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DEVELOPMENT OF N/P AlGaAs FREE-STANDING TOP SOLAR CELLS FOR TANDEM APPLICATIONS*

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ABSTRACT

The combination of a free-standing AlGaAs top solar cell and an existing bottom solar cell is the highest performance, lowest risk approach to implementing the tandem cell concept. The solar cell consists of an AlGaAs substrate layer, an AlGaAs base layer, an AlGaAs emitter, and an ultra-thin AlGaAs window layer. The window layer is compositionally graded which minimizes reflection at the window layer/emitter interface and creates a built-in electric field to improve quantum response in the blue region of the spectrum. Liquid phase epitaxy (LPE) is the only viable method to produce this free-standing top solar cell. We have already demonstrated small (0.125 cm^2), transparent p/n AlGaAs top solar cells of the optimum bandgap for combination with a silicon bottom solar cell. The efficiency of an AlGaAs/Si stack using the free-standing AlGaAs device upon an existing silicon bottom solar cell is 24% (1X, AM0). The n/p AlGaAs top solar cell is being developed in order to facilitate the wiring configuration. The two-terminal tandem stack will retain fit, form, and function of existing silicon solar cells. Progress in the development of large area (8 cm^2 and 16 cm^2), free-standing AlGaAs top solar cells will be discussed.

INTRODUCTION

During a past development effort, small (0.126 cm^2) p/n AlGaAs concentrator solar cells were developed [ref. 1]. Two device structures were investigated: free-standing AlGaAs concentrators and a concentrator based upon a Burrus diode structure [ref. 2]. The results of the early work included the growth and fabrication of a 17.2% AlGaAs solar cell with a bandgap of 1.80 eV. Mechanically stacking this AlGaAs solar cell upon a thin silicon solar cell designed by Spectrolab [ref. 3] (for mechanically stacked applications) should result in a tandem stack efficiency of 24% (1x, AM0) as illustrated in Table I

Table I

Predicted Performance for Two-Terminal Configuration of
AlGaAs/Si Mechanical Stack with Spectrolab Bottom Solar Cell [ref. 3]
(AM0, 135 mW/cm^2)

Material	Eg (eV)	Voc (volts)	Jsc (mA/cm^2)	FF	Efficiency (%)
AlGaAs	1.80	1.295	21.4	0.84	17.2
Silicon	1.13	0.565	21.4	0.76	6.8
		TWO-TERMINAL STACK ---------------------------->			24.0

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Presently the effort is targeted to develope large area AlGaAs top solar cells for mechanical attachment to a silicon solar cell flat panel array. Our approach will adapt demonstrated AlGaAs solar cell performance and enhanced growth technology for the fabrication of a self-supporting top solar cell. The top cell will be designed for a two-terminal wiring configuration, hence a n/p configuration is investigated.

MODELING

The theoretical limits for the proposed tandem stack were determined using a solar cell model by Nell [ref. 4] based upon tabulated standard spectra, the fit of experimentally achieved open circuit voltages, and the assumption of unit quantum efficiency. More recent work [ref. 5] indicates that Nell's model underestimates open-circuit voltages. Incorporating this change, a theoretical AM0 efficiency of 38.5% at 1 sun is predicted for the tandem stack. The theoretical maximum efficiency was analyzed and is shown in Table II. A sub-bandgap transparency of 100% is assumed.

Table II

Predicted Theoretical Maximum Efficiency for a Two-Terminal AlGaAs/Si Mechanical Stack (AM0, 135 mW/cm^2)

Material	Eg (eV)	Voc (volts)	Jsc (mA/cm^2)	FF	Efficiency (%)
AlGaAs	1.76	1.414	26.6	0.91	25.3
Silicon	1.13	0.788	26.6	0.85	13.2
		TWO-TERMINAL STACK ---------------------------->			38.5

A goal of 95% transparency to sub-bandgap photons was used in the prediction of the "best case" performance. For direct-bandgap materials, predictions were determined by reducing the open-circuit voltage, short-circuit current, and fill factor to 96%, 91%, and 96%, respectively, of their theoretical limits. Indirect bandgap material reductions are correspondingly 91%, 96%, and 96%, respectively [ref. 6]. This permits stack performance predictions for the various combinations. Performance of the "best case" AlGaAs top solar cell with a 1.76 eV bandgap on a silicon bottom solar cell is listed in Table III.

Table III

"Best Case" Prediction for Two-Terminal Configuration of AlGaAs/Si Mechanical Stack (AM0, 135 mW/cm^2)

Material	Eg (eV)	Voc (volts)	Jsc (mA/cm^2)	FF	Efficiency (%)
AlGaAs	1.76	1.35	24.3	0.87	21.1
Silicon	1.13	0.71	24.3	0.82	10.5
		TWO-TERMINAL STACK ---------------------------->			31.6

The "best case" performance of the individual solar cells assumes the following additional reductions in current for the bottom solar cell. The short-ciruit current of the bottom solar cell is decreased by the energy absorbed in the top solar cell. An additional 5% reduction in the short-circuit current is added to account for parasitic absorption or reflection losses in the top solar cell or the inter-cell connection.

SOLAR CELL DESIGN

Aluminum gallium arsenide is the material of choice for the wide-bandgap top solar cell since it is the most developed of the potential top solar cell materials. This ternary compound exhibits a tunable bandgap while maintaining lattice-matched compositions which permit sophisticated designs leading to high performance devices. Formed on a thick, transparent AlGaAs substrate ($Al_xGa_{1-x}As$, $x \geq 0.45$), device yield is greatly improved due to the relatively robust wafer. Liquid phase epitaxy (LPE) provides the material quality and growth rates necessary for the free-standing AlGaAs top solar cells.

The solar cell consists of an AlGaAs substrate layer (typically 100 microns thick), an AlGaAs base layer (5 microns thick), an AlGaAs emitter, and an ultra-thin AlGaAs window layer (0.05 microns). The AlGaAs emitter is formed by tellurium diffusion from the window layer into the base layer. Using an isothermal growth process permits sufficient time to diffuse the emitter while growing the thin, compositionally graded window layer. The compositionally graded window layer minimizes reflection at the window layer/emitter interface and creates a built-in electric field to improve quantum response in the blue region of the spectrum [ref. 7]. The role of the substrate is two fold: i) support, and ii) formation of a rear cladding layer to enhance carrier confinement. This double heterostructure design results in high open-circuit voltages. The solar cell structure is shown in Figure 1.

Previously, tin (Sn) and beryllium (Be) were used as the n-type and p-type dopants when developing the p/n AlGaAs concentrator solar cells. For the growth of the n/p large area AlGaAs solar cells, these dopants are not compatible with the growth process. Zinc (Zn) and tellurium (Te) are being used as the p-type and n-type dopants. These dopants have been adequately characterized for the production of ultra-bright light emitting diodes (LEDs) which are similar in design [ref. 8].

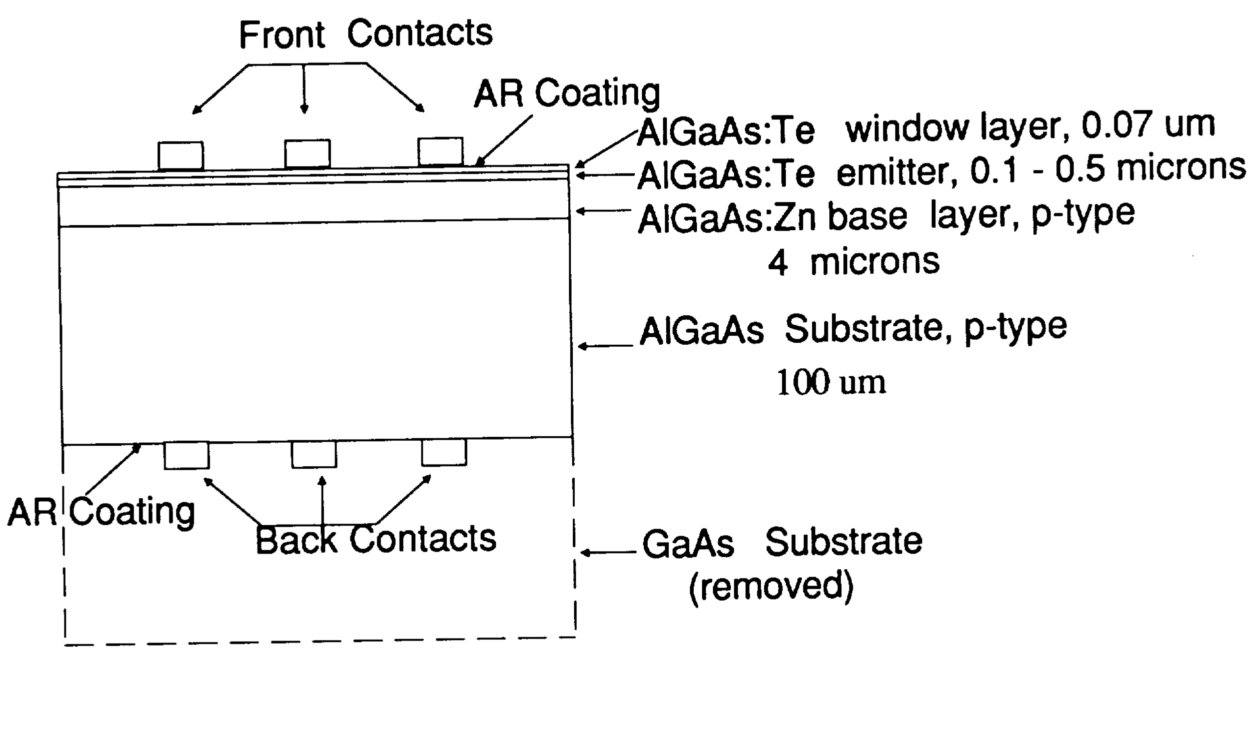

Figure 1. N/p free-standing AlGaAs top solar cell design.

RESULTS

Building on previous results [ref.1], AstroPower has directed the program to produce large area, free-standing AlGaAs solar cells with a n/p configuration. The n/p AlGaAs top solar cell is being developed to facilitate the wiring configuration. The two-terminal tandem stack will retain fit, form and function of existing silicon solar cells.

Initial work with the n/p configuration has been encouraging. The development effort has been divided into two phases: optimization of the AlGaAs solar cell on a GaAs substrate, and optimization of the AlGaAs substrate. The preliminary emphasis has focused on obtaining high open-circuit voltages. To date, the highest value obtained is 1.320 volts (Device F8719 #2). Figure 2 is the corresponding external quantum efficiency of this device. The I-V characteristics are shown in Figure 3.

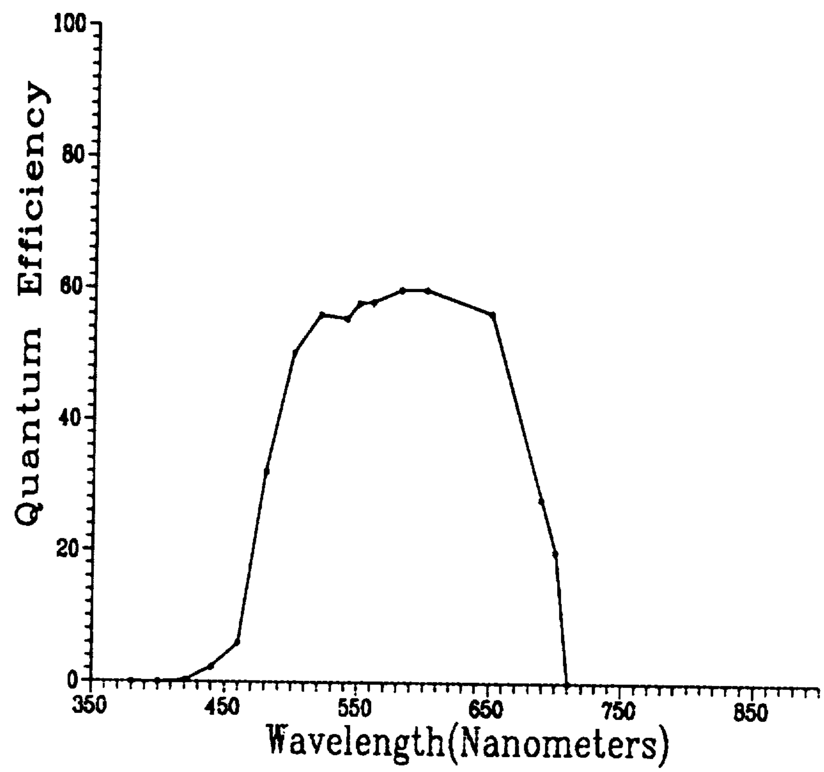

Figure 2. External quantum efficiency of F8719 #2. No AR coating has been applied to this sample. The energy bandgap is estimated to be approximately 1.80 eV.

As can be seen, the current density is limited by the lack of blue response. This problem has been traced to melt-mixing which results in high initial growth rates during the isothermal growth process. Modifications to the epitaxial growth equipment have been made to eliminate this problem.

Presently, our growth process for the AlGaAs structures is limited to a 6 cm^2 area. New epitaxial boats have been designed for the growth of 2 cm x 4 cm devices. In addition, a new LPE growth system based upon solute transport has been designed for the fabrication of 5 cm x 5 cm devices or 3 inch diameter wafers. This system is under construction and is expected to be on line shortly. The system has been designed to obtain high growth rates (30 microns/hour) while maintaining the high material quality associated with LPE material.

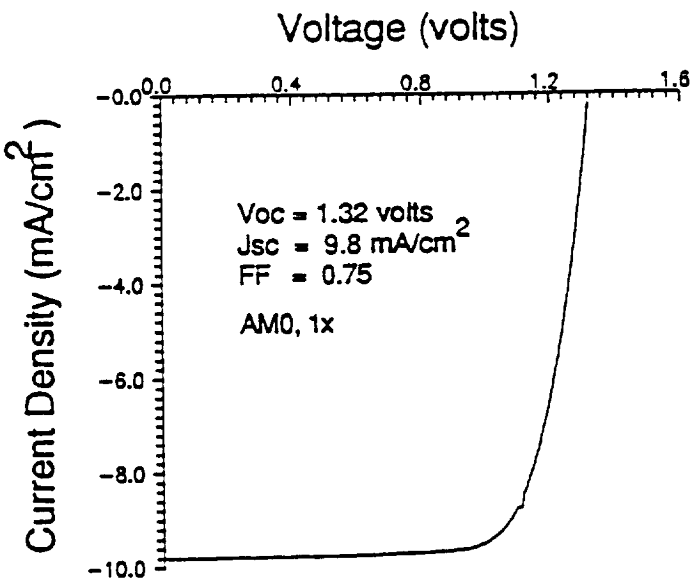

Figure 3. I-V characteristics of F8719 #2 using solar simulator (no AR coating)

During our AlGaAs concentrator development effort, sub-bandgap transparency greater than 91% was obtained [ref.1]. Of the losses, 2% was attributed to free-carrier absorption while the remaining loss was purely reflective. Presently, the AlGaAs substrate is being optimized in terms of doping in order to obtain low specific contact resistance and high sub-bandgap transparency.

SUMMARY

Large area, free-standing AlGaAs solar cells are being developed for mechanical attachment to existing silicon solar cells. The n/p configuration is being optimized for a two-terminal wiring. Scale up of the areas to 2 cm x 4 cm are presently underway. The growth and fabrication of 4 cm x 4 cm devices will begin in the near future with a large scale LPE system using solute transport to achieve high growth rates.

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