https://doi.org/10.31705/BPRM.v3(1).2023.17

How can We Turn Heat into Useful Energy using Nanotechnology?

Figure 1: Thomas Seebeck (Source: Wikipedia)

In 1821, the German physicist Thomas Seebeck made a groundbreaking discovery that revealed the direct conversion of heat energy into electricity. He did so by bringing two different metals together and holding one end heated and the other end cooled. This process is famously known as the Seebeck effect. William Thomson, a British physicist later known as Lord Kelvin, further developed the concept of thermoelectric circuits and introduced the idea of a temperature-dependent voltage in a circuit made of two dissimilar metals. Lord Kelvin's contribution to the field of thermoelectricity paved the way for various applications in temperature sensors, power generators, refrigeration, and cooling systems.

Heat and electricity are two closely related forms of energy, while they differ in some key aspects. Heat energy is a disordered or "random" form of energy associated with the motion of particles in a substance. In contrast, electricity is an ordered form of energy resulting from the movement of charged particles such as electrons and holes. The use of electrical energy to generate heat energy, causes "an energy loss" and should therefore be

Figure 2: An early thermoelectric generator design in 1829 (Source: Museo Galileo Virtual Museum)

kept at the minimum. On the contrary, generating electricity from heat energy is a complex and challenging process. This is where thermoelectric materials shine, as they possess the unique ability of converting disordered heat energy directly into electricity without the need for moving parts. These materials have immense potential of capturing the energy in waste heat of various sources like industries, automobiles, and households while providing a perpetual source of energy for wearable devices and biomedical equipment.

One of the key advances in thermoelectric materials came in the 1950s, when researchers began to use new semiconductor materials such as silicon and germanium to improve the efficiency of thermoelectric generators. These materials had a high thermoelectric figure of merit (ZT), which is a measure of their efficiency in converting heat into electricity. However, they were also expensive

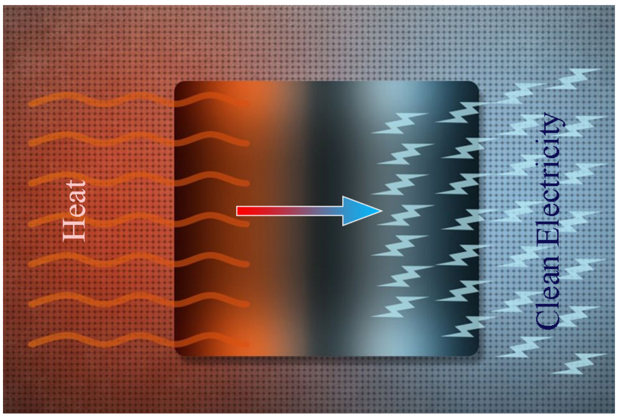

Figure 3: The concept of thermoelectric conversion (Source: MIT News)

to produce until 1990s when efficient and cost-effective materials began to develop.

One of the most promising of these new materials is bismuth telluride. It has a high ZT and can be produced relatively cheaply at the same time. With the advent of nanotechnology in the recent years, there were other efforts to develop new nanostructured materials with improved efficiency [1,2]. These novel materials possess complex nanoscale structures that allow for better control of heat and electricity flow. Therefore, they have the potential to revolutionize the field of thermoelectricity in a manner which was previously unimaginable.

Today, thermoelectric materials are used in a wide range of applications, from power generation in space probes, and satellites to waste heat recovery in cars and industrial processes. They are also being studied for use in cooling devices, such as refrigerators and air conditioners, which could significantly reduce energy consumption and greenhouse gas emissions. As the demand for more efficient and sustainable energy sources continues to grow, it is likely that thermoelectric materials will play an increasingly important role in meeting these needs.

As countries strive towards more sustainable and efficient energy systems, the development of advanced thermoelectric materials with higher efficiencies becomes a crucial undertaking. This is particularly important for developing countries where energy wastage is a significant issue. The development of these materials can not only help reduce energy wastage but also decrease the cost of energy production.

At present, the cost of producing thermoelectric devices is greater than the savings obtained by installing them, limiting their practicality in most applications. However, wearable devices that require a small and lightweight footprint, coupled with long-lasting operation, offer a promising application for thermoelectric materials. While the cost of installing a thermoelectric generator inside a wearable device may be higher than that of a battery, the ability to use the device perpetually without replacing or recharging batteries makes thermoelectric generation an attractive alternative.

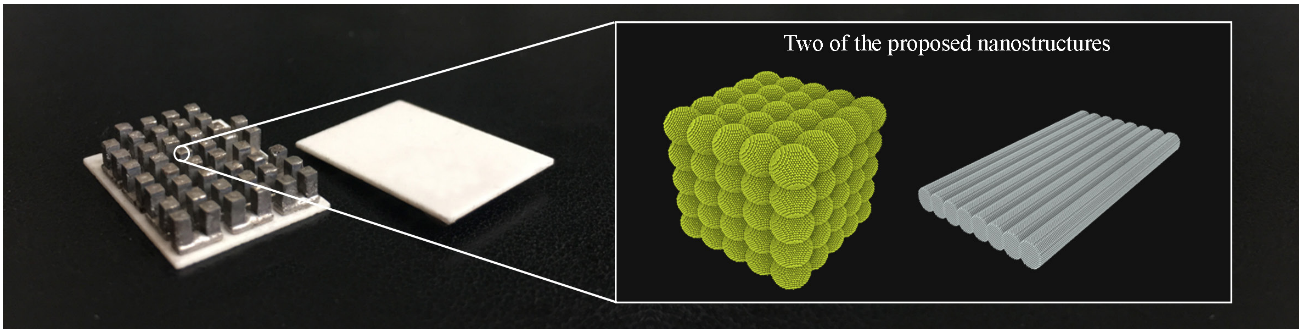

Figure 4: Proposed advanced nanostructures

> "Nanostructured materials possess the unique ability to be tuned to achieve superior performance to match any application. Our task is to figure out the most suitable configuration for the application."

At the University of Moratuwa, we are currently engaged in developing novel nanostructured thermoelectric materials. We aim to develop materials that are both cost-effective to manufacture and highly efficient in operation. Our initial findings indicate that the thermal sintering of silicon nanoparticle and nanowire arrays, as illustrated in Figure 4, has resulted in a significant enhancement in thermoelectric ZT[3,4]. This can be attributed to a considerable reduction in the material's thermal conductivity. Moreover, we have observed that the nanostructured materials exhibit a substantial improvement in the Seebeck effect compared to commonly found bulk silicon.

When compared to other methods aimed at enhancing the thermoelectric performance, the thermal sintering of nanoparticles and wires has demonstrated encouraging results. This approach warrants further exploration and refinement through computational and experimental studies. Therefore, it is worth noting that thermoelectric energy harvesting devices based on thermally sintered nanostructures could hold the solution to achieving energy sustainability in the foreseeable future.

References:

[1] N. Samaraweera, J.M. Larkin, K.L. Chan, K. Mithraratne, Reduced thermal conductivity of Si/Ge random layer nanowires: A comparative study against superlattice counterparts, J. Appl. Phys. 123 (2018) 244303. https://doi.org/10.1063/1.5030711.

[2] A.I. Hochbaum, R. Chen, R.D. Delgado, W. Liang, E.C. Garnett, M. Najarian, A. Majumdar, P. Yang, Enhanced thermoelectric performance of rough silicon nanowires, Nature. 451 (2008) 163–167. https://doi.org/10.1038/nature06381.

[3] P. Henadeera, N. Samaraweera, C. Ranasinghe, A. Wijewardane, Ultra-low thermal conductivity of nanoparticle chains: A nanoparticle based structure for thermoelectric applications, J. Appl. Phys. 130 (2021) 064301. https://doi.org/10.1063/5.0060487.

[4] P. Henadeera, N. Samaraweera, C. Ranasinghe, A. Wijewardane, Surface and Constriction Engineering of Nanoparticle Based Structures Towards Ultra-Low Thermal Conductivity as Prospective Thermoelectric Materials, Nanoscale Microscale Thermophys. Eng. (2023) 1–17. https://doi.org/10.1080/15567265.2023.2180458.

Article by

Pasan Henadeera, Nalaka Samaraweera, Chathura Ranasinghe, Anusha Wijewardane.

Department of Mechanical Engineering, University of Moratuwa, Sri Lanka.