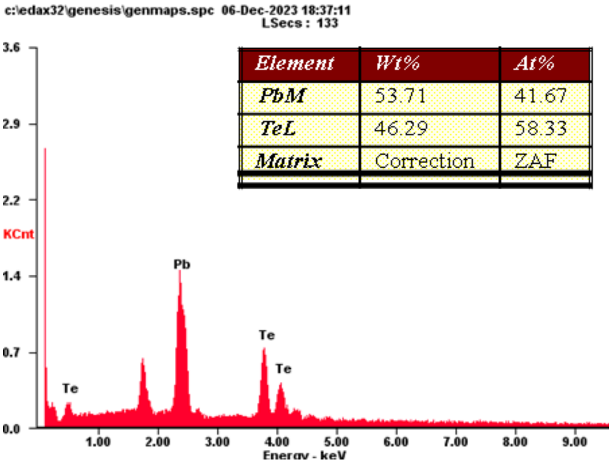


Fig. 1. SEM image of the structure of lead telluride (PbTe) obtained at different distances (a-5 cm, b-7.5 cm, c-10 cm).

It was found that the distance between the substrate and the evaporation source has a significant effect on the structure and thickness of lead telluride. The optimal distance between the substrate and the evaporation source for the formation of homogeneous PbTe nanostructures by vacuum thermal evaporation is 10 cm. At this distance, PbTe nanostructures have more uniform sizes and shapes.



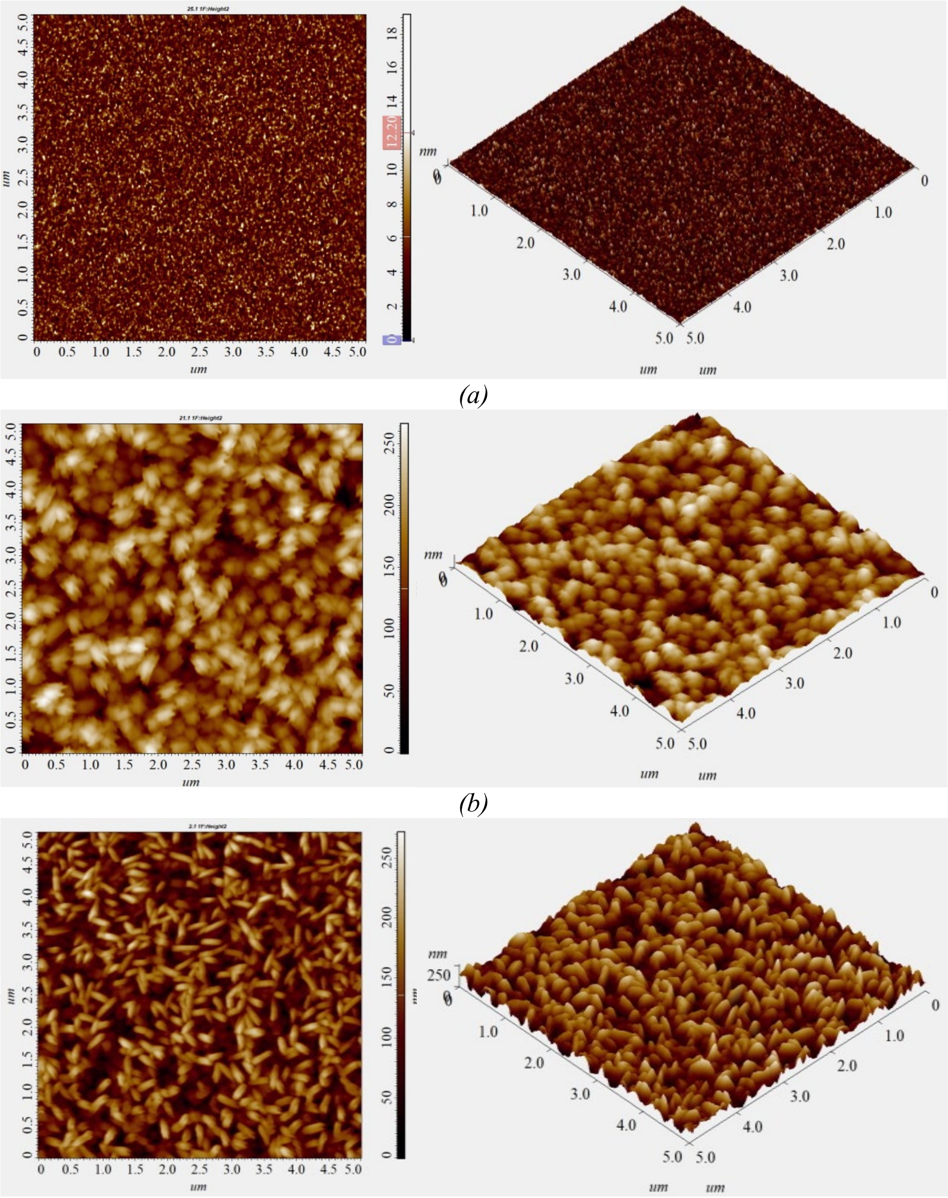
Element	Wt%	At%
PbM	53.71	41.67
TeL	46.29	58.33
Matrix	Correction	ZAF

Fig. 2. Energy dispersive analysis and elemental composition of lead telluride (PbTe).

Figure 2 shows an analysis of the elemental composition and energy distribution of a lead telluride dispersion obtained at an optimal distance (10 cm) by scanning electron microscopy (SEM). The results show that the atomic fraction of lead is 41.67% and tellurium is 58.33%. Analysis of the elemental composition and energy of the dispersion confirms that this structure consists exclusively of Pb and Te atoms.

In addition to scanning electron microscopy (SEM), atomic force microscopy (AFM) was used to study the surface morphology of PbTe films. The results of the study are presented in Figure 3. Analysis of the data obtained by AFM allows us to determine the average surface roughness of PbTe films. Evaluate the influence of various factors (substrate temperature, film thickness, deposition method) on roughness.

Information about surface roughness is important when using PbTe films as active elements in optoelectronic devices such as IR detectors and laser LEDs. The AFM method is an effective tool for studying the surface morphology of PbTe films.



(a)

(b)

(c)

Fig. 3. AFM image of the surface morphology of lead telluride (PbTe) obtained at different distances (a-5cm, b-7.5cm, c-10cm).

This study presents the surface morphology of lead telluride (PbTe) obtained by atomic force microscopy (AFM) at various distances from the deposition source. Figure 3 shows AFM images of a PbTe surface formed at distances of 5 cm (a), 7.5 cm (b) and 10 cm (c). Figure 3(a) - the surface is rough with minor inhomogeneities. Figure 3(b) - the formation of individual structures with more pronounced roughness is observed. Figure 3(c) - The PbTe surface becomes more homogeneous, with free-standing structures. The results of the AFM study demonstrate the influence of the distance of the substrate from the deposition source on the morphology of the PbTe surface. At a distance of 10 cm, the PbTe structure becomes most homogeneous. The thickness of the PbTe (100) film is one of the factors affecting its roughness, and the structure of the film also affects its roughness. As the deposition distance increases, nanoobjects on the surface increase in both width and height. The dominant mechanism of their formation is diffusion in the vapor phase. As the deposition distance increases, repeated evaporation and aggregation of objects begin to play a role, which leads to their merging and a decrease in structural perfection. The surface of a thinner film reflects the structure of a thicker film, which makes it possible to study the properties of the film based on its thickness. If nanoobjects of a certain shape are present on the surface of a thin film, they are “sealed” in a thicker film. The surface of these objects scatters free charge carriers, which can lead to a qualitative change in kinetic parameters when the film thickness changes. However, quantitative changes will be insignificant. Vapor phase diffusion plays a key role in the formation of nanocrystals. Repeated evaporation and aggregation of nanoobjects affects their size and structure.

The nanostructures obtained by vacuum thermal evaporation, with an optimal distance, were studied by X-ray diffraction analysis. X-ray diffraction data showed that the nanostructure has an fcc structure with a lattice parameter a = 6.45 Å and space group Fm-3m. X-ray diffraction measurements showed that the structure was polycrystalline and had a characteristic face-centered cubic lattice structure. The characteristic diffraction lines of cubic crystals of lead telluride were identified.

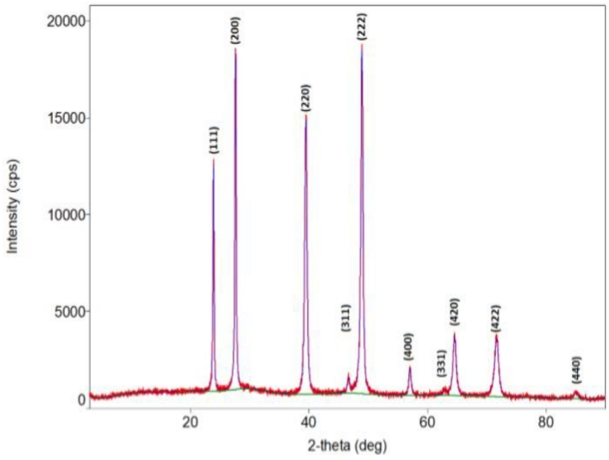


Fig. 4. X-ray analysis of PbTe nanostructures.

The X-ray diffraction pattern of PbTe (Figure - 4) shows a different polycrystalline structure compared to the standard ICCD card No. 65-0324. These peaks in an x-ray diffraction pattern correspond to the reflection of x-rays from atomic planes in a crystal. Very sharp peaks are observed, with the highest intensity for the (200) plane, followed by (220), (222), (111), (420), (422) and (400). These results are consistent with data for face-centered cubic PbTe in card no. 65-0324. One phase has been identified with the (200) plane having the maximum relative X-ray intensity. The X-ray diffraction pattern demonstrates that the crystallites in the film are predominantly oriented in the (200) plane, which corresponds to an angle of 27.52°. A diffraction pattern with pronounced peaks is a sign of the polycrystalline structure of the film. For PbTe, the calculated lattice parameter (a) is 6.45 Å, which is the same as the standard card value obtained from the (200) peak with the highest intensity. Thus, X-ray phase analysis confirms the high quality of the synthesized PbTe with a face-centered cubic structure.

4. Conclusion

The dependence of the structure of PbTe obtained by vacuum thermal evaporation on the distance between the evaporation source and the substrate has been established. The optimal distance (10 cm) for the formation of a PbTe nanostructure with specified characteristics was determined. At the optimal distance, a homogeneous PbTe nanostructure with a tiny particle size of 51 nm was obtained. Elemental analysis confirmed that the nanostructure consists of pure Pb (41.67%) and Te (58.33%) atoms. Atomic force microscopy showed the homogeneity of the nanostructure.

The distance between the evaporation source and the substrate plays a key role in the formation of PbTe nanostructures. The thermal evaporation method in vacuum can be used to obtain lead telluride nanostructures with a cubic crystal structure.

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