Performance Analysis of Solar Cells for Low-Power Energy HarvestingWireless Embedded Systems

Himanshu Sharma[1], Ahteshamul Haque[2], Prince Sachan[3], Mayank Sharma[4]
[1,3,4] KIET Group of Institutions, Ghaziabad, U.P. India
[2]Jamia Millia Islamia, New Delhi

Abstract:-In this paper, we analyse the performance of low-power energy harvesting solar cells for wireless embedded devices like wireless sensor networks (WSN) nodes.The average cell efficiency of a solar panel is between 10 – 20% worldwide. From our analysis, it is clear that the system efficiency of GaAs material solar cells is highest (24.10 %) as compared to all other solar cells.

Keywords:- Solar Cells, Energy Harvesting, Wireless Sensor Nodes

1. Introduction:

The solar energy harvesting wireless sensor networks (SEH-WSN) are used for monitoring and control applications such as light, temperature, humidity, pressure, acceleration of the industrial plants, smart cities, farms, forests, greenhouses and remote locations. The conventional Wireless Sensor Networks (WSNs) has the design limitation of high power consumption during their operation, which has been tackled by mainly duty cycle based approach till now [1]. In this paper, we propose and survey the solar energy harvesting technique as a new design solution for the energy constrained WSN nodes [2]. The solar photovoltaic (PV)energy harvesting refers to converting solar light energy into electrical energy to operate an electrical or electronic device. As applied toWSNs, the solar

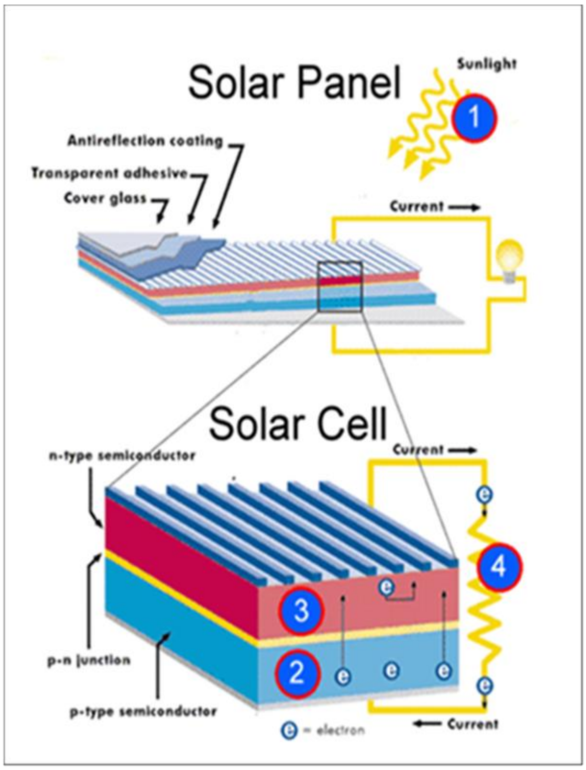


Fig.1 A Solar Cell inside the Solar Panel

light energy is converted into electrical energy and isutilized to recharge the battery of a WSN node at the operation site itself. Therefore, no need for battery replacement repeatedly once the battery energy has been discharged (as such happens in the conventional non-rechargeable battery based WSNs). Theelectrical energy harvested from solar energy (sunlight) can also be used directly to power a WSN node. Alternatively, the collected energy may be warehoused in a rechargeable battery (or

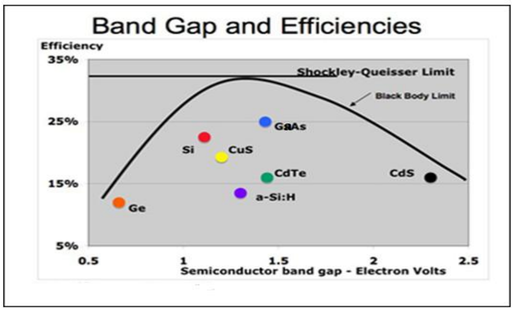
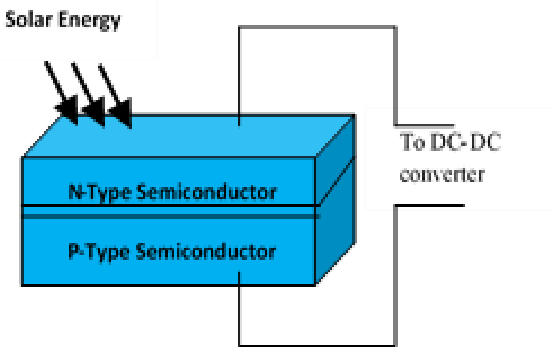


Fig.2 Band Gap and Efficiencies of various semiconductors used for solar cells

supercapacitor) for the future purpose (e.g. during nighttime when sunlight is not available). The SEH-WSNs consists of small autonomous WSN nodes attached to small size solar panels for their energy harvesting needs.The fig.1 shows a solar cell constructed inside the solar panel. A number of solar cells are connected in series-parallel combination to achieve the desired output voltage e.g. 3volts, 6 volts, 9 volts, 12 volts 48 volts and so on. The fig.2 shows the energy band gap (electron volts) and efficiency of various materials chosen for construction of solar cells. Clearly, the efficiency of GaAs material solar cells is highest 30% (theoretically) at the band gap of 1.24eV.The main design challenges at solar energy harvesting level in Solar Energy Harvesting Wireless Sensor Networks (SEH-WSN) are as follows:

- All the light energy coming from sunlight rays should be fully utilized. The SEH-WSN node should use solar energy as primary source and rechargeable battery energy as the secondary source.
- To expand the battery charging-discharging life cycle.
- Designing of simple and inventive solar charger
- To shrink the overall power use.
- To enhance the stability of the overall SEH-WSN system.
- Energy harvester circuits should be compatible existing WSN industry communication standards like IEEE 802.15.4 (ZigBee) and IEEE 1451.5 standards.
- To achieve the highest power from the sun.
- To ensure small power consumption for DC-DC Boost converter operation.
- To convey maximum power to the SEH-WSN node using the harvested energy.
- To start-up (or bootstrap) the SEH-WSNnode.
- Variations is solar radiation level, Solar Cell efficiency (η), DC –DC converter design, MPPT design and Energy Prediction Algorithms.
- Cost Effective energy harvesting solutions (cheaper than battery replacement cost)

Pertaining to the use of solar energy to power WSNs, a lot of researchers have done a lot of research work. But still, there are many design challenges in SEH-WSNs which need to be explored for further optimization.Solar panels are given a power rating in Watts, based on the amount of electricity they can produce in one hour of peak sunlight. However, these ratings are classified under ideal conditions in a laboratory, and therefore don't represent the amount of power that could be expected of that panel on a day-to-day basis. So a 250mW panel is not going to produce 250 mW of electricity, even in peak sun.



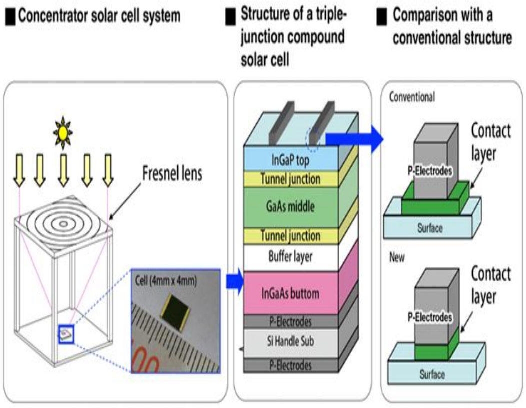


Fig.4 Concentrator System for a Heterojunction

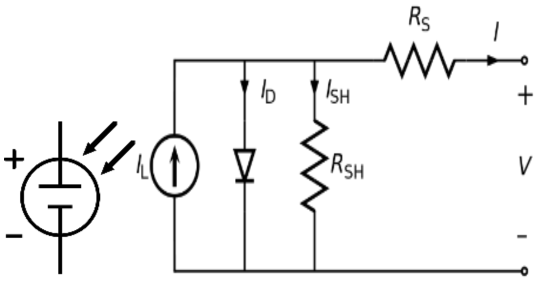


Fig. 5. Symbol Solar Cell **Fig. 6. Equivalent circuit of**

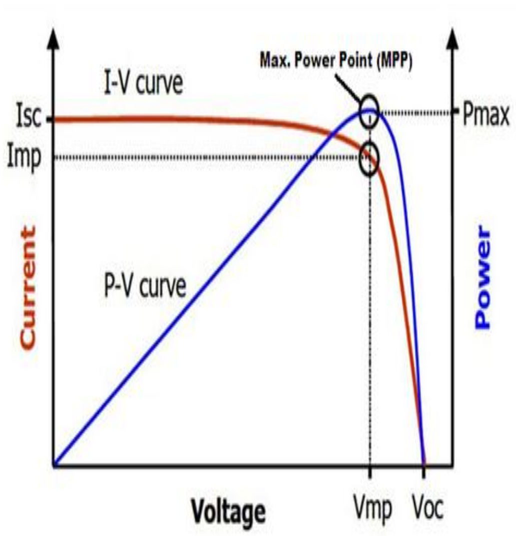


Fig. 7. V-I and P-V Characteristics

The fig. 4 shows the concentrator System for a Heterojunction solar cell which consists of different types of semiconductor layers to increase the overall efficiency. Here, the materials used in heterojunction solar cell are GA solar cell's energy conversion efficiency is the percentage of power converted from sunlight to electrical energy under "standard test conditions" (STC). Solar cell efficiency refers to the portion of energy in the form of sunlight that can be GaAs, InGaAs and silicon semiconductors.converted via photovoltaics into electricity. A Solar Cell is a semiconductor PN junction made from Si, GaAs or CdTe. The basic solar cell construction is shown in fig.3. Itconsists of N-type and P-type silicon semiconductors. The solar cellsymbol is shown in fig.5. The solar cell equivalent circuit consists of a current source, a diode, and two resistances (series and shunt) connected as shown in fig.6.

Fig.7 shows the Voltage current (V-I) and Power Voltage (P-V) characteristics of a solar cell. There are various parameters in these characteristics like Open Circuit Voltage (Voc), Short Circuit Current (Isc), Max. Voltage (Vm), Max. Current (Im) and max. power point are shown.Mathematically, the current equation of a solar cell is given as:

$$I = I_L - I_o\left(\exp\left(\frac{V}{V_T}\right) - 1\right) (1)$$

Where, I = Output current from solar cell, V = Diode voltage, Thermal Voltage(V_T)= kT/q, I_L = Light photons generated current, and I_o = Reverse saturation current. At room temperature (300K), the thermal voltage is equal to 0.0259 volts (or ~26 mV). The ability of the solar cell to convert light energy into electrical energy is called conversion efficiency and given as:

$$Efficiency\ (\eta) = \frac{FF.V_{oc}.I_{sc}}{P_i} \quad (2)$$

the maximum power can be extracted from the solar cell.Ideally, the solar cell efficiency should be high. But practically, it is limited to 5 - 15% only.

2. Literature Survey of solar (PV) cell Efficiency:

The main research issue is Optical to electrical energy conversion efficiency (η) which is tackled by choice of suitable construction materials. Ian Mathews et al.[20] have shown that column III–V solar cells (GaAs, GaInP) are better than amorphous Silicon (a-Si) solar cells. At low radiation levels, the power density of GaAs and GaInP solar cells is twice as compared to a-Si solar cells. Jung-Chuan Chou et al.[21] have shown the result of various Graphene Oxide (GO) materials on Dye-Sensitized Solar Cells (DSSCs). They obtained the optimal photoelectric conversion efficiency (η) of 5.26% using graphene material.

Li Cai and Ajeet Rohatgi[10] have investigated the effect of Post-Plasma Enhanced Chemical Vapor Deposition (PECVD) photo-assisted anneal over multi-crystalline silicon (mc-Si) solar cells. Shih-Yung Lo et al.[11] have shown fabrication of flexible Amorphous-Si (a-Si) thin-film solar cells over a parylene pattern using a direct separation process. Luigi Vesce et al.[12]have shown the formulation, implementation, and processing of the catalyst layers in monolithic dye-sensitized solar cells. Valerie Depauw et al.[13]have shown that the two-dimensional photonic crystals (2DPC) are a potential approach to maximize the light absorption in the active region of solar cells. A company named Sanyo Electric Company Ltd., a subsidiary of Panasonic, Japan manufactures volts with a short circuit current (I_{SC}) of 20 µA.

Where,FF = Fill Factor, V_{oc} is Open Circuit Voltage, I_{sc} is Short Circuit Current, and P_i is incident optical power.The maximum power point (MPP) is a point on the Powervoltage (P-V) characteristic of the solar cell, where

For outdoor applications, the AM-5608CAR solar module which is a 60 x 41 mm amorphous silicon solar cell that produces 5 V and ISC of 18 mA, is used to power a WSN node.

The efficiency of various solar cells has been compared in Table I. It compares the performances of Amorphous, Crystalline, and Polycrystalline Silicon, Dye-Sensitized, GaAs and Perovskite (CaTiO3) solar cells. The efficiency of DSSC is computed from small size solar cells of 1cm^2 each which is considered to be 10-20% high as compared to big-size cells. Here, the unit efficiency η_{cell} (%)refers to single solar cell efficiency and system efficiencyη_{panel} (%) means complete PV panel efficiency. Generally, the system efficiency is less than unit efficiency due to various interconnection losses of solar cells in a panel as shown in Table I. From the comparison table I, it is clear that the system efficiency of GaAs solar cells is highest (24.10 %) as compared to all other solar cells. But the manufacturing cost of GaAs solar cells is very high. Therefore, if we take trade-off between cost and efficiency then DSSC is the best choice having efficiency 22.74 %.

3. Solar Cell Efficiency Calculations:

$$\eta = \frac{P_{max}}{E.A_c} X\ 100\ \% \quad \ldots(3)$$

Where,

$P_{max.}$ = Max. power output (watts)

E= Incident radiation flux (Watts/m^2)

A_c = Area of Collector (m^2)

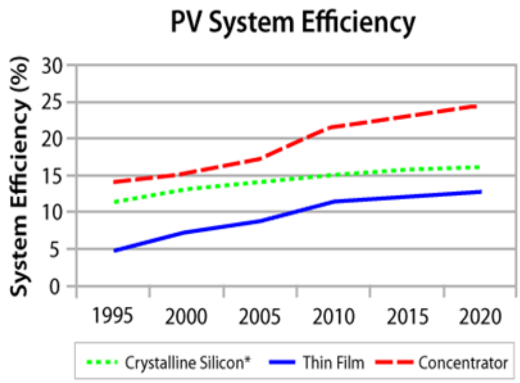


Fig. 8 PV system efficiency

manufacturer's panel will perform within 3% of its Watts rating.

- **The effect of dirt on solar panels:**
  Dirt and grime also affect the efficiency of a solar panel. This varies from panel to panel, however, it's best to factor in a loss of performance. In all of our calculations, we equate the loss of efficiency due to dirt and grime to be 5%. If you were to clean your panels regularly, they would perform better.

Sr. no.	Type of Solar Cell	No. of Cells in Panel	Open Circuit Voltage, V_{oc} (V)	Short Circuit Current, I_{sc} (µA)	Dimension (cm)		Area of Unit Cell (cm^2)	Total Area of Panel (cm^2)	Power Density At MPP ($\mu W/cm^2$)	Unit Efficiency η_{cell} (%)	System Efficiency η_{panel}(%)
1	Crystalline Silicon	8	2.0	699.56	7.7	1.2	9.24	73.12	7.91	10.22	9.10
2	Polycrystalline Silicon	8	1.5	319.07	5.6	1	5.6	44.8	3.99	5.16	4.54
3	Amorphous Silicon	9	2.89	233.35	5.2	0.61	3.18	28.62	12.07	15.59	14.03
4	Dye-Sensitized solar cell (DSSC)	4 (parallel)	0.6	194.41	1	1	1	4	22.0	28.42	22.74
5	GaAs	1	0.90	-	-	-	8.55	8.55	26.07	28.03	24.10
6	Perovskite ($CaTiO_3$)	1	0.71	200.08	-	-	5.44	5.44	19.32	20.4	17.34

Table 1: Solar Cell Efficiency Comparison:

The system efficiency of three main types of solar cells is (crystalline silicon, Thin film and concentrator) solar cells is shown in fig.8. Here, the solar cells efficiency using sunlight concentrators over the solar cells is the highest up to 25% theoretically.

4. Factors that affect the efficiency and output of a solar panel:

There are several factors that affect the panel output and efficiency of a solar panel. All of these factors must be considered when calculating solar power at any given location.

- **Manfacturer's output tolerance:**
  Most solar panels have an output tolerance +/- 3%, which means that the

- **Temperature derating:**
  Solar panels are affected by temperature. If the temperature is increased, then the efficiency of the solar panel is decreased and vice-versa.
- **Orientation Angle:**
  The direction that solar panels face, and the angle that they are mounted, also have an affect on the output of the panel. If they are not positioned at the optimum angle and direction, then the panels will not produce rated output for that location. This is a must when accurately calculating solar output.
- **DC-DC Converter efficiency:**
  The DC-DC Converter converts Direct Current (DC) at one voltage level into another DC voltage level. This process is not

100% efficient. Whilst DC-DC Converter efficiency technology is improving, it can still account for as much as an loss in efficiency. We allow for an average of 5% loss in all of our calculations.

- **Rechargeable Battery Efficiency:** If we have a hybrid system with a solar battery, the battery will not operate at its rated Wattage or power capacity always.
- **Commercial Aspects:** The most efficient commercially available solar panels on the market today have efficiency ratings as high as 22.5%, whereas the majority of panels range from 14% to 16% efficiency rating. SunPower panels are known for being the most efficient solar panel brand available on the market. Though they will come with a higher price tag, SunPower will often be the consumer favourite for anyone concerned with efficiency as a primal metric of interest.

5. Results and Conclusion:

In this paper, the design challenges of solar energy harvesting and efficiency of various solar cells have been analysed for low power energy harvesting applications like wireless sensor networks. From the comparison table I, it is clear that the system efficiency of GaAs solar cells is highest (24.10 %) as compared to all other solar cells. But the manufacturing cost of GaAs solar cells is very high. Therefore, if we take trade-off between cost and efficiency then DSSC is the best choice having efficiency 22.74 %.

References:

[1]. Akyildiz I.F., W. Su, Y. Sankarasubramaniam, E. Cayirci, “Wireless sensor networks: a survey”,Computer Networks, Elsevier 38, 393–422 (2002).

[2]. Sujesha Sudevalayam and Purushottam Kulkarni, “Energy Harvesting Sensor Nodes: Survey and Implications”,IEEE CommunicationsSurveys&Tutorials 13(3), 443-461 (2011).

[3]. National Renewable Energy Laboratory (NREL), U.S. Department of Energy, Golden, Colorado, USA [https://www.nrel.gov].

[4]. M. Rasheduzzaman, P. B. Pillai, A. N. C. Mendoza, and M. M. De Souza, “A study of the performance of solar cells for indoor autonomous wireless sensors,” IEEE 10th International Symposium on Communication Systems, Networks and Digital Signal Processing (CSNDSP), pp. 1–6, IEEE, 2016.

[5]. Martin A. Green, Keith Emery, Yoshihiro Hishikawa, Wilhelm Warta and Ewan D. Dunlop, “Solar cell efficiency tables (version 47)”, Journal of Progress in photovoltaics: research and applications, Volume 24, Issue 1, 24 Nov. 2015, Wiley Online Library [Available online] http://onlinelibrary.wiley.com/ doi/10.1002/pip.2728/pdf.

[6]. Himanshu Sharma, Ahteshamul Haque, and Zainul A. Jaffery “Solar energy harvesting wireless sensor network nodes: A survey”, Journal of Renewable and Sustainable Energy, published by American Institute of Physics (AIP), USA, vol.10, no.2, pp 1-33, March 2018.(SCI Journal, Impact Factor: 2.14). [Available online: https://doi.org/10.1063/ 1.5006619]

[7]. Himanshu Sharma, Ahteshamul Haque, Zainul Abdin Jaffery, “Design Challenges in Solar Energy Harvesting Wireless Sensor Networks” Nanotechnology for Instrumentation and Measurement (NANOFIM) Workshop, 3rd IEEE International Conference, Gautam Budh University (GBU), Greater Noida, November 16, 2017.

[8]. Himanshu Sharma, Pooja Agarwal, “A survey of Energy Harvesting Techniques for Wireless sensor Networks” AKGEC International Journal of Technology, vol.8, issue 1, pp.6, June 2017.

[9]. Himanshu Sharma, Rohit Tiwari, “Industrial Wireless Sensor Networks (IWSN): Design and Challenges”, IOSR Journal of Electronics and Communication Engineering (IOSR-JECE), ISSN: 2278-2834, volume11, issue 4, ver.1, DOI:10.9790/2834-1104, Aug.2016.(UGC approved Journal)

[10]. Li Cai and Ajeet Rohatgi, “Effect of Post-PECVD Photo-Assisted Anneal on Multicrystalline Silicon Solar Cells”, IEEE

Transactions on electrondevices, 44(1), 97-102 (1997).

[11]. Shih-Yung Lo, Dong-Sing Wuu, Chia-Hao Chang, Chao-Chun Wang, Shui-Yang Lien, and Ray-Hua Horng, "Fabrication of Flexible Amorphous-Si Thin-Film Solar Cells on a Parylene Template Using a Direct Separation Process", IEEE Transactions on Electron Devices, 58(5),1433-1438 (2011).

[12]. Luigi Vesce, Riccardo Riccitelli, Girolamo Mincuzzi, Alessio Orabona, Giuseppe Soscia, Thomas M. Brown, Aldo Di Carlo, "Fabrication of Spacer and Catalytic Layers in Monolithic Dye-Sensitized Solar Cells, IEEE Journal of Photovoltaics, 3(3), 1004-1011 (2013).

[13]. Valerie Depauw, Xianqin Meng, Ounsi El Daif, Guillaume Gomard, Lo¨ıc Lalouat, Emmanuel Drouard, Christos Trompoukis, Alain Fave, Christian Seassal, and Ivan Gordon, "Micrometer-Thin Crystalline-Silicon Solar Cells Integrating Numerically Optimized 2-D Photonic Crystals", IEEE Journal of Photovoltaics, 41, 215-223 (2014).