Supporting information

Milliwatt-Scale 3D Thermoelectric Generators via Additive Screen Printing

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S1. Structures of print-TEGs



Figure S1: a) Schematic representation of print-TEG-I with and without top contact b) Schematic representation of print-TEG-II with and without Top contact c) Carbon tape encapsuted print-TEG for characterization (d-f) Schematic representation of thermal map.

The print-TEG I and print-TEG II with/without top electrodes are shown in Figure S1 (a-b). It can be observed that the print TEG-I and print TEG-II comprise 18 and 50 thermocouples respectively. The dimensions of the TE legs are to be 4 mm x 4 mm and 2.5 mm x 2.5 mm for Print-TEG-I and Print-TEG-II respectively. As we discussed in Section 2.3, Fig S1(c) shows the encapsulated print-TEG. We have encapsulated print-TEG using a 5 micron carbon to avoid electrical shortcut during measurement and achieve better mechanical stability. We simulated the thermal map of print-TEG-II at legs and dielectric in order to analyse heat flow through the different materials. It can be observed that the thermal gradient across the n- and p-type low temperature gradient TE legs is lower compared to that for dielectric filler. This attributes most of the heat flow through the TE legs due to higher thermal conductivity, converting the heat into electricity.



S2. Comparison of thermovoltages of the print-TEGs

Figure S2: (a) Seebeck coefficient per thermocouple for print TEG-I and Print TEG-II. (b) Seebeck coefficient per thermocouple for print TEG-I Fab $A(600\mu m)$ and Fab $B(620\mu m)$. (c) Seebeck coefficient per thermocouple for print TEG-II Fab $A(720\mu m)$ and Fab $B(780\mu m)$. (d) Open circuit voltages for the print-TEG I and print-TEG II.

As the number of thermocouples in print-TEG-I and print-TEG-II are 18 and 50, respectively, print-TEG-II contains \sim 2.77 times higher number of thermocouples than print-TEG I. Theoretically, this increase in the number of thermocouples should lead to similar increase in the open-circuit voltage. However, from Fig. S2(a), we observe that the effective Seebeck coefficient of print-TEG-II is lower than that of Print-TEG-I. This explains the reduction in the measured open-circuit voltage of print-TEG-II (128 mV), whereas the expected value based on the equation is 153.05 mV.

 $V_{OC} = N \cdot \left(S_p - S_n\right) \cdot \Delta T$

The reduction thermovoltage in the print-TEGs is probably due to higher thermal resistance. Additionally, Figure. S2 (b) and (c) show that the Seebeck coefficients of both Fab-A and Fab-B both Print-TEG's exhibit similar trends, indicating reproducibility in device properties. This consistency highlights the effectiveness of the printing process in achieving desirable thermoelectric characteristics.



S3. Performance of the print-TEGs

Figure S3: (a) Max power vs Δ T for print-TEG I and II, (b) Power density vs delta T for print-TEG I and II, (c) Max power per gram for print-TEG I and II, (d) Max power per gram for print-TEG II Fab A and Fab B.

The voltage characteristics of print-TEG-I and print-TEG-II exhibit a similar trend, with the open-circuit voltage increasing as the number of thermocouples increases. However, due to differences in resistance—3.6 Ω for print-TEG-I and 15 Ω for print-TEG-II—the power output in Figure S3(a) shows only a minimal difference, with print-TEG-II generating 269.8 μ W compared to 192 μ W for print-TEG-I at ~22K . This effect is also reflected in power density in Figure S3(b) and weight-normalized power output in Figure S3(c). Weight Normalized power output for 780 μ m and 720 μ m device is observed to be similar, shown in Figure S3 (d).



S4: Geometric optimization and cost analysis of Print-TEG-II

Figure S4: Geometric optimization and cost analysis of Print-TEG-II, a) Power density contours as function of leg thickness and geometry factor, b) Power density vs geometry factor, c) Cost distribution of current scenario (reported Print-TEG-II), d) Cost distribution of geometrically optimized Print-TEG-II.

Table S1. Structural parameters of the 3D print-TEG II device used in COMSOL

Table 1 Structural parameters of the COMSOL 3D print-TEG-II device.					
No. of Layers	Material	Thickness (µm)			
Layer 1	Anodized aluminum (substrate)	65			
Layer 2	Bottom silver conductor	10			
Layer 3	Bottom carbon paste	10			
Layer 4	TE material (n- and p-type) & Glass dielectric	625			
Layer 5	Top carbon paste	10			
Layer 6	Top silver conductor	10			
Layer 7	Carbon encapsulation	50			
3D print-TEG-II	-	780			

Table 1 | Structural parameters of the COMSOL 3D print-TEG-II device.

Table S2:Summarized performance data of print-TEG-I and print-TEG-II

Print-TEGs	V _{oc} in mV		<i>P_{max}in</i> μW		P_d in μ Wcm ⁻²	
	Fab A	Fab B	Fab A	Fab B	Fab A	Fab B

Print-TEG-I	62.3 (ΔT=22 K)	52.8	187	190	11.7	12
Print-TEG-II	197.5	268	592	1216.5	32.8	67.4
	(ΔT=32 K)	(ΔT=43 K)	(ΔT=32 K)	(ΔT=43 K)	(ΔT=32 K)	(ΔT=43 K)

We have summarized the open circuit voltage (V_{oc}), maximum power output (P_{max}) and power density of both devices print TEG-I (Fab-A with 600µm and Fab-B with 620µm) and print TEG-II (Fab-A with 720µm and Fab-B with 780µm). The highest power density of ~67.4µW/cm² is observed in Print-TEG-II for ΔT =43 K.

Table S3. TEG manufacturing cost analysis

Table S3: Material and	processing	costs
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TEG fabrication cost analysis				
Components and/or st	teps	Cost	Source	
involved		Cost	Source	
p-type TE material (Bi _{0.5} Sb _{1.5} T	e_3)	300 €/kg	www.everredtronics.com	
n-type TE material (Ag ₂ Se)		866 €/kg	www.sigmaaldrich.com	
Anodized aluminum substrate (Al ₂ O ₃)	(Al-	125 €/kg	www.steinertglobal.com	
Dielectric (Thermally cu insulator)	ured	10 €/kg	www.aksharchemindia.com	
Contact material (Ag)		2000 €/kg	www.novacentrix.com	
Diffusion barrier (C)		463 €/kg	www.dycotecmaterials.com	
Ink preparation (Ball milling)		35.428 €/kg	Own assessment	
Printing (Screen printing)		4.629 €/m ²	Own assessment	
Drying (Hot plate drying)		40.26 €/kg	Own assessment	
Sintering		2.03 €/ m ²	Own assessment	

Table S4. TEG interface material

Table S4: Empirical investigation of a suitable printable interface material to lower contact resistances in a printed TEG device. The two-probe measurement was taken from the top of the conductive silver to the printed p-type material.

Contact types	Two probe resistivity measurement (Ω), Fluke 289
Ag ₂ Se/p-type TE leg	15.34
Silver/p-type TE leg	11.54
Silver/PEDOT/ p-type TE leg	1.5
Silver/graphene/ p-type TE leg	0.72
Silver/carbon/ p-type TE leg	0.42

Two primary factors contribute to the high internal resistance of the TEG: (a) low TE material density and (b) high electrode–leg interface resistance. The low material density results from the pressure-free fabrication process, which reduces overall electrical conductivity and increases internal resistance. Applying pressure after printing may help reduce this resistance. Silver ink is commonly used as an electrode material in printed TEGs due to its high conductivity and low curing temperature. However, high contact resistance between printed silver electrodes and Bi-Te-based TE legs remains a significant challenge. This is likely due to surface roughness, porosity, and diffusion of silver into the TE material. In bulk TEGs, metals like Ni and Fe are often used as diffusion barrier layers, but printable inks based on these metals are not readily available. To address this, we investigated the variation in contact resistance using different printable interface materials (see Table S4). Among the tested materials, the carbon interface showed the lowest contact resistance. Notably, omitting the carbon interface increased the resistance by more than 20 times. Further improvements may be possible by replacing carbon ink with more conductive carbon-based printable compounds.