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# Enhanced Thermoelectric Properties of WS<sub>2</sub>/Single-Walled Carbon Nanohorn Nanocomposites

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**Abstract:** Recently, two-dimensional tungsten disulfide (WS<sub>2</sub>) has attracted attention as a next generation thermoelectric material due to a favorable Seebeck coefficient. However, its thermoelectric efficiency still needs to be improved due to the intrinsically low electrical conductivity of WS<sub>2</sub>. In the present study, thermoelectric properties of WS<sub>2</sub> hybridized with highly conductive single-walled carbon nanohorns (SWCNHs) were investigated. The WS<sub>2</sub>/SWCNH nanocomposites were fabricated by annealing the mixture of WS<sub>2</sub> and SWCNHs using a high-frequency induction heated sintering (HFIHS) system. By adding SWCNHs to WS<sub>2</sub>, the nanocomposites exhibited increased electrical conductivity and a slightly decreased Seebeck coefficient with the content of SWCNHs. Hence, the maximum power factor of 128.41 μW/mK<sup>2</sup> was achieved for WS<sub>2</sub>/SWCNHs with 0.1 wt.% SWCNHs at 780 K, resulting in a significantly improved thermoelectric figure of merit (*zT*) value of 0.027 compared to that of pristine WS<sub>2</sub> with *zT* 0.017.

**Keywords:** tungsten disulfide; single-walled carbon nanohorns; thermoelectric materials; high frequency induction heated sintering system

## 1. Introduction

As resources are finite and technologies advance, it is necessary to address issues impacting the global environment and energy to protect environmental degradation and achieve renewable energy [1–3]. Thermoelectric materials, which directly convert thermal energy into electrical energy, have been intensively studied. Therefore, waste heat can be recycled into useful electrical power. The conversion efficiency of thermoelectric energy is represented by a dimensionless value referred to as the figure of merit (*zT*) as per the following equation [4]:

$$zT = (\sigma S^2 \kappa^{-1}) T \quad (1)$$

where  $\sigma$  is the electrical conductivity;  $S$  is Seebeck coefficient;  $\kappa$  is thermal conductivity; and  $T$  is absolute temperature. To date, several studies have focused on designing thermoelectric materials based on

heavy elements such as Bi, Se, Te, Sb, Pb, Si, and Ge, which are usually toxic, scarce, and expensive, thereby limiting the practical applications of these materials [5–7]. Therefore, it is necessary to develop novel thermoelectric materials containing non-toxic earth-abundant elements and achieve superior performance and high thermoelectric efficiency in a wide temperature range.

Tungsten disulfide ( $WS_2$ ), which is a two-dimensional layered transition metal dichalcogenide, has attracted attention as a promising thermoelectric material not only due to its environmental stability and earth-abundant elemental composition, but also low thermal conductivity (1.2–2.3 W/mK) and high Seebeck coefficient (380–1000  $\mu$ V/K) [8–10]. Despite the advantageous properties of  $WS_2$ , its use as a thermoelectric material has been limited by a relatively low power factor and low  $zT$  value due to its intrinsically low electrical conductivity [11,12]. Therefore, the design of hybrid materials of  $WS_2$  with highly conductive carbonaceous materials such as carbon nanotubes (CNTs) and graphene has been investigated to improve its electrical conductivity. However, incorporating carbonaceous materials led to significantly reduced Seebeck coefficients as well as poor dispersion by their agglomeration, even though the electrical conductivity was increased [12].

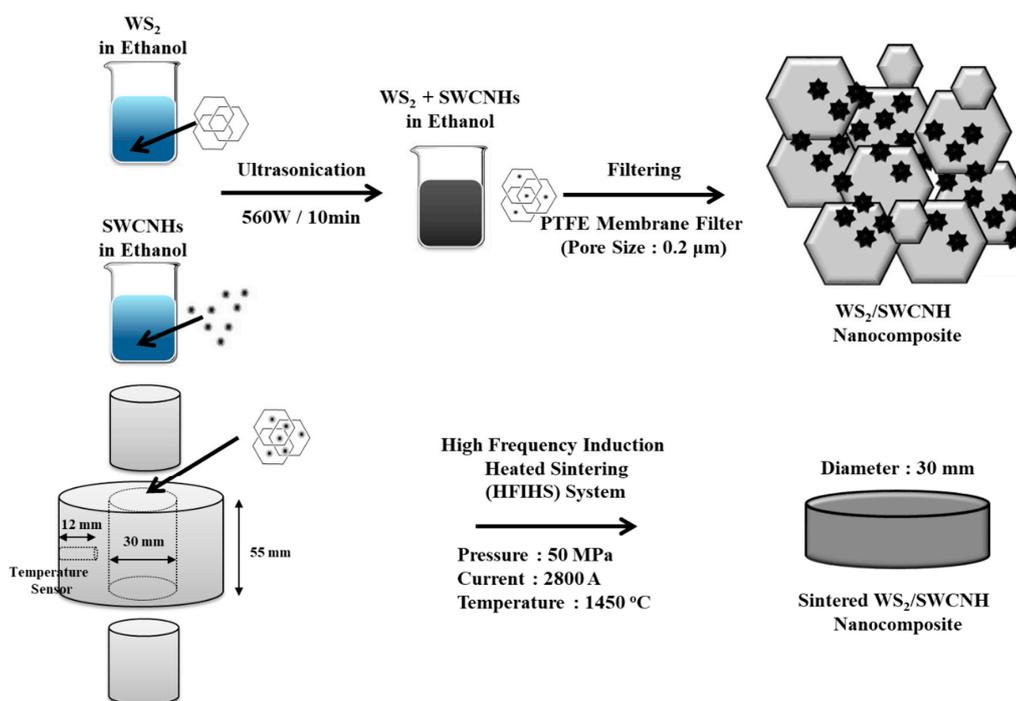
Recently, single-walled carbon nanohorns (SWCNHs) composed of spherical clusters of tubular graphite have been used as a substituent for conventional carbonaceous materials due to their excellent dispersion performance in various mediums, thus enabling easy composite processing [13,14]. The practical use of these SWCNHs is also advantageous because of their favorable electrical characteristics viz. low resistance value (4.3  $\Omega$  cm) as well as simple fabrication process by catalyst-free  $CO_2$  laser ablation of a pure graphite target [15–17].

In this study,  $WS_2$ /SWCNH nanocomposites were fabricated by annealing using a high-frequency induction heated sintering (HFIHS) system, which efficiently controls the grain size, resulting in reduced thermal conductivity and also reduces the sintering time to within a few minutes [18,19]. The morphological and structural properties of the sintered  $WS_2$  and  $WS_2$ /SWCNH nanocomposites were characterized. Moreover, the thermoelectric characteristics of the sintered  $WS_2$  and  $WS_2$ /SWCNH nanocomposites were investigated by measuring their electrical and thermal transport properties as well as carrier characteristics.

## 2. Materials and Methods

### 2.1. Preparation of Tungsten Disulfide ( $WS_2$ )/Single-Walled Carbon Nanohorn (SWCNH) Nanocomposites via High-Frequency Induction Heated Sintering (HFIHS)

Figure 1 shows a schematic illustration of the preparation process of the  $WS_2$ /SWCNH nanocomposite through a HFIHS.  $WS_2$  (Alfa Aesar, 99.8% metal basis) and SWCNH (Sigma Aldrich, St. Louis, MO, USA) powders with a given ratio were dispersed in ethanol under sonication at 560 W for 10 min, and then mixed together. The mixed dispersion of  $WS_2$  and SWCNH powders was vacuum-filtrated using a polytetrafluoroethylene (PTFE) membrane filter with a pore size of 0.2  $\mu$ m (Millipore, San Francisco, CA, USA), and the sediments on the filter were dried under vacuum ( $\sim 10^{-2}$  torr) for 24 h at 300 K. The dried powders of the  $WS_2$ /SWCNH mixture were introduced into a graphite die with a diameter of 30 mm and compressed under a pressure of 10 MPa for 30 min, followed by sintering under a pressure of 50 MPa at 1450  $^{\circ}$ C and pulsed-current 2800 A for 5 min using the HFIHS system (Vacuum Science Laboratory) (Figure S1, see Supplementary Materials). For comparison, a pristine  $WS_2$  composite was fabricated using the same methodology. As-sintered composites were cut and polished into the desired shapes for measuring thermal conductivity ( $\Phi 12.7 \times 2$  mm<sup>3</sup>), electrical conductivity, and Seebeck coefficient ( $2 \times 3 \times 10$  mm<sup>3</sup>) as well as carrier concentration and mobility ( $10 \times 10 \times 1$  mm<sup>3</sup>). The composite specimens were denoted as  $WS_2$ ,  $WS_2$ /SWCNH(0.1),  $WS_2$ /SWCNH(0.5), and  $WS_2$ /SWCNH(1.0) corresponding to 0, 0.1, 0.5, and 1.0 wt.% content of SWCNH, respectively.



**Figure 1.** Schematic illustration of the preparation process of the tungsten disulfide ( $WS_2$ )/single-walled carbon nanohorn (SWCNH) nanocomposites.

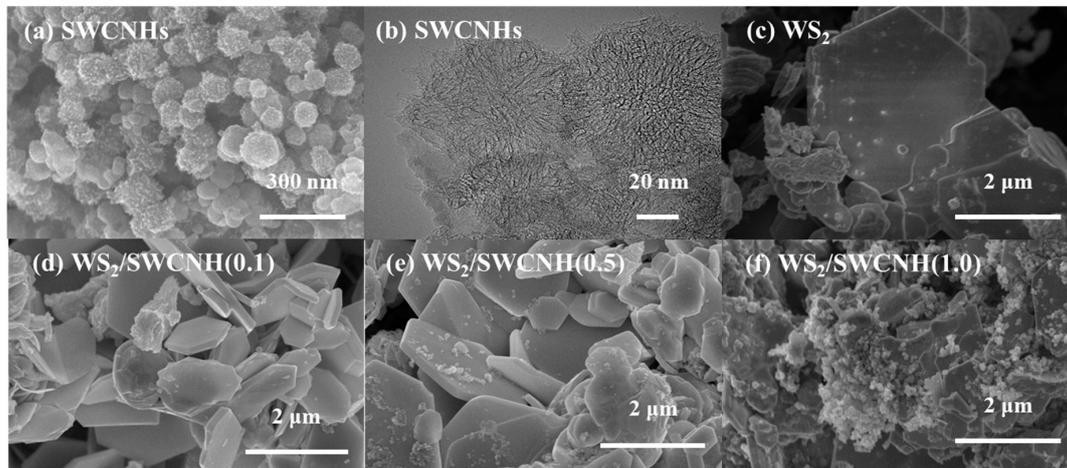
## 2.2. Characterizations

The morphologies of the  $WS_2$  and SWCNH powders and their composites were analyzed using field emission scanning electron microscopy (FE-SEM, Nova NanoSEM 450, FEI, Hillsboro, Oregon, USA), energy-dispersive x-ray spectroscopy (EDX, FEI, Hillsboro, Oregon, USA), and high-resolution transmission electron microscopy (HR-TEM, Tecnai G2 F20, FEI, Hillsboro, Oregon, USA). The surface chemical states of the specimens were analyzed using Raman spectroscopy with an excitation laser wavelength of 514 nm (in Via Reflex Raman microscope, Renishaw, Wotton-under-Edge, Gloucestershire, UK) and x-ray diffraction (XRD) patterns (one dimensional x-ray diffractometer, Rigaku SmartLab, Akishima-shi, Tokyo, Japan) using  $CuK\alpha$  radiation (wavelength 0.154 nm). The electrical conductivity and Seebeck coefficient of the sintered composites in the in-plane direction were measured in a temperature range from 300 to 780 K in a He atmosphere using a thermoelectric measurement machine (ZEM-3 M10, ULVAC-RIKO, Chigasaki, Kanagawa, Japan). The carrier concentration and mobility were measured through the Van der Pauw method under a magnetic field of 0.56 T using a Hall effect measurement system (HMS-5000, ECOPIA, Anyang, Korea). Thermal diffusivity was measured using a laser flash method (LFA447, Netzsch, Selb, Germany) based on a Xenon flash lamp source from 300 to 780 K. The specific heat was measured using differential scanning calorimetry (DSC, Q20, TA Instruments, New Castle, Delaware, USA). The density was measured by Archimedes' method. Finally, the thermal conductivity ( $k$ ) in the in-plane direction was calculated from the equation  $k = T_d \times a \times \rho$ , where  $T_d$ ,  $a$ , and  $\rho$  are the specific heat (J/gK), thermal diffusivity ( $mm^2/s$ ), and density ( $g/cm^3$ ), respectively.

## 3. Results and Discussion

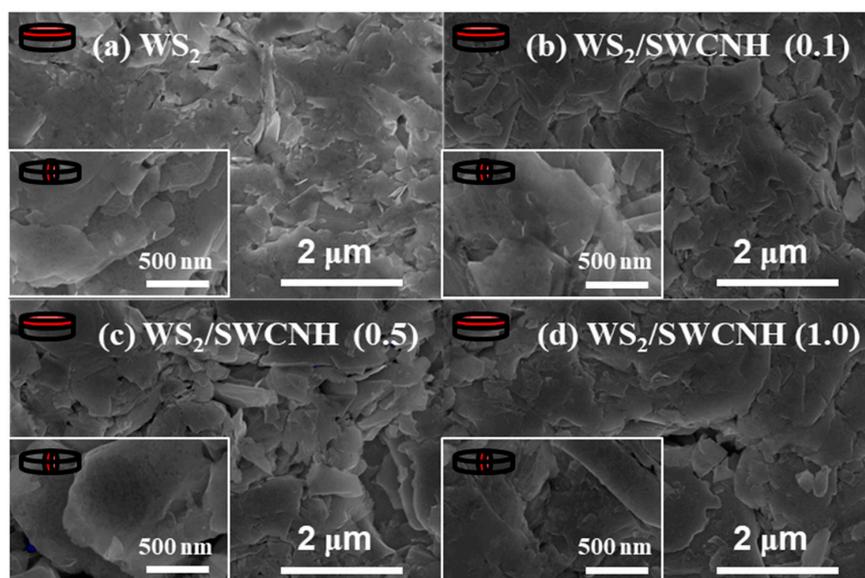
The morphologies of the SWCNHs,  $WS_2$ , and  $WS_2$ /SWCNH hybrids were analyzed using electron microscopy as shown in Figure 2. The FE-SEM and HR-TEM results shown in Figure 2a,b clearly exhibit the dahlia-like morphology of the SWCNHs with a diameter of approximately 90 nm. Additionally, the FE-SEM results in Figure 2c exhibit the two-dimensional hexagonal crystals of  $WS_2$  flakes with a diameter and thickness of approximately 3.4  $\mu m$  and 200 nm, respectively. After hybridization,

the SWCNHs were distributed on the surface of the WS<sub>2</sub> flakes with the content of SWCNHs, as shown in Figure 2d–f.

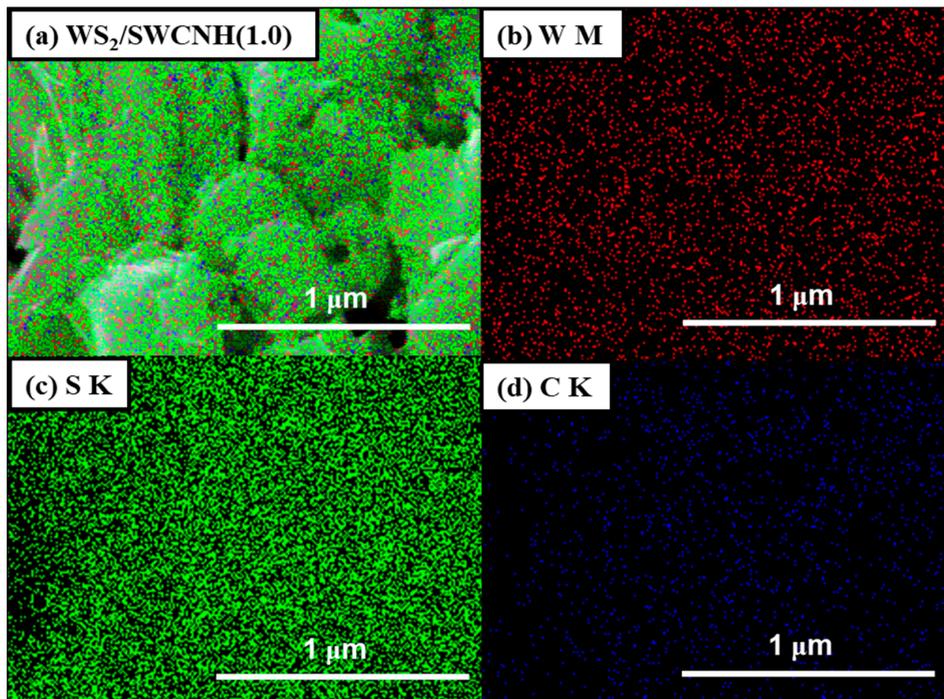


**Figure 2.** (a) Field emission scanning electron microscopy (FE-SEM) and (b) high-resolution transmission electron microscopy (HR-TEM) images of SWCNHs; FE-SEM image of (c) WS<sub>2</sub>, (d) WS<sub>2</sub>/SWCNH(0.1), (e) WS<sub>2</sub>/SWCNH(0.5), and (f) WS<sub>2</sub>/SWCNH(1.0).

Figure 3 shows the FE-SEM images of the as-sintered WS<sub>2</sub> and WS<sub>2</sub>/SWCNH nanocomposites in the surface and cross-sectional views, respectively. The pristine bulk WS<sub>2</sub> exhibited the typical morphology of sintered WS<sub>2</sub> grains, as shown in Figure 3a (the grain sizes observed from the surface and cross-sectional views were distributed in the range of 0.5–5 and 0.5–2 μm, respectively). Introducing SWCNHs clearly reduced the grain size of WS<sub>2</sub> with the content of SWCNHs (the grain sizes observed from the surface and cross-sectional views were distributed in the range of 0.5–2 and 0.5–1 μm, respectively), in which the elemental fraction of C atoms from the SWCNHs increased from 13.20 to 22.84 at%, which is indicative of the successful incorporation of SWCNHs, as shown in Figure 3b–d (Figure S2). It is noteworthy that the use of SWCNHs as filler allowed for the uniform dispersion of graphitic tubules within the WS<sub>2</sub> matrix due to their advantageous dispersibility by morphological characteristics (Figure 4).

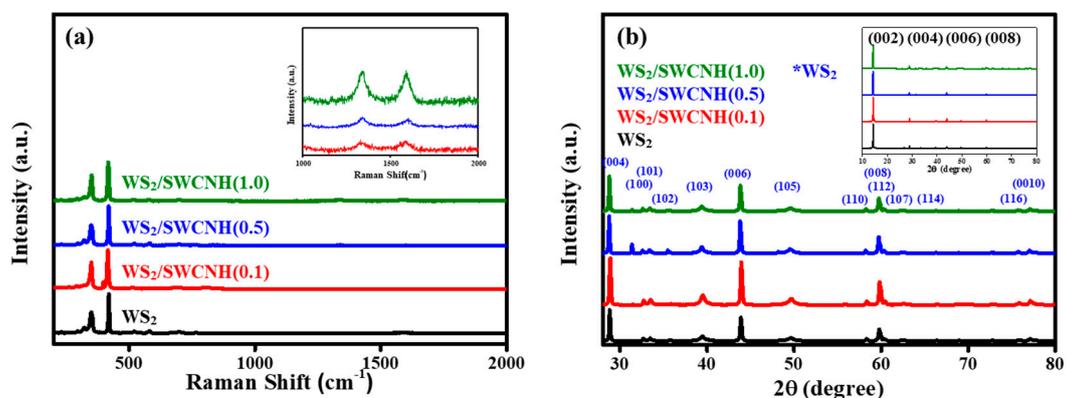


**Figure 3.** FE-SEM images of as-sintered (a) WS<sub>2</sub>, (b) WS<sub>2</sub>/SWCNH(0.1), (c) WS<sub>2</sub>/SWCNH(0.5), and (d) WS<sub>2</sub>/SWCNH(1.0).



**Figure 4.** FE-SEM-EDX mapping of the sintered  $WS_2/SWCNH(1.0)$  nanocomposite: (a)  $WS_2/SWCNH(1.0)$ , (b) W M, (c) S K, and (d) C K.

Figure 5 shows the Raman spectra of the sintered  $WS_2$  and  $WS_2/SWCNH$  nanocomposites. The  $E_{2g}^1$  and  $A_{1g}$  peaks at approximately  $351.25$  and  $420.86$   $cm^{-1}$  are attributed to the in-plane and out-of-plane vibrational modes of S atoms in the  $WS_2$  crystal, respectively, as shown in Figure 5a [20]. Additionally, peaks were observed at approximately  $1335$  and  $1580$   $cm^{-1}$  for the  $WS_2/SWCNH$  nanocomposites, which are attributed to the defect-induced structural disorder and  $sp^2$  hybridized bonding of carbon atoms, respectively. Based on these two distinctive peaks, the intensity ratio ( $R$ ,  $(I_D/I_G)$ ) can be obtained to estimate the number of  $sp^2$  carbon clusters. The  $R$  values of the nanocomposites gradually increased from 1.23 to 1.44 with the content of SWCNHs, which was greater compared to that of the pristine SWCNH powder ( $R = 1.04$ ) (Figure S3). This can be ascribed to the number of defects that slightly developed in SWCNHs during the high-temperature sintering process.

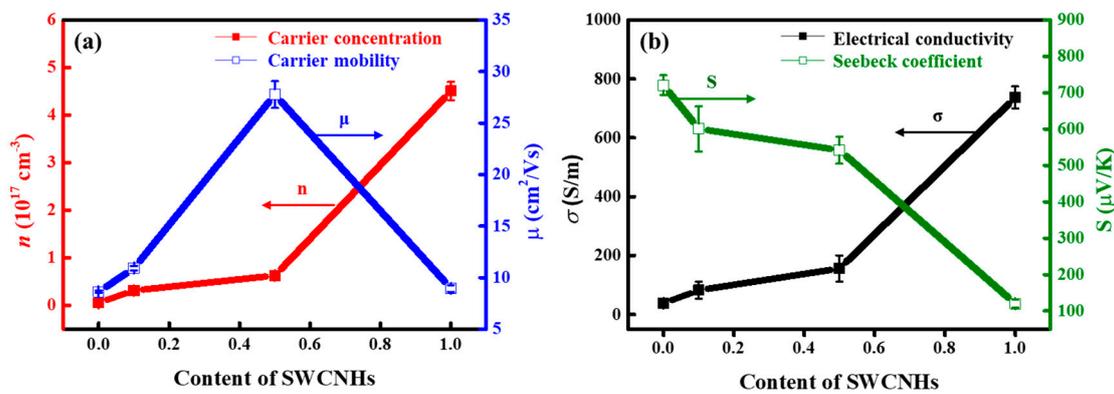


**Figure 5.** (a) Raman spectra and (b) x-ray diffraction (XRD) patterns of the as-sintered  $WS_2$  and  $WS_2/SWCNH$  nanocomposites. Insets show the respective magnified graphs.

The crystal characteristics of the sintered  $WS_2$  and  $WS_2/SWCNH$  nanocomposites were confirmed by XRD patterns, as shown in Figure 5b. The pristine  $WS_2$  exhibited multiple diffraction peaks by the

phase matching for different principal planes (JCPDS #08-0237). It was also observed that the intensive peak of the (002) plane occurred at 14.28 degrees, followed by (004), (006), and (008) planes at 28.81, 43.92, and 59.73 degrees, respectively, which is attributed to the layered nature of the WS<sub>2</sub> flakes [21,22]. After sintering, the whole samples maintained the characteristic peaks from WS<sub>2</sub>, indicative of the independent grain growth of WS<sub>2</sub> regardless of the existence of SWCNHs. In addition, the peaks from the tungsten carbide (WC) phase were not observed, despite the possible formation of WC with SWCNHs under high-temperature annealing. This can be attributed to the lower concentration of SWCNHs in the composite.

The majority carrier behavior of the sintered WS<sub>2</sub> and WS<sub>2</sub>/SWCNH nanocomposites were analyzed by measuring the carrier concentration ( $n$ ) and mobility ( $\mu$ ) at 300 K based on the Van der Pauw method, as shown in Figure 6a. The pristine WS<sub>2</sub> exhibited approximately  $5.82 \times 10^{15} \text{ cm}^{-3}$  of carrier concentration. By adding SWCNHs, the value was gradually increased with the content of SWCNHs to  $4.51 \times 10^{17} \text{ cm}^{-3}$ . Meanwhile, the maximum carrier mobility of  $27.76 \text{ cm}^2/\text{Vs}$  was achieved in the WS<sub>2</sub>/SWCNH(0.5), followed by a decrease to  $8.95 \text{ cm}^2/\text{Vs}$  in the WS<sub>2</sub>/SWCNH(1.0). It is assumed that the excess amount of SWCNHs causes large carrier scattering at the enlarged interfaces between SWCNHs and WS<sub>2</sub> [23].



**Figure 6.** (a) Carrier concentration and carrier mobility plots. (b) Electrical conductivity and Seebeck coefficient of the WS<sub>2</sub>/SWCNH nanocomposites with the content of SWCNHs.

The thermoelectric properties of the sintered WS<sub>2</sub> and WS<sub>2</sub>/SWCNH nanocomposites were evaluated by considering the carrier behavior, as shown in Figure 6b. The electrical conductivity ( $\sigma$ ) is proportional to the carrier concentration and mobility as per the following equation ( $e$  is charge of electron:  $1.6 \times 10^{19} \text{ C}$ ):

$$\sigma = ne\mu \quad (2)$$

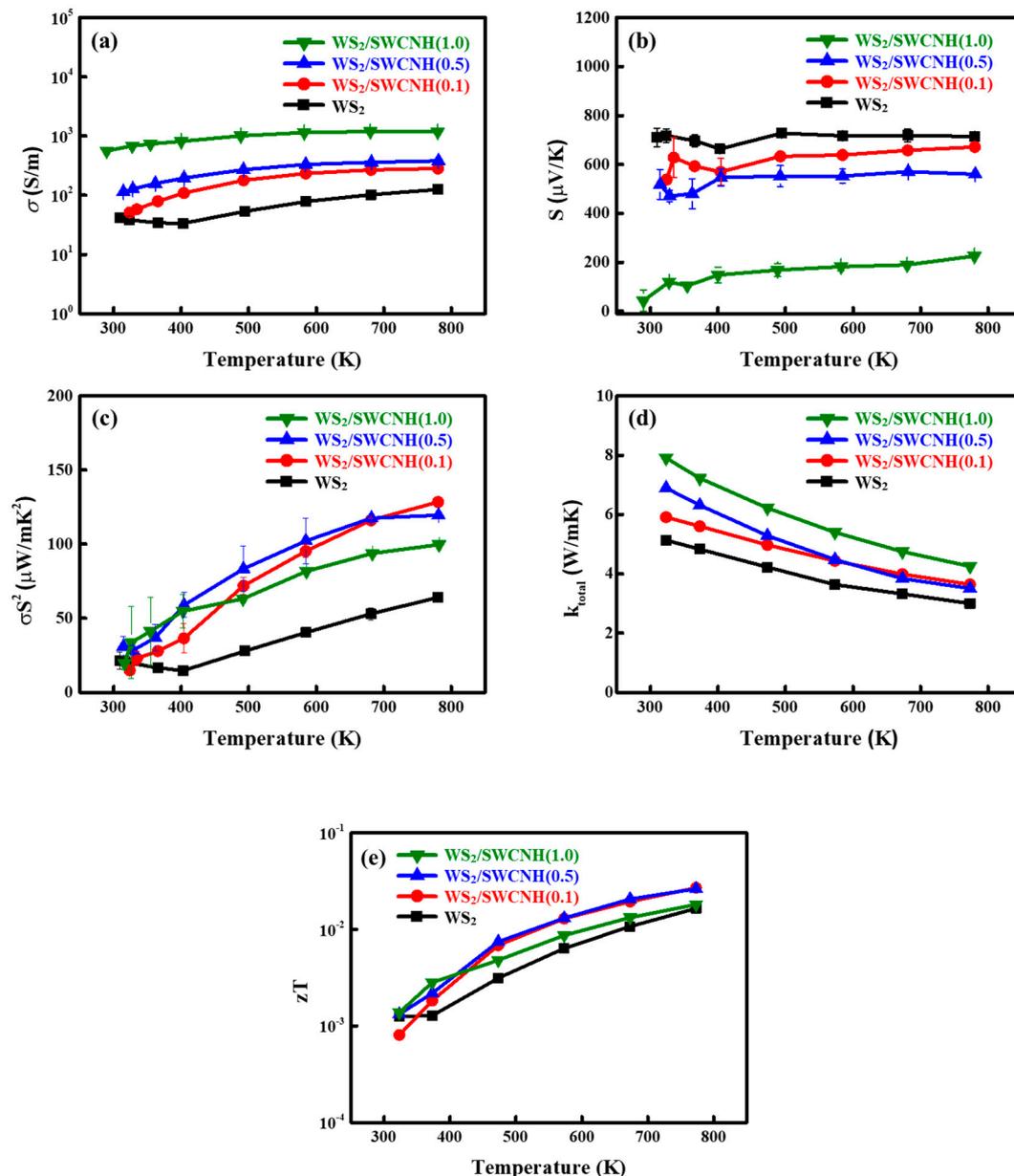
The pristine WS<sub>2</sub> exhibited an electrical conductivity of 38.18 S/m, and the value increased to 737.19 S/m in the WS<sub>2</sub>/SWCNH(1.0), which is approximately 19 times greater than that of the pristine WS<sub>2</sub> sample because SWCNHs have an intrinsically higher electrical conductivity [24]. The electrical conductivity values were also identical to the trend of carrier concentration, because the difference in carrier concentration was significantly greater than the carrier mobility change. However, the Seebeck coefficient ( $S$ ) is inversely proportional to carrier concentration ( $n$ ) as per the following equation [23]:

$$S = \frac{8\pi^2 k_B^2}{3eh^2} m^* T \left(\frac{\pi}{3n}\right)^{2/3} \quad (3)$$

where  $k_B$  is the Boltzmann constant;  $h$  is the Planck constant;  $m^*$  is the effective mass of charge carrier; and  $T$  is the absolute temperature. In our measurement environment, the generated voltage with temperature difference ( $\Delta T$ ) indicates reliability with linear slope (Figure S4a). The pristine WS<sub>2</sub>

exhibited a Seebeck coefficient of 700.78  $\mu\text{V}/\text{K}$ . By adding SWCNHs, the values of the nanocomposites gradually decreased with the content of SWCNHs due to the increase in carrier concentration.

The temperature dependent thermoelectric properties of the sintered  $\text{WS}_2$  and  $\text{WS}_2/\text{SWCNH}$  nanocomposites were further investigated between 300 and 780 K, as shown in Figure 7. The electrical conductivity values of the whole samples increased with temperature, indicating conventional semiconductor like behavior, as shown in Figure 7a [25]. The pristine  $\text{WS}_2$  exhibited an electrical conductivity of 125.51 S/m at 780 K. By adding SWCNHs, the electrical conductivity of the nanocomposites is increased to 1181.37 S/m for  $\text{WS}_2/\text{SWCNH}(1.0)$ , which was similar to the behavior at room temperature.



**Figure 7.** (a) Electrical conductivity, (b) Seebeck coefficient, (c) power factor, (d) thermal conductivity, and (e) dimensionless figure of merits of the  $\text{WS}_2/\text{SWCNH}$  nanocomposites with temperature.

The pristine  $\text{WS}_2$  exhibited a Seebeck coefficient of 710.53  $\mu\text{V}/\text{K}$  at 300 K and the value increased by 714.32  $\mu\text{V}/\text{K}$  at 780 K, as shown in Figure 7b. Meanwhile, the Seebeck coefficient values were gradually decreased by adding the SWCNHs in the complete temperature range, and reached a

minimum for the WS<sub>2</sub>/SWCNH(1.0). As per Equation (3), by considering the dependence on increased carrier concentration, the Seebeck coefficient decreased with the content of SWCNHs. Additionally, the whole samples of WS<sub>2</sub>/SWCNH nanocomposites showed less temperature dependency on the Seebeck coefficient with a slightly increased value.

The power factor (*PF*) values of the WS<sub>2</sub> and WS<sub>2</sub>/SWCNH nanocomposites were calculated from the equation  $PF = \sigma S^2$ , as shown in Figure 7c. The power factor values of the samples increased with temperature, which depends on the electrical conductivity behavior. The highest power factor value was obtained for WS<sub>2</sub>/SWCNH(0.1) due to the increased electrical conductivity and slightly reduced Seebeck coefficient. The WS<sub>2</sub>/SWCNH(0.1) exhibited a power factor value of 14.93  $\mu\text{W}/\text{mK}^2$  at 300 K, and the value was increased to 128.41  $\mu\text{W}/\text{mK}^2$  at 780 K.

The thermal conductivity, which is an important thermoelectric property, was measured for the WS<sub>2</sub> and WS<sub>2</sub>/SWCNH nanocomposites, as shown in Figure 7d. The thermal conductivity values decreased with temperature, thus indicative of the dominant Umklapp phonon–phonon scattering [26]. The pristine WS<sub>2</sub> exhibited a thermal conductivity of 3.0 W/mK, while the WS<sub>2</sub>/SWCNH(1.0) exhibited a slightly higher value of 4.25 W/mK at 780 K. The total thermal conductivity ( $\kappa_{total}$ ) is calculated as the sum of electronic and lattice vibrational contributions as per the following equation [23]:

$$\kappa_{total} = \kappa_e + \kappa_l = L\sigma T + \kappa_l \quad (4)$$

where  $\kappa_e$  is the electronic thermal conductivity, and  $\kappa_l$  is the phononic thermal conductivity by lattice vibration. For the WS<sub>2</sub> and WS<sub>2</sub>/SWCNH nanocomposites, the phonons traveling by lattice vibration were responsible for the total thermal conductivity rather than the electronic contribution because electronic thermal conductivity is negligible (Figure S4c–d). The total thermal conductivity increased with the content of SWCNHs, which is likely due to the percolation of segregated SWCNHs with individually high thermal conductivity arising from their graphitic structure [27].

The thermoelectric figure of merit (*zT*) of the WS<sub>2</sub> and WS<sub>2</sub>/SWCNH nanocomposites were investigated using Equation (1), as shown in Figure 7e. In total, the *zT* values of the whole samples increased with temperature due to the increased electrical conductivities without a reduction in Seebeck coefficient, which dramatically reduced the thermal conductivities. The *zT* value of WS<sub>2</sub>/SWCNH(0.1) yielded a maximum of 0.027 at 780 K, which was 1.63 times greater than that of the pristine WS<sub>2</sub>. Thus, the use of SWCNHs to control the carrier concentration is beneficial for improving electrical properties, giving rise to achieving high *zT* values for next generation thermoelectric materials.

#### 4. Conclusions

Thermoelectric WS<sub>2</sub>/SWCNH nanocomposites were fabricated by physically mixing two-dimensional WS<sub>2</sub> flakes and dahlia-like SWCNHs, followed by annealing using a HFIHS system. In the sintered WS<sub>2</sub>/SWCNH nanocomposites, the SWCNHs were homogeneously dispersed at the interfaces of the aggregated WS<sub>2</sub> flakes without the unnecessary formation of secondary phases. The electrical conductivity of the nanocomposites was significantly improved with the content of SWCNHs, while the Seebeck coefficient was slightly decreased depending on the carrier concentration and mobility. Combining the electrical conductivity and Seebeck coefficient, the power factor of the composite achieved a value of 128.41  $\mu\text{W}/\text{mK}^2$  at 780 K for the WS<sub>2</sub>/SWCNH(0.1). Furthermore, the improved power factor allowed for a maximum *zT* value of 0.027 at 780 K for WS<sub>2</sub>/SWCNH(0.1), which was 1.63 times greater than that of pristine WS<sub>2</sub>, and the thermal conductivity increased with the percolation of SWCNHs. Therefore, designing WS<sub>2</sub> hybridized with SWCNHs suggests a new strategy to improve their thermoelectric performance by controlling electrical properties. We expect that our approach for producing WS<sub>2</sub>/SWCNH nanocomposites with enhanced thermoelectric properties can contribute to the development of thermoelectric devices such as radioisotope thermoelectric generators and wearable thermoelectric devices.

**Supplementary Materials:** The following are available online at <http://www.mdpi.com/2073-4352/10/2/140/s1>. Figure S1: Sintering profiles and mass densities of the sintered WS<sub>2</sub> and WS<sub>2</sub>/SWCNH nanocomposites. Figure S2: FE-SEM-EDX of the sintered WS<sub>2</sub> and WS<sub>2</sub>/SWCNH nanocomposites. Figure S3: Raman spectrum of the SWCNH powder. Table S1: Raman factors of the SWCNH powder. Table S2: Raman factors of the sintered WS<sub>2</sub> and WS<sub>2</sub>/SWCNH nanocomposites. Figure S4: Thermoelectric characteristics of the sintered WS<sub>2</sub> and WS<sub>2</sub>/SWCNH nanocomposites.

**Author Contributions:** C.-M.Y., S.W.L., and Y.A.K. were responsible for initiating and designing the research. J.H.K., S.-Y.L., and K.S.K. performed the experiments and analyzed the data. J.H.K., S.Y., and C.-M.Y. wrote the paper. All authors have read and agreed to the published version of the manuscript.

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**Conflicts of Interest:** The authors declare no conflicts of interest.

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