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# Flexible thermoelectric generator using bulk legs and liquid metal interconnects for wearable electronics

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## HIGHLIGHTS

- Flexible thermoelectric generator (TEG) with bulk legs.
- Flexible thermoelectric generator with liquid metal interconnects.
- Flexible TEG with potential to match the performance of rigid TEGs.
- Flexible TEG for wearable electronics.

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## ABSTRACT

Interest in wearable electronics for continuous, long-term health and performance monitoring is rapidly increasing. The reduction in power levels consumed by sensors and electronic circuits accompanied by the advances in energy harvesting methods allows for the realization of self-powered monitoring systems that do not have to rely on batteries. For wearable electronics, thermoelectric generators (TEGs) offer the unique ability to continuously convert body heat into usable energy. For body harvesting, it is preferable to have TEGs that are thin, soft and flexible. Unfortunately, the performances of flexible modules reported to date have been far behind those of their rigid counterparts. This is largely due to lower efficiencies of the thermoelectric materials, electrical or thermal parasitic losses and limitations on leg dimensions posed by the synthesis techniques. In this work, we present an entirely new approach and explore the possibility of using standard bulk legs in a flexible package. Bulk thermoelectric legs cut from solid ingots are far superior to thermoelectric materials synthesized using other techniques. A key enabler of the proposed technology is the use of EGaIn liquid metal interconnects, which not only provide extremely low interconnect resistance but also stretchability with self-healing, both of which are essential for flexible TE modules. The results suggest that this novel approach can finally produce flexible TEGs that have the potential to challenge the rigid TEGs and provide a pathway for the realization of self-powered wearable electronics.



## 1. Introduction

Interest in body area networks (BANs) is rapidly growing for both residential and medical applications [1]. These networks include a multitude of sensors for monitoring different health parameters and they transmit the data to a base-station (e.g. cell phone). Through these gateway devices, the information can be transferred to the internet allowing medical professionals to access patient data online. Advanced BANs target achieving a comprehensive assessment of human health by correlating data provided by many sensors. Unfortunately, as the complexity of the BANs grow, so does the power consumed by such systems. This poses a key challenge for BANs in health applications for which long-term and continuous health monitoring is highly desirable. These applications call for autonomous systems that completely rely on electrical energy harvested from the human body or the ambient environment. Thermoelectric generators (TEGs) that convert body heat to electrical energy offer a promising solution for realizing self-powered BANs. The application has been the focus of many previous studies [2–10].

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For wearable applications, a flexible TEG is desirable for a number of reasons. First, a TEG that is conformal to the body would increase the surface area used for heat collection and reduce the thermal contact resistance [8]. Second, without a flexible TEG, one would have to connect many rigid TEGs on a flexible band to reach an acceptable level of output power. The performance of such a device would suffer from the electrical resistance of the metal interconnects between individual TEGs since the electrical resistivity of printable Ag/AgCl flexible interconnects widely used in flexible electronics today is too high for this application. This is a critical issue since the power produced by a TEG is inversely proportional to the source resistance, which includes the electrical resistance of the legs and the interconnects. Finally, a flexible TEG would provide a more comfortable and attractive solution, which are important factors to consider to increase user compliance.

Beyond wearable devices, there are many other applications of flexible TEGs in power generation and heat-flow sensing [11–13]. In principle, any curved surface (e.g. pipes, heat ducts, motors) that can yield a temperature differential between the source and the ambient can benefit from large-area flexible thermoelectric modules.

Despite the growing interest in flexible thermoelectric modules, the performance of the flexible devices produced to date has been far below the performance of the best rigid TEGs, which can be attributed to lower quality of the thermoelectric materials, parasitic thermal losses in polymeric substrate materials and factors that pause limitations on achieving the desired dimensions of the thermoelectric legs.

In previous studies, both organic and inorganic materials were employed to produce flexible TEGs. Techniques used to deposit inorganic materials include sputtering and evaporation [14–18], electrodeposition [19,20], screen printing [21–23], dispenser printing [12,24–26]. These studies mainly focused on room-temperature applications and focused on composites of Bi, Te, Sb and Se. New organic materials are also being actively pursued for flexible thermoelectric devices and recent progress in this field can be found in excellent review articles [27–30]. While the results are certainly encouraging, these materials cannot yet compete with commercial bulk legs. For wearable applications, the TEG thermal resistance must be comparable to the large skin resistance to achieve an appreciable temperature differential ($\Delta T$) [8]. To achieve this, the thermoelectric legs must possess a fairly high aspect ratio (leg height to base width) to achieve a sufficiently large thermal resistance compared to the external resistances, which include the thermal resistances of the skin, the skin/module interface and the heatsink. This poses an important challenge for many of the deposition techniques mentioned above.

To address these challenges, we have developed an entirely different approach and devised a novel packaging solution, which relies on high quality bulk thermoelectric legs embedded in a stretchable elastomer. A eutectic alloy of gallium and indium (EGaIn) is used as a stretchable low-resistivity interconnect between the legs. This report presents the first demonstration of a flexible thermoelectric module with liquid metal interconnects.

The new technology has several important advantages. First and foremost, the approach is compatible with the bulk legs used in rigid modules. As such, they can incorporate the best available materials produced by any manufacturer at any time. This implies that these modules will also benefit from any advances made in producing the thermoelectric materials (e.g. nanocomposites [31]). Second, the thermoelectric materials used to produce the legs can be optimized for different temperature ranges as long as the elastomer can withstand the higher temperatures. Finally, because the approach is compatible with standard thermoelectric legs used in rigid modules and pick-and-place tooling, it provides entry to the field with low cost-of-ownership. As such, this new approach presents for the first time, the opportunity to produce flexible thermoelectric modules whose performance can match that of their rigid counterparts. While this paper focuses on energy harvesting from the human body, the same modules can also be used in electronic cooling applications.

## 2. Design and fabrication

Fig. 1 shows the conceptual transition of a standard rigid TEG to an EGaIn-based flexible device, where the hard ceramic plates and metal interconnects (Fig. 1A) are replaced with stretchable EGaIn interconnects (Fig. 1B-C) and finally encapsulated in a stretchable elastomer (Fig. 1D). Since thermoelectric modules employ legs that range in length from hundreds of microns to several millimeters, there exists a non-negligible difference in the radii of curvature between the two faces of the module. This means that when the module is flexed, the material around the legs as well as the metal interconnects on the two faces must compress or stretch without any degradation to the electrical resistance, which is only possible with stretchable materials (i.e. elastomer and interconnects).

For an efficient thermoelectric module, the contribution of the interconnect resistance to the total device resistance must be negligibly small. This requires an interconnect material with very low electrical resistivity. Unfortunately, there are not many options for producing low-resistivity, stretchable interconnects. One of the best approaches is the use of silver nanowires (AgNW) embedded in an elastomer [32]. While the technology provides excellent stretchability, its resistivity ($\approx$100 $\mu\Omega$ . cm) is too high for this application. Silver nanowire - silver nanoparticle hybrid inks can actually provide 10x lower resistivities [33]. However, these inks have limited flexibility and hence cannot yield stretchable interconnects needed to produced flexible TEGs using bulk legs. The problem is amplified by the fact that it is difficult and expensive to produce thick AgNW interconnects producing interconnects with sheet resistance values below 0.2 $\Omega$/square [34].

The stretchable interconnect used in our modules is a eutectic alloy of gallium (Ga) and indium (In), in a 3:1 ratio by weight referred to as EGaIn here. At room temperature, EGaIn is a liquid, since its melting point is 15.5 °C. Because it is a liquid, the material provides super stretchability. It is also inexpensive, non-toxic and commercially available [35,36]. Furthermore, the resulting interconnects are self-healing, significantly increasing the long-term reliability of the flexible modules. It has been demonstrated that

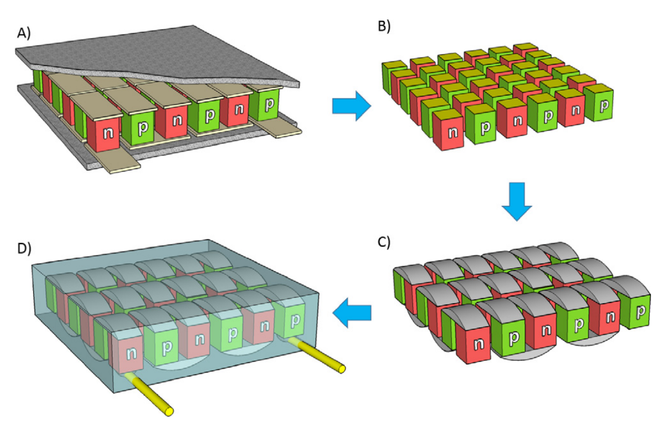


**Fig. 1.** Transition of a rigid device to a flexible EGaIn-based device. (A) Traditional device with rigid metal interconnects and rigid top and bottom ceramic substrates (headers). (B) Removal of rigid construction around the legs, but retaining the same high quality bulk thermoelectric legs. (C) Replace rigid interconnects with stretchable liquid metal. (D) Solder connections to the device and encapsulate in a stretchable elastomer.