ABSTRACT
Modern CPUs generate considerable wasted heat due to increased power dissipation from high-performance computation. Lots of research effort has extensively focused on using thermoelectric generators (TEGs) to harvest CPU waste heat to increase overall system energy efficiency. To harvest waste heat using TEGs requires a significant temperature differential between the processor as a heat source and the heat spreader/heat sink, as well as a high heat flow. However, the heat-to-electricity conversion efficiency is typically limited to 15 to 20 percent, due to large heat conductivity, low Seebeck coefficient, and low figure of merit of TEGs. In addition, TEGs on a CPU could significantly increase CPU junction temperature compared to the baseline CPU temperature due to its high thermal resistance. Contrary to using TEGs to harvest waste heat from a fixed, spatial temperature differential, this paper presents an approach to harvest CPU waste heat using pyroelectric (PE) materials from the time-varying, temporal temperature differential that is common in current processors. PE materials can generate electricity when subjected to a temporal temperature gradient. The operation of PE materials is distinctly different from TEGs and they have the following advantages. First, the theoretical efficiency is up to 50% using thin films. Second, the overall optimization of PE material is easier than thermoelectric material, since the conversion ratio, the ratio of net harvested energy divided by the heat taken from the hot reservoir, of PE material is independent of the material properties, whereas that of TEG is highly dependent on material properties. Although PE material is also a long-researched energy harvesting material, it is less explored by researchers compared to TEG in the application domain of processor waste heat management. In this paper, we review current PE materials in terms of pyroelectric coefficient and thermal conductivity, and also investigate the harvested power generation from CPU waste heat in a modern computing system.

INTRODUCTION
In recent decades, energy conversion using low (<100 °C) grade waste heat has attracted attention to develop efficient and reliable electronic systems and sensors. A number of recent articles have presented TEGs-based energy harvesting approaches to recover processor waste heat [1-8]. In particular, a CPU in computing devices such as desktop, smartphone, and tablet PC generates a considerable amount of waste heat when performing computations [9-12], as shown by the infrared image in Fig. 1. TEGs have advantages, e.g., environmentally friendly, scalability (commercially available in any size) and are commonly used to recycle wasted heat energy. Solbrekken et al. [1] proposed an alternate configuration, i.e., shunt attach configuration as a viable solution for using TEG in the thermal management of portable electronic equipment. Emil et al. [2] presented a new theoretical model for thermoelectric module with experimental validation. Zhou et al. [3] developed a model to analyze non-uniform temperature distribution on the die surface to estimate TEG efficiency and proposed an arrangement for using TEGs on an Intel Pentium III processor.
Their results showed that the amount of power that can be harvested is in the order of a few milliwatts.

Figure 1. Infrared (IR) image for an active computing system (Intel Core i5 3470 Processor) running 400.pernbench benchmark.

Gould et al. [4] presented a method for TEGs-based waste heat harvesting from outside of the heat sink in a desktop personal computer (PC). Wu [5] experimentally measured the amount of processor waste heat that can be harvested with commercially-available TEGs and showed that hundreds of milliwatts of power can be recovered from modern high-performance processors. However, a naive TEG placement hinders the critical heat dissipation path and could introduce a significant temperature overhead. Lee et al. [6] proposed a new design that uses the harvested processor waste heat based on TEGs to cool processor hot spots using TECs and evaluated the cooling potential with a model-based approach. Choday et al. [7] proposed on-chip energy harvesting, indicating that 5-20mW was generated by using 1.75 x 1.75mm² and 8μm thick nanoscale superlattice TEG arrays with a perfectly matched load resistance. Sullivan et al. [8] presented the 3 x 3 mm² and 5-12 μm thick embedded TEGs inside an electronic package, showing that 72.91mW was harvested from the waste heat generated at CPU hot spots provided a matched load resistance.

TEGs also have disadvantages, e.g., low energy conversion efficiency, constant heat source required, slow technology progression, as well as relatively high cost. Therefore, in addition to the high temperature overhead, the applicability of TEG-based waste heat harvesting methods also hinges on the material efficiency [1-8]. Therefore, recently pyroelectric, piezoelectric, and ferroelectric materials have been increasingly studied to overcome TEG’s problems. Among them, pyroelectricity harvests thermal energy by exploiting the time varying temperature fluctuations to generate electrical current in a short amount of time when the electrons in the crystalline material leak from one end to the other [13]. Even though marginalization leads to low efficiency of the PE materials, there is a lot of potential to increase the efficiency of the applications. For these reasons, pyroelectric material has continuously gained attention from researchers [14-22]. Bowen et al. [14] provided a recent review of pyroelectrics. Hunter et al. [15] proposed the micro-electro-mechanical (MEMS)-based cantilever to enhance the efficiency from small gadgets to power plants. Since the tip of the hot cantilever contacts with a cold surface, it rapidly loses its heat. Then, the cantilever moves back and make contact with the hot surface due to bimaterial effect when the temperature of hot and cold sides maintained. Sebald et al. [16] examined pyroelectric cycles in detail to calculate energy density. Sebald et al. [17] also compared pyroelectric energy results with thermoelectric results. Hsiao et al. [18] proposed the idea to enhance the temperature variation rate of a thicker PZT sheet with etching. Fang et al. [19] suggested harvesting nanoscale thermal radiation using pyroelectric materials by combining pyroelectric energy conversion and nanoscale thermal radiation. Krishnan et al. [20] presented a practical solution for generating thermal fluctuations for pyroelectric-based solar and wind energy harvesting. Goudarzi et al. [21] presented a hybrid harvesting method from both piezoelectric and pyroelectric effects at the same time using PZT and PMN-0.25PT ceramics. Yang et al. [22,23] presented using ZnO nanowires to convert wasted energy into electricity for operating nanodevices and wireless sensors.

In this paper, low efficiency and performance degradation of computing systems due to excessive waste heat is improved by applying PE material between a CPU and a heat sink. We first present the power generation results using PE material for scientific applications running on a desktop PC processor. This offers a comparison point for the previous thermoelectric-based designs and the PE material-based design investigated in detail here. Taking a step further, we explore the applicability of PE materials in low power smartphone processors that typically run in an energy-constrained environment.

We find that the unique computation and utilization patterns on smartphones are particularly suitable for PE material-based energy harvesting. Smartphones today do not require continuous computation compared to desktop PCs because smartphones are typically used for short-term tasks, such as texting, web browsing, and photo browsing [24,25]. Such usage patterns correspond to bursts of computations performed on the smartphone processors, that leads to quick temperature changes over time. Thus, pyroelectricity offers an interesting energy harvesting opportunity with a potentially outstanding power generation performance in the smartphone application domain, taking advantage of fast temperature fluctuations. In this paper, we offer quantitative power generation evaluations using PE materials in the smartphone application domain.

**NOMENCLATURE**

C Thermal capacitance (J K⁻¹)
THERMAL ANALYSIS

In order to theoretically explore PE material energy harvesting, a two node thermal network is required, as shown in Fig. 2 [6]. First, we use the two-node thermal network analysis to understand the temperature implication brought by the PE-based CPU processor in the desktop PC setting. This takes into account the thermal capacitance of the processor package and the heat sink. Also, the thermal resistance of all components are also determined. The thermal capacitance and thermal resistance are given as:

\[ C = c_p m \]

where \( C \) is the thermal capacitance, \( c_p \) the specific heat, and \( m \) the mass.

The rate of heat input is determined with the performance counter, which is sampled every 100 milliseconds (ms) to generate a thermal trace when an application is running on the CPU core. We calculate the rate of heat input \( \dot{Q}_{CPU} \) based on the CPU temperature obtained with the performance counter at the ambient temperature of 30 °C and use the total thermal resistance of all layers using [6]:

\[ \dot{Q}_{CPU} = \frac{T_{CPU} - T_a}{R_{tot}} \]

Greek symbols

\[ \Delta T \] Temperature difference of TEG (K)
\[ \Delta t \] Time difference (s)
\[ \varepsilon_{33} \] Permittivity (F/m)

Subscripts

a Ambient
max Maximum
tot Total
HS Heat sink
C Case
TP Thermal Paste
Cond Conduction heat transfer
Conv Convective heat transfer
sub Substrate
PE Pyroelectric
fc Forced convection

Fig. 2. Schematic diagram of two-node thermal network for thermal analysis based on a desktop PC.

The thermal resistance \( R \) is given by:

\[ R_{\text{cond}} = \frac{L}{kA} \]
\[ R_{\text{conv}} = \frac{1}{hA} \]  

where \( R_{\text{cond}} \) is the conduction thermal resistance, \( R_{\text{conv}} \) the convection thermal resistance, \( k \) the thermal conductivity, \( h \) the heat transfer coefficient, \( L \) the layer thickness, and \( A \) the cross-sectional area. Also, the convective heat transfer coefficient for forced convection with a fan (sickle flow 120, 2000 RPM, 69.69 CFM) can be obtained from [26]:

\[ \text{Nu}_f = \frac{2h_{fc}s}{k_{air}} \]

where \( \text{Nu} \) is the Nusselt number, \( s \) the distance between two fins, and \( k \) the thermal conductivity:

\[ \text{Nu}_f = 7.55 + \frac{0.024X^{-1.14}}{1 + 0.0358X^{-0.64}Pr^{0.17}} \]

where \( X = \frac{x}{2s + \text{Re}Pr} \), \( \text{Re} \) the Reynolds number, \( Pr \) the Prandtl number, and \( x \) the length of heat sink. With the dimensionless numbers, i.e., \( \text{Re}, \text{Pr} \), the Nusselt number in Eq. (4) can be obtained. Then, the obtained Nusselt number can be used for calculating the convective heat transfer coefficient in Eq. (3).
where \( T_{\text{CPU}} \) is the temperature of the CPU, \( T_a \) the ambient temperature, and \( R_{\text{tot}} \) the total thermal resistance including all layers in electronic packaging, and is equal to \( R_{\text{tot}} = R_C + R_{TP} + R_{PE} + R_{TP} + R_{HS} + R_{\text{CONV}} \).

Finally, the resistances \( R_1 \) and \( R_2 \) in Fig. 2 are calculated:

\[
R_1 = R_C + R_{TP} + R_{PE} + R_{TP} \quad R_2 = R_{HS} + R_{\text{CONV}}
\]  

(6)

Then, the heat flows for two nodes in Fig. 2 are defined as:

\[
\dot{Q}_{\text{CPU}} - \dot{Q}_{\text{SUB}} = C_{\text{CPU}} \frac{dT_{\text{CPU}}}{dt} + \frac{T_{\text{CPU}} - T_{\text{HS}}}{R_1} \]

(7)

\[
0 = C_{\text{HS}} \frac{dT_{\text{HS}}}{dt} + \frac{T_{\text{HS}} - T_a}{R_2}
\]

(8)

\( \dot{Q}_{\text{SUB}} \) (8% of \( \dot{Q}_{\text{CPU}} \)) is the downward heat transfer from the CPU to the substrate. It is calculated from the CPU and substrate properties. Taking the derivatives and using homogeneous and particular solutions \([6, 27, 28, 29]\) yields the temperature of the CPU as:

\[
T_{\text{CPU}} = a_1 \exp \left( -\frac{1}{R_1 C_{\text{CPU}}} \right) + a_2 \exp \left( -\frac{1}{R_2 C_{\text{HS}}} \right) + T_a + R_1 \left( \dot{Q}_{\text{CPU}} - \dot{Q}_{\text{SUB}} \right)
\]

(9)

The coefficients \( (a_1 \text{ and } a_2) \) are obtained by initial conditions, such as 30°C for \( T_{\text{CPU}} \) at the initial time, which is the same as the constant ambient temperature (30°C) and 0°C/s as the derivative of \( T_{\text{CPU}} \) at the initial time [6].

### HARVESTING WASTE HEAT THROUGH PYROELECTRIC CYCLE

#### Pyroelectric materials

The pyroelectric effect is the flow of charges due to the time varying temperature fluctuation of pyroelectric material [13-22]. It offers a way to convert waste heat into electricity due to heating or cooling a pyroelectric material [13]. Based on previous studies [13, 15, 22], very small temperature changes (mK) lead to electricity generation. Therefore, its use in infrared (IR) detection for imaging and motion has gained significant attention [13]. However, only a few experimental studies have been performed to develop a pyroelectric energy conversion model. In this paper, we review PE materials with pyroelectric and thermal properties in Table 1, and propose employing PE materials for harvesting processor waste heat in computing devices.

#### The Pyroelectric cycle for harvesting waste heat

Various thermal cycles based on PE materials can be used for energy harvesting, such as the Carnot cycle, Synchronized electric charge extraction (SECE), Synchronized switch damping on inductor (SSDI) cycle, Olsen cycle, Brayton cycle, and Resistive cycle [13, 14, 16]. Among them, the resistive cycle is chosen in this work since it is a simple approach to connect the PE material to an external resistive electrical load for energy harvesting [13, 14, 16]. Harvested power could be obtained by applying resistive loading with a sinusoidal temperature variation [13, 14, 16]:

\[
P_{\text{PE}} = I^2 R_e = \frac{\pi V(p\Delta T)^2}{4 \Delta t \varepsilon_{33} \theta}
\]

(10)

where \( I \) is the current, \( R_e \) the electrical resistance, \( V \) the volume of the PE, \( p \) the pyroelectric coefficient, \( \Delta T \) the temperature change of the pyroelectric material, which is obtained by thermal resistance, the rate of heat input, and temperature of PE, \( \Delta t \) the time during which the temperature change occurs, and \( \varepsilon_{33} \theta \) is the permittivity. In addition, this optimal resistive load depends on frequency and material permittivity.

#### Harvesting waste heat of the CPU in a desktop PC

In order to harvest waste heat of a CPU efficiently in a desktop PC, both the pyroelectric coefficient and thermal conductivity should be considered when a PE material is selected. Table 1 shows the review of a wide range of pyroelectric materials with pyroelectric and thermal properties.

![Figure 3. Architecture – Lidded electronic packaging with pyroelectric material, and thermal network](image-url)
Table 1. Comparison of pyroelectric materials with pyroelectric and thermal properties (1 Hz) [11,12,14]

<table>
<thead>
<tr>
<th>Materials</th>
<th>p (μCm²K⁻¹)</th>
<th>ε₀₃₃ (ε₀)</th>
<th>V (cm³)</th>
<th>C (x10⁶, Jm⁻³K⁻¹)</th>
<th>k (Wm⁻¹K⁻¹)</th>
<th>P_max (mW)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PZN-PT and PMN-PT single crystal</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>111 PMN-0.25PT</td>
<td>1790</td>
<td>2100</td>
<td>22.5</td>
<td>2.5</td>
<td>2.5</td>
<td>14.97</td>
</tr>
<tr>
<td>110 PMN-0.25PT</td>
<td>1187</td>
<td>2500</td>
<td>22.5</td>
<td>2.5</td>
<td>2.5</td>
<td>2.53</td>
</tr>
<tr>
<td>001 PMN-0.25PT</td>
<td>603</td>
<td>3000</td>
<td>22.5</td>
<td>2.5</td>
<td>2.5</td>
<td>0.54</td>
</tr>
<tr>
<td>001 PMN-0.33PT</td>
<td>568</td>
<td>5820</td>
<td>22.5</td>
<td>2.5</td>
<td>2.5</td>
<td>0.25</td>
</tr>
<tr>
<td>011 PMN-0.33PT</td>
<td>883</td>
<td>2940</td>
<td>22.5</td>
<td>2.5</td>
<td>2.5</td>
<td>1.19</td>
</tr>
<tr>
<td>111 PMN-0.33PT</td>
<td>979</td>
<td>650</td>
<td>22.5</td>
<td>2.5</td>
<td>2.5</td>
<td>6.62</td>
</tr>
<tr>
<td>001 PMN-0.28PT</td>
<td>550</td>
<td>5750</td>
<td>22.5</td>
<td>2.5</td>
<td>2.5</td>
<td>0.24</td>
</tr>
<tr>
<td>011 PMN-0.28PT</td>
<td>326</td>
<td>2680</td>
<td>22.5</td>
<td>2.5</td>
<td>2.5</td>
<td>0.18</td>
</tr>
<tr>
<td>111 PMN-0.28PT</td>
<td>1071</td>
<td>660</td>
<td>22.5</td>
<td>2.5</td>
<td>2.5</td>
<td>7.80</td>
</tr>
<tr>
<td>001 PZN-0.08PT</td>
<td>520</td>
<td>3820</td>
<td>22.5</td>
<td>2.5</td>
<td>2.5</td>
<td>0.32</td>
</tr>
<tr>
<td>011 PZN-0.08PT</td>
<td>744</td>
<td>1280</td>
<td>22.5</td>
<td>2.5</td>
<td>2.5</td>
<td>1.94</td>
</tr>
<tr>
<td>111 PZN-0.08PT</td>
<td>800</td>
<td>950</td>
<td>22.5</td>
<td>2.5</td>
<td>2.5</td>
<td>3.03</td>
</tr>
<tr>
<td><strong>Bulk ceramics</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PZT</td>
<td>533</td>
<td>1116</td>
<td>22.5</td>
<td>2.5</td>
<td>0.8</td>
<td>1.14</td>
</tr>
<tr>
<td>Barium titanate (BaTiO3)</td>
<td>200</td>
<td>1200</td>
<td>22.5</td>
<td>2.5</td>
<td>3</td>
<td>0.15</td>
</tr>
<tr>
<td>Strontium barium niobate</td>
<td>550</td>
<td>400</td>
<td>22.5</td>
<td>2.3</td>
<td>0.6</td>
<td>3.40</td>
</tr>
<tr>
<td>PMN-0.25PT ceramic</td>
<td>746</td>
<td>2100</td>
<td>22.5</td>
<td>2.5</td>
<td>-</td>
<td>1.19</td>
</tr>
<tr>
<td>Lithium niobate (LiNbO3)</td>
<td>83</td>
<td>28.7</td>
<td>22.5</td>
<td>2.32</td>
<td>1.1</td>
<td>1.08</td>
</tr>
<tr>
<td>(BaSrCa)O3</td>
<td>4000</td>
<td>16000</td>
<td>22.5</td>
<td>2.5</td>
<td>-</td>
<td>4.49</td>
</tr>
<tr>
<td>PLZT 0.5/53/47</td>
<td>360</td>
<td>854</td>
<td>22.5</td>
<td>2.5</td>
<td>-</td>
<td>0.68</td>
</tr>
<tr>
<td>PLZT 8/53/47</td>
<td>97</td>
<td>238</td>
<td>22.5</td>
<td>2.5</td>
<td>-</td>
<td>0.18</td>
</tr>
<tr>
<td>PLZT 14/53/47</td>
<td>19</td>
<td>296</td>
<td>22.5</td>
<td>2.5</td>
<td>-</td>
<td>0.01</td>
</tr>
<tr>
<td><strong>Thin films</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(PZT)/PZT composite</td>
<td>180</td>
<td>1200</td>
<td>22.5</td>
<td>2.5</td>
<td>-</td>
<td>0.12</td>
</tr>
<tr>
<td>PbCaTiO3</td>
<td>220</td>
<td>253</td>
<td>22.5</td>
<td>2.5</td>
<td>-</td>
<td>0.86</td>
</tr>
<tr>
<td>PZT 700nm</td>
<td>211</td>
<td>372</td>
<td>22.5</td>
<td>2.5</td>
<td>-</td>
<td>0.54</td>
</tr>
<tr>
<td>PMZT 700nm</td>
<td>352</td>
<td>255</td>
<td>22.5</td>
<td>2.5</td>
<td>-</td>
<td>2.18</td>
</tr>
<tr>
<td><strong>Polymers and composites</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PVDF</td>
<td>33</td>
<td>9</td>
<td>22.5</td>
<td>1.8</td>
<td>-</td>
<td>0.54</td>
</tr>
<tr>
<td>PZT/P(VDF-TrFE) 50%</td>
<td>33.1</td>
<td>69.2</td>
<td>22.5</td>
<td>2</td>
<td>-</td>
<td>0.07</td>
</tr>
<tr>
<td>PZT/PVCD-HFP 50/50 vol%</td>
<td>450</td>
<td>85</td>
<td>22.5</td>
<td>2</td>
<td>-</td>
<td>10.70</td>
</tr>
<tr>
<td>PZT0.3/PU0.7 vol%</td>
<td>90</td>
<td>23</td>
<td>22.5</td>
<td>2</td>
<td>-</td>
<td>1.58</td>
</tr>
<tr>
<td><strong>Semiconductors</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zinc oxide (ZnO)</td>
<td>9.4</td>
<td>11</td>
<td>22.5</td>
<td>2.8</td>
<td>147</td>
<td>0.04</td>
</tr>
<tr>
<td>Aluminium nitride (AlN)</td>
<td>8</td>
<td>10</td>
<td>22.5</td>
<td>2.38</td>
<td>140</td>
<td>0.03</td>
</tr>
<tr>
<td>Cadmium sulphide (CdS)</td>
<td>4</td>
<td>10.3</td>
<td>22.5</td>
<td>1.82</td>
<td>40</td>
<td>0.01</td>
</tr>
<tr>
<td>Gallium nitride (GaN)</td>
<td>4.8</td>
<td>11</td>
<td>22.5</td>
<td>2.97</td>
<td>150</td>
<td>0.01</td>
</tr>
</tbody>
</table>
Given the properties in Table 1, the PMN-0.25PT material shows better pyroelectric characteristics, i.e., figure of merit (FOM), which is obtained by the pyroelectric coefficient, the volume specific heat capacity, and the permittivity [14], thus it is chosen to determine the power generation based on a CPU in the desktop PC architecture, shown in Fig. 3. For the theoretical analysis, 30 mm in width, 30 mm in length, and 3 mm in thickness of the PMN-0.25PT is used for comparison with the TEG & TEC-based design in the previous work [6]. To model a realistic computational load on the CPU, we run applications from the SPEC2006 CPU Benchmark Suite [30] that covers file compression, machine learning algorithms, optimization algorithms, etc., on the Dell Optiplex desktop machine.

In this paper, among the SPEC2006 CPU applications, we use 400.perlbench as an application example for temperature measurement validation and result analysis [6]. The calculated thermal resistances of all layers using Eq. (2) are given in Table 2. The theoretical CPU temperature based on the PMN-0.25PT is calculated based on the thermal resistance of all layers in Table 2. This theoretical method was validated with thermal trace-based experimental results in previous work [6].

### Table 2. Thermal conductivity and calculated thermal resistance of all layers in a desktop PC

<table>
<thead>
<tr>
<th>R</th>
<th>Thermal Conductivity [W m⁻¹ K⁻¹]</th>
<th>Thermal Resistance [K W⁻¹]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rₐₜ</td>
<td>30</td>
<td>0.02</td>
</tr>
<tr>
<td>Rₚₜ</td>
<td>8.7</td>
<td>0.01</td>
</tr>
<tr>
<td>Rₚₑ</td>
<td>2.5 (PMN-0.25PT)</td>
<td>0.49</td>
</tr>
<tr>
<td>Rₕₑ</td>
<td>429 (Silver electrode)</td>
<td>0.49</td>
</tr>
<tr>
<td>Rₑₑ</td>
<td>166</td>
<td>0.22</td>
</tr>
<tr>
<td>Rₑₑ</td>
<td>h=154 [W m⁻²K⁻¹]</td>
<td>0.03</td>
</tr>
</tbody>
</table>

Based on the CPU temperature changes in Fig. 4, the power generation of PMN-0.25PT is obtained as shown in Fig. 5. The maximum power generation is 305 mW. This maximum power generation typically occurs when an application starts and finishes execution. As the application starts its execution on the idle processor, the temperature of the processor quickly ramps up from the ambient temperature to around 70 °C (in the example 400.perlbench application) in a short time duration. During the application execution, the temperature of the processor stays at a steady state.

![Figure 4. The calculated CPU temperature based on 3mm in thickness PMN-0.25PT material on a desktop PC](image)

Likewise, when the application finishes its execution, the processor temperature decreases to the ambient temperature quickly that again leads to a larger degree of power generation. However, it is difficult to gain a continuous time varying temperature difference in a desktop PC, thus the average power generation over the entire application execution is small compared to the results from TEG power generation. Therefore, another, potentially more suitable, application, which tends to exhibit continuous temperature changes, e.g., in the smartphone setting, is explored in this paper. The theoretical model is modified to take into account the smartphone-specific components and is presented in the next section.

### Harvesting waste heat of the CPU in a smartphone

Typically, a desktop PC is used for continuous computation, whereas a smartphone is used for bursty, short-term usages, such as texting, web browsing, and photo browsing [22,23]. Therefore, the smart phone-based environment as shown in Fig. 6 could be more suitable for harvesting waste heat using a PE material, which requires fast temperature changes.
Therefore, the power generation using PMN-0.25PT on Odroid XU3 development platform [29] is studied. Note, the development platform used in our study houses a mobile processor that is used commonly in modern smartphones, e.g., Samsung Galaxy S4 smartphones. To model a realistic smartphone computational load on the smartphone processor, we run web browsing activities from BBench/MobileBench, which is an automatic web page rendering tool to evaluate browser performance [22,30]. Users can evaluate the characteristics of different web pages and web technologies. Based on the thermal resistance in Table 3, the comparison shown in Fig 7 between the theoretical and the measured CPU temperature is examined and the model accuracy between theoretical and experimental result indicates ± 2%. Therefore, we could believe our approach in terms of high accuracy.

Table 3. Thermal conductivity and calculated thermal resistance of all layers in a smartphone

<table>
<thead>
<tr>
<th></th>
<th>Thermal Conductivity [Wm⁻¹K⁻¹]</th>
<th>Thermal Resistance [KW⁻¹]</th>
</tr>
</thead>
<tbody>
<tr>
<td>R_C</td>
<td>30</td>
<td>0.08</td>
</tr>
<tr>
<td>R_TP</td>
<td>8.7</td>
<td>0.05</td>
</tr>
<tr>
<td>R_PE</td>
<td>2.5 (PMN-0.25PT) 429 (Silver electrode)</td>
<td>1.7</td>
</tr>
<tr>
<td>R_HS</td>
<td>166</td>
<td>0.04</td>
</tr>
<tr>
<td>R_CONV</td>
<td>h=215 [W m⁻²K⁻¹]</td>
<td>0.03</td>
</tr>
</tbody>
</table>

In order to validate the temperature model, the CPU temperature without PMN-0.25PT material is obtained with a fan on and fan off to represent the default baseline setup as shown in Fig. 7. With careful modification of the convective heat transfer coefficient using Eqs (3) and (4), we obtain the reliable theoretical results [10,31]. Based on the method, the CPU temperature without PMN-0.25PT and with 1mm and 3mm thick PMN-0.25PT is calculated in a smartphone in Fig. 8, and the corresponding power generation of the two different PMN-0.25PT configurations is also calculated in Fig. 9.

Figure 6. (a) Schematic of smartphone architecture based on Odroid XU3 with pyroelectric material, and (b) a typical Odroid XU3 [29]

Figure 7. (a) The measured CPU temperature (Fan on) with the calculated CPU temperature, (b) The measured CPU temperature (Fan off) with the calculated CPU temperature based on page delay: 0 and scroll size: 500 (1.2GHz processor)

Fig. 8 indicates CPU hot spot temperature difference by PE thickness changes due to the thermal resistance difference. Since CPU temperature is measured every 0.25 sec using a performance counter, power generation of PMN-0.25PT is calculated by 4 Hz as shown in Fig. 9. Even though the power generation of 3mm thick PMN-0.25PT is greater than that of 1mm thick due to the thermal capacitance, 3mm thick PMN-0.25PT significantly increases CPU temperature. Therefore, further thickness optimization is required to employ PMN-0.25PT for harvesting waste heat from CPU. At this point, it is difficult to conclude that the power generation in a smartphone is more suitable than in a desktop PC based on the results, since the maximum power generation (29mW) and the efficiency (~2.9%) of 3mm thick PMN-0.25PT material are still low.
In addition, the power generation of PE in a desktop is obtained by an intense computation workload and with a large chip size, compared to a smartphone; therefore, the power generation of PE is more pronounced in the desktop PC setting than in the smartphone.

**DISCUSSION**

In this paper, we propose to harvest CPU waste heat using PE materials. As such, we perform a theoretical analysis for modeling CPU temperature in the presence and absence of PE materials and use the temperature model to quantify the degree of PE material-based energy harvesting in processors.

The use of PE materials is a promising solution for processor waste heat harvesting. That is, it could offer one route toward obtaining more power from waste heat in many applications. In the desktop PC setting, the maximum power generation of PE is higher than its TEG alternative; however, the averaged power generation of PE is lower. The CPU temperature (70 °C) with PE is higher than the baseline CPU temperature (55 °C) without PE due to the additional thermal resistance introduced by the PE. Thus a short term usage-based smartphone or a tablet, which is usually less restricted to CPU temperature [21], could be a more plausible application than desktop PCs.

Also, in the resistive cycle-based system, Cuadras et al. [32] achieved $10^{-7}$ A (pyroelectric current) and $10^{-5}$ C (charges) based on 60K temperature amplitude over 100s. In Sebald et al.’s work [14], the maximum efficiency based on the resistive cycle could be up to 40%, which is significantly higher than the TEG material efficiency. As a result, the fast rate of exchange in the temperature across the PE material and the increased temperature amplitude is the key to the energy conversion efficiency and high electrical power generation. Therefore, further work should be focused on enhancing both properties.

In addition, PMN-0.25PT in pyroelectric materials could be a promising candidate for harvesting waste heat in computing devices based on the results. Therefore, PEs and TECs-based model, similar to [10], could be employed to replace the TEGs in the TEGs and TECs model for the energy harvesting and hot spot cooling design.

**CONCLUSIONS**

In this paper, we examine PE materials for harvesting waste heat in computing devices. With a two-node thermal network, we prove that it is accurately tracking the hot spot temperature of CPU. Also, we review PE materials with thermal properties to determine which PE material is suitable for harvesting waste heat in both a desktop PC and a smartphone. Based on the results, PMN-0.25PT is chosen and investigated and its power generations using the resistive cycle in a desktop PC and in a smartphone is calculated. Based on the computation intensity and the temporal workload...
characteristics, the waste heat harvesting using PE materials on low-power mobile processors could be a more promising application that recovers more power from processor waste heat compared to TEGs in modern computing devices.

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REFERENCES


