May 2000 • NREL/CP-590-28060

Conference Paper

Recent Developments in High-Efficiency PV Cells

Preprint

Satyen K. Deb

To Be Presented at the World Renewable Energy Congress VI
Brighton, U.K.
July 1-7, 2000

National Renewable Energy Laboratory

1617 Cole Boulevard
Golden, Colorado 80401-3393

NREL is a U.S. Department of Energy Laboratory
Operated by Midwest Research Institute • Battelle • Bechtel

Contract No. DE-AC36-99-GO10337

RECENT DEVELOPMENTS IN HIGH-EFFICIENCY PV CELLS

SATYEN K. DEB
National Renewable Energy Laboratory
Golden, CO 80401-3393 USA

ABSTRACT

Enormous progress has been made in recent years on a number of photovoltaic (PV) materials and devices in terms of conversion efficiencies. Ultrahigh-efficiency (>30%) PV cells have been fabricated from gallium arsenide (GaAs) and its ternary alloys such as gallium indium phosphide ($GaInP_2$). The high-efficiency GaAs-based solar cells are being produced on a commercial scale, particularly for space applications. Efficiencies in the range of 18%–24% have been achieved in traditional silicon-based devices fabricated from both multicrystalline and single-crystal materials. Major advances in efficiency have also been made on various thin-film solar cells based on amorphous silicon (aSi:H), copper gallium indium diselenide (CIGS), and cadmium telluride materials. This paper gives a brief overview of the recent progress in PV cell efficiencies based on these materials and devices.

KEYWORDS

Thin films, solar cells, photovoltaics, amorphous silicon, copper gallium indium diselenide, cadmium telluride, gallium arsenide, gallium indium phosphide, titanium dioxide

INTRODUCTION

The primary objective of the worldwide photovoltaic (PV) solar cell research and development is to reduce the cost of PV cells and modules to a level that will be competitive with conventional ways of generating power. One way to achieve this is to significantly increase the conversion efficiency of PV materials and devices. Major advances have been made in recent years in improving the efficiency of almost all of the leading PV materials and devices. Basically, there are two approaches to increasing the efficiency of solar cells: (1) selecting the semiconductor materials with appropriate energy gaps to match the solar spectrum and the optimizing their optical, electrical, and structural properties; and (2) innovative device engineering, which enables more effective charge collection as well as better utilization of the solar spectrum through single and multijunction approaches. Although, there is no accepted definition of what constitutes a high efficiency device it is very much a function of a given technology and how it impacts the overall cost structure. However, in the current scenario it is possible to arbitrarily classify a select group of materials into different efficiency regimes: (1) ultrahigh-efficiency devices (η>30%) are typically achieved by using multijunction tandem cells involving semiconductors like GaAs and $GaInP_2$; (2) high-efficiency cells (η>20%) are generally fabricated by using high-quality, single-crystal silicon materials in novel device configurations that take advantage of advances in microelectronic technologies; (3) high-efficiency cells (η=12%-20%) 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); and (4) moderate-efficiency cells (η<12%) 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 representative materials and devices in each of the above categories.

ULTRAHIGH EFFICIENCY III-V SOLAR CELLS (η=30%–40%)

In designing tandem cell structures, one of two approaches is generally taken: (1) individual cells are grown separately and then mechanically stacked one above the other, or (2) each cell is grown monolithically with a tunnel-junction interconnect. The tandem combination of a $GaInP_2$ (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 (29.5%) monolithic tandem cell (Fig. 1) consisting of $GaInP_2$ (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 $GaInP_2$ tunnel junction and AlInP diffusion barrier (Takamoto *et al.,* 1997a). By virtue of its superior radiation resistance, these cells are now being produced on a large scale for space applications. A new world-record efficiency of 26.9% AMo has been reported recently (Takamoto *et al.,* 1997b), which is an improvement over the previously reported efficiency of 25.7%.

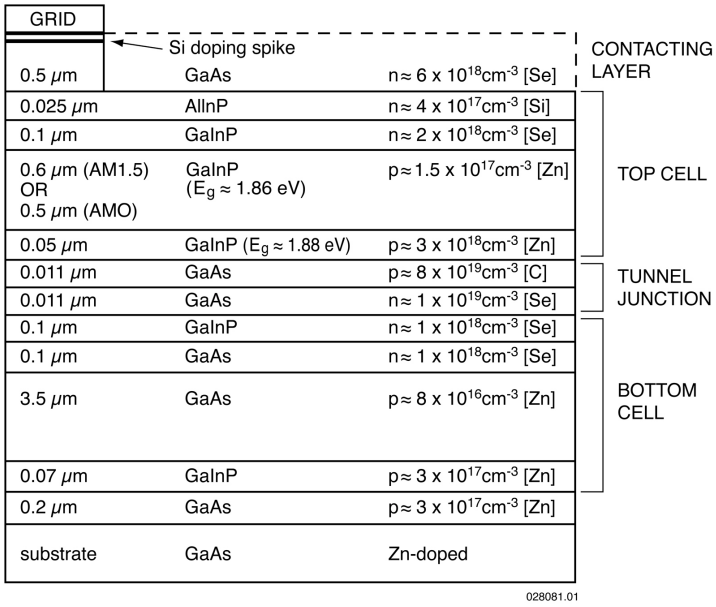

Fig.1. GaInP/GaAs tandem cell

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 0.95–1.1 eV. Theoretical efficiency for a three-junction cell at AM 1.5 is over 45%, which implies a practically achievable efficiency approaching 40% if a suitable combination of materials can be developed.

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 (η>35%) can be achieved if the third junction could be fabricated from a 1-eV material that is lattice-matched to GaAs(Ge). One such material currently being investigated involves GaInNAs, whose bandgap can be adjusted to 1 eV by adding a small concentration (~3%) of N in GaInAs and can be latticed-matched to GaAs.

HIGH-EFFICIENCY CELLS (η>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 (1) the point-contact solar cells developed by the Stanford University group in Fig. 2, and (2) the passivated emitter rear localized (PERL) cell developed by the University of New South Wales (UNSW) group in Fig. 3. A modified version of the PERL cell, the laser-grooved buried-contact solar cell, is under intense development at UNSW. However, the processing techniques used for the fabrication of these 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 CZ-Si.

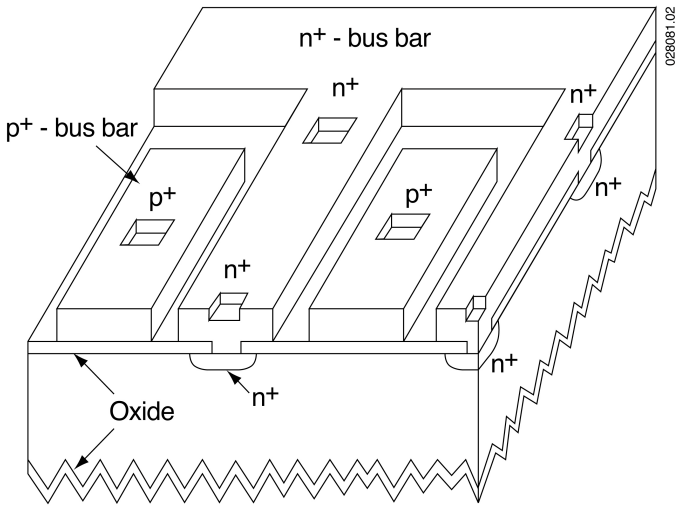

Fig. 2 Rear point contact solar cell

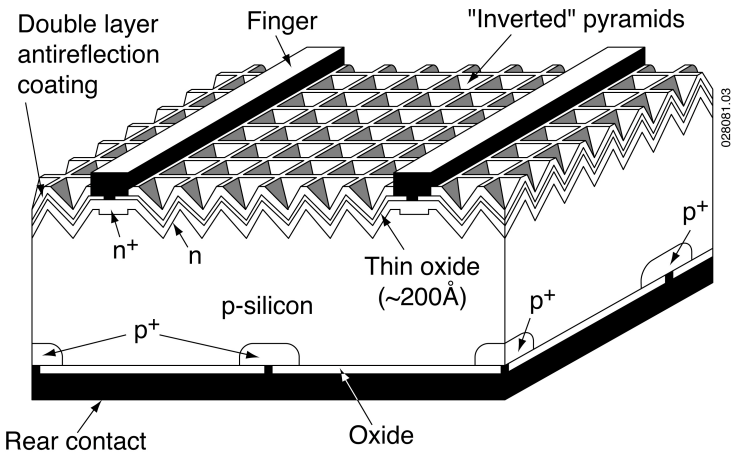

Fig. 3. Structure of the PERL cell

A novel approach involving simultaneous diffusion of B and P in Si from a spin on solid source and growth of an in situ passivating oxide in a single-step process has been successfully used to achieve 20.1% in FZ-grown Si (Krygowski *et al.,* 1997).

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%–21% have been achieved on a submillimeter grain-size poly-Ge substrate, which has the potential for significant cost reduction (Venkatasubramanian *et al*., 1977).

MULTICRYSTALLINE SILICON AND THIN FILM SOLAR CELLS (η=12%-20%)

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.

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 18.2% 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 10^3 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).

THIN-FILM SILICON SOLAR CELLS

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 $10^6 cm^{-2}$. A 17.6% conversion efficiency for a thin-film silicon solar cell deposited by chemical vapor deposition onto a highly doped, electrically inactive Si-wafer has been 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).

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 multijunction p-i-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 multijunction 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-cm^2 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 opto-electronic 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.

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

$Cu(In,Ga)Se_2$(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 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 electroless deposition offer a low-cost option for fabricating. Recently, 15.4%- and 12.4%-efficient thin-film

CIGS-based PV devices have been fabricated from solution-based electrodeposited and electroless-deposited 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.

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%–16%. Some of the low-cost deposition methods that show promise include (1) closed-space sublimation, (2) spray deposition, (3) electrodeposition, (4) screen printing, and (5) sputtering. 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.

MODERATE-EFFICIENCY LOW-COST SOLAR CELLS: (η>12%)

A new type of PV cell based on the dye-sensitization of thin (10–20μm) nanocrystalline films of TiO_2 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 photoelectrochromic windows.

CONCLUSION

Remarkable progress has been made in recent years in improving the conversion efficiencies of a number of PV devices. Ultrahigh-efficiency (η>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.

ACKNOWLEDGEMENT

This work was supported by the U.S. Department of Energy under Contract No. DE-AC36-99GO10337.

REFERENCES

Aramoto T., Kumazawa S., Higuchi H., Arita T., Shibutani S., Nishio T., Nakajima J., Tsuji M., Hanafusa A., 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.

Bertness K., Kurtz S., Friedman D., Kibbler A., Kramer C. and Olson J. (1994). 29.5% efficient GaInP/GaAs tandem solar cells. *Appl Phys Lett,* **65:** 989-991.

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.

Contreras, M., Egaas, B., Ramanathan, K., Hiltner, J., Swartzlander, A., Hasoon, F., and Noufi, R. (1999). Progress toward 20% efficiency in Cu(In,Ga)Se_2 polycrystalline thin-film solar cells. *Prog. Photovolt: Res. Appl*. **7**, 311-316.

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

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.

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.

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

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.

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.

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

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

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

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.

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

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**: 169-174.

REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	May 2000	conference paper

4. TITLE AND SUBTITLE
Recent Developments in High-Efficiency PV Cells

5. FUNDING NUMBERS
C
TA: PV001501

6. AUTHOR(S)
Satyen K. Deb

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401-3393

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
CP-520-28060

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

Enormous progress has been made in recent years on a number of photovoltaic (PV) materials and devices in terms of conversion efficiencies. Ultrahigh-efficiency (>30%) PV cells have been fabricated from gallium arsenide (GaAs) and its ternary alloys such as gallium indium phosphide ($GaInP_2$). The high-efficiency GaAs-based solar cells are being produced on a commercial scale, particularly for space applications. Efficiencies in the range of 18%–24% have been achieved in traditional silicon-based devices fabricated from both multicrystalline and single-crystal materials. Major advances in efficiency have also been made on various thin-film solar cells based on amorphous silicon (aSi:H), copper gallium indium diselenide (CIGS), and cadmium telluride materials. This paper gives a brief overview of the recent progress in PV cell efficiencies based on these materials and devices.

14. SUBJECT TERMS
photovoltaics ; thin films ; solar cells ; amorphous silicon ; copper gallium indium diselenide ; cadmium telluride ; gallium arsenide ; gallium indium phosphide ; titanium dioxide

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UL