Original article
UDC 621.52
DOI: https://doi.org/10.18721/JPM.16207

FORMATION OF Mn_4Si_7 FILMS BY MAGNETRON SPUTTERING AND A WIDE RANGE OF THEIR THERMOELECTRIC PROPERTIES

I. R. Bekpulatov [1] ✉, V. V. Loboda [2], M. T. Normuradov [3]

B. D. Donaev [4], I. Kh. Turapov [1]

[1] Tashkent State Technical University, Tashkent, Uzbekistan;

[2] Peter the Great St. Petersburg Polytechnic University, St. Petersburg, Russia;

[3] Karshi State University, Karshi, Uzbekistan;

[4] Karshi Engineering-Economics Institute, Karshi, Uzbekistan

✉ bekpulatov85@rambler.ru

Abstract. In the paper, films of higher manganese silicide Mn_4Si_7 have been made and a lot of their properties have been investigated. The composition and structure of the films formed by ion-plasma magnetron sputtering were examined by scanning electron microscopy and X-ray analysis. The temperature dependences of film resistivity (by the four-probe method), of their Seebeck coefficient (by the two-probe method), as well as their Hall constant and optical reflectivity spectra (at room temperature). Their thermoelectric figure of merit, the energy-gap width (0.66 eV), charged-particle density and mobility, etc., were calculated. The properties of the films in the amorphous and polycrystalline phases were compared. The thermopower of the Mn_4Si_7 film was established to increase by about 6 times during the transition from the amorphous phase to the polycrystalline one. The results obtained indicate that it is possible to use this film in heat wave detectors.

Keywords: magnetron sputtering, cleaning of silicon wafer, resistivity, silicon, thermoelectric properties

Funding: The studies are being done within the Fundamental Scientific Project No. F-OT-2021-422 of The Republic of Uzbekistan and The Ministry of Science and Higher Education of the Russian Federation. The research is funded by the Ministry of Science and Higher Education of the Russian Federation within the framework of the program “The World-Class Research Centre: Advanced Digital Technologies” (Contract No. 075-15-2022-311 dated April 20, 2022).

For citation: Bekpulatov I. R., Loboda V. V., Normuradov M. T., Donaev B. D., Turapov I. Kh., Formation of Mn_4Si_7 films by magnetron sputtering and a wide range of their thermoelectric properties, St. Petersburg State Polytechnical University Journal. Physics and Mathematics. 16 (2) (2023) 78–88. DOI: https://doi.org/10.18721/JPM.16207

Научная статья
УДК 621.52
DOI: https://doi.org/10.18721/JPM.16207

ПОЛУЧЕНИЕ ПЛЕНОК Mn_4Si_7 МЕТОДОМ МАГНЕТРОННОГО РАСПЫЛЕНИЯ И ШИРОКИЙ СПЕКТР ИХ ТЕРМОЭЛЕКТРИЧЕСКИХ СВОЙСТВ

И. Р. Бекпулатов [1] ✉, В. В. Лобода [2], М. Т. Нормурадов [3]

Б. Д. Донаев [4], И. Х. Турапов [1]

[1] Ташкентский государственный технический университет, г. Ташкент, Узбекистан;
[2] Санкт-Петербургский политехнический университет Петра Великого, Санкт-Петербург, Россия;
[3] Каршинский государственный университет, г. Карши, Узбекистан;
[4] Каршинский инженерно-экономический институт, г. Карши, Узбекистан
✉ bekpulatov85@rambler.ru

Аннотация. В работе были изготовлены пленки высшего силицида марганца Mn_4Si_7 и изучен широкий спектр их свойств. Состав и структура пленок, полученных методом ионно-плазменного магнетронного распыления, исследовались методами сканирующей электронной микроскопии и рентгенофазового анализа. Были измерены температурные зависимости удельного сопротивления пленок (четырехзондовый метод), их коэффициента Зеебека (двухзондовый метод), а также постоянная Холла и спектры оптического отражения (при комнатной температуре). Рассчитаны термоэлектрическая добротность, ширина запрещенной зоны (0,66 эВ), концентрация и подвижность заряженных частиц и др. параметры. Проведено сравнение свойств пленок, находящихся в аморфной и поликристаллической фазах. Установлено, что термоэдс пленки при переходе из аморфного состояния в поликристаллическое увеличивается примерно в 6 раз. Полученные результаты доказывают, что пленку можно применять в детекторах тепловолнового излучения.

Ключевые слова: магнетронное распыление, высший силицид марганца, удельное сопротивление, коэффициент Зеебека, термоэлектрические свойства

Финансирование: Работа осуществляется в рамках Фундаментального научного проекта № Ф-ОТ-2021-422 Республики Узбекистан и Министерства науки и образования Российской Федерации. Исследование финансируется Министерством науки и образования Российской Федерации в рамках программы «Исследовательский класс мирового уровня: передовые цифровые технологии» (контракт № 075-15-2022-311 от 20 апреля 2022 года).

Для цитирования: Бекпулатов И. Р., Лобода В. В., Нормурадов М. Т., Донаев Б. Д., Турапов И. Х. Получение пленок Mn_4Si_7 с методом магнетронного распыления и широкий спектр их термоэлектрических свойств // Научно-технические ведомости СПбГПУ. Физико-математические науки. 2023. Т. 16. № 2. С. 78–88. DOI: https://doi.org/10.18721/ JPM.16207

Introduction

Many research centers around the world are currently conducting studies on the creation of environmentally friendly and low-cost energy sources. In this regard, great results have been achieved in the conversion of wind, light and heat energy into electrical one, which has led to an increase in the efficiency of the generated photovoltaic and thermoelectric elements [1 – 8]. In addition, scientific research on the creation of new types of photo- and thermoelectric films has been constantly developing [9 – 14]. Among these materials, the most promising one is a film based on a higher manganese silicide (HMS), whose thermoelectric figure of merit can reach 0.4 in the temperature range of 20 – 700 °C [15 – 21]. A Mn_4Si_7 thin film can be used for fabrication high-quality thermal elements and show the possibility of creating nanostructures with high thermal properties based on fundamental research on various physical properties, quantum effects, and size factors. Sensitivity cells based on HMS structures are also promising when using highly sensitive receivers of electromagnetic waves in visible and IR fields.

The goal of the present paper is to form the Mn_4Si_7 film by the ion-plasma magnetron sputtering method and to study its thermoelectric properties.

Material and methods

Magnetron sputtering synthesis of HMS films is carried out using SiO_2/Si substrate. Before the formation of the HMS film, the SiO_2/Si substrate was cleaned in two stages:

1. The cleaning of the silicon wafers surface SiO_2/Si (d = 60 mm) was carried out using an ammonia-peroxide mixture at a temperature of 60 – 70 °C, washing in deionized water, drying in a centrifuge;

2. The vacuum treatment (cleaning) of the silicon wafer surface was carried out using an argon plasma flow on EPOS-PVD-DESK-PRO magnetron sputtering machine. The plasma flow was created by a source of ions with a cold cathode at a voltage of 2 – 3 kV and a current of up to 100 mA during 3 – 5 min. A group of plates (2 – 4 pieces) was located on a rotating tool during the treatment.

HMS films were formed using an EPOS-PVD-DESK-PRO magnetron sputtering machine at a pressure of 10^{-4} Pa and room temperature. The purity of Mn_4Si_7 target was 99,5 %. The diameter and the thickness of the target were 76 mm and 6 mm, respectively [22, 23].

The composition and structure of the target were studied by Quanta 200 3D scanning electron microscope (SEM) from the Dutch Company FEI before placing the target into the magnetron machine (Fig. 1).

a) *b*)

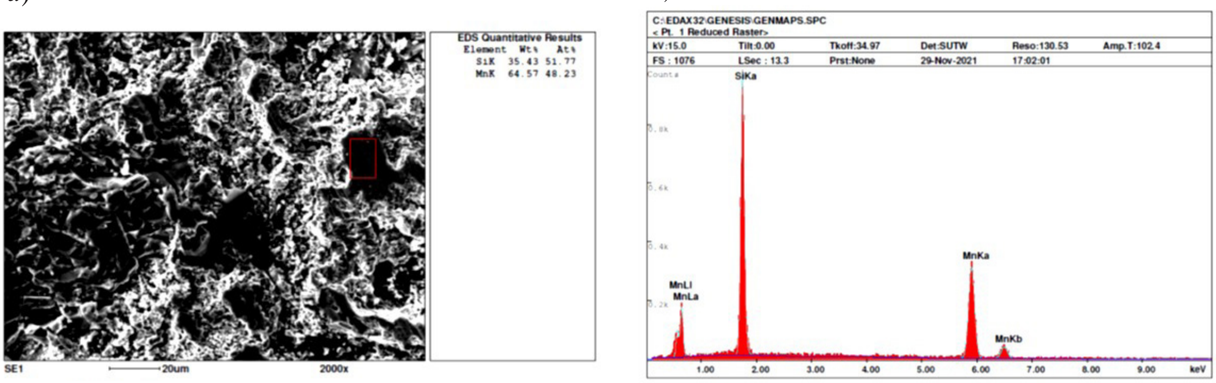

Fig. 1. The results of studying the Mn_4Si_7 target with a scanning electron microscope (SEM): the surface image (*a*) and energy dispersive *X*-ray spectrum (*b*)

The thermoelectric properties (the resistivity and the Seebeck coefficient) of the manufactured Mn_4Si_7 film were determined by placing it in a vacuum of 10 Pa, using the four-probe method and two-probe one, respectively [24].

It is known that the thermoelectric figure of merit ZT of thermoelectric materials is a dimensionless quantity determining by the following formula:

$$ZT = \alpha^2 \sigma T / \kappa, \quad (1)$$

where α, μV/K, is the Seebeck coefficient; σ, S/cm, is the electrical conductivity; κ, W/(m·K), is the thermal conductivity; T, K, is the temperature [25 – 27].

Results and discussion

The Mn_4Si_7 film formed by magnetron sputtering is in an amorphous phase before thermal annealing; this was identified by electron microscope. Fig. 2 presents the SEM-images of the Mn_4Si_7 film before and after annealing. Silicon and manganese atoms deposited on silicon oxide almost completely cover the substrate. The annealing of the Mn_4Si_7 film was carried out at 620 K for 1 h. at a pressure of 10^{-3} Pa using an equipment. The annealed film was cooled in vacuum to room temperature.

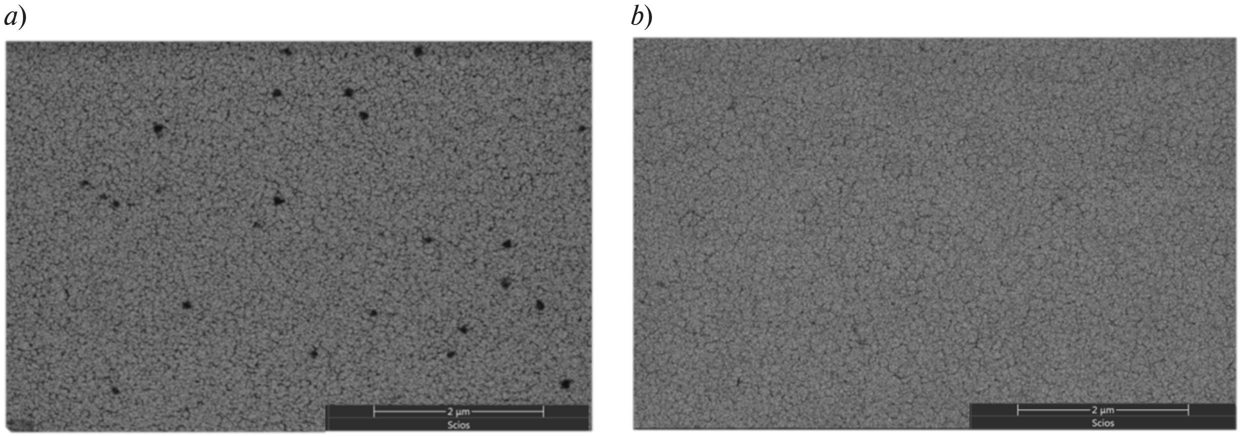

Fig. 2. SEM-images of the Mn_4Si_7 film surface before (*a*) and after (*b*) annealing at 620 K and 10^{-3} Pa

The resistivity of the formed Mn_4Si_7 film was $2 \cdot 10^{-5}$ Ω·cm at room temperature; when heated to a temperature of 750 K, its resistivity rose to $5 \cdot 10^{-5}$ Ω·cm (see Fig. 3, *a*). The electrical conductivity of this film was $5.0 \cdot 10^4$ S/cm at room temperature. As evident from Fig. 3, *b*, its electrical conductivity dropped to $1.2 \cdot 10^4$ S/cm when heated to 750 K.

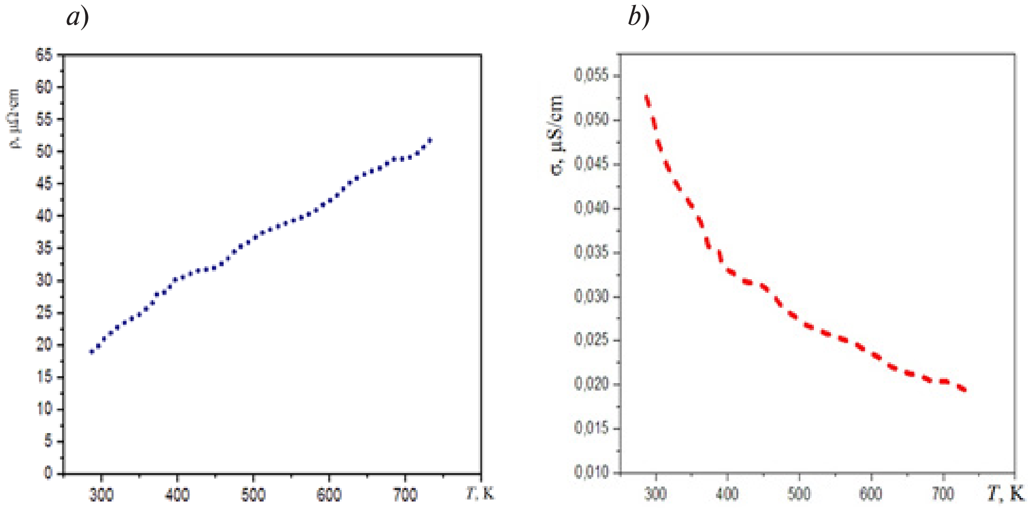

Fig. 3. Temperature dependences of the resistivity (*a*)
and electrical conductivity (*b*) for the Mn_4Si_7 film in amorphous phase

The graphs of the resistivity and electrical conductivity versus temperature for the Mn_4Si_7 annealed film are presented in Fig. 4. It was $7.86 \cdot 10^{-6}$ Ω·cm at room temperature, and when heated to 700 K, its resistivity dropped to $3.90 \cdot 10^{-6}$ Ω·cm (see Fig. 4, *a*). The electrical conductivity of this film was $1.2 \cdot 10^5$ S/cm at room temperature. When heated to 700 K, it rose to $2.7 \cdot 10^5$ S/cm (see Fig. 4, *b*).

As can be seen from these graphs, a decrease in resistivity with increasing temperature (see Fig. 4, *a*) and an increase in electrical conductivity (see Fig. 4, *b*) confirm that the film has a polycrystalline structure.

Fig. 5 presents temperature dependences of the Seebeck coefficient for the Mn_4Si_7 film in amorphous and polycrystalline phases. As evident from these graphs, the Seebeck coefficient in the case of the polycrystalline phase turned out to be approximately 6 times higher than that in the case of the amorphous one.

The thermoelectric figure of merit of the Mn_4Si_7 film was calculated by Eq. (1). Thermal conductivity value of the Mn_4Si_7 film was taken from Ref. [28].

The purification process concurrently enhances the σ and S values, and decreases the κ value for the Mn_4Si_7 samples, leading to an extraordinarily high thermoelectric figure of merit ZT. The

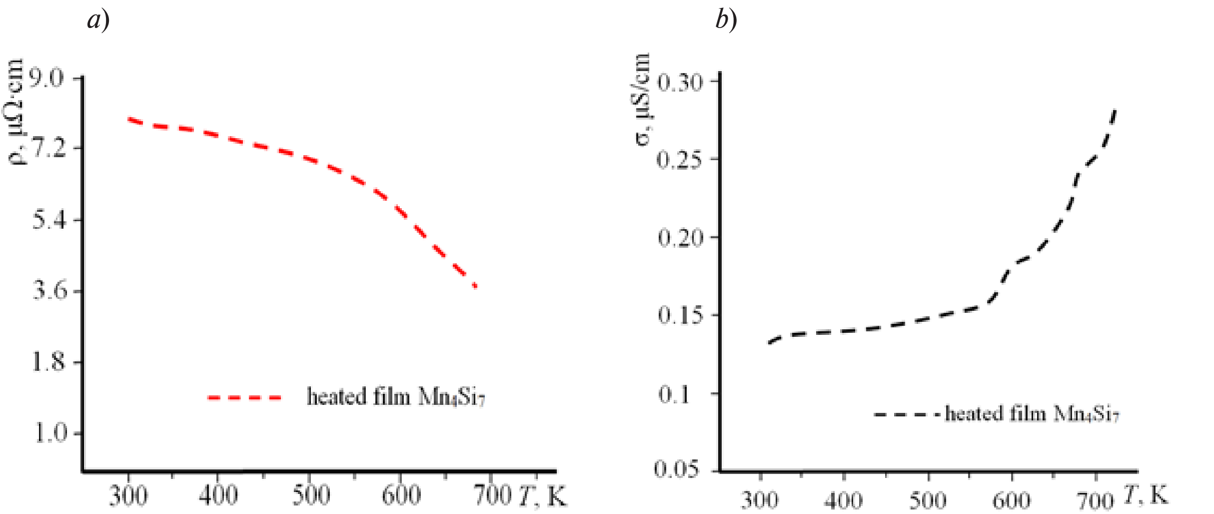

Fig. 4. Temperature dependences of the resistivity (*a*) and electrical conductivity (*b*) of the Mn_4Si_7 annealed film in polycrystalline phase

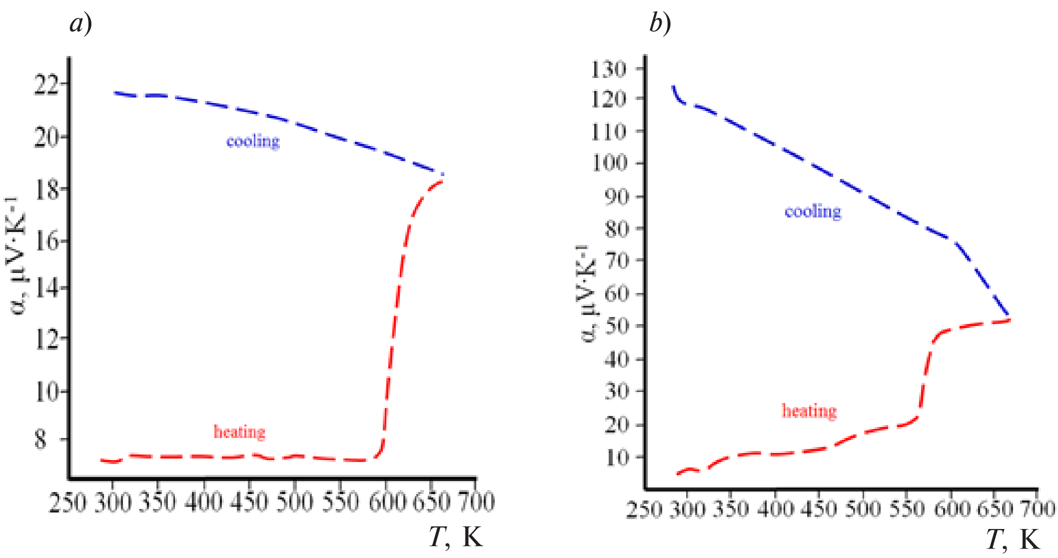

Fig. 5. Temperature dependences of the Seebeck coefficient for the Mn_4Si_7 film in amorphous (*a*) and polycrystalline (*b*) phases

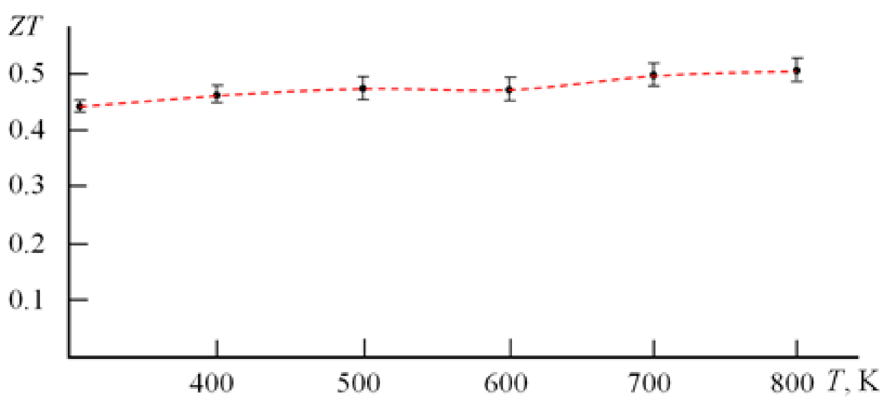

Fig. 6. Temperature dependence of *ZT* for the Mn_4Si_7 film in polycrystalline phase

corresponding curve for the Mn_4Si_7 film exhibits the maximum ZT ($(ZT)_{max}$), namely, about 0.5 at 800 K, and this is the highest value currently known and reported for thermoelectric systems (Fig. 6).

As a result of the experiments conducted with the HMS film, it was found that the thermoelectric properties of the film are better in the crystalline phase than in the amorphous one. This is due to the fact that the bond between manganese and silicon atoms is very weak and there are surface defects on the areas that are not completely covered of material. Surface defects of the film are disappeared as a result of structural relaxation and forming new bonds between the manganese and silicon atoms during the annealing, and the total structure acquires semiconductor properties.

Optical properties of the Mn_4Si_7/SiO_2 film were measured using an HR-4000 high-precision spectrometer according to the law of light reflection (Fig. 7). The graphs showed that the Mn_4Si_7 film had a high sensitivity in the visible and IR regions for the corresponding wavelengths. In addition, it is possible to determine the band gap of the Mn_4Si_7 silicide film from these data, using the Kubelka – Munk equation. The band gap of the film is 0.66 eV. Here α is the absorption coefficient, $h\nu$ (eV) is the photon energy, R (%) is the reflection coefficient, λ (nm) is the light wavelength [29, 30].

a) *b*)

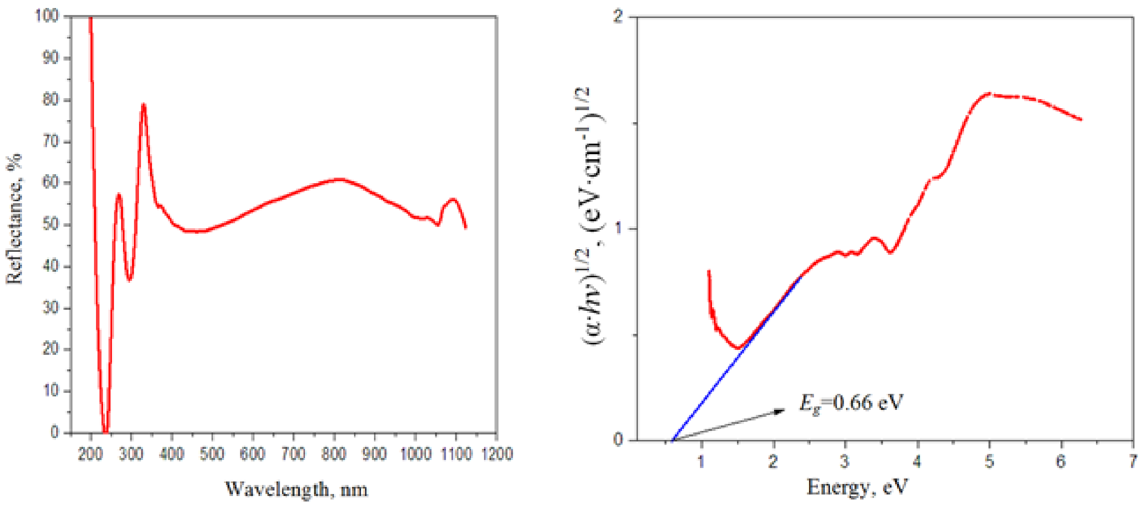

Fig. 7. The Mn_4Si_7 film: the graphs of the light reflection coefficient versus the light wavelength (*a*) and of the absorbed photon energy versus the incident photon one (*b*)

The probability of absorbing a photon depends on the likelihood of having a photon and an electron interact in such a way as to move from one energy band to another. For photons which have an energy very close to that of the band gap, the absorption is relatively low since only those electrons directly at the valence band edge can interact with the photon to cause absorption. As the photon energy increases, not just the electrons already having energy close to that of the band gap can interact with the photon. Therefore, a larger number of electrons can interact with the photon and result in the photon being absorbed.

The absorption coefficient α is related to the extinction coefficient k by the following formula:

$$\alpha = 4\pi k/\lambda, \tag{2}$$

Electrophysical properties of the Mn_4Si_7/SiO_2 film were measured on HMS-3000 Hall Measurement System. Obtained electrophysical parameters of the Mn_4Si_7 thin film are listed in Table.

Table

The obtained results on electrophysical properties of the Mn_4Si_7 film

Parameter	Unit	Value
Volumetric concentration of charged particles	cm^{-3}	$4.5\cdot10^{21}$
Mobility of charged particles	$cm^2/(V\cdot s)$	1.65
Surface resistance	Ω	313
Resistivity	Ω·cm	$7.83\cdot10^{-4}$
Hall coefficient	cm^3/C	$1.28\cdot10^{-3}$
Magnetoresistance	Ω	$1.73\cdot10^{-1}$
Surface concentration of charged particles	cm^{-2}	$1.2\cdot10^{17}$
Electrical conductivity	S/cm	$1.28\cdot10^{3}$

Summary

The paper has been studied a formation of Mn_4Si_7 (higher manganese silicide) films and their electrophysical properties. It was established that the thermoelectric power (the Seebeck coefficient) of the film increased during the transition from the amorphous phase to the nanocrystalline one. This effect is associated with the selective scattering of charge carriers at the boundaries of nanoclusters. The Seebeck coefficient of the film in the polycrystalline phase turned out to be approximately 6 times higher than that in the amorphous phase. The thermoelectric efficiency of Mn_4Si_7 film exhibited the maximum value ZT_{max} of approximately 0.5 at 800 K.

Moreover, it was revealed that Mn_4Si_7 films grown on a SiO_2/Si substrate had the highest conversion coefficient, and this is explained by the low thermal conductivity κ = 149 W/mK of SiO_2/Si. The films of Mn_4Si_7 on SiO_2/Si exhibited the high response speed, high sensitivity.

The results obtained indicate that the Mn_4Si_7 films can be recommended for use in thermal wave radiation detectors in the visible and infrared electromagnetic ranges.

REFERENCES

1. **Deng T., Xu Zh., Yamashita Y., et al.,** Modeling the effects of defect parameters on the performance of a *p*-$BaSi_2$/*n*-Si heterojunction solar cell, Sol. Energy Mater. Sol. Cells. 205 (February) (2020) 110244.
2. **Todorov T. K., Bishop D. M., Lee Y. S.,** Materials perspectives for next-generation low-cost tandem solar cells, Sol. Energy Mater. Sol. Cells. 180 (15 June) (2018) 350–357.
3. **Matsui T., Sai H., Saito K., Kondo M.,** High-efficiency thin-film silicon solar cells with improved light-soaking stability, Prog. Photovolt. 21 (6) (2013) 1363–1369.
4. **Müller J., Rech B., Springer J., Vanecek M.,** TCO and light trapping in silicon thin film solar cells, Sol. Energy. 77 (6) (2004) 917–930.
5. **Chopra K. L., Paulson P. D., Dutta V.,** Thin-film solar cells: an overview, Prog. Photovolt. 12 (2–3) (2004) 69–92.
6. **Shah A. V., Schade H., Vanecek M., et al.,** Thin-film silicon solar cell technology, Prog. Photovolt. 12 (2–3) (2004) 113–142.
7. **Nakamura T., Suemasu T., Takakura K., et al.,** Investigation of the energy band structure of orthorhombic $BaSi_2$ by optical and electrical measurements and theoretical calculations, Appl. Phys. Lett. 81 (6) (2002) 1032–1034.
8. **Kishino S., Imai T., Iida T., et al.,** Electronic and optical properties of bulk crystals of semiconducting orthorhombic $BaSi_2$ prepared by the vertical Bridgman method, J. Alloys Compd. 428 (1–2) (2007) 22–27.

9. **Donaev S. B., Tashatov A. K., Umirzakov B. E.,** Effect of Ar^+-ion bombardment on the composition and structure of the surface of $CoSi_2$ / Si(111) nanofilms, J. Surf. Investig. 9 (2) (2015) 406–409.

10. **Lu Z., Zhou H., Ye C., et al.,** Fabrication of iron pyrite thin films and photovoltaic devices by sulfurization in electrodeposition method, Nanomaterials. 11 (11) (2021) 2844.

11. **Donaev S. B., Umirzakov B. E., Mustafaeva N. M.,** Emissivity of laser-activated Pd-Ba alloy, Tech. Phys. 64 (10) (2019) 1541–1543.

12. **Isakhanov Z. A., Umirzakov Y. E., Ruzibaeva M. K., Donaev S. B.,** Effect of the O^{2+}-ion bombardment on the TiN composition and structure, Tech. Phys. 60 (2) (2015) 313–315.

13. **Donaev S. B., Djurabekova F., Tashmukhamedova D. A., Umirzakov B. E.,** Formation of nanodimensional structures on surfaces of GaAs and Si by means of ion implantation, Phys. Status Solidi C. 12 (1–2) (2015) 89–93.

14. **Normuradov M. T., Rysbaev A. S., Bekpulatov I. R., et al.,** Formation and electronic structure of barium-monosilicide and barium-disilicide films, J. Surf. Investig. 15 (Suppl. 1) (2021) S211–S215.

15. **Saleemi M., Famengo A., Fiameni S., Toprak M.,** Thermoelectric performance of higher manganese silicide nanocomposites, J. Alloys Compd. 619. (15 January) (2015) 31–37.

16. **Joo S., Lee H., Jang J.,** Thermoelectric properties of higher manganese silicide films deposited by radio frequency magnetron co-sputtering, J. Alloys Compd. 747 (30 May) (2018) 603–610.

17. **Rysbaev A. S., Khuzhaniyazov Z. B., Rakhimov A. M., Bekpulatov I. R.**, Formation of nanosize silicides films on the Si (111) and Si (100) surfaces by low-energy ion implantation, Techn. Phys. 59 (10) (2014) 1526–1530.

18. **Bekpulatov I. R., Imanova G. T., Kamilov T. S., et al.,** Formation of *n*-type CoSi monosilicide film which can be used in instrumentation, Int. J. Mod. Phys. B. 36 (32) (2022) 2350164.

19. **Orekhov A. S., Kamilov T. S., Ibragimova B. V., Ivakin G. I., Klechkovskaya V. V.,** Structure of thermoelectric films of higher manganese silicide on silicon according to electron microscopy data, Semiconductors. 51 (6) (2017) 706–709.

20. **Kamilov T. S., Rysbaev A. S., Klechkovskaya V. V., et al.,** Influence of structural defects in silicon on formation of photosensitive heterostructures Mn_4Si_7-Si-Mn_4Si_7 and Mn_4Si_7-Si-M, Eurasian J. Phys. Funct. Mater. 2 (4) (2018) 360–366.

21. **Kamilov T. S., Rysbaev A. S., Klechkovskaya V. V., et al.,** The influence of structural defects in silicon on the formation of photosensitive Mn_4Si_7-Si(Mn)-Mn_4Si_7 and Mn_4Si_7-Si(Mn)-M heterostructures, Appl. Sol. Energy. 55 (6) (2019) 380–384.

22. **Liu H., She G., Huang X., et al.,** Synthesis and magnetic properties of Mn_4Si_7 and Si-Mn_4Si_7 axial heterostructure nanowire arrays, J. Phys. Chem. C. 117 (5) (2013) 2377–2381.

23. **Zolotarev V. M., Nikonorov N. V., Ignatiev A. I.,** Sovremennyye metody issledovaniya opticheskikh materialov. Chast II. Metody issledovaniya poverkhnosti opticheskikh materialov i tonkikh plenok [Modern methods of studying optical materials. Part II. Methods of studying the surface of optical materials and thin films], NIU ITMO, St. Petersburg, 2013 (in Russian).

24. **Mavrokefalos A., Pettes M. T., Zhou F., Shi L.,** Four-probe measurements of the in-plane thermoelectric properties of nanofilms, Rev. Sci. Instrum. 78 (3) (2007) 034901.

25. **Pitarch B. B., Gonjal J. P., Powell A., et al.,** Thermal conductivity, electrical resistivity, and dimensionless figure of merit (ZT) determination of thermoelectric materials by impedance spectroscopy up to 250 °C, J. Appl. Phys. 124 (2) (2018) 025105.

26. **Stevens K. R., Kanatzidis M. G., Johnsen S., Girard S. N.,** Investigation of the thermoelectric properties of metal chalcogenides with SnSe, Nanoscape. 7 (1) (2010) 52–57.

27. **Yin Y., Tiwari A.,** Understanding the effect of thickness on the thermoelectric properties of $Ca_3Co_4O_9$ thin films, Sci. Rep. 11 (2021) 6324.

28. **Choia S., Kuboa K., Uchiyamaa N., Takeuchi T.,** Thermoelectric properties of higher manganese silicide consolidated by flash spark plasma sintering technique, J. Alloys Compds. 921 (15 November) (2022) 166104.

29. **Riungu G. G., Mugo S. W., Ngaruiya J. M., et al.,** Optical band energy, Urbach energy and associated band tails of nano crystalline TiO_2 films at different annealing rates, Am. J. Nanosci. 7 (1) (2021) 28–34.

30. **Salah K. H.,** The determination of optical band and optical constants of MnO_2 thin films prepared by spray pyrolysis, Berk. Fis. Indones. 5 (1) (2013) 1–6.

СПИСОК ЛИТЕРАТУРЫ

1. **Deng T., Xu Zh., Yamashita Y., Sato T., Toko K., Suemasu T.** Modeling the effects of defect parameters on the performance of a p-$BaSi_2$/n-Si heterojunction solar cell // Solar Energy Materials & Solar Cells. 2020. Vol. 205. February. P. 110244.

2. **Todorov T. K., Bishop D. M., Lee Y. S.** Materials perspectives for next-generation low-cost tandem solar cells // Solar Energy Materials & Solar Cells. 2018. Vol. 180. 15 June. Pp. 350–357.

3. **Matsui T., Sai H., Saito K., Kondo M.** High-efficiency thin-film silicon solar cells with improved light-soaking stability // Progress in Photovoltaics. 2013. Vol. 21. No. 6. Pp. 1363–1369.

4. **Müller J., Rech B., Springer J., Vanecek M.** TCO and light trapping in silicon thin film solar cells // Solar Energy. 2004. Vol. 77. No. 6. Pp. 917–930.

5. **Chopra K. L., Paulson P. D., Dutta V.** Thin-film solar cells: an overview // Progress in Photovoltaics. 2004. Vol. 12. No. 2–3. Pp. 69–92.

6. **Shah A. V., Schade H., Vanecek M., Meier J., Sauvain E. V., Wyrsch N., Kroll U., Droz C., Bailat J.** Thin-film silicon solar cell technology // Progress in Photovoltaics. 2004. Vol. 12. No. 2–3. Pp. 113–142.

7. **Nakamura T., Suemasu T., Takakura K., Hasegawa F., Wakahara A., Imai M.** Investigation of the energy band structure of orthorhombic $BaSi_2$ by optical and electrical measurements and theoretical calculations // Applied Physics Letters. 2002. Vol. 81. No. 6. Pp. 1032–1034.

8. **Kishino S., Imai T., Iida T., Nakaishi Y., Shinada M., Takanashi Y., Hamada N.** Electronic and optical properties of bulk crystals of semiconducting orthorhombic $BaSi_2$ prepared by the vertical Bridgman method // Journal of Alloys and Compounds. 2007. Vol. 428. No. 1–2. Pp. 22–27.

9. **Донаев С. Б., Ташатов А. К., Умирзаков Б. Е.** Влияние бомбардировки ионами Ar^+ на состав и структуру поверхности нанопленок $CoSi_2$ / Si(111) // Поверхность. Рентгеновские, синхротронные и нейтронные исследования. 2015. № 4. С. 95–98.

10. **Lu Z., Zhou H., Ye C., Chen S., Ning J., Halim M. A., Donaev S. B., Wang S.** Fabrication of iron pyrite thin films and photovoltaic devices by sulfurization in electrodeposition method // Nanomaterials. 2021. Vol. 11. No. 11. P. 2844.

11. **Донаев С. Б., Умирзаков Б. Е., Мустафаева Н. М.** Эмиссионные свойства сплава Pd-Ba, активированного лазерным облучением // Журнал технической физики. 2015. Т. 89. № 10. С. 1589–1591.

12. **Исаханов З. А., Умирзаков Ю. Е., Рузибаева М. К., Донаев С. Б.** Влияние бомбардировки ионов O^{2+} на состав и структуру TiN // Журнал технической физики. 2015. Т. 85. № 2. С. 156–158.

13. **Donaev S. B., Djurabekova F., Tashmukhamedova D. A., Umirzakov B. E.** Formation of nanodimensional structures on surfaces of GaAs and Si by means of ion implantation // Physica Status Solidi C. 2015. Vol. 12. No. 1–2. Pp. 89–93.

14. **Normuradov M. T., Rysbaev A. S., Bekpulatov I. R., Normuradov D. A., Tursunmetova Z. A.** Formation and electronic structure of barium-monosilicide- and barium-disilicide films // Journal of Surface Investigation. 2021. Vol. 15. No. 1 (Supplement). Pp. S211–S215.

15. **Saleemi M., Famengo A., Fiameni S., Toprak M.** Thermoelectric performance of higher manganese silicide nanocomposites // Journal of Alloys and Compounds. 2015. Vol. 619. 15 January. Pp. 31–37.

16. **Joo S., Lee H., Jang J.** Thermoelectric properties of higher manganese silicide films deposited by radio frequency magnetron co-sputtering // Journal of Alloys and Compounds. 2018. Vol. 747. 30 May. Pp. 603–610.

17. **Рысбаев А. С., Хужаниязов Ж. Б., Рахимов А. М., Бекпулатов И. Р.** Формирование наноразмерных пленок силицидов на поверхности Si(111) и Si(100) методом низкоэнергетической ионной имплантации // Журнал технической физики. 2014. Т. 84. № 10. С. 107–111.

18. **Bekpulatov I. R., Imanova G. T., Kamilov T. S., Igamov B. D., Turapov I. K.** Formation of n-type CoSi monosilicide film which can be used in instrumentation // International Journal of Modern Physics B. 2022. Vol. 36. No. 32. P. 2350164.

19. **Орехов А. С., Камилов Т. С., Ибрагимова Б. В., Ивакин Г. И., Клечковская В. В.** Структура термоэлектрических пленок высшего силицида марганца на кремнии по данным электронной микроскопии // Физика и техника полупроводников. 2017. Т. 51. № 6. С. 740–743.

20. **Kamilov T. S., Rysbaev A. S., Klechkovskaya V. V., Orekhov A. S., Dzhuraev Sh. Kh., Kasymov A. S.** Influence of structural defects in silicon on formation of photosensitive heterostructures Mn_4Si_7-Si-Mn_4Si_7 and Mn_4Si_7-Si-M // Eurasian Journal of Physics and Functional Materials. 2018. Vol. 2. No. 4. Pp. 360–366.

21. **Kamilov T. S., Rysbaev A. S., Klechkovskaya V. V., Orekhov A. S., Igamov B. D., Bekpulatov I. R.** The influence of structural defects in silicon on the formation of photosensitive Mn_4Si_7-Si(Mn)-Mn_4Si_7 and Mn_4Si_7-Si(Mn)-M heterostructures // Applied Solar Energy. 2019. Vol. 55. No. 6. Pp. 380–384.

22. **Liu H., She G., Huang X., Qi X., Mu L., Meng X., Shi W.** Synthesis and magnetic properties of Mn_4Si_7 and Si-Mn_4Si_7 axial heterostructure nanowire arrays // The Journal of Physical Chemistry C. 2013. Vol. 117 No. 5. Pp. 2377–2381.

23. **Золотарев В. М., Никоноров Н. В., Игнатьев А. И.** Современные методы исследования оптических материалов. Часть II. Методы исследования поверхности оптических материалов и тонких пленок. СПб.: НИУ ИТМО, 2013. 166 с.

24. **Mavrokefalos A., Pettes M. T., Zhou F., Shi L.** Four-probe measurements of the in-plane thermoelectric properties of nanofilms // Review of Scientific Instruments. 2007. Vol. 78. No. 3. P. 034901.

25. **Pitarch B. B., Gonjal J. P., Powell A., Ziolkowski P., Canadas J. G.** Thermal conductivity, electrical resistivity, and dimensionless figure of merit (ZT) determination of thermoelectric materials by impedance spectroscopy up to 250 °C // Journal of Applied Physics. 2018. Vol. 124. No. 2. P. 025105.

26. **Stevens K. R., Kanatzidis M. G., Johnsen S., Girard S. N.** Investigation of the thermoelectric properties of metal chalcogenides with SnSe // Nanoscape. 2010. Vol. 7. No. 1. Pp. 52–57.

27. **Yin Y., Tiwari A.** Understanding the effect of thickness on the thermoelectric properties of $Ca_3Co_4O_9$ thin films // Scientific Reports. 2021. Vol. 11. P. 6324.

28. **Choia S., Kuboa K., Uchiyamaa N., Takeuchi T.** Thermoelectric properties of higher manganese silicide consolidated by flash spark plasma sintering technique // Journal of Alloys and Compounds. 2022. Vol. 921. 15 November. P. 166104.

29. **Riungu G. G., Mugo S. W., Ngaruiya J. M., John G. M., Mugambi N.** Optical band energy, Urbach energy and associated band tails of nano crystalline TiO_2 films at different annealing rates // American Journal of Nanosciences. 2021. Vol. 7. No. 1. Pp. 28–34.

30. **Salah K. H.** The determination of optical band and optical constants of MnO_2 thin films prepared by spray pyrolysis // Berkala Fisika Indonesia. 2013. Vol. 5. No. 1. Pp. 1–6.

THE AUTHORS

BEKPULATOV Ilkhom R.
Tashkent State Technical University
2 Universitetskaya St., Tashkent, 100095, Uzbekistan
bekpulatov85@rambler.ru
ORCID: 0000-0001-6311-6631

LOBODA Vera V.
Peter the Great St. Petersburg Polytechnic University
29 Politechnicheskaya St., St. Petersburg, 195251, Russia
vera_loboda@mail.ru
ORCID: 0000-0003-3103-7060

NORMURADOV Muradulla T.
Karshi State University
17 Kuchabog St., Karshi, 180103, Uzbekistan
m.normuradov@mail.ru
ORCID: 0000-0003-1771-0853

DONAEV Burkhon D.
Karshi Engineering-Economics Institute
225 Mustakillik Sqr., Karshi, 180100, Uzbekistan
donaev.sardor@gmail.com
ORCID: 0000-0001-7152-1610

TURAPOV Ilkhom Kh.
Tashkent State Technical University
2 Universitetskaya St., Tashkent, 100095, Uzbekistan
turapov_19_86@mail.ru
ORCID: 0000-0001-8946-4079

СВЕДЕНИЯ ОБ АВТОРАХ

БЕКПУЛАТОВ Ильхом Рустамович – *PhD, доцент кафедры общей физики Ташкентского государственного технического университета, г. Ташкент, Узбекистан.*
100095, Узбекистан, г. Ташкент, Университетская ул., 2.
bekpulatov85@rambler.ru
ORCID: 0000-0001-6311-6631

ЛОБОДА Вера Владимировна – *кандидат физико-математических наук, директор Высшей школы электроники и микросистемной техники Санкт-Петербургского политехнического университета Петра Великого, Санкт-Петербург, Россия.*
195251, Россия, г. Санкт-Петербург, Политехническая ул., 29
vera_loboda@mail.ru
ORCID: 0000-0003-3103-7060

НОРМУРАДОВ Мурадулла Тогаевич – *доктор физико-математических наук, профессор кафедры экспериментальной и теоретической физики Каршинского государственного университета, г. Карши, Узбекистан.*
180103, Узбекистан, г. Карши, ул. Кучабог, 17
m.normuradov@mail.ru
ORCID: 0000-0003-1771-0853

ДОНАЕВ Бурхон Донаевич – *кандидат физико-математических наук, доцент кафедры теоретической механики Каршинского инженерно-экономического института, г. Карши, Узбекистан.*
180100, Узбекистан, г. Карши, пл. Мустакиллик, 225
donaev.sardor@gmail.com
ORCID: 0000-0001-7152-1610

ТУРАПОВ Ильхом Химматалиевич – *кандидат физико-математических наук, доцент кафедры общей физики Ташкентского государственного технического университета, г. Ташкент, Узбекистан.*
100095, Узбекистан, г. Ташкент, Университетская ул., 2.
turapov_19_86@mail.ru
ORCID: 0000-0001-8946-4079

Received 16.01.2023. Approved after reviewing 25.01.2023. Accepted 26.01.2023.
Статья поступила в редакцию 16.01.2023. Одобрена после рецензирования 25.01.2023. Принята 26.01.2023.