Indian J.Sci.Res.. 2(1) : 20-26, 2014 ISSN : 2250-0138 (Online)
ISSN: 0976-2876(Print)

USING OF THERMOELECTRIC DEVICES IN PHOTOVOLTAIC CELLS IN ORDER TO INCREASE EFFICIENCY

SHIRIN AHADI[a1] , HAMID REZA HOSEINI[b] , RAHIM FAEZ[c]

[a] Electronics Department, Arak Branch, Islamic Azad University, Arak, Iran
[b]Electronics Department, Arak Branch, Islamic Azad University ,Arak, Iran
[c] Electronics Department, Sharif University Of Technology, Tehran, Iran

ABSTRACT

Outdoor performance of photovoltaic (PV) modules suffers from elevated temperatures. Conversion efficiency losses of up to about 25% can result, depending on the type of integration of the modules in the roof. Cooling of modules would therefore enhance global PV performance. Instead of module cooling we propose to use the thermal waste by attaching thermoelectric (TE) converters to the back of PV modules, to form a PV–TE hybrid module. A new approach to thermoelectric power generation using large area pn-junctions is presented. Thermally generated electron-hole pairs are separated by the built-in potential gradient of the pn-junction. A temperature gradient applied along this pn-junction causes a flux of both carrier types from the hot to the cold region, which has higher efficiency and lower cost than convention methods of thermoelectric power generation. The use of thermoelectric devices based on silicon material results in increasing efficiency of PV cell from 6.8% up to 10.92% at 83°C.

KEYWORDS : Thermoelectric Conversion; Efficiency;Solar Cells; Large Area Pn-Junction; Temperature Increasing

Today, human faces to two major crises which are related to each other more than what we recognize at appearance. On the one hand, industrial communities and cities face the problem of environmental pollution, on the other hand, it can be seen that the need fuel and raw materials are running out rapidly. The effects of high consumption of energy in the Earth's and climate are identified clearly, and we know the only solution is decreasing the consumption of fossil energies. Hence, the desires for new and renewable energy sources such as solar powers have been growing in recent decades. In this method, photovoltaic effect is one of the ways to generate electricity from the sun in which solar energy changes to electricity by the photovoltaic effect directly. So due to solar energy can be converted to other forms of energy like electricity and heat directly and indirectly, with the installation of solar powers, this clean energy can be converted into electricity. The development of the solar cell seems from the researches of the French physicist *Antoine-César Becquerel* in 1839, but the first solar cell was built by American inventor *Charles Fritts*, who coated the selenium with thin layer of gold to form the junctions with 1% conversion efficiency. In planning for the future scaling-up photovoltaic power generation, it is essential to carefully choose the semiconductor materials. Recent development seemingly indicates that GaAs is most materials for promising PV technologies; however, since the cost of the GaAs solar cells is relatively more expensive than those made of crystalline silicon, over 80% of the world's solar cells are currently made of sliced single crystal or polycrystalline silicon cells (Radziemska; 2003). However, a lot of issues, considering the long term stability and temperature effect on the cells, need to be clarified prior to commercial breakthrough of the technology (Toivola, et al; 2007)But, note that in solar cell technology, reducing the costs and increasing efficiency has been attracted most experts attention. The operating cell temperature greatly affects its efficiency through the functional dependence of the different physical parameters, such as short-circuit current, open-circuit voltage, light absorption and the fill factor, on the cell temperature(Radziemska; 2003, Sabounch; 1998). Depending on integration type temperatures of panels can reach 60–80°C, resulting in a loss in efficiency of about 20%, see, e.g., *Drews* (Drews, et al; 2007).In general, life expectancy of a solar cell will be decreased with increasing temperature. Therefore, controlling the operating temperature is an important factor for the solar cell (Hirata, et al;1988). One of the proposed methods for temperature control is using the thermoelectric devices that using this device for PV panels increase their performance. The devices that are connected to the rear PV panels can use the waste heat of solar cells (Tsung-Chieh, et al; 2011) and thereby, increase the efficiency of solar cells. Thermoelectric material can be used to directly convert heat into electricity, or vice versa. It can be used in two major operating models: thermoelectric generator (TEG) (Hsiao, et al; 2010)and thermoelectric cooler (TEC)(Cheng, et al; 2010). The amount of additional TE power is determined by the so-called figure of merit (*Z)* of the TE material and the temperature difference over the TE module (Rowe; 1995). Where the figure of merit Z depends on material parameters i.e. Seebeck coefficient α [V/K], total thermal conductivity k_T [W/cm K] and electrical resistivity ρ [Ω cm], and is defined as: (Kosalathip, et al; 2007)

$$Z = \frac{\alpha^2}{\rho k_T} \qquad (1)$$

To increase the figure of merit, a good TE material, both n and p type is required to have a large Seebeck coefficient, high thermal conductivity and low electrical resistivity (Ioffe; 1957).There are some various thermoelectric materials, but based on the figure of merit value at a certain temperature, these materials are used only at specific temperature ranges.For example, lead telluride (PbTe) is used at

---

[1] **Corresponding author**

temperatures between 600 and 800 K. At higher temperatures (800–1300 K) silicon germanium ($Si_{1-x}Ge_x$)alloys are used, while at lower temperatures (200–400 K) bismuth telluride (Bi_2Te_3) is preferred(Tritt, et al; 2008 , Rowe; 1995, Omer and Infield; 1998).silicon as a cheap and abundant material is an excellent candidate for future TE devices(Vining; 2008).If there are p and n materials which have high *ZT*, it warrants a study into the possible use of these materials in PV-TE hybrid systems. These systems have not been studied so much till now, because of low conversion efficiency. In this paper we demonstrate the performance enhancement as a result of attaching TE system to back of PV modules, so we create a PV-TE hybrid system. In 2011, the hybrid system was designed by *M. G. Molina*. In this hybrid module, conventional thermoelectric devices are used for thermoelectric power generation. It consists of two type semiconductor, p and n (Fig 1,1), which n and p slabs are serial in electric circuit and are parallel in heating circuitry(Molina, et al; 2012).

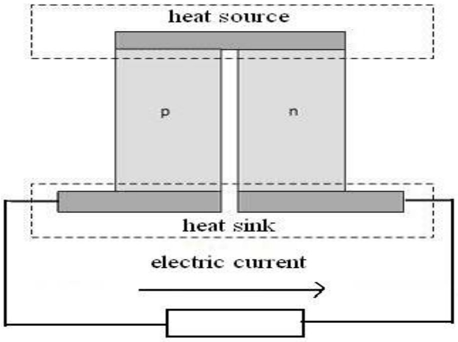

Fig 1,1- Schematic sketch of a conventional thermoelectric generator with applied temperature gradient.

In this paper a new approach to thermoelectric power generation using large area pn-junctions is presented, which has higher efficiency and lower cost in compare to other methods of TE power generation. Initially, we investigate the effect of temperature on the efficiency of a conventional solar cell, then we calculate the amount of electric power generation in TE device resulting of waste energy (heat) in photovoltaic cell and finally calculate the efficiency of the hybrid system.

ASSUMPTIONS

Incident solar radiation is converted to electric power by the PV module with efficiency of η_{PV}. The waste solar energy in heat form is assumed to be absorbed by TE module and is converted to electric energy with efficiency of η_{TE}. Then, the total amount of generated power is:(van Sark; 2011)

$$P_{PVTE} = P_{PV} + P_{TE} = \eta_{PV} G + (1-\eta_{PV})\, G\, \eta_{TE} \qquad (2)$$

And the efficiency of hybrid PV-TE system is written as

$$\eta_{PVTE} = \eta_{PV} + (1-\eta_{PV})\eta_{TE} \qquad (3)$$

In next section we will show that all efficiencies depend on radiation rate G.

SOLAR CELL MODEL

In here we assume a silicon pn junction as solar cell that is suitable for examine efficiency of PV cells in the hybrid system. The module temperature needs to be determined by ambient temperature and solar radiation. For simplification we assume that the difference of module temperature T_M and ambient temperature T_A is proportional to radiation rate G:(Drews, et al; 2007)

$$T_M = T_A + CG \qquad (4)$$

The coefficient *C* depends on installation conditions, as shown in T-1,3(Sauer; 1994).

Table 1,3- Parameter c and module temperature T_M at G = 1000 W/m^2 and $T_A = 25^{0C}$ as a function of the integration type of PV system installation(Sauer; 1994).

PV system installation	C	T_M (G = 1000 W/m^2,$T_A = 25^{0C}$)
Roof-integrated	0.058	83
On top of roof, with small roof-module distance(< 10cm)	0.036	61
On top of roof, with large roof-module distance(< 10cm)	0.027	52
Free-standing	45	0.02

I. Thermoelectric power generation device

In recent decades, thermoelectric power generation technology was one of the interest clean energy sources. Because of simplicity and low cost, this technology can be a viable alternative to many conventional techniques to produce heat and chill. Conversion of heat into electrical energy makes it possible that waste heat energy may be stored in electrical form. Although the efficiency of this kind of conversion is low, it has been attending because of renewability. Early in 19th century, *Thomas Seebeck* discovered that if a thermal gradient establish between two dissimilar conductors, an electric current will flows. On the other hand, *Jean Peltier* found that the electrical current through two dissimilar conductors causes heat in the bonding material be dispersed or absorbed. After the middle of the twentieth century, many studies carried out to find semiconductor materials which are suitable for using two mentioned effects and getting the desired results. There are several obstacles in energy harvesting in thermoelectric method, some of them are low rate, toxicity and limited access to chemical elements that are used in it. But thermoelectric methods have some advantages. They have not mechanical parts but use of clean and quiet, compact size, light weight, reliable, simple maintenance requirements, ability to operate in small and large units. Using these generators in solar cells is very suitable because of harvesting more electrical energy form solar irradiation. Where we have used Eq.(4), the efficiency η_{TE} depends on Z "Eq.(1)" and on operational temperatures T_M and T_A, and thus depends on irradiance G too. The efficiency of a TE module can be expressed as:(Rowe; 1995)

Parameter	Value
$W_p(\mu m)$	100
$W_n(\mu m)$	0.3
$n_p(cm^{-3})$	10^{17}
$n_n(cm^{-3})$	10^{18}
$\tau_n(s)$	10^{-6}
$\tau_p(s)$	10^{-6}

$$\eta_{TE}=\eta_{carnot}\frac{\sqrt{1+Tave\ Z}-1}{\sqrt{1+Tave\ Z}+\frac{TA}{TM}} \qquad (5)$$

With the Carnot efficiency defined as:

$$\eta_{carnot}=1-\frac{TA}{TM} \qquad (6)$$

And the average temperature T_{ave} of the TE module as:

$$T_{ave}=\frac{1}{2}(T_M+T_A) \qquad (7)$$

TE MODEL

A new approach to thermoelectric power generation using large area pn-junctions is presented.(Fig 2,4)

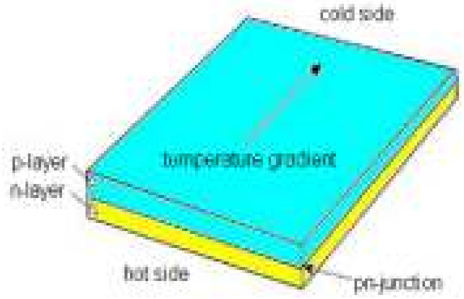

Fig 2,4-Large area pn-junction with temperature gradient(Wagner, et al; 2005).

Unlike conventional thermoelectric devices, in the p-n junction electron and hole pairs are generated by thermal coupling. In this structure, due to the temperature gradient, electron-hole pairs' generation increases and results in efficiency improve considerably at higher temperature in compare to conventional thermoelectric devices(Wagner, et al; 2006) Thermally generated electron-hole pairs are separated by the built-in potential gradient of the pn-junction. A temperature gradient applied along this pn-junction causes a flux of both carrier types from the hot to the cold region. Now, using selective contacts to n and p type layers, this circular current can be diverted to an external load and a power source as a TE element is established (Fig 3,4). Since this element only consists of one type material, mechanical tensions between two parts are completely avoided and thermal cycling will not lead to fatigue. Using semiconductor material with high band gap energy, even very high temperatures above 1000°C can be used for thermoelectric power conversion.

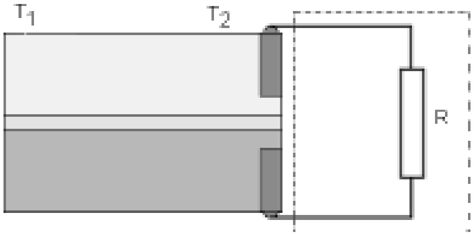

Fig 3,4- Schematic plan of a thermoelectric element [19]

An equivalent circuit can be described as a network of diodes and ohmic resistors for a thermoelectric element (Fig 4,4).The diodes represent the pn-junction and the ohmic resistors are electric resistance of p and n layers.

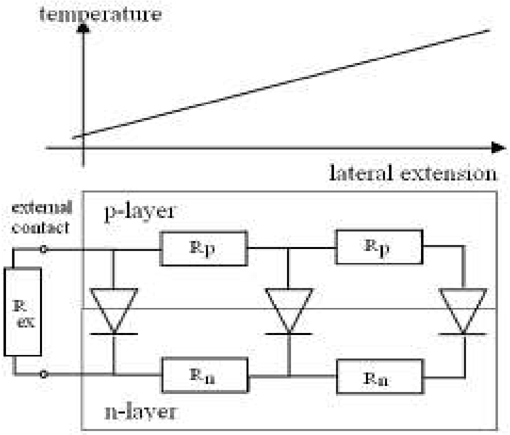

Fig 4,4- Equivalent circuit for a thermoelectric element

RESULTS

A. PV simulation results

In order to simulate the solar cell and perform analysis on it, Atlas simulation is used. This simulator can simulate thermal, electrical and optical behavior of semiconductor devices. Here, quantities and sizes of solar cell will be introduced to software according to T- 2,5.

Table2,5- Input parameters of p-n silicon solar cell

In this paper we investigate effect of increasing temperature on solar cell parameters. Simulation results can be seen in figures 5,5-10,5.

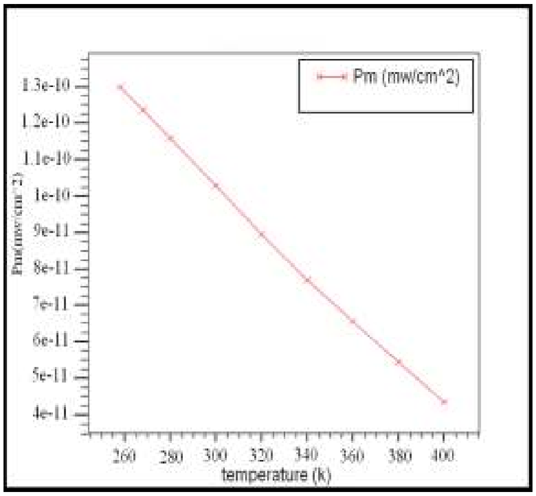

Fig 5,5-The effect of temperature on the maximum electric power of silicon p-n cell

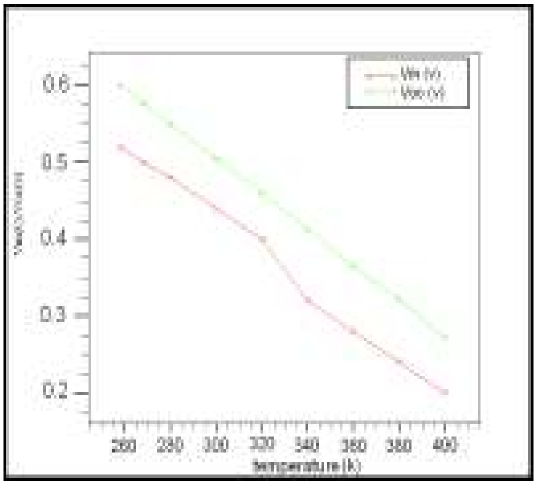

Fig 6,5-The effect of temperature on the maximum voltage and open circuit voltage of silicon p-n cell

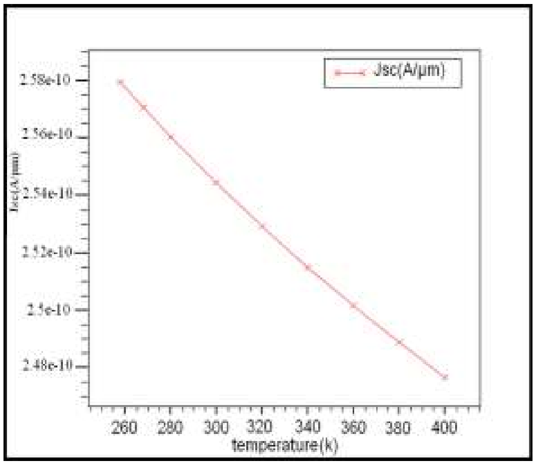

Fig7,5-The effect of temperature on the current density of silicon p-n cell

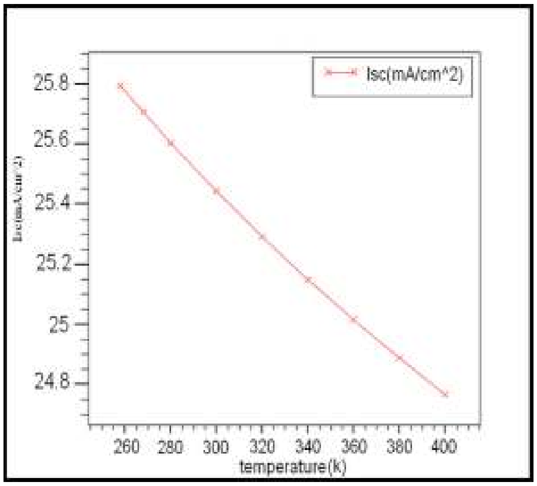

Fig8,5-The effect of temperature on short circuit curret of silicon p-n Cell

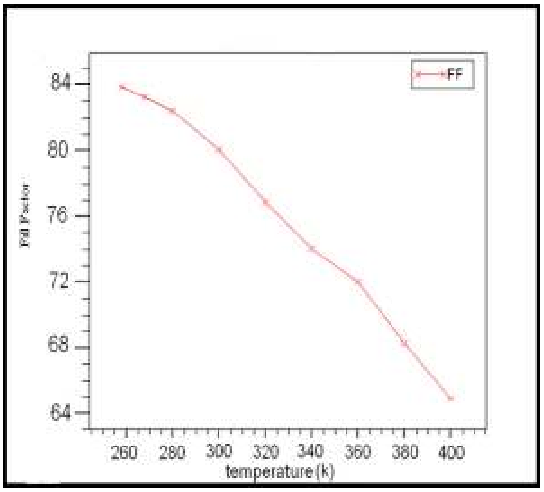

Fig9,5-The effect of temperature on the fill factor of silicon p-n cell

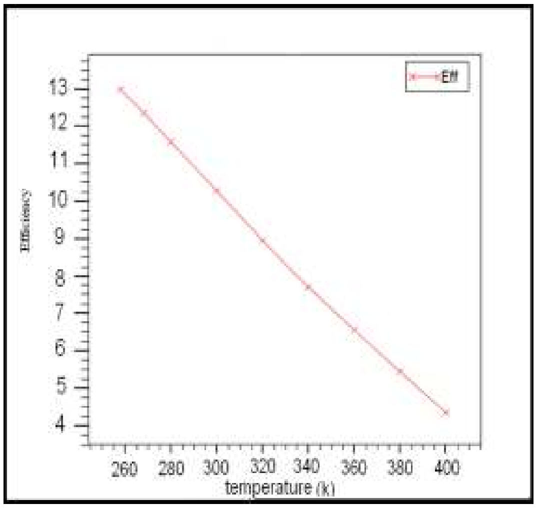

Fig10,5-The effect of temperature on efficiency of silicon p-n cell

As can be seen, by increasing temperature, the efficiency of p-n silicon solar cell reduced 25% approximately. For different module integration, as indicated in T-3,5 ,different temperatures result for the same irradiance values; this in turn results in lower efficiency values. Consequently, the higher the coefficient *C* results lower efficiency. In table 3 efficiency of PV module is shown for different values of C, and at different temperatures of module in uniform irradiation of 1000 w/m^2. Note that for these calculations a constant ambient temperature of 25 ^{0}C is used.

Table3,5- Efficiency of photovoltaic modules at different temperatures.

C Coefficient	Temperatures(K)	Efficiency(%)
0.058	356	6.8
0.036	334	8.3
0.027	325	8.6
0.02	318	9.2

TE SIMULATION RESULTS

Atlas Silvaco simulator was used to simulate the large area pn junction based thermoelectric device and perform analysis on it.(ATLAS User's Manual DEVICE SIMULATION SOFTWARE) Several parameters contribute to thermoelectric power device, as p and n layer geometry and doping densities. As a primary assumption, doping density for both p and n layers is assumed 10^{19}cm^{-3}. The device length, width and thickness are assumed 20, 10 and 1.2mm respectively. These parameters can be varied to obtain maximum output thermoelectric power. As mentioned above, after electrical contacts have been placed on the cold side a linear temperature gradient is applied from right (high temperature, x = 20 mm) to left (low temperature, x = 0 mm). The experiments were performed Silicon based. Silicon has a very high heat conductivity which limits the achievable efficiency considerable but allows low cost solutions for prototyping. However, one advantage of the high heat conductivity would be a very high heat flux density to achieve high energy densities. At first, we apply a temperature gradient to pn junction. Temperature gradient within this structure leads to generation an electrical current because there is an electrostatic potential between hot and cold ends of device in each layer. Basically (Eq. 8), the higher temperature T1 leads to the smaller energy step, ΔE1, between n and p layer compared to ΔE2 at lower Temperature T2 (Fig 11,5).

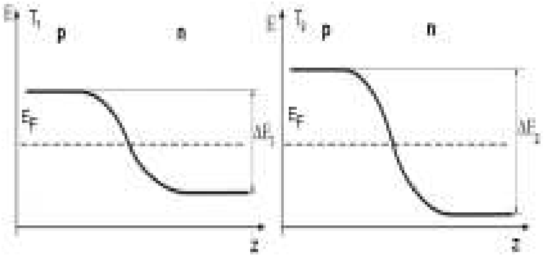

Fig 11,5- Temperature influence on electrostatic potential of a pn junction(Wagner, et al; 2005).

$$E_g(t)=E_g(0) - \frac{\alpha T^2}{T+\beta} \qquad (8)$$

Electrostatic potential changes are altered because of temperature effect that causes potential difference between p and n in hot side is less than cold side. This potential difference is along the length of device and cases to transfer productive carriers from hot side to the cold side (Fig12,5).

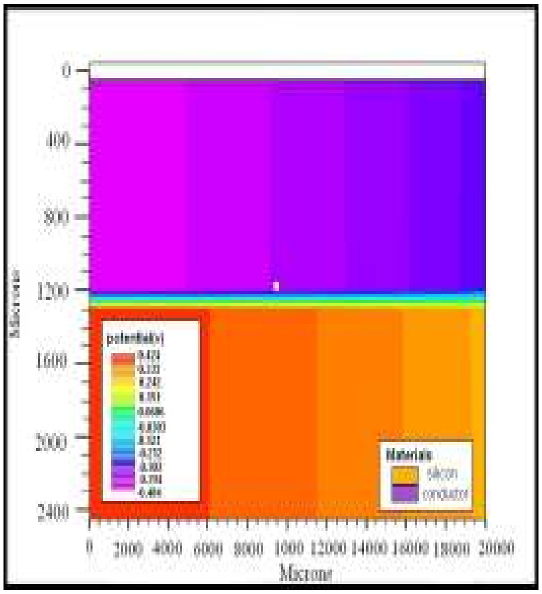

Fig12,5-Electrostatic potential changes are altered by effect of temperature gradient

Since potential difference come into each layer and in opposite direction in p and n regions, both types of carriers, electrons and holes, migrate in the same direction (ambipolar drift and diffusion) and away from the higher temperature T1 end of pn-junction to cold end (Fig13,5). This region becomes depleted and the local thermal equilibrium is disturbed.

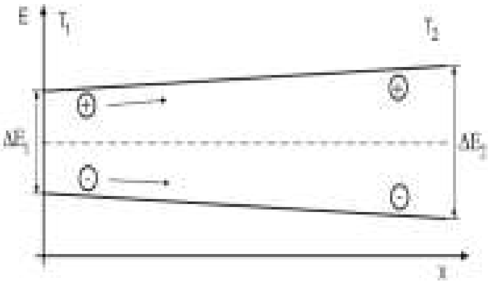

Fig13,5- Driving forces to generate ambipolar drift and diffusion(Wagner, et al; 2005).

Based on generation-recombination balance, higher generation occurs to compensate migrated carriers (Fig14,5) At lower temperature (T2) carriers recombine and incoming carriers enhance the recombination (Fig15,5). So the net effect is a circular electrical current within the large area pn-junction from the hot region to the cold side.

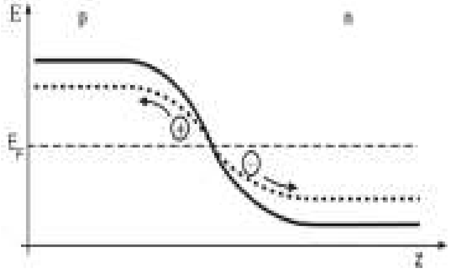

Fig14,5-Higher generation because of depletion

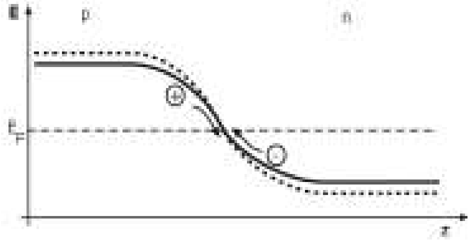

Fig15,5- Recombination at the cold side

In order to use this current, the structure should be put in an electric circuit. we measured the generated output current of device by connecting an output resistor between two connectors. To accomplish this, we used the mixed mode simulator in silvaco software. This simulator provides using of designed physical devices in Atlas environment in an electrical circuit. Mixed mode is one of the very efficient algorithms for DC, transient and small signal analysis of network. The maximum power output is reached at Ri = Rext. R_i is the internal resistance of the structure and it is obtained through $R=\frac{\rho L}{A}$.(9) equation. Productive power by TE module at different temperatures that can be applied to the hot side of device, are calculated below"T-4,5". In all calculations, the temperature of the cold side of thermoelectric transducer is considered 25^{0}C.

Table4,5-Electric power generated by thermoelectric converters at different temperatures.

C value	Generated TE power as a function of irradiance for four different ways of module integration
0.058	4134.43e-12(w)
0.036	216.73e-12(w)
0.027	51.68e-12(w)
0.02	14.32e-12(w)

PV–TE Generated Power

Using equation (2), we can obtain power generated by PV-TE hybrid system that is shown for different temperatures in T-5,5.

Table 5,5-PV-TE generated power

C value	Electrical power(w/m^2)
0.058	109.22
0.036	85.16
0.027	86.51
0.02	92.14

PV-TE Efficiency

Efficiency of PV-TE hybrid system obtained 10.92% at 1000w/m^2 radiation and module temperature of 83^{0}C, of course, it depends on type of PV module integration, and on this fact that the temperate of cold side of TE module has been cooled sufficiently; it should be equal to the environment temperature. And also it can be related to material type of thermoelectric device.

DISCUSSION

Loss

The model described above allows for a calculation of the maximum efficiency as a result of adding a TE converter. Several losses are not considered, such as reflection losses, which typically is 5–10% for PV modules. Heat flux and radiation losses from the side and front cover are also not taken into account. Further, although it is yet unclear if such arrangement may be realized in practice, it is assumed that the back side temperature of the TE converter always equals the ambient temperature. This is a critical assumption, and may not be realized in experiment. Clearly, a higher back side temperature lowers the TE efficiency and possible benefits are thus reduced.

Cost

Although using of TE module can increase the efficiency of PV-TE hybrid system, the extra cost of applying the TE module is important; it should be balanced by the extra power output due to the TE module. In summary, the required increase in efficiency, another very important issue is to reduce the cost. As new, high efficient TE modules are still being developed; present high prices should come down with increased amounts of units produced (Van Sark, et al; 2008).

CONCLUSIONS

In this paper, we conclude that as the temperature increases from room temperature to 100^{o}C, the efficiency of solar cell is reduced by about 25%. By using thermoelectric device which is coupled with solar cell and perform a hybrid PV-TE system, efficiency of PV module will be increased. We used large area pn-junction thermoelectric module and a pn silicon solar cell that was coupled with each other, so the result of simulation show that adding a TE device in rear PV module at 83^{0}C results in increasing of PV module efficiency from 6.8% to 10.92%. Also total efficiency depends on type of module integration, material type and the assumption that the backside is sufficiently cooled such that it is at ambient temperature.

REFERENCES

ATLAS User's Manual DEVICE SIMULATION SOFTWARE. http://www.silvaco.com

Cheng CH., Huang SY., Cheng TC.; 2010.A three-dimensional theoretical model for predicting transient thermal behavior of thermoelectric coolers.International Journal of Heat and Mass Transfer,**53**(9-10): 2001-2011.

Drews A., Keizer AC., Beyer HG., Lorenz E., Betcke J., van Sark W.G.J.H.M., et al; 2007.Monitoring and remote failure detection of grid-connected PV systems based on satellite observations.Solar Energy,**81**(4): 548–564.

Hirata Y., Inasaka T., Tani T.; 1988.Output variation of photovoltaic modules with environmental factors-II: seasonal variation.Solar Energy,**63**(3): 185-189.

Hsiao YY., Chang WC., Chen SL.; 2010.A mathematic model of thermoelectric module with applications on waste heat recovery from automobile engine.Energ,**35**(3): 1447-1454.

Kosalathip V., Migot S., Lenoir B., Dauscher A.; 2007.fabrication of p-n junction from conventional namo-sized thermoelectric materials.Proc .5 th European conference on Thermoelectrics,38.pdf.

Ioffe AF.; 1957.Semiconductor thermoelements and thermoelectric cooling.London,UK: Infosearch Ltd.

Molina M.G., Juanico L.E., Rinalde G.F.; 2012 .Design of innovative power conditioning system for the grid integration of thermoelectric generators.international journal of hydrogen energy,**37**(13): 10057-10063.

Omer SA., Infield DG.; 1998.Design optimization of thermoelectric devices for solar power generation.Solar Energy Mater Solar Cells,**53**(1-2): 67–82.

Radziemska E.; 2003.Thermal performance of Si and GaAs based solar cells and modules: a review .Progress in Energy and Combustion Science.**29**(5): 407-424.

Radziemska E.; 2003.The effect of temperature on the power drop in crystalline silicon solar cells.Renewable Energy,**28**(1):1-12.

Rowe DM. editor; 1995.CRC handbook of thermoelectrics.London, NY, USA: CRC Press.

Sauer DU.; 1994.Untersuchungen zum Einsatz und Entwicklung von Simulationsmodellen für die Auslegung von Photovoltaik-Systemen. Thesis, TH Darmstadt..

Sabounch AM.; 1998.Effect of ambient temperature on the demanded energy of solar cells at different inclinations.Renewable Energy,**14**(1): 149-155.

Toivola M., Peltokorpi L., Halme J. and Lund P.; 2007.Regenerative effects by temperature variations in dye-sensitized solar cells .Solar Energy Materials & Solar Cells,**91**(18): 1733-1742.

Tsung-Chieh Cheng., Chin-Hsiang Cheng., Zhu-Zin Huang., Guo-Chun Liao.; 2011.Development of an energy-saving module via combination of solar cells and thermoelectric coolers for green building applications.Energy,**36**(1): 133-140.

Tritt TM., B◌ttner H., Chen L.; 2008.Thermoelectrics: direct solar thermal energy conversion.MRS Bull,**33**(4): 366–368.

Vining CB.; 2008.Desperately seeking silicon. ,Nature,**451**(10): 132–133.

van Sark W.G.J.H.M.; 2011.Feasibility of photovoltaic – Thermoelectric hybrid modules.Applied Energy,**88**(8): 2785–2790.

Van Sark W.G.J.H.M., Alsema E.A., Junginger H.M., Moor H.H.C.De., Schaeffer G.J.; 2008.Accuracy of progress ratios determined from experience curves: the case of photovoltaic technology development.Prog Photovolt Res Appl,**16**(5): 441–453.

Wagner M., Spant G., and Grasser T.; 2005 .Thermoelectric Power Generation Using Large Area pn- Junctions.3 th European Conference on thermoelectric,ECT , France.

Wagner M., Span G., Holzert S., and Grasser T.; 2006.Design Optimization of Large Area Si/SiGe Thermoelectric Generators.in proc,International Conference on the Simulation of Semiconductor Process and Devices(SISPAD), Monterey,CA,: 397-400.