Accepted Manuscript

Electrical transport characterization of Al and Sn doped Mg₂Si thin films

Bo Zhang, Tao Zheng, Ce Sun, Zaibing Guo, Moon J. Kim, Husam N. Alshareef, Manuel Quevedo-Lopez, Bruce E. Gnade

PII: S0925-8388(17)31842-X

DOI: [10.1016/j.jallcom.2017.05.224](https://doi.org/10.1016/j.jallcom.2017.05.224)

Reference: JALCOM 41955

To appear in: *Journal of Alloys and Compounds*

Received Date: 3 April 2017

Revised Date: 12 May 2017

Accepted Date: 20 May 2017

Please cite this article as: B. Zhang, T. Zheng, C. Sun, Z. Guo, M.J. Kim, H.N. Alshareef, M. Quevedo-Lopez, B.E. Gnade, Electrical transport characterization of Al and Sn doped Mg₂Si thin films, *Journal of Alloys and Compounds* (2017), doi: 10.1016/j.jallcom.2017.05.224.

This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

Electrical Transport Characterization of Al and Sn Doped Mg₂Si Thin Films

Bo Zhang¹, Tao Zheng¹, Ce Sun¹, Zaibing Guo⁴, Moon J. Kim¹, Husam N. Alshareef³, Manuel Quevedo-Lopez¹, Bruce E. Gnade^{1,2*}

¹*Materials Science Department, University of Texas at Dallas, Richardson, TX, USA 75080*

²*Lyle school of Engineering, Southern Methodist University, Dallas, TX, USA 75275*

³*Physical Sciences and Engineering Division (PSE), 4700 King Abdullah University of Science and Technology (KAUST), Thuwal 23955-6900, Kingdom of Saudi Arabia*

⁴*Nanofabrication Core Lab, 4700 King Abdullah University of Science and Technology (KAUST), Thuwal 23955-6900, Kingdom of Saudi Arabia*

Abstract

Thin-film Mg₂Si was deposited using radio frequency (RF) magnetron sputtering. Al and Sn were incorporated as n-type dopants using co-sputtering to tune the thin-film electrical properties. X-ray diffraction (XRD) analysis confirmed that the deposited films are polycrystalline Mg₂Si. The Sn and Al doping concentrations were measured using Rutherford backscattering spectroscopy (RBS) and energy dispersive X-ray spectroscopy (EDS). The charge carrier concentration and the charge carrier type of the Mg₂Si films were measured using a Hall bar structure. Hall measurements show that as the doping concentration increases, the carrier concentration of the Al-doped films increases, whereas the carrier concentration of the Sn-doped films decreases. Combined with the resistivity measurements, the mobility of the Al-doped

Mg₂Si films is found to decrease with increasing doping concentration, whereas the mobility of the Sn-doped Mg₂Si films is found to increase.

Keywords: thin films, sputtering, Sn, Al doped Mg₂Si films, thermoelectric, electrical properties, Hall measurements

* Corresponding author :

E-mail: bgnade@mail.smu.edu; Tel: +1-214-768-1891 (Bruce E. Gnade)

1. Introduction:

Mg₂Si is a promising material for thermoelectric generators because of its low density, the main constituent materials have a high natural abundance making them low cost, and the materials are non-toxic [1–6]. The performance of thermoelectric materials is defined as the material thermoelectric figure of merit $ZT = \frac{\sigma S^2}{\kappa}$, where σ is the electrical conductivity, S is the Seebeck coefficient and κ is the thermal conductivity. The ZT of Mg₂Si peaks in the temperature range of 500–850 K, which makes it ideal for automotive applications [7]. Much of the previous research has focused on improving ZT of Mg₂Si, with the most commonly used method being to dope the material. We selected Sn and Al as two doping elements. Sn was chosen as a dopant because Sn is a well-known doping material for enhancing the ZT of Mg₂Si. Most research has focused on high concentrations (20–100 at.%) of Sn [8–10]. For low concentration of Sn doping, Sn is expected to substitute on the silicon lattice, since it is isoelectronic to Si, generating a large mass contrast and increasing phonon scattering [11]. Thermal conductivity should be reduced while the electronic properties should remain similar. In this study, our goal is to investigate the doping effect at low concentrations (0–5 at%) and determine the electronic properties of thin-film Mg₂Si as a function of Sn doping concentration. According to Han et al.'s [12] study on the origin of n-type behavior of Sn-doped Mg₂Si, the co-doping states of interstitial Mg and substitutional Si are more stable than interstitial Sn or any other co-doping states. The interstitial Mg next to the interstitial Sn can act as donors contributing charge to the host system. Therefore Sn should act as an n-type dopant. Al was selected as a second dopant as it is expected to substitute on the Mg site and function as a donor [13].

Thin-film Mg₂Si was used because the microstructure and the doping levels can be better controlled. RF sputtering was used to deposit the thin-film Mg₂Si. The effect of deposition

temperature was also studied. Co-sputtering was used to introduce Sn or Al dopants. The crystalline structure of the deposited films was determined using XRD. The doping concentration was measured using RBS and EDS. The carrier concentration and mobility of the doped and not intentionally doped films were determined using Hall measurements.

2. Experimental details

A Mg_2Si compound target (99.9%, Angstrom Sciences) was used for the sputter deposition of thin-film Mg_2Si . Four-inch wafers (Silicon Valley Microelectronics, Inc) were used as substrates ($\text{Si}_3\text{N}_4/\text{SiO}_2/\text{Si}$ (100), P-doped), where approximately 500 nm of Si_3N_4 was deposited using low-pressure chemical vapor deposition (LPCVD) on top of approximately 500 nm of thermally grown SiO_2 . The substrate was loaded into the sputter deposition chamber when the base pressure in the chamber reached 10^{-8} Torr. The substrate was heated at 200°C for two hours to remove volatile surface contaminants. After the substrate cooled to room temperature, the deposition was started. For depositions done at higher temperatures, the substrate was preheated for two hours to stabilize the substrate temperature. The thin-film Mg_2Si was deposited using an RF power of 3.7 W/cm^2 , an Ar gas flow of 20 sccm, a deposition time of 100 min and a pressure of 4 mTorr. The thickness of the Mg_2Si films varied from 190 to 250 nm for different deposition temperatures. The thicknesses were determined using a Veeco Dektak VIII Profilometer.

The dopants were introduced by controlling the deposition time for Sn or Al using a second RF gun. An RF power of 0.44 W/cm^2 was used for the Sn doping. Total deposition times of 2 min, 4 min, 10 min and 20 min were used for $0.4 \pm 0.1 \text{ at\%}$, $0.9 \pm 0.1 \text{ at\%}$, $2.0 \pm 0.2 \text{ at\%}$ and $4.1 \pm 0.3 \text{ at\%}$ Sn doping, respectively. An RF power of 0.59 W/cm^2 was used for the Al

doping. Total deposition times of 8 min, 16 min, 40 min and 80 min were used for 0.3 ± 0.4 at%, 0.6 ± 0.1 at%, 0.7 ± 0.1 at% and 1.4 ± 0.1 at% Al doping, respectively.

The electrical transport properties were determined using a Hall bar structure (**Figure 1**), which was fabricated using a pattern and etch process. Buffered Oxide Etchant (BOE 7:1) was used as the etchant for Mg_2Si . The top metal contact layer was patterned using a lift-off process. Before depositing the metal contacts, the devices were pre-sputtered using Ar^+ at 10 mTorr with 50 W power to remove surface contamination. The contact metal consists of sputter deposited 300 nm Ti and 100 nm Au.

Grazing incidence x-ray diffraction (GIXRD, Rigaku Ultima III) measurements were performed to analyze the crystalline phase of the thin-film Mg_2Si with copper radiation ($\lambda_{\text{Cu.K}\alpha} = 1.54 \text{ \AA}$), and an incident angle of 0.5° . The RBS data were collected using a KOBE HRBS-V500 system at the Nanofabrication Core Lab at KAUST. A 400 keV beam of He^{2+} ions and a detection angle of 107.5° was used for the detector.

3. Results and discussion

Figure 2 shows that Mg_2Si films deposited at substrate temperatures of 100°C , 200°C , 250°C and 300°C are polycrystalline. Films deposited at room temperature are amorphous. The labeled peaks of (111), (200), (220), (311) and (400) correspond to the Mg_2Si phase with the space group $\text{Fm}\bar{3}\text{m}$ [14, 15, 16]. In addition to the Mg_2Si phase, an elemental Mg phase is also observed, as indicated by the peaks at 36.59° , 34.27° and 32.15° [17]. It has been reported in the literature that in order to synthesize bulk stoichiometric Mg_2Si , extra Mg (1-3 at%) is added to make up for the Mg loss due to its high vapor pressure and low condensation rate [18,19]. We use a compound bulk Mg_2Si target for depositing the thin films. A possible explanation is that during sputter deposition, more time is needed for completely forming the Mg-Si bonds at low

temperatures [20]. When the deposition temperature increases, Mg atoms gain more energy to react with Si, becoming incorporated in the matrix. This explains our observation that the Mg phase gradually decreases in the Mg_2Si films with increasing deposition temperature. In previous studies by Le-Quoc et al., a similar phenomenon was also reported for Mg_2Si films prepared by sputtering [17,21].

Figure 3 shows the resistivity, carrier concentration and mobility of the not intentionally doped thin-film Mg_2Si for different deposition temperatures. Because z is proportional to carrier mobility μ , and also because the peak mobility point (200°C) has a carrier concentration of $5.5 \times 10^{17} \text{ cm}^{-3}$, we chose this deposition temperature to conduct the doping experiments, aiming for a fine tuning of the carrier concentration to further enhance the thin film thermoelectric performance [22]. The amount of Sn or Al atoms that were incorporated into the Mg_2Si films was controlled by changing the deposition time from the Sn or Al target. The Sn doping concentrations were determined using high resolution RBS, with the concentrations being $0.4 \pm 0.1 \text{ at\%}$, $0.9 \pm 0.1 \text{ at\%}$, $2.0 \pm 0.2 \text{ at\%}$ and $4.1 \pm 0.3 \text{ at\%}$, respectively. The RBS data show that Sn is uniformly distributed throughout the film (**Figure 4, 5**). Also, depth profiles obtained from RBS analysis show that the atomic ratios between Mg and Si are approximately 2.0 ± 0.1 (**Figure 5**), indicating the Mg_2Si films deposited using RF magnetron sputtering are nearly stoichiometric. The doping concentrations of Al were determined using EDS, because the overlapping peaks of Al, Mg and Si are difficult to resolve in RBS spectra. The Al doping concentrations are $0.3 \pm 0.4 \text{ at\%}$, $0.6 \pm 0.1 \text{ at\%}$, $0.7 \pm 0.1 \text{ at\%}$ and $1.4 \pm 0.1 \text{ at\%}$. The experimentally determined doping concentrations for Sn and Al are given in **Table 1**.

Table 1. Summary of Sn or Al doping concentrations

Sample #	Doping concentration for Sn (at%) ^a	Doping concentration for Al (at%) ^b
1	0.4 ± 0.1	0.3 ± 0.4
2	0.9 ± 0.1	0.6 ± 0.1
3	2.0 ± 0.2	0.7 ± 0.1
4	4.1 ± 0.3	1.4 ± 0.1

a: data obtained using RBS; b: data obtained using EDS.

The electrical properties of the thin-film Mg_2Si were determined using Hall measurements. The Hall voltages of the doped and not intentionally doped Mg_2Si films are all negative, indicating an n-type semiconductor. In the Al doped films, the carrier concentration increases as the Al concentration increases (**Figure 6 (b)**). First-principle calculations show that the formation energy for Al substitution into a Mg-site is generally lower than for an Al atom in a Si site [13]. The added Al atoms tend to function as electron donors by substituting for Mg in the lattice, which is in a good agreement with our experimental results. A decrease of the carrier mobility is observed (**Figure 6 (b)**) as the aluminum concentration increases, which is likely due to the increased electron scattering by the added Al atoms.

In contrast, the carrier concentration decreases as the Sn concentration increases (**Figure 6 (a)**). In order to help understand this result, grazing angle XRD measurements were performed. As shown in **Figure 7**, the Mg peaks disappear after adding Sn dopants, suggesting that the added Sn reacts with the excess Mg in the film. Because excess Mg is the main charge carrier [12], the carrier concentration would decrease as the Sn dopant concentration increases. In order to compare with the Mg peaks in the Al doped Mg_2Si films, the XRD results for Al doped films are shown in **Figure 8**. Mg peaks are observed in every doping concentration, consistent with the statement that the added Al will substitute for Mg atoms in the lattice.

Analysis of the XRD pattern shows that with increasing Sn dopant concentration: (1) all of the peaks shift to a lower diffraction angle; (2) the Mg_2Si (200) peak intensity gradually decreases; (3) the Mg_2Si (111) peak intensity gradually increases. The added Sn causes the peaks to shift to a lower diffraction angle because the larger Sn atom generates strain within the film. By calculating the lattice constants based on the shift of the diffraction peaks, we observe that the lattice constants of the film linearly increase with the increase of Sn doping concentration (**Figure 9**). According to reference [12], Sn is energetically more favorable to substitute for Si instead of becoming interstitial Sn. Combined with our observation from XRD results, the mechanism of Sn doping is revealed: the added Sn atoms tend to react with the excess Mg, as well as substitute for Si atoms in the lattice, and form $\text{Mg}_2\text{Si}_{1-x}\text{Sn}_x$ alloy. In addition, the linear relationship is consistent with the RBS results.

The disappearance of the (200) peak and the increase for the (111) peak are due to Sn atoms substituting for Si atoms as well. The intensity (I) of the XRD peaks are proportional to the square of the absolute structure factor ($I \propto |F_{hkl}|^2$), where the structure factor is determined by the crystalline structure, atom positions and their form factors [23]. Since Mg_2Si has an anti-fluorite crystalline structure (PDF#35-0773), the calculated structure factors for certain scattering planes are shown in Table 2, where f_{hal} represents the form factor of Si or Sn and f_{met} is the form factor of Mg. Therefore, the intensity of the (200) peak is proportional to $16(f_{\text{hal}} - 2f_{\text{met}})^2$, while the intensity of the (111) peak is proportional to $16f_{\text{hal}}^2$. Sn has a larger form factor compared to Si and Mg, 50, 14 and 10 e/atom, respectively [24]. Adding a small amount of Sn will lead to the increase of f_{hal} , so a peak intensity change in the XRD pattern should be expected, consistent with our observations [23].

Table 2. The structure factor for antiferroite structure under certain condition [25]

The value of structure factor	For certain conditions
0	h, k, l mixed
$4 f_{\text{hal}} + 2f_{\text{met}} $	$h + k + l = 4n$
$4 f_{\text{hal}} - 2f_{\text{met}} $	$h + k + l = 2n$
$4f_{\text{hal}}$	h, k, l uneven

The mobility of the Sn-doped Mg_2Si films (**Figure 6** (a)) increases with respect to the non-doped Mg_2Si film. A peak value is observed at the 0.9 at% dopant concentration. As discussed above, this effect could be either due to the reduced electron scattering as the amount of interstitial Mg decreases, or it could be due to a change in the electronic structure of the $\text{Mg}_2\text{Si}_{1-x}\text{Sn}_x$ solid solution. Further study is necessary to explicitly understand the mobility improvement mechanism.

4. Conclusion

In conclusion, we studied the effects of deposition temperature, doping element, and doping concentration on the electrical properties of sputter deposited Mg_2Si thin films. Increasing deposition temperature increases the film resistivity and decreases the carrier concentration. The mobility peaks at a deposition temperature of 200 °C. We evaluated Al and Sn doping. For the Al-doped thin films, the carrier concentration increases and mobility decreases as the doping concentration increase. An opposite trend is observed in the Sn-doped Mg_2Si films. Although adding Sn was not expected to have an electrical impact on Mg_2Si films, we did observe an electrical property change due to the interaction with excess Mg. Our results suggest that Al atoms substitute for Mg atoms while Sn atoms substitute for Si atoms in the lattice. This

demonstration of tuning the electrical properties of Mg_2Si thin films provides insight into the future optimization of Mg_2Si based thermoelectric devices.

Acknowledgements

The work was partially supported by the II-IV foundation and the University of Texas at Dallas. We thank Mr. Wallace Martin, Dr. Gordon Pollock and Mr. John Maynard from the cleanroom of the University of Texas at Dallas for their help with film preparation. We acknowledge Dr. Jian Wang from the University of Texas at Dallas for his fruitful discussions.

References

- [1] Q. Zhang, J. He, T.J. Zhu, S.N. Zhang, X.B. Zhao, T.M. Tritt, High Figures of Merit and Natural Nanostructures in $\text{Mg}_2\text{Si}_{0.4}\text{Sn}_{0.6}$ Based Thermoelectric Materials, *Appl. Phys. Lett.* 93 (2008) 6–9.
- [2] A. U. Khan, N. Vlachos, T. Kyratsi, High thermoelectric figure of merit of $\text{Mg}_2\text{Si}_{0.55}\text{Sn}_{0.4}\text{Ge}_{0.05}$ materials doped with Bi and Sb, *Scr. Mater.* 69 (2013) 606–609.
- [3] W. Liu, Q. Zhang, K. Yin, H. Chi, X. Zhou, X. Tang, et al., High figure of merit and thermoelectric properties of Bi-doped $\text{Mg}_2\text{Si}_{0.4}\text{Sn}_{0.6}$ solid solutions, *J. Solid State Chem.* 203 (2013) 333–339.
- [4] Y. Thimont, Q. Lognoné, C. Goupil, F. Gascoin, E. Guilmeau, Design of apparatus for Ni/ Mg_2Si and Ni/ $\text{MnSi}_{1.75}$ contact resistance determination for thermoelectric legs, *J. Electron. Mater.* 43 (2014) 2023–2028.
- [5] T. Sakamoto, T. Iida, Y. Honda, M. Tada, T. Sekiguchi, K. Nishio, et al., The use of transition-metal silicides to reduce the contact resistance between the electrode and sintered n-type Mg_2Si , *J. Electron. Mater.* 41 (2012) 1805–1810.
- [6] J. de Boor, C. Gloanec, H. Kolb, R. Sottong, P. Ziolkowski, E. Müller, Fabrication and characterization of nickel contacts for magnesium silicide based thermoelectric generators, *J. Alloys Compd.* 632 (2015) 348–353.
- [7] V.K. Zaitsev, M.I. Fedorov, I.S. Eremin, E.A. Gurieva, Thermoelectrics on the base of solid solutions of Mg_2BIV compounds (BIV = Si, Ge, Sn), in: D.M. Rowe (Ed.), *Thermoelectrics Handbook: Macro to Nano*, CRC Press, New York, 2006, pp 29.1-29.11.
- [8] R.B. Song, T. Aizawa, J.Q. Sun, Synthesis of $\text{Mg}_2\text{Si}_{1-x}\text{Sn}_x$ solid solutions as thermoelectric materials by bulk mechanical alloying and hot pressing, *Mater. Sci. Eng. B*

- Solid-State Mater. Adv. Technol. 136 (2007) 111–117.
- [9] X.J. Tan, W. Liu, H.J. Liu, J. Shi, X.F. Tang, C. Uher, Multiscale calculations of thermoelectric properties of n-type $\text{Mg}_2\text{Si}_{1-x}\text{Sn}_x$ solid solutions, Phys. Rev. B-Condens. Matter Mater. Phys. 85 (2012) 1–10.
- [10] X. Zhang, Q. Lu, L. Wang, F. Zhang, J. Zhang, Preparation of $\text{Mg}_2\text{Si}_{1-x}\text{Sn}_x$ by Induction Melting and Spark Plasma Sintering, and Thermoelectric Properties, J. Electron. Mater. 39 (2010) 1413–1417.
- [11] G.J. Snyder, E.S. Toberer, Complex thermoelectric materials, Nat. Mater., 7, (2008) 105 - 114.
- [12] X. Han, G. Shao, Origin of n-type conductivity of Sn-doped Mg_2Si from first principles, J. Appl. Phys. 112, (2012), 013715.
- [13] J.I. Tani, H. Kido, First-principles and experimental studies of impurity doping into Mg_2Si , Intermetallics. 16 (2008) 418–423.
- [14] P. Gao, I. Berkun, R.D. Schmidt, M.F. Luzenski, X. Lu, P. B. Sarac, E. D. Case, T.P. Hogan, Transport and mechanical properties of high-ZT $\text{Mg}_{2.08}\text{Si}_{0.4-x}\text{Sn}_{0.6}\text{Sb}_x$ thermoelectric materials, J. Electron. Mater. 43 (2014) 1790-1803.
- [15] P. Gao, X. Lu, I. Berkun, R.D. Schmidt, E.D. Case, T.P. Hogan, Reduced lattice thermal conductivity in Bi-doped $\text{Mg}_2\text{Si}_{0.4}\text{Sn}_{0.6}$, Appl. Phys. Lett. 105 (2014) 202104.
- [16] P. Gao, J.D. Davis, V.V. Poltavetsb, T.P. Hogan, The p-type $\text{Mg}_2\text{Li}_x\text{Si}_{0.4}\text{Sn}_{0.6}$ thermoelectric materials synthesized by a B_2O_3 encapsulation method using Li_2CO_3 as the doping agent, J. Mater. Chem. C, 4 (2016) 929-934.
- [17] H. Le-Quoc, a. Lacoste, S. Béchu, a. Bès, D. Bourgault, D. Fruchart, Deposition of thin films of $\text{Mg}_2\text{Si}_{1-x}\text{Sn}_x$ solid solution by plasma-assisted co-sputtering, J. Alloys Compd.

- 538 (2012) 73–78.
- [18] K. Morrison, S.M. Podgornykh, Y.V. Shcherbakova, A.D. Caplin, L.F. Cohen, Effect of Al Substitution on the Magnetocaloric Properties of $\text{La}(\text{Fe}_{0.88}\text{Si}_{0.12-x}\text{Al}_x)_{13}$, *Phys. Rev. B.* 83 (2011) 144415.
- [19] C. Soon-mok, K. Kyung-ho, S. Won-seon, K. Il-ho, K. Sun-uk, Synthesis Characteristics and Thermoelectric Properties of the Rare-earth-doped Mg_2Si System, *J. Korean Phys. Soc.* 57 (2010) 1072.
- [20] M. Ioannou, K. Chrissafis, E. Pavlidou, F. Gascoin, T. Kyratsi, Solid-state synthesis of Mg_2Si via short-duration ball-milling and low-temperature annealing, *J. Solid State Chem.* 197 (2013) 172–180.
- [21] H. Le-Quoc, A. Lacoste, E.K. Hlil, A. Bs, T.T. Vinh, D. Fruchart, et al., Thin films of thermoelectric compound Mg_2Sn deposited by co-sputtering assisted by multi-dipolar microwave plasma, *J. Alloys Compd.* 509 (2011) 9906–9911.
- [22] X. Lu, D.T. Morelli, Y. Xia, F. Zhou, V. Ozolins, H. Chi, et al., High performance thermoelectricity in earth-abundant compounds based on natural mineral tetrahedrites, *Adv. Energy Mater.* 3 (2013) 342–348.
- [23] L. Alexander, S. Allen, N.L. Bindoff, Summary for Policymakers, *J. Chem. Inf. Model.* 53 (2013) 1–36.
- [24] <http://physics.nist.gov/PhysRefData/FFast/html/form.html>
- [25] <https://www.ill.eu/sites/BS-review/structure%20factors.htm>

Figure caption

Figure 1. A schematic example of the Hall bar structures used in this study, the open features represent the metal contacts. The black filled features represent the Hall bar structures. (a) The four-bar structure is used for Hall measurements; (b) the six-bar structure is used for resistivity measurements.

Figure 2. The GIXRD patterns for thin film Mg_2Si deposited at substrate temperatures of 100°C, 200°C, 250°C and 300°C.

Figure 3. The measured resistivity, carrier concentration and mobility of not intentionally doped Mg_2Si films as a function of deposition temperature determined using Hall measurements.

Figure 4. 400 keV- He^{2+} Rutherford backscattering spectra for Sn doped thin-film Mg_2Si . RBS data for Mg_2Si films with (a) 0.4 at%, (b) 0.9 at%, (c) 2.0 at%, and (d) 4.1 at% Sn doping concentration, respectively.

Figure 5. Depth profiles determined from RBS data for Sn doped Mg_2Si thin films on Si_3N_4 with Sn doping concentrations of (a) 0.4 at%, (b) 0.9 at%, (c) 2.0 at% and (d) 4.1 at%. (e) Mg/Si ratio as a function of depth for all Sn doped Mg_2Si thin films.

Figure 6. The measured resistivity, carrier concentration and mobility of: (a) Sn doped, and (b) Al doped Mg_2Si films as a function of doping concentration as determined using Hall measurements.

Figure 7. (a) XRD patterns for Mg_2Si films deposited at 200°C, with 0.4 at%, 0.9 at%, 2.0 at% and 4.1 at% Sn doping concentration, (b) expanded region of Mg peaks.

Figure 8. (a) XRD patterns for Mg_2Si films deposited at 200°C, with 0.3 at%, 0.6 at%, 0.7 at% and 1.4 at% Al doping concentration, (b) expanded region of Mg peaks.

Figure 9. Linear relationship between lattice constant and Sn doping concentration for thin-film Mg_2Si obtained using XRD.

Figure 1. A schematic example of the Hall bar structures used in this study, the open features represent the metal contacts. The black filled features represent the Hall bar structures. (a) The four-bar structure is used for Hall measurements; (b) the six-bar structure is used for resistivity measurements.

Figure 2. The GIXRD patterns for thin film Mg_2Si deposited at substrate temperatures of 100°C, 200°C, 250°C and 300°C.

Figure 3. The measured resistivity, carrier concentration and mobility of not intentionally doped Mg_2Si films as a function of deposition temperature determined using Hall measurements.

Figure 4. 400 keV- He^{2+} Rutherford backscattering spectra for Sn doped thin-film Mg_2Si . RBS data for Mg_2Si films with (a) 0.4 at%, (b) 0.9 at%, (c) 2.0 at%, and (d) 4.1 at% Sn doping concentration, respectively.

Figure 5. Depth profiles determined from RBS data for Sn doped Mg_2Si thin films on Si_3N_4 with Sn doping concentrations of (a) 0.4 at%, (b) 0.9 at%, (c) 2.0 at% and (d) 4.1 at%. (e) Mg/Si ratio as a function of depth for all Sn doped Mg_2Si thin films.

Figure 6. The measured resistivity, carrier concentration and mobility of: (a) Sn doped, and (b) Al doped Mg₂Si films as a function of doping concentration as determined using Hall measurements.

Figure 7. (a) XRD patterns for Mg₂Si films deposited at 200°C, with 0.4 at%, 0.9 at%, 2.0 at% and 4.1 at% Sn doping concentration, (b) expanded region of Mg peaks.

Figure 8. (a) XRD patterns for Mg₂Si films deposited at 200°C, with 0.3 at%, 0.6 at%, 0.7 at% and 1.4 at% Al doping concentration, (b) expanded region of Mg peaks.

Figure 9. Linear relationship between lattice constant and Sn doping concentration for thin-film Mg_2Si obtained using XRD.

Highlights:

- RF magnetron sputtering was used to deposit thin film Mg_2Si .
- Al and Sn atoms were incorporated into Mg_2Si using co-sputtering.
- The RBS results show that Sn is uniformly distributed in depth in the Mg_2Si films.
- Electrical transport properties of the films were determined by Hall measurements.
- The mechanism of Sn doping was studied using XRD.