Multiprinter Additive Manufacturing of Flexible and Lightweight Thermoelectric Energy Harvesters Using Colloidal Nanoparticles

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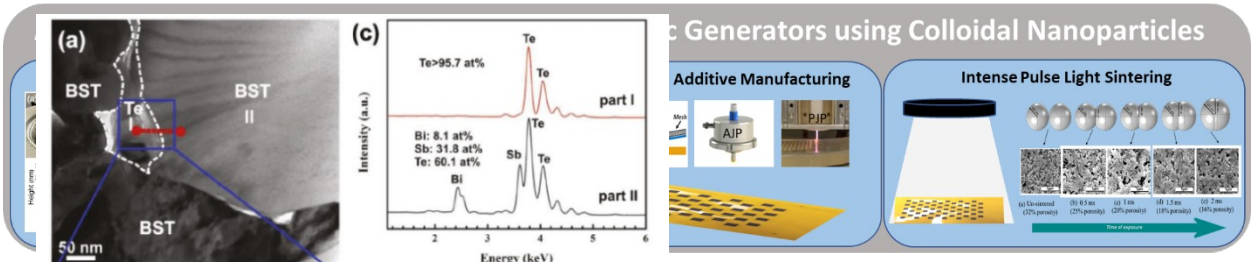
Thermoelectric generators are being used as a successful power sources for space applications since 1960's in radioisotope- thermoelectric generators (RTGs) to supply power to space systems in deep space. RTG's are capable of directly converting heat energy to uninterrupted electric power with no moving parts involved. The ability of thermoelectric materials to convert heat energy to electrical energy is defined by a dimensionless value known as the thermoelectric figure of merit (ZT)[1]. This value quantifies the maximum thermoelectric efficiency of a thermoelectric generator (TEG) and is calculated by $ZT=S^2\sigma T/\kappa$, where S, σ, T, and κ represent Seebeck coefficient, electrical conductivity, temperature, and thermal conductivity, respectively. Among all of the thermoelectric materials, Bi_2Te_3 and its alloys have been reported to have high ZT values for low temperature energy harvesting and are highly suitable for powering wearables and self-powering sensors[2,3].



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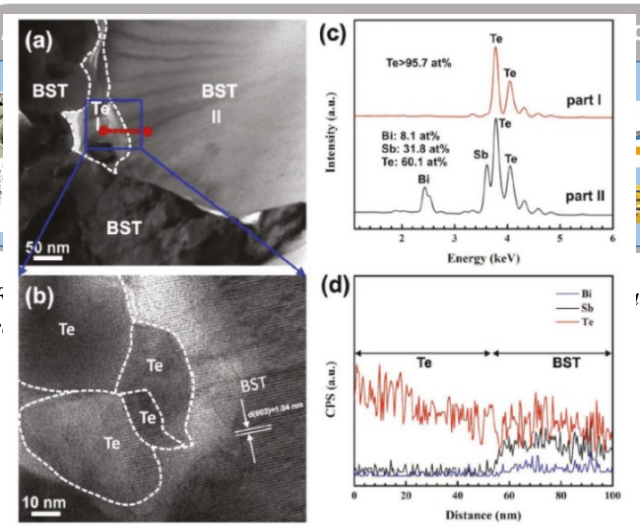

Figure 2. *(a)-(d) TEM and EDS analysis of liquid phase tellurium (Te) at the grain boundaries of Bismuth antimony telluride (BST)[2].*

Figure 1 summarizes the development of thermoelectric nanomaterials and their functional devices using multiple printing methods and sintering techniques. The thermoelectric performance of devices is highly dependent on the material properties. Large scale and uniform synthesis of these materials are important for maintaining sustainable performance. Here we use a solution-phase synthesis for high purity and scalable synthesis of layered nanomaterials. In this method, nanostructured materials are synthesized from the bottom up through controlled chemical reactions, offering fine control over materials composition and crystal dimensions. Despite advances in thermoelectric material properties, direct conversion and integration of nanomaterials into a functional device remains a challenge. This work demonstrates, development of a flexible printed thermoelectric

generator using multiple additive electronics manufacturing techniques such as screen printing, Aerosol Jet Printing (AJP) and Plasma Jet Printing (PJP) methods. These methods deposit a thin layer of materials on flexible and lightweight materials for a variety of applications. Screen printing offers a large-scale synthesis of thermoelectric film on to flexible substrates, whereas AJP helps to develop both 2D and 3D conformal printing of materials of on multiple substrate surfaces with high precision. PJP helps to deposit material on to a large number of substrates at room temperature with increased adhesion and plasma assisted sintering while printing. Finally, as printed material will undergo Intense Pulse Light Sintering using UV/Visible light produced by a Xenon lamp to improve the material properties without destroying the low temperature substrates, offering large scale and ultrafast synthesis of TEG's.

Thermoelectric performance of TE devices can be fine-tuned by controlling charge carrier concentration and mobility of the printed films. **Figure 2**, shows addition of small fraction of tellurium powders into the BST matrix to improve the thermoelectric properties of the screen-printed devices. Liquified tellurium acts as an interface material at the grain boundaries helping to scatter phonons, while simultaneously reducing porosity and increasing the electrical performance and overall performance of the printed thermoelectric devices[2]. **Figure 3** shows the thermoelectric performance of a flexible TE device developed using screen printing. The printed device shows a ZT of 1 at room temperature with a power factor of $3mW.m^{-1}K^{-2}$. 4 leg P- type bismuth antimony telluride films connected using silver electrodes exhibits an exceptional power density of 18.8 $mW.cm^{-2}$ at a relatively small temperature difference of 80°C.

This work demonstrates development of flexible and high performing TEG's using multiple additive electronics manufacturing and sintering techniques. Flexibility and lightweight with improved power density of the *f*-TEG devices will help to implement thermoelectric generators for space applications and wearables. Low cost and scalable manufacturing methods developed in this work present significant leap in the field of thermoelectrics towards commercially viable technology for energy harvesting, sensing and thermal management applications.

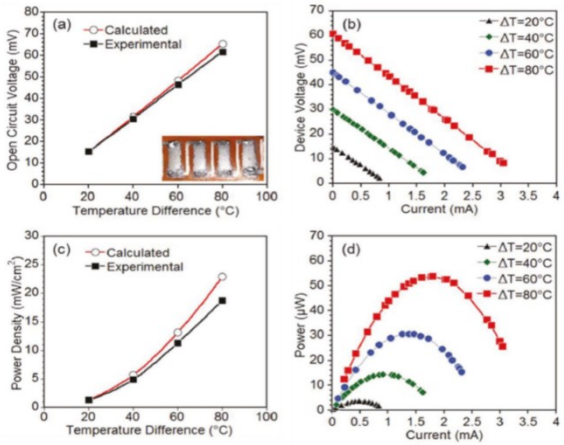

Figure 3. *(a)-(d) Performance of a flexible TE device fabricated using screen-printing process*[2]

References

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3. Hollar, C. *et al.* High-Performance Flexible Bismuth Telluride Thin Film from Solution Processed Colloidal Nanoplates. *Adv. Mater. Technol.* **5**, 1–8 (2020).