بسم الله الرحمن الرحيم

Thermoelectric energy harvesting and its applications in nuclear industry

Dr. Kaleem Ahmad

6th series of short lectures in sustainable energy
23rd November 2017

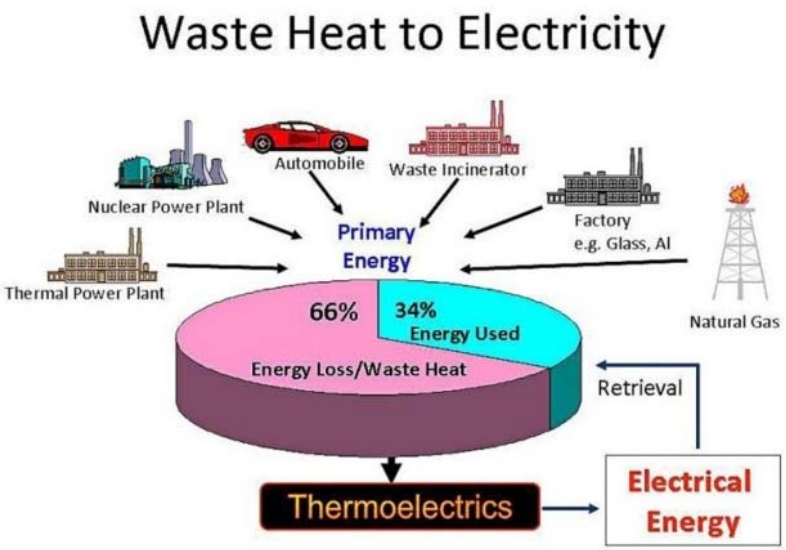
Outline

- ✓ Overview
- ✓ Applications
- ✓ Applications in Nuclear Industry
- ✓ R&D at SET Center
- ✓ Strategy to Improve Efficiency
- ✓ Research Methodology
- ✓ Results & Discussion
- ✓ Summary

Overview

- Approximately 90% of world's power is generated by heat engines that use fossil fuels combustion
  - Operates at 30-40% of the Carnot efficiency
  - Serves as a heat source of potentially 15 terawatts lost to the environment

- Thermoelectric could potentially generate electricity from waste heat



Advantages:

- ➢ Environmental friendly
- ➢ Recycles wasted heat energy
- ➢ Scalability
- ➢ Reliable source of energy

Overview

- The pioneer in thermoelectrics was a German scientist Thomas Johann Seebeck (1770-1831)
- **Thermoelectricity** refers to a class of phenomena in which a temperature difference creates an electric potential or an electric potential creates a temperature difference.
- ***Thermoelectric power generator*** ***is a device that converts the heat energy into electrical energy based on the principles of Seebeck effect***
- Later, In 1834, French scientist, **Peltier** and in 1851**, Thomson** (later Lord Kelvin) described the thermal effects on conductors

Overview

Thermoelectric materials

- The good thermoelectric materials should possess

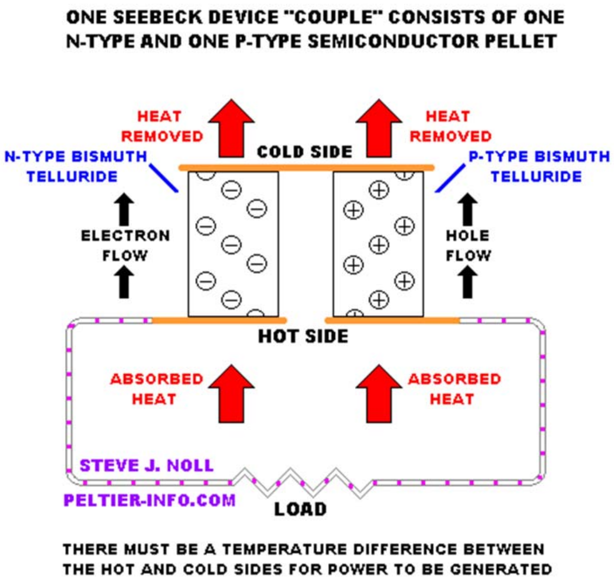
  1. Large Seebeck coefficients
  2. High electrical conductivity
  3. Low thermal conductivity

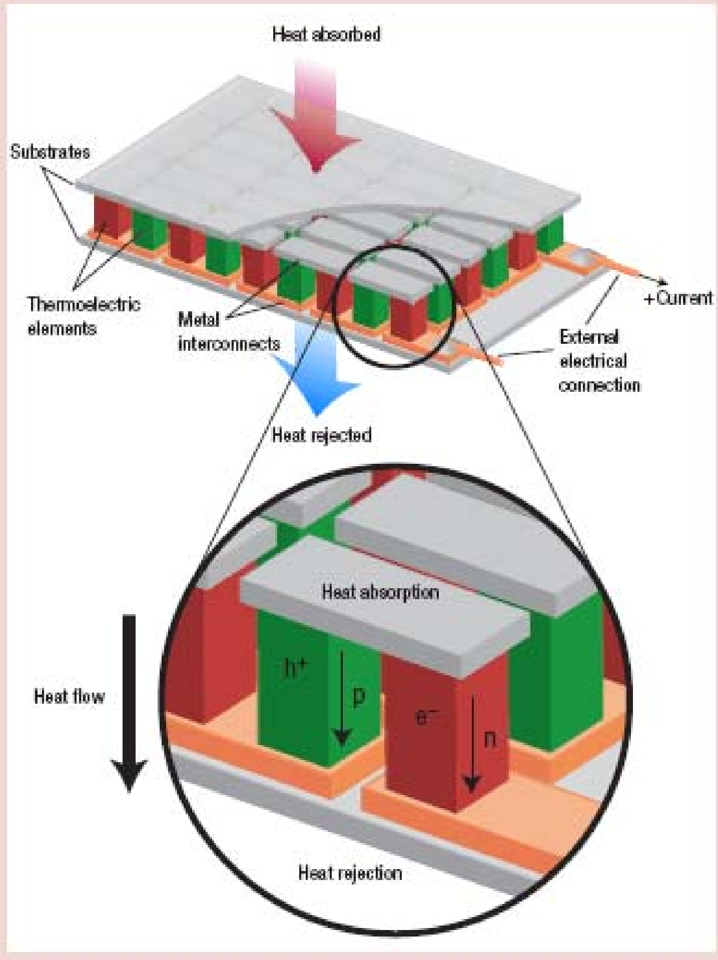
- The example for thermoelectric materials

  - BismuthTelluride (Bi_2Te_3),
  - Lead Telluride (PbTe),
  - SiliconGermanium (SiGe),
  - Bismuth-Antimony (Bi-Sb)

Overview

Thermoelectric power generator





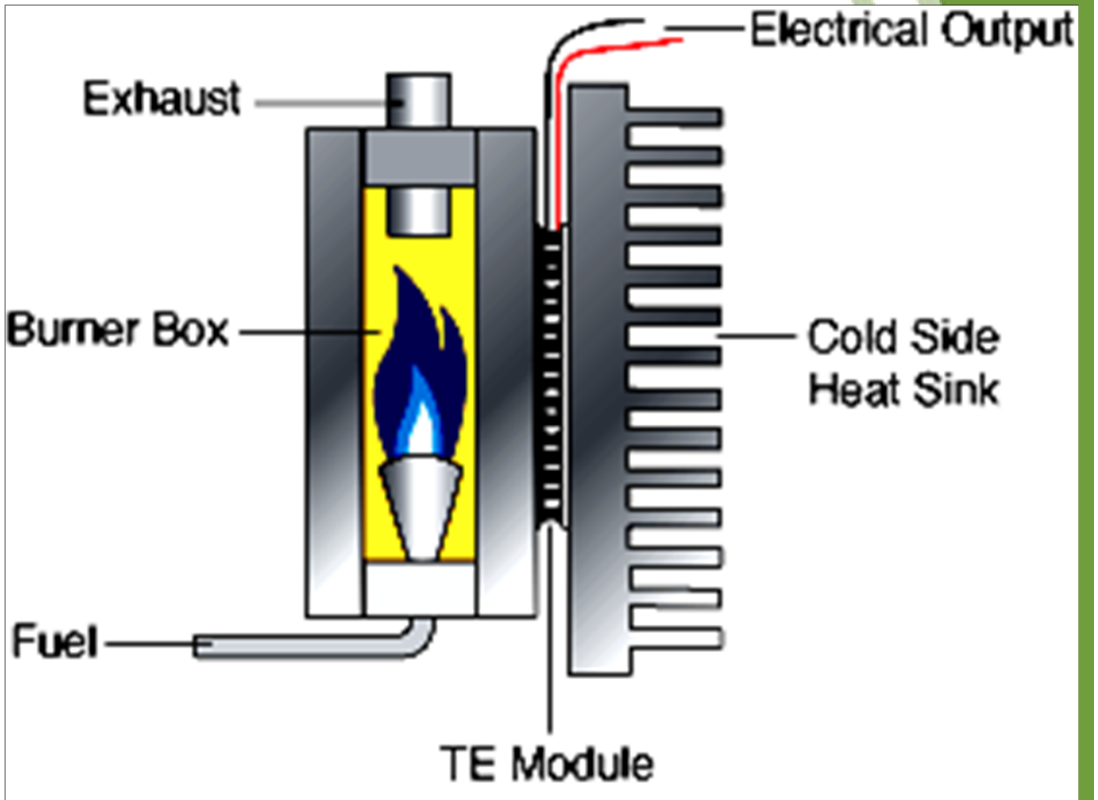
Snyder et al. *Nature* 7, 105-114, (2008).

Thermoelectric power generator based on the principle of **Seebeck effect** that when the junctions of two different metals are maintained at different temperature, the emf is produced in the circuit

Overview

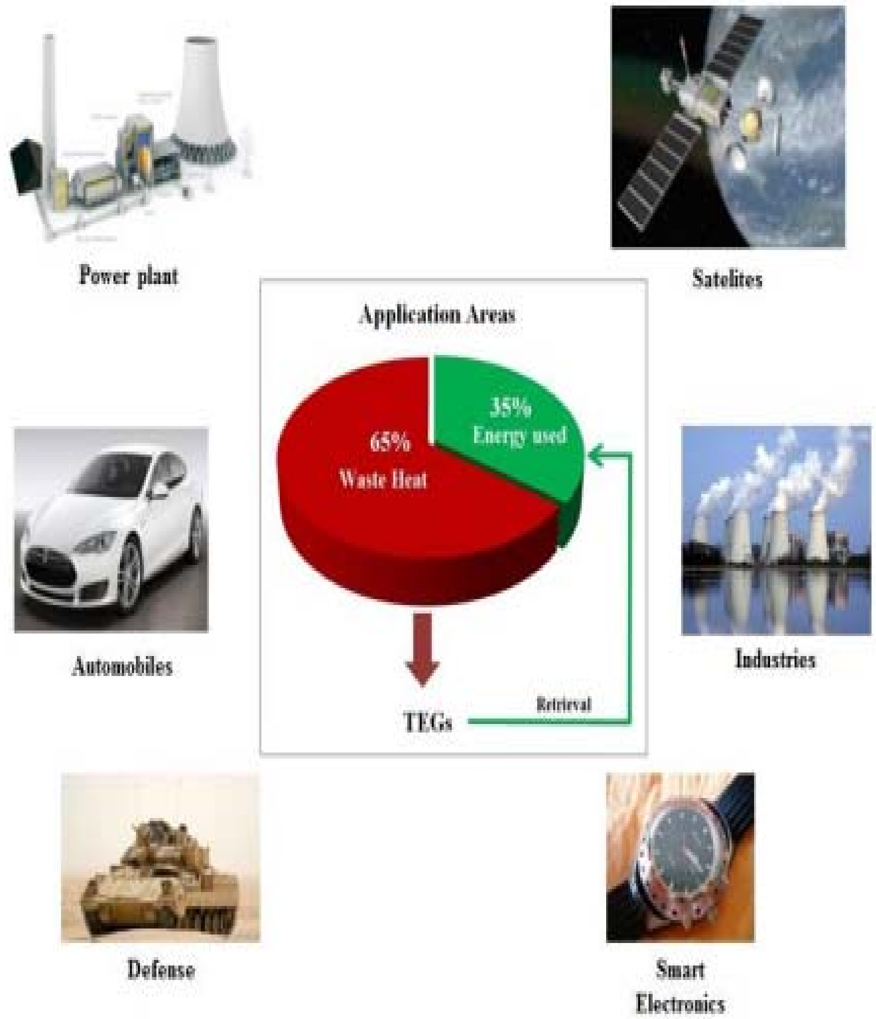
Therefore, for any TEPG, there are four basic component required such as

- Heat source (fuel)
- P and N type semiconductor stack (TE module)
- Heat sink (cold side)
- Electrical load (output voltage)



Applications

- Nuclear Power Plants
- WSN in Conventional Power Plants
- STEG
- Automobiles.
- Outside Space Applications/Satellites.
- Industrial Waste Heat.
- Human Wearables.



Applications

Wireless sensor networks

TEGs provide condition monitoring solutions without the need to replace battery as they are self powered.

ABB's Wireless temperature transmitter

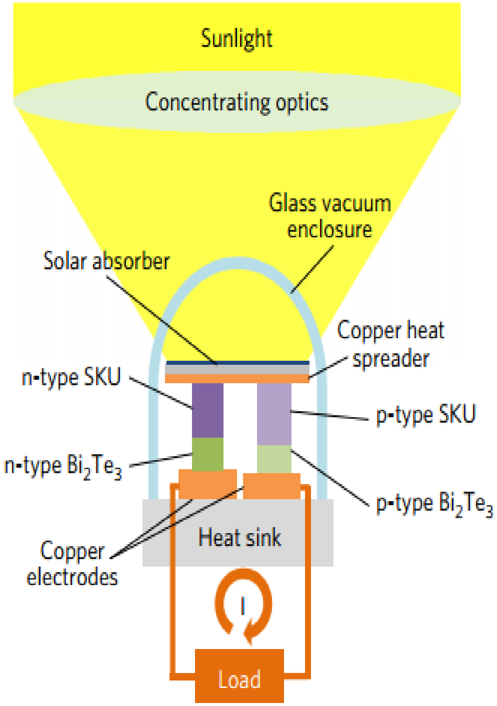
Small node sensors

Can be mount directly onto internal combustion engines/high temp devices commonly used in power plants & well drilling rigs to produce power.

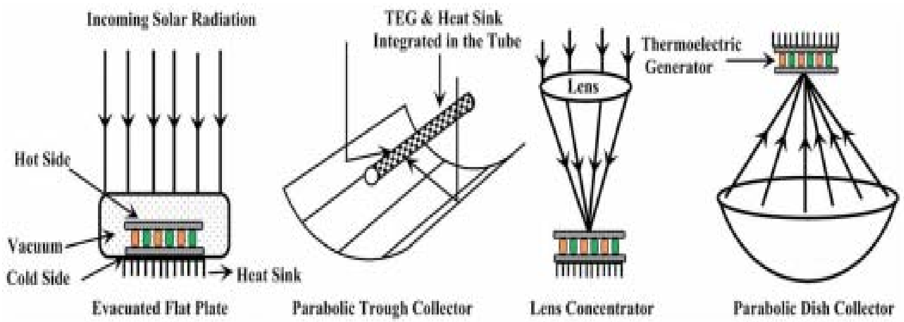
Applications

Solar Thermoelectric Generators (STEG)

- Photovoltaic (PV) cells can directly convert parts of the solar spectrum, but a significant part is absorbed as heat.
- STEGs can utilize this heat to convert into electricity thus improving efficiency.
- Also used in solar thermal systems.

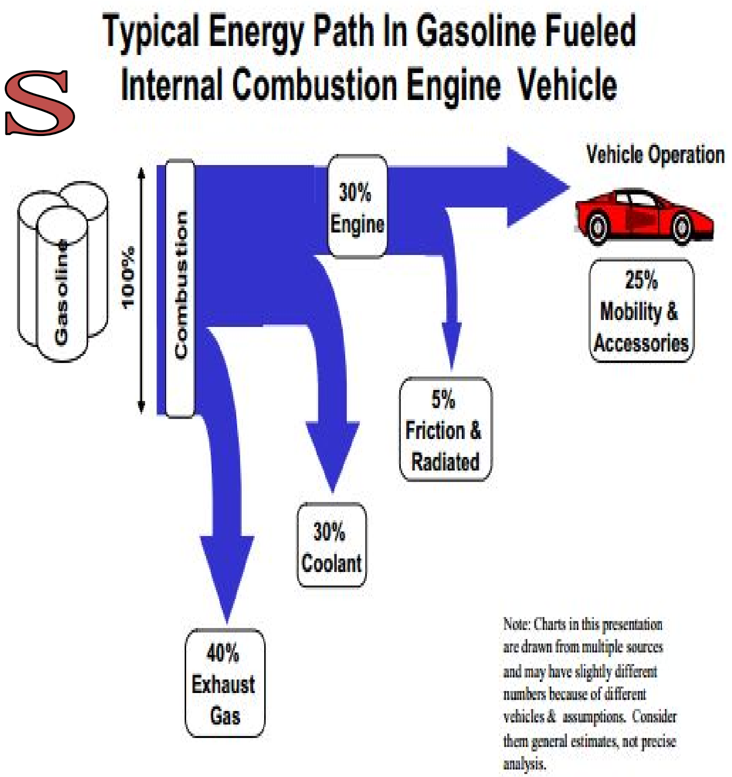


- STEGs can be categorized into 4 broad types.
  - Non-concentrated STEGs,
  - Concentrated STEGs
  - Thermal TEG hybrids
  - PV TEG hybrids.



Applications

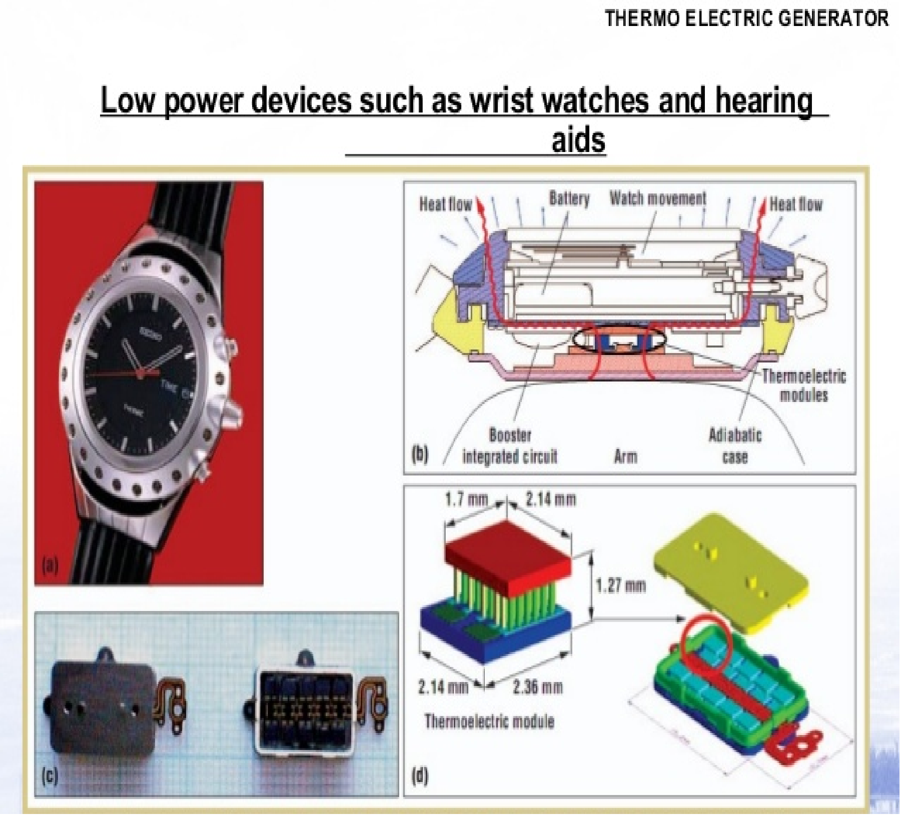
- Only 25-30% of the fuel energy is utilized, the remaining is lost in the form of waste heat in the exhaust, friction and coolant.
- Reduce the fuel consumption of the car by reducing the load on the car alternator.
- Provide 30% of car's electrical requirement
- ~ 10% reduction in fuel consumption
- 18 million vehicles in KSA



Applications

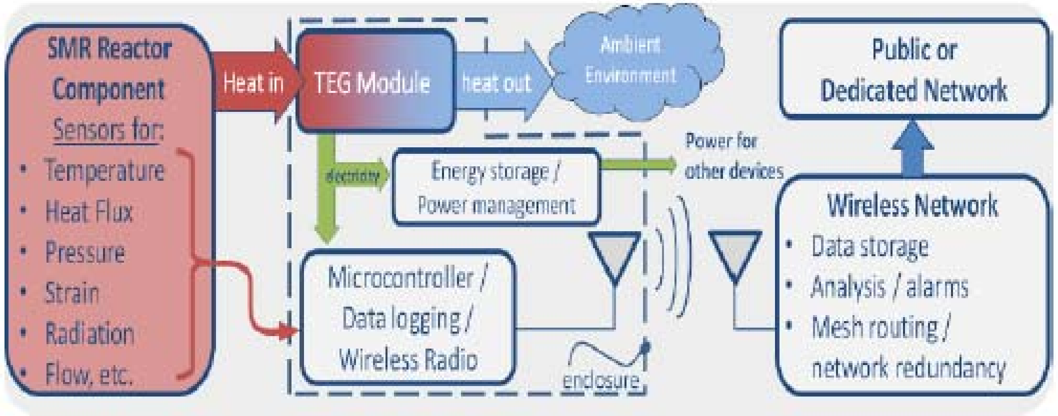
Wearables

– It uses the temperature difference between the body heat
and the air flow to create current.



Thermoelectric cell phone charger using stove

Applications in Nuclear Industry



- There is an huge amount of waste heat available in a nuclear power plant.
- The main benefit of the thermoelectric energy harvester is that it provides an independent power source to the facility as long as there is heat within the reactor.
- This system will provide an additional level of defense at nuclear facilities to ensure that their vital safety functions remain operational over a sufficient period of time and maintain control over the facility.

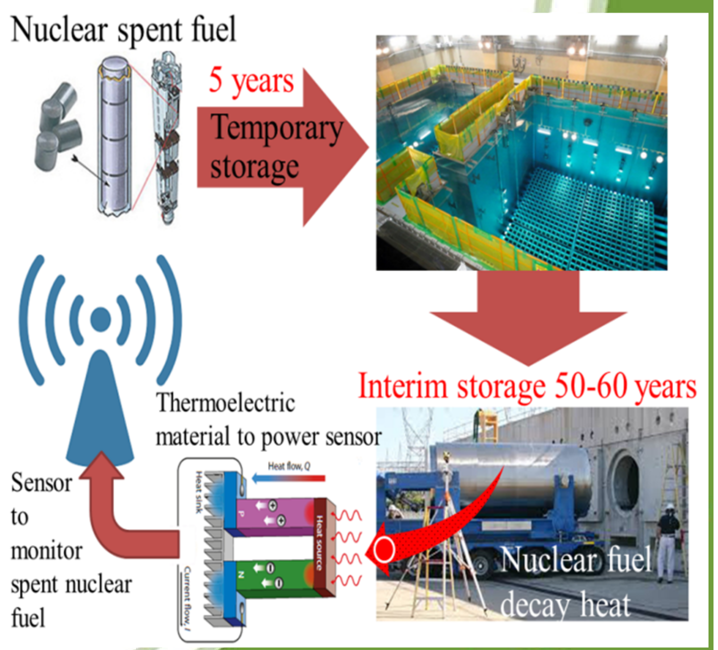
C. Chieh et al, Thermoelectrically Powered Sensing for Small Modular Reactors, 2013

Applications in Nuclear Industry

Spent fuel monitoring in nuclear industry

Currently, there is ≈24,000 metric tons of spent nuclear fuel in dry-cask storage. A major concern in this area is the safe storage of this nuclear fuel before final disposal. The regulatory body requires to address the following areas of concern:

- Stress corrosion cracking of stainless steel canister body, welds and degradation of cask bolts
- Effects of fuel pellet swelling and fuel rod pressurization on cladding stress
- In-service monitoring methods for dry storage systems is an important consideration for non-proliferation

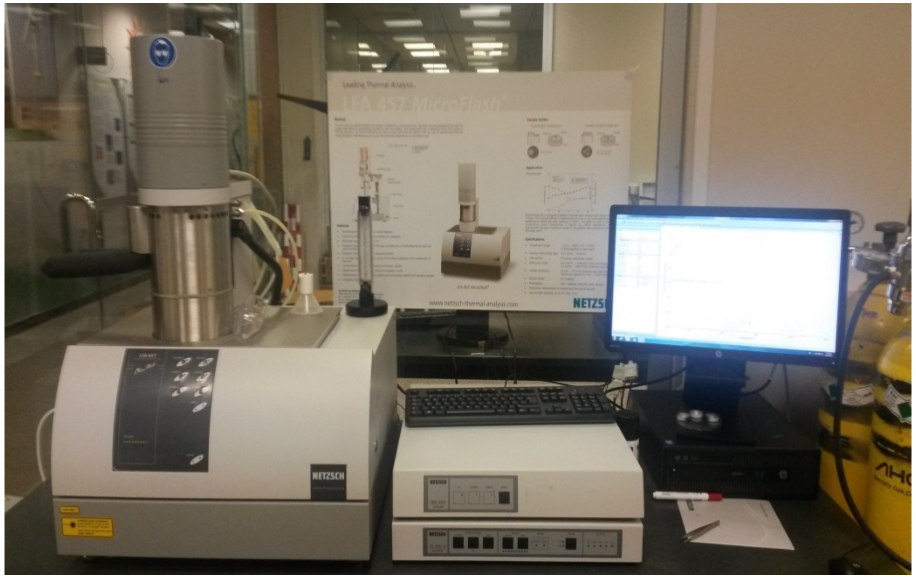


Thermoelectric Powered Wireless Sensors for Dry-Cask StorageIEEE Transactions on Nuclear Science (Volume: 60, Issue: 2, April 2013)

R&D at SET Center

Development of high performance thermoelectric bulk materials

State of the art thermoelectric materials research infrastructure at SET Center

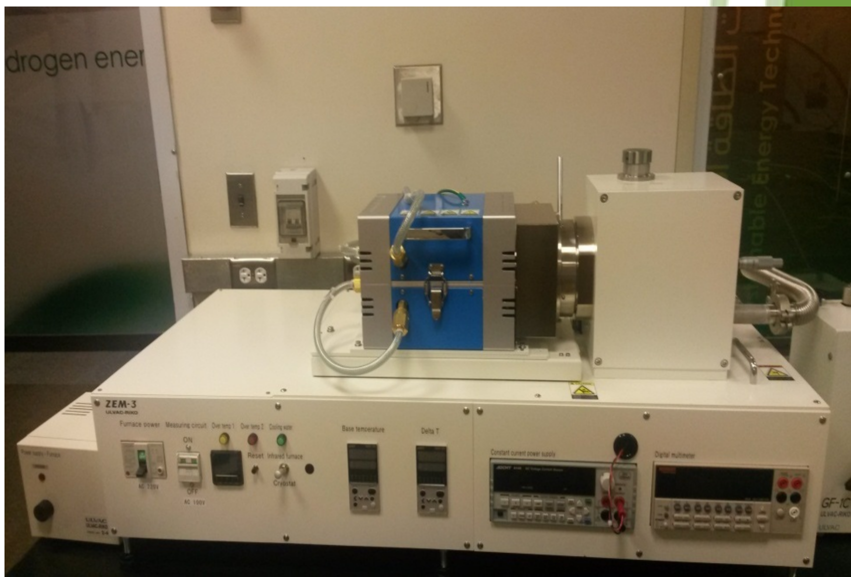


Laser Flash (LFA-457)
Thermal Conductivity Measurement System

Developed a state of the art thermoelectric materials research infrastructure at King Saud University

Collaborators:

- The Center of Research Excellence in Nanotechnology, KFUPM
- Nuclear Research Institute, KACST



Seebeck Coefficient/Electrical Resistance Measurement System

Introduction

A Figure of Merit – Conflicting Properties

$$ZT = \frac{S^2 \sigma T}{\kappa} \quad => \quad Z = \frac{S^2 \sigma}{\kappa}$$

S - Seebeck Coefficient

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

σ - Electron Conductivity

$$\sigma = \frac{1}{\rho} = ne\mu$$

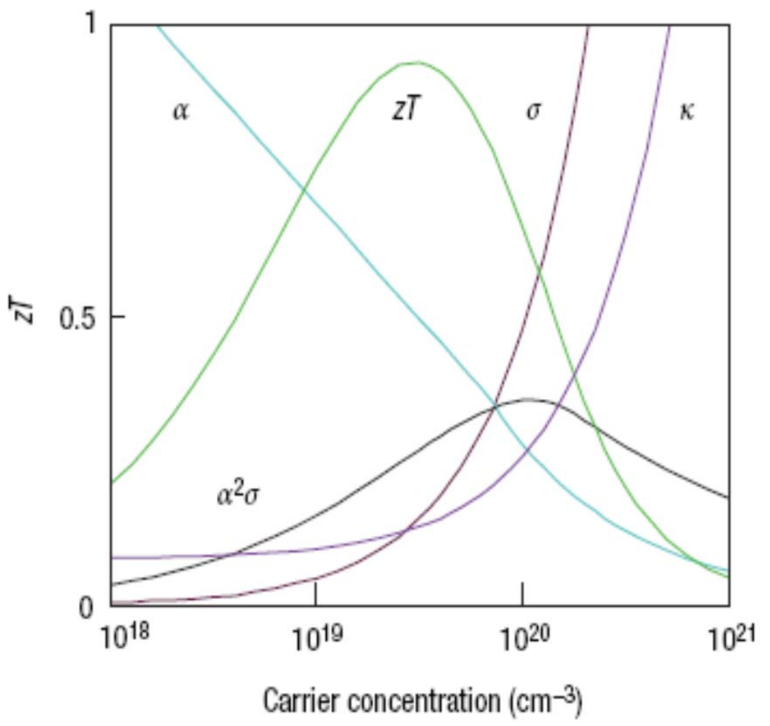
κ - Thermal Conductivity

$$\kappa = \kappa_e + \kappa_l$$

$$\kappa_e = L\sigma T = ne\mu LT$$

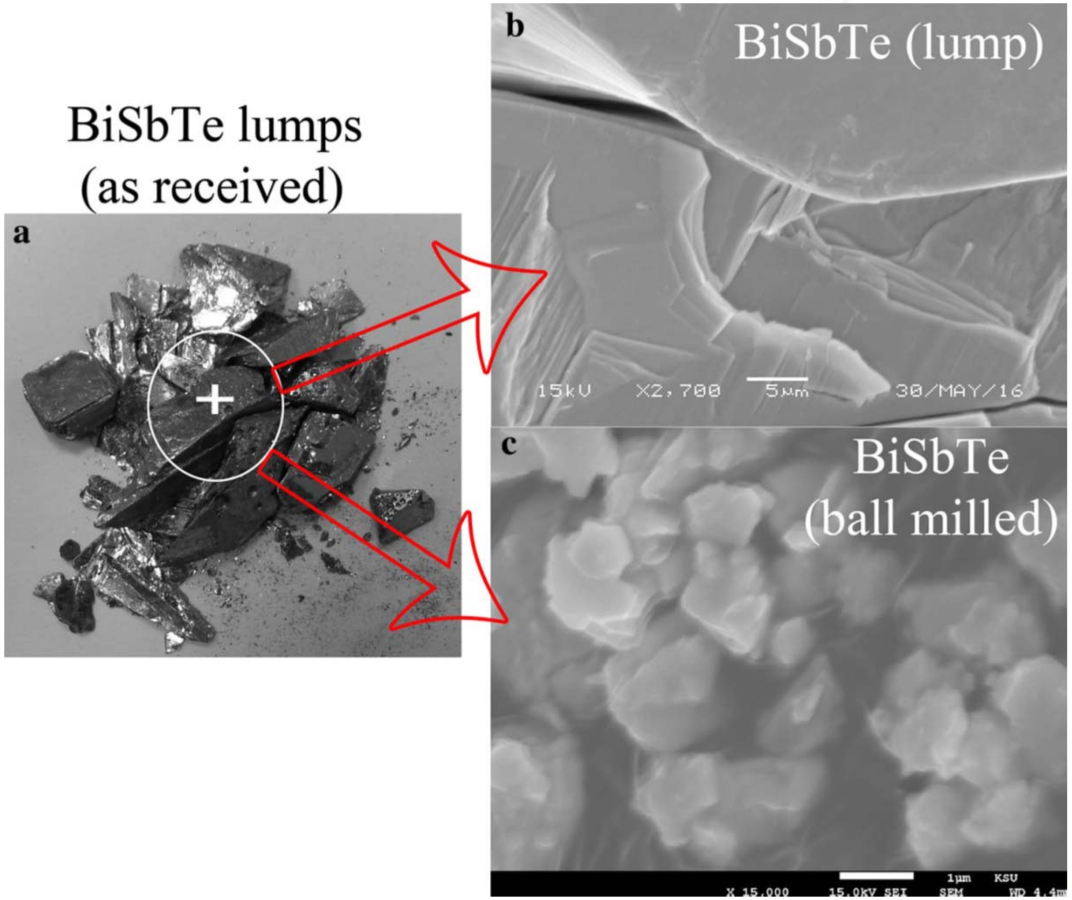
n - carrier concentration
m - effective mass of carrier
μ - carrier mobility

Effect of Carrier Concentration



Snyder et al. *Nature* 7, 105-114, (2008).

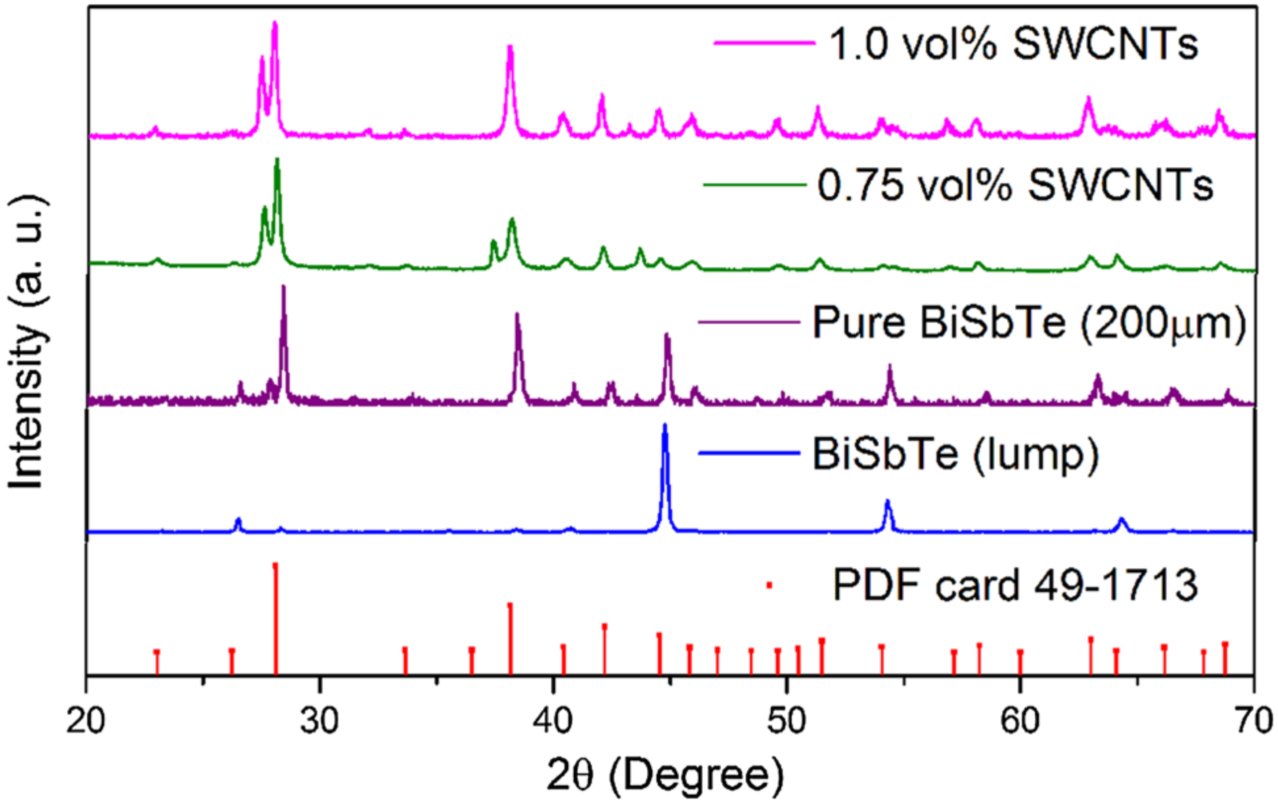
Reduction in thermal conductivity of BiSbTe

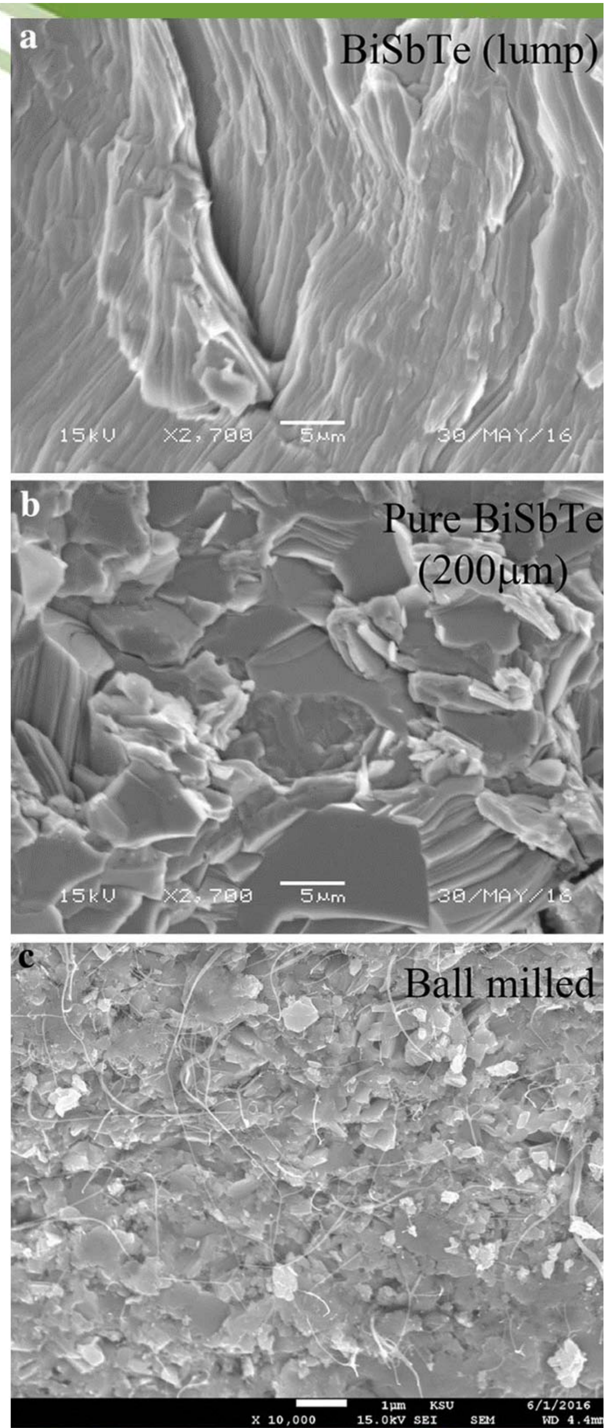


Bismuth antimony telluride was ball milled for 24 hours in an inert environment

Results and discussion

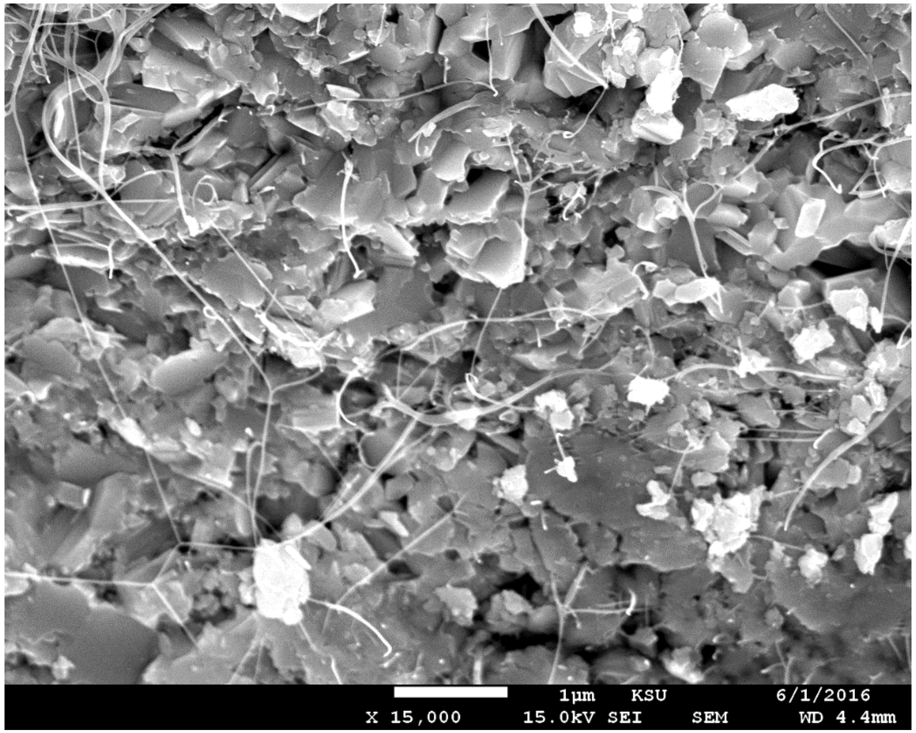
- A two pronged strategy has been employed.
- First, additional refinement of BiSbTe (200 μm) were performed through ball milling in an inert environment.
- Second, SWCNTs in 0.75, and 1.0 vol% were distributed uniformly in the fine BiSbTe ball milled powder.

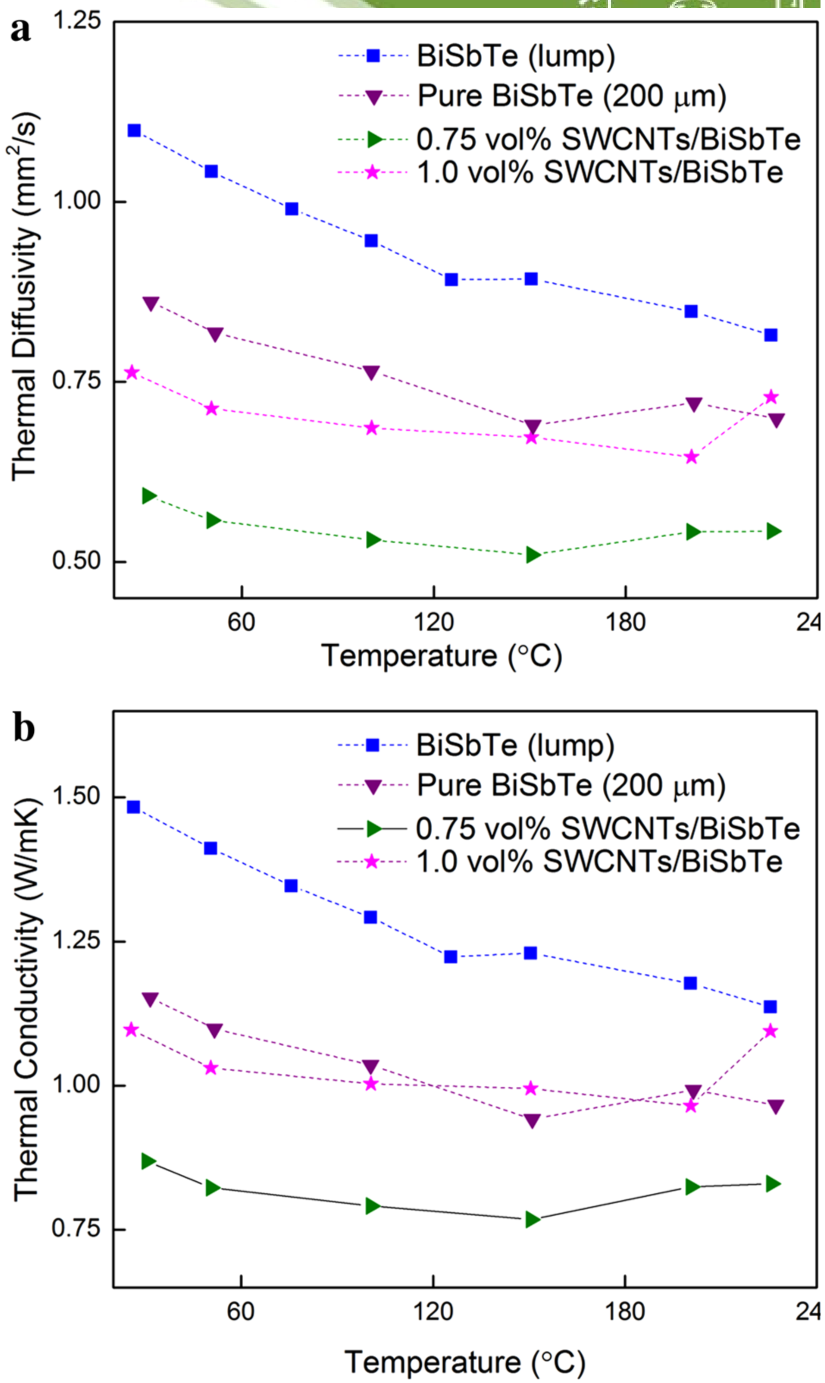




Results & discussion

$$K_e = \kappa \rho C_p$$





Summary

- A two pronged strategy has been has been found effective in reducing the effective thermal conductivity of the BiSbTe.
- The particle size reduction of BiSbTe (lump) has significant contribution on the thermal conductivities of BiSbTe bulk alloy
- The addition of SWCNTs in the composites dramatically reduces
- the thermal conductivities at 0.75 vol% of SWCNTs

Appl. Phys. A (2017) 123:173
DOI 10.1007/s00339-016-0738-8

Applied Physics A
Materials Science & Processing

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Reduction in thermal conductivity of BiSbTe lump

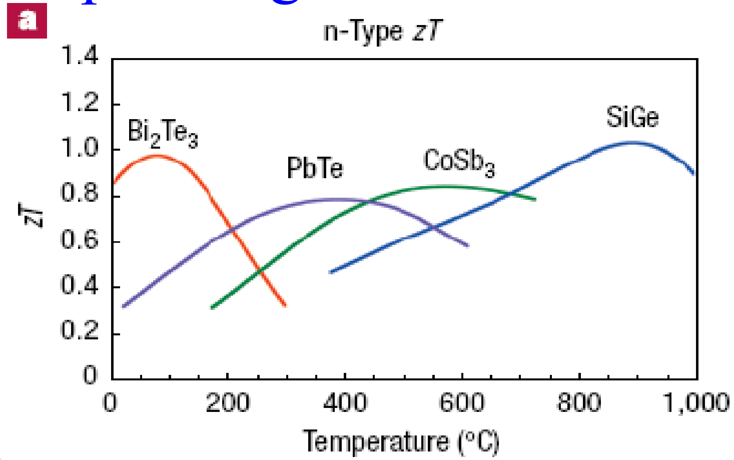
Kaleem Ahmad[1] · C. Wan[2] · M. A. Al-Eshaikh[3] · A. N. Kadachi[3]

Enhanced thermoelectric performance of Bi2Te3 through uniform dispersion of single wall carbon nanotubes

Strategy to improve efficiency

- ✓ Bismuth telluride is a narrow gap layered semiconductor with a trigonal unit cell.
- ✓ Bismuth telluride based material used for power generation or cooling applications.

$$ZT = \frac{S^2 \sigma T}{\kappa}$$



Nanocomposite

↓

Reduction in Thermal Conductivity

K ↓

- Two-pronged strategy
  - Nanostructuring
  - Inclusions of graphene/CNTs

Power Factor Enhancement

σS^2 ↑

- Improved conductivity, through introduction of graphene/CNTs
- Improved Seebeck coefficient through quantum confinement effect

ZT

Kaleem et al. Nanotechnolgy (2017).

Kaleem et al. Applied Physics A (2017).

Experimental methods

Composite Fabrication

- Bismuth telluride was ball milled for 24 hours in an inert environment
- Bismuth telluride powder was ultrasonically mixed with different (0.5, 0.75 and 1.0) volume percentages of SWCNTs and consolidated by the high frequency induction heated sintering to form disc-shaped samples.

Thermal Conductivity Measurements

- Thermal diffusivity was measured using Laser flash thermal diffusivity system LFA 457 NETZSC Germany.

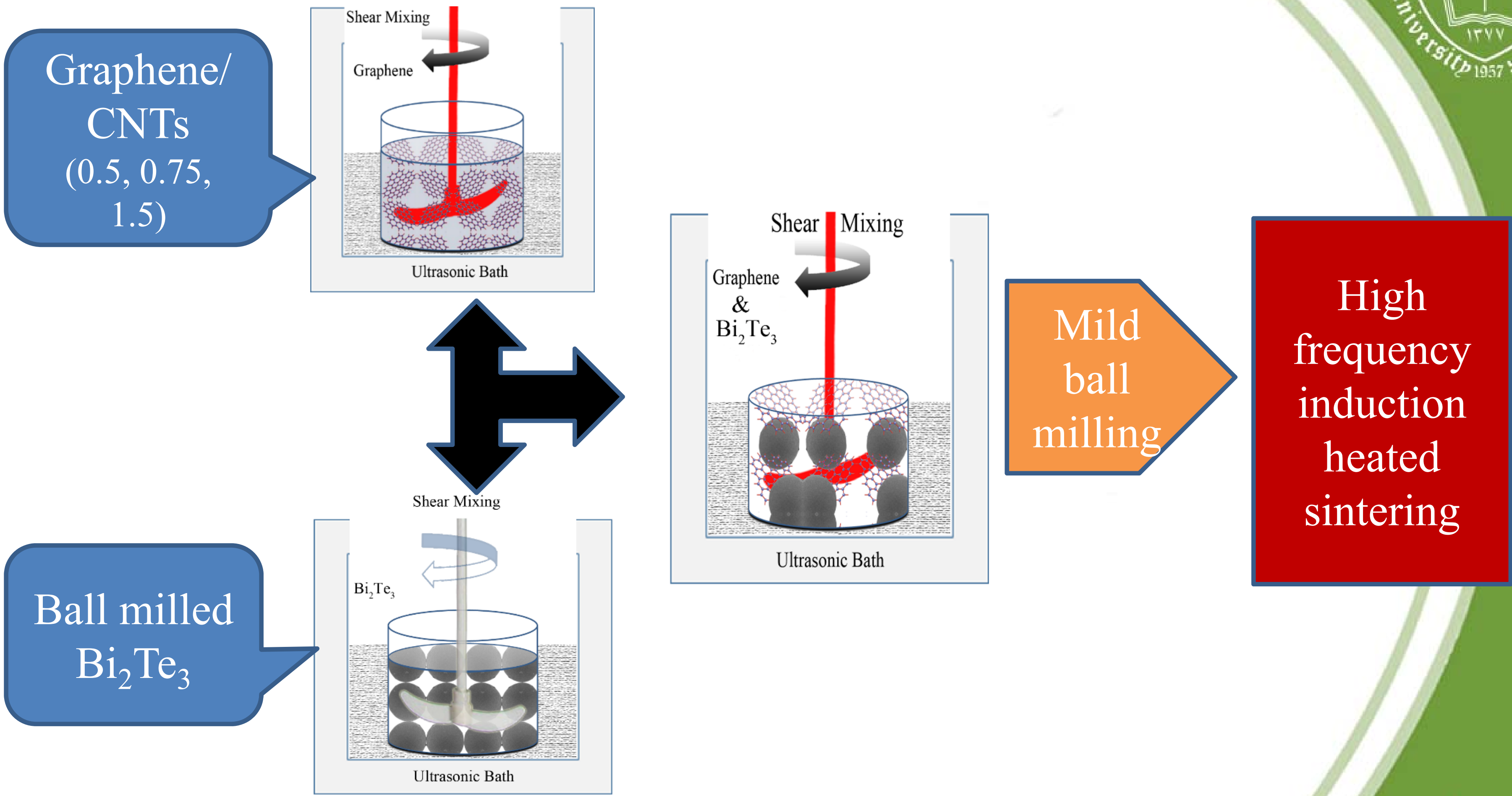
Thermoelectric Property Measurements

- The electrical conductivity and Seebeck coefficient was estimated on ZEM-3 system (ULVAC Co., Ltd., Japan).

Thermoelectric Figure of Merit (ZT) and Power Factor

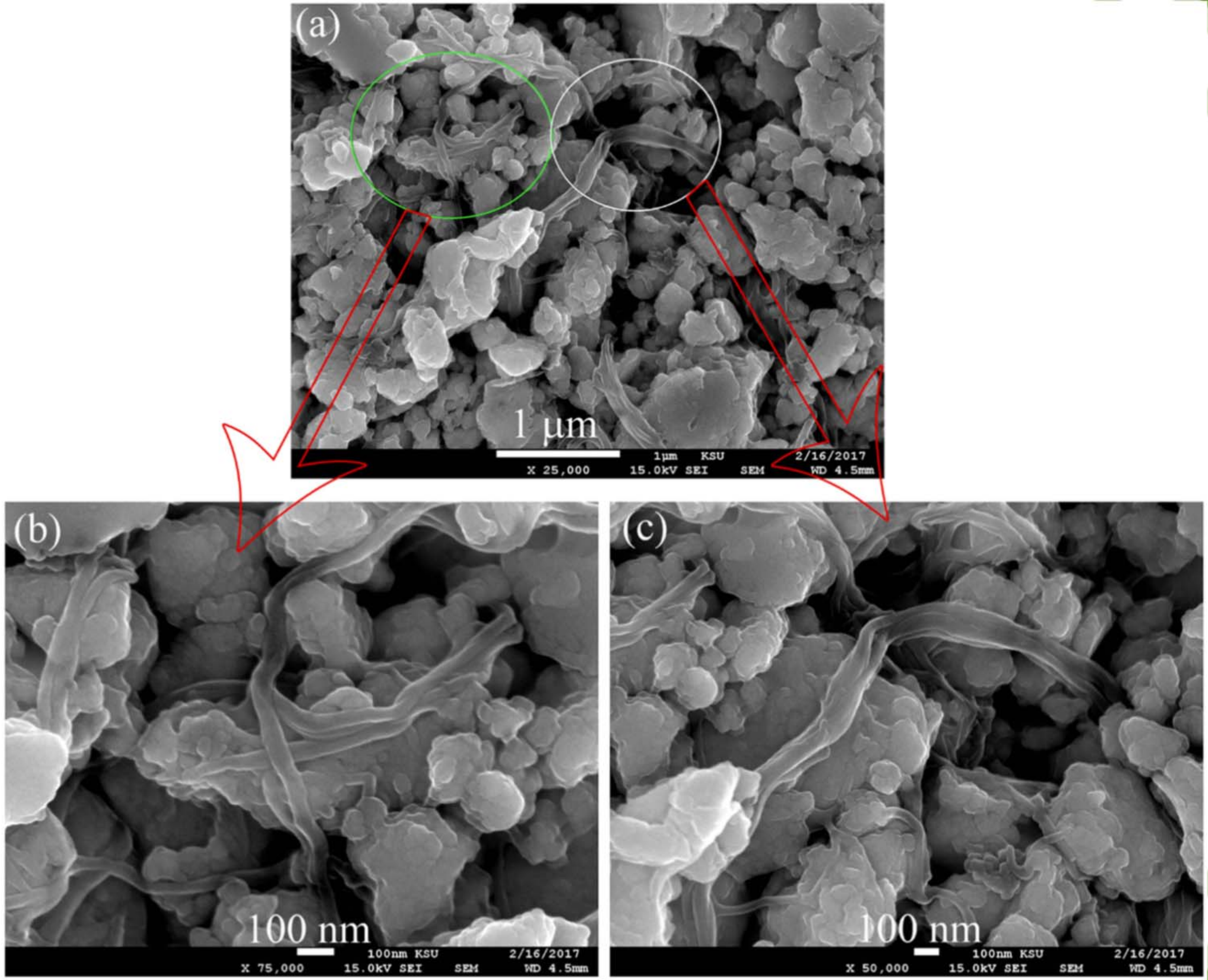
- After measuring all the above parameters, the thermoelectric figure of merit was evaluated.

Experimental methods



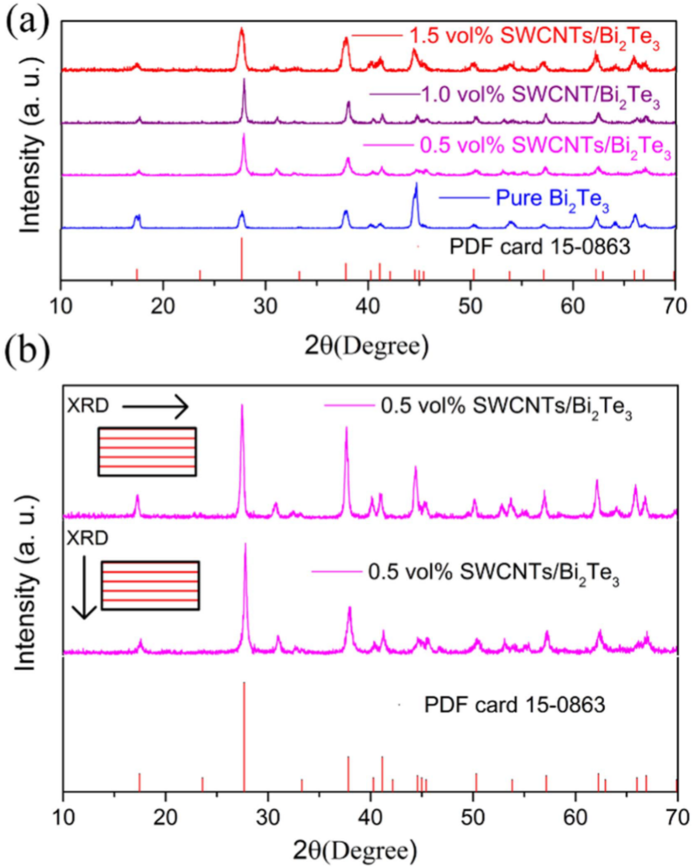
Kaleem et al. *RSC Advances* 5, 33607–33614, (2015).

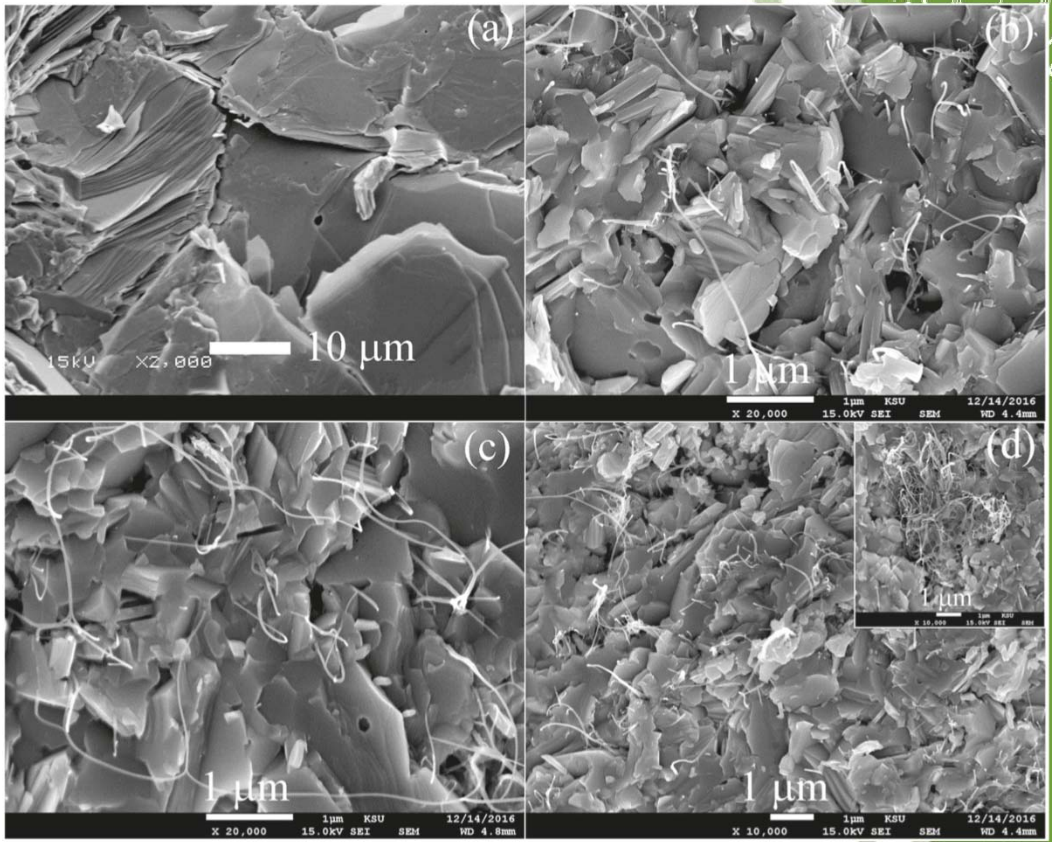
Results and discussion



(a) Uniform dispersion of 1.0 vol% SWCNTs in fine Bi_2Te_3 powder (b), (c) close-ups show ropes of SWCNTs are passing through nanostructured particles of Bi_2Te_3 powder.

Results and discussion

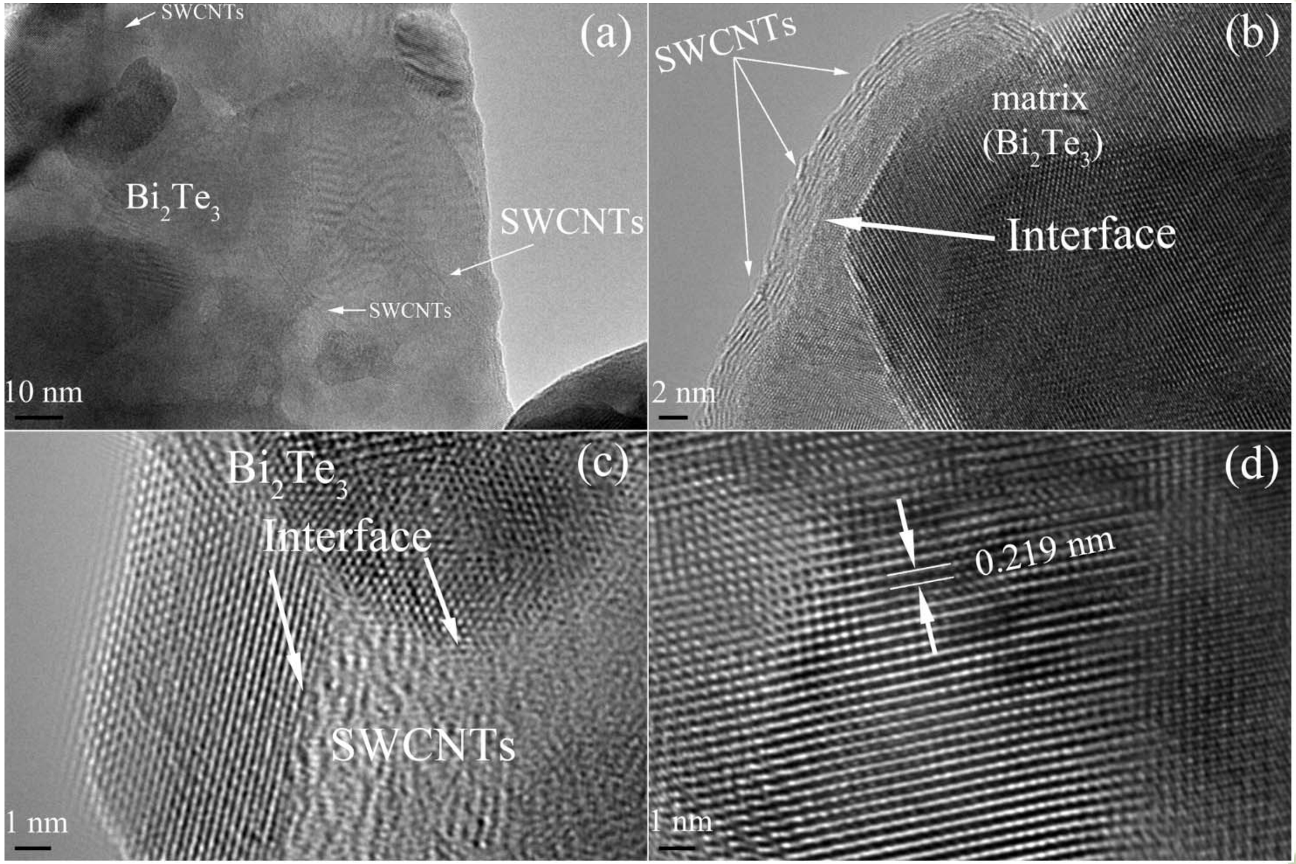




(a) XRD patterns of consolidated Bi2Te3 and SWCNT/Bi2Te3 bulk composites (b) XRD analysis of 0.5 vol% SWCNT/Bi2Te3 bulk composite, performed perpendicular and parallel to the pressing direction

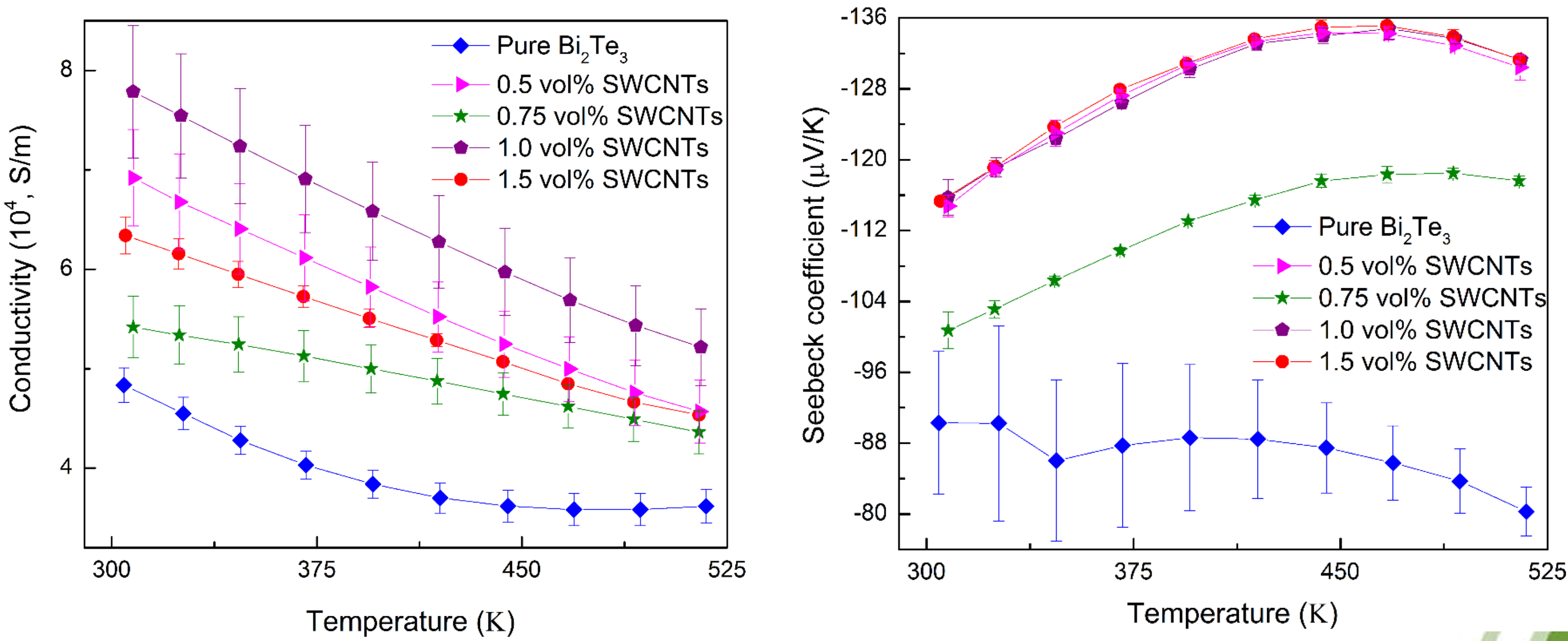
Fractured surface of (a) pure Bi2Te3 bulk (b) 0.5 vol% SWCNT/Bi2Te3 (c) 1.0 vol% SWCNT/Bi2Te3 (d) 1.5 vol% SWCNT/Bi2Te3 bulk composites

Results and discussion



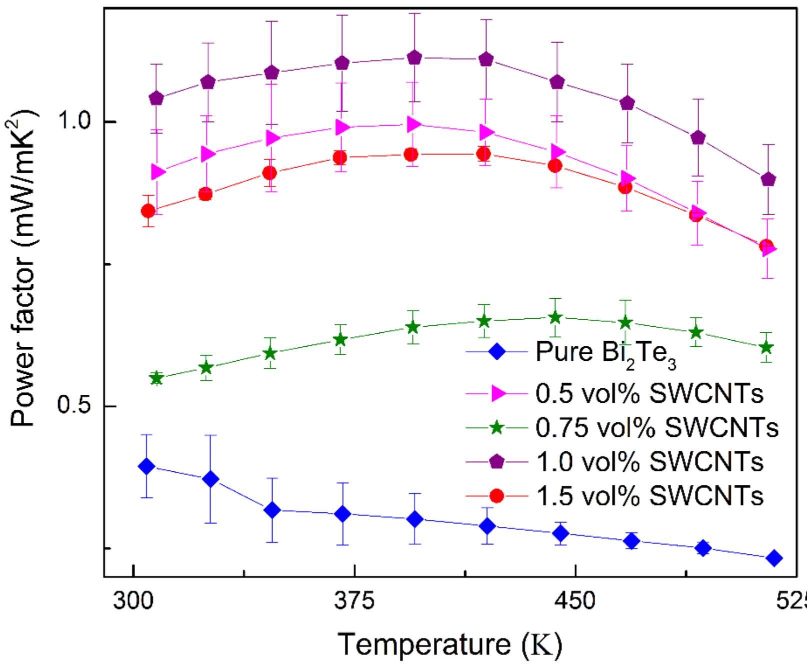
TEM image of 1.0 vol% SWCNT/Bi2Te3 bulk composite (b), (c) High resolution TEM images showing interfaces between Bi2Te3 and SWCNTs phases for 0.5 and 1.0 vol% of SWCNTs respectively (d) High resolution image of Bi2Te3.

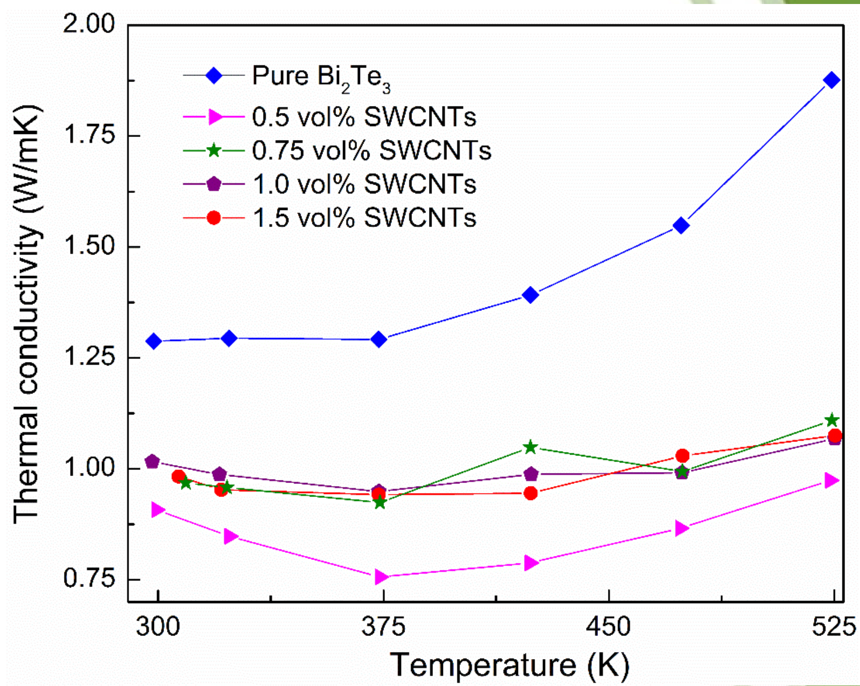
Results and discussion



Temperature dependence of (a) electrical conductivity (b) Seebeck coefficient of SWCNT/Bi2Te3 composites.

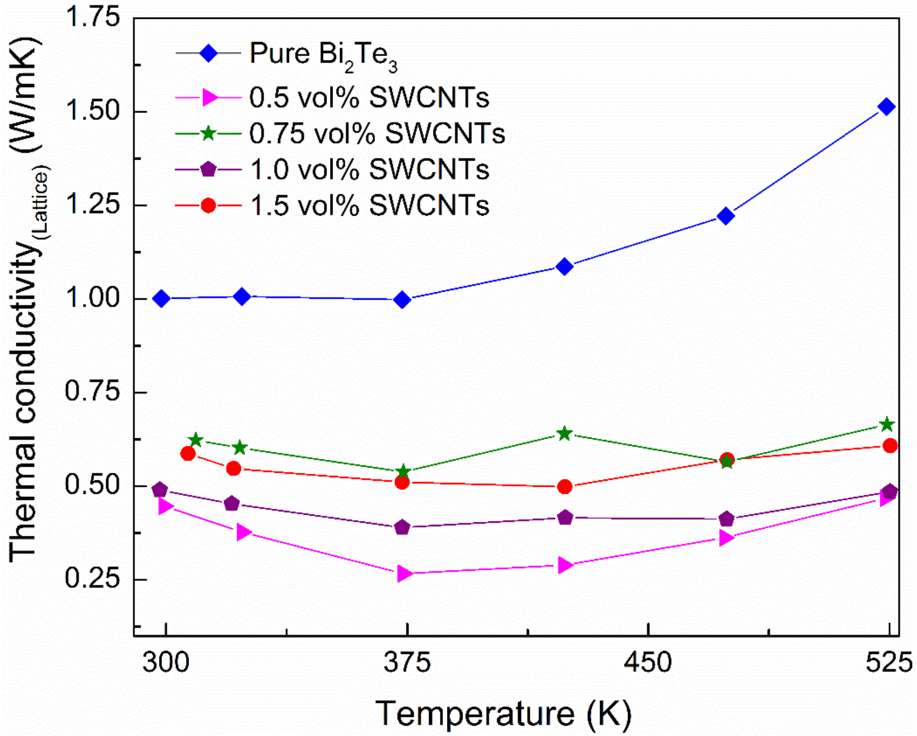
Results and discussion

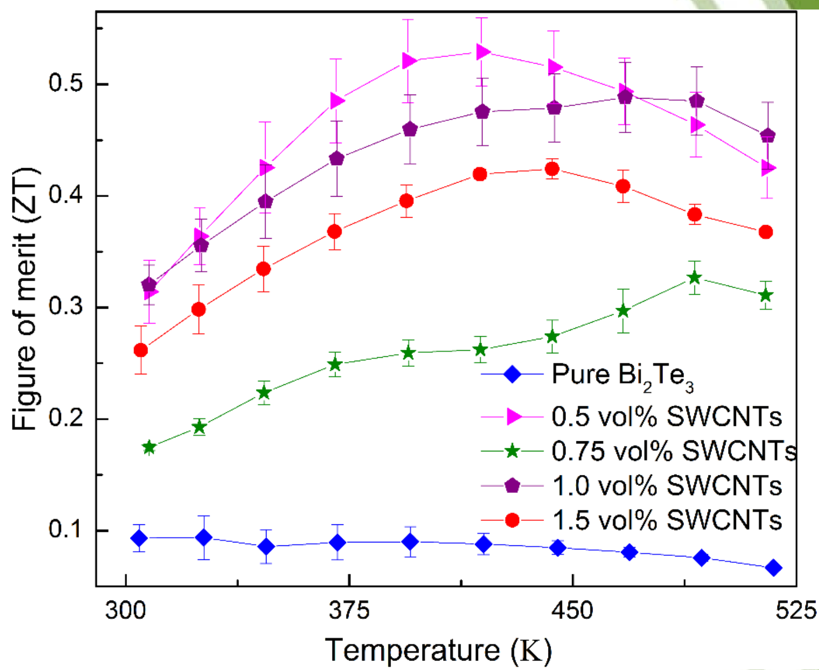




Temperature dependence of (a) power factor (b) Thermal conductivity of pure bulk Bi2Te3 and SWCNT/Bi2Te3 composites.

Results and discussion





Temperature dependence of (a) lattice thermal conductivity (b) figure of merit of pure Bi2Te3 bulk and SWCNT/Bi2Te3 composites.

Summary

- SWCNTs in different (0.5, 0.75, 1.0 and 1.5) vol% were incorporated in Bi2Te3 matrix.
- An extremely uniform dispersion of SWCNTs were achieved through a combination of ultrasonication, magnetic stirring and mild ball milling.
- The interconnected network of 1D SWCNTs acts as a conduit for unimpeded transport of electrons through the matrix, and considerably increases the electrical conductivity of the composites.
- The interface between SWCNTs and Bi2Te3 acts as an energy-dependent carrier scattering barrier in the composites, and thus improves the Seebeck coefficient via the electron energy filtering effect.
- The strong phonon scattering through nanostructured phase boundaries in conjunction with the SWCNTs significantly reduces lattice thermal conductivity at 0.5 vol% of the SWCNTs. Therefore, an increased power factor with substantial reduction in thermal conductivity at 0.5 vol% SWCNT/Bi2Te3 composite leads to a several-fold improvement in the thermoelectric figure of merit over pristine bulk Bi2Te3 at ~400 K.

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Enhanced thermoelectric performance of Bi_2Te_3 through uniform dispersion of single wall carbon nanotubes

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Abstract

Thanks for your attention

تقنيات الطاقة المستدامة

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