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Complete List of Authors:	Tan, Gangjian; Northwestern University, Department of Chemistry Shi, Fengyuan; Northwestern University, Department of Materials Science and Engineering Sun, Hui; University of Michigan, Department of Physics Zhao, Li-Dong; Northwestern University, Department of Chemistry Uher, Ctirad; University of Michigan, Department of Physics Dravid, Vinayak; Northwestern University, Department of Materials Science and Engineering; Northwestern University, Kanatidis, Mercouri; Northwestern University, Department of Chemistry

# SnTe-AgBiTe<sub>2</sub> as efficient thermoelectrics with low thermal conductivity

Gangjian Tan,<sup>1</sup> Fengyuan Shi,<sup>2</sup> Hui Sun,<sup>3</sup> Li-Dong Zhao,<sup>1</sup> Ctirad Uher,<sup>3</sup>  
Vinayak P. Dravid,<sup>2</sup> and Mercuri G. Kanatzidis<sup>1,4,\*</sup>

<sup>1</sup>Department of Chemistry, Northwestern University, Evanston, Illinois 60208, United States

<sup>2</sup>Department of Materials Science and Engineering, Northwestern University, Evanston, Illinois 60208, United States

<sup>3</sup>Department of Physics, University of Michigan, Ann Arbor, Michigan 48109, United States

<sup>4</sup>Materials Science Division, Argonne National Laboratory, Argonne, Illinois 60439, United States

\*Corresponding author: [m-kanatzidis@northwestern.edu](mailto:m-kanatzidis@northwestern.edu)

## Abstract

SnTe is an intriguing alternative to its sister compound PbTe in thermoelectric energy conversion because of their electronic and structural similarity; however, it is challenging to optimize its thermoelectric performance to the level of PbTe because of the difficulties in decreasing its intrinsically large hole population and high thermal conductivity arising from the tin vacancies. We demonstrate here that by alloying some AgBiTe<sub>2</sub> in SnTe, thus forming AgSn<sub>x</sub>BiTe<sub>x+2</sub> compositions the hole concentration can be duly decreased because of the high efficiency of Bi as an electron donor. The lattice thermal conductivity is also decreased due to the strong scattering of phonons (by point defect scattering as well as Ag-rich nanostructures) to achieve a value of  $\sim 0.7 \text{ Wm}^{-1}\text{K}^{-1}$  at  $\sim 750 \text{ K}$ . As a result, a high thermoelectric figure *ZT* of merit of  $\sim 1.1$  at  $775 \text{ K}$  is achieved by chemical composition optimization, making lead free SnTe-AgBiTe<sub>2</sub> promising thermoelectric materials.

**Keywords:** lead free; SnTe; thermoelectric; nanostructuring

## 1. Introduction

Lead chalcogenides and their solid solutions have been extensively investigated during the past several decades as robust thermoelectric materials with the highest figure of merit  $ZT$  exceeding 2.0 and have been proven to be very thermally stable.<sup>1-7</sup> The perceived toxicity of lead chalcogenides has raised interest in exploring Pb-free alternatives such as the isostructural SnTe for thermoelectric power generation.<sup>8-12</sup>

SnTe is well-known as a non-stoichiometric p-type semiconductor with a very high hole concentration of  $10^{20}$ - $10^{21}$   $\text{cm}^{-3}$  at room temperature arising from the intrinsically present Sn vacancies.<sup>13, 14</sup> These inevitably lead to a very low Seebeck coefficient and a high electronic contribution to the total thermal conductivity in SnTe. Conventional doping cannot significantly decrease the hole population of SnTe,<sup>12, 15</sup> although we recently reported a relatively low hole concentration of  $\sim 5 \times 10^{19}$   $\text{cm}^{-3}$  in Sn self-compensated SnTe via Cd doping.<sup>11</sup>

It was previously reported that by alloying a proper amount of AgSbTe<sub>2</sub> with SnTe, creating the quaternary system AgSn<sub>m</sub>SbTe<sub>m+2</sub>, the hole concentration of SnTe can be reduced (not by Hall measurement) as evidenced by the variation of the Seebeck coefficient as a function of  $m$ .<sup>8</sup> The most recent study of this system by Xing et al., however, pointed towards an opposite direction that the hole concentration of SnTe increases with increasing AgSbTe<sub>2</sub> although curiously the Seebeck coefficient also increased in this process.<sup>16</sup> These results suggest that the introduction of AgSbTe<sub>2</sub> warrants additional investigations regarding its role in affecting the hole population of SnTe. Despite this, the presence of AgSbTe<sub>2</sub> in SnTe can greatly decrease the lattice

thermal conductivity of SnTe by the nanostructuring scattering of phonons<sup>8, 17, 18</sup> (AgSn<sub>m</sub>SbTe<sub>m+2</sub> system (TAST) is a nanostructured composite<sup>17, 18</sup>) similar to the AgPb<sub>m</sub>SbTe<sub>m+2</sub> systems (LAST)<sup>1</sup>.

As a dopant bismuth has a contrasting role in lead chalcogenides<sup>4, 19</sup> with respect to antimony although they are very chemically similar, lying in the fact that Bi is a more efficient electron donor while Sb is more helpful to create nanostructures. This motivates us to investigate what would happen if Sb is totally replaced by Bi in AgSn<sub>m</sub>SbTe<sub>m+2</sub>. We demonstrate here that the SnTe-AgBiTe<sub>2</sub> system with general chemical composition of AgSn<sub>x</sub>BiTe<sub>x+2</sub> has much higher Seebeck coefficients than those of AgSn<sub>m</sub>SbTe<sub>m+2</sub>. This affirms that Bi is more powerful in neutralizing the holes in SnTe than Sb, with the highest value approaching ~180 μV/K around 800 K by tuning x. Interestingly, we also observe dispersed nanoscale precipitates that are evenly and coherently distributed within the SnTe matrix, which suggests that the SnTe-AgBiTe<sub>2</sub> system is not only a solid solution. These distinctive nanostructures coupled with the point defect scattering by Ag and Bi alloying at Sn sites give rise to a very low lattice thermal conductivity of ~0.7 W/mK at ~750 K in AgSn<sub>x</sub>BiTe<sub>x+2</sub>. Consequently, an optimized  $ZT$  of ~1.1 is achieved around 800 K for the nominal composition of x=15, which makes the SnTe-AgBiTe<sub>2</sub> system attractive in mid-temperature thermoelectric power generation.

## 2. Experimental section

### Synthesis

Reagent chemicals were used as obtained: Ag chunk (99.99%, American

Elements, US), Sn chunk (99.999%, American Elements, US), Bi shot (99.999%, American Elements, US), and Te shot (99.999%, 5N Plus, American Elements).

**Synthesis of Starting Materials:** Samples with nominal compositions SnTe and  $\text{AgSn}_x\text{BiTe}_{x+2}$  ( $x=25, 20, 15, 10,$  and  $5$ ) were prepared as follows. Appropriate amounts of Ag, Sn, Bi, and Te were weighed and mixed in 10 mm diameter silica tubes. The tubes were then evacuated to a residual pressure of  $\sim 10^{-4}$  Torr, flame-sealed, slowly heated to 1273 K in 10 h, soaked at this temperature for 6 h, then slowly cooled down to 1073 K in 2 h, dwelled at this temperature for 4 h, and then slowly cooled to room temperature by switching off the furnace power. To help improve the homogeneity of the samples, the tubes were periodically shaken in the melting process. For a typical experiment: Ag (0.2023 g, 1.8751 mmol), Sn (3.3384 g, 28.1268 mmol), Bi (0.3919 g, 1.8751 mmol), and Te (4.0675 g, 31.8770 mmol) were used to prepare 8 g of  $\text{AgSn}_{15}\text{BiTe}_{17}$  sample.

The melt grown ingots were ground into fine powders using a mechanical mortar and pestle to reduce the grains to less than 4  $\mu\text{m}$  in diameter. These powders were then densified by spark plasma sintering (SPS) method (SPS-211LX, Fuji Electronic Industrial Co., Ltd.) at 723 K for 5 min in a 12.7 mm diameter graphite die under an axial pressure of 40 MPa in vacuum. Highly dense ( $>97\%$  of theoretical density, Table S1) disk-shaped pellets with dimensions of 12.7 mm diameter and 8 mm thickness were obtained. Bars and squares were cut from the same sample pellets for high temperature thermoelectric property measurements.

### Physical Characterization

**Electrical Properties:** The SPSed pellets were cut into 12 mm × 3 mm × 3 mm bars for simultaneous measurement of the Seebeck coefficient and the electrical conductivity using an Ulvac Riko ZEM-3 instrument under a low-pressure helium atmosphere from room temperature to 800 K. The uncertainty of the Seebeck coefficient and electrical conductivity measurements is 5%.

**Thermal Conductivity:** The SPSed pellets were cut and polished into a squared shape of 6×6×2 mm<sup>3</sup> for thermal diffusivity measurements. The thermal diffusivity coefficient ( $D$ ) was measured using the laser flash diffusivity method in a Netzsch LFA457, the specific heat capacity ( $C_p$ ) was indirectly derived using a representative sample (Pyroceram 9606) in the range 300-800 K, and the density ( $d$ ) was determined using the dimensions and mass of the sample. The thermal conductivity was calculated from  $\kappa = D \cdot C_p \cdot d$ . The uncertainty of the thermal conductivity is estimated to be within 8%, considering the uncertainties from  $D$ ,  $C_p$ , and  $d$ . The thermal diffusion and the heat capacity data for all samples can be found in the Supporting Information (Figure S1). The combined uncertainty for all measurements involved in the calculation of  $ZT$  is less than 15%.

**Hall Measurements:** The room temperature Hall measurement was performed on a homemade apparatus (University of Michigan). The Hall resistance was monitored with a Linear Research AC Resistance Bridge (LR-700), with constant magnetic fields of  $\pm 1$  T applied by using an Oxford Superconducting magnet.

### Electron Microscopy and X-ray Diffraction

(Scanning) transmission electron microscopy ((S)TEM), STEM electron energy

loss spectroscopy (EELS) and STEM energy dispersive spectroscopy (EDS) investigations were carried out using a JEOL 2100F microscope operated at 200 kV. Thin TEM specimens were prepared by conventional methods, including cutting, grinding, dimpling, tripod, with minimal duration of Ar-ion milling, and followed by liquid nitrogen cooling, low energy (900 eV) ion milling by Fischione Nanomill. Samples pulverized with an agate mortar were used for powder X-ray diffraction (XRD). The powder diffraction patterns were obtained with Cu K $\alpha$  ( $\lambda = 1.5418 \text{ \AA}$ ) radiation in a reflection geometry on an Inel diffractometer operating at 40 kV and 20 mA and equipped with a position-sensitive detector.

### 3. Results and discussion

#### Phase composition

Figure 1(a) shows the powder XRD patterns for SnTe and AgSn $_x$ BiTe $_{x+2}$  after SPS processing in this study. All Bragg diffraction peaks can be indexed in the cubic NaCl-type structure, space group  $Fm-3m$ , and no obvious second phase can be detected. The lattice parameters decrease with increasing AgBiTe $_2$  content, which is consistent with the difference of lattice parameter between NaCl-structured SnTe ( $6.3093 \text{ \AA}$ )<sup>20</sup> and AgBiTe $_2$  ( $6.155 \text{ \AA}$ )<sup>21</sup>, Figure 1(b). However, it should be noted that the variation of the lattice parameter for AgSn $_x$ BiTe $_{x+2}$  does not strictly follow the Vegard's law indicated by the solid line, Figure 1(b). This suggests that SnTe-AgBiTe $_2$  system cannot be simply viewed as a solid solution. Indeed, as will be shown later (Figure 5), a considerable amount of nanoscaled precipitates is found in AgSn $_x$ BiTe $_{x+2}$

under TEM observation (see below), which is quite similar to the SnTe-AgSbTe<sub>2</sub> and LAST systems<sup>1, 17, 18</sup>.

Figure 2(a) displays the room temperature hole concentration as a function of AgBiTe<sub>2</sub> fraction in AgSn<sub>x</sub>BiTe<sub>x+2</sub>. For typical semiconductors, if iso-electronically substituted, the carrier density will remain unchanged. However, we find that the hole density of the samples is decreased even when a small amount of AgBiTe<sub>2</sub> (x=25) is involved, while when more AgBiTe<sub>2</sub> participates (x<25), the hole concentration increases gradually. We conjecture that at a small level of AgBiTe<sub>2</sub>, Ag and Bi mainly occupy Sn lattices. Unlike SnTe, AgBiTe<sub>2</sub> is stoichiometric.<sup>22</sup> Thus the incorporation of AgBiTe<sub>2</sub> in SnTe can effectively compensate the Sn vacancies and decrease the hole population. However, when more AgBiTe<sub>2</sub> is added, the AgSn<sub>x</sub>BiTe<sub>x+2</sub> compositions tend to be phase segregated (on the nanoscale as we show below) rather than form a complete solid solution. The phase segregation is associated with formation of nanostructures which change the chemical composition of the matrix and thus the hole density. On the other hand, when more AgBiTe<sub>2</sub> is involved, the band gap of SnTe becomes smaller (see discussion below), which would probably decrease the defect formation energy and increase the Sn vacancies, contributing to increased hole densities. A comparison of the hole concentrations of AgSn<sub>x</sub>BiTe<sub>x+2</sub> and AgSn<sub>m</sub>SbTe<sub>m+2</sub>,<sup>16</sup> Figure 2(a), clearly shows that the former has much lower hole concentrations than the latter under the same x or m. This indicates that Bi is a more effective electron donor than Sb in SnTe and is consistent with previous findings in other II-VI systems.<sup>4, 19</sup> The carrier mobility decreases monotonically with increasing

AgBiTe<sub>2</sub> content, Figure 2(b), suggesting an enhanced point defect and interfacial scattering by nanostructures (described below).

### Electrical properties

The temperature dependent electrical conductivities for AgSn<sub>x</sub>BiTe<sub>x+2</sub> are shown in Figure 3(a). For all samples, the electrical conductivity steadily decreases with increasing temperature (typical of metallic behavior) except for the sample with x=5 which clearly shows turnover behavior around 600 K (inset of Figure 3(a)) despite the fact that it has the highest hole density at room temperature (Figure 2(a)). With increasing AgBiTe<sub>2</sub> content the room temperature electrical conductivity decreases gradually from ~7800 S/cm for SnTe to ~1000 S/cm for x=5 sample, which is mainly ascribed to the loss of carrier mobility, Figure 2(b).

The Seebeck coefficients as a function of temperature for AgSn<sub>x</sub>BiTe<sub>x+2</sub> are shown in Figure 3(b). They clearly indicate an increasing trend at room temperature with increasing AgBiTe<sub>2</sub> content although the hole concentrations also increase (SnTe excluded). This abnormal dependence of the hole concentration is related to the two-valence band nature of the electronic structure of SnTe.<sup>11, 12, 23, 24</sup>

The band gap  $E_g$  of typical semiconductors can be assessed using the Goldsmid relation:  $E_g = 2eS_{\max}T_{\max}$ ,<sup>25</sup> where  $e$  is the electron charge and  $T_{\max}$  is the temperature at which the maximum Seebeck coefficient  $S_{\max}$  occurs. Applying this relation to resolve  $E_g$  for samples with lower AgBiTe<sub>2</sub> content is unsuccessful in this case because no sign of turnover is reflected in the  $S$ - $T$  plot. However, we can estimate the band gaps of x=10 and x=5 samples (they clearly show turnover of Seebeck coefficient) to be

$\sim 0.22$  and  $\sim 0.14$  eV, respectively. This decreasing trend in band gap of  $\text{AgSn}_x\text{BiTe}_{x+2}$  with increasing  $\text{AgBiTe}_2$  content can reasonably explain why the  $x=5$  sample shows a turnover in  $\sigma$ - $T$  plot at a very low temperature despite its highest hole concentration, and is consistent with the very low band gap of  $\text{AgBiTe}_2$  ( $\sim 0.16$  eV) which is in fact smaller than that of  $\text{SnTe}$  ( $\sim 0.19$  eV) at room temperature<sup>26</sup> (we note that the band gap of  $\text{SnTe}$  is temperature dependent, so at elevated temperature the band gap of  $\text{SnTe}$  should be larger than 0.19 eV. This can account for the estimated band gap of the  $x=10$  sample being slightly larger than the end compositions).

The composition dependent Seebeck coefficients for  $\text{SnTe-AgBiTe}_2$  and  $\text{SnTe-AgSbTe}_2$  systems at room temperature and at 700 K are plotted in Figure 3(c). Clearly, with identical  $\text{AgBiTe}_2$  and  $\text{AgSbTe}_2$  content,  $\text{AgSn}_x\text{BiTe}_{x+2}$  have much higher Seebeck coefficients because Bi is more effective than Sb in neutralizing holes of  $\text{SnTe}$  as mentioned above,<sup>4, 19</sup> Figure 2(a).

Figure 3(d) shows the temperature dependent power factors for  $\text{AgSn}_x\text{BiTe}_{x+2}$  samples. For the samples with less  $\text{AgBiTe}_2$  content ( $\text{SnTe}$ ,  $x=25$ , 20, and 15), the power factors increase steadily with rising temperature. The  $x=10$  and 5 samples have higher power factors near room temperature but much lower at elevated temperatures due to bipolar conduction. The maximum power factor reaches  $\sim 23 \mu\text{Wcm}^{-1}\text{K}^{-2}$  around 750 K for the  $\text{AgSn}_{15}\text{BiTe}_{17}$  sample, which is comparable to that of the optimized  $\text{AgSn}_m\text{SbTe}_{m+2}$  system.<sup>8, 16</sup> However, lower electrical conductivities in  $\text{AgSn}_x\text{BiTe}_{x+2}$  than in  $\text{AgSn}_m\text{SbTe}_{m+2}$  suggest smaller electronic contributions to the respective total thermal conductivities.

### Thermal conductivity

The temperature dependent total thermal conductivities ( $\kappa_{\text{tot}}$ ) for  $\text{AgSn}_x\text{BiTe}_{x+2}$  are shown in Figure 4(a). For SnTe itself  $\kappa_{\text{tot}}$  is very high at  $\sim 8 \text{ Wm}^{-1}\text{K}^{-1}$  at 300 K and decreases steadily with increasing temperature, approaching  $\sim 3.3 \text{ Wm}^{-1}\text{K}^{-1}$  at 800 K. It is evident that the introduction of  $\text{AgBiTe}_2$ , even in a very small amount, can efficiently decrease  $\kappa_{\text{tot}}$  of SnTe. For example,  $\kappa_{\text{tot}}$  for  $\text{AgSn}_{25}\text{BiTe}_{27}$  are only  $\sim 3.4$  and  $\sim 2.2 \text{ Wm}^{-1}\text{K}^{-1}$  at 300 and 800 K respectively. Moreover, further reduction in  $\kappa_{\text{tot}}$  is obtained when more  $\text{AgBiTe}_2$  is introduced. The lowest  $\kappa_{\text{tot}}$  at room temperature is  $\sim 1.6 \text{ Wm}^{-1}\text{K}^{-1}$  achieved in  $\text{AgSn}_5\text{BiTe}_7$ , which is quite close to that of  $\text{Bi}_2\text{Te}_3$ -based materials.<sup>27</sup> In the samples with high  $\text{AgBiTe}_2$  ( $x=10$  and  $5$ ), however, serious bipolar diffusion phenomena are observed due to band gap narrowing, giving rise to a very high  $\kappa_{\text{tot}}$  at high temperature.

The lattice thermal conductivity  $\kappa_{\text{lat}}$  can be obtained by removing the electronic contribution  $\kappa_{\text{ec}}$  from  $\kappa_{\text{tot}}$  according to the Wiedemann-Franz relation  $\kappa_{\text{ec}}=L\sigma T$ . The Lorenz number  $L$  is calculated by fitting the Seebeck coefficient data to the reduced chemical potential using a single parabolic band model with acoustic phonon scattering,<sup>28</sup> Figure S1. Figure 4(b) shows the lattice thermal conductivity ( $\kappa_{\text{lat}}$ ) as a function of temperature for  $\text{AgSn}_x\text{BiTe}_{x+2}$ . Clearly, SnTe has the highest  $\kappa_{\text{lat}}$  among all samples over the entire temperature range. With increasing  $\text{AgBiTe}_2$  content,  $\kappa_{\text{lat}}$  decreases gradually and bipolar diffusion becomes evident. A rather low  $\kappa_{\text{lat}}$  of  $\sim 0.7 \text{ Wm}^{-1}\text{K}^{-1}$  at  $\sim 750 \text{ K}$  is seen in the  $x=15$  sample, which is very close to the value found in Cd-doped SnTe nanostructuring with  $\text{CdS}^{11}$  and also approaches the theoretically

minimum thermal conductivity  $\kappa_{\min}$  of  $\sim 0.5 \text{ Wm}^{-1}\text{K}^{-1}$  for SnTe based materials calculated using the model proposed by Cahill et al.<sup>29</sup>:

$$\kappa_{\min} = \frac{\pi}{4} k_B V^{-\frac{2}{3}} \nu \quad (1)$$

where  $V$  is the unit cell volume,  $k_B$  the Boltzmann constant, and  $\nu$  the sound velocity ( $\sim 1800 \text{ m/s}$  for SnTe<sup>30</sup>).

To examine the origin of low  $\kappa_{\text{lat}}$  in the  $\text{AgSn}_x\text{BiTe}_{x+2}$  system, the Klemens-Drabble (KD) theory<sup>31</sup> of disordered alloys was adopted to analyze the contribution of point defect scattering (pure alloying effect of  $\text{AgBiTe}_2$  with SnTe) to the reduction of  $\kappa_{\text{lat}}$  of SnTe based materials. In KD theory, the lattice thermal conductivity of a disordered alloy  $\kappa_{\text{lat}}^{\text{d}}$  is determined by<sup>31-33</sup>:

$$\kappa_{\text{lat}}^{\text{d}} = \frac{\tan^{-1}(u)}{u} \kappa_{\text{lat}}^{\text{p}} \quad (2)$$

where  $\kappa_{\text{lat}}^{\text{p}}$  is the lattice thermal conductivity of a pure alloy and  $u$  can be expressed by:

$$u^2 = \frac{\pi^2 \Theta_D \Omega}{h \nu^2} \kappa_{\text{lat}}^{\text{p}} \Gamma \quad (3)$$

here  $\Theta_D$  is the Debye temperature,  $\Omega$  the molar volume,  $h$  the Plank constant,  $\nu$  the sound velocity, and  $\Gamma$  the disorder scaling parameter depending on mass and strain field fluctuations. For a pseudo-binary  $((\text{AC})_{1-x}(\text{BC})_x$  type) system:

$$\Gamma = x(1-x) \left[ \left( \frac{\Delta M}{M} \right)^2 + \varepsilon \left( \frac{\Delta a}{a} \right)^2 \right] \quad (4)$$

where  $\varepsilon$  is a phenomenological parameter related to the Grüneisen parameter  $\gamma$ ,  $M$  and  $a$  are the molar mass and lattice constant of the alloy,  $\Delta M$  and are the difference in mass and lattice constant between the two constituents. We then used the reference

values of  $\Theta_D=140$  K,<sup>34</sup>  $v=1800$  m/s,<sup>30</sup> and  $\varepsilon=65$ <sup>35</sup> for the calculation of lattice thermal conductivities as a function of AgBiTe<sub>2</sub> fraction for AgSn<sub>x</sub>BiTe<sub>x+2</sub>, see the solid line in Figure 4(c). It is clear that KD prediction line lies well above the experimental data points, especially for those with higher AgBiTe<sub>2</sub> content. This suggests that additional phonon scattering factors are at play in these materials. We show later that the endotaxial Ag-rich nanoscale precipitates homogeneously embedded within SnTe matrix may serve as additional strong phonon scattering agents.

The  $ZT$  values as a function of temperature for AgSn<sub>x</sub>BiTe<sub>x+2</sub> are shown in Figure 4(d). The samples show monotonically increasing  $ZT$  with rising AgBiTe<sub>2</sub> content around room temperature, however, occurrence of bipolar conduction seen in the samples with high AgBiTe<sub>2</sub> content ( $x=10$  and  $5$ ) leads to serious deterioration of  $ZT$  at high temperatures for these systems. A maximum  $ZT$  of  $\sim 1.1$  is achieved around 775 K for AgSn<sub>15</sub>BiTe<sub>17</sub>, which is  $\sim 140\%$  improvement over the pristine SnTe. This value is also higher than the best result ( $\sim 1.0$ ) achieved in AgSn<sub>m</sub>SbTe<sub>m+2</sub><sup>8</sup> and arises from the larger Seebeck coefficients of the SnTe-AgBiTe<sub>2</sub> system.

### All-scale hierarchical microstructures

The microstructure, crystallography, grain structure and composition analysis of the specimens were investigated using high-resolution TEM (HRTEM), STEM electron energy loss spectroscopy (EELS) and STEM energy dispersive spectroscopy (EDS).

Meso-scale microstructures shown in Figure 5(a) are created by the powder processing and SPS treatment. Figure 5(b) shows nanoscale precipitates with darker

contrast in the medium magnification TEM image taken along  $B = [001]$ . The upper left inset HRTEM image depicts a nanoscale precipitate with coherent interfaces with the matrix, highlighted by the dashed white circle. The lower left inset shows a selected area electron diffraction (SAED) pattern along  $[001]$  orientation with an aperture capturing both the matrix and the nanoscale precipitates, which shows only one set of Bragg diffraction points, suggesting no distinguishable difference between the matrix and the nanoscale precipitate lattice spacings, owing to their small lattice mismatch and endotaxial relationship.

STEM EELS and EDS were also applied to study the compositions of the nanoscale precipitates as shown in the supplementary results (Figure S2). STEM EELS spectrum imaging (SI) reveals that the nanoscale precipitates are rich in Ag but deficient in Sn and Te, which is very similar to the observations in LAST system<sup>1, 36-39</sup>. STEM EDS results also suggest that Ag and Bi are alloyed in the matrix (Figure S2(e)), which may create additional point defects for scattering phonons. We have also employed statistical analysis to obtain the grain size distribution (Figure 5(c)) and the precipitates size distribution (Figure 5(d)) of the specimen along  $[001]$  orientation with the representative areas shown in Figure 5(a) and (b), respectively. The grain size is estimated ranging from 300 nm to 1.6  $\mu\text{m}$  and the precipitate size is ranging from 3 nm to 9 nm. The all-scale hierarchical structures are proven to be effective to scatter phonons with different mean free paths,<sup>7, 40</sup> which decreases the lattice thermal conductivity as shown in Figure 4(b) and improves the  $ZT$  values of SnTe as shown in Figure 4(d).

#### 4. Concluding remarks

The introduction of AgBiTe<sub>2</sub> in SnTe can yield high thermoelectric performance. Compared to the SnTe-AgSbTe<sub>2</sub> system, much higher Seebeck coefficients can be achieved in SnTe-AgBiTe<sub>2</sub> because Bi is more efficient than Sb in neutralizing holes. We also uncovered that similar to SnTe-AgSbTe<sub>2</sub>, SnTe-AgBiTe<sub>2</sub> system is more than a solid solution. As evidenced by TEM observations, dense nanoprecipitates with Ag-rich composition are homogeneously distributed within the matrix, together with significant point defect scattering by AgBiTe<sub>2</sub> alloying, giving rise to a sufficiently low lattice thermal conductivity in AgSn<sub>x</sub>BiTe<sub>x+2</sub> system. Consequently, a high *ZT* value of ~1.1 is achieved at 775 K for the sample with x=15, which makes lead free SnTe-AgSbTe<sub>2</sub> as promising materials for thermoelectric power generation.

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**Electronic supplementary information (ESI) available:** room temperature densities for all the samples investigated in this study (Table S1); thermal diffusivity, heat capacity, and Lorenz number for  $\text{AgSn}_x\text{BiTe}_{x+2}$  samples (Figure S1); Compositional analysis by STEM EELS for  $\text{AgSn}_{15}\text{BiTe}_{17}$  (Figure S2).

## Figure captions

Figure 1. (a) Powder XRD patterns and (b) room temperature lattice parameters  $a$  for SnTe and  $\text{AgSn}_x\text{BiTe}_{x+2}$  samples. Blue line in (b) is a theoretical prediction of lattice parameter according to Vegard's law.

Figure 2. Room temperature (a) Hall hole concentration  $N_p$  and (b) carrier mobility  $\mu$  for SnTe and  $\text{AgSn}_x\text{BiTe}_{x+2}$  samples. The hole densities of  $\text{AgSn}_m\text{SbTe}_{m+2}$  system<sup>16</sup> are also included in (a) for comparison.

Figure 3. (a) Electrical conductivities  $\sigma$ , (b) Seebeck coefficients  $S$ , and (d) power factors  $S^2\sigma$  as a function of temperature for SnTe and  $\text{AgSn}_x\text{BiTe}_{x+2}$  samples. Inset of (a) is an enlarged view of electrical conductivity for  $x=5$  sample which shows a clear turnover around 600 K. (c) Seebeck coefficients for  $\text{AgSn}_x\text{BiTe}_{x+2}$  (circles) and  $\text{AgSn}_m\text{SbTe}_{m+2}$  (stars)<sup>8, 16</sup> at 300 (in blue) and 800 K (in red), respectively. The lines are guide to eyes.

Figure 4. (a) Total thermal conductivities  $\kappa_{\text{tot}}$ , (b) lattice thermal conductivities  $\kappa_{\text{lat}}$ , and (d)  $ZT$  values as a function of temperature for SnTe and  $\text{AgSn}_x\text{BiTe}_{x+2}$  samples. The solid line in (b) represents the theoretically minimum thermal conductivity for SnTe based materials. (c) room temperature lattice thermal conductivities as a function of  $\text{AgBiTe}_2$  content for  $\text{AgSn}_x\text{BiTe}_{x+2}$ . 15 % error bars are indicated. The red line is a solid solution line predicted by the Klemens-Drabble (KD) model.

Figure 5. Electron microscopy of specimen  $\text{AgSn}_{15}\text{BiTe}_{17}$ . (a) A low-magnification image of meso-scale grains. False colors are used as guide to the eye. (b) Nanoscale precipitates with dark contrast are shown in the HRTEM image. The upper inset shows a HRTEM image of a nanoscale precipitate, highlighted by the dashed white circle. The lower inset is a selected area electron diffraction pattern with  $B=[001]$ . (c) and (d) are size distributions of meso-scale grains and nanoscale precipitates, respectively.

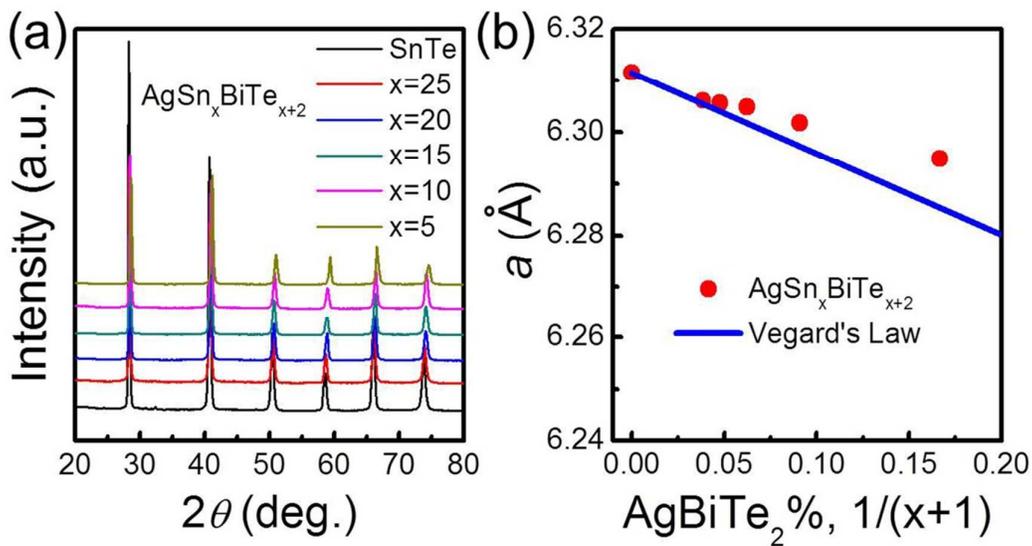


Figure 1

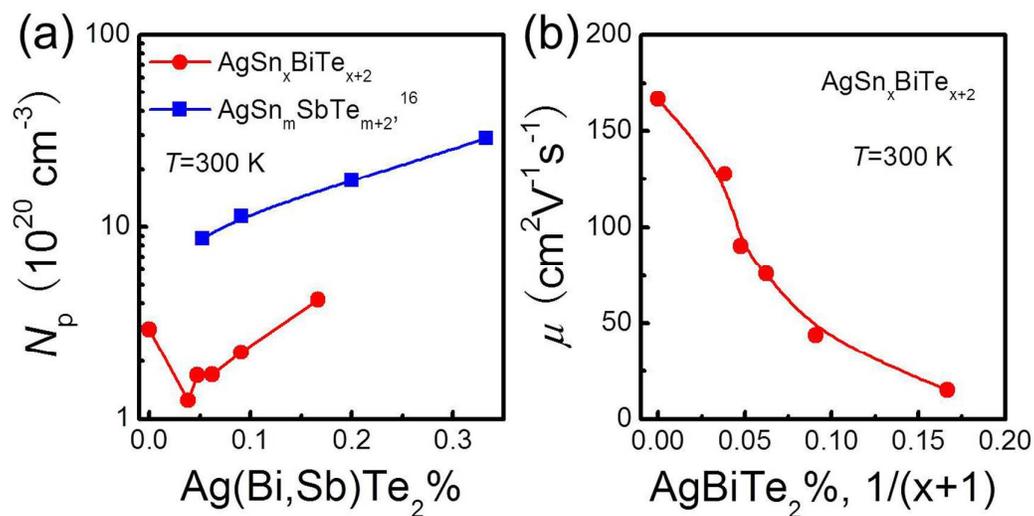


Figure 2

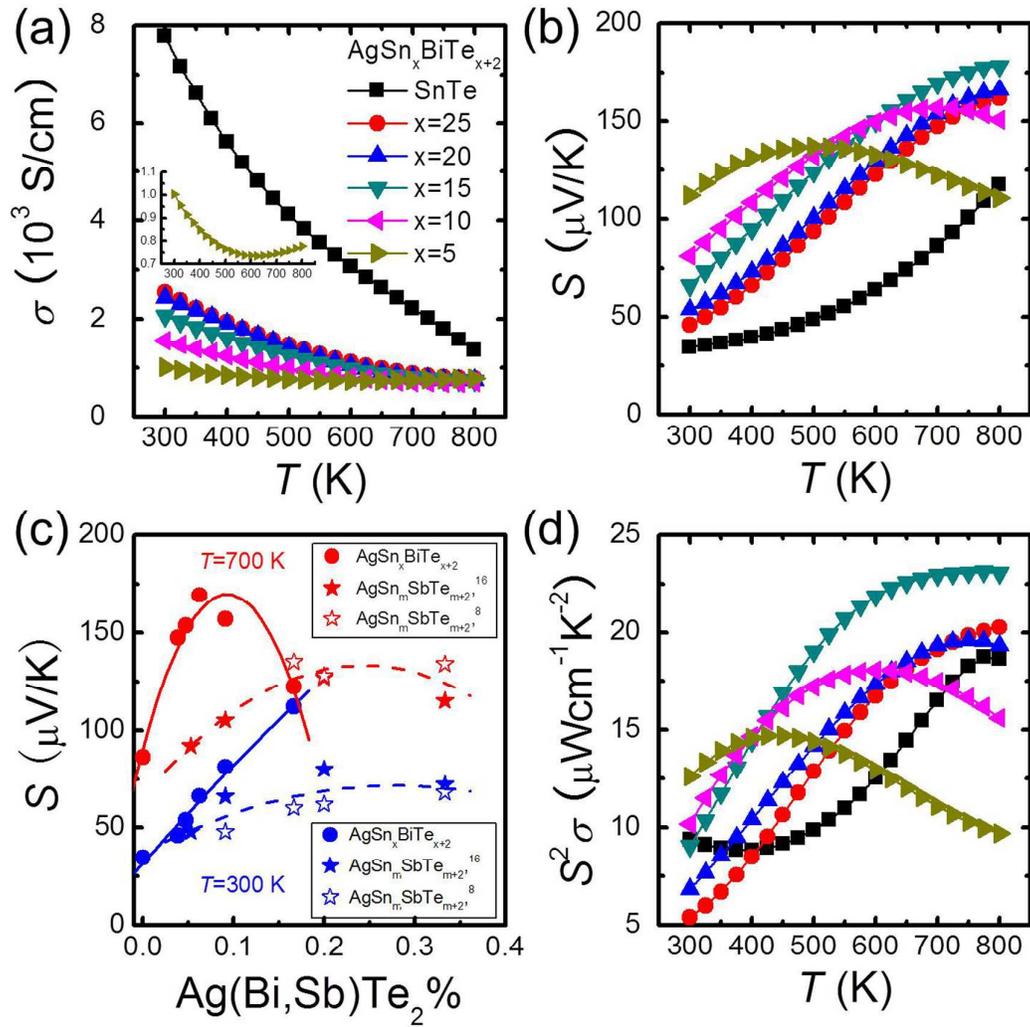


Figure 3

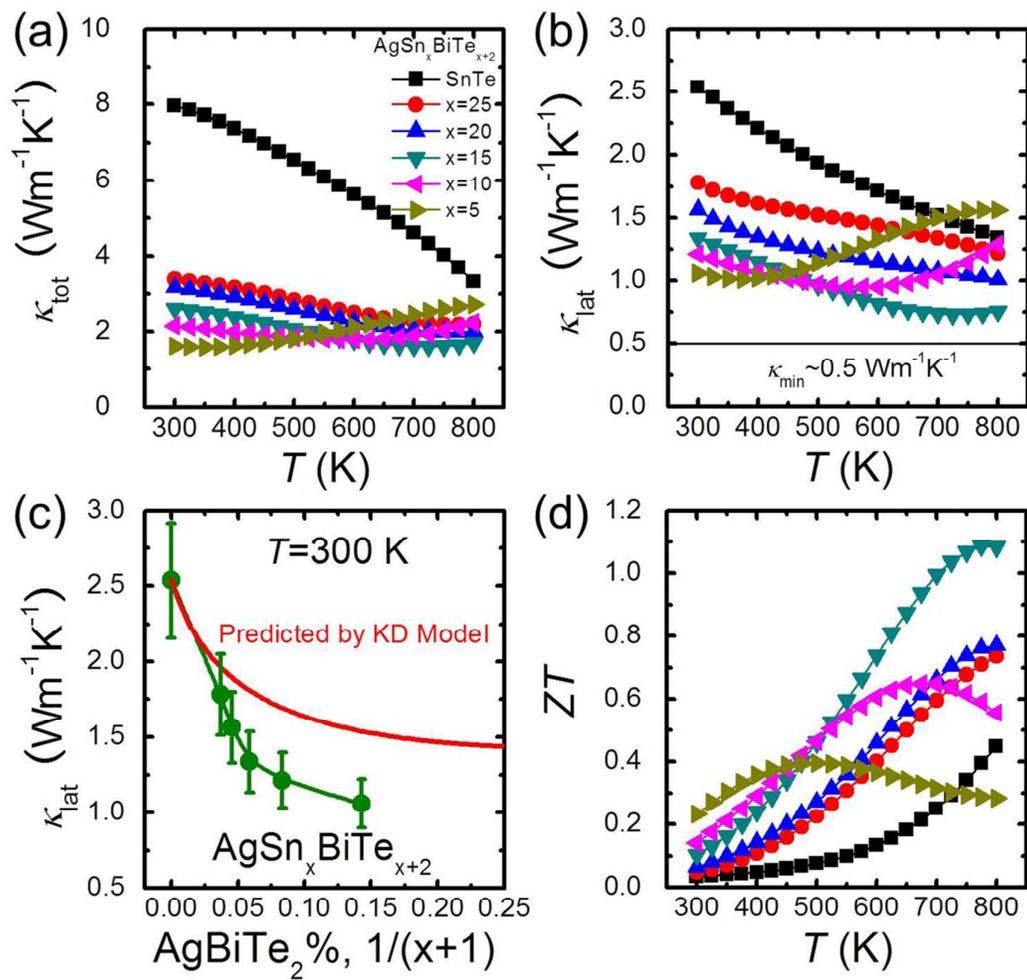
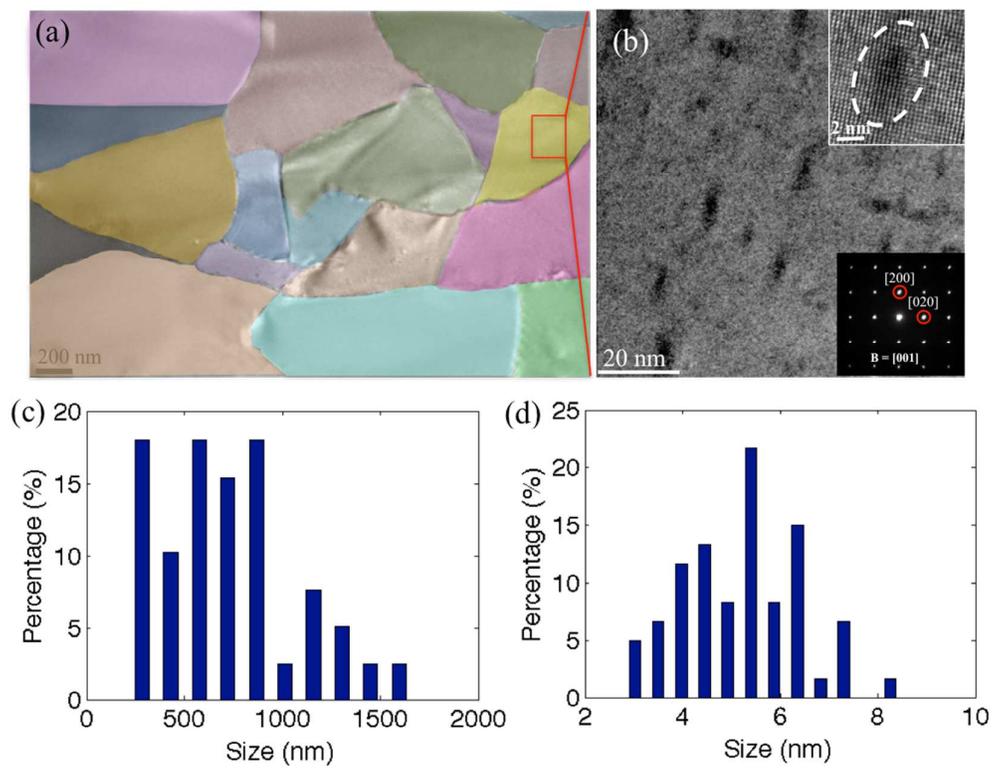


Figure 4

**Figure 5**