

Thermoelectric Hotspot Cooling using Thermally Conductive Fillers

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Abstract

The commercial application of thermoelectric coolers (TECs) is limited to niche markets because of their low cooling efficiency. The cooling efficiencies of TECs have been optimized by improving power factors or by decreasing thermal conductivities of constituent materials for refrigeration applications in which the Peltier heat flux is compensated for by the Fourier heat flux in the opposite direction. In contrary, for hotspot cooling, in which the Fourier heat is added to the Peltier heat flux, TE materials with large power factors and high thermal conductivities are required, posing developmental challenges owing to the interdependence between the TE properties of materials. This further complicates the simultaneous optimization of the power factor and thermal conductivity at the material level. Herein, we provide a novel solution at the device level to overcome these material challenges by utilizing a filler-embedded-thermally-conductive TEC (F-TEC) that enables the simultaneous optimization of the power factor and thermal conductance. As proof of concept, we demonstrated the F-TEC by embedding polymer-ceramic composites into a commercially available TEC, which increased the thermal conductance of TEC by over 120% at 300 K without affecting the TE properties. Using the F-TEC, the hotspot temperature under a heat flux of $56\ 250\ \text{W/m}^2$ decreased by 14.8 K for an electrical current flow of 1 A owing to the 42.5% improvement in effective thermal conductance at $\Delta T = 100\ \text{K}$. Additionally, infrared imaging and numerical analyses revealed that the filler can release thermal stress of the TE legs to a considerable extent, which extends the thermal stability of the TECs and the maximum heat flux range, over which TECs can be applied. We envision that the proposed F-TEC concept can facilitate the development of an effective TEC device that can be widely used in hotspot cooling applications, such as microprocessors and batteries.

KEYWORDS: thermoelectric cooler, hotspot cooling, refrigeration, solid-state cooling,
thermal management, filler

Nomenclature

Bare	Conventional TEC without filler
BN0	Ecoflex–0wt.% BN composite or F-TEC using the composite as filler
BN23	Ecoflex–23wt.% BN composite or F-TEC using the composite as filler
BN33	Ecoflex–33wt.% BN composite or F-TEC using the composite as filler
COP	Coefficient of performance
c_p	Specific heat capacity (J/kg K)
e	Electron charge (C)
I_p	Electrical current intensity applied to the TECs or legs (A)
I_p^{Opt}	Optimal electrical current intensity for TEC operation (A)
L	Lorentz factor ($J^2/K^2 C^2$)
K	Thermal conductance (W/K)
K_{Device}	Thermal conductance of the device including K_{TE} and K_{Filler} (W/K)
K_{Filler}	Thermal conductance of the filler (W/K)
K_{TE}	Thermal conductance of the TE legs (W/K)
k_B	Boltzmann constant (J/K)
m^*	Effective mass of the carrier (kg)
n	Carrier concentration (m^{-3})
PF	Power factor ($= \sigma S^2$) ($W/(m \cdot K^2)$)
Q	Heat transfer rate (W)
Q''	Heat flux (W/m^2)
R_{TEC}	Electrical resistance of the TEC (Ω)

S	Seebeck coefficient (V/K)
TE	Thermoelectric
TEC	Thermoelectric cooler
F-TEC	Filler-embedded (high- K) TEC
T	Absolute temperature (K)
T_{Heat}	Absolute temperature at the head-loaded side of the TEC (K)
T_{Sink}	Absolute temperature at the heat sink of the TEC (K)
ΔT	Temperature difference at the ends of the TEC defined as $T_{\text{Heat}} - T_{\text{Sink}}$ (K)
ΔT_{Bare}	ΔT of the Bare sample
ΔT_{BN33}	ΔT of the BN33 sample
∇T	Temperature gradient (K/cm)
$T_{\text{Legs}}^{\text{Max}}$	Maximum temperature of the TE legs
zT	Thermoelectric figure of merit
<i>Greek symbols</i>	
α	Thermal diffusivity (mm ² /s)
η	Degree of improved cooling performance by the filler defined as $\Delta T_{\text{Bare}} - \Delta T_{\text{BN33}}$ (K)
μ	Carrier mobility (cm ² /V s)

κ	Thermal conductivity (W/m K)
κ_{ele}	Electron contribution on κ (W/m K)
κ_{eff}	Effective thermal conductivity defined as $\kappa_{\text{eff}} = \kappa + \frac{\text{PF} \cdot T_{\text{Heat}}^2}{2\Delta T}$ (W/m K)
κ_{Filler}	Thermal conductivity of the filler (W/m K)
κ_{lat}	Lattice contribution on κ (W/m K)
ρ	Mass density (kg/cm ³)
σ	Electrical conductivity (S/m)

1. Introduction

With devices becoming increasingly miniaturized and densified, the dissipation of localized heat has become a central issue in electronics and battery technologies [1,2]. According to various studies [3,4], a high heat flux exceeding 300 W/cm^2 can be generated at the hotspot of a microprocessor, which can cause a locally overheated region. To guarantee the performance and lifetime of devices that strongly depend on operating temperatures, these heat fluxes must be extracted instantly [5,6]. Although conventional convection-based cooling systems can dissipate such large heat fluxes, recent studies have pointed out that they can be inefficient in dissipating heat from small areas, in which handling zones are limited, owing to their bulky design and high thermal inertness [4,7,8]. In this regard, solid-state thermoelectric coolers (TECs) with various advantages can provide a suitable solution by applying the Peltier effect. These advantages include high-dynamic thermal transients (heat transfer rates), compact size, low weight, and the absence of mechanical moving parts and a working refrigerant; therefore, TECs are suitable for small-scale hotspot cooling [9–12]. However, despite the potential of TECs in heat-dissipation applications, their commercial use has been limited to niche markets because of their low cooling efficiencies [13].

The cooling efficiencies of TECs have been estimated using the coefficient of performance (COP), which generally depends on the thermoelectric (TE) figure of merit zT ($= \sigma S^2 T / \kappa$) of the constituent materials. Here, σ is the electrical conductivity, S is the Seebeck coefficient, κ is the thermal conductivity from the electrical (κ_{ele}) and lattice vibration (κ_{lat}) contributions, and T is the absolute temperature [14]. To improve the cooling efficiency, zT has been improved over the past decades by increasing the power factor ($\text{PF} = \sigma S^2$) or decreasing the κ of TE materials [15]. A higher PF leads to an increase in the pumped heat by the Peltier

effect owing to an increased Seebeck coefficient or a lowered internal power dissipation if the electric conductivity is increased. Lowering the thermal conductivity improves the performance of refrigeration applications owing to the decreased Fourier heat flux. In refrigeration [15], the temperature of the heat-loaded side T_{Heat} is lower than that of the heat sink T_{Sink} (usually at room temperature) (**Fig. 1a**), and the direction of the active Peltier heat flow ($SI_P T_{\text{Heat}}$) owing to an applied current I_P through the TE legs is opposite to the direction of the passive Fourier heat flow ($K_{\text{TE}} \Delta T$, where K_{TE} is the thermal conductance of the TE legs and $\Delta T = T_{\text{Heat}} - T_{\text{Sink}}$). As a low κ blocks the backflow of Fourier heat that compensates for the Peltier heat, the use of zT by incorporating the denominator κ is justified as a criterion for determining cooling efficiency. By contrast, in hotspot cooling [16,17], in which T_{Heat} is higher than T_{Sink} , the Peltier heat flows in the same direction as the Fourier heat flow (**Fig. 1b**). Here, a low κ prohibits the Fourier heat transport by acting as a thermal barrier. Therefore, neither a high zT nor COP guarantees a high heat-dissipation capability in this case [16,17]. This distinctive feature of hotspot cooling necessitates specific material properties and an adapted device design. However, most commercial TECs have been optimized to achieve a high zT for refrigeration, which renders them a good thermal insulator (**Fig. 1c**). This optimization criterion has limited the widespread use of TECs for hotspot cooling conditions, which are found in most thermal management systems of electronics and batteries.

To address the aforementioned issue, Zebarjadi [16] highlighted the necessity of TE materials with a high κ and large PF, which are contrary to traditional high- zT materials. Adams *et al.* [17] and Li *et al.* [18] experimentally demonstrated TE hotspot cooling using high κ materials combined with large PFs such as CePd₃, Co, and Cu-Ni alloys. Additionally, as a criterion for designing efficient hotspot cooling materials, the effective thermal conductivity

was suggested and expressed as follows [17]: $\kappa_{\text{eff}} = \kappa + \frac{\text{PF} \cdot T_{\text{Heat}}^2}{2\Delta T}$, which includes the intrinsic thermal conductivity of the material and extrinsic PF-driven thermal conductivity. Nimmagadda and Sinha [19] used numerical simulations to study the TE properties required for transient on-chip cooling using a Si die. They determined that TE materials with a $\text{PF} > 50$ mW/m K² and $\kappa > 100$ W/m K are necessary to justify the use of TECs for on-chip hotspot cooling.

Despite the efforts to explore novel materials for hotspot cooling, the interdependence of S , σ , and κ complicates development strategies for simultaneous optimization of the PF and κ of a material [20,21]. Specifically, S is inversely proportional to $n^{2/3}$ according to [20] $S = \frac{8\pi^2 k_B^2}{3eh^2} m^* T \left(\frac{\pi}{3n}\right)^{2/3}$ for metals, which are promising candidates for the TE materials applied in hotspot cooling, under the parabolic band and energy-independent scattering approximation. Here, n is the carrier concentration, m^* is the effective mass of the carrier, k_B is the Boltzmann constant, e is the electron charge, and h is the Plank constant. Additionally, σ is proportional to n according to $\sigma = ne\mu$, where μ is the carrier mobility. Furthermore, κ_{ele} is related to n by the Widemann–Frantz law [14] $\kappa_{\text{ele}} = L\sigma T$ and is, therefore, proportional to n , where L is the Lorentz factor. Therefore, PF (σS^2) can be optimized at a finite n but κ_{ele} cannot [20], which complicates the simultaneous optimization of PF and κ . In addition to improving the intrinsic κ and PF of materials, the efficiency of the TECs can be improved by tailoring their internal design using adapted filling factors and lengths of thermoelectric legs or by filling the voids between legs and bridges with thermally good conducting materials. Specifically, the device thermal conductance K_{Device} and PF can be engineered separately at the device level by

embedding thermoelectric legs and bridges inside the TEC with thermally conductive but electrically insulating fillers (**Fig. 1d**).

Herein, we propose a novel TE device structure that consists of high-PF TE legs and high- κ fillers for efficient hotspot cooling. This filler-embedded TEC (F-TEC) enables the simultaneous optimization of the PF and K_{Device} because the filler provides an additional degree of freedom to the system. The TE legs mainly dissipate heat via the Peltier effect while the filler acts as a passive heat conductor for Fourier heat only. Thus, the filler and TE legs could be optimized to possess different material properties, high κ and PF, respectively. In this study, we demonstrated the enhancement of cooling performance owing to the enhanced effective thermal conductance using commercial high-PF low- κ TE legs and high- κ polymer–ceramic composite filler as the experimental platform. We systematically investigated the role of a filler on the cooling efficiency of a single Peltier cooler module by varying its K_{Device} using various filler materials. Moreover, an infrared (IR) camera and COMSOL simulations were used to study the effect of the filler on the temperature gradient-induced thermal stress. Additionally, this study investigated whether the cooling performance and thermal reliability of the proposed device could be improved by tailoring the thermal design for hotspot cooling. Our study may extend the application of TECs to thermal management applications for hotspot cooling, such as in microprocessors, fuel cells, and batteries.

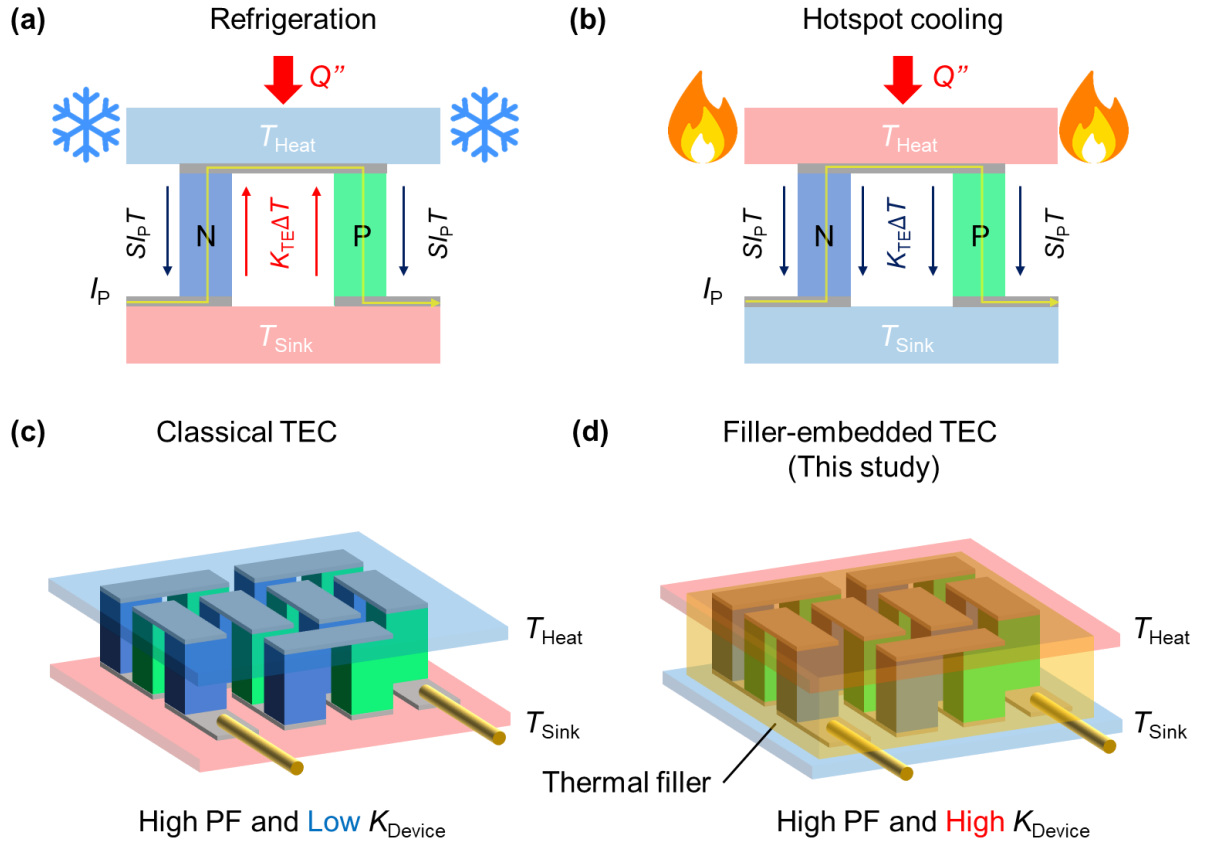


Fig. 1. Schematic illustration of a thermoelectric cooler (TEC) used for (a) refrigeration and (b) hotspot cooling, in which the Peltier ($S I_P T$) and Fourier ($K_{TE} \Delta T$) heat flows have the opposite or same directions, respectively. Here, S , I_P , T , K_{TE} , and ΔT are the Seebeck coefficient, electrical current applied to the Peltier, absolute temperature, thermal conductance of thermoelectric legs, and temperature difference between heat loaded (T_{Heat}) and sink sides (T_{Sink}), respectively. Additionally, Q'' indicates the heat load required for heat dissipation. The effect of Joule heating is not shown for simplicity, each half of which is dissipated to the heat-loaded side and heat sink, respectively, for both cases. The corresponding optimized device structures with (c) low and (d) high device thermal conductance (K_{Device}) values. (d) Filler-embedded high K_{Device} TEC (F-TEC) proposed in this study.

2. Materials and methods

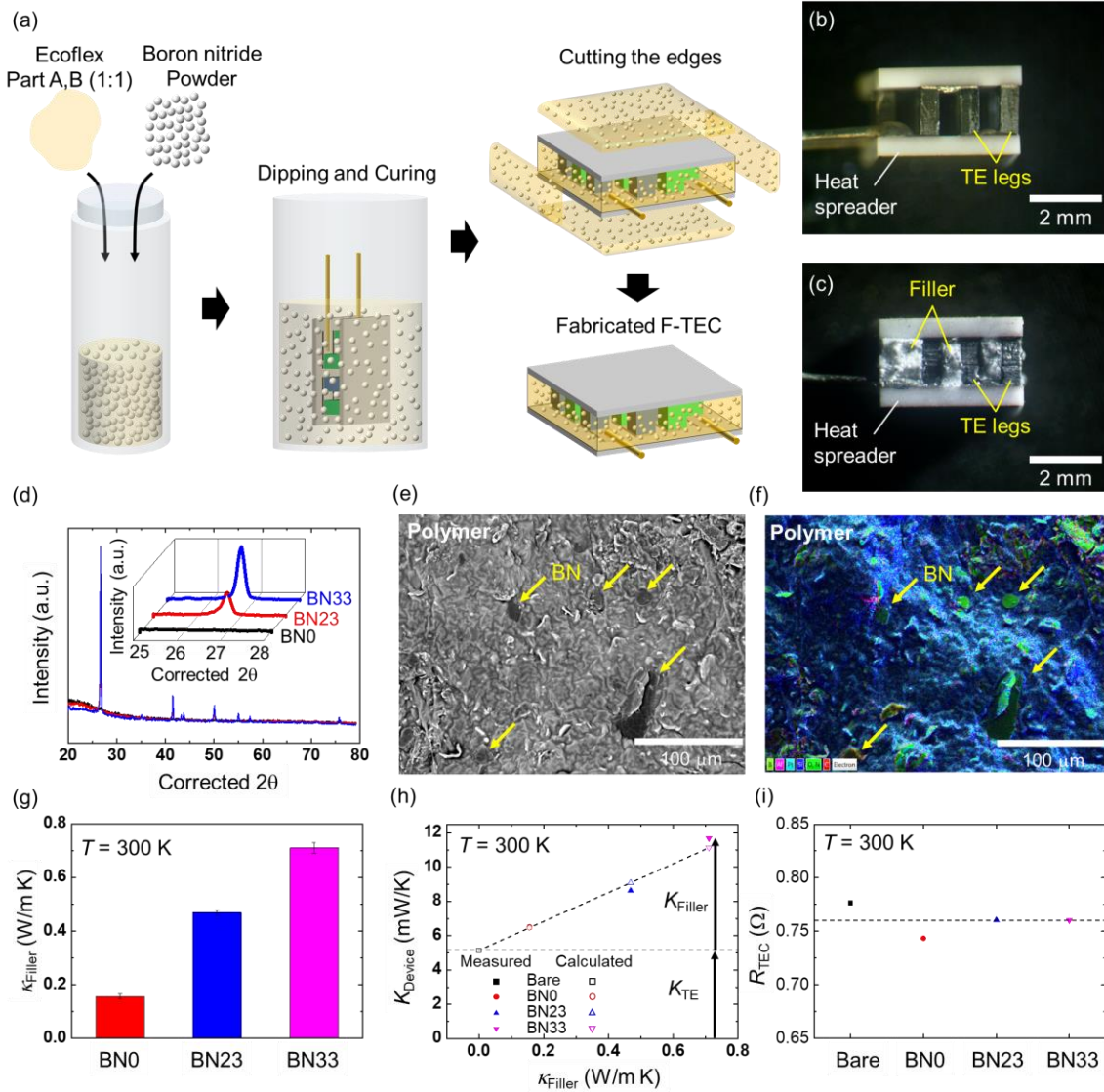


Fig. 2. (a) Fabrication process of filler-embedded thermoelectric coolers (F-TEC). Photographs of the (b) classical TEC without a filler and (c) F-TEC. (d) X-ray diffraction patterns of the fillers. Additionally, 2θ is corrected using the Si [111] peak (not shown in the figure). The inset depicts the main peaks of BN. (e) Back-scattered electron and (f) energy-dispersive X-ray spectroscopy images of the filler containing 33 wt.% BN powder. (g) Thermal conductivity of the fillers (κ_{Filler}). The device conductance of the F-TEC was compared to the starting value without a filler, which is indicated by the horizontal dashed line. (h) Device thermal conductance (K_{Device}) measured and calculated based on the thermal conductance of the TE legs (K_{TE}) and fillers (K_{Filler}) as a function of κ_{Filler} . The device conductance of the F-TEC was compared to the starting value without a filler, which is

indicated by the horizontal dashed line. (i) Electrical resistance (R_{TEC}) of the TECs. All transport data were acquired at 300 K.

2.1 Fabrication of F-TEC

The F-TECs used for hotspot cooling were fabricated by filling the interior of a TEC with a polymer–ceramic composite (**Fig. 2**). We selected polymer–ceramic composites as the filler materials in this study for the following reasons. First, the thermal conductivities of polymer–ceramic composites depend on the type and concentration of the ceramic additive material [22–25]; therefore, they provide an ideal platform to control the thermal conductance of a device by changing the composition as an experimental variable. In this study, we systematically investigated the impact of filler on K_{Device} and on the resulting cooling performance of the device, instead of simply maximizing the K_{Device} . Second, polymers do not cause significant thermal stress in the TECs during fabrication and cooling operations because of their elasticity and softness. Finally, polymers and ceramics are generally electrically insulating, which prevents electrical interference, such as shunting and electromagnetic heating, with the operation of TE legs. Commercially available polymer Ecoflex (Ecoflex 00-30, Smooth-on) and agglomerated BN powder (CFA 250S, 3M Co., Ltd.) were used as the constituents of the composite. Since the viscosity of a polymer–ceramic mixture rapidly increases with increasing the mass fraction of the ceramic component [26,27], a polymer formulation with low viscosity is preferred in fillers. Ecoflex 00-30 was chosen because it possesses low viscosity [28] and thus its composite mixtures are suitable for filling the complex inside the TECs (**Figs. 1 and 2b**). BN is an electrically insulating and thermally conductive material that is lightweight with a large energy band gap. Furthermore, BN is robust to

oxidation and chemical reactions and exhibits high thermal stability [23,24]. The BN powder used in this study was agglomerated and consequently thermally isotropic [29].

The Ecoflex–BN composite samples were prepared by mixing the base and curing agents of Ecoflex in a 1:1 weight ratio (wt.%) (**Fig. 2a**). After vacuuming the Ecoflex mixture to remove pores, 23 and 33 wt.% of the BN powder were added to the Ecoflex mixture. Generally, a high ceramic concentration imparts a high thermal conductivity to the resulting composite. In this study, 33 wt.% of BN was the maximum mass fraction of BN since higher concentrations become too viscous to firmly fill the complex inside the millimeter-sized TEC (**Fig. 2b**). Subsequently, commercial high-PF low- K_{Device} TECs (NL1010T-01AC, Marlow Industries Inc.) were dipped into the different Ecoflex–BN mixtures and vacuumed. The F-TEC samples were cured at 393 K for 2 h and finally shaped into their original dimensions by cutting off the protruding parts of the solidified fillers (**Figs. 2a and c**). Four samples were used for this study, *i.e.* one reference TEC without a filler and three experimental F-TECs, which were prepared with Ecoflex fillers containing 0, 23, and 33 wt.% BN powder. These samples are labeled Bare, BN0, BN23, and BN33, respectively, according to the mass fraction of BN in the filler (**Table 1**).

Table 1. Thermal properties of the samples at 300 K (blanks: irrelevant properties).

Sample label	BN concentration of the filler [wt.%]	Thermal conductivity of the filler κ_{Filler} [W/m K]	Thermal conductance of the device K_{Device} [mW/K]
Bare	-	-	5.15
BN0	0	0.156	6.52
BN23	23	0.469	8.63
BN33	33	0.710	11.67

2.2 Characterization of fillers and F-TECs

The crystal structures of the Ecoflex–BN composite fillers were investigated by measuring the X-ray diffraction (XRD) patterns using a combination of Cu-Ka1 and Ka2 radiation with an average wavelength of $\lambda = 1.5418 \text{ \AA}$ (D2 phaser, Bruker). The polymer-based samples may cause a significant misalignment in the XRD measurements owing to sample warping and elasticity; therefore, the fillers were carefully molded to maintain a flat surface, and crystalline Si powder was sprinkled onto the samples to correct the misalignment-induced 2θ shift (See ref. [30] for the technical details). In addition, the 2θ , based on wavelength $\lambda = 1.5418 \text{ \AA}$, was converted to the commonly used 2θ based on Cu-Ka1 with $\lambda = 1.5406 \text{ \AA}$. The microstructures of the Ecoflex–BN composites were investigated using the back-scattered electron mode in field emission scanning electron microscopy (JSM-IT800HL, JEOL) combined with energy-dispersive X-ray spectroscopy (EDS).

The thermal conductivity of each filler κ_{Filler} was obtained by multiplying the thermal diffusivity α , mass density ρ , and specific heat c_p as follows: $\kappa_{\text{Filler}} = \alpha \times \rho \times c_p$ [31]. The Ecoflex–BN composites were carefully molded into 12.7 mm diameter disks for measuring α . The samples were coated with a graphite spray (Graphit-33, Kontakt Chemie), and α was measured by laser flash analysis (LFA 467, Netzsch), during which the temperature was increased from 300 to 400 K in 20 K increments. This corresponded to the temperature range required for the active cooling experiment described in **Section 3 (Fig. 3)**. The densities of the composites were obtained using Archimedes' method (XS105, Mettler Toledo) at room temperature (295 K), and the specific heat was measured using differential scanning

calorimetry (Q200, TA instruments) while increasing the temperature from 300 to 400 K at a heating rate of 5 K/min.

The K_{Device} values of the F-TECs were evaluated via the steady-state method [31] using a customized liquid nitrogen cryostat system (Lake Shore Cryotronics, Inc.) according to $Q = K_{\text{Device}}\Delta T$ with Q being the heat flow rate and ΔT the temperature difference across the sample (**Fig. 3a**). Two T-type thermocouples for measuring $\Delta T = T_{\text{Heat}} - T_{\text{Sink}}$ were attached to the heat spreaders at the heat-loaded side (T_{Heat}) and at the heat sink (T_{Sink}) using silver epoxy (H20E, EPO-TEK). Here, Cu and constantan wires with a diameter of 25.4 μm (SPCP- and SPCI-001-50, Omega Engineering, Inc.) were used to form thin thermocouples to minimize heat losses along the wires. Subsequently, a 1000 Ω resistive heater (SGD-7/1000-LY13, Omega Engineering, Inc.) was connected using wires with a diameter of 76.2 μm . The heat flow rate Q was determined according to $Q = I_{\text{H}}V_{\text{H}}$ with I_{H} being the supplied electric current to the heater and V_{H} the corresponding voltage drop measured by a multimeter (2000, Keithley). The heater was attached to a BeO heat spreader with high thermal conductivity ($\kappa \sim 300 \text{ W}/(\text{m K})$ [32]) and subsequently placed on the top of TEC with thermal grease in between (H grease, Apiezon) to improve the thermal contact resistance and to homogenize the temperature distribution and heat flux at the hot side of the TEC. The thermocouple voltages for measuring T_{Heat} and T_{Sink} were monitored using a nanovoltmeter (2182A, Keithley) while applying $I_{\text{H}} = 3 \text{ mA}$ to the heater using a current source (6221, Keithley). The T_{Sink} was maintained at 300 K during the measurement. All measurements were conducted in the cryostat under a high vacuum of $\sim 10^{-4} \text{ Pa}$ and under the cover of a gold-plated radiation shield to minimize heat losses by convection and radiation, respectively. These heat losses were consequently not considered for the determination of K_{Device} .

3. Experimental results and discussion

3.1 Structural analysis of filler

The 2θ -corrected XRD patterns revealed a clear BN peak, which increased with increasing the mass fraction of BN, while BN0 (Ecoflex) exhibited a broad peak that indicated an amorphous structure of polymer (**Fig. 2d**). The BSE image in **Fig. 2e** shows that the lighter elements B and N appear to be dark compared with the bright area of Ecoflex matrix with the heavier element Si. The composition of the dark dots was verified to be B and N using the corresponding EDS maps (**Fig. 2f**). These results indicated the absence of a chemical reaction between BN and Ecoflex.

3.2 Controlling the thermal properties of filler and F -TEC

First, we investigated the effect of the concentration of embedded BN on the thermal properties of the Ecoflex–BN composites. **Figure 2g** shows that κ_{Filler} at 300 K is 0.156, 0.469, and 0.710 W/m K for BN0, BN23, and BN33, respectively. The maximum concentration of BN33 provides an overall increase of thermal conductivity of 355% compared to pure Ecoflex (BN0). The κ_{Filler} of BN33 is comparable to that of a polymer composite consisting of Ecoflex and 76 wt% liquid metal EGaIn (0.7 W/m K) [33]. The results are summarized within **Table 1** while details including α , ρ , c_p , and the temperature dependence of κ_{Filler} can be found in **Fig. S1** in **Supplementary Information**.

Next, we quantified the effect of the composite fillers on K_{Device} . As shown in **Fig. 2h**, K_{Device} monotonically increases with increasing thermal conductivity of the filler κ_{Filler} . BN33

exhibited the highest K_{Device} of 11.67 mW/K at 300 K, which was 127 % higher than that of Bare ($K_{\text{TE}} = 5.15$ mW/K). The measured K_{Device} was in good agreement with its calculated counterpart, which was determined for simplicity under the assumption of a parallel thermal connection [31] between the TE legs and the filler (i.e., $K_{\text{Device}} = K_{\text{TE}} + K_{\text{Filler}}$). K_{TE} was kept constant for all calculations while K_{Filler} was estimated using κ_{Filler} and the TE fill factor ($\sim 24\%$), which is the fractional area coverage of the TE legs per unit substrate area [34]. Furthermore, evaluating results for the sample Bare (without filler) at 300 K with $K_{\text{Device}} = K_{\text{TE}} = 5.15$ mW/K revealed a thermal conductivity $\kappa_{\text{TE}} = 1.91$ W/m K for the TE legs, which is in good accordance with typical values reported for Bi-Te-based TE materials [35–37]. The deviation between the measured and calculated values may be attributed to the uncontrolled pores in the filler in the TEC or the thermal contact resistance between the filler and TEC, which were neglected for the K_{Device} calculation. The temperature-dependent K_{Device} data are presented in **Fig. S2 (Supplementary Information)** for the range 300–400 K. The standard uncertainty of thermocouple voltage measurements equals typically less than 0.2% and has a maximum of 0.38%. Although thermocouples and heater wires have small diameters of 25.4 and 76.2 μm , respectively, heat loss through the wires was inevitable and resulted in an overestimation of the applied Q'' and K_{Device} . The total thermal conductance of the attached wires was calculated and lies in the range 0.140–0.186 mW/K, which equals a few percentages of K_{Device} whose maximum value is 3.6% for Bare.

To verify whether the electrical properties of the TE legs are affected by the embedding of the fillers and to measure the cooling performance at a high temperature (~ 430 K) (**Section 3**), we measured the electrical resistance R_{TEC} of the samples using the four-probe [38] and Delta mode measurements [39] (6221/2182A, Keithley) at 300 K in the cryostat. The standard

measurement uncertainty was determined to be less than 0.001%, which is estimated from the standard deviation of twenty-five repeated measurements. **Figure 2g** displays the R_{TEC} values of the TEC and F-TEC samples, which are in the range 744–777 m Ω with a standard deviation of 11.7 m Ω . As the R_{TEC} values of three different Bare samples were in the range 761–791 m Ω with a similar standard deviation of 12.4 m Ω (**Fig. S3, Supplementary Information**), we consider that the deviation of the R_{TEC} values for F-TEC samples was neither caused nor influenced by the degradation of the TE legs during fabrication and measurement but just a results of typical manufacturing tolerances. These results indicated that the thermal conductance of the device can be separately optimized at the device level without significantly affecting the thermoelectric properties by embedding the interior of the TEC by thermal fillers. In the following subsections we discuss the improvement in the cooling performances of the F-TECs owing to the K_{Device} enhanced by the fillers.

3.3 Evaluation of the heat-dissipation capabilities of the F-TECs

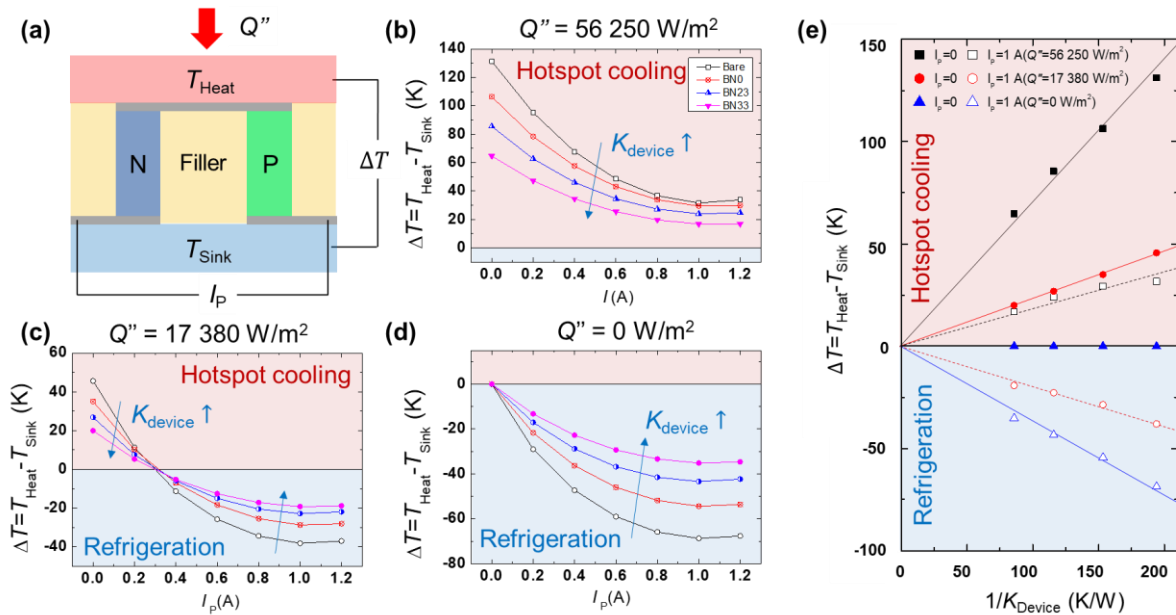


Fig. 3. (a) Experimental configuration for evaluating cooling performance. Temperature difference between the heat-loaded side and the heat sink under the heat flux Q'' of (b) 56 250, (c) 17 380, and (d) 0 W/m². (e) Temperature difference as a function of device thermal resistance ($1/K_{\text{Device}}$). All data were acquired at $T_{\text{Sink}} = 300$ K.

The cooling performance of the F-TECs was evaluated by monitoring the temperature difference ΔT between the heat-loaded T_{Heat} and sink T_{Sink} sides ($\Delta T = T_{\text{Heat}} - T_{\text{Sink}}$) at $T_{\text{Sink}} = 300$ K (**Fig. 3**). ΔT was measured using the thermocouples in the cryostat as discussed in **Section 2**. The measurements have been conducted under various heat fluxes that corresponded to different operation modes such as hotspot cooling ($Q'' = 56\,250$ W/m² in **Fig. 3b**), refrigeration ($Q'' = 0$ W/m² in **Fig. 3d**), and at intermediate conditions ($Q'' = 17\,380$ W/m² in **Fig. 3c**) (Refer to **Fig. 1** and **Introduction** for details). An electrical current I_P was applied to the TECs by a current source (E3546A, Agilent) in the range 0–1.2 A in 0.2 A increments. The TECs exhibited the best performance at $I_P = 1$ A; a further increase in I_P caused the cooling performance to degrade owing to Joule heating.

First, we discuss the cooling performance at $Q'' = 56\,250$ W/m² that corresponds to the hotspot cooling situation for all I_P values. As shown in **Fig. 3b**, ΔT decreases in F-TECs compared to the classical TEC owing to the increased Fourier heat conduction due to the filler. When no current was applied ($I_P = 0$ A), at which the Peltier effect was absent and Fourier conduction dominated (**Fig. S4, Supplementary Information**), ΔT decreased from 131.24 K for Bare (ΔT_{Bare}) to 64.616 K for BN33 (ΔT_{BN33}). When $I_P = 1$ A was applied, at which the Peltier effect delivered highest cooling performance and dominated (**Fig. S4, Supplementary Information**), ΔT decreased from $\Delta T_{\text{Bare}} = 31.599$ K to $\Delta T_{\text{BN33}} = 16.764$ K. Degree of improved cooling performance by the filler, defined as $\eta = \Delta T_{\text{Bare}} - \Delta T_{\text{BN33}}$,

decreased while increase in I_P decreased the contribution of Fourier conduction compared to that of the Peltier effect (Refer to **Fig. S4** for the quantitative analysis, **Supplementary Information**). In this case, the filler-induced high K_{Device} improved the cooling performance by providing an additional heat path that contributed to Fourier conduction. Next, we investigated the cooling performance under $Q'' = 0 \text{ W/m}^2$ that corresponded to refrigeration, in which the direction of the Fourier heat flow was opposite to that of the Peltier heat flow. In contrast to hotspot cooling, $|\Delta T_{\text{BN33}}|$ was smaller than $|\Delta T_{\text{Bare}}|$ for all I_P values. In this case, the filler-induced high K_{Device} degraded the cooling performance by increasing Fourier conduction, which compensated for the Peltier effect. Lastly, we demonstrated the case of $Q'' = 17\,380 \text{ W/m}^2$, which involved hotspot cooling and refrigeration (**Fig. 3c**). The F-TECs performed better than the Bare sample in hotspot cooling (where $I_P < \sim 0.3 \text{ A}$), whereas the performances of the F-TECs were worse than that of the Bare sample in refrigeration (where $I_P > \sim 0.3 \text{ A}$). This coincided with the results obtained from the previous cases. To further clarify that the improved and degraded cooling performances for the hotspot cooling and refrigeration situations, respectively, originated from the filler-induced K_{Device} engineering, we plotted ΔT at $I_P = 0$ and 1 A as a function of the device thermal resistance $1/K_{\text{Device}}$ (**Fig. 3e**). The fitted lines in **Fig. 3e** indicate that ΔT increases linearly with the increase in $1/K_{\text{Device}}$ for hotspot cooling and refrigeration. The minimum coefficient of determination (adjusted R^2) of the fitted curves was 0.99713 for $I_P = 0 \text{ A}$ and 0.98739 $I_P = 1 \text{ A}$, which implied that the increased K_{Device} directly improved and degraded the cooling performances of the TECs in hotspot cooling and refrigeration situations, respectively, without substantially affecting the thermoelectric properties of the TE legs. The deviation in ΔT from the fitted lines, which

was especially relatively large for $I_P = 1$ A, possibly occurred from the slight differences in R_{TEC} values (**Fig 2i**) and/or the effect of radiative heat transfer at a high T_{Heat} .

Even though most of the applications that require substantial heat dissipation are hotspot cooling situations [4,40], in which the proposed F-TECs can be advantageous, one may expect to develop a universal F-TEC that can be applied to all cooling situations, including hotspot cooling, refrigeration, and their intermediate. To achieve this, we may introduce a filler that has a large K_{Filler} for $T_{Heat} > T_{Sink}$ (for hotspot cooling) and small K_{Filler} for $T_{Heat} < T_{Sink}$ (for refrigeration). In particular, thermal diode materials and structures [41–43] can be suitable fillers as their thermal conductivities can be modulated using a magnetic field [30,44], electric field [45,46], and thermal energy [47].

3.4 COP and effective thermal conductance of the F-TECs in hotspot cooling

The COP, defined as the heat dissipation from the heat-loaded side to heat sink Q_{Heat} per input electrical power P_{Sup} , has been used to evaluate the cooling efficiency of TECs

$$COP = \frac{Q_{Heat}}{P_{Sup}} \quad (1)$$

The heat dissipation from the heat-loaded side can be determined by a net energy balance (**Fig. 1a and 1b**):

$$Q_{Heat} = S_{TEC} T_{Heat} I_P + K_{Device} (T_{Heat} - T_{Sink}) - \frac{1}{2} I_P^2 R_{TEC} \quad (2)$$

From the first law of thermodynamics, input electrical power can be defined as $P_{\text{Sup}} = Q_{\text{Heat}} - Q_{\text{Sink}}$ the difference between the heat dissipations from the heat-loaded side and to the heat sink Q_{Sink} , and expressed as

$$P_{\text{Sup}} = I_p^2 R_{\text{TEC}} - S_{\text{TEC}} I_p (T_{\text{Heat}} - T_{\text{Sink}}) \quad (3)$$

Combining **equations (1)-(3)**, the COP can be expressed as

$$\text{COP} = \frac{S_{\text{TEC}} T_{\text{Heat}} I_p + K_{\text{Device}} (T_{\text{Heat}} - T_{\text{sink}}) - \frac{1}{2} I_p^2 R_{\text{TEC}}}{I_p^2 R_{\text{TEC}} - S_{\text{TEC}} I_p (T_{\text{Heat}} - T_{\text{sink}})} \quad (4)$$

As mentioned in **Introduction**, COP is a good indicator for evaluation of the cooling efficiency in refrigeration. However, in hotspot cooling, the COP cannot be applied as in the refrigeration case, since the portion of Fourier heat flux $K_{\text{Device}}(T_{\text{Heat}} - T_{\text{Sink}})$ leads to an infinite COP at $I_p = S(T_{\text{Heat}} - T_{\text{Sink}}) / R_{\text{TEC}}$, according to **equation (4)**. Accordingly, we present the cooling efficiency of the TECs in hotspot cooling by means of effective thermal conductance $K_{\text{TEC}}^{\text{Eff}}$, proposed by Adams *et al.* [17]. The $K_{\text{TEC}}^{\text{Eff}}$ captures the maximum heat dissipation of TECs $Q_{\text{Heat}}^{\text{Max}}$ at an optimal current I_p^{Opt} . By taking derivative of **equation (2)**, the optimal current and maximum heat dissipation can be determined as

$$I_p^{\text{Opt}} = S_{\text{TEC}} T_{\text{Heat}} / R_{\text{TEC}} \quad (5)$$

$$Q_{\text{Heat}}^{\text{Max}} = (K_{\text{Device}} + \frac{(S_{\text{TEC}} T_{\text{Heat}})^2}{2 R_{\text{TEC}} \Delta T}) \Delta T \quad (6)$$

In analogous to the Fourier's law $Q = K \Delta T$, the effective thermal conductance of TEC is defined in **equation (6)** as follows [17]

$$K_{\text{TEC}}^{\text{Eff}} = K_{\text{Device}} + \frac{(S_{\text{TEC}} T_{\text{Heat}})^2}{2R_{\text{TEC}} \Delta T} \quad (7)$$

, which includes the passive thermal conductance by the Fourier conduction and active thermal conductance by the Peltier effect, respectively. In proposed F-TEC, the filler provides additional contribution to K_{TEC} , which increases $K_{\text{TEC}}^{\text{Eff}}$. By applying parameter values quantified in **Section 3.2**, the $K_{\text{TEC}}^{\text{Eff}}$ of the (F-)TEC samples were determined and compared at $\Delta T = 100$ K (**Fig. 4**). $K_{\text{TEC}}^{\text{Eff}}$ monotonically increases as K_{Device} increases owing to additional contribution of the filler. Accordingly, the BN33 sample exhibits a 42.5% larger $K_{\text{TEC}}^{\text{Eff}}$ (21.86 mW/K) compared to the Bare sample ($K_{\text{TEC}}^{\text{Eff}} = 15.34$ mW/K), which corresponds to the previous observation in hotspot cooling (**Section 3.3** and **Fig. 3b**).

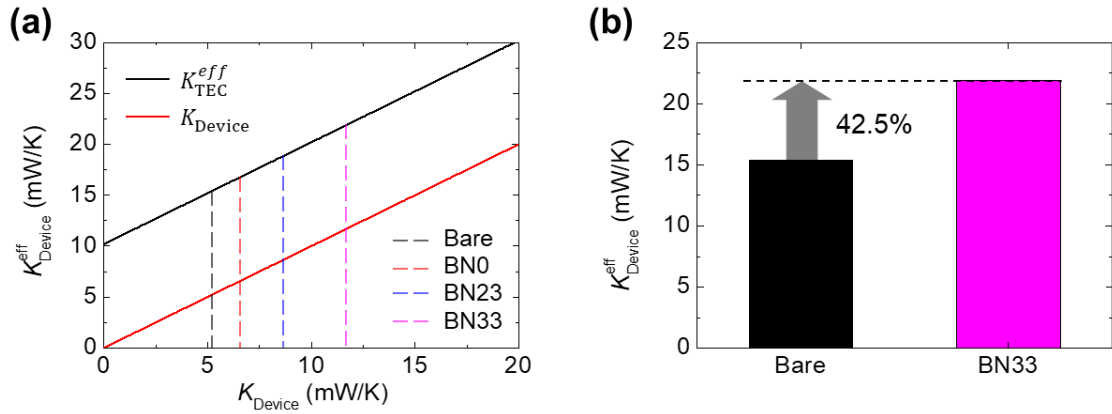


Fig. 4. (a) Effective thermal conductance of the samples $K_{\text{TEC}}^{\text{Eff}}$ calculated based on $T_{\text{Heat}} = 400$ K and $T_{\text{Sink}} = 300$ K and passive thermal conductance K_{Device} . The vertical dashes lines correspond to K_{Device} of the experimental samples. (b) Comparison of $K_{\text{TEC}}^{\text{Eff}}$ between Bare and BN33.

3.5 Visualization of the temperature gradient using an IR camera

Considering the TE fill factor of ~ 0.24 of the Bare sample, the TE legs experienced a large heat flux exceeding $234\,000\text{ W/m}^2$ and longitudinal temperature gradient ∇T exceeding 65.6 K/mm under the heat load condition $Q'' = 56\,250\text{ W/m}^2$ (hotspot cooling situation in **Section 3.2**). Such large ∇T applied to the TE legs turns our attention to the thermomechanical stability of the TE legs, which can directly affect the lifespan of the TECs. We began the thermomechanical analysis by visualizing the temperature profile of the TE legs under hotspot cooling using an IR camera (Image IR 7300, InfraTec). The technical details of IR imaging can be found in the authors' previous paper [48,49]. In TECs, the ∇T is forming from individual contributions of a linear temperature profile due to Fourier heat conduction and Peltier heat flow, and a parabolic temperature profile due to current-induced volumetric Joule heating [17,31]. To investigate the ∇T generated by both these effects, the temperature profile of TE legs was recorded by applying $Q'' = 46\,500\text{ W/m}^2$ to the heater, attached to the heat-loaded side of TECs, and with $I_p = 0$ and 1 A while the temperature of Cu block was kept as $\sim 300\text{ K}$ using a water circulator (**Fig. 5**). The Q'' of $46\,500\text{ W/m}^2$ was the maximum value that could be applied for the IR experiment. Although it is smaller than that in **Section 3.3**, but still corresponds to hotspot cooling case. Note that the Peltier, Fourier, and Joule heating effects determined the longitudinal temperature profile, even though the TEC lost heat by natural air convection during the IR experiment.

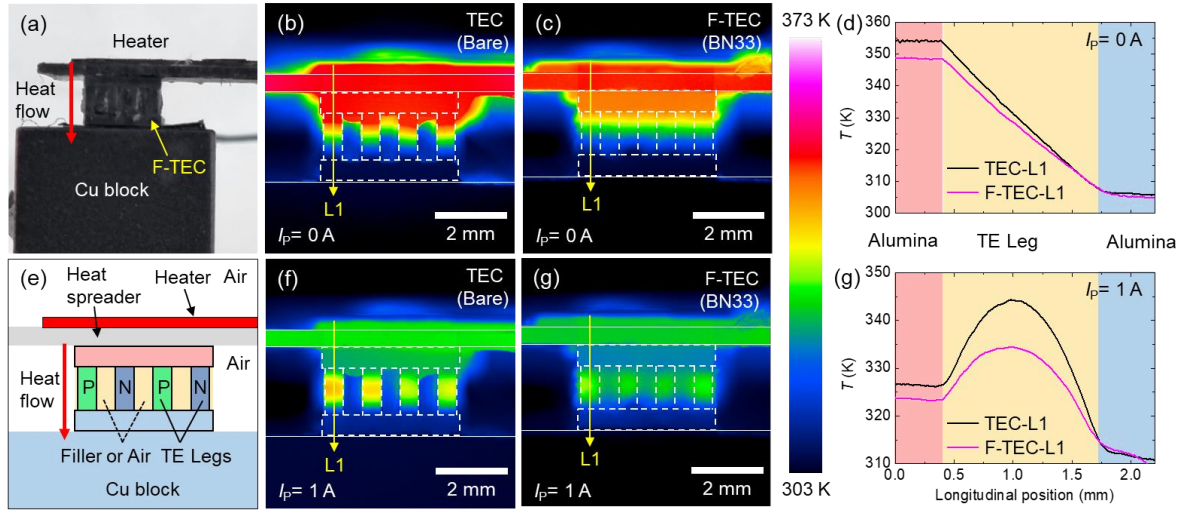


Fig. 5. (a) Photograph and (e) Schematic illustration of experimental configurations for IR visualization. A heat flux of $46\,500\text{ W/m}^2$ was applied by the heater while temperature of Cu block was maintained to be $\sim 300\text{ K}$ using a water circulator. Temperature contour of TEC (Bare) for (b) $I_p = 0\text{ A}$ and (f) $I_p = 1\text{ A}$. Temperature contour of F-TEC (BN33) for (c) $I_p = 0\text{ A}$ and (g) $I_p = 1\text{ A}$. The white lines are guides to the eye, indicating the boundaries of TE legs, filler, heat spreaders, and Cu block. Temperature profiles of the TEC and F-TEC for (d) $I_p = 0\text{ A}$ and (g) $I_p = 1\text{ A}$ following the line (L1) through a TE leg sandwiched between alumina heat spreaders.

The IR-tests have been conducted with the TEC (Bare) and F-TEC (BN33) samples, which were covered by a graphite spray for uniform emissivity of their side faces (**Fig. 5a**). The IR signals of each pixel were recorded and subsequently converted to the corresponding temperatures using pre-calibrated data. For $I_p = 0\text{ A}$ only Fourier heat is flowing through the configurations yielding almost uniform ∇T along the TE legs of the TEC and F-TEC (**Fig. 5b** and **c**). The corresponding temperature profiles along the longitudinal line (L1) from the heat-loaded side to the heat sink were almost linear in the TE legs (**Fig. 5d**), thereby indicating that the longitudinal heat load and not air convection dominated the longitudinal temperature profile. The TE leg in the F-TEC exhibited smaller temperature profile and ∇T than those in the TEC owing to the heat dissipation by filler. As a result, the heat-loaded side in F-TEC exhibited

lower temperature ($T_{\text{Heat}} \sim 348 \text{ K}$) compared to TEC ($T_{\text{Heat}} \sim 354 \text{ K}$), although the F-TEC experienced a larger heat load than the TEC because of larger thermal conductance. Based on simple calculation for the heat losses by air convection with natural heat transfer coefficient of 5-20 W/m² K, the F-TEC experienced 12-39% higher heat load than TEC from the heater, which led to a conservative estimation of ∇T inside the TECs. Next, $I_p = 1 \text{ A}$ was applied to both TECs with the same experimental conditions. The heat generation inside the TE legs due to Joule heating is equal for the TEC and F-TEC unless different module properties. The Joule heat is partwise dissipated from the legs to the gaps in between. In case of the F-TEC this dissipation is much higher owing to the higher thermal conductivity of the filler compared to air in TEC. Therefore, the TE legs in BN33 exhibited a smaller ∇T and maximum temperature of the legs ($T_{\text{Legs}}^{\text{Max}} = 334.4 \text{ K}$) in comparison with those of Bare ($T_{\text{Legs}}^{\text{Max}} = 344.3 \text{ K}$) (**Fig. 5g**). The temperature profiles in **Fig. 5g** confirm the parabolic temperature profile due to Joule heating with a maximum at the middle of the legs. The temperature difference between the legs in the TECs (**Figs. 5f and g**) possibly resulted from the differences in (1) TE properties of n- and p-type materials such as σ , S , and κ or (2) the heat transfer condition at the surfaces facing to air or filler. These results clearly implied that the embedded filler in the F-TECs reduced the ∇T along the TE legs.

4. Numerical analysis for the evaluation of thermal stress

Next, we focus on the reduction of the large ∇T -induced thermal stress in the TE legs that may lead to functional failure. Numerical simulations were conducted to evaluate the thermal stress inside F-TEC using COMSOL Multiphysics 5.4, which can couple thermomechanical and thermoelectric analyses. The maximum values of the von Mises stress, which indicates the level of thermal stress, and the maximum temperature of the TE legs $T_{\text{Legs}}^{\text{Max}}$ were evaluated as a function of the electrical current applied to the TE legs I_P and the thermal conductivity κ_{Filler} of the filler under a constant heat flux condition. The detailed methodologies of the numerical simulations and the corresponding results and discussion are provided in the following subsection.

4.1 Model geometry and materials used for simulation

In the F-TEC, different TE legs are exposed to different thermal and mechanical boundary conditions owing to their individual positions inside the TEC and consequently different embedding situations. This may result in non-uniform temperatures and thermal stress distributions. For instance, the TE legs at the corner of the F-TEC may experience higher stress than those at the center with the filler surrounding all outer leg planes. To reflect this phenomenon, a three-dimensional F-TEC was modeled, which comprised a series of seven n- and p-type Bi_2Te_3 legs that were electrically connected by Cu electrodes, Al_2O_3 heat spreaders, and surrounded by an Ecoflex–BN composite filler (**Fig. 6**). Solder was not considered in the simulation to avoid unnecessary calculation. The size of each element is displayed in **Fig. S5** and **Table S1 (Supplementary Information)**. The thermoelectric and

thermomechanical properties of the materials used in the numerical simulations are listed in **Tables S2 and S3 (Supplementary Information)**, respectively, which includes results from preceding studies [28,50–56] on material characterization. The n- and p-type Bi_2Te_3 were considered to possess the same material properties but with different signs of S (**Table S2, Supplementary Information**). The experimentally obtained properties of BN33 in **Section 2** were used as the thermal properties of the filler. The thermomechanical properties of the filler were obtained from available literature about Ecoflex 00-30 (**Table S3, Supplementary Information**) [28,54–56].

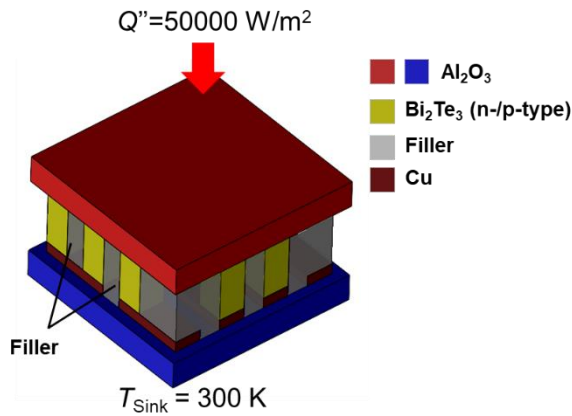


Fig. 6 Geometrical model of the F-TEC and boundary conditions used in the numerical simulation. The heat load Q'' of 50 000 W/m^2 and constant temperature $T_{\text{Sink}} = 300 \text{ K}$ were set to the ends of TEC as boundary conditions.

4.2 Physical models and boundary conditions

The numerical simulations consider all heat contributions to the energy balance for steady-state conditions [31], such as the Fourier effect ($K\Delta T$ for all materials including the filler), Joule heating (I_p -induced ohmic heating of Bi_2Te_3 and Cu), and the Peltier effect

(thermoelectric cooling owing to Bi_2Te_3). The energy balance equation yielded the temperature distribution for the bodies that cause thermal expansion-induced strain [57] and the thermal stress in the F-TEC can be described as a form of von Mises stress using the stress–strain relation [52,58]. The governing equations for thermoelectric and thermomechanical analyses can be found in previous studies [51,59]. The following assumptions were introduced to simplify the calculations without causing significant differences from realistic situations. (1) All surfaces except the heat-loaded and heat-sink sides were thermally insulating (adiabatic). (2) No electrical or thermal contact resistances were considered, thereby excluding the unimportant factors in the role of the filler on thermal stress relaxation. (3) The Al_2O_3 heat spreaders and fillers were perfect insulators and, therefore, did not influence the thermoelectric analysis. **Figure 6** shows the physical model of the F-TECs and the supposed boundary conditions. A constant heat flux ($Q'' = 50\,000\text{ W/m}^2$) was applied at the heat-loaded side, and the temperature of the heat sink was set to be constant ($T_{\text{Sink}} = 300\text{ K}$) effectively following the experimental conditions for hotspot cooling tests. An electrical current, in the range $I_p = 0\text{--}2.0\text{ A}$ was applied to the electrical circuit comprising the TE legs and Cu electrodes. The upper heat-loaded side and the bottom side of the heat sink were considered to be firmly fixed (zero displacement).

4.3 Relaxation of the thermal stress owing to the thermal filler

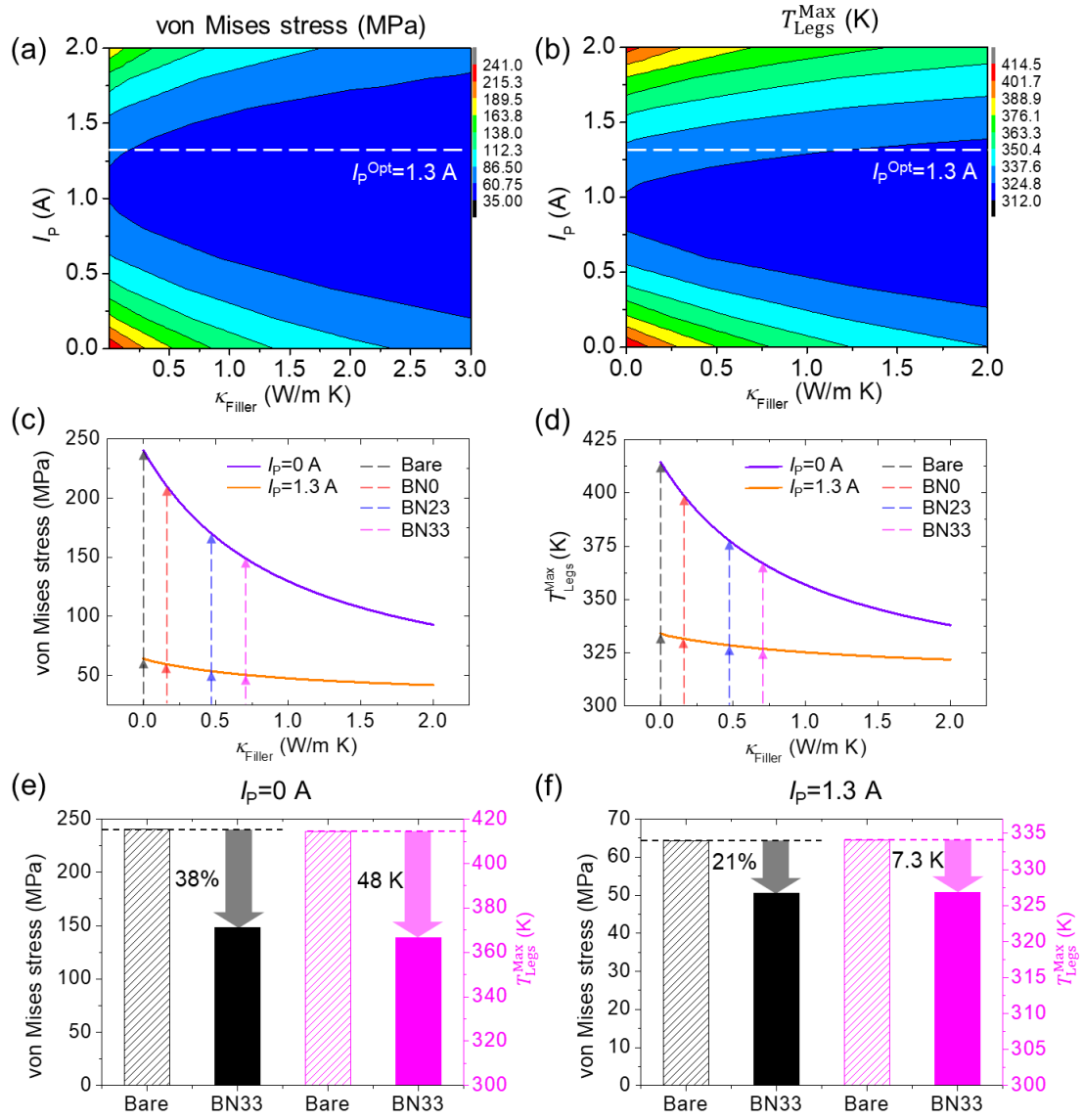


Fig. 7 Numerically calculated (a) maximum von Mises stress and (b) maximum temperature $T_{\text{Legs}}^{\text{Max}}$ of the TE legs as a function of filler thermal conductivity κ_{Filler} and electrical current I_p through a TEC under a heat load of $Q'' = 50\,000$ W/m² and at a constant sink temperature of $T_{\text{Sink}} = 300$ K. (c) Maximum von Mises stress and (d) maximum temperature $T_{\text{Legs}}^{\text{Max}}$ as a function of κ_{Filler} for $I_p = 0$ A and the optimal current $I_p^{\text{Opt}} = 1.3$ A. Comparisons of the maximum von Mises stress and $T_{\text{Legs}}^{\text{Max}}$ in Bare and BN33 for (e) $I_p = 0$ A and (f) $I_p^{\text{Opt}} = 1.3$ A.

First, the maximum von Mises stress of the TE legs was presented as a function of κ_{Filler} and I_P (**Fig. 7a**). All results in **Fig. 7** were obtained under $Q'' = 50\,000\text{ W/m}^2$, which corresponded to hotspot cooling. The von Mises stress was reduced when a suitable value of I_P decreased the heat flux-induced temperature gradient ∇T . As I_P increased further, the von Mises stress increased owing to Joule heating, which resulted in high ∇T in the TE legs, which corresponded to a high $T_{\text{Legs}}^{\text{Max}}$ in **Fig. 7b**. Next, we focused on the von Mises stress and $T_{\text{Legs}}^{\text{Max}}$ as a function of κ_{Filler} when both the TECs were not actively operated ($I_P = 0$) and for an operation close to the optimum with maximum cooling performance ($I_P = 1.3\text{ A}$). Here, the $I_P = 1.3\text{ A}$ was the optimal current of the F-TEC I_P^{Opt} in the simulation (**Fig. S6, Supplementary Information**), which was higher than that from the experiment ($I_P = 1\text{ A}$) mainly owing to the neglect of electrical contact resistances in the simulation. Note that I_P^{Opt} is inversely proportional to the device resistance R_{TEC} , according to **equation (5)**. **Figures 7c and d** reveal the monotonic decrease of the von Mises stress as the increase in κ_{Filler} causes $T_{\text{Legs}}^{\text{Max}}$ to decrease (**Figs. 7e and f**). The F-TEC with $\kappa_{\text{Filler}} = 0.71\text{ W/(m K)}$, which represented the BN33 sample, exhibited 38% and 21% lower von Mises stress at $I_P = 0$ and 1.3 A , respectively, compared to a conventional TEC without filler, which represented the Bare sample ($\kappa_{\text{Filler}} = 0$). The release of the von Mises stress was attributed to the filler-induced decreases in $T_{\text{Legs}}^{\text{Max}}$ by 48 K at $I_P = 0\text{ A}$ and 7.4 K at $I_P = 1.3\text{ A}$. Considering that the maximum stresses of Bi-Te-based TE materials are in the range 100–250 MPa [59,60], the filler can substantially improve the reliability of the TECs. Moreover, the filler can extend the maximum heat flux range, over which TECs can be applied (**Fig. S7, Supplementary Information**).

5. Conclusion

We proposed a novel TEC device concept for hotspot cooling applications by embedding the interior of a commercial TEC with a thermally conductive and electrically insulating filler material. The filler improves the integral thermal device conductance K_{Device} of the F-TEC, which is an important parameter for hotspot cooling, by opening a new heat conduction path next to the conduction through the TE legs. In this way, the proposed F-TEC can overcome the engineering challenges at the material level that are caused by the interdependence among the TE parameters, which impedes the individual adjustment of thermal and thermoelectric transport properties. Consequently, the relatively easy application of a thermally conductive filler material provides an additional degree of freedom to the system design. Embedding a filler into a TEC enables the independent control of Fourier heat conduction without any influence on the Peltier-driven heat transport. The F-TECs were experimentally demonstrated using various Ecoflex–BN composite fillers, with which K_{Device} was systematically controlled at 300 K in the range of 5.15–11.67 mW/K (127% change). The cooling performances of the F-TECs improved owing to the fillers; the hotspot temperature under the heat flux $Q'' = 56\,250\text{ W/m}^2$ decreased from 431.2 K (Bare) to 364.6 K (BN33) at $I_P = 0$ and 331.6 K to 316.8 K at $I_P = 1\text{ A}$. The effective thermal conductance ($K_{\text{Device}}^{\text{eff}}$) was used to evaluate the heat-dissipation efficiency of TECs. The BN33 sample exhibited 42.5% higher $K_{\text{Device}}^{\text{eff}}$ than Bare at $\Delta T = 100\text{ K}$. Moreover, IR imaging and numerical simulations coupling thermoelectric and thermomechanical analyses revealed that the filler can release the large- ∇T -induced thermal stress on the TE legs to a high extent. We envision that the proposed F-TEC concept can assist the development of an effective TEC device that can be widely used for hotspot cooling applications, such as in microprocessors, fuel cells and batteries.

Additionally, we presented considerations to further improve the proposed F-TEC according to the following aspects. First, using high- κ filler materials can largely improve the cooling efficiency of an F-TEC for hotspot cooling, although we employed polymer–ceramic composites with relatively low κ in this study to exclude other technological challenges, such as matching the thermal expansion coefficients and suppressing electrical interferences between the TE legs and filler material. As the heat dissipation in an F-TEC is primarily unidirectional from the heat-loaded side to the heat sink (i.e. longitudinal), thermally anisotropic materials, such as transition metal dichalcogenides [61,62], hexagonal BN [63], and graphene [64], may be useful. Furthermore, the fillers are not limited to solid materials; highly thermally conductive liquid metals [65,66] could be considered fillers if outer surfaces of legs and bridges were electrically insulated by application of suitable layers. Second, the thermal expansion coefficient of the filler should be matched with those of the TE materials to reduce the thermomechanical stress in the TE legs[12,14,67], although this did not cause a significant problem in this study when using an elastic polymer composite filler. Third, the fill factor can be used as a design parameter to control the fractions of the Peltier and Fourier heat transfer, which mainly dissipate heat through the TE legs and filler, respectively. Fourth, although an F-TEC possess better cooling performance than a classical TEC, it requires more material and thus leads to increase in the device cost. Analyzing the thermoelectric operating cost (in units of $\$/\text{kWh}_{\text{th}}$) may help to optimize the trade-off relation between the cooling performance and device cost [68]. The fill factor, length of TE legs, and materials used for the TE legs and filler can be used as optimization parameters. Lastly, introducing thermal diodes may facilitate the development of a universal TEC that could be applicable for hotspot cooling, refrigeration, and under intermediate conditions (Refer to the last paragraph of **Section 3** for details). In addition to filler engineering, we emphasize the development of hotspot cooling TE

materials with high κ and large PF [16–19,69].

CRedit authorship contribution statement

Sang J. Park: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing - Original Draft, Writing - Review & Editing.

Junyoung Park: Data curation, Investigation, Methodology, Validation, Writing - Review &

Editing. **Ki Mun Bang:** Investigation, Methodology, Validation, Visualization, Writing -

Review & Editing. **Jung Min Lee:** Data curation, Visualization. **Woosung Park:** Resources,

Writing - Review & Editing. **Pawel Ziolkowski:** Validation, Writing - Review & Editing.

Hyungyu Jin: Funding acquisition, Project administration, Resources, Supervision, Writing - Review & Editing.

Declaration of competing interest

The authors declare no competing financial interest.

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Appendix A. Supplementary Information

Supplementary Information associated with this article can be found, in the online version, at [DOI].

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