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Efficiency Analysis of Thermoelectric Generators as Source of Electricity for Domestic Use

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Abstract – Silicon semiconductor was explained. Thermoelectric generators were discussed, giving details of how they work through Peltier effect. Also, thermoelectric plates have been vividly explained with respect to how temperature difference created on its sides can result to electricity being generated. Key equations relating to thermoelectric generators in terms of power, temperature and energy were expressed and numbered appropriately. Related work was considered; it is a simple experiment where thermoelectric plates are used to covert simple candle temperature to electricity. It has also been concluded that the output voltage from such generator is proportional to temperature differential across the plates.

Keywords – Silicon semiconductors, Thermoelectric plate, Peltier effect, Seebeck effect, Thermoelectric generators, Temperature gradient.

I. Introduction

Silicon (Si), a hard grey chemical element found in nature was discovered in Stockholm, 1824 by J.J Berzelius. It mainly comes from sand, quartz, agate, and other sources. After oxygen, it is actually the second most abundant element found on earth, occupying 27.8% of the earth's crust. Silicon is the most used semi-conductor applications, which obviously means that it is not a good electrical conductor.

Silicon does not exist in the free-state but in the form of Compounds, Dioxide silicon (SiO_2), Silica, Sand, Quartz, and so on. Silicon belongs to the 4th column of the periodic table of elements because it has 4 electrons on its peripheral layer [12].

Silicon based units will be the bases for this paper. As they work within systems, they generate enormous amount of heat, depending on what they do and how long they run, powering a sub-unit or processing information. This heat expelled is a byproduct of electricity the components run on, which is also a percentage of electricity supplied to them. While ingenuity in manufacturing has helped made such components simpler and energy efficient, they still giveaway some level of electricity in form of heat. To compensate for the lost power, the heat has to either be reversed back to power or more work needs to be done in manufacturing, making the silicon semiconductors even more efficient.

Fig. I: Fabricated silicon structure

1.1 How Thermoelectric Plates Work

In this system, electrons are driven by temperature differential, thereby inducing current. This current is given by:

$$I = \frac{U_0}{R_L + R_g} \quad (1.0)$$

Where,

$U_0 = \int_e^h \alpha(T)dT$ = Voltage of thermocouple; (1.1)

R_g = Electrical resistance of the TEG cell;

R_L = Load resistance;

$\alpha(T)dT = \alpha_P(T) - \alpha_n(T)$ = Seebeck coefficient;

From equations (1.0) and (1.1), the output power of thermoelectric plates can be written as:

$$P_{out} = q_h - q_c = I^2 R_L \quad (1.2)$$

And the energy conversion efficiency can be given as:

$$\eta = \frac{P}{q_h} \quad (1.3)$$

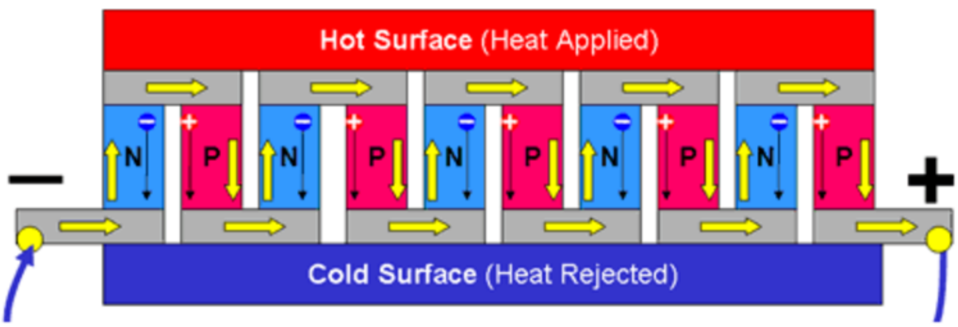

Fig. II: working principle of a thermoelectric generator

In 1821, J. T. Seebeck, born 1770 and died in 1831 discovered that dissimilar metals that are connected at two different points will develop a micro-voltage if the two junctions are held at different temperatures. The use of both N and P type materials in a single power generation device allows the optimization of the Seebeck effect as shown in figure II. As opposed to independent electron and hole flows, the current generating potentials in the pellets that form the electro-thermal plate do not oppose one another, but are series-aiding. Thus, if each pellet produces a Seebeck voltage of 50mV, then the combination of an N pellet and a P pellet would generate approximately 100mV.

The power factor of thermoelectric device is:

$$PF = \sigma S^2 \quad (1.4)$$

Its efficiency given by:

$$\eta = \frac{Energy\ provided\ to\ load}{Heat\ absorbed\ at\ hot\ junction} \quad (1.5)$$

Power limitation in thermoelectric generator is given by:

$$\eta_{max} = \left[(-TH + TC)\sqrt{1 - ZT}\right] - \frac{1}{[(TH)(\sqrt{1+ZT})] + \left(\frac{TH}{TC}\right)} \quad (1.6)$$

Where,

TH = Hot temperature and TC = Cold temperature, and:

$$ZT = \frac{\left[(S_p - S_n)^2 (T)\right]}{\left[(\rho_n k_n)^{\frac{1}{2}} + (\rho_p k_p)^{\frac{1}{2}}\right]^2} \quad (1.7)$$

Where,

ρ = Electrical resistivity

T = Average temperature

k = Thermal conductivity

[3]

1.2 Peltier Effect

Peltier effect occurs when heat is given off or absorbed by a thermoelectric device when electricity passes through it.

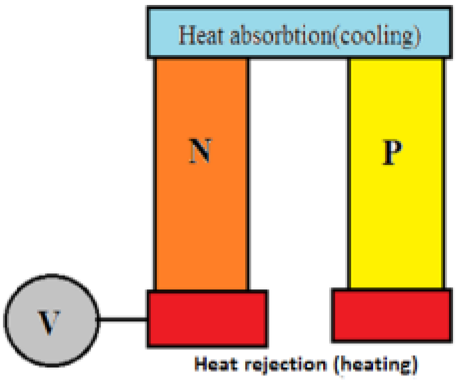

Fig. III: Peltier effect

Figure III is a demonstration of how Peltier effect is used in cooling. This is achieved when constant voltage (usually direct current) is passed through the thermoelectric plates. Temperature differential created about thermoelectric generator can result to the production of electricity [1].

II. Heat Extraction From Semiconductors

Much work has been done in the area of energy conversion in semiconductors but not recycling. In recycling, energy in form of heat given off is expected to be converted to electricity and rechanneled back into the system generating the heat. However, only conversion of certain parameters such as frequency and voltage from one level or form to another has been successfully developed and implemented over the years [11].

In conversion of power from alternating current voltage to direct current voltage or one frequency state to another, power semiconductors such as power transistors and power diodes are used to achieve that. These semiconductors have other applications such as in varying the speeds of electric motors and supplying power to grids with energy generated by solar cells, providing stable electricity to homes [2].

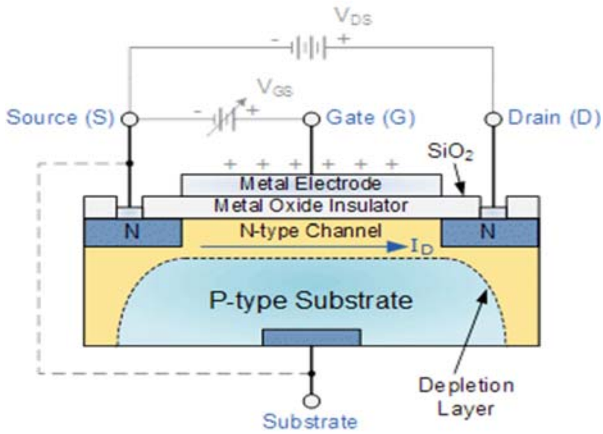

Fig. IV: Structure of the MOSFET (power transistor) [9]

As silicon-based units, particularly transistors consume power, some of it is lost in form of heat. This study proposes a solution to recycling and reusing the energy. This involves some experiments using thermal-electric plates to construct a thermoelectric generator, obtaining heat from transistor.

III. Silicon Components And Temperature Release

In silicon based electronic components, the required amount of heat needed to generate some amount of electricity can be gotten due to certain drawback in such component.

3.1 Silicon Drawbacks

To understand this challenge, the reason why silicon has become the material of choice in electronics must be understood. Silicon is relatively easy to process, it has good physical properties and possesses a stable native oxide (SiO_2), which happens to be a good insulator. Despite all these, it has several drawbacks. One of the major drawbacks include:

Rapid temperature:

Most electronic components, especially Integrated Circuits are made from Silicon. Silicon is a semiconductor material whose band gap is well adapted and suitable to the constraints imposed by applications on temperatures ranging from 0 to 100 ° C. These consistent temperatures degrade silicon component performance unlike Gallium Nitride (GaN) and Silicon Carbide (SiC). Due to lots and lots of transistors that make-up an integrated circuit, very high tendencies of rising temperatures are unavoidable. For this reason, cooling fans and heat-sinks are used to drop such damaging temperatures in silicon chips [3].

Instead of cooling silicon components to get them stable and running efficiently, the heat given off can be harvested and converted into electricity.

IV. Organization Of Work

The remaining part of the paper is organized as follows: section 5.0 explicitly describes work relating to this one, identifying the gaps this research paper attempts to fill. Section 6.0 gives details of the materials and methods applied to clearly prove that the heat given off from silicon-based components can be harnessed and converted to electricity using thermoelectric plates. The benefits and contributions of this proposed techniques to knowledge, conclusion as well as suggested work for researchers in the future are stated also.

V. Related Work

Due to the growing demand for cheap, efficient and alternative sources of energy, extensive research work was done to find ways of harnessing waste heat for conversion into electricity. Using thermoelectric generators, the above energy conversion is a possibility. These plates use solid state devices which are capable of converting thermal energy to electrical energy from a temperature gradient. In rural or remote areas, where electricity is very little or not available at all, thermoelectric generators can be used to provide power for the populace [4].

In the related work, the potential of thermoelectric generator in power generation is demonstrated using Peltier plates. Figure V shows how the entire setup was done:

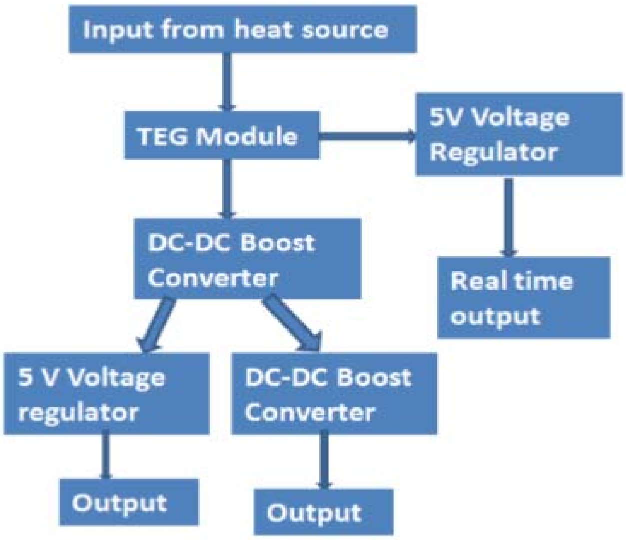

Fig.V: Thermoelectric generator block diagram for related work

From figure VI, the thermoelectric generator (TEG) is heated using two candles at a metallic extension.

Fig. VI: Experimental setup for the thermoelectric generator in related work

From the experiment in figure VI, only a maximum of 2.7 Volts is obtained. A voltage regulator is used to boost the voltage from 2.7 Volts to 5 Volts using a boost converter. The current produced is up to 300-400 mA output [4].

VI. METHODOLOGY

This methodology centers on steps followed in executing the research experiment, taking a different approach from the related work. The gap to consider here is the use of silicon-based units as sources of heat instead of candle as shown in figure VI. A variable heat emitting setup is developed using a set of silicon power transistors, implemented in a way that it will be used to simulate, at variable levels, heat given off by a system which is made up of majorly certain silicon-based units.

The block diagram for execution of the project is as shown in figure VII:

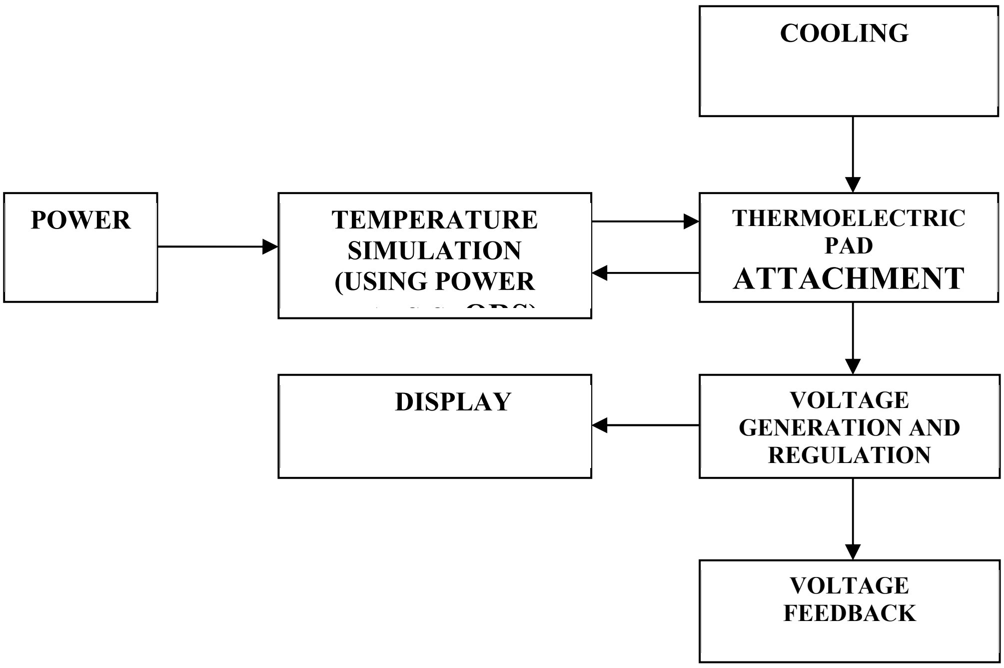

Fig. VII: Block diagram of the entire experimental setup

Details of the individual blocks

POWER: The power supply used is an Alternating type. This alternating current (AC) is converted to direct current (DC) and then supplied to the temperature simulation section, powering the silicon transistors (drivers). This power would also be made to be variable, in that the temperature rise can also be controlled from that end, going up or down as required.

TEMPERATURE SIMULATION: Here, power transistors will be used to generate the required temperature that can be varied within limits of expelled heat of a device of choice. For a laptop computer for example, generally, the safe operational temperature is between 10℃ to 35℃ [5]. To successfully carry out the experiment, the transistor setup should provide temperature within this boundary, absorbed and expelled by heat sinks and channeled to the thermoelectric heat pads, generating electricity.

THERMOELECTRIC PAD ATTACHMENT: The thermoelectric pad attachment is a point where one side of the pad gets linked with the heat surface of the heat-sink, simulating the semiconductor temperature discharge. This is made possible by the use of heat resistant glue.

COOLING: As the temperature on the side of the thermoelectric pad attached to the heat-sink rises, the other side of the pad needs to be cooled, if voltage must flow. This operation defines seebeck effect. The higher the difference between the hot and cold temperatures, the higher electricity flows from the pad, ready for use.

VOLTAGE GENERATION AND REGULATION: Once temperature differential is created on both sides of the thermoelectric pad, significant amount of voltage flows. This voltage maybe high enough to be fed back into the system generating the heat or it may not. For this reason, it will be absolutely important to develop a voltage boosting circuit to step it up if low, and as well as a regulator to allow only the required amount of voltage to flow through to the heat generating system.

Before any design or conclusions are made, it is imperative to know the power specification of the thermoelectric pad to be used for creating the thermoelectric generator (TEG). For the thermoelectric pad to be used, at a temperature difference of 140℃, the pad can generate up to $4.5W$ of electric power [6]. By the power generation specification, it shows that for every 10℃ difference in temperature, the thermoelectric pad is able to generate off load:

$\frac{140}{10} = 14$; $\frac{4.5}{14} = 0.3W$ of power.

During the experiment, this value will be used to multiply to tens of the temperature difference to obtain the total power generated.

The reference system (laptop) power consumption consideration is $19V/4.74A$, which is about $90W$ of power drain. At temperature difference of 140℃, and by the power generation and consumption specification, it clearly shows that:

$\frac{90}{4.5} = 20W$; this means that the power from the thermoelectric pad has to be boosted to at least 20 times to obtain an instantaneously complete 1% drive. Also, as a laptop consumes power, not all the power goes to the same place, some percentage of the power is exhausted as light while another in form of sound if any audio is being played. It is important to make these deductions so as to maximize the output from the thermoelectric pad during experiment. A computer monitor consumes up to 26% of the total power, [13]. By this deduction, it means only 64% out of the $90W$ total power consumption will be used as reference in basic calculation and experiments.

$$64\% \; of \; 90 = 57.6W$$

For $4.5W$ power supply and current drain of $4.74A$, the required voltage for operation on the heat emitting system will be:

$$\frac{4.5}{4.74} = 0.9V$$

But this amount of voltage is too low, hence it will have to be boosted significantly to about 21 times.

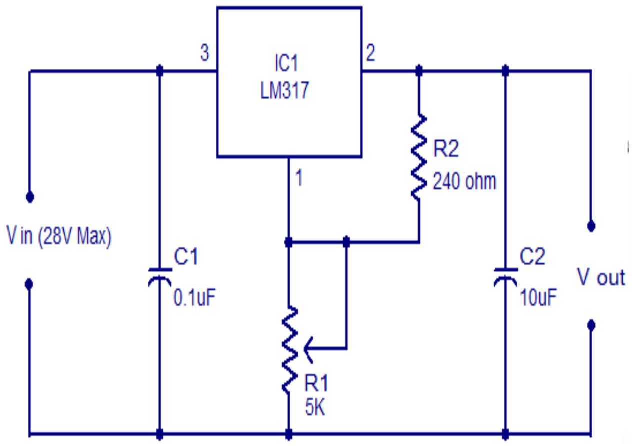

Fig. VIII: 0 to 25 volts regulator circuit [8]

VII. Electricity Computational Analysis Of Thermoelectric Plates

From Seebeck effect, if the heat source has a temperature T_1, and the temperature of the heat sink attached to the thermo-electric plates is T_0, then the temperature of the hot side and that of the cold side of the thermo-electric plates given as T_h and T_c can be written as:

$$T_1 - T_h = R_{th}, hq_h \quad (7.1)$$

$$T_c - T_0 = R_{th}, cq_c \quad (7.2)$$

Where,

R_{th} = Thermo-electric resistance

q = Heat flow;

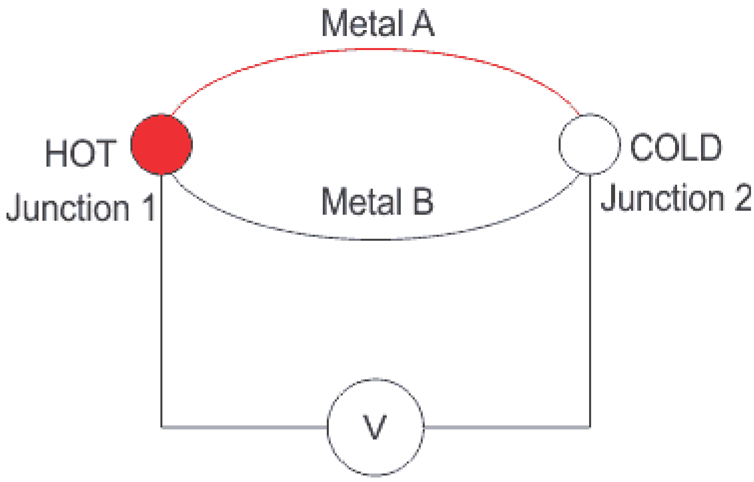

Fig. IX: T_h and T_c configuration [10]

As heat gets applied, the junction with higher temperature causes electrons in the n-type region and also holes in the p-type region to flow away from the high temperature region, producing electrical potential difference. As load is connected to V, current begins to flow through the load resistance, R_L. circuit is completed by connecting a load where V is written.

The voltage produced is given by:

$$V = \alpha\Delta T \tag{7.3}$$

Where,

$\alpha =$ Seebeck coefficient

$\Delta T =$ Temperature difference between hot and cold regions

To determine the current drawn by a load at V, let the internal resistance of the thermoelectric plate be R.

Current, $I = \frac{V}{R+R_L}$ (7.4)

Substituting equation (7.3) into (7.4), we have:

$$I = \frac{\alpha\Delta T}{R+R_L} \tag{7.5}$$

But,

Power flowing through loads is given by:

$$P_L = I^2 R_L \tag{7.6}$$

Hence, substituting equation (7.5) into (7.6), we have:

$$P_L = \left(\frac{\alpha\Delta T}{R+R_L}\right)^2 R_L \tag{7.7}$$

$$P_L = \frac{\left(\alpha\Delta T\sqrt{R_L}\right)^2}{R^2+R_L^2} \tag{7.8}$$

At maximum power, internal resistance has to be equal to load resistance. That is:

$$R = R_L \tag{7.9}$$

Substituting relation (7.9) into (7.8):

Maximum power, $P_{max} = \frac{\left(\alpha\Delta T\sqrt{R}\right)^2}{R^2+R^2}$

$$P_{max} = \frac{(\alpha \Delta T \sqrt{R})^2}{2R^2} \quad (8.0)$$

VIII. Benefits And Contributions Of Proposed Techniques

Some benefits of the proposed techniques are:

i. Maintaining a clean, safe and carbon pollution free environment.

ii. Providing affordable means of generating electricity.

iii. Proposing sustainable energy source.

iv. Suggesting and opening up a new area of research.

IX. Conclusion/Future Work

From the discussions made and calculations written, it has been clearly deduced that temperature differential created about thermoelectric plates can result to the production of electricity. This is made possible through Peltier effect.

As recommendation for future work, a better method of cooling thermoelectric plates for more efficiency can be created or improvised. Also, the plates themselves can be designed in smaller units and permanently attached to silicon semiconductors found in electronic devices.

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