Development of High-Efficiency Photovoltaic Solar Cells

Musa Abubakar Bilya(1)

ABSTRACT—In this paper, we look into the tremendous progress made in recent years on a number of photovoltaic (PV) materials and devices in terms of their conversion efficiencies. Ultrahigh-efficiency (Eff. > 30%) PV cells have been fabricated from gallium arsenide (GaAs) and its ternary alloys such as gallium indium phosphide (GaInP2). The high-efficiency GaAs based solar cells are being produced on a commercial scale, particularly for space applications. Efficiencies in the range of 17.7% to 23.8% have been achieved in silicon-based devices fabricated from both multi-crystalline and single-crystal materials. The major advances made in the efficiency of various thin-film solar cells based on amorphous silicon (a Si:H), copper gallium indium diselenide (CIGS2), and cadmium telluride materials are also discussed. And finally, this paper gives a brief overview of the recent progress made in Photovoltaic cell efficiencies.

Index Terms-—Amorphous, Efficiency, Thin-film, Photovoltaic, polycrystalline.

◆

1.0 **INTRODUCTION**

The primary objective of the photovoltaic (PV) solar cell research and development is to bring about increased efficient Photovoltaic Solar Cells, and the reduction in the cost of production to a level that will be competitive with the conventional ways of generating power. To achieve this, there has to be a tremendous increase in the efficiency of Photovoltaic materials and devices. In recent years, leading progress has been made to improve the efficiency of almost all the leading Photovoltaic materials and devices. Basically, there are two approaches to increasing the efficiency of solar cells:

i. Selecting the semiconductor materials with appropriate energy gaps to match the solar spectrum and optimizing their electrical, structural and optical properties.

ii. Innovative device engineering, which can enable more effective charge collection as well as better use of the solar spectrum, through single and multi-junction approaches.

However, in this scenario it is possible to arbitrarily classify a select group of materials into different efficiency regimes:

1. Ultrahigh-efficiency Solar Cell devices (Eff. >30%): are typically achieved by using multi-junction tandem cells involving semiconductors such as GalliumArsenide and GalliumIndiumPhosphide .

2. High-efficiency solar cells (Eff. >20%): which are generally fabricated by the use of high-quality, single-crystal silicon materials in a novel device configurations that take advantage of the advances in microelectronic technologies.

3. High-efficiency Solar cells (with efficiency between 11.5% to 19.5%) are typical of a number of polycrystalline and amorphous thin-film semiconductor materials such as polycrystalline silicon, amorphous and microcrystalline silicon, copper gallium indium selenide (CIGS), and cadmium telluride (CdTe).

4. Moderate-efficiency cells (Eff. <13%) are typical of some of the newer materials such as dye-sensitized nanostructure TiO_2 solar cells, which have the potential for being very low-cost devices.

This paper gives a brief overview of the current status of efficiencies in some materials and devices in each of the above categories.

1.10 ULTRAHIGH EFFICIENCY SOLAR CELLS (Eff. >30)

In designing solar cell structures, one of the following two approaches is generally taken:

i. Individual solar cells are grown separately, and then mechanically stacked one above the other. For the combination of a high and low bandgap material, the illumination should first strike the absorber with the high bandgap, because, the light with high energy will be absorbed with a high output voltage. Furthermore, this material will be transparent for low energy light which can be passed on to the second absorber with the lower bandgap.

ii. Each cell is grown monolithically with a tunnel-junction interconnect. The tandem (where two absorbers are stacked), combination of a GaInP2 (with the band gap, Eg = 1.9 eV) and GaAs has a theoretical efficiency of ~36%. The most exciting development in recent years has been the fabrication of a high-efficiency (Eff. about 30%) monolithic tandem cell consisting of GaInP2 (top cell) and GaAs (bottom cell) with a low-resistivity tunnel-junction interconnect. This was invented and developed at the National Renewable Energy Laboratory (Bertness *et al.*, 1994). Very recently, the efficiency has been improved further to 30.28% in an essentially similar structure that incorporates a GaInP2 tunnel junction and AlInP diffusion barrier (Takamoto *et al.*, 1997a).

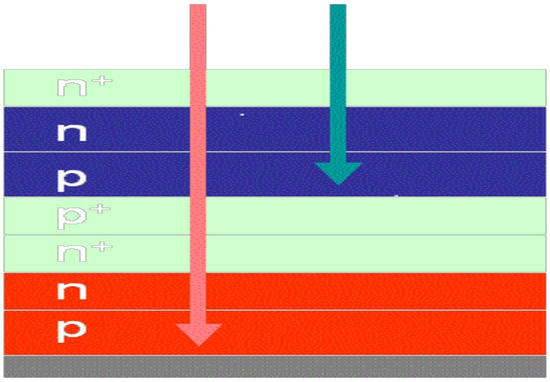

Fig 1: Monolithic Tandem Cells

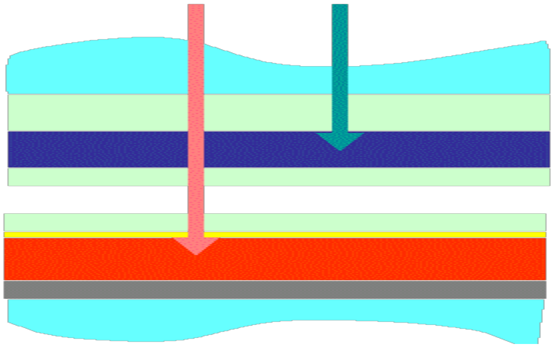

Fig 2: Stacked Tandem Cells

Fig 1&2: Schematic design of monolithic (top) and stacked (bottom) tandem cells. Irradiation passes from the top into a high bandgap absorber for high energy photons (blue colour). Light with lower energy is passed through a low band gap absorber (red colour). The Monolithic approach (top) requires a transparent tunneling junction. The stacked devices (bottom) consist of two isolated cells, here a thin film design for the combination of a superstrate and a substrate solar cell (K.W Mitchel et. al 1990).

The efficiency of a two-junction tandem cell has almost reached its practical limit and any further improvement will require incorporation of a third junction consisting of a semiconductor with a bandgap in the range of 0.95ev to 1.10 eV. The addition of a third junction involving Ge has been shown to boost the efficiencies further. However, the bandgap of Ge is not optimal for a three-junction device. Significantly higher efficiencies (Eff. >35%) can be achieved if the third junction could be fabricated from a 1.0-eV material that is lattice-matched to GaAs(Ge). One such material currently being investigated involves GaInNAs, whose bandgap can be adjusted to 1.0 eV by adding a small concentration (~3%) of N in GaInAs and can be latticed-matched to GaAs.

1.20 HIGH-EFFICIENCY CELLS (Eff. >20%)

Photovoltaic conversion efficiencies greater than 20% can be achieved by using single-crystal silicon or single junction GaAs semiconductor materials. Extraordinary progress has been made in recent years in achieving record-level efficiencies of 22% and 24% in single-crystal Si materials grown by the Czochralski (CZ) and Float Zone (FZ) methods, respectively. Two of the device structures that incorporate many improved design features that led to such high efficiencies are:

i. **The point-contact solar cells**:

Is designed to convert as many incident photons into electrical current as possible. A new type of silicon photovoltaic cell designed for high-concentration applications is presented. The device is called the point-contact cell and shows potential for achieving energy conversion efficiencies close to 28 percent at the design operation, and 60° cell temperature. This cell has alternating n and p regions. A two-layer metallization on the bottom provides contact. Gradual refinements of the first generation of silicon solar cells eventually led to designs with surfaces employing texturing and anti-reflective coatings to minimize light reflection across the solar spectrum (Kurt Muella and Ricardo, 2010).

ii. **The passivated emitter rear localized (PERL) cell**:

A modified version of the PERL cell, the laser grooved buried-contact solar cell, is under intense development at UNSW (University of New South Wales). However, the processing techniques used for the fabrication of this laboratory-scale, high-efficiency solar cells are very complex for cost-effective production of terrestrial solar cells. Hence, recent research and development efforts are directed toward simplified processing schemes. One such processing scheme involves random pyramid passivated emitter and rear cell (RP-PERC), which provides a significant advantage over the modified PERL process (Glunz *et al.*, 1997). The process has led to a new record value of 22% efficiency for Czochralski-silicon, CZ-Si.

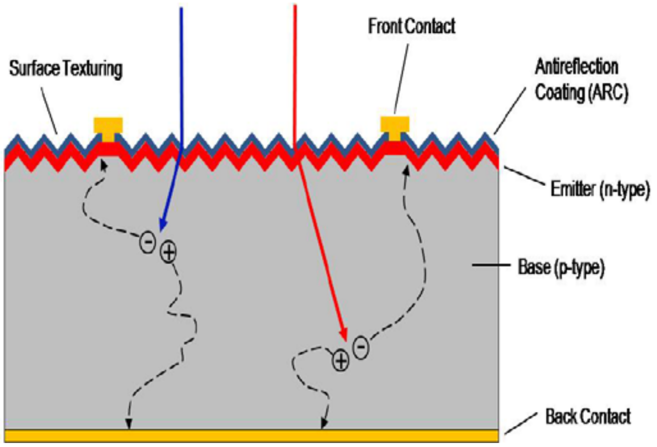

Fig 4: The Point Contact Solar Cell

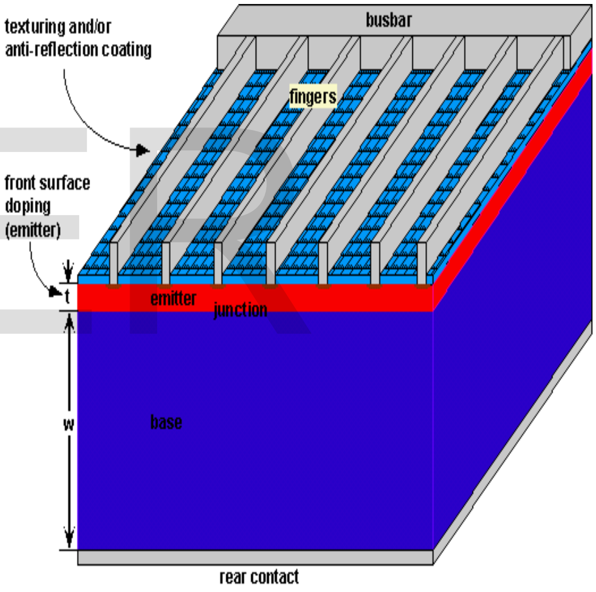

Fig 5: Passivated emitter rear localized solar cell

PV-conversion efficiencies greater than 25% have been achieved on single-junction solar cells fabricated in epitaxially grown GaAs on a single-crystal substrate. Efficiencies of 20% to 21% have been achieved on a submillimeter grain-size poly-Ge substrate, which has the potential for significant cost reduction (Venkatasubramanian *et al*., 1977).

1.21 Thin-Film Silicon Solar Cells: Thin-film Si solar cells have received attention due to their potential for large areas and low-cost manufacturing. The abundance of raw materials makes these solar cells more attractive as a renewable energy source compared to other compound semiconductor thin-film solar cells. In addition, these solar cells exhibit a low temperature coefficient, which is especially beneficial in high insolation areas, including the Sun Belt region**.** Thin-film silicon offers an exciting opportunity for the development of efficient low-cost solar cells. Recent theoretical calculations show that it is possible to achieve 17% efficiency in a 2-µm-thick silicon film if the grain size is larger than 10-µm and the dislocation density is less than 106cm-2.17.6% conversion efficiency for a thin-film silicon solar cell deposited by chemical vapor deposition onto a highly doped, electrically inactive Si-wafer as reported by the UNSW group. The most exciting recent development in this area is the achievement of 9.8% efficiency in a 3.5-µm poly-silicon thin film in the so-called STAR cell structure (Yamamoto *et al*., 1997).

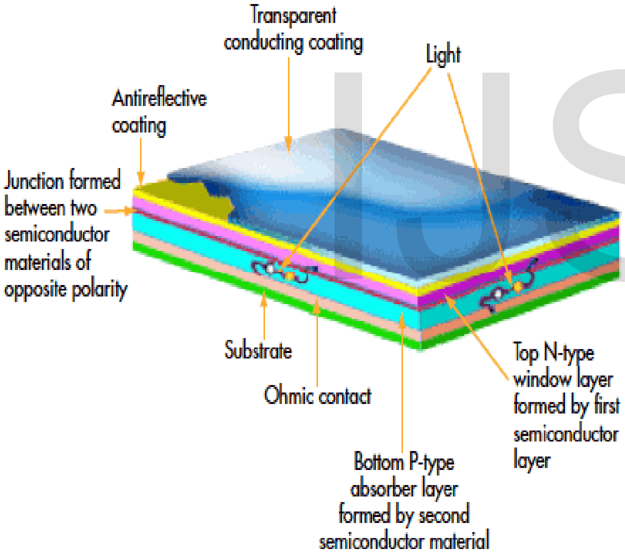

Fig 5: Thin Film solar Cell

Thin film solar panels are also called amorphous silicon photovoltaic cells and tend to be flexible, not rigid like poly or mono panels. They are made of silicon material placed between flexible laminate, steel or glass. One benefit of thin film solar panels that the other types do not have, is that they don't suffer decrease in output when temperatures go up. Some may even have a slight increase in their outputs. Because of this, thin film solar panels often have an actual output that's very close to the one they are rated for. (ontariosolarfarms.com)

1.22 Amorphous Silicon Thin-film Solar Cells

Among the thin-film PV technologies, hydrogenated amorphous silicon (a-Si:H) holds one of the most promising options for low-cost solar cells. It is by far the most mature and commercially viable technology. The technology of a-Si:H for PV is based on two types of device design: a single-junction and multi-junction p-n structure. Although major progress has been made in recent years in improving the deposition processes, material quality, device design, and manufacturing processes, the improvement of cell efficiency appeared to hit a bottleneck. It is generally recognized that any significant increase in efficiency can only be achieved by using multi-junction devices. It is indeed the case as shown by the achievement of a world-record stable efficiency of 13% (initial efficiency of 14.6%) in a triple-junction structure (Yang *et al.*, 1997). The previous best stable efficiency was 11.8%. This was accomplished by optimization of factors such as hydrogen dilution for film growth, bandgap profiling, current matching, and microcrystalline tunnel junction. Similarly, a new record in stabilized efficiency of 9.5% for 1200-cm2 a-Si:H/a-SiGe:H has been reported recently (Hishikawa *et al.*, 1997).
This was possible by low-temperature (180°C) deposition of a-SiGe:H film while maintaining good optoelectronic properties.

In an effort to improve the efficiency, stability, and structural properties of a-Si thin films, a new class of material, hydrogenated microcrystalline silicon (µC-Si:H), is emerging as a contender for PV applications.

1.30 MULTICRYSTALLINE SILICON AND THIN FILM SOLAR CELLS (Eff. =12.5% -19.5%)

The efficiencies of most of the leading solar cell materials and devices that are currently being developed for large-scale commercialization falls in the range of 12%-20%. These include large-grain polycrystalline silicon, thin-film amorphous silicon, and microcrystalline silicon thin films, polycrystalline CIGS, and CdTe. The conversion efficiencies and current status of these materials are briefly reviewed here, thus:

1.30 Polycrystalline Silicon Solar Cells

Presently, cast polycrystalline silicon (MC-Si), accounting for nearly 50% of the Si-based solar cells manufactured worldwide, is a dominant PV technology. For the first time, solar cell efficiencies of 18.15% have been achieved in large-grained poly-Si ingots by using a processing temperature not exceeding 900°C (Rohatgi *et al.*, 1996a). Further improvement in cell efficiency to 18.6% has been achieved by decreasing the rear surface recombination velocity to 2 x 103 cm/s with deeper Al alloys (Rohatgi *et al.*, 1996b). Subsequently, the UNSW group has achieved 18.2% efficiency in a MC-Si grown by the heat exchange method (HEM) by using their standard PERL process with processing temperatures exceeding 1050°C (Zhao *et al.*, 1997).

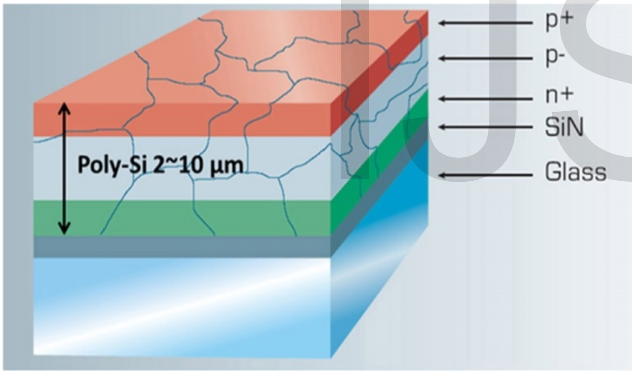

Fig 6: Schematic structure of polycrystalline silicon (poly-Si) thin film solar cells (not to scace)

From Figure 6 above, p: p-type silicon (doped with boron), n: n-type (doped with phosphorous). SiN: silicon monotride.

1.32 THIN-FILM COPPER INDIUM GALLIUM DISELENIDE (CIGS) SOLAR CELLS

Cu(In,Ga)Se2(CIGS) is by far the most promising material for thin-film PV devices. Recently, a record efficiency of 18.8% has been achieved in a typical device structure consisting of glass/Mo/CIGS/CdS/ZnO fabricated by the physical vapor deposition (PVD) technique (Contreras *et al.*, 1999). This remarkable achievement was made possible by optimization of the optical, electrical, and structural properties of CIGS absorber layer and appropriate design and control of the component layers and their interfaces under different growth conditions. The deposition of a high-quality CIGS absorber layer is the crucial processing step and thus far, the PVD technique appears to be the preferred method. Although PVD (the Physical Vapor Deposition) is the preferred method for high-efficiency cell fabrication, recent results suggest that a wide variety of techniques, such as sputtering, spray pyrolysis, closed-space sublimation (CSS), molecular-beam epitaxy (MBE), and electrodeposition, are currently being pursued. Among these, electrodeposition and electrolysis deposition offer a low-cost option for fabricating. Recently, 15.4%- and 12.4%-efficient thin-film precursors (Bhattacharya *et al.*, 1999). In all of these processes, tailoring of the bandgap of the CIGS absorber layer toward the optimum range of 1.3 to 1.5 eV and adjusting the Ga/(Ga+In) ratio to 0.4:0.75, respectively, is crucial. The optimum ratio for high efficiency cells thus far has been approximately 0.27. The effort to increase the Ga content generally results in a decrease of cell efficiency, which is largely due to compositional non-uniformity, phase separation, film morphology, and spatial distribution of Ga caused by diffusion. The spatial non-uniformity is sometimes tailored into the device structure to optimize cell efficiency.

1.33 CADMIUM TELLURIDE THIN-FILM SOLAR CELL

Enormous progress has been made in recent years on CdTe/CdS thin-film solar cells in which CdTe is the p-type absorber material. The optimum bandgap (1.44 eV) and high absorption coefficient due to direct optical transition make it an ideal PV material with theoretical efficiency of 30%. One of the major advantages of CdTe/CdS thin-film solar cells is the low-cost fabrication option. A number of relatively simple, low-cost methods have been used to fabricate solar cells with efficiencies in the range 10% to 16%. Some of the low-cost deposition methods that show promise include: i.closed-space sublimation, ii.spray deposition, iii. electrodeposition iv. screen printing, and v. puttering. All of these techniques are being considered for large scale manufacturing by several industries. Most recently, a record 16% efficiency has been reported in a CdS(0.4-µm)/CdTe (3.5-µm) thin-film solar cell in which

CdS and CdTe films are deposited by metal-organic CVD deposition (MOCVD) and CSS techniques, respectively (Aramoto *et al*., 1997). Most of the high-efficiency solar cells use a superstrate device configuration in which CdTe is deposited on the CdS window layer. A typical device structure consists of glass/CdS/CdTe/Cu-C/Ag. In most cases, the post-deposition heat treatment of the CdTe layer in the presence of $CdCl_2$ is essential for the optimization of device performance.

1.40 MODERATE-EFFICIENCY LOW-COST SOLAR CELLS: (Eff. >12%)

A new type of PV cell based on the dye-sensitization of thin (10.20µm) nanocrystalline films of TiO2 in contact with a non-aqueous electrolyte has received a great deal of attention worldwide. The cell is very simple to fabricate and, in principle, its color can be tuned through the visible spectrum, ranging from being completely transparent to black opaque by changing the absorption characteristics of the dye. The highest present efficiency of the dye-sensitized photochemical solar cell is about 11%. The cell has the potential to be a low cost PV option. Unique applications include PV power windows and photoelectrochronic windows.

2.0 CONCLUSION

Remarkable progress has been made in recent years in improving the conversion efficiencies of a number of PV devices. Ultrahigh-efficiency (Eff.>30%) solar cells have been fabricated from gallium arsenide and its ternary alloys. Record-level efficiencies have been achieved on a silicon-based solar cell based on single-crystal and polycrystalline silicon. Various thin-film technologies such as amorphous silicon, CIGS, and CdTe materials and devices continue to show significant advances in their conversion efficiency. Some exciting possibilities are emerging on new PV devices with moderate efficiencies and potential for lower cost.

3.0 REFERENCES

[1] Hibino T., Omura K., Ohyama H. and Murozono M. (1997): "16% efficient thin-film CdS/CdTe solar cells". *Proc. 26th IEEE PVSC* , Anaheim, 343-346.

[2] Bertness K. et al. "(1994). 29.5% efficient GaInP/GaAs tandem solar cells". *Appl Phys Lett*, **65:** 989-991.

[3] Bhattacharya R.N., Batchelor W., Hitner, J., and Sites, J., (1999). Thin-film CIGS photovoltaic cells from solution-based precursor layers. *Applied Phys. Letts*., **75**, 1431-1433.

[4] Contreras, M., Egaas, B., Ramanathan, K., Hiltner, J., Swartzlander, A., Hasoon, F., and Noufi, R. (1999).

[5] Progress toward 20% efficiency in Cu(In,Ga)Se2 polycrystalline thin-film solar cells. *Prog. Photovolt: Res.Appl*. **7**, 311-316.

[6] Glunz S.W., Knobloch J., Biro D. and Wettling W. (1997). Optimized high-efficiency silicon solar cells. *Proc 14th Europ PVSC*, Barcelona.

[7] Hishikawa Y., Kinoshita T., Shima M, Tanaka M., Kiyama S., Tsuda S. and Hakano S. (1997). Optical confinement and optical loss in high-efficiency a-Si solar cells. *Proc. 26th IEEE PVSC,* Anaheim, 615-618.

[8] Krygowski T., Rohatgi A. and Ruby D. (1997). Simultaneous P&B diffusion, in situ surface passivation, impurity filtering and gettering for high efficiency Si solar cells. *Proc 26th IEEE PVSC*, Anaheim, 235-238.

[9] Narasimha S. and Rohatgi A. (1997). Optimized Al back surface field techniques for Si solar cells. *Proc. 26th IEEE PVSC*, Anaheim, 63-66

[10] Rohatgi A., Narasimha S., Kamra S. and Khattak C.P. (1996a). Fabrication and analysis of record high 18.2% efficient solar cells on multicrystalline silicon material. *IEEE Elec Dev Lett*, **17**, 401-403.

[11] Rohatgi A., Narasimha S., Kamra S., Doshi P., Khattack C.P., Emery K. and Field H. (1996b). Record high 18.6%

efficient solar cell on HEM multicrystalline material. *Proc 25th IEEE PVSEC*, 741-744.

[12] Takamoto T., Ikeda E., Kurita H. and Ohmori M. (1997a). Over 30% efficient InGaP/GaAs tandem solar cells. *Appl Phys Lett*, **70**, 381-383.

[13] Takamoto T., Yamaguchi, M., Taylor S.J., Ikeda E., Agui T. and Kurita H. (1997b). High-efficiency radiationresistant InGaP/GaAs tandem solar cells. *Proc. 26th IEEE PVSC* , Anaheim, 887-890.

[14] Venkatasubramanian R., Siivola E., O.Quinn B., Keyes B., and Ahrenkiel R. (1997). Pathways to highefficiency GaAs solar cells on low-cost substrates. *Future Generatio*16. *16.* Photovoltaic Technologies*: First NREL Conference,* Denver, AIP Conf. Proceedings 404, McConnell R., (ed.), 411-418.

[15] Yamamoto K., Yoshimi M., Suzuki T., Okamoto Y., Tawada Y., and Nakajima A. (1997). Thin film poly-Si solar cell with star structure on glass substrate fabricated at low temperature. *Proc. 26th PVSC*, Anaheim, 575-580.

[16] Yang J., Banerjee A., Glatfelter T., Sugiyama S. and Guha S. (1997). Recent progress in amorphous silicon alloy leading to 13% stable efficiency. *Proc. 26th IEEE PVSC,* Anaheim, 563-668

[17] Zhao J., Wang A. and Green M.A. (1997). High efficiency multicrystalline silicon solar cells using standard high-temperature float-zoned cell processing. *Prog Photovolt*, 1997, **5**: 169-

Author's Details_
Name_Musa Abubakar Bilya
Institution_ Currently pursuing M.Sc. Physics at the Jodhpur National University, Rajasthan India
Country: Nigeria
Email_ musbilrak.2007@yahoo.com
Paper ID_ I068939