Technical analysis of the optimization of the thermoelectric renewable sources of energy by applying nanotechnology

Kamal Nain Chopra
Applied Physics Department, Maharaja Agrasen Institute of Technology, Rohini, GGSIP University, New Delhi - 110086, India.

E-mail: kchopra 2003@gmail.com

(Received 19 November 2014, accepted 26 September 2015)

Abstract

Technical Analysis of the Maximization of the renewable sources of energy by application of Nanotecnology, has been presented in this paper. Mathematical Formulations of some of the thermoelectric systems based on the nanostructures have been briefly discussed. The paper is expected to be useful to the new entrants in this exciting field, and also for the designers of some novel devices based on Nanotecnology.

Keywords: Nanotechnology, Nanoenergy, Nanowire Heterostructures Renewable energies, Thermeoelectric Power based on Nanodevices.

Resumen

En el presente documento se presenta el análisis técnico de la maximización de las fuentes renovables de energía mediante la aplicación de nanotecnología. Se discuten brevemente las formulaciones matemáticas de algunos de los sistemas termoeléctricos basados en las nanoestructuras. Se espera que este artículo sea ser útil a los nuevos participantes en este apasionante campo, y también para los diseñadores de algunos dispositivos novedosos basados en la nanotecnología.

Palabras clave: Nanotecnología, Nanoenergía, heteroestructuras de nanocable para energías renovables, Fuerza termoeléctrica basada en nanodispositivos.

PACS: 87.85.Ox, 87.85.dh, 42.79.Bh **ISSN 1870-9095**

I. INTRODUCCIÓN

In spite of the research and development of the new renewable sources of energy [1, 2, 3, 4], it is felt that these efforts are to be augmented by the development of renewable energy technologies [5, 6, 6 8, 9], due to serious problems related with the production and use of energy. The recently growing nanotechnologies are being exploited to solve this problem. Many important applications of nanotechnology in renewable energy systems, dealing with theoretical and experimental investigations in solar, hydrogen, wind, biomass, geothermal and tidal energies have already been reported. Really, the role of nanotechnology in serving as bridge to link with all kinds of available renewable energies for enhancing their efficiency has been very useful.

A Effective approaches of nanostructurization

Nanostructuration has found tremendous utility and many applications in various types of devices, *e.g*. nanostructuration of the anode for rechargeable lithium batteries with storage capacities of 340 mAh/g. It has been done to improve their efficiency, by substituting LiC_6 electrode, by graphite nanoparticles and carbon nanotubes, and even further replacing them by nanosized metal oxides *e. g*. TiO_2, Al_2O_3, VO, CoO, SnO, and SiO_2. Mostly in the form of nanotubes [10] and nanowires, and thus avoiding (i) the lithium deposition and (ii) some safety problems.

It is interesting to note that the synthesis of silicon nanowires further anchored to the substrate acting as current collector has led to achieving a charge capacity of 3000 mAh/g. Electrochemical capacitors (ECs), also named supercapacitors and ultracapacitors, have also been found to be quite useful for storing electrical energy, like batteries, by using a different mechanism.

Nanotechnology has provided great improvement potential for the development of both, conventional energy sources and renewable energy sources. Interestingly, the breakthroughs in nanotechnology have opened up the possibility of exploring novel approaches different from the current alternatives for energy supply, by introducing technologies which are more efficient, inexpensive, and environmentally sound. It is now being increasingly established that nanotechnologies provide the potential for enhancing the energy efficiency, related to all branches of industry. Also for assisting in reducing the economic leverage for the renewable energy production, by employing new technological solutions and optimized production technologies. It has been expected that nanotechnology innovations would have a strong impact on all parts of the value-added chain in the energy sector.

Nanotechnology has the possibility of providing cheap and clean energy by its strategic applications. Its combination with energy has already started to change the method of energy generation, storage, transmission, distribution, and management. One of the steps in this direction is that, of the coating of the nano-coated, wear resistant drill probes, which allows the optimization of the lifespan and the efficiency of systems for the development of oil and natural gas deposits or geothermal energy, and thereby reducing the costs.

One other interesting component developed is double layer supercapacitor or ultracapacitor, that can be used for storing the power generated by solar panels and the wind farms, because both –the solar energy and wind energy– are intermittent. These can even be used to recover energy *e.g*. the energy when the elevator is lowered. Also, fibers of carbon nanotubes are increasingly being used as replacement for the conventional wiring, as they have many advantages, like being lighter, stronger, thinner, and having increased corrosion resistance.

High –duty nanomaterials provide lighter and more rugged rotor blades of wind and tidepower plants as well as wear and corrosion protection layers for mechanically stressed components like– ball bearings and gear boxes.

Nanotechnologies can also contribute to the optimization of the layer design and the morphology of organic semiconductor mixtures in the component structures; *e.g*. the utilization of nanostructures –like quantum dots and wires–, can enhance the solar cell efficiencies by ~ 60%.

Nanotechnological approach of quantum caged atoms (QCAs) can be really useful for achieving a strong reduction of energy consumption for illumination, and thereby increasing considerably the electrical energy conversion into light by the light bulbs, from 5% in the normal systems.

Many nanomaterials, based on nanoporous metal-organic compounds have the development potential, and are less expensive for use in case of the operation of fuel cells in portable electronic devices. In addition, the reduction of fuel consumption in automobiles through lightweight construction materials on the basis of nanocomposites, leads to the optimization in fuel combustion through wear-resistant, lighter engine components and nanoparticular fuel additives, or even nanoparticles for optimized tyres having lower rolling resistance are some of the examples of nanotechnology development.

Ertekin *et al.* [11] have shown that nanowire heterostructures, due to their unique boundary conditions, may exhibit defect-free interfaces even for systems with large lattice mismatch, because the nanowire heterostructures are more effective at relieving mismatch strain coherently. Ertekin *et al.* [11] have shown that the nanowire geometry should allow the integration of disparate class of materials, that cannot be realized in planar systems at equilibrium. Strain relaxation is very useful in improving the efficiency of many devices. Strain relaxation in nanowire heterostructures –as reported in the literature [11] – has been illustrated below:

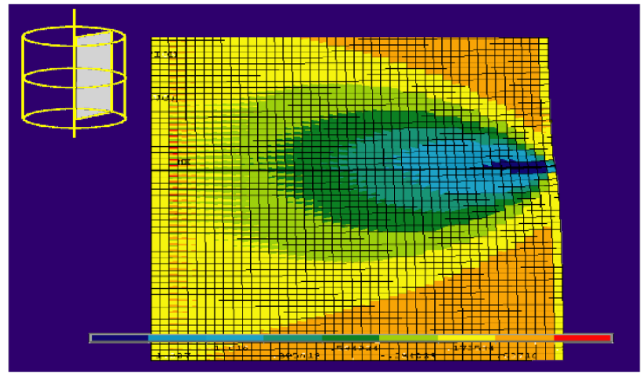

FIGURE 1. Strain relaxation in nanowire heterostructures. Figure courtesy (Ertekin et al., JAP,2005).

The contours in the Figure 1 show the manner in which strain is relaxed in the nanowire heterostructures.

Nanocomposite coatings are also given for producing the protective coatings designed to enhance wear and abrasion resistance, UV-protection and other functional properties. In addition, the Cerium oxide nanopowder is used in the engines for reducing the carbon soot emission, without affecting the engine durability. And thus, improves the fuel economy by promoting more complete combustion inside the combustion chamber, through providing extra reactive oxygen through its catalytic activities; which lower the carbon burning temperature significantly at which carbon deposit in the engine is burnt off, providing clean environment for the combustion system to improve efficiency.

Successful efforts have also been made on developing more efficient devices for LED-based lighting, thermoelectric refrigeration, thermoelectric and thermo photovoltaic conversion of waste heat, and photovoltaic conversion of solar energy and production of hydrogen.

In thermoelectrics, many breakthroughs have been achieved:

(i) Thermoelectric primer,

(ii) Progress in ZT (thermoelectric power is related to its dimensionless figure of merit ZT) enhancement by nanostructuring (MBE and bulk),

(iii) A scalable approach with nanoscale control: electro deposition into porous templates,

(iv) Mitigating parasitics –removing/replacing the template, and scaling to thicknesses > 100 mm, and

(v) TE element fabrication from nanoscale materials.

Many novel applications of thermoelectrics are as:

- Radioisotope TE generators powering deep space probes,
- Automotive seat coolers/heaters,
- Temperature stabilizers for laser diodes used in fiber optic communications systems, and
- Remote power generators in harsh environments.
- Bell [12] has provided good report on the use of thermoelectric systems for cooling, heating, generating power, and recovering waste heat.

II MATHEMATICAL OPTIMIZATION OF THE THERMOELECTRIC POWER

It is important to note that, the materials with $ZT = (2-3)$; and the Systems with $ZT = (1.5-2)$, are now available, and have been used for various applications:

(i) Exhaust waste heat recovery for gasoline and diesel engines to improve mileage by 10%,
(ii) Cogenerators for 5-20 kW diesel generators, improving system efficiency by 5-10%,
(iii) Split-spectrum solar generators (PV + TE),
(iv) Industrial waste heat recovery in metal, glass and cement processing,
(v) Flex fuel powered small engines,
(vi) Microprocessor cooling, and
(vii) Greenhouse-gas-free HVAC for vehicles and residences.

The thermoelectric power is studied in terms of the Wiedemann-Franz law, which states that the ratio of the electronic contribution of the thermal conductivity (κ) to the electrical conductivity (σ) of a metal is proportional to the temperature (T); and is given by:

$$\frac{\kappa}{\sigma} = LT, \tag{1}$$

where L, is the proportionality constant, called as the Lorenz number, given by:

$$L = \frac{\kappa}{\sigma T} = \frac{\pi^2}{3}\left(\frac{\kappa_B}{e}\right)^2 = 2.44x10^{-8} W\Omega K^{-2}. \tag{2}$$

This empirical law is called Wiedemann-Franz. It is well established that that $(\frac{\kappa}{\sigma})$ has approximately the same value for different metals at the same temperature. Also, the relationship of the proportionality of $(\frac{\kappa}{\sigma})$ with temperature is given by:

$$ZT = \{\frac{S^2\sigma}{\kappa}\}.T, \tag{3}$$

Where:

$$\kappa = (\kappa_e + \kappa_{ph}) = \{(L_{os}T) + \kappa_{ph}\}. \tag{4}$$

ZT is the dimensionless figure of merit to describe the ability of a given material, to efficiently produce thermoelectric power. κ_e and κ_{ph} are respectively, the values of κ corresponding to electric and photoelectric effect. L_{os} is the Lorenz number for the oscillator (the Lorenz oscillator is a 3D dynamical system exhibiting chaotic flow, noted for its lemniscate shape). S is the Seebeck coefficient, and (σS^2) is defined as the power factor. The equation (3) can be modified as:

$$ZT = [\frac{S^2}{\{L_{OS} + \frac{\kappa_{ph}}{(\sigma T)}\}}]. \tag{5}$$

It is important to note that the materials with high power factor are able to generate more energy in a space-constrained application, though they are necessarily not efficient.

Thus, we note that for increasing the value of ZT, we have to (i) increase S, (ii) decrease L_O, and (iii) vary κ_{ph}, σ, and T in such a manner that $\{\frac{\kappa_{ph}}{(\sigma T)}\}$ decreases. This requires a lot of designing combined with the experience of the designer, which has now been made possible by nanotechnology.

The efficiency of a thermoelectric device for electricity generation is given by: $\eta = \frac{E_{pl}}{HE_{hj}}$, where E_{pl}, is the energy provided to the load, and HE_{hj} is the heat energy absorbed at the hot junction. The maximum efficiency of the thermoelectric device is given by:

$$\eta_{\max} = \{\frac{(T_H - T_C)}{T_C}\}.[\frac{(1+ZT_{av})^{\frac{1}{2}} - 1}{\{(1+ZT_{av})^{\frac{1}{2}} + \frac{T_C}{T_H}\}}]. \tag{6}$$

Where T_H is the temperature at the hot junction, T_C is the temperature at the surface being cooled, and ZT_{av} is the modified dimensionless figure of merit, on the basis of the thermoelectric capacity of both, thermoelectric materials being used in the device, and also the geometrical optimization. Nanotechnology has been helping in increasing the efficiency of light conversion by using nanostructures with a continuum of bandgaps, which has led to successful efforts in increasing the efficiency of energy production in the solar cells and the internal combustion engines. Nanofabrication, used for making devices smaller than 100 nanometers, is the process useful for the development of new ways for capturing, storing, and transferring energy; because of the inherent level of control, and hence it is hoped that nanotechnology has the capacity and potential of solving many problems in enhancing the efficiency of the renewable sources of energy.

Snyder and Toberer [13] have achieved some good values of ZT for different materials. They have emphasized that the thermoelectric materials, which can generate electricity from waste heat or can be used as solid-state

Peltier coolers, are able to play an important role in a global sustainable energy solution.

Because of the modern synthesis and characterization techniques –particularly for nanoscale materials–, many new complex thermoelectric materials are being developed.

Snyder and Toberer [13] have reviewed some important advances in the field, highlighting the strategies used to improve the thermo power and reduce the thermal conductivity. Some of the values for n-type ZT and p-type ZT, and their dependence on temperature from 0°C to 1000°C, as reported in literature, have been reproduced below:

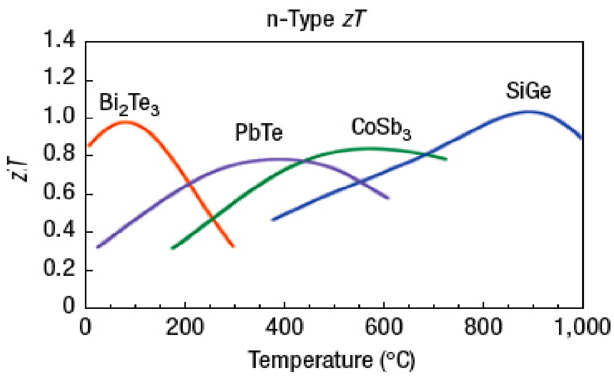

FIGURE 2. State-of-the-art commercial and NASA Thermoelectric materials (a) n-type ZT .

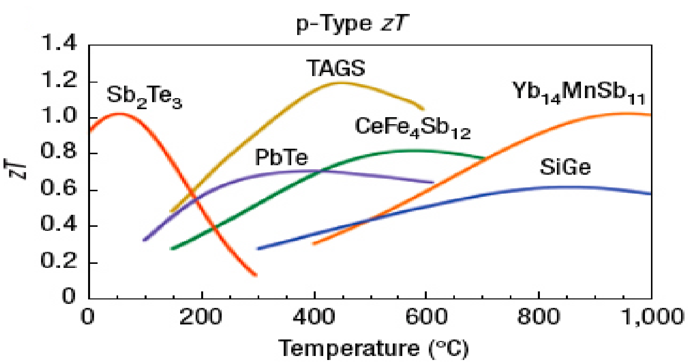

FIGURE 3. State-of-the-art commercial and NASA Thermoelectric materials (b) p-type ZT . Figure courtesy Snyder, G. J. and Toberer, E. S., Nat. Mater **7**, 105 (2008).

An interesting feature –common to all the materials for both n-type and p-type– , is that the curves have a peak ZT value, though at different temperatures. So, the designers of the nanodevices have to take this factor into consideration, and choose the material most suitable for the required temperature range. It has been established that for the lower temperature range Bi_2Te_3 and Sb_2Te_3 are respectively the most suitable for n-type materials and p-type materials, and the corresponding materials for the higher temperature range are SiGe and $Yb_{14}MnSb_{11}$.

III CONCLUDING REMARKS

It has been observed that owing to the importance of the renewable energy, after the research efforts on finding the novel unconventional sources of renewable energy, scientists and researchers have concentrated their efforts on using the nanotechnology for increasing the efficiency of the devices generating power, especially thermoelectric devices.

Chopra [14] has given an overview of Biophotonics and Optofluidics Technology for improving the efficiency of some renewable sources of energy. Recently, was held a Workshop on Nanotechnologies for Thermal and Solar Energy Conversion and Storage [10]. There, Baxter *et al.* [6] have presented a very important and exhaustive review of the nanoscale design to enable the revolution in renewable energy.

Chandler [15] has reported that the research investments and growing markets have fueled a huge rise in new patents.

A new Conference [16] on Bioenvironment, Biodiversity and Renewable Energies BIONATURE 2015, is going to be held, which will focus on:

(i) Renewable and Sustainable Energies, in which the emphasis will be on replacing the classical energy, with alternative renewable energy (green energy), such as bioenergy, aeolian energy or solar energy, increasing of self-sufficiency rate of energy, and promoting use of clean energy, and that way, reducing the polluting emissions to the air; and

(ii) Bioenvironment (climate, global warming, hydrology, wind science, pollution, economics). In view of these studies, it is clear that the subject of the use and applications of nanotechnology in renewable sources of energy is on a firm footing, and growing rapidly.

ACKNOWLEDGEMENTS

The author is grateful to the Dr. Nand Kishore Garg, Chairman, Maharaja Agrasen Institute of Technology, GGSIP University, in Delhi, for providing the facilities for carrying out this research work, and also for his moral support.

The author is thankful to Dr. M. L. Goyal, Director, for encouragement.

Thanks are due to Dr. V. K. Jain, Deputy Director, for his support during the course of the work.

Thanks are also due to the listed agencies for providing the images.

The author is thankful to Prof. V. K. Tripathi, Department of Physics, Indian Institute of Technology, Delhi for many useful discussions and suggestions, resulting in considerable improvement in the quality and presentation of the paper. Thanks are due to the listed agencies for providing the images.

REFERENCES

[1] Chopra, K. N., *Solar energy collectors for harnessing solar energy. A Review*, Atti Fond G. Ronchi **68**, 107-118 (2013).
[2] Chopra, K. N., *A short note on the hydro power and optimization of the power output of the hydro turbines*, Inv. J. Renewable Energy **3**, 1-8 (2013).
[3] Chopra, K. N., *A note on comparison of the utility of various forms of renewable energy on basis of the technical data*, Atti Fond G. Ronchi, **68**, 825-836 (2013).
[4] Chopra, K. N., *Ocean Energy Thermal Conversion (OTEC) and its mathematical modeling. A Short Technical Note*, Inv. J. Renewable Energy **3**, 1-8 (2013).
[5] *Workshop on Nanotechnologies for Thermal and Solar Energy Conversion and Storage*, Jacksonville, USA, 10-11 August (2008).
[6] Baxter J., Bian Z., Chen G., Danielson D., Dresselhaus M.S., Fedorov A.G., Fisher T.S., Jones C.W., Maginn E., Kortshagen U., Manthiram A., Nozik A., Rolison D.R., Sands T., Shi L., Sholl D. and Wuo Y., *Nanoscale design to enable the revolution in renewable energy*, Energy and Environmental Science **2**, 559-588 (2009).
[7] Serrano E., Rus Guillermo and García-Martínez Javier, *Nanotechnology for sustainable energy*, Renewable and Sustainable Energy Reviews **13**, 2373-2384 (2009).
[8] Chopra, K. N., *An overview of optofluidics technology as the novel approach for renewable energy*, Inv. J. Renewable Energy **4**, 140-148 (2014).
[9] Chopra, K. N., *An overview of novel sources of renewable energy with special emphasis on waste-to-energy conversion and the compressed air production using vehicle suspension*, Inv. J. Renewable Energy **4**, 101-106 (2014).
[10] Chopra, K. N., *A short note on the mathematical modeling and analysis for carbon nanotubes*, Atti Fond G. Ronchi **69**, 1-11 (2014).
[11] Ertekin, E., Greaney, P. A., Chrzan, D. C. and Sands, T. D., *Equilibrium limits of coherency in strained nanowire heterostructures*, J. Appl. Phys. **97**, 114325 (2005).
[12] Bell, L., *Cooling, heating, generating power, and recovering waste heat with thermoelectric systems*, Science **321**, 1457 (2008).
[13] Snyder, G. J. and Toberer, E. S., *Complex thermoelectric materials*, Nat. Mater. **7**, 105 (2008).
[14] Chopra, K. N., *Biophotonics and optofluidics technology. Technical analysis and qualitative review of the novel applications*, Lat Am J. Phys. Edu. (communicated).
[15] Chandler, D. L., *Innovation in renewable-energy technologies is booming*, MIT News Office, 10 October (2013).
[16] *The Sixth International Conference on Bioenvironment, Biodiversity and Renewable Energies BIONATURE 2015*, 24-29 May 2015, Rome, Italy.