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Research Paper

Amplification of Output Voltage by Using Silicon Based Solar Cells, Piezoelectric and Thermoelectric Conversion Transducers: A Triple Energy Harvester

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Abstract:
We purpose a hybrid energy harvester made of silicon solar cell, piezoelectric and thermoelectric. Our simulations are carried out using the COMSOL software. For this purpose, MEMS, heat transfer and electromagnetic modules were used. We connected nine piezoelectric, one thermoelectric and one solar cell modules in series to maximize the harvested energy and provide the appropriate voltage level. It is observed that the maximum electric current and voltage is about 200mA and 5V, respectively, which is equivalent to approximately 1W. The total obtained energy was amplified by two DC/DC converters and the voltage level increased to 5V. Also, we theoretically proved that the use of an optical window (as top and bottom contact layers) based on photonic multilayer can control surface reflection. It is found that if we use two contact layers in the front and back of the solar cell, the transmittance increases from 33% (without contact layer) to 67% (with double contact layer).

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1. INTRODUCTION

Supplying energy for various processes is one of the most key challenges in the field of knowledge and technology. The use of renewable energy resources freely exist in the nature and environment has been considered as a favorable way to provide continuous energy sensors or any devices that need small amounts of energy for continuous operation [1]. Today, with the advancement of technology, favorable conditions have been created for the use of solar energy. Solar energy technologies have made significant progress in the last 20 years. Photovoltaic cells are designed to directly convert solar energy into electrical power with nearly 20% efficiency. Currently, the active materials used to make solar cells are basically inorganic materials such as silicon, gallium oxide, and cadmium telluride and cadmium indium selenide. Silicon solar cells are one of the most widely used solid state components. Electron and hole pairs are produced by sunlight in semiconductors. These moving charge carriers generate current [1-3].

In solar cells, the thickness of the absorbent material and the amount of light reflection from the surface of the photovoltaic cell are of the most important challenges. The thickness of the absorbent material in the first is around 150 to 300 micrometers. The attention of researchers has been drawn to the second generation of solar cells with a thickness of about a few nanometers to several tens of micrometers. The problem that arises after reducing the thickness of the absorbent material is the reduction of the effective length of absorption [4]. Therefore, finding a way to increase the optical absorption inside the cell is of particular importance. Our proposed solution in this article is to use optical windows based on photonic crystals in order to trap light inside the absorbent material. Placing an optical window on the surface of the cell absorbs part of the reflected light from the cell. Also using the same window at the end of the cell also helps to increase the absorption.

On the other hand, photovoltaic (PV) phenomenon occurs only with certain wavelengths because photons must have a minimum energy to excite electrons in matter. Parts of the photons that do not have enough energy to excite the electron in the semiconductor are not absorbed by the photovoltaic material. On the other hand, if the photon energy is more than required energy to excite the electron, the excess energy is wasted as heat. Therefore, there is a need for an approach that can filter these unwanted waves. Also, the reflected waves from the surface of the cell can cause its heating, so in order to use this energy as well as the thermal energy of the environment; a thermoelectric module was used to strengthen the production power. Small-scale electrical generators that exploit this environmental energy, such as miniature thermoelectric generators and solar cells often have low output voltage and do not have sufficient voltage to provide the power required by electronic systems. In addition to the photovoltaic and thermoelectric modules, in this paper we utilized piezoelectric module to increase power generation capacity [5, 6]. In the next section, we will briefly introduce the three used modules.

In our work a triple energy harvester as a single system composed of piezoelectric, solar photovoltaic cells and thermoelectric conversion transducers has been selected. We connected nine piezoelectric, one thermoelectric and one solar cell modules in series to maximize the harvested energy and provide the appropriate voltage level. There are many articles in which the production power is in the low-power range and the resulting values are about µW to several mW [7-14]. But in our paper, it is observed that the maximum electric current and voltage is about 200mA and 5V, respectively, which is equivalent to approximately 1W. Also, our paper has been set on medium power hybrid energy harvesters while numerous research investigations such as above mentioned papers have been set on low power hybrid energy harvesters.

2. THEORY

2.1 Solar cell energy generator

The solar cell basically consists of bonding two thin layers of dissimilar semiconductor materials, i.e. N and P types. As a result of sunlight shining on the photovoltaic panel, free electrons are generated and an electric current is obtained [15-19]. The simplest solar cell model consists of diode and current source. Current equation of ideal solar cell is:

$$I = I_L - I_S(e^{\frac{V}{n.V_T}} - 1) \quad [1]$$

where I_L is light-generated current, I_s is reverse saturation current (approximate range 10^{-8} A/m^2), V is diode voltage (V), V_T is thermal voltage as

$$V_T = \frac{k.T}{q} \quad [2]$$

where k, T and q are Boltzmann constant, temperature and charge of electron, respectively [20,21].

2.2 Thermoelectric Energy Generator (TEG)

Among the technologies based on renewable energy, thermoelectricity has been proposed as an important option for green and clean energy. Thermoelectricity, a renewable energy source with the ability to convert temperature difference into electrical energy and vice versa, was first discovered in the early 19th century by the German scientist Thomas-Seebeck [22]. The Seebeck voltage can be written as:

$$V = \underbrace{(\alpha_A - \alpha_B)}_{\alpha_{AB}} . \underbrace{(T_h - T_c)}_{\Delta T} \quad [3]$$

where α_A and α_B are the Seebeck coefficients. The basis of the thermoelectric materials is the movement of energy carriers. In the presence of a temperature gradient, these carriers diffuse from the hot to the cold region, and this diffusion continues until it reaches equilibrium. Semiconductors are usually used as base materials because of their large Seebeck coefficients. Also, the sign of Seebeck coefficients is positive for p-type and n-type semiconductors; So that if two bases with opposite poles are used side by side, the resulting voltage will add up. In thermoelectric devices for applications up to 500 K, Bi_2Te_3 and Sb_2Te_3 are used. To produce electrical energy at medium temperatures (900-500 K), materials based on telluride such as PbTe, GeTe and SbTe or are commonly used [23, 24]. At higher temperatures (T>900 K), Si-Ge alloys are usually selected [25]. Almost all materials discussed above are semiconductors composed of heavy elements that are either toxic or have low abundance in nature. These restrictions limit the sustainable development of TEG materials in large-scale sizes, even if they have high efficiency [26].

2.3 Piezoelectric Energy Generator

Harvesting energy from environmental vibrations is one of the suitable options to supply the energy consumption of these devices. Piezoelectric systems are used as an attractive technology to harvest small amounts of energy from environmental vibrations. The type of piezoelectric sensor is an important factor in energy harvesting. Normally, PZT materials are used due to high dielectric and piezoelectric coefficients. If these materials are subjected to strain, bipolarity will appear in them. So strain will create potential difference and produce electric current. It is necessary to mention that piezoelectric materials are not suitable for producing high power levels. This method is very suitable for use in small electronic equipment. By studying different aspects of this technology, its performance can be improved and by changing the material of the sensor, changing the frequency and input power, the output power can be increased. Compared to other methods, this energy harvesting method has advantages such as high power density, ease of use and the ability to manufacture [27-30]. It is necessary to mention that the equations of linear piezoelectricity are provided in Ref. [28].

2.4 Photonic Multilayer as a Window Film

Our supposed window thin film is based on a photonic crystal containing ZnO and Ag as S_1 (without front or back contacts) S_2 (with front contact) and S_3 (with both front and back contacts) are plotted. (see Fig. 1).

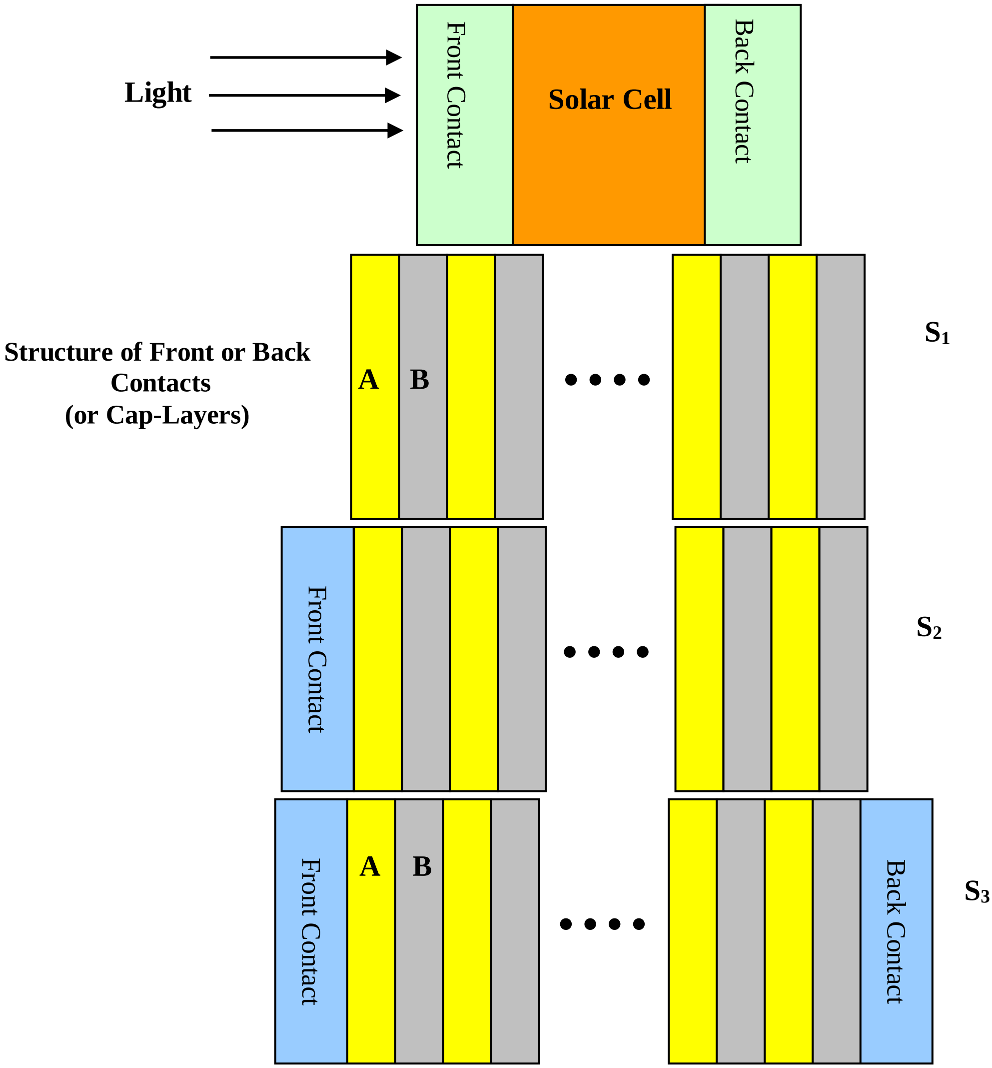

Fig. 1. The supposed front or back contacts as S_1 (without contacts) S_2 (with front contact) and S_3 (with both front and back contacts). Front or Back contacts are made of a photonic multilayer.

These structures are composed of ZnO and Ag layers. The electrical permittivity of zinc oxide has little dependency on frequency, so it can be assumed as constant in the visible region [31-32]. Also, among all precious metals, Ag is an efficient conductor of electricity and heat energy and is used as a coating in electrical conductors. Today, there is a great demand for silver in the electronics and solar energy industries.

Here, the numerical method used in this part of the article is the transfer matrix method. For the transverse electric polarization (TE) mode by entering the boundary conditions at the interface between the layers, the transfer matrix between the layers is obtained according to the following equation [33]:

$$M_j(\Delta z,\omega)=\begin{pmatrix}\cos(k_z^j\Delta z) & j/q_j\sin(k_z^j\Delta z)\\ jq_j\sin(k_z^j\Delta z & \cos(k_z^j\Delta z)\end{pmatrix} \quad [4]$$

Where $k_z^j=(\omega/c)\sqrt{\varepsilon_j}\sqrt{\mu_j}\sqrt{1-\sin^2/\varepsilon_j\mu_j}$ is the component of the wave vector along the z axis, c indicates the speed of light, $q_j=\sqrt{\varepsilon_j}/\sqrt{\mu_j}\sqrt{1-\sin^2/\varepsilon_j\mu_j}$ for TE mode. The transmission coefficient can be expressed as

$$t(\omega,\theta)=\frac{2\cos\theta}{(m_{11}+m_{22})\cos\theta+i(m_{12}\cos^2\theta-m_{21})} \quad [5]$$

Here m_{ij} (i,j=1;2) are the matrix elements.

3. RESULTS AND DISCUSSION

The experimental hybrid setup is shown in Fig. 2. In the experimental setup, ceramic piezoelectric transduction, photovoltaic solar cell and thermoelectric converter are used to harvest energy. It should be noted that in this paper, the COMSOL software is used. Here, the designed 3D model can be imported to the COMSOL multiphysics in order to analysis it's mechanical and electrical properties. We present the results of three different modules separately.

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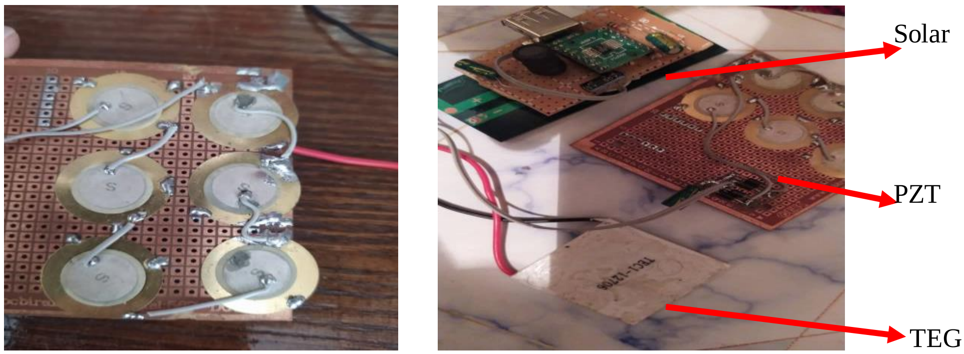

Fig. 2. The schematic (a) and experimental (b) view of considered hybrid setup. Three modules solar, PZT and TEG are used in this work.

3.1 Piezoelectric Energy Harvester

In this work, the diameter and thickness of the piezoelectric disk are considered 1.5 cm and 1 mm respectively. The amount of natural pressure on the piezoelectric module is numerically applied to the COMSOL software and the maximum amount of displacement is obtained (see Fig. 3). Based on the result, when the applied pressure increases, more output energy is obtained. Figure 3 shows the output voltage of piezoelectric cells. In Fig. 4, the peak voltage (Vp) of piezoelectric modules is 0.7V. A decrease in pressure corresponds to a decrease in voltage (dip point in Fig. 4) and vice versa (peak point in Fig. 4).

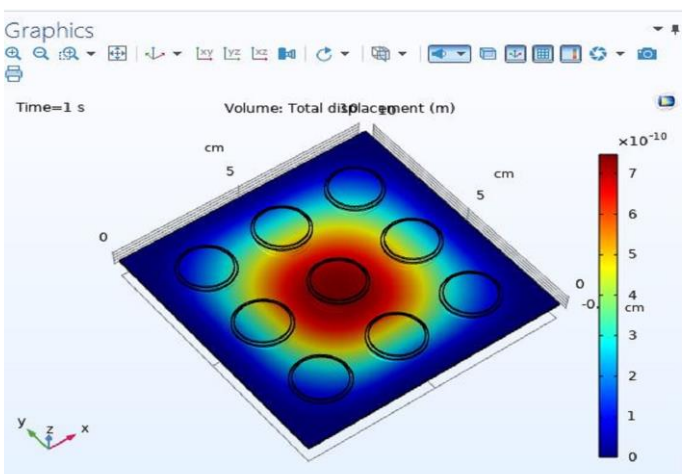

Fig. 3. The arrangement of the piezoelectric disk modules and total displacement.

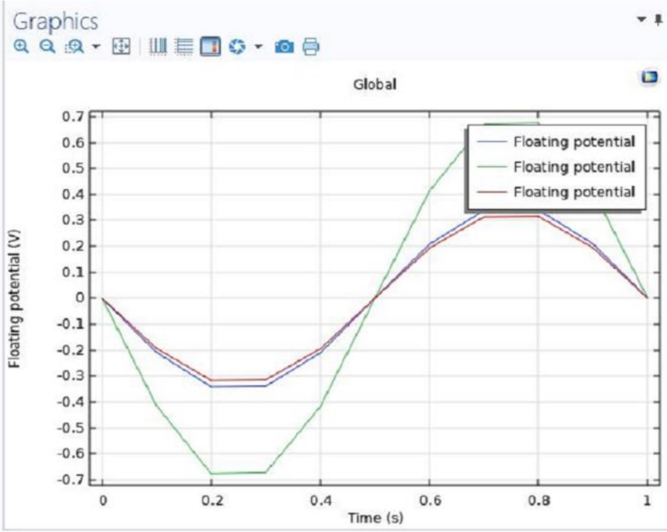

Fig. 4. Peak voltage of disk module.

Because of existence empty space between the piezoelectric disks, we have selected piezoelectric modules in a square shape (see Fig. 5). It is shown in Fig. 6 that Vp of the square shape piezoelectric modules increases to 2.5V.

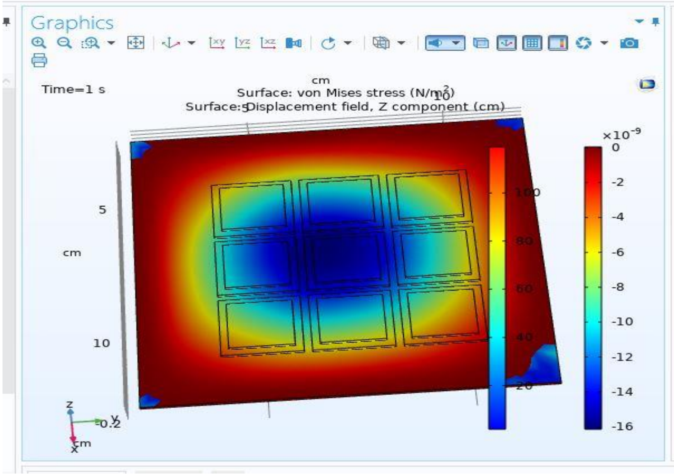

Fig. 5. The arrangement of the square shape piezoelectric modules and total displacement.

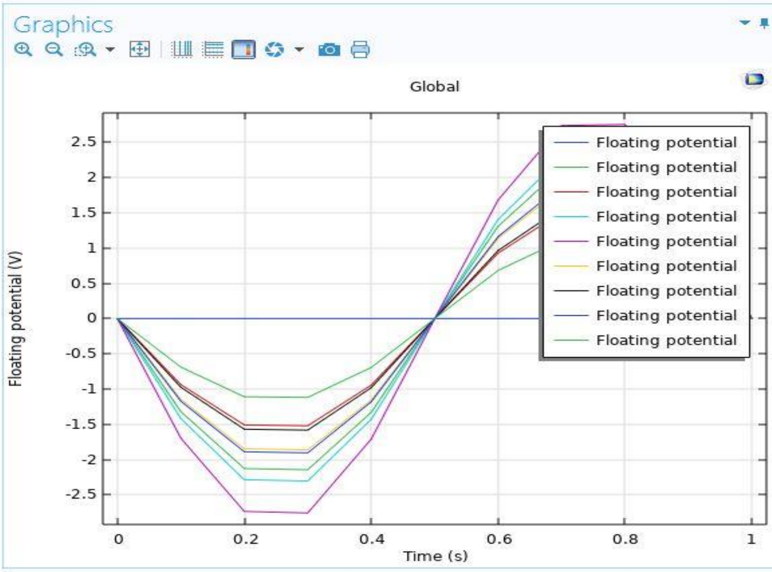

Fig. 6. Output voltage of the square shape piezoelectric module.

3.2 Thermal Energy Harvester

To obtain the appropriate temperature difference between two plates of the TEG module, by using EDS analysis (Energy-Dispersive x-ray Spectroscopy) required materials for simulation were obtained (see Fig. 7). These materials are selected in the COMSOL simulation software, and the resulting temperature difference causes the generation of electrical energy.

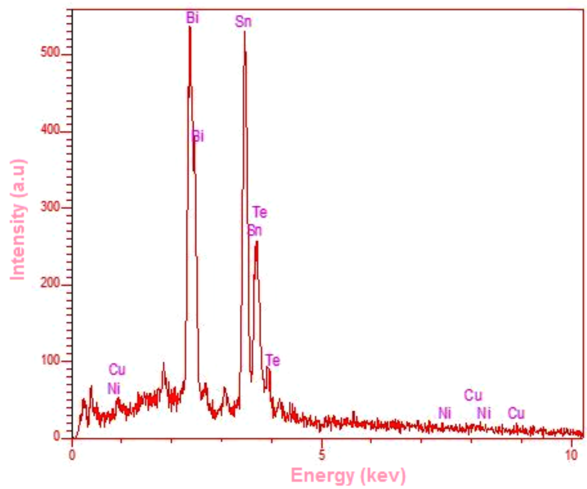

Fig. 7. The required materials for simulation by using EDS analysis.

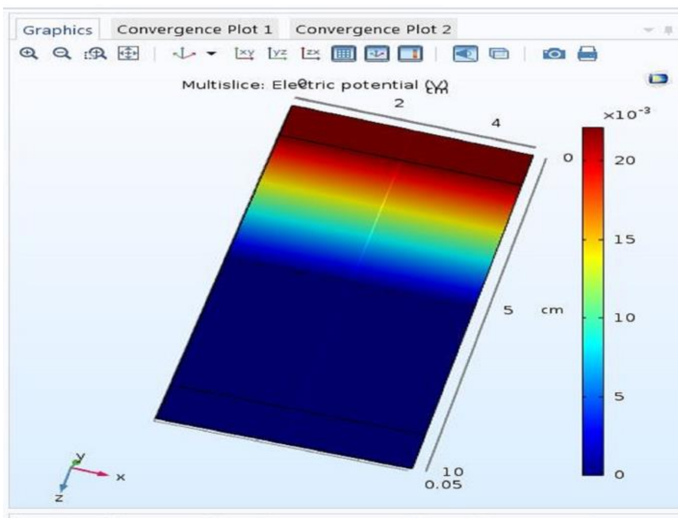

Fig. 8. The output potential related to the temperature difference.

The size of TEG module used here is 0.1*10*5cm^3. As is shown in Fig. 8, approximately 20mV was obtained at a temperature difference of $20^{\circ K}$. Our

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results show that as the temperature decreases, the obtained power also decreases. The supposed TEG harvester is used in low power applications. The maximum amount of energy received from PZT and TEG modules is about 180mV to 200 mV. By considering the low amount of harvested piezoelectric and thermoelectric energy and the requirement of at least 250mV, we connected 9 piezoelectric and 1 thermoelectric modules in series to provide the appropriate voltage level.

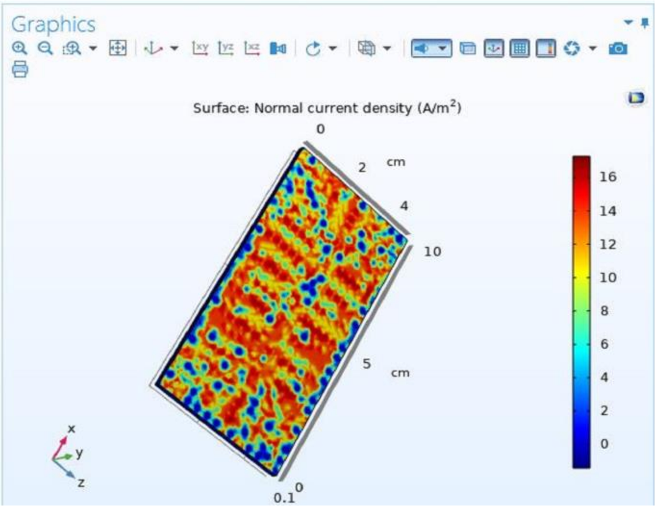


Fig. 9. The current density achieved from TEG module.

3.3 Solar Energy Harvester

A solar cell is an electronic component that captures sunlight and converts it directly into electricity. Solar cells are usually joined together to form larger units called solar modules. Fig. 10 shows the measured values of the output voltage in the utilized solar cell. Negative values of voltage indicated the current flow direction through the module. It is observed that the highest output voltage that can be produced is about 4.5V.

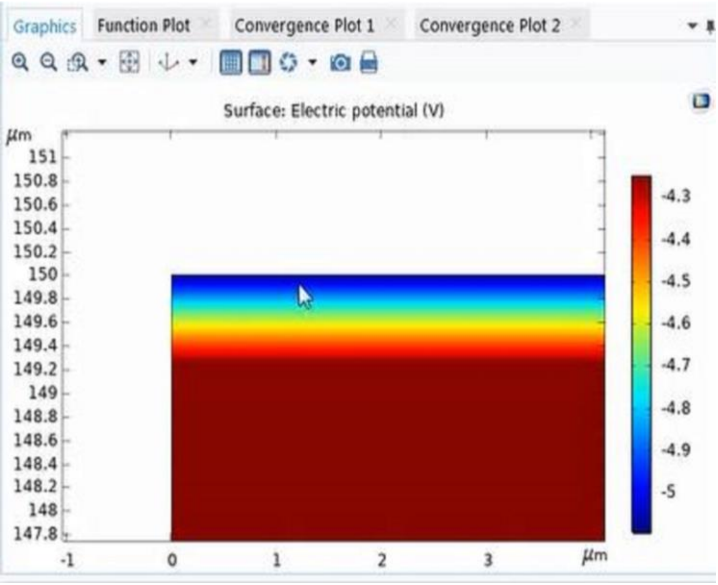


Fig. 10. Output voltage in the utilized solar cell.

It is necessary to mention that to obtain a higher voltage from a low voltage, a DC/DC converter is normally used in low voltage harvesting. In this article the obtained energy by using piezoelectric, thermal and optical modules was amplified by two DC/DC converters (see Fig. 11) and the voltage level increased to 5V. The outputs from each harvester module are merged together to produce a single output voltage. With an output of 5V, many personal electronics can be powered up. The voltage needs to be in the range of 4.5V to 5.2V, and the current can vary from 0.5A to 0.1A. Higher the current, the faster the mobile product can charge.

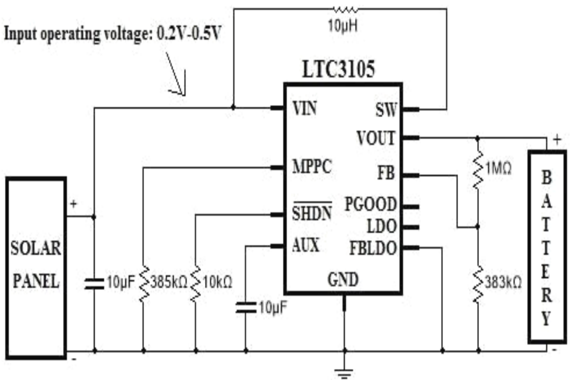
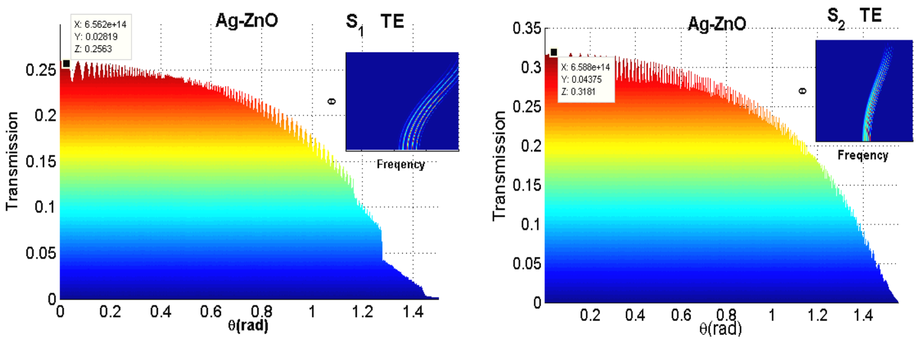


Fig.11. The utilized DC/DC converter circuit.

As we mentioned in the introduction section, the use of an optical window based on photonic crystal to control surface reflection and incoming light is of the goals of this article. For this purpose, we considered the structure as Figure 1. The structure parameters are $\epsilon_A=1-\omega_p^2/\omega(\omega+i\gamma)$, ϵ_B =4.24, $\mu_A=\mu_B$ =1, d_A=50nm, d_B=100nm. The plasma frequency and damping constant of Ag are equal to $\omega_p=2\pi\times2.175\times10^{15}$ rad/s and $\gamma=2\pi\times4.35\times10^{12}$ rad/s, respectively.



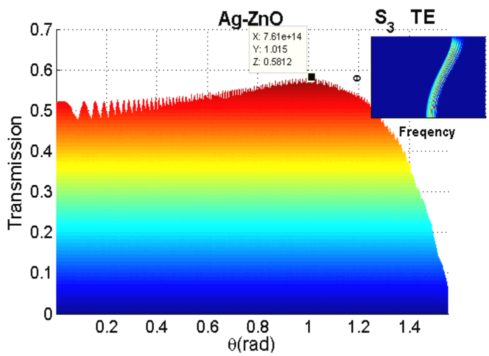
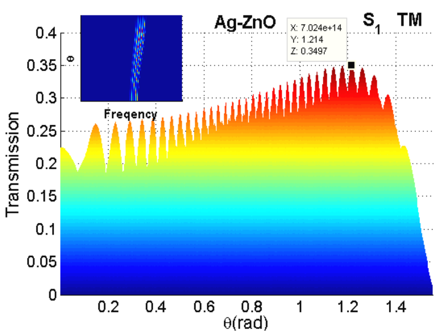
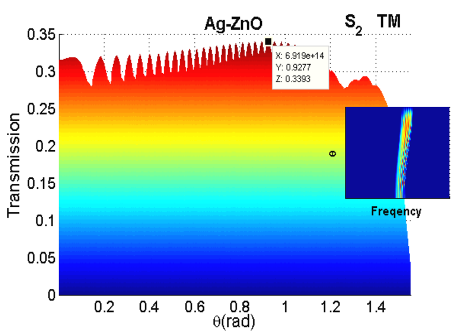


Fig. 12. TE transmission spectra of S_1, S_2, and S_3.

In the S_1 structure (without contact), the maximum value of TE transmission (T_{max}) is approximately 26% (see Fig. 12 for S_1). To increase T_{max}, we offer a contact layer on the front of S_1 as S_2 structure. By adding a contact layer to the top, T_{max} is nearly enhanced to 32%. So, compared to the S_1, T_{max} is almost increased by 23%. To explore the possibility of further increase of T_{max}, another contact is inserted at the bottom of the S_2 as S_3 structure. It is found that in the S_3 structure T_{max} reach to 57% which is significant compared to the S_1 and S_2 arrangements. In addition, for the TE mode (the TM mode), the maximum amount of transmission in the S_1 and S_2 structures occurs at angles close to normal incidence (around 1 radian) while in the S_3 multilayer it happens around 1 radian (normal incidence), that is, the behavior of the TE mode is the opposite of the TM mode (see Figs. 12 and 13).





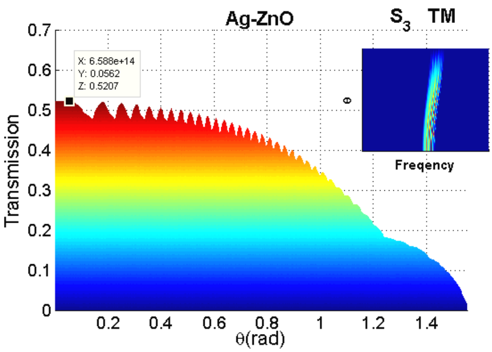


Fig. 13. TM transmission spectra of S_1, S_2, and S_3.

4. CONCLUSION

In the current research hybrid silicon photovoltaic cell, thermoelectric and piezoelectric modules have been developed to harvest wasted energy. The simulations for this experiment are analyzed by using COMSOL software. In this paper, we connected 9 piezoelectric and 1 thermoelectric modules in series to provide the appropriate voltage level. The maximum amount of energy received from PZT and TEG modules is about 180mV to 200mV. Also, one can see that in utilized solar cell the highest output voltage that can be produced is about 4.5V. The total obtained energy was amplified by two DC/DC converters and the voltage level increased to 5V. In solar cell module, the use of an optical window (as top and bottom contact layers) based on photonic crystal to control surface reflection and incoming light is of the goals of this article. It is found that if we use two contact layers, the transmittance increases from 33% (without contact layer) to 67% (with double contact).

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