High-performance concentrator tandem solar cells based on IR-sensitive bottom cells

M. W. Wanlass, J. S. Ward, K. A. Emery, T. A. Gessert, C. R. Osterwald and **T. J. Coutts**
Solar Energy Research Institute (SERI), 1617 Cole Boulevard, Golden, CO 80401 (U.S.A.)

(Received October 25, 1990)

Abstract

Computer simulations of two-junction, concentrator tandem solar cell performance show that IR-sensitive bottom cells are required to achieve high efficiencies. Based on this conclusion, two novel concentrator tandem designs are under investigation: (1) a mechanically stacked, four-terminal GaAs/GaInAsP (0.95 eV) tandem, and (2) a monolithic, lattice-matched, three-terminal InP/GaInAs tandem. In preliminary experiments, terrestrial concentrator efficiencies exceeding 30% have been achieved with each of the above tandem designs. Methods for improving the efficiency of each tandem type are discussed.

1. Introduction

Recent computer modeling studies of two-junction, concentrator tandem solar cells have shown that IR-sensitive bottom cells are required in order to achieve maximum performance levels [1, 2]. As an illustration of this conclusion, the results from a typical modeling calculation are shown in Fig. 1. In this figure, the iso-efficiency contours for a two-junction, independently connected tandem cell operated under the direct spectrum at 100 Suns, 25 °C are given as a function of the top and bottom cell band gaps. Also shown in the diagram are the iso-band-gap lines for single-crystal, direct band gap semiconductors presently under consideration for top and bottom cell applications. These include AlGaAs (1.93 eV), GaInP (1.90 eV), GaAs (1.425 eV) and InP (1.35 eV) for the top cells and GaSb (0.72 eV), GaInAs (0.75 eV), GaInAsP (0.95 eV) and GaAs (1.425 eV) for the bottom cells. The top cell and bottom cell band gap coordinates for typical combinations of these materials have been identified to illustrate the potential tandem cell efficiency from such designs.

In the past, tandem cells based on GaAs bottom cells have been the subject of intense research since lattice-matched compositions of high band gap alloys such as AlGaAs and GaInP can be readily grown on GaAs substrates, thereby forming monolithic, high and medium band gap tandem cell structures [3]. The convenience and elegance of the GaAs-based tandem designs cannot

0379-6779/91/$3.50

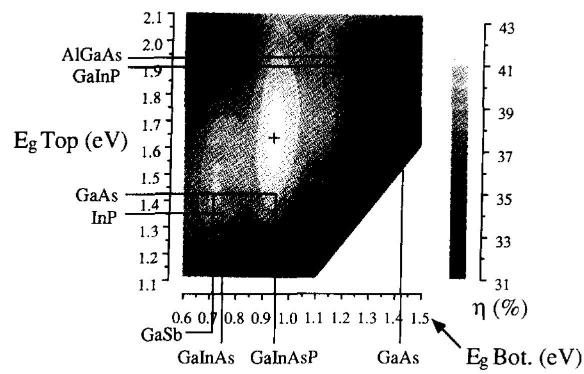


Fig. 1. Computer-modeled iso-efficiency contours as a function of the top and bottom cell band gaps for an independently connected, two-junction tandem solar cell under the direct spectrum, 100 Suns, 25 °C. Also shown are the iso-band-gap lines for single-crystal, direct band gap semiconductors considered useful for tandem cell applications.

be disputed, however, it is clear from the data shown in Fig. 1 that GaAs-based tandems are inappropriate for concentrator applications since the maximum efficiency obtainable with such designs is less than 84% of the maximum modeled efficiency for two-junction tandems. The relatively low efficiency potential of GaAs-based tandems is easily understood: GaAs is transparent to 53% of the photovoltaically useful photons (*i.e.* photons with energies greater than 0.65 eV) in the direct spectrum, resulting in a large conversion efficiency loss.

In contrast, from Fig. 1 it is evident that concentrator tandems employing IR-sensitive bottom cells with band gaps in the range 0.7–1.0 eV are capable of efficiencies which are 95%–100% of the maximum theoretical efficiency. An additional advantage of tandems using low band gap bottom cells is that a wide range of top cell band gaps (1.3–2.0 eV) become useful for high-efficiency operation, resulting in considerable flexibility in choosing high-efficiency top and bottom cell materials combinations. In particular, medium and low band gap tandem pairs using simple, technologically mature binary top cell materials such as GaAs and InP, have theoretical efficiencies which are very close to the maximum attainable value, thereby making them extremely attractive candidates for practical applications. In a previous modeling study [1], it was shown that the above conclusions are largely unaffected at higher operating temperatures (80 °C) since the normalized efficiency temperature coefficients for low band gap cells improve substantially at high solar concentration ratios. Therefore, medium and low band gap tandem pairs appear to be the preferred choice for concentrator applications.

At the Boeing Technology Center, recent research into developing GaAs/GaSb mechanically stacked, concentrator tandem cells has resulted in the highest photovoltaic efficiency yet reported [4]. These results corroborate the modeling predictions discussed above (note the modeled efficiency for

GaAs/GaSb in Fig. 1). In the work presented in this paper, we have extended the medium and low band gap, two-junction tandem concept to two novel, practically relevant materials combinations which have high theoretical efficiencies. These are indicated in Fig. 1 and consist of the following. (1) A mechanically stacked, four-terminal GaAs/GaInAsP tandem utilizing the optimum band gap of 0.95 eV for the quaternary bottom cell. The composition of the quaternary is approximately $Ga_{0.25}In_{0.75}As_{0.54}P_{0.46}$. (2) A monolithic, lattice-matched, three-terminal InP/GaInAs tandem. In this case, the bottom cell has a band gap of 0.75 eV and the composition is $Ga_{0.47}In_{0.53}As$. Both of these designs have theoretical terrestrial efficiencies of greater than 40% at concentration ratios of 100 or more. The progress made in developing each of these tandem designs is reviewed in the next two sections.

All of the device structures described in this paper were grown by atmospheric-pressure metal–organic vapor phase epitaxy using a home-built system. The system employs a patented reactor vessel design [5] which yields highly uniform epilayers in all respects, a feature which is particularly important for devices involving ternary and quaternary compounds. Trimethylindium, trimethylgallium, phosphine and arsine were used as the primary reactants and hydrogen sulfide, hydrogen selenide and diethylzinc were used as doping sources. The carrier gas employed was palladium-purified hydrogen and the growth temperature ranged from 600 to 700 °C. Additional details regarding the epitaxial growth and device processing procedures for the various materials and devices can be found in previous publications [2, 6].

The tandem cell efficiency *vs.* solar concentration ratio C data were obtained using the data acquisition system described in ref. 7 along with an unfiltered, 1000 W xenon-arc light source. Using the short-circuit current I_{sc} measured at 1 Sun intensity under the direct spectrum (ASTM E891-87, 1000 W m^{-2} total irradiance, 25 °C) and assuming a linear relationship between the I_{sc} measured under concentration and C, the current–voltage characteristics were measured and the efficiency was calculated based on the value of C determined. The total estimated uncertainty in the efficiency is $\pm 2\%$ for the medium band gap (greater than or equal to 1 eV) cells and $\pm$ 8% for the low band gap (less than or equal to 1 eV) cells. In order to keep the tandem cell junctions at the standard reference temperature (25 °C) during the current–voltage measurements, the following procedure was used. (1) Initially, the cell was maintained at the reference temperature on a thermoelectrically controlled vacuum plate in the dark behind a high-speed shutter (approximately 2 ms opening time). (2) A high-speed voltmeter was then used to sample (at approximately 1000 readings per second) the open-circuit voltage V_{oc} of the cell as the cell was illuminated using the shutter. The highest measured V_{oc} was taken as the V_{oc} under concentration at 25 °C. (3) With the cell under continuous illumination, the vacuum plate was then cooled until the V_{oc} obtained in step 2 above was reached. The current–voltage data at 25 °C were then taken. A temperature difference of about 10 °C between the vacuum plate and the cell junction is typical at a concentration ratio of around 50 Suns.

2. GaAs/GaInAsP (0.95 eV) mechanically stacked, four-terminal tandem cells

A schematic diagram of the GaAs/GaInAsP mechanically stacked tandem concept is given in Fig. 2. The GaInAsP bottom cell is grown lattice matched on an InP substrate and uses InP as a window layer to passivate the emitter surface. An n–p doping configuration has been used to minimize the emitter/window sheet resistance and emitter grid contact resistance. Positioned on the bottom cell surface is an Entech prismatic cover to eliminate optical losses due to grid obscuration. Reference 8 contains further details of the GaInAsP cell construction. As shown in the diagram, the quaternary bottom cells have been tested under IR-transparent GaAs filters and also under actual GaAs concentrator cells grown on IR-transparent GaAs substrates. In both cases, the GaAs-based top structure is mirror smooth on the front and back surfaces with appropriate antireflection coatings (ARCs) on each of the surfaces.

Efficiency *vs.* C data for a high-efficiency GaInAsP concentrator cell under a GaAs filter are shown in Fig. 3. The efficiency data show the expected increase as C is increased initially (as compared with the modeled performance data) and then exhibit a broad plateau at about 9.4% for C in the range 20–130. The fill factor FF data show that the cell becomes series resistance limited at about 30 Suns, thus prohibiting further efficiency gains for higher values of C and resulting in the broad efficiency plateau. It is clear that GaAs-filtered GaInAsP cell efficiencies exceeding 10% at $C \geq 100$ could be achieved through a reduction in the cell series resistance R_s. Furthermore, the modeled cell performance data suggest that the efficiency could improve by 1%–2% at low values of C even with the present value of R_s. An analysis of internal quantum efficiency and absolute external quantum efficiency data

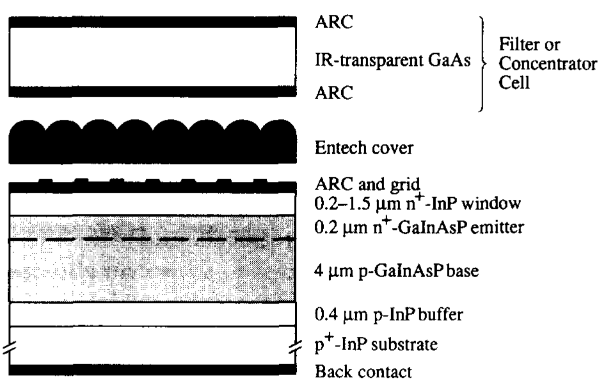
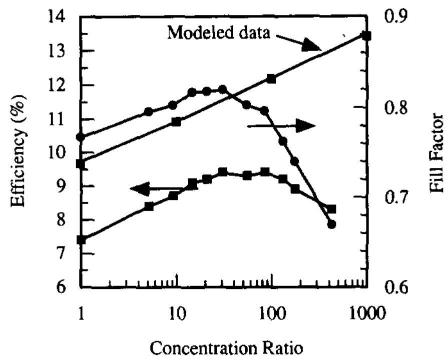


Fig. 2. Schematic diagram of the GaAs/GaInAsP (0.95 eV) mechanically stacked tandem cell concept. Details of the GaInAsP bottom cell construction are shown. The GaInAsP cells were tested under a GaAs filter and also in actual tandem cell stacks.



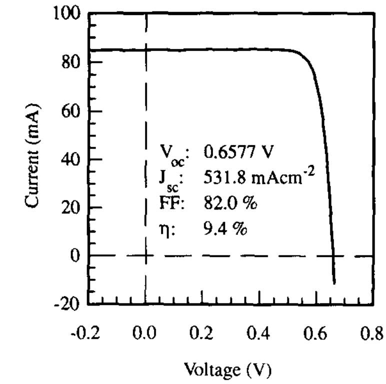


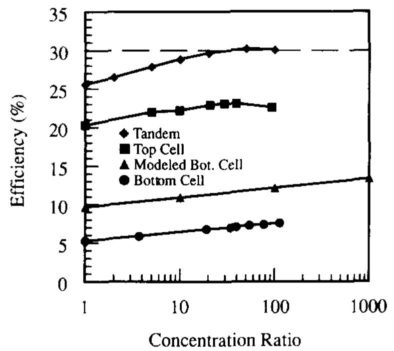
Fig. 3. Efficiency *vs.* concentration ratio data for a high-efficiency GaInAsP concentrator cell under an IR-transparent, AR-coated GaAs filter. Also shown are the fill factor data for the same cell along with the modeled efficiency as a function of the concentration ratio.

Fig. 4. Current–voltage data for a GaInAsP cell at peak efficiency under concentration (30.6 Suns, direct, 25 °C).

for these cells (not given here) shows that the majority of the discrepancy between the modeled and measured efficiency data is due to external optical losses. Therefore, improved optical coupling techniques should lead to higher efficiencies. Nevertheless, the present efficiency boost offered by the GaInAsP cells is substantial and immediately useful in tandem stacks.

The illuminated current–voltage data for a GaInAsP concentrator cell at peak efficiency under a GaAs filter are shown in Fig. 4. The cell has an efficiency η of 9.4% at 30.6 Suns under the direct spectrum at 25 °C. The high values of V_{oc} and FF (0.658 V and 82% respectively) are particularly noteworthy for this low band gap cell.

We have been successful in a preliminary attempt to fabricate actual GaAs/GaInAsP mechanically stacked tandem cells. The cells have been tested under concentration using an aperture to define the illuminated cell area. Efficiency *vs.* C data for our best stacked tandem are shown in Fig. 5. The performance of the GaInAsP bottom cell in the stack was hampered somewhat by the use of the aperture since only about one third of the total area of the bottom cell was illuminated during the measurement process. Likewise, the quality of the GaAs concentrator top cells which were used in the stack are far from state-of-the-art. Despite the obvious deficiencies in the stacked device, the tandem efficiency still exceeded 30% for C values ranging from 30 to 100. A top cell and bottom cell current–voltage data composite for the GaAs/GaInAsP tandem at peak efficiency is given in Fig. 6. At 39.5 Suns, the top cell is 23.1% efficient and the bottom cell has an efficiency of 7.1%, yielding a tandem efficiency of 30.2%. With improvements in the top cell quality, stacking procedure and optical coupling into the bottom cell, we feel that concentrator tandem efficiencies approaching 40% may be achieved in the future.



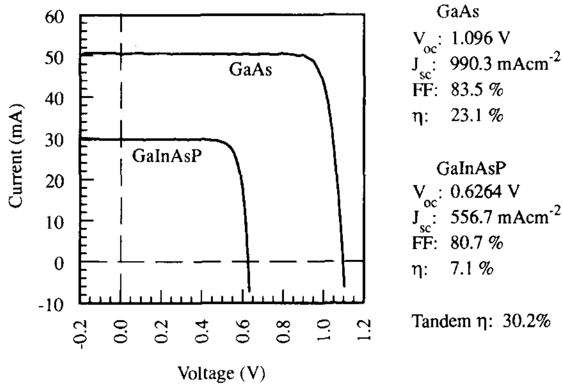


Fig. 5. Efficiency *vs.* concentration ratio data for a mechanically stacked GaAs/GaInAsP concentrator tandem cell. The modeled efficiency *vs.* concentration ratio data for the GaInAsP bottom cell are also included.

Fig. 6. Composite current–voltage data for a GaAs/GaInAsP mechanically stacked tandem cell at peak efficiency under concentration (39.5 Suns, direct, 25 °C).

3. InP/GaInAs (0.75 eV) monolithic, three-terminal tandem cells

The InP/GaInAs monolithic, three-terminal tandem cell was originally conceived for space applications because it has several advantages, including a radiation-resistant InP top cell [2]. However, it may also be very useful in terrestrial concentrator applications since it has a high theoretical efficiency. The tandem performance under terrestrial conditions is presented here.

An illustration of the InP/GaInAs tandem cell construction is shown in Fig. 7. The device consists of twelve epitaxial layers which are deposited in a continuous growth sequence. The lattice-matched, monolithic structure consists of three major components, including the GaInAs bottom cell, a middle contact region and the InP top cell. The details and function of each of these components have been outlined previously [2]. The three-terminal cell utilizes a two-level, interdigitated top/middle contact grid system and a contact on the back surface of the InP substrate. The Entech prismatic cover on the cell surface is an integral part of the tandem design since it directs all of the incoming photons away from the top cell gridlines and middle contact trenches and onto the InP top cell surface.

In Fig. 8, concentrator efficiency data are shown for a high-efficiency InP/GaInAs tandem cell. The GaInAs bottom cell has performance characteristics which are extremely close to the limits predicted by computer modeling, which suggests that further improvements in the GaInAs junction quality appear unlikely. The InP top cell also performs quite well, reaching a broad efficiency peak of 23% over the 20–40 Suns concentration range. This is the first report of high-efficiency InP concentrator cells and the highest efficiency yet reported for InP. As C approaches 100 Suns, each of the tandem subcells becomes series resistance limited, which results in a broad

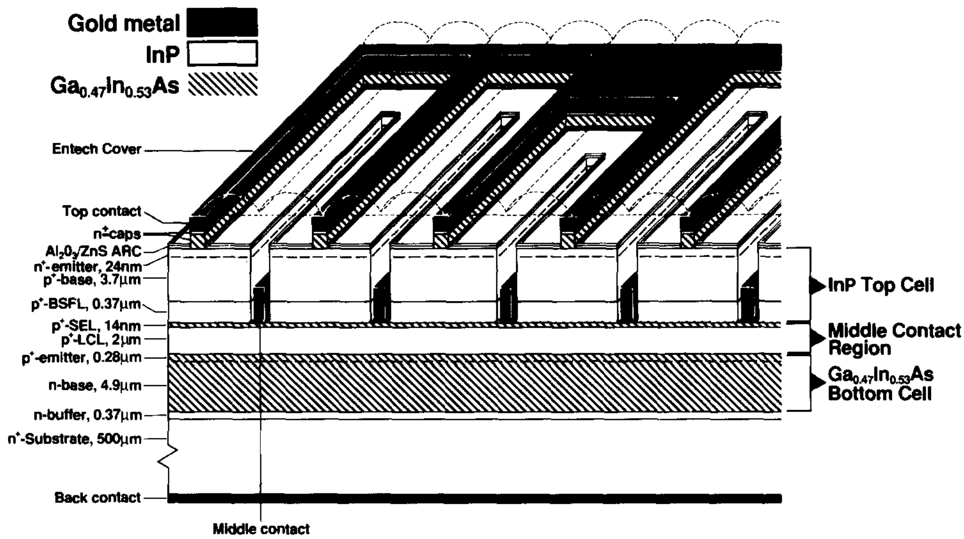
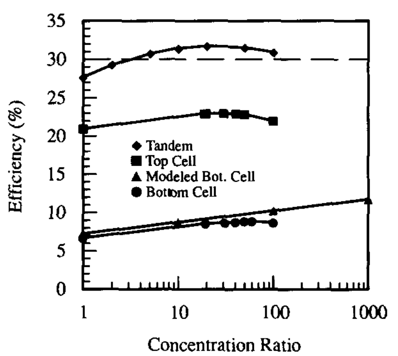


Fig. 7. Three-dimensional, cross-sectional schematic diagram of the InP/GaInAs monolithic, three-terminal tandem solar cell. Important features include (1) two level, interdigitated top and middle grid contacts, (2) a middle contact which is common to both subcells, and (3) an Entech prismatic cover which eliminates optical losses due to grid obscuration and loss of top cell area.



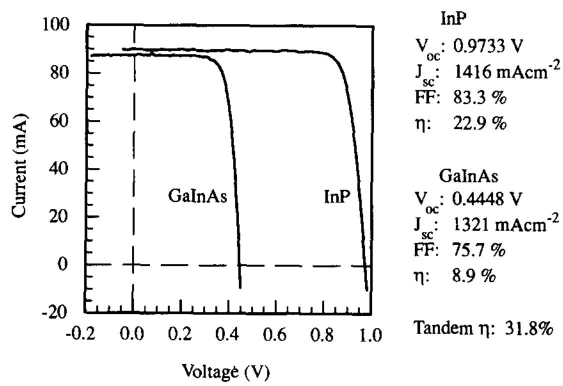


Fig. 8. Efficiency *vs.* concentration ratio data for a high-efficiency InP/GaInAs monolithic tandem cell. The modeled efficiency for the GaInAs bottom cell is also given.

Fig. 9. Composite current–voltage data for an InP/GaInAs tandem cell at peak efficiency under concentration (50.0 Suns, direct, 25 °C).

tandem efficiency maximum which approaches 32% from 10 to 50 Suns. The concentrator J_{sc}–V_{oc} data have been used to determine the ideality factors and reverse-saturation current densities for the top and bottom cell junctions. For the InP cell, $n = 1.02$ and $J_0 = 9.7 \times 10^{-14}$ mA cm^{-2}, and for the GaInAs cell, $n = 1.03$ and $J_0 = 7.0 \times 10^{-5}$ mA cm^{-2}. These values reflect the excellent quality of both junctions. Further improvements in the tandem cell efficiency are still possible. A reduction of the series resistance in each of the subcells would allow the tandem to operate at a higher efficiency at higher concentration ratios. Passivation of the InP emitter surface would lead to higher top cell efficiencies [2]. Solutions to these efficiency-limiting problems are being pursued and concentrator terrestrial efficiencies greater than 35% appear possible for this tandem design.

A composite current–voltage data plot for the InP/GaInAs tandem at peak efficiency is given in Fig. 9. At 50 Suns concentration, the top and bottom cell efficiencies are 22.9% and 8.9% respectively, which sum to give a tandem efficiency of 31.8%. This result marks the first time that a monolithic tandem cell has exceeded 30% efficiency.

4. Conclusion

Computer modeling studies have shown that IR-sensitive bottom cells are required to achieve high-performance in concentrator tandem solar cells. Based on this conclusion, we have investigated two promising tandem cell designs which incorporate IR-sensitive bottom cells: (1) a mechanically stacked, four-terminal GaAs/GaInAsP (0.95 eV) tandem, and (2) a monolithic, three-terminal InP/GaInAs (0.75 eV) tandem. The preliminary performance results for these designs corroborate the modeling predictions and are very encouraging since both types of tandems have exceeded 30% efficiency at mild concentration ratios under standard terrestrial measurement conditions.

Under a GaAs filter, GaInAsP concentrator cells have efficiencies as high as 9.4% at 20 to 130 Suns concentration. With a reduction in R_s and improved optical coupling, efficiencies exceeding 10% are anticipated for these cells in the future. Preliminary GaAs/GaInAsP mechanically stacked tandems have achieved efficiencies as high as 30.2% at 39.5 Suns. By improving the GaAs top cell quality and the tandem stacking procedure, tandem efficiencies approaching 40% should be achievable at higher solar concentrations.

Monolithic InP/GaInAs tandem cells have reached efficiencies of 31.8% at 50 Suns. This is the first report of a monolithic tandem cell with an efficiency greater than 30%. The GaInAs bottom cell has near-theoretical performance at low concentration ratios; however, the InP top cell efficiency could be improved substantially with a passivated emitter and an improved ARC. If the tandem cell series resistance were reduced, efficiencies exceeding 35% could be realized by operating at high concentration ratios.

Acknowledgments

We wish to thank Mark O'Neill at Entech, Inc. for helpful discussions regarding the installation of Entech prismatic covers on the various concentrator cells. We also thank Jose Carranza for his assistance in applying antireflection coatings to the InP/GaInAs tandem cells. Support for this work was provided by the U.S. Department of Energy under contract DE-AC02-83CH10093, the Naval Research Laboratory under interagency RU-11-W70-AD and the NASA Lewis Research Center under interagency order C-300005-K.

References

1 M. W. Wanlass, K. A. Emery, T. A. Gessert, G. S. Horner, C. R. Osterwald and T. J. Coutts, *Sol. Cells, 27* (1989) 191–204.
2 M. W. Wanlass, T. A. Gessert, G. S. Horner, K. A. Emery and T. J. Coutts, *Proc. NASA Conf. on Space Photovoltaic Research and Technology*, NASA, Cleveland, OH, 1989, in the press.
3 *Proc. 19th IEEE Photovoltaic Specialists' Conf.*, IEEE, New York, 1987.
Proc. 20th IEEE Photovoltaic Specialists' Conf., IEEE, New York, 1988.
Proc. 21st IEEE Photovoltaic Specialists' Conf., IEEE, New York, 1990.
4 L. M. Fraas, J. E. Avery, V. S. Sundaram, V. T. Dinh, J. M. Gee and K. A. Emery, *Proc. 21st IEEE Photovoltaic Specialists' Conf., Kissimmee, FL, 1990*, IEEE, New York, 1990, pp. 190–195.
5 M. W. Wanlass, *U.S. Patent 4,649,859*, March 17, 1987.
6 M. W. Wanlass, G. S. Horner, T. A. Gessert and T. J. Coutts, *Proc. 1st Int. Conf. on InP and Related Materials, Norman, OK, 1989*, SPIE, 1989, Vol. 1144, pp. 445–458.
7 K. A. Emery and C. R. Osterwald, Solar cell efficiency measurements, *Sol. Cells, 17* (1986) 253–274.
8 M. W. Wanlass, J. S. Ward, T. A. Gessert, K. A. Emery, G. S. Horner and T. J. Coutts, *Proc. 21st IEEE Photovoltaic Specialists' Conf., Kissimmee, FL, 1990*, IEEE, New York, 1990, pp. 172–178.