



# Thermal Properties of Carbon Nanotubes

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**Abstract:** Nanomaterials are defined as engineered materials with at least one dimension in the range of 1-100 nm. Particles of “nano” size have been shown to exhibit enhanced and novel properties including reactivity, greater sensing capability, and increased mechanical strength. The nanotechnology offers simple, clean, fast, efficient, and economic method for the synthesis of a variety of organic molecules, which has to provide the momentum for many chemists to switch from traditional method. To optimize the utilization of thermal conversion systems, it is essential to integrate them with thermal energy storage. In addition, study of the thermal properties of nanostructure materials against important grain growth is both scientific and technological interest. A sharp increase in grain size during consolidation of nanocrystalline powders to obtain full dense material may consequently result in the loss of some unique properties of nanocrystalline materials. The present review paper is aimed at understanding the thermal properties and its applications of nanostructure materials.

**Keywords:** Thermoelectric, Nanostructured Materials, Nanowires, Thermal Conductivity

## I. INTRODUCTION

Nanotechnology is the engineering of functional systems at the molecular scale. Nanotechnology is likely to have a profound impact on our economy and society and hence it may lead to the next industrial revolution. Nanotechnology is defined as the manipulations of matter with at least one dimension sized from 1-100 nanometers. Nanotechnology may be able to create many new materials and devices with a vast range of applications, such as in medicine, electronics, bio materials and energy production. From the beginning there was an issue in the thermal characterization of nanomaterials during their processing steps and in the applications, especially for the inorganic materials. Thermo analytical and thermo physical testing methods are successfully applied for the determination of phase transitions, thermally induced chemical reactions and decompositions, gas adsorption and desorption studies, and thermal transport properties. Nanomaterials are used as additives to enhance the properties of base materials. When it is added to the fluid, the produced mixture is denoted by nanofluid; while by adding the nanomaterials to phase change material (PCM), the produced mixture is denoted by nanocomposites. The different synthesis

methods of preparation and the characterization of nanofluid, suspension, and the convection and conduction heat transfer in nanofluids have been reported by many authors [1-3]. Within the area of nanomaterials for thermal energy applications, many researchers have focused on the thermal conductivity effectiveness of nanofluids/composites which can improve their thermophysical properties [4-9]. In the last decade, nanostructured materials have been one of the most studied subjects, and nanotechnology applications are expected in practically all areas of science to produce higher performance products which will be faster, more sensitive and more accurate. Presently, a wide variety of synthesis procedures are available to obtain nanostructured materials [10-14], and material sizes, shapes, chemical compositions and consequently properties can vary by changing the process route. This paper critically reviews the existing studies dealing with the use of nanostructure materials. The aim of this paper is to demonstrate that the sensitivity of modern thermoanalytical methods are well suited with general applications on materials with a reduced particle size into the sub-micrometer range and that the results provide important parameters for the thermal characterization of nanomaterials.

## II. NANOMATERIALS

Nanotechnology is considered to be one of the most important future technologies involving several disciplines of science including solid state physics, solid state chemistry, solid state ionic, materials engineering, medical science and biotechnology. Manipulating matter at the nanometer scale, using building blocks with dimensions in the nano-size range, makes it possible to design and create new materials with unprecedented functionality and novel or improved properties. Nanostructured materials are made of nanosized grains or nanoparticles as building blocks, have a significant fraction of grain boundaries with a high degree of disorder of atoms along the grain boundaries (or particle surfaces), and a large ratio of interface (or surface) area to volume. A wide range of materials, including metals and ceramics in crystalline, quasi-crystalline, or amorphous phases have been synthesized as nanosized or nanostructured materials. World energy crisis has

triggered more attention to energy saving and energy conversion systems with high efficiency. There is a growing awareness that nanoscience and nanotechnology can have a profound impact on energy generation, conversion, and recovery. Nanotechnology based solutions are being developed for a wide range of energy problems such as, solar electricity, hydrogen generation and storage, batteries, fuel cells, heat pumps and thermoelectric. Organic nanomaterials consist of fullerenes, carbon nanotubes (CNT), single-walled carbon nanotubes (SWCNT), multi-walled carbon nanotubes (MWCNT), graphite and nanofibers. Most of the organic nanomaterials are carbon based nanomaterials [15]. While, metal and metal oxide based nanomaterials such as aluminium, zinc, copper, iron, aluminium oxide, iron oxide, titanium oxide are categorized as inorganic nanomaterials [16]. Quantum dots, such as CdSe, ZnS, ZnO etc are metalloid nanomaterials and are also categorized as inorganic nanomaterials [17, 18]. Hybrid nanomaterials are the combination of organic – organic nanomaterials, organic – inorganic nanomaterials and inorganic – inorganic nanomaterials through synthesis such as chemical vapor deposition (CVD), Electro spinning, atom transfer radical polymerization (ARTP) etc. [19,20].

### III. NANOSTRUCTURE MATERIALS FOR THERMOELECTRIC ENERGY CONVERSION

High performance thermoelectric materials in a wide range of temperature are essential to broaden the application spectrum of thermoelectric devices. In addition the improvement of thermoelectric material device optimization is crucial factor for efficient heat to power conversion. As long as appreciable temperature difference can be created over thermometric legs, good power output can be achieved. For a mid-temperature n-type doped skutterudite material an efficiency of over 11% at a temperature difference of 600 °C could be achieved. Besides the improvement of thermoelectric materials, device optimization is a crucial factor for efficient heat-to-electric power conversion and one of the key challenges is how to create a large temperature across a thermoelectric generator especially in the case of a dilute incident heat flux. For the solar application of thermoelectrics we investigated the concept of large thermal heat flux concentration to optimize the operating temperature for highest solar thermoelectric generator efficiency. A solar-to-electric power conversion efficiency of ~5% could be demonstrated. Solar thermoelectric generators with a large thermal concentration which minimizes the amount of thermoelectric nano structured bulk material shows great potential to enable cost-effective electrical power generation from the sun.

The Seebeck effect can be exploited to generate power from a temperature difference. The efficiency of thermoelectric power generation systems depends on the

material-specific thermoelectric figure of merit, the heat source and sink temperatures, and the heat transfer into and out of the devices. The efficiency of ideal thermoelectric devices ( $\eta_{te}$ ) is determined by the operating temperatures and the materials' dimensionless figure of merit ( $ZT$ ), defined as  $ZT = (S^2\sigma/k)T$ , where  $S$ ,  $\sigma$ ,  $k$ , and  $T$  are the Seebeck coefficient, electrical conductivity, thermal conductivity, and absolute temperature, respectively [1,2]. The device efficiency can be expressed as

$$\eta_{te} = \frac{T_h - T_c}{T_h} \frac{\sqrt{1 + (ZT)_M} - 1}{\sqrt{1 + (ZT)_M} + \frac{T_c}{T_h}} \quad (1)$$

Where  $T_c$  is the cold-side temperature, the hot-side temperature, and  $(ZT)_M$  the effective  $ZT$  of the thermoelectric materials between  $T_c$  and  $T_h$ . According to Eq. (1), an efficiency of approximately 8.6% can be reached by imposing a temperature difference of 200 °C across an ideal thermoelectric device with  $(ZT)_M = 1$  and  $T_c = 20$  °C. In recent years, significant progress has been made on improving thermoelectric materials.

### IV. NANOSTRUCTURED MATERIALS FOR THERMOELECTRIC

Thermoelectric are considered those materials have low thermal conductivity with a large electrical conductivity. Low dimensional materials are high efficient thermoelectric because it can become thermal insulators with high electrical conductivities. Thermal insulation is widely present in chemical plants (e. g. pipes, furnaces, etc.), so thermoelectric materials could replace current insulations to harvest that thermal energy and transform it into electricity. Thermoelectric devices can play a very important role in clean energy generation, conversion and recovery. Thermoelectric are 'fuel-free' purely solid-state devices with no moving parts and therefore are extremely reliable. Thermoelectric can harvest residual low-grade energy which otherwise is wasted. Next generation thermoelectric devices shall certainly revolutionize several concepts of energy harvesting and conversion for power generation, refrigeration/heating, and thermal sensing both in terrestrial and space applications. The key factor for improving the performance of thermoelectric devices can be through the nanotechnology development of thermoelectric materials with novel composition, low dimensionality, and advanced architectures. Another approach for improving the performance of thermoelectric materials is through nanostructuring. A nano crystalline material with grain size is in the nanometer regime which have significant amount of grain boundaries. Grain boundaries are more selective for the diffraction of phonon as compare to that of electrons. Thermoelectric materials convert heat directly into electricity (and vice versa) and can thus recycle some of the energy contained in, for instance, hot exhaust streams. While low efficiency has traditionally limited the use of thermoelectric to niche markets, recently developed

nanostructured thermoelectric, with much better performance than bulk thermoelectric, mark the beginning of a new era. Progress has also been made towards inexpensive, large-scale production methods. Beyond transport and industrial production, interesting application areas include the transformation of low-grade solar thermal or geothermal energy, or the use of human body heat to power portable electronics.

## V. THERMAL CONCEPT OF NANOMATERIALS

A number of methods, from first principle calculations to empirical models, were applied to understand the metastable phase formation in nanocrystalline materials. The fundamental difference between coarse grain and nanocrystalline materials lies in the formation of large volume fraction of interfaces in nanocrystalline materials that has significant influence on the thermodynamics of phase formation/transformation. In the bulk state, the thermodynamic condition for phase  $\alpha$  to be stable over metastable phase  $\beta$  is that  $G_\alpha < G_\beta$ . In case of nanocrystalline materials, the contribution of interfacial energy term ( $G_{int}$ ) to the free energy cannot be neglected as in coarse-grained polycrystalline materials. The interfacial free energy of nanocrystalline materials, can be expressed as:

$$\Delta G_{int} = 3g_{int}V_m/d \quad (2)$$

Where  $V_m$  is the molar and  $d$  is the crystallite size. In the nanocrystalline state,  $\beta$  may become stable if  $G_\alpha + G_{int} > G_\beta + G_{int}$ . In other words, if the rate of increase of total free energy ( $G + G_{int}$ ) with decrease in crystallite size of  $\alpha$  phase is higher than that of  $\beta$  phase, the latter will become stable over the former below a critical crystallite size materials. The interfacial free energy of nanocrystalline materials, can be expressed as:

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## VI. NANOSTRUCTURED MATERIALS FOR SOLAR THERMOELECTRIC GENERATORS

One of the novel uses of thermoelectric nanostructured materials is in the field of solar thermoelectric generators. Solar thermoelectric generators are devices that convert the heat from sunlight into electrical energy. Solar thermoelectric generators allow more efficient use of the solar energy because it captures a wide solar spectrum which is not possible for photovoltaic cells [29, 30]. A solar thermoelectric generator is made up of several elements: thermoelectric materials, heat

absorption element, metal interconnects, and substrates. Such devices use the traditional p and n-type semiconductor junctions with high thermoelectric efficiency materials such as SiGe alloy [30] and Bi<sub>2</sub>Te<sub>3</sub> [31]. However, the efficiency of solar thermoelectric generator units is about 1% which is low compared to the 11% for silicon-based photovoltaic cells [31, 32]. New thermoelectric materials and harvesting techniques have been developed to overcome efficiency 100 Suresh Sagadevan and B. Janarthanan: A Review on Influence of Thermal Studies of Nanomaterials barriers, increase absorbed solar energy, and reduce radiation losses [29, 31]. Current developments are also focused on materials that can provide higher operating temperatures and higher thermoelectric efficiencies with efficiencies close to 4.6% [32, 33]. The thermoelectric energy efficiency can be quantified by the dimensionless thermoelectric figure of merit ( $ZT = S^2\sigma T/K$ , where  $S$ ,  $\sigma$ ,  $T$  and  $K$  are the Seebeck coefficient, electrical conductivity,

absolute temperature, and thermal conductivity respectively) [34]. Materials with large  $\sigma$  and low  $K$  (electron-crystal, phonon-glass materials) are desirable to obtain a high  $ZT$ , so nanostructured materials are perhaps the best option for high efficient solar thermoelectric generator. Another important parameter to take into consideration is the thermoelectric power ( $S^2\sigma$ ) which strongly dependent on the  $\sigma$  ( $S$  is inversely proportional to the  $\sigma$ ). Nanostructuring could affect  $S^2\sigma$  due to the influence of surface state effect [35], or quantum confinement [36]. Sample preparation and crystalline quality are also factors that contribute to the good quality of thermoelectric materials. For example, the thermoelectric characteristics of n-type Bi<sub>2</sub>Te<sub>3</sub> nanowire bundles (nanowire diameter approx. 70 nm). It was found that  $S^2\sigma$  is about  $6.2 \times 10^{-4}$  W/m-K<sup>2</sup> at 300 K which is a factor of 10 larger than the value reported for n-type Bi<sub>2</sub>Te<sub>3</sub> single nanowires [37] and a factor of 3 smaller than nanocrystalline Bi<sub>2</sub>Te<sub>3</sub> [38] (all these power factors were measured at similar  $\sigma$ ).

## VII. THERMOELECTRIC NANOWIRE SENSORS

Rapid and highly sensitive detection of chemical and biological species is critical in many fields such as medical treatment, monitoring of toxic agents, and safety. The use of nanostructured materials for those applications has led to the development of a series of impressive sensor technologies. The large impact of nanosensors can be understood by the broad number of applications ranging from the detection of transmembrane pore-forming proteins by silicon nanowires, [39] to chemical sensing by ZnO nanoribbons [40], to the sensing of biomolecules by silver triangular nanoparticles [41]. Some of the reasons for such interest are: the large density of sensing devices in a small area with different functionalities given their small dimensions [42, 43]; the mass transfer rate of target species from solution to the surface of the nanosensor is not a limiting process (contrary to their

bulk counterpart); and the ability to detect small concentration of target species. Generally, nanosensors are divided into 2 groups: the electrical and optical based sensing approaches. For the electrical based nanosensors, the sensing approach includes measuring electrical changes of nanostructured materials due to chemical, biochemical, or cell activity events. For optical based nanosensors, the sensing event will trigger an optical response, which could be either a change of the fluorescence intensity (also known as fluorescent tagged approach), or a change of a material's property (e. g. refractive index) known as label free approach. Despite these considerable advantages, optical methods present limitations such as photo bleaching, interaction of non-target species in solution with the fluorescent probes, and inability to be used in turbid solutions. Thermoelectric sensor response would be based on changes of carrier density due to surface binding events, so small diameter nanowires with large mobilities are expected to improve signal to noise ratio.

### VIII. THERMAL STABILITY OF CARBON NANOTUBES

The stiff  $sp^3$  bonds in diamond structure result in high phonon speed and consequently high thermal conductivities of the material. In carbon nanotubes, the carbon atoms are held together by the even stronger  $sp^2$  bonds, so that the nanotube structures, consisting of seamlessly joined graphitic cylinders are expected to have extraordinarily high thermal conductivities. The rigidity of these nanotubes, combined with virtual absence of atomic defects or coupling to soft phonon modes of the embedding medium, should make isolated nanotubes very good candidates for efficient thermal conductors. Recently Motoo Fujii et al measured the thermal conductivity of single Carbon nanotube using a suspended sample-attached T-type nanosensor, and reported values exceeding 2000 W/mK for a carbon nanotube of 9.8 nm diameter. These experimental values were in the range of the theoretical calculations, which provides high thermal conductivity of the carbon nanotubes experimentally. Due to their high thermal conductivities, carbon nanotubes or nanotubes based nanocomposite could be promising candidates for heat transport management in many applications such as in the integrated circuits, optoelectronic devices and MEMS structures. The two samples tested reveal the same oxidizable carbon content of 92.67 %, which burns out in the temperature range 400 to 750 °C, but the volatile content before start of oxidation is 10 times higher in the modified sample, and the residue at 1000 °C (ash) is 3 times less in the modified CNT sample. The oxidation range of this CNT samples is much lower compared with known ranges for bulk graphite and diamond samples. Though carbon atoms are involved in aromatic rings like for graphite, the C=C bond angles are no longer planar in the CNTs and the C-C bond length is actually elongated by the curvature imposed.

### IX. THERMAL PROPERTIES OF NANOWIRES

One-dimensional nanowires may offer ultra-low thermal conductivities, quite different from that of carbon nanotubes. In nanowires, phonons behave differently from those in the corresponding bulk materials due to the quantum confinement in the one dimension structures. The nanowire surface can introduce surface phonon modes, resulting in many different phonon polarizations other than the two transverse and one longitudinal acoustic branch found in bulk semiconductors. Those changes in the dispersion relation can modify the group velocity and the density of states of each branch. The phonon lifetime also changes due to the strong phonon-phonon interactions and the boundary scattering within the nanostructures. Thus the phonon transports and the thermal properties of the nanowires will be significantly different from that of the bulk materials. Deyu et al measured the thermal conductivity of silicon nanowires using a micro fabricated suspended device over a temperature range of 20–320K. Although the nanowires had well-defined crystalline order as in bulk materials, the observed thermal conductivity was more than two orders of magnitude smaller than that of bulk silicon, which also showed a strong dependence on the nanowire size. For a silicon nanowire with 22nm diameter, the thermal conductivity was reduced to be in the sub 10 W/m range. The appreciable change of the thermal conductivity compared to the bulk materials was ascribed to phonon-boundary scattering and the possible change in phonon dispersion due to confinement within the nanostructures. The same research group also measured the thermal conductivity on Si/SiGe super lattice nanowires, with even smaller thermal conductivity reported on the superlattice nanowires compared to pure silicon nanowires. These experimental results agreed fairly well with the theoretical calculations based on phonon dispersion approach. The low thermal conductivity in these one dimensional semiconducting nanowires will find applications in thermoelectric power generation and the thermoelectric refrigeration. However, they are not desired in for thermal management in electronics, which generally need much higher thermal transport capabilities. The interfaces is also an important factor in determine the phonon transport properties due to the high density of interfaces in the multilayers or super lattices structures. For example, if the two materials in the super lattice have large mismatch in the phonon dispersion relations, phonons in certain frequency range cannot propagate to the neighbouring layer unless there are mode conversions at the interface; The interfaces between two different materials with different lattice constants can contain dislocations and defects, which can also scatter phonons and reduce thermal conductivity; physical roughness and alloying will also exist at the interface depending on the processing, and affect the phonon transport. The overall effect in these factors on the phonon transport is the

multilayer and super lattice structures are a general decrease of thermal conductivities.

## X. CONCLUSION

Nanostructured materials are becoming the materials of choice for thermoelectric applications mostly due to the reduction of the thermal conductivity without a negative influence on the electronic properties. In spite of the large improvements of the thermoelectric efficiency by nanostructuring, ZT values are still not high enough for a wide spread use of thermoelectrics. However, a large number of applications could presently benefit from nanostructured thermoelectric. Engineers in collaboration with materials scientists would make possible to expand the horizon of applications for thermoelectric nanostructured materials. American Journal of Nanoscience and Nanotechnology 2014; 2(5): 97-104 103.

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## REFERENCES

- [1] American Journal of Nanoscience and Nanotechnology 2014; 2(5): 97-104.
- [2] Ghadimi, A.; Saidur, R.; Metselaar, H.S.C. A review of nanofluid stability properties and characterization in stationary conditions. *Int. J. Heat Mass Tran.*, 2011, 54, 4051-4068.
- [3] Saidur, R.; Leong, K.Y.; Mohammad, H.A. A review on applications and challenges of nanofluids. *Renew. Sust.Energ. Rev.*, 2011, 15, 1646-1668.
- [4] Haddad, Z.; Oztop, H.F.; Abu-Nada, E. A review on natural convective heat transfer of nanofluids. *Renew. Sust. Energ.Rev.*, 2012, 16, 5363-5378.
- [5] Taylor, R.; Coulombe, S.; Otanicar, T. Critical review of the novel applications and uses of nanofluids, Proceedings of the 3rd International Conference on Micro/Nanoscale Heat & Mass Transfer, Atlanta, GA, March, Anonymous, 2012, 3-6.
- [6] Kandlikar, S.G. History, advances, and challenges in liquid flow and flow boiling heat transfer in microchannels: a critical review. *J. Heat Trans-T ASME*, 2012, 134, 034001.
- [7] Mahian, O.; Kianifar, A.; Kalogirou, S.A. A review of the applications of nanofluids in solar energy. *Int. J. Heat Mass Tran.*, 2013, 57(2), 582-594.
- [8] Sureshkumar, R.; Mohideen, S.T.; Nethaji, N. Heat transfer characteristics of nanofluids in heat pipes: a review. *Renew. Sust.Energ. Rev.*, 2013, 20, 397-410.
- [9] Barber, J.; Brutin, D.; Tadrist, L. A review on boiling heat transfer enhancement with nanofluids. *Nanoscale Res. Lett.*, 2011, 6(1), 1-16.
- [10] Fan, J.; Wang, L. Review of heat conduction in nanofluids. *J.Heat Transf.*, 2011, 133(4), 133-138
- [11] Morales A.M, Lieber C. M, *Science* 279: 208(1998)
- [12] Wang S R, Huang J, Zhao Y Q, *Mater Lett* 60:1706(2006)
- [13] Xu C K, Xu G D, Liu Y K, *Scr Mat* 46:789(2002)
- [14] Gotoh Y, Fujimura K, Koike M, *Mater Res Bull*36:2263(2001)
- [15] Zhu H L, Ji X, Yang D R, *J Mater Sci* 41:3489(2006)
- [16] Scida, K.; Stege, P.W.; Haby, G.; Messina, G.A.; Garcia, C.D. Recent application of carbon-based nanomaterials in analytical chemistry: critical review. *Anal. Chim. Acta*, 2011, 691, 6-17.
- [17] Dreizin, E.L. Metal-based reactive nanomaterials. *Prog.Energ. Combust.*, 2009, 35, 141-167.
- [18] Singh, S.C.; Ram, G. Drop shape zinc oxide quantum dots and their self-assembly into dendritic nanostructure: *Appl.Surf. Sci.*, 2012, 258, 2211-2218.
- [19] Gong, S.; Yang, G.; Ban, D.; Fu, J.; Fu, Y. Three-pulsed photon echo induced by the optical transitions of excitons in core-shell CdSe/ZnS nanocrystal quantum dots. *Opt. Mater.*, 2011, 34, 36-41.
- [20] Sebaa, M.; Nguyen, T.Y.; Paul, R.K.; Mulchandani, A.; Liu, H. Graphene and carbon nanotubes-graphene hybrid nanomaterials for human embryonic stem cell culture. *Mater.Lett.*, 2013, 92, 122-125.
- [21] Yuan, J.; Muller, A.H.E. One-dimensional organic-inorganic hybrid nanomaterials. *Polymer*, 2010, 51, 4015-4036
- [22] Goldsmid, H. J., *Thermoelectric Refrigeration*. Plenum, New York, (1964).
- [23] Rowe, D. M. *Thermoelectrics Handbook Nano to Macro*, CRC Taylor & Francis, Boca Raton, (2006).
- [24] Hsu, K. F., Loo, S., Guo, F., Chen, W., Dyck, J. S. "Cubic AgPb(m)SbTe(2+m): bulk thermoelectric materials with high figure of merit", *Science*, 303, 818-821 (2004).
- [25] Dresselhaus, M. S., Chen, G., Tang

- [26] Hsu, K. F., Loo, S., Guo, F., Chen, W., Dyck, J. S. "Cubic  $\text{AgPb(m)SbTe(2+m)}$ : bulk thermoelectric materials with high figure of merit", *Science*, 303, 818-821 (2004). [24] Dresselhaus, M. S., Chen, G., Tang, M. Y., Yang, R. G., Lee, H., et al., "New Directions for Low-Dimensional Thermoelectric Materials", *Advanced Materials*, 19, 1043-1053, (2007).
- [27] Poudel, B., Hao, Q., Ma, Y., Lan, Y., Minnich, A. "High-Thermoelectric Performance of Nanostructured Bismuth Antimony Telluride Bulk Alloys", *Science*, 320, 634-638 (2008).
- [28] Heremans, J. P., Jovovic, V., Toberer, E. S., Saramat, A., Kurosaki, K., et al., "Enhancement of Thermoelectric Efficiency in PbTe by Distortion of the Electronic Density of States", *Science*, 321, 554-557, (2008).
- [29] Tritt, T. M., Subramanian, M. A., "Thermoelectric Materials, Phenomena, and Applications: A Bird's Eye View", *MRS Bulletin*, 31, 188-198, (2006).
- [30] Minnich, A., Dresselhaus, M. S., Ren, Z. F., Chen, G., "Bulk nanostructured thermoelectric materials: current research and future prospects", *Energy & Environmental Science*, 2, 466-479, (2009).
- [31] Kraemer D, Poudel B, Feng HP, Caylor
- [32] Kraemer D, Poudel B, Feng HP, Caylor JC, Yu B, Yan X, et al. High-performance flat-panel solar thermoelectric generators with high thermal concentration. 2011; *Nat Mater*. 10: 532-538.
- [33] Fuschillo N, Gibson R. Germanium-silicon, lead telluride, and bismuth telluride alloy solar thermoelectric generators for venus and mercury probes. *Advanced Energy Conversion*. 1967; 7: 43-52.
- [34] Amatya R, Ram RJ. Solar Thermoelectric Generator for Micropower Applications. *Journal of Electronic Materials*. 2010; 39: 1735-1740.
- [35] Kraemer D, Poudel B, Feng HP, Caylor JC, Yu B, Yan X. High-performance flat-panel solar thermoelectric generators with high thermal concentration. 2011; *Nat Mater*. 10: 532-538.
- [36] Baranowski LL, Snyder GJ, Toberer E.S. Concentrated solar thermoelectric generators. *Energy & Environmental Science*. 2012; 5: 9055-9067.
- [37] Tritt TM. Thermoelectric Phenomena, Materials, and Applications. *Annual Review of Materials Research*. 2011; 41: 433-448. [35] Martinez JA, Cho JH, Liu XH, Luk TS, Huang JY, Picraux ST, et al. Contribution of radial dopant concentration to the thermoelectric properties of core-shell nanowires. *Applied Physics Letters*. 2013; 102: 103101.
- [38] Cornett JE, Rabin O. Thermoelectric figure of merit calculations for semiconducting nanowires. *Applied Physics Letters*. 2011; 98: 182104.
- [39] Zhou JH, Jin CG, Seol JH, Li XG, Shi L. Thermoelectric properties of individual electrodeposited bismuth telluride nanowires. *Applied Physics Letters*. 2005; 87: 133109.
- [40] Takashiri M, Takiishi M, Tanaka S, Miyazaki K, Tsukamoto H. Thermoelectric properties of n-type nanocrystalline bismuth-telluride-based thin films deposited by flash evaporation. *Journal of Applied Physics*. 2007; 101: 074301.
- [41] Martinez JA, Misra N, Wang Y, Stroeve P, Grigoropoulos CP, Noy A. Highly efficient biocompatible single silicon nanowire electrodes with functional biological pore channels. 2009; *Nano Lett*. 9: 1121-1126.
- [42] Fan ZY, Wang DW, Chang PC, Tseng WY, Lu JG. ZnO nanowire field-effect transistor and oxygen sensing property. *Applied Physics Letters*. 2004; 85: 5923-5925.
- [43] McFarland AD, Van Duyne RP. Single silver nanoparticles as real-time optical sensors with zeptomole sensitivity. *Nano Letters*. 2003; 3: 1057-1062.
- [44] Cui Y, Wei Q, Park H, Lieber CM. Nanowire nanosensors for highly sensitive and selective detection of biological and chemical species. 2001; *Science*. 293: 1289-1292.
- [45] Misra N, Martinez JA, Huang SCJ, Wang YM, Stroeve P, Grigoropoulos CP, et al. Bioelectronic silicon nanowire devices using functional membrane proteins. *Proceedings of the National Academy of Sciences of the United States of America*. 2009; 106: 13780-13784.

