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Thermal Model for Harvesting Waste Heat From Microprocessor using Shunt Configuration

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ABSTRACT

Microprocessor energy consumption has been growing especially in datacenter environment. However, there is a lack of investigation on using the thermal heat generated by the microprocessor as an alternative energy source. This study focused on the thermal profiling of the microprocessor integrated with an Microelectromechanical Systems (MEMS) Thermoelectric Generator (TEG) using shunt configuration. A 2D thermal model is developed to estimate the heat transfer of a complex geometry system. MATLAB simulation based on the thermal model is presented with two types of heat spreader material, copper and pyrolytic graphite. The advantages and their shortfalls with respect to the microprocessor heat dissipation and the effectiveness to generate a temperature gradient at the MEMS TEG are discussed.

Key words: Microprocessor, thermal modeling, MEMS thermoelectric

INTRODUCTION

According to Institute of Energy Economics, Japan through APEC, Malaysia energy consumption has been growing from 5,263 MW in year 2000 8,283 MW in year 2009 (Anonymous, 2006). In August 2009, Malaysia government has introduced National Green Technology Policy to promote efficient use of energy (The Institute of Energy Economics Japan, 2011). Various alternative energy solution has been proposed such as harvesting energy through mechanical vibration (piezoelectric) (Bhuyan *et al.*, 2013) and solar and wind (An and Singh, 2011). One of the energy sources that lack investigation is using microprocessor thermal heat as an alternate form of energy source. The thermal energy generated by the microprocessor after it is converted to electrical energy can be channeled to other applications, hence, improving the overall energy efficiency. This study focuses on the thermal modeling of MEMS based Thermoelectric Generator (TEG) integrated into a microprocessor in a shunt configuration.

Microprocessors are present in various applications from general purpose computing to datacenter. In ISSCC (2011) Trend Report, microprocessor density trend has grown to a record of 3.1 billion transistors per die (ISSCC, 2011). The increase of the density will increase the power consumption and heat dissipation which is a byproduct of microprocessor system. This trend will impact the datacenter environment leading to higher power consumption and cooling cost which is highlighted by Brill (2007). For example, IBM z196 mainframe produces maximum

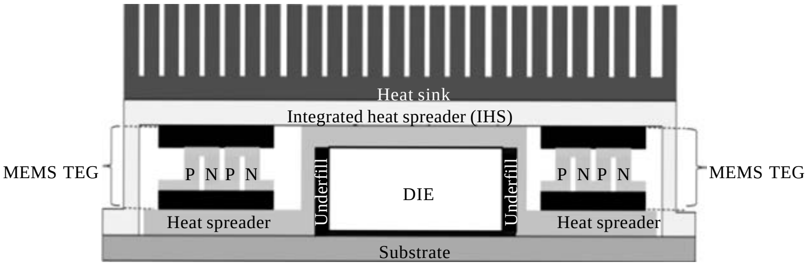

Fig. 1: MEMS TEG integrated in the processor

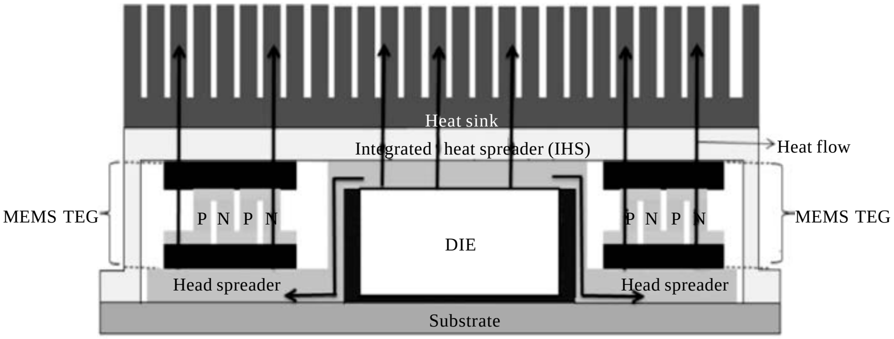

Fig. 2: Heat flow of the microprocessor to the heat sink and the integrated MEMS TEG

heat dissipation of 93.16 kBtu/h (Bill *et al*., 2011). Based on IBM z196 mainframe, the heat dissipated from the datacenter is worth exploiting.

In this study, we have performed thermal modeling and analysis of the profile of the microprocessor integrated using MEMS thermoelectric. This study will focus on the thermal profile using shunt configuration. The concept of using TEG was first patented and described by Suski (1995) who proposed to harvest the waste heat where the thermoelectric is connected thermally in serial with the microprocessor. However, Solbrekken *et al*. (2004) showed the concept is ineffective and an alternative configuration was proposed. The alternative configuration was to place the TEG thermally in parallel with the microprocessor. However, additional heat sink and convective heat loss during the heat transfer process reduces the amount of heat that is received by the thermoelectric. In this study, MEM's TEG was placed inside the microprocessor with a heat spreader connected to the thermoelectric while microprocessor lid act as a heat sink as shown in Fig. 1 and 2.

This research studies and analyzes the heat transfer profile from the heat source (microprocessor's die) to the MEM's thermoelectric. An analytical model is developed to estimate the temperature of the entire system including the temperature at the TEG.

MODELING

Previous study presented in Solbrekken has tried to analyze the shunt configuration temperature profile in a one dimension. However, the model does not take into account multidimensional effects during heat transfer. This will lead to an inaccurate thermal model for complex geometry structures.

Temperature difference occurs in a system will cause heat to be transferred from a higher temperature (heat source) to the lower temperature (heat sink) until equilibrium or steady-state is reached. Heat is transferred in a solid medium through conduction. The conduction is model at its steady state using Eq. 1:

$$Q'' = k\frac{\Delta T}{\Delta x} \tag{1}$$

where, Q” is the heat flux, k is the thermal conductivity of the material, ΔT is the temperature gradient and Δx is the total length between the temperature gradient. In order to convert to a 2D conduction model, Eq. 1 is integrated to the first law of thermodynamics that is conservation of energy. The 2D conduction equation at steady state can be described by Eq. 2:

$$k\frac{T_{x-1,y} - T_{x,y}}{\Delta x}\Delta y + k\frac{T_{x,y-1} - T_{x,y}}{\Delta y}\Delta x = k\frac{T_{x,y} - T_{x+1,y}}{\Delta x}\Delta y + k\frac{T_{x,y} - T_{x,y+1}}{\Delta y}\Delta x \tag{2}$$

where, k is the thermal conductivity, T_x and T_y are the temperatures at the location x, y and Δx and Δy are the total length between the temperature gradient at x-axis and y-axis, respectively. In order to obtain rate of heat diffused into the material, the diffusivity rate is given by Eq. 3:

$$k\frac{T_{x-1,y,t} - T_{x,y,t}}{\Delta x}\Delta y + k\frac{T_{x,y-1,t} - T_{x,y,t}}{\Delta y}\Delta x = k\frac{T_{x,y,t} - T_{x+1,y,t}}{\Delta x}\Delta y + k\frac{T_{x,y,t} - T_{x,y+1,t}}{\Delta y}\Delta x + \rho c\Delta x\Delta y\left(\frac{T_{x,y,t+\Delta t} - T_{x,y,t}}{\Delta t}\right) \tag{3}$$

where, p is the density of the material, c is the heat capacity of the material and Δt is the time difference. In order to reach steady state, Eq. 3 is iterated until the temperature reaches equilibrium. Equation 3 has a feedback mechanism therefore, care must be taken to define the Δt to ensure that the system is stable at all times. Δt is constraint by Eq. 4:

$$\Delta t = \frac{1}{4}\times\alpha_{\min}\times\frac{1}{\Delta x\Delta y} \tag{4}$$

where, $\alpha_{\min}$ is the minimum heat diffusivity of the material. Based on the Eq. 1-4, it is now possible to model the heat transfer of the microprocessor integrated with the MEM’s TEG in shunt configuration.

The system is first partition into small discrete segments. The discrete segments which consist of Δx and Δy are defined based on the thinnest material used in the system. In order to simplify the simulation, Δx and Δy are made to be identical. Equation 3 is not robust to handle complex geometric structures with segments which have incomplete unit squares and multiple materials with different thermal conductivity, density and heat capacity.

In order to overcome this, a single segment is partition into 4 smaller sub-segments with individual thermal conductivity at x and y axis as well as individual density and heat capacity as shown in Fig. 3. The general equation can be represented in Eq. 5:

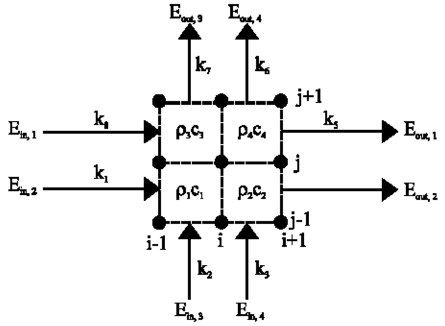

Fig. 3: Heat diagram of a single segment

$$T_{i,j,t+\Delta t} = T_{i,j,t} + \frac{2\Delta t}{(\rho_1c_1+\rho_2c_2+\rho_3c_3+\rho_4c_4)\Delta x^2}[(k_1+k_8)T_{i-1,j,t}+(k_2+k_3)T_{i,j-1,t}+(k_4+k_5)T_{i+1,j,t}+(k_6+k_7)T_{i,j+1,t}-\left(\sum_{n=1}^{8}k_n\right)T_{i,j,t}] \tag{5}$$

RESULTS AND DISCUSSION

Here, thermal profiling is carried out based on the thermal model. The simulation model is based on Fig. 2 that consists of three major components. The first component is the microprocessor which is based on Intel Pentium 4, 3.40 GHz and LGA 775 microprocessor. The second component is Micropelt MPG-D751 MEM's TEG . The last component is a heat spreader where two types of heat spreader material are used in the study. The heat spreaders that are used are copper and pyrolytic graphite.

Heat sink that is placed on the microprocessor lid is set as a boundary condition with ambient temperature of 25°C. The microprocessor die which is the heat source is set as a boundary condition with a temperature 65°C assuming a uniform heat source. Other components which are the substrate and underfill are insulators hence it is assume to be adiabatic in the model.

Mechanical parameters values that are used in the simulation to generate the geometric structure are identified in Table 1.

The model is then simulated using MATLAB program. Since the geometry is symmetrical only one of the symmetry is analyzed. The subsequent sub-section will discuss the results and finding of different heat spreader materials and its effectiveness to transfer heat to the MEMS TEG.

Shunt configuration TEG using copper heat spreader: Shunt configuration of the TEG using copper heat spreader with a thermal conductivity of 401 W m^{-1} K^{-1} (Incropera *et al.*, 2010) was analyzed. Heat is observed to spread away from the heat source as shown in Fig. 4. The temperature difference between the inner and outer Integrated Heat Spreader (IHS) gradually drops towards the edge of the IHS. The gradual drop is related to the placement and the structure of the IHS. The length from the inner to the outer IHS is constant therefore vertical thermal resistance is constant. When the heat travels across the horizontal axis, the horizontal thermal resistance will increase gradually. Since the outer layer of the IHS is connected to the heat sink, most of the heat will be redirected to the sink as it moves away from the heat source. As a result a smaller delta temperature is observed at the inner and outer IHS once it approaches the edge.

The heat spreader that is introduced between the die and the IHS increases the temperature of the die by 0.05°C. The small temperature difference indicates that the placement of a thin copper on the die and the IHS has minimum impact on the heat dissipation of the microprocessor.

Table 1: Mechanical parameters for modeling

Component	Parameter	Value (mm)
Processor	Die length	13
	Die thickness	1.1
	Underfill gap (left and right)	2
	IHS nickel plating thickness	0.1
	IHS copper thickness	0.8
	Processor length	29.2
TEG	Substrate thickness	0.525
	TEG element thickness	0.04
	Distance from underfill edge	2.4
Heat spreader	Spreader thickness	0.03

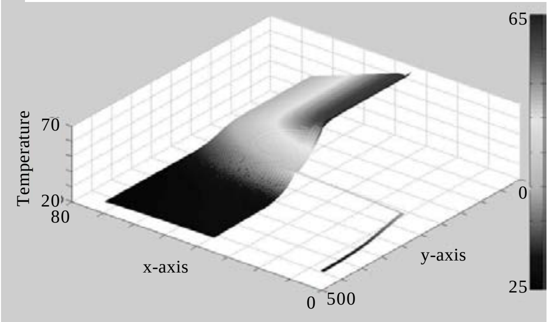

Fig. 4: Thermal profile for microprocessor and copper heat spreader

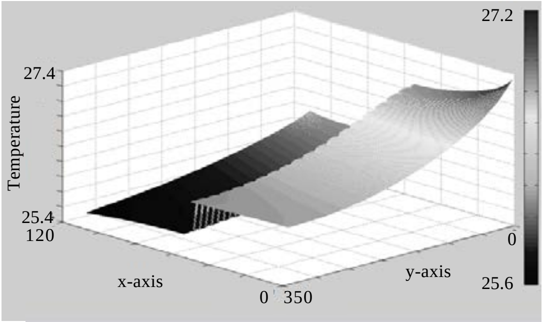

Fig. 5: Thermal profile for MEMS thermoelectric integrated with copper heat spreader

The gradient is observed at the hot and cold side of the TEG due to the thermoelectric element Bi_2Te_3 low thermal conductivity of 2.0 to 3.0 W m^{-1} K^{-1}. Non-uniform temperature is observed at the hot and cold side. Since the TEG is thermally connected to the heat sink through the IHS the increase of the thermal resistance as the heat spreader moves further away from the heat source results in a smaller heat rate as shown in Fig. 5.

The average delta temperature between the cold and hot side element is 0.5112°C. The small temperature difference indicates that very small amount of heat is available to be converted to electrical energy.

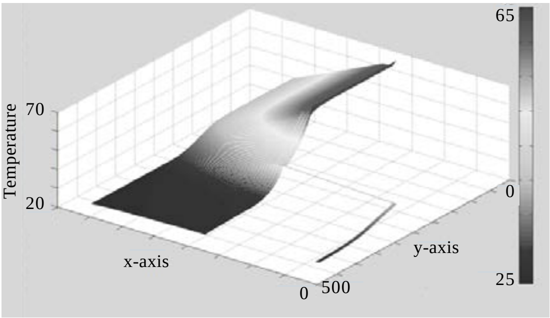

Fig. 6: Thermal profile for microprocessor and pyrolytic graphite heat spreader

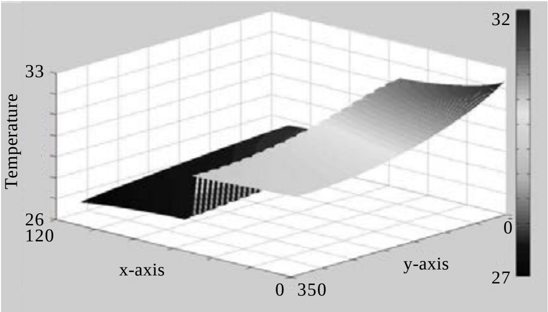

Fig. 7: Thermal profile of MEMS TEG integrated

Shunt configuration TEG using pyrolytic graphite spreader: In this scenario, the shunt configuration of the TEG is integrated with a pyrolytic graphite spreader instead of copper. The pyrolytic graphite heat spreader has a parallel surface thermal conductivity ranging from 1500 to 1700 W m^{-1} K^{-1} (Panasonic Industrial Co., 2011). However, the thermal conductivity perpendicular to the surface is poor with a value of 5.70 W m^{-1} K^{-1} (Bottner *et al.*, 2004).

The heat spreader that was placed in between the die and the IHS affects the heat dissipation of the microprocessor as shown in Fig. 6. This is shown that the heat spreader increases the average die temperature by 3.095°C. As such, the pyrolytic heat spreader thickness should be kept to the minimum assuming uniform heat source.

On the other hand, a larger gradient is observed on the TEG integrated with the pyrolytic graphite heat spreader in comparison with the copper heat spreader as shown in Fig. 7.

The average temperature delta between the cold and hot side element is 2.3057°C. The temperature difference is much larger relative to copper heat spreader. This allows a larger amount of heat from the microprocessor to be converted to electrical energy. It is too noted that the MEMS TEG does not have a uniform heat source at its surfaces.

CONCLUSION

In this study, we have presented a model to accurately estimate the thermal profile of a microprocessor integrated the TEG with shunt configuration. Using the model we have analyzed two types of heat spreader which are copper and pyrolytic graphite integrated to the TEG. Result shows that pyrolytic graphite heat spreader is more effective in transferring heat to the TEG compare to copper. Care must be taken to use pyrolytic graphite heat spreader as it reduces the thermal dissipation of the microprocessor. The TEG surface temperature is observed to be non-uniform. The non-uniformity of the temperature is required to be taken into consideration during modeling of the energy generated by the TEG.

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