

Experimental Characterization of Microfabricated Thermoelectric Energy Harvesters for Smart Sensor and Wearable Applications

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Microfabricated thermoelectric generators (μ TEGs) are excellent candidates for sustainable power delivery for the next generation of smart sensors and wearable devices through harvesting of waste heat. However, the assembly process and inherently small contact areas for thermal and electrical transport introduce losses which can significantly reduce the effective figure of merit ZT . Further, the form factor of μ TEGs makes these losses extremely challenging to quantify. The relative contributions of the thermoelectric film and interfaces greatly impact the choice of materials, device geometry, and maximum power point operation. A comprehensive study of μ TEG devices including microfabrication, detailed modeling and optimization, and electrical, structural, and thermal characterization of modules and their constituent films is presented. Using a combination of novel infrared microscopy and thin-film characterization techniques, the average thermoelectric material properties and the power output as a function of the true temperature difference across the device are isolated. Power outputs as high as 1 mW for a μ TEG with 13.8 mm² footprint and device ΔT of 7.3 K are measured. An order of magnitude reduction in figure of merit for the devices ($ZT \approx 0.03$) compared to the constituent thermoelectric films ($zT \approx 0.3$), with implications for the selection of maximum power point operation, is demonstrated.

1. Introduction

Thermoelectric energy harvesting technology, which uses the Seebeck effect to convert thermal gradients into electrical potential, is poised to take advantage of the nexus between advances in microfabrication technology and the widespread demand for small low-power devices such as autonomous sensors in the Internet of Things (IoT) and wearable electronics spaces. Thermoelectric generators (TEGs) have been manufactured on the mm- to cm-scale for thermal energy conversion in the Watts to kilo-Watts-electric range since the 1950s for niche applications in the aerospace and transportation industries.^[1–4] However, developments in microscale fabrication technologies since the 1990s have enabled a push toward small form factor “micro” thermoelectric generators (μ TEGs) assembled by patterned additive manufacturing such as physical vapor deposition^[5,6] or electrodeposition.^[7–10] These approaches allow for a very high thermocouple density (>1000 cm^{−2}) and can be optimized^[11] to reach voltages on

the order of 1 V for small temperature gradients (e.g., <10 K). These voltages enable the efficient use of power management circuitry^[12] to buffer transients in the thermoelectric system from temperature fluctuations or to trickle-charge a battery or capacitor for periodic high-current discharge bursts (e.g., low duty cycle wireless transmissions).^[10] Microfabricated TEGs produced in a streamlined wafer-scale process offer a cost-effective, small form factor, and maintenance-free alternative to battery-powered or hard-wired devices that may be impractical to reaccess after installation.

Significant early efforts in the fabrication of microscale TEGs include the deposition of Bi₂Te₃-based materials by magnetron sputtering by Stordeur and Stark onto thin substrates which were then diced and arranged in a stack to form a large thermopile.^[13] Similar “in-plane deposition, stacked assembly” methods were later used by Stordeur and Stark,^[14] Kim,^[15] and by Weber et al. in a coiled assembly.^[16] In 1999, Fleurial et al. demonstrated direct deposition of thermoelectric material to form vertical arrays of thermoelements using photoresist

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templates,^[9,10] motivating similar efforts in monolithic vertical fabrication by Glatz et al.^[7,8] and Cornett et al.^[6] In addition to the use of system-level analyses by Dunham et al.^[11] which demonstrated the impact of a variety of geometric design parameters on the performance of vertically assembled μ TEGs, this work aims to improve upon the characterization techniques common in the literature which are particularly susceptible to uncertainty from thermal contact resistances.

In this work, we report the comprehensive design, fabrication, and experimental characterization of wafer-processed μ TEGs for thermal energy harvesting applications. We use IR microscopy to measure the in situ device temperature gradient with micrometer-scale spatial resolution. We simultaneously measure the temperature across the active region of the device while recording current–voltage sweeps across a variable load resistance to measure the full set of electrical output characteristics from the open circuit through the optimal matched-load conditions. Through cross-sectioning and optical microscopy, we are able to extract information about bonding-induced deformation and the relative parasitic contributions to the electrical resistance and potential for improvement. In addition to measuring load power versus temperature gradient, we use the described technique to determine device thermal resistance, thermal efficiency, and a device-level thermoelectric figure of merit ZT .

2. Design of Microfabricated TEGs

The design of μ TEGs in this study is guided by the models and conclusions developed by Dunham et al.^[11] for the optimization of power density. The energy harvesters operate by forming a

thermal pathway from a heat source (e.g., hot water pipe surface, machinery casing, or human skin) to a heat sink (e.g., ambient air or a cold solid surface). The thermal resistance of the μ TEG establishes a temperature gradient across an array of thermocouples which are arranged thermally in parallel, such that each thermocouple sees approximately the same temperature gradient, and electrically in series, such that the Seebeck voltage generated by each thermocouple adds together for a large electrical potential. A representative model of the μ TEGs in this study, scanning electron microscopy (SEM) image of internal thermocouple array, example packaged assembly for water pipe thermal harvesting, and illustrations of reduced 3D unit cell and 1D thermal resistor network models are shown in **Figure 1**.

For a fixed thermal resistance between the heat source and heat sink external to the generator (e.g., spreading and bond interface resistance on the hot side and heat sink on the cold side), illustrated by $R_{t,c}$ and $R_{t,h}$ in the 1D resistor network in Figure 1, the power output of an ideal μ TEG is optimized when the thermal resistance of the active thermoelectric region approximately equals the total sum of external thermal resistances. An optimal thermal resistance ratio occurs because the primary mechanism for increasing thermal resistance (increasing the aspect ratio of the thermoelements, or individual leg of a thermocouple) also increases the electrical resistance. As the ratio of internal to external thermal resistance goes to infinity, the temperature difference across the μ TEG asymptotically approaches the source–sink temperature difference, while the electrical resistance increases without bound.^[17] This is a one-direction optimization, meaning if the external thermal resistance is known and fixed, the thermal resistance of the thermoelectric region should be designed to match it. However,

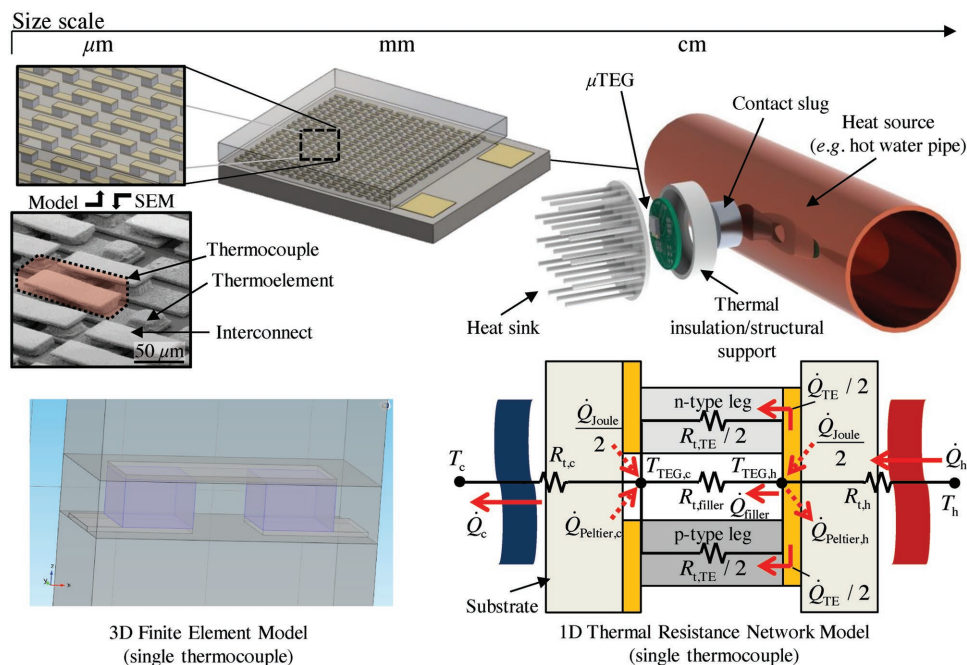


Figure 1. Illustration of size scales from individual thermoelement (μm) to device-level μ TEG (mm) to example system-level implementation (cm), with insets of SEM showing thermocouples, thermoelements, and interconnects (center left), and illustrations of reduced 3D unit cell and 1D thermal resistance network models.

reducing the external thermal resistance will always lead to an increase in power output as it increases the thermal gradient across the generator, ΔT_{TEG} , and electrical power generated is proportional to the square of this temperature difference.

The relation for power delivered to an electrical load resistance matching the electrical resistance of the generator, $R_{\text{e,TEG}}$, is given in Equation (1), where S_{TEG} is the total Seebeck coefficient including all thermocouples in series. While parasitic losses, primarily Peltier heating and cooling from electrical current flow, in reality shift the optimal electrical load resistance to be larger than the generator electrical resistance, the assumption of maximum load power delivered at matched electrical loading conditions is a reasonable approximation for small ΔT_{TEG} and low device-level figure of merit ZT (discussed in Section 5.4)

$$P_{\text{load, matched}} = \frac{V^2}{4R_{\text{e,TEG}}} = \frac{(S_{\text{TEG}}\Delta T_{\text{TEG}})^2}{4R_{\text{e,TEG}}} \quad (1)$$

The devices in this study are designed to be coupled to external thermal resistances totaling $\approx 5\text{--}10 \text{ K W}^{-1}$. This range is intended to be representative of a solid bond contact on the hot side and a high-performance natural convection heat sink, radiation heat sink, or solid contact to a heat pipe on the cold side. The device thermal resistance is calculated using a 1D resistor model, illustrated in Figure 1, accounting for the series contributions of the silicon substrates, passivation layers, and thermocouple region including air surrounding the thermocouples. Four different device geometries are studied, plus one duplicate geometry which is die-bonded under higher pressure. Table 1 provides a summary of the device designs. The nominal thermal resistance for each design is calculated using an assumed thermal conductivity (k) of $1.3 \text{ W m}^{-1} \text{ K}^{-1}$ for Bi_2Te_3 and Sb_2Te_3 thin films formed by physical vapor deposition (PVD). While stoichiometric single crystal material in macro-scale ingots is typically assumed to have thermal conductivity of $\approx 1.6\text{--}2.0 \text{ W m}^{-1} \text{ K}^{-1}$,^[18,19] thin films are typically more thermally resistive (e.g., $\approx 1.2\text{--}1.4 \text{ W m}^{-1} \text{ K}^{-1}$ measured for coevaporated Bi_2Te_3 thin films^[20]) due to defects and grain disorder. All devices have a footprint of $4.3 \text{ mm} \times 3.2 \text{ mm}$, corresponding to the area of the larger substrate in the illustration presented in Figure 1.

3. μTEG Fabrication

The μTEGs are fabricated on 3 in. $\langle 100 \rangle$ Si wafers coated with a 500 nm thick SiO_2 insulation layer deposited via

plasma-enhanced chemical vapor deposition. Separate n- and p-type wafers are fabricated in parallel. Following the blanket SiO_2 deposition, $\approx 4 \text{ }\mu\text{m}$ of Au (measured by SEM to be $3.2 \text{ }\mu\text{m}$ on the n-type wafer and $3.9 \text{ }\mu\text{m}$ on the p-type wafer) is electroplated to form the interconnect layer. The wafers are then patterned with a $15 \text{ }\mu\text{m}$ thick lift-off photoresist layer (AZ-9620). The thermoelectric depositions are done at room temperature in an RF-sputtering physical vapor deposition (PVD) system. The n-type thermoelectric material is deposited by cosputtering from Bi_2Te_3 (60 W) and Te (10 W) targets, while the p-type film is sputtered from a single Sb_2Te_3 target (60 W). The additional Te target for deposition of the n-type material is used to supplement low Te compositions consistently observed using energy-dispersive X-ray spectroscopy (EDX) when using a single Bi_2Te_3 target. The power factor of our test p-type films shows less sensitivity to variations in Te content, and a supplemental target is not required. The deposited Bi_2Te_3 and Sb_2Te_3 films are $\approx 8 \text{ }\mu\text{m}$ thick. In both cases, 10 nm of Cr is used to promote adhesion between the thermoelectric material and the Au. Following the thermoelectric film depositions, $1 \text{ }\mu\text{m}$ of Bi is sputtered to form an eutectic with Au during die bonding. Lift-off of the Cr/ Bi_2Te_3 /Bi (Cr/ Sb_2Te_3 /Bi) stack is performed by stripping the AZ-9620 in acetone for several hours. After lift-off, the wafers are annealed under nitrogen (to prevent oxidation) at $250 \text{ }^\circ\text{C}$ for 30 min, which brought the films closer to ideal stoichiometry and also reduced the electrical resistivity. Prior to bonding, the wafers are diced into individual die, with the cap die slightly smaller to expose electrical contact pads on the die below.

Bonding is performed using a SETNA FC150 flip-chip bonder. In a typical thermocompressive bond recipe, the die are ramped up to $350 \text{ }^\circ\text{C}$ under N_2 flow, with bonding force applied for a total of 150 s. The bond process accounts for $\approx 10\%$ of the total thermal budget including annealing, and we do not expect it to significantly alter the material properties. Annealing is performed as a separate process to enable blanket film characterization after annealing and prior to bonding. An eutectic bond is formed between the Bi layer on the n-type (p-type) wafer and the Au interconnect on the p-type (n-type) wafer. The bonding force varies depending on the particular device fill factor, with the nominal pressure on the thermoelectric legs relatively close to 44 MPa.

The deposited thermoelectric materials are characterized using X-ray diffraction (XRD) and SEM, with the film compositions determined by EDX. The thermoelectric properties of the films are determined using an Ecopia HMS-3000 Hall measurement system and a Seebeck measurement system based on a four-probe differential measurement technique. Electrical contact resistances between the thermoelectric materials and

Table 1. Nominal design parameters for μTEGs in this study.

Device no.	No. of TCs	Thermoelement height/width [μm]	Average nominal bond pressure on thermoelements [MPa]	Nominal thermoelectric layer thermal resistance [K W^{-1}]	Nominal device thermal resistance [K W^{-1}]
1	700	10/30	44	5.6	6.9
2	900	10/30	44	4.4	5.6
3	1100	10/30	44	3.7	4.7
4	348	10/40	44	6.2	7.6
5	348	10/40	53	6.2	7.6

Table 2. Measured properties for deposited thermoelectric and interconnect materials.

Material	S [$\mu\text{V K}^{-1}$]	ρ [$\Omega \text{ m}$]	PF [$\text{mW m}^{-1} \text{ K}^{-2}$]	$\rho_{\text{contact,Au}}$ [$\Omega \text{ m}^2$]
Bi_2Te_3 (n-type)	−102	1.56×10^{-5}	0.7	9.42×10^{-10}
Sb_2Te_3 (p-type)	+110	0.90×10^{-5}	1.3	3.42×10^{-8}
Au	–	2.6×10^{-8}	–	–

Au depositions are measured using patterned Kelvin structures, and represent an average, effective contact resistance that includes the adhesion and bonding materials in the interfacial regions (Cr and Bi). A summary of the results of these measurements is given in Table 2.

4. Device Characterization

The most challenging aspect of module-level characterization for μTEGs is determining the operating temperature gradient across the generator in the presence of multiple parasitic resistances and interfaces. The small contact surfaces and impracticality of using a high-conductance permanent bond in the test fixture lead to large thermal contact resistances at the boundaries. For example, a representative thermal resistivity for an aluminum/aluminum interface with Dow Corning 340 grease and $\approx 100 \text{ kN m}^{-2}$ contact pressure may be $\approx 7 \times 10^{-6} \text{ m}^2 \text{ K W}^{-1}$.^[21] In this study, the larger contact face is $\approx 4.3 \text{ mm} \times 3.2 \text{ mm}$ and the smaller contact face is $\approx 3.3 \text{ mm} \times 3.2 \text{ mm}$, leading to total thermal contact resistances above 1 K W^{-1} , which is around 20% of the design thermal resistance of the μTEGs . Further, the exterior silicon surfaces of these devices are unpolished, which could easily increase the total contact resistance to the magnitude of the generator resistance itself. For these reasons, a more precise thermal measurement technique is needed than the conventional approach of embedded thermocouples in adjacent source/sink materials, which grossly overpredicts the temperature gradient experienced by the functional part of the device.

4.1. Infrared Microscopy

We use an IR microscope (QFI InfraScope II) to directly measure the through-plane device temperature gradient with a spatial resolution of $\approx 20 \mu\text{m pixel}^{-1}$. The emissivity at the surface of the undoped silicon substrate edges is increased by applying a thin coating of black liquid electrical tape (Gardner Bender LTB-400), observed under an optical microscope to be $\approx 10\text{--}20 \mu\text{m}$ thick after solidifying. The IR microscope uses a pixel-by-pixel emissivity calibration feature to accurately convert the emission from surfaces to temperature without assuming a spatially homogeneous value of emissivity. Further details of this technique have been previously published.^[22,23] The calibrated emissivity of the coating is typically observed to be 0.88–0.94. This particular coating is chosen for the μTEGs and reference layers instead of graphite lubricant spray^[24] to avoid electrical shorting of the device or boron nitride spray^[25] because of difficulty masking the narrow device edges and a

concern for possible thermal shunting across the substrate gap. Boron nitride spray is used to increase the emissivity of the copper block surfaces, as it can cover a large area with acceptable uniformity and thermal shunting on the copper blocks is not a concern. Finite element models verify both that the film does not introduce appreciable thermal shunting and that the apparent surface temperature is not compromised by the thin resistive film. A piece of nonporous alumina ceramic (96–99.8% alumina composition purchased from McMaster-Carr) with known thermal conductivity of $27 \text{ W m}^{-1} \text{ K}^{-1}$ cut to the footprint dimensions of the μTEG is similarly coated with the black liquid tape on the measurement edge, and placed in series with the device. We use the measured temperature gradient across this reference sample to determine the heat flux in the μTEG . A custom heating and linear compression apparatus is used to support the device under the infrared objective lens (see Figure 2a,c). A miniature button load cell is placed in-line with the compression apparatus to ensure a consistent force of $\approx 18 \text{ N}$ during characterization. On the smaller ($3.2 \text{ mm} \times 3.3 \text{ mm}$ face) substrate this provides a pressure of $\approx 1.7 \text{ MPa}$ which is within the bounds of contact pressures for grease-joined solid-to-solid thermal interfaces referenced by Incropera et al.^[21] For the smallest measured fill fraction (FF) of 0.18, this translates to $\approx 9.5 \text{ MPa}$ on the individual legs, which is well below the minimum 44 MPa applied for bonding. During the experiment, copper blocks are heated by resistive Joule heaters with water line connections on one side. Thermocouples (K-type) are embedded into the copper blocks to monitor the reservoir temperatures. Electrical contact is made to 1 mm^2 gold contact pads on the device with beryllium-copper probe tips to minimize electrical contact resistance. Comparative tests with and without probe tip contact to the device demonstrate insignificant thermal losses through the probes.

Throughout the experiment, open-circuit device voltage and copper block temperature is recorded at a frequency of 4 Hz using an NI cDAQ-9174 chassis with modules for voltage (NI-9207) and thermocouples with cold-junction compensation (NI-9213). Data are visualized and recorded in a Labview interface. The system is brought to steady state at temperatures intended to give a range of temperature differences across the μTEG from $\Delta T_{\text{TEG}} = 0$ to $\approx 10 \text{ K}$. The steady state criterion used is a total fluctuation of less than 0.2 K in the thermocouple readings of each copper block and their difference over a 5 min period. After reaching steady state conditions, an infrared image is acquired averaging over 20 frames to reduce noise. For IR imaging, the load circuit is left open to prevent Peltier heating, although this is estimated from measured V – I curves to have a negligible contribution relative to the heat input ($< 7\%$ for minimum load resistance, and $\approx 3\%$ at maximum power point). After reaching steady state and recording the IR image, the μTEG is connected to a circuit containing a $10 \text{ k}\Omega$ potentiometer to sweep a range of load resistances. Voltage is read across a fixed low-resistance sense resistor (4.8Ω) to determine current and potentiometer resistance simultaneously, and the voltage across the sense resistor in series with the potentiometer is recorded as load voltage. The sense resistor value must be less than the nominal electrical resistance of the device to present a peak in the load power versus load resistance curve, as we generally expect the maximum power point to occur near matched

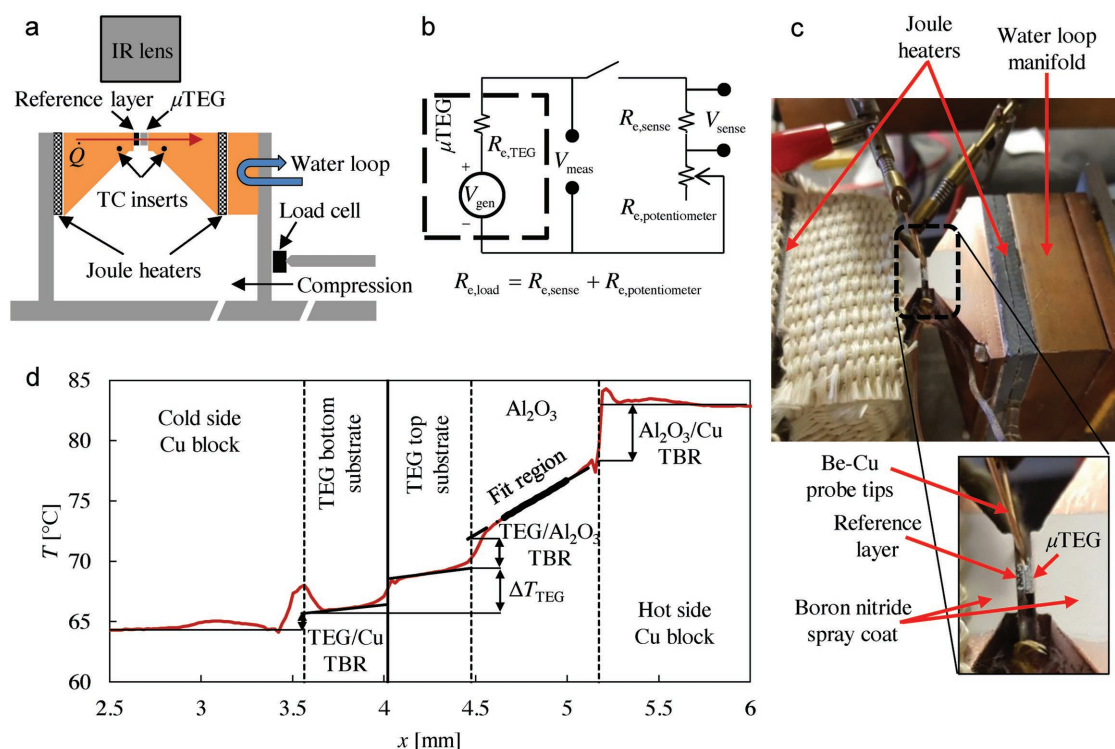


Figure 2. a) Schematic of thermal measurement structure, b) electrical measurement circuit diagram, c) photograph close-ups of thermal measurement structure, and d) representative plot of temperature versus position from infrared microscope data. We attribute the visible temperature fluctuations near interfaces to error induced by large spatial gradients in calibrated emissivity, for example, when the coating has been damaged by sample loading/unloading.

electrical loading, but large enough to permit stable measurements for small currents at the higher range of the resistance sweep. The electrical resistance of the μ TEG at room temperature is measured using the Harman method, and we note that for a module the measured quantity includes both volumetric and interfacial contributions to resistance.^[24] For each load resistance, electrical data are averaged over 20 acquisitions (i.e., 5 s).

For analysis, a rectangular region of interest spanning the device and several millimeters of each copper block is selected, and the temperature averaged in the direction perpendicular to heat flow to reduce noise. By using the extracted heat flux and the midpoint temperature of each device substrate, we extrapolate to determine the temperatures at the outer surfaces of the device. Further details and validation of this approach, as well as discussions of uncertainty, are provided in the Supporting Information. A representative set of temperature profiles, best fits, and extrapolation lines is shown in Figure 2d. The temperature drops due to thermal boundary resistance (TBR) between adjacent layers are directly observable using IR temperature mapping and illustrate the difficulty in relying on external thermocouple measurements for characterization. The measured values for open-circuit voltage and maximum load power as a function of extracted temperature difference across the μ TEG are plotted in Figure 3a,b.

The trends shown in Figure 3a,b are consistent with thermoelectric device models, exhibiting a highly linear dependence of open-circuit voltage on temperature difference

(the slope defines the effective Seebeck value), and a quadratic dependence of load power on temperature difference ΔT_{TEG} . For an externally imposed temperature difference and all other parameters fixed, an increasing density of thermocouples will increase the open-circuit voltage and the load power from the generator.^[11] This is apparent in the sequence of devices with 700, 900, and 1100 thermocouples (Devices 1–3). For the two identical devices bonded using different nominal bonding pressure, Device 4 (bonded at 44 MPa) demonstrates a higher open-circuit voltage but lower output power than Device 5 (bonded at 53 MPa). This is determined to be the result of deformation of the internal structure (see Section 4.2). At the higher bond pressure, the legs are crushed to a lower aspect ratio, leading to lower thermal and electrical resistances. Since Figure 3 only considers a fixed temperature difference across the device and not the heat load, the 53 MPa bonded device appears to produce more power despite having a lower device Seebeck value. A summary of measured and extracted parameters for all five devices is provided in Table 3. Values of device Seebeck S_{TEG} and device Seebeck per thermocouple $S_{TEG,TC}$ are extracted from the data in Figure 3. We note that the parameter $S_{TEG,TC}$ is not the net material Seebeck coefficient $S_{Bi2Te3} - S_{Sb2Te3}$, but rather the Seebeck voltage of the entire device (open-circuit voltage divided by ΔT_{TEG} , divided by number of thermocouples n_{TC}). Therefore, it is impacted by the relative contributions to thermal resistance in the device of the active and inactive regions of each μ TEG and is always less than the net material Seebeck coefficient because it includes parasitic temperature

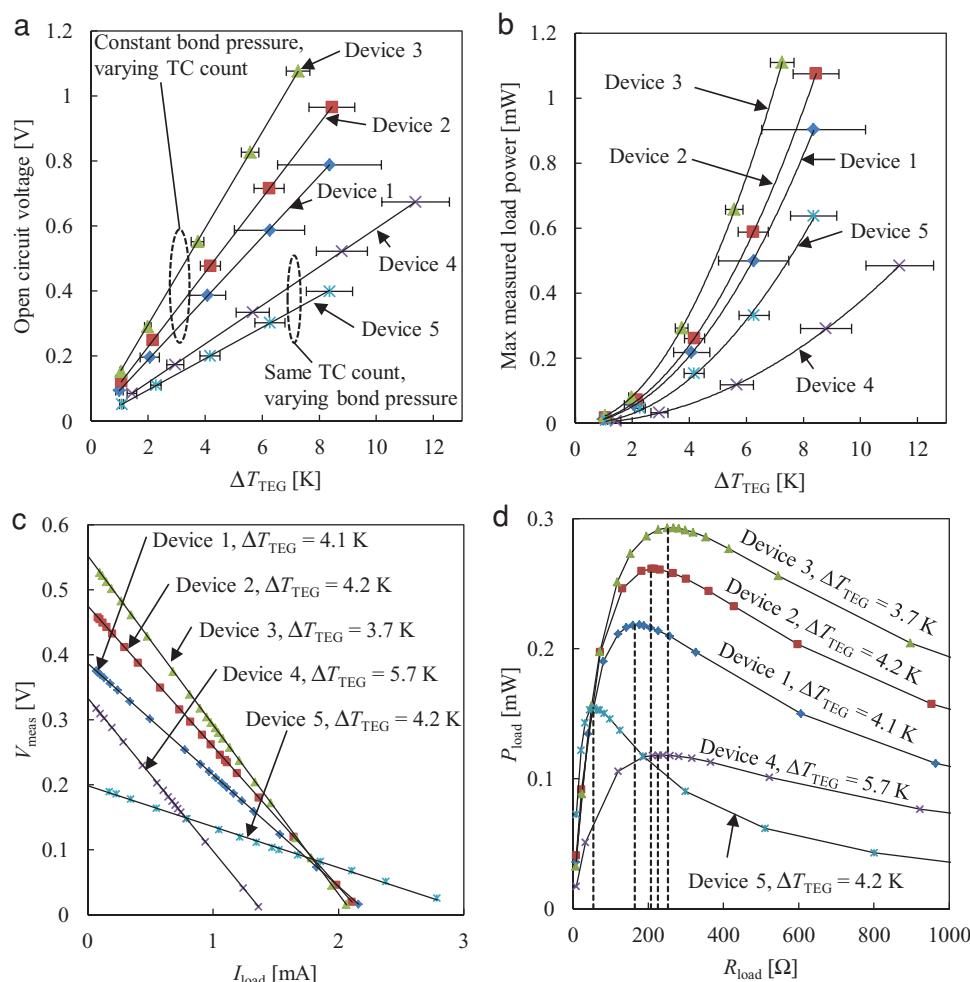


Figure 3. Measured values for a) μTEG open-circuit voltage and b) maximum load power as a function of the μTEG temperature difference extracted using the infrared microscopy methodology. Solid lines are linear and quadratic best fit lines. Plots of c) voltage versus load current with fit lines and d) load power versus load resistance with visual aid lines. All data in (c) and (d) are shown at the $\Delta T_{\text{Cu}} \approx 20$ K steady state condition. Vertical dashed lines in (d) show the μTEG electrical resistance as extracted from data in (c).

drops through the substrates and other materials not contributing to the Seebeck voltage. Device 4 has a notably larger $S_{\text{TEG,TC}}$ value because less deformation occurs in the legs than in all other devices, preserving an aspect ratio closer to the nominal design and larger thermal resistance of the active region. The impact of the geometric parameters of each device is illustrated quantitatively by the estimated values for the 1D thermal resistance of the parallel array of thermoelements $R_{\text{t,TE}}$ using the number of thermocouples, the extracted leg geometries, and the fit value for average thermal conductivity. The net material Seebeck coefficient ($231 \mu\text{V K}^{-1}$) is extracted using the method detailed in Section 5.3.

The thermocouple-normalized Seebeck value $S_{\text{TEG,TC}}$ is helpful in interpreting the data. For Devices 1–3 bonded using the same pressure per leg, the value remains relatively constant. However, there is a significant difference between the values obtained for Devices 4 and 5 which underwent different bonding pressures. Since the deformation in Device 5 affected only the active thermoelectric region and not the silicon substrates, the ratio of thermocouple-to-device thermal resistance

is significantly lower. This means that for a given temperature difference across the entire μTEG (including substrates), the thermocouples in Device 5 see a smaller fraction of that gradient than do the thermocouples in Device 4. The result is a larger Seebeck voltage, and consequently larger $S_{\text{TEG,TC}}$, from Device 4 for the same temperature drop from substrate to substrate.

Using the measured load voltage, I – V profiles and load resistance curves are produced for each μTEG . For comparison, the data for each device under the steady state condition of $\Delta T_{\text{Cu}} \approx 20$ K (temperature difference of the Cu blocks measured by embedded thermocouples) are shown in Figure 3c. The minimum load resistance ($R_{\text{e,sense}}$ plus a small contribution from the nominally zeroed potentiometer) can be subtracted from the slope of the voltage versus load current data shown in Figure 3c to calculate the electrical resistance of the μTEG under test, $R_{\text{e,UT}}$. There is no significant deviation in device electrical resistance between room temperature and test conditions, although the electrical resistance generally trends downward with increasing temperature.

Table 3. Summary table of measured and extracted device parameters.

	Device 1	Device 2	Device 3	Device 4	Device 5
No. of TCs	700	900	1100	348	348
TE bond pressure [MPa]	44	44	44	44	53
S_{TEG} [mV K ⁻¹]	94	114	149	59	48
$S_{\text{TEG,TC}}$ [$\mu\text{V K}^{-1} \text{ TC}^{-1}$]	134	127	135	170	137
$R_{\text{e,RT}}$ [Ω]	166	211	255	246	59
$R_{\text{e,UT}}$ [Ω]	164	207	252	226	54
$R_{\text{e,TE}}$ [Ω]	37	53	71	20	7.5
$R_{\text{e,IC}}$ [Ω]	20	23	25	12	10
ρ_{c} [$\Omega \text{ m}^2$]	7.9×10^{-11}	6.7×10^{-11}	7.2×10^{-11}	3.7×10^{-10}	1.1×10^{-10}
Nominal/imaged leg height [μm]	8.2/4.4	8.2/4.4	8.2/5.3	8.2/6.2	8.2/3.5
Nominal/imaged leg width [μm]	30/(45.2 $\pm$ 3.5)	30/(43.0 $\pm$ 1.8)	30/(45.0 $\pm$ 3.2)	40/(51.5 $\pm$ 3.3)	40/(63.3 $\pm$ 6.0)
Nominal/imaged FF	0.12/0.28	0.15/0.32	0.19/0.43	0.11/0.18	0.11/0.27
$R_{\text{t,TE}}$ [K W ⁻¹]	1.18	1.02	0.92	2.58	0.97
$R_{\text{t,TEG}}$ [K W ⁻¹]	2.4 $\pm$ 0.5	1.7 $\pm$ 0.2	1.5 $\pm$ 0.2	3.0 $\pm$ 0.4	2.2 $\pm$ 0.3
$\Delta T_{\text{Cu}}^{\text{a})}$ [K]	19.9	19.9	20.1	19.7	19.7
$\Delta T_{\text{TEG}}^{\text{a})}$ [K]	4.1	4.2	3.7	5.7	4.2
$\dot{Q}^{\text{a})}$ [W]	1.7	2.5	2.6	1.9	1.9
$P_{\text{load,max}}^{\text{a})}$ [mW]	0.22	0.26	0.29	0.12	0.15
$P_{\text{a,load,max}}^{\text{a})}$ [mW cm ⁻²]	1.6	1.9	2.1	0.9	1.1
$\eta_{\text{max}}^{\text{a})}$	1.29×10^{-4}	1.06×10^{-4}	1.15×10^{-4}	6.21×10^{-5}	7.98×10^{-5}
$\eta_{\text{Carnot}}^{\text{a})}$	0.012	0.012	0.011	0.016	0.012
$ZT^{\text{a})}$	0.044 $\pm$ 0.018	0.035 $\pm$ 0.008	0.043 $\pm$ 0.007	0.015 $\pm$ 0.004	0.027 $\pm$ 0.006

^{a)} Measured at $\Delta T_{\text{Cu}} \approx 20$ K.

We measure maximum load power levels on the order of hundreds of μW to single mW for a device temperature difference $\Delta T_{\text{TEG}} < 10$ K. A similar μTEG would typically be integrated with a power management circuit, in which a capacitor or other energy storage medium would be trickle-charged by the generator and power could be provided to functional components with regulated voltage. This type of circuitry for μW to mW power sources is typically reported with $\approx 60\%$ end-to-end conversion efficiency in the literature.^[26–29] Higher voltages generally result in higher efficiency of the power management circuit, highlighting one of the distinct advantages of the high thermocouple densities enabled by a μTEG architecture. Tan and Panda performed calculations for operational lifetime of a fully autonomous wireless sensor node assuming 1 mW average power consumption.^[30] Assuming this is the average power consumption including typical losses in a power management circuit, the ΔT_{TEG} values required for Devices 1–5 to produce 1 mW are 8.8, 8.1, 6.9, 16.3, and 10.5 K, respectively. Depending on the data rate, RF transmission technology, and operational duty cycle, power requirements can be significantly reduced. Zhang et al.^[31] developed an electrocardiogram module powered by body heat and a TEG+power management circuit which wirelessly transmits data in multiple modes. In raw-data transmit mode at 200 kbps and 100% duty cycle operation, the module consumes 397 μW . In “AFib detection mode,” designed only to transmit a short buffer of recent data on the occurrence of an unusual atrial fibrillation event, the module consumes

just 19 μW . The ΔT_{TEG} required for Device 3 to run these two extreme modes would be 4.3 and 1.0 K, respectively.

4.2. Thermal Resistance and Structural Imaging

Determining an accurate temperature drop across thermoelectric generators is critical for a true power versus temperature difference measurement. However, to simulate device performance accounting for realistic thermal boundary conditions such as contact and heat sink resistances, we must have knowledge of the μTEG 's thermal resistance.

Measurements of the μTEG thermal resistances using the Al_2O_3 reference layer are consistently lower than anticipated from available models^[11] and assumed parameters. After repeated tests we hypothesized that the force from die bonding may have reduced the aspect ratio of the thermoelements, resulting in shorter, wider legs than the nominal design and lowering both the thermal and electrical resistances. This theory is confirmed by optical microscopy after filling the devices with epoxy for mechanical stability and mechanically polishing to expose a row of thermoelements inside the device. Average and standard deviation of leg dimensions obtained from cross-sectional imaging of a row of thermocouples are compared to nominal assumptions for each device in Table 3. Values for leg widths are obtained by measuring and averaging the widths of a full row of individual thermoelements, while leg heights are calculated by measuring

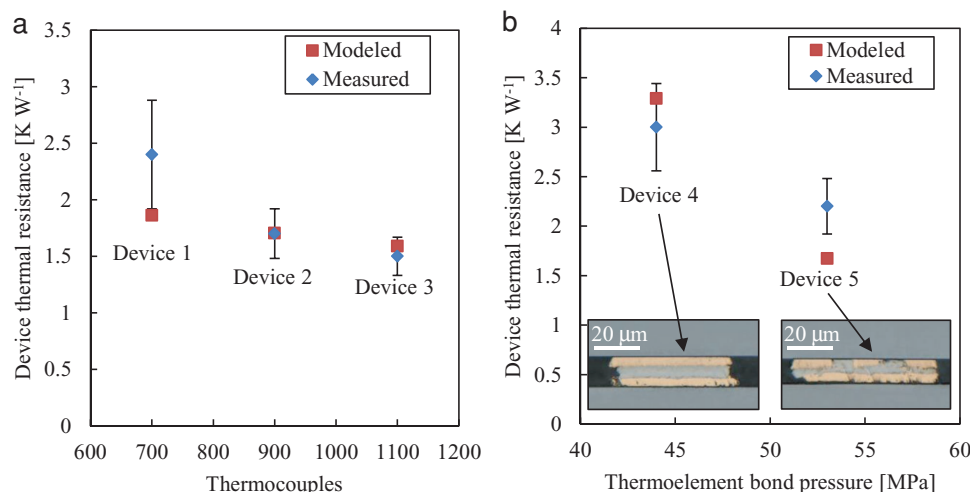


Figure 4. a) Comparison of experimental values with numerical values using fit thermal conductivity of $1.3 \text{ W m}^{-1} \text{ K}^{-1}$ for the average TE material value. b) The impact of higher bonding force resulting in strong deformation of the thermoelements in Device 5.

the spacing between the substrates and subtracting the measured thicknesses of the Au interconnect layers (3.2 and 3.9 μm). It is particularly noteworthy that Device 5 (bonded at a thermoelement pressure of 53 MPa) maintained full electrical integrity across 348 thermocouples despite severe deformation (shown in Figure 4b). This is a positive observation from the standpoint of device robustness, but must serve as a warning that strong deformation can occur for a relatively small increase in applied pressure without an obvious indication of device failure.

5. Determination of Material and Device Properties

5.1. Thermoelectric Material Thermal Conductivity

The average thermal conductivity of the p- and n-type thermoelectric materials can be estimated using the calculated thermal resistances and imaged leg dimensions from Table 3 in a numerical model to fit across the five studied devices. The numerical model used is a 1D thermal resistor network model neglecting Peltier and Joule heating since thermal resistance values are measured with the μTEGs in open-circuit configuration.^[11] Assuming $1 \times 10^{-7} \text{ m}^2 \text{ K W}^{-1}$ thermal contact resistance at the $\text{Bi}_2\text{Te}_3/\text{Au}$ and $\text{Sb}_2\text{Te}_3/\text{Au}$ interfaces,^[19] a least-squares fit of $1.3 \text{ W m}^{-1} \text{ K}^{-1}$ is determined for the average thermoelectric material thermal conductivity. This value compares well with the thin film thermal conductivity range of $\approx 1.2\text{--}1.4 \text{ W m}^{-1} \text{ K}^{-1}$ previously measured for coevaporated Bi_2Te_3 .^[20] The measured experimental thermal resistances are plotted with the values calculated using the fit value for thermal conductivity in Figure 4a,b.

5.2. Thermoelement/Interconnect Electrical Contact Resistance

Using the device electrical resistances and imaged leg dimensions, we can estimate the interconnect resistance contribution and the electrical contact resistance of the $\text{Bi}_2\text{Te}_3/\text{Au}$ and $\text{Sb}_2\text{Te}_3/\text{Au}$ interfaces. We note that this approach yields

an effective electrical contact resistance, which averages the resistance at both ends of the thermoelement and includes the interfacial regions (Cr on one end and Bi–Au eutectic on the other). With an average p- and n-type electrical resistivity (R_e) of $1.2 \times 10^{-5} \Omega \text{ m}$ and measured Au deposition resistivity of $2.6 \times 10^{-8} \Omega \text{ m}$, we calculate the parasitic electric contribution and resulting electrical contact resistance as

$$R_{e, \text{TE}} = \rho_{\text{TE, avg}} \frac{2n_{\text{TC}} l_{\text{leg}}}{A_{\text{leg}}} \quad (2)$$

$$R_{e, \text{ICs}} = 2n_{\text{TC}} \rho_{\text{IC}} \frac{1}{t_{\text{IC}} \sqrt{FF}} \quad (3)$$

$$\rho_{\text{contact}} = \frac{R_e - R_{e, \text{TE}} - R_{e, \text{ICs}}}{4n_{\text{TC}}} A_{\text{leg}} \quad (4)$$

The electrical resistance of the interconnects in Equation (3) is derived assuming a square grid of thermoelements, and an average travel distance for electrical current through each interconnect equal to the center-to-center spacing between the elements. The TE/IC electrical contact resistance is consistently less than $1.0 \times 10^{-10} \Omega \text{ m}^2$ for Devices 1–3, while it jumps by approximately a factor of 4 in Device 4. The exact reason for this increase is not known, as we initially assumed that the larger (nominally) $40 \mu\text{m} \times 40 \mu\text{m}$ thermoelement cross sections would form a better thermocompression bond and possibly reduce electrical contact resistance. However, the opposite seems to be true and could indicate issues with surface roughness or nonuniformity over larger bond areas. All calculated electrical contact resistances are at least a factor of 2 lower than the values measured on the n- and p-type wafers prior to bonding. We attribute this change to improved electrical contact due to the high-temperature/high-pressure bond process. We also note the significant estimated contribution from the Au interconnects which, despite high electrical conductivity and relatively thick $\approx 4 \mu\text{m}$ height, essentially match the electrical resistance due to the thermoelectric legs. For

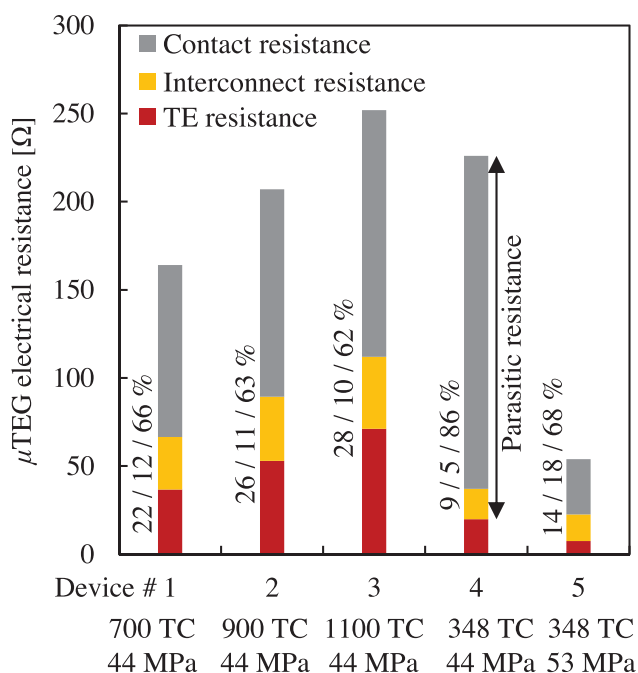


Figure 5. Illustration of the estimated component resistances in each μ TEG. The relative percentage of each contribution to total electrical resistance for each device is listed alongside the bar graphics.

higher aspect ratio legs, the ratio of interconnect resistance to TE leg resistance should decrease. Devices 1 and 5 possess comparable fill fraction after bonding (0.28 and 0.27) and illustrate the conclusion drawn in ref [11], that for a given fill fraction it is beneficial to use a larger number of legs with smaller cross section, in part because the ratio of TE material resistance to total parasitic resistance will be higher. Estimated contributions from the TE material, interconnects, and TE/interconnect contacts are illustrated in Figure 5. The large fraction of total resistance due to parasitics represents significant potential for device optimization. For example, if the contact resistance of Device 3 could be improved by a factor of 2, total electrical resistance would decrease from 252 to 174 Ω , and maximum load power for $\Delta T_{\text{TEG}} = 5$ K would increase from 290 to 420 μ W.

In this work, we have assumed that transport in the PVD Bi_2Te_3 and Sb_2Te_3 films is isotropic, taking values measured in-plane (parallel to the Si substrate) to be approximately equal to those out-of-plane (along the TE legs). This assumption is supported by XRD spectra from these materials, which show relatively weak texturing and no preferential alignment along 00 l crystal plane that is often seen in such films. While the electrical and thermal conductivities of highly textured Bi_2Te_3 and Sb_2Te_3 exhibit strong anisotropy,^[3,32] the transport properties of polycrystalline Bi_2Te_3 -based materials with a low degree of grain orientation are essentially isotropic.^[33,34] Should the properties be anisotropic, the primary impact on the present analysis would be in the calculation of electrical contact resistance. In the case of highly ordered Bi_2Te_3 -based films, the electrical conductivity anisotropy ratio could be as high as 4,^[32] and the true contribution of the thermoelements to electrical resistance could differ from what is reported in Table 3. Since

the calculated contribution of electrical resistance from the thermoelements is subtracted from the measured device electrical resistance to determine the contact resistance, a change in resistivity due to anisotropy could impact these values.

5.3. Material Seebeck Coefficient and Load Power Modeling

We can calculate the net Seebeck coefficient of an individual thermocouple independent of the material measurements performed on the deposited wafers by using information obtained from IR and optical microscopy. Since the interior geometry and material thermal conductivities are now known, we can calculate the thermal resistance $R_{t,\text{TE}}$ of the active thermoelectric region (thermocouples in parallel with air filler material). By using the measured temperature difference across the generator ΔT_{TEG} and the calculated thermal resistance of the μ TEG, $R_{t,\text{TEG,modeled}}$, the temperature difference across the thermocouple region is found using a voltage divider analog

$$\Delta T_{\text{TE}} = \frac{R_{t,\text{TE}}}{R_{t,\text{TEG,modeled}}} \Delta T_{\text{TEG}} \quad (5)$$

The device-level Seebeck coefficient per thermocouple $S_{\text{TEG,TC}}$ from Table 3 is divided by the thermal resistance ratio $R_{t,\text{TE}}/R_{t,\text{TEG,modeled}}$ to obtain the net material Seebeck coefficient, with uncertainty determined by the uncertainties in ΔT_{TEG} . The net Seebeck values are plotted in Figure 6a. The average value is 231 $\mu\text{V K}^{-1}$, or 9% higher than the value of 212 $\mu\text{V K}^{-1}$ measured from the prebonded wafers. The higher value is used with the other parameters determined in this study to model maximum load power versus ΔT_{TEG} . We compare measured maximum load power values with model outputs in Figure 6b, which show good agreement (less than 10% deviation from measured values).

5.4. Device ZT from Thermal Efficiency

With the thermal conductivity data extracted from measured device resistances, we can estimate an average material zT using the following relation

$$zT = \frac{S_{\text{net}}^2}{4k_{\text{avg}}\rho_{\text{avg}}} T_{\text{avg}} \quad (6)$$

Using values of $S_{\text{net}} = 231 \mu\text{V K}^{-1}$, $k_{\text{avg}} = 1.3 \text{ W m}^{-1} \text{ K}^{-1}$, $\rho_{\text{avg}} = 1.23 \times 10^{-5} \Omega \text{ m}$, and $T_{\text{avg}} = 70^\circ \text{C}$, we obtain an average material zT of 0.29. Although electrical and Seebeck measurements are performed in-plane and thermal conductivity is effectively out-of-plane, we reasonably assume the transport properties to be isotropic as described in Section 5.2. Material properties S_{net} and ρ_{avg} are measured at room temperature, while device characteristics are measured in the range of $\approx 60\text{--}80^\circ \text{C}$ for increased IR sensitivity. The μ TEG electrical resistance is not observed to change significantly between room temperature and the elevated characterization temperatures.

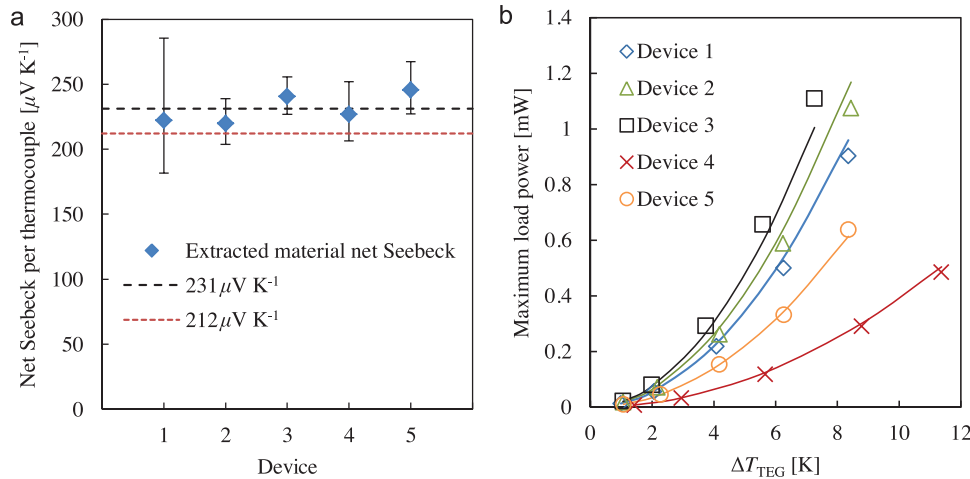


Figure 6. a) Comparison of extracted material net Seebeck coefficient with prebond wafer measured value ($212 \mu\text{V K}^{-1}$) and average of extracted values ($231 \mu\text{V K}^{-1}$), and b) modeled (lines) and measured (markers) maximum load power versus ΔT_{TEG} . The model assumes the average extracted material net Seebeck coefficient value of $231 \mu\text{V K}^{-1}$.

While material zT presents interesting information about the active thermoelectric materials in the μTEG , we know that significant device-level losses motivate an analysis at the module level. To compare the average material zT with an effective device-level ZT accounting for thermal and electrical losses, we begin with the relationship for maximum efficiency,^[18] assuming that $T_c/T_h \approx 1$ at small temperature differences

$$\eta_{\max} = \eta_{\text{Carnot}} \frac{\sqrt{1+ZT} - 1}{\sqrt{1+ZT} + 1} \quad (7)$$

where η_{Carnot} is the Carnot efficiency. We can then solve algebraically for ZT , giving the relation

$$ZT = \frac{4\eta_{\text{Carnot}}\eta_{\max}}{(\eta_{\text{Carnot}} - \eta_{\max})^2} \quad (8)$$

Using the measured heat flow and the maximum load power, we calculate the device efficiency and the effective device-level ZT of Equation (8) as given in Table 3. In these calculations, it is assumed that variation of the electrical load resistance does not significantly affect the heat flow through the device, $\dot{Q}$, in which case the point of maximum load power delivery is also the point of maximum thermal efficiency because $\eta = P_{\text{load}}/\dot{Q}$ and $\dot{Q}$ is constant in this case. This assumption is supported by the relatively small Peltier heat contribution.

From the data in Table 3, we can see that the higher electrical contact resistances significantly reduce the device ZT values of all evaluated devices. Furthermore, the impact of device design and fabrication conditions on the contribution of parasitic losses makes this ZT value geometry- and process-dependent. Devices 4 and 5 show the largest reduction, with the losses in Device 4 coming primarily from high electrical contact resistance and the losses in Device 5 coming primarily from the small thermal resistance of the low-aspect-ratio thermoelements.

Taking the first term of the Taylor series expansion of Equation (8) about $\eta_{\max} = 0$ gives the expression

$$ZT \approx 4 \frac{\eta_{\max}}{\eta_{\text{Carnot}}} \quad (9)$$

Assuming maximum power at matched electrical load, $\eta_{\max} = P_{\max}/\dot{Q} = \Delta V^2/(4 \times R_{e,\text{TEG}} \times \dot{Q})$. The Carnot efficiency, assuming $T_{\text{avg}} \approx T_h$ for small temperature differences, is given by $\eta_{\text{Carnot}} = \Delta T_{\text{TEG}}/T_{\text{avg}}$. Combining terms we have

$$ZT \approx 4 \frac{\eta_{\max}}{\eta_{\text{Carnot}}} = \frac{\left(\frac{\Delta V^2}{R_{e,\text{TEG}} \dot{Q}}\right)}{\left(\frac{\Delta T_{\text{TEG}}}{T_{\text{avg}}}\right)} = \frac{\left(\frac{\Delta V}{\Delta T_{\text{TEG}}}\right)^2}{R_{e,\text{TEG}} \times \frac{1}{R_{t,\text{TEG}}}} T_{\text{avg}} \quad (10)$$

Substituting the device-level Seebeck coefficient $S_{\text{TEG}} = \Delta V/\Delta T_{\text{TEG}}$ and μTEG thermal conductance $K_{\text{TEG}} = 1/R_{t,\text{TEG}}$ (with S_{TEG} and $R_{t,\text{TEG}}$ reported in Table 3), we return to the familiar form of the thermoelectric figure of merit at the device level, with electrical and thermal losses lumped into the constituent parameters of Z

$$ZT_{\text{lumped}} = \frac{(S_{\text{TEG}})^2}{R_{e,\text{TEG}} \times K_{\text{TEG}}} T_{\text{avg}} \quad (11)$$

It is often reported in the literature^[35–37] that power delivery (and efficiency, depending on the boundary conditions) in thermoelectric generators is maximized for an electrical load resistance higher than the electrical resistance of the TEG, by a factor related to the figure of merit as $R_{e,\text{load,max}} = \sqrt{1+zT} \times R_{e,\text{TEG}}$. This observation differs from the common assumption of load power being maximized when load resistance matches the internal resistance of the power source, and is due to the presence of the parasitic Peltier heating and cooling produced when electrical current flows in the generator. In this study, a negligible difference is observed between measured load power at $R_{e,\text{load,max}}$ using the material zT of 0.29 compared to loads near the matched resistance $R_{e,\text{UT}}$. This is because in a real, nonideal device,

the effective device ZT must be used in order to account for electrical and thermal losses. For Device 3, for example, using the material zT (0.29) gives an optimal electrical load resistance of $286\ \Omega$ while the device ZT (0.043) yields $257\ \Omega$, which is much closer to the measured $R_{e,UT} = 252\ \Omega$. Maximum measured load power is observed for $R_{e,load} \approx 251 \pm 20\ \Omega$, although measured power does not decrease by more than 1% from the maximum value until $R_{e,load} \approx 320\ \Omega$. In higher- ΔT applications, this effect becomes more significant, and the design of matched electrical load conditions should be based on the effective device ZT rather than material zT .

6. Summary and Concluding Remarks

μ TEGs have the potential to provide battery-free and wireless power to a growing number of low-power distributed sensor modules. Use of thin film fabrication techniques make high thermocouple densities possible, allowing load voltages on the order of 1 V from small temperature differences. This work demonstrates the successful design and fabrication of a set of functional μ TEGs, and characterization using infrared microscopy for accurate determination of the generator temperature gradient and thermal resistance independent of large thermal contact resistances which challenge accurate characterization of small form factor μ TEGs. Information from device cross sections is used with measured material properties to estimate the relative contributions to electrical resistance from active and parasitic components, confirming conclusions from previous theoretical work and illustrating pathways to significant performance enhancements through reduction of parasitic electrical losses. A formula for a device-level figure of merit ZT is derived using measured thermal efficiency, made possible by the use of the infrared microscopy technique, which includes all thermal and electrical losses. Despite a modest average material thermoelectric figure of merit $zT \approx 0.3$, load power levels above 1 mW for μ TEG temperature gradients as low as 7.3 K are produced that would easily satisfy power requirements for a variety of wireless sensor nodes and other small devices.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

connected sensor power supplies, infrared microscopy, microfabricated thermoelectric generators, thermal energy harvesting, thermoelectric figure of merit

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