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High Performance Thermoelectric Generator with High Aspect Ratio Thermolegs for Implantable Medical Devices

Concept

Thermoelectric generator (TEG), a mechanism for energy harvesting, has great potential to prolong the longevity of implantable medical devices [1]. It can utilize the temperature differential inside human body and generate electricity through the Seebeck effect in thermoelectric material.

In this work, we investigate the applicability of a TEG embedded in the human cranial bone. As shown in Figure 1, the TEG is packaged by a polyether ether ketone (PEEK) housing. Two metal plates are adapted to the skull surfaces, providing thermal contact to the surrounding tissue. A heat spreader covers the upper surface of the skull for better heat dissipation. The packaged TEG has a diameter of 30 mm and features multiple p- and n-type bismuth telluride thermolegs with a height of 4 mm.

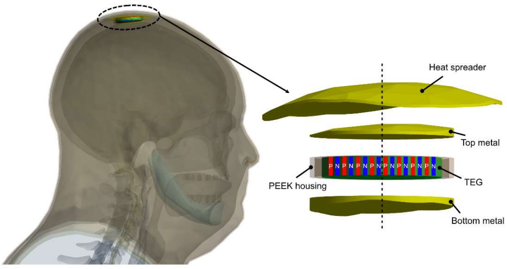
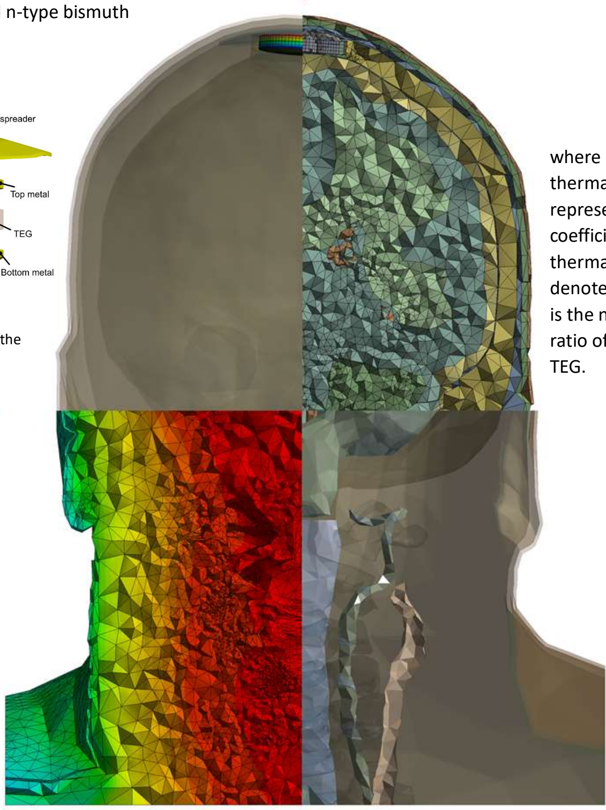


Figure 1. Packaged TEG embedded in the human cranial bone, utilizing the temperature differential to power implantable medical devices.



Modelling

To estimate the performance of the packaged TEG, we implemented the geometry in the numerical simulation tool ANSYS. The effects of blood perfusion and metabolic heat generation were considered in the tissues and organs. The effects of convection and radiation were applied to the skin surface as the primary means of heat removal [2]. The ambient temperature was set to 22°C.

In order to support parametric studies, the detailed TEG model was simplified into a TEG surrogate model [3]. Instead of changing the geometry of thermolegs, the TEG surrogate model uses effective material properties of its representative thermoelectric material:

$$\alpha' = n \cdot \frac{(\alpha_p - \alpha_n)}{2} \qquad (1)$$

$$\kappa' = \eta \cdot \frac{(\kappa_p + \kappa_n)}{2} \qquad (2)$$

$$\rho' = \frac{n^2}{\eta} \cdot \frac{(\rho_p + \rho_n)}{2} \qquad (3)$$

where α', κ' and ρ' are the equivalent Seebeck coefficient, thermal conductivity and electrical resistivity of the representative thermopile; α_p and α_n are the Seebeck coefficients of the p-type and n-type Bi_2Te_3; κ_p and κ_n are thermal conductivities of p-type and n-type Bi_2Te_3; ρ_p and ρ_n denote the electrical resistivity of p-type and n-type Bi_2Te_3; n is the number of thermolegs; η is the fill factor indicating the ratio of the cross-sectional area of all thermolegs and the TEG.

Simulation

Since the size of the TEG is restricted by the implantation environment, the array configuration of the implanted TEG impacts much on output power and voltage. During parametric studies, the resistance of the load was adapted to maintain maximum power delivery.

An optimal fill factor provides a maximum power output of 84 µW (see Figure 2). When the fill factor is fixed, the number of thermolegs has no effect on the power output, but is proportional to the voltage output. To obtain sufficient voltage output, a large number of thermolegs are required, which results in a high aspect ratio of thermolegs. The implanted TEG with the optimum fill factor has a temperature difference of 1.2 K (see Figure 3).

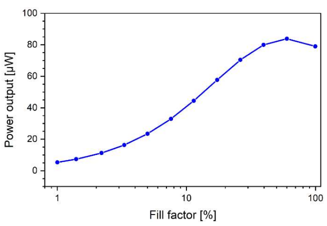


Figure 2. Power output dependent on fill factor, where the optimum factor is 60%.

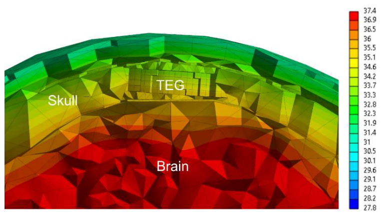


Figure 3. Temperature distribution of TEG implanted in human head in sagittal plane.

Fabrication and Characterization

High aspect ratio thermolegs pose challenges to TEG fabrication processes such as assembly and pick & place. We proposed a novel fabrication strategy for these TEGs, which allows the thermolegs to stand freely with the help of a detachable assembly mechanism (see Figure 4). This method is applicable to the fabrication of TEGs with miniaturized and high-density thermolegs (see Figure 5). Figure 6 shows an assembled TEG with integrated boost converter for higher voltage output. The fabricated TEGs with same fill factor were characterized for a temperature difference of 3 K (see Table 1).

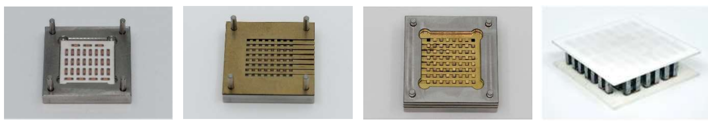


Figure 4. Assembly sequence for TEGs with high aspect ratio thermolegs (here: TEG-1). Bottom ceramic substrate in assembly rig (a), intersecting alignment fixtures (b), inserted thermolegs (1×1×4 mm³) (c), TEG-1 after soldering in reflow oven (d).

Figure 5. TEG-2 with 0.5×0.5×4 mm3 thermolegs in 16×16 array (20×20 mm²).

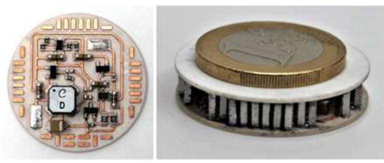


Figure 6. Ceramic substrate with boost converter circuit (left); Assembled TEG-3 with 1×1×4 mm3 thermolegs and integrated boost converter (right).

	Thermal resistance [K/W]	Internal series resistance [Ω]	Open-circuit voltage [mV]	Maximum power output [µW]
TEG-1	42.6	3.2	38.7	117.0
TEG-2	42.6	55	157.8	113.2
TEG-3	41.3	n.a.	3800	42.5

Table 1. Characterization of TEGs with a temperature difference from 33°C to 36°C.

References

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[2] Yuan C et al. ,"Towards Efficient Design Optimization of a Miniaturized Thermoelectric Generator for Electrically Active Implants via Model Order Reduction and Submodeling Technique," *International Journal for Numerical Methods in Biomedical Engineering* 2020, 36.

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