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MECHANICALLY-STACKED TANDEM SOLAR CELLS WITH GaAsP ON GaP AND SILCON*

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The development of GaAsP top solar cells for mechanical attachment to silicon bottom solar cells can lead to AM0 conversion efficiency increases of 48% to 76% over the best state-of-the-art single junction silicon solar cells. These tandem solar cells can also be expected to be more radiation-resistant and mechanically and electrically stable.

Design rules are presented for the development of a high efficiency tandem stack. The system efficiency can range from 26.7% to 29.4% depending on the performance of the bottom solar cell. Consideration of the near term goal of a 25% efficient tandem solar cell is addressed. Guidelines for the achievement of this near term goal are given in terms of device parameters.

Liquid phase epitaxy is being used for this development of GaAsP on GaP top solar cells. Considerable progress has been demonstrated in the liquid phase epitaxial growth of GaAsP on GaP substrates. Multiple graded layers of GaAsP with up to 65% GaAs have been prepared with surface quality equivalent to commercial GaP on GaP epitaxial wafers. Techniques for stacking fault and dislocation density reduction are being developed. High quality active layers have been prepared with lattice parameters that differ from the GaP substrate by 2.41%.

The first experimental two-junction, four-terminal tandem cells with a GaAsP top solar cell on a conventional silicon bottom solar cell have been fabricated. Top solar cell transmission of 95% of the photons less energetic than the top cell bandgap has been accomplished. Initial results for these tandem solar cells will be presented. Future work will focus on increasing current in the top cell and increasing the device area.

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Introduction

The addition of a GaAsP on GaP top solar cell over existing silicon solar cells has the potential of increasing the power output of a practical system by 48 to 76%. This is dependent on the bottom solar cell performance. The tandem solar cell efficiency can range from 26.7 to 29.4%. In this paper the design rules for the achievement of these performance levels are discussed. Next, those performance requirements necessary to achieve the near term goal of 25% are addressed. These performance goals can be described in terms of transparency, voltage, fill factor and current. Liquid phase epitaxy is being used for the growth of GaAsP on GaP. The progress in the development of a GaAsP top solar cell is presented.

Design

The design of the mechanically stacked GaAsP on GaP top cell is based on a model used to calculate theoretical maximum efficiencies of tandem solar cell systems. The model that is being used is by Nell (1) and is based upon tabulated standard spectra, the fit of experimentally achieved open-circuit voltages, and assumes unit quantum efficiency.

Using solar irradiance information, the performance is calculated for the top solar cell. The remaining part of the spectrum, $E < E_g$ (top), is then used to calculate the performance of the bottom cell. In this way, a complete set of isoefficiency curves is generated for various energy bandgap combinations. Assuming unit quantum efficiency and no losses, the model predicts a maximum solar cell efficiency of 35.8% at AM0 and one sun insolation. This performance is based upon a four-terminal configuration for the tandem stack.

The maximum theoretical efficiency of 35.8% corresponds to a 1.97eV top solar cell and a 1.12eV bottom solar cell. This is equivalent to a $GaAs_{.54}P_{.46}$ top cell and a conventional silicon bottom solar cell. The device parameters for the "ideal" tandem stack are shown in Table I.

Table I

Predicted Theoretical Maximum Efficiency for the Four-Terminal Configuration according to Nell's Model

Bandgap (eV)	Voc (volts)	Jsc (mA/cm^2)	FF	Efficiency (%)
1.97	1.53	20.75	.91	21.4
1.12	.71	32.68	.84	14.4
				35.8

Anticipated Performance for a Practical System

To obtain the maximum efficiency for a practical system both the top and bottom solar cells must be state-of-the-art. The overall efficiency of the tandem stack must include electrical and optical losses. Loss calculations for this tandem structure have been anticipated by others (2). In this work, the performance of other types of solar cells is used as the basis for predicting feasible system performance.

To obtain the maximum practical efficiency, both the top and bottom solar cells must be approaching their theoretical limit. The maximum efficiency predicted by the model for a silicon space solar cell is 23.9% at AMO and one sun (1). Swanson's (3) record efficiency concentrator solar cell is equivalent to 19.9% efficient for an AMO spectrum at one sun, while Green's (4) best results correspond to an efficiency of 18.6% (AMO, 1 sun). These results are 22% to 31% better than the average commercial silicon space solar cells. Table II shows a comparison of these results.

Table II

Modelled Theoretical Maximum for Silicon Space Solar Cells Compared to Actual Silicon Results

	Voc (volts)	Jsc (mA/cm^2)	FF	Efficiency (%)
Model	.710	53.43	.840	23.9
Swanson	.681	50.30*	.784	19.9
Green	.663	45.40*	.833	18.6
Commercial	.595	46.00	.750	15.2

*Corrected from AM1.5G to AMO

The modelled theoretical efficiency of the 1.97eV top solar cell is 21.4%. Again, losses must be included to obtain the best "real" case. Since the $GaAs_{.54}P_{.46}$ top solar cell is still in the experimental stages, tabulation of the limit predicted by the model with the best results to date does not allow a fair comparison of the overall tandem stack. However, if one surveys the literature and compares the performance of well-developed solar cells with their expected limit, one may easily predict the expected performance of the 1.97eV GaAsP top cell. Mid-range achievements of open-circuit voltage, short-circuit currents and fill factors are 96%, 91%, and 96%, respectively, of the expected limits from the model. Using these assumptions, the best case 1.97eV GaAsP top solar cell should peak at 17.9% efficiency. This is shown in Table III.

Table III

Expectation of Best Case $GaAs_{.54}P_{.46}$ (1.97eV)

	Voc (volts)	Jsc (mA/cm^2)	FF	Efficiency (%)
Model	1.53	20.75	.91	21.4
Best Case	1.47	18.90	.87	17.9
% Theoretical	96%	91%	96%	

With the expectations of the top and bottom solar cells, one can view the performance of the GaAsP-Si tandem stack. The best case tandem structure with various bottom solar cells is shown in Table IV. The tandem stack efficiencies range from 29.4% to 26.7% depending on the bottom solar cell.

Table IV

Best Case Tandem Solar Cell with
Various Silicon Bottom Solar Cells
(AMO)

	Swanson	Green	Commercial
GaAsP Top Cell	17.9	17.9	17.9
Si bottom cell	11.5*	10.8*	8.8*
Stack Efficiency(%)	29.4	28.7	26.7

*Includes an extra 5% reduction in Jsc due to optical transmission losses.

Requirements for a 25% Efficient Tandem Solar Cell

The near term goal is a 25% efficient solar cell at AM0. An inherent requirement to achieve this goal is the utilization of a state-of-the-art bottom solar cell. From Table II, the choice is the 19.9% efficient solar cell produced by Swanson. The performance requirements necessary for achievement of a 25% tandem device can be described in terms of transparency, voltage, fill factor and current.

The transparency can be determined once the choice of the energy bandgap for the top solar cell is made. From solar spectral irradiance data (5), one determines the portion of the spectrum absorbed in the top solar cell. The remaining part of the spectrum may be utilized by the bottom solar cell. However, due to loss mechanisms, such as free carrier absorption, the actual transmitted light may be less than that predicted by the solar spectral irradiance data. The ratio of the actual transmitted light to the theoretical maximum predicted by the irradiance data gives the overall transparancy of the material for photons less energetic then the bandgap.

The transparency of the top solar cell determines the overall reduction in performance of the bottom solar cell. This reduction is in the short-circuit current. Allowing for an additional 5% loss due to optical losses, the best state-of-the-art silicon solar cell should be 11.5% efficient when placed under a $GaAs_{.54}P_{.46}$ top solar cell. Hence, a 13.5% efficient top solar cell is needed to achieve the goal of a 25% efficient tandem stack.

To achieve a 13.5% efficient top solar cell, an open-circuit voltage of 1.46 volts, a short-circuit current density of 14.9 mA/cm^2 and a fill factor of 0.84 are needed. This short-circuit current density corresponds to a total quantum efficiency of 71.8%.

A comparison of the best case GaAsP solar cell parameters to those required for the achievement of a 25% efficient tandem solar cell is shown in Table V.

Table V

Comparison of Best Case GaAsP to Requirements for a 25% Efficient Tandem Solar Cell

	Voc (volts)	Jsc (mA/cm^2)	FF	Efficiency (%)
Best Case	1.47	18.9	.87	17.9
Required	1.46	14.9*	.84	13.5

*Requires total quantum efficiency of 71.8%.

Progress of GaAsP Top Cell Device Fabrication

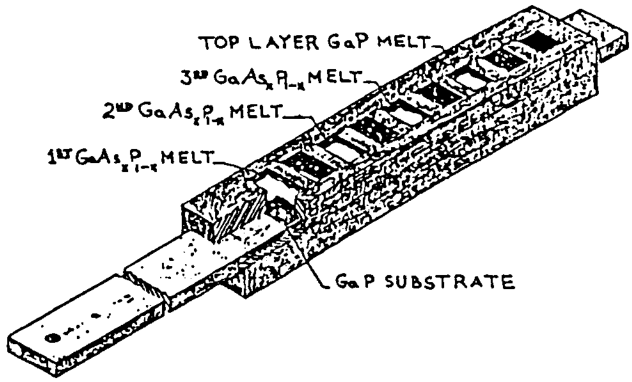
The GaAsP solar cell structure is being grown by liquid phase epitaxy (LPE). Liquid phase epitaxial crystal growth has, in general, produced devices that are superior in performance to those grown by other methods (6, 7). The superior performance of LPE devices when compared to vapor phase or diffused devices can be attributed to fewer deep level impurities, longer diffusion lengths and the fact that the impurities tend to segregate to the liquid rather than the solid.

The actual crystal growth of the multi-layer GaAsP on GaP structure is achieved using the slider method for LPE growth (8). The slider apparatus serves as a substrate holder and melt container for the growth solutions. Advantages of the slider method over other techniques are 1) the substrate can be brought in and out of contact with the melts, 2) several melts can be used, 3) growth is restricted to a single side of a wafer, 4) substrate - solution contact is from the bottom of the melts where there are no floating oxides or other contaminants, 5) excess solution can be wiped off by the sliding action of the apparatus, and 6) thermal equilibration and temperature profiling are easily facilitated. The slider assembly fits into a temperature gradient or cooling furnace. The zones of the furnace are controlled to better than 1°C. Currently, in our furnace, we use a high purity hydrogen atmosphere which sweeps the growth apparatus and tube during the growth process.

The slider assembly contains up to nine melts and consists of a graded well design such that each successive layer is narrower than the former layer. This can be seen in Figure 1. This allows testing and analysis of each individual layer. Individual melts are composed of approximately eight grams of solvent with appropriate amounts of GaP and GaAs - determined by phase equilibria data for the compositions desired. Growth is achieved by placing the GaP substrate under the first melt to grow a transition layer of $GaAs_xP_{1-x}$ by controlling the temperature level, cooling rate, and time of exposure. This procedure, continues, in turn, to each melt in the growth apparatus. Since GaP segregates preferentially over GaAs in metallic systems, melt depletion can be used to grade the layers from pure GaP to the desired final layer composition.

Figure 1

Slider Boat Growth Apparatus Showing
the Graded Well Width



Multiple graded structures of GaAsP with up to 65% GaAs have been grown in our laboratories with surface qualities equivalent to commercial GaP on GaP epitaxial wafers. Currently, a combination of melt depletion and step grading has produced the best surface morphologies. This consists of a 10% GaAs layer grown on the GaP substrate. This 10% GaAs layer is depleted to approximately 12% GaAs before moving the substrate to the next melt for another step grade. The following step is to a 15% GaAs layer which, in turn, is depleted to about 17% GaAs. Then, the substrate is contacted to a 20% GaAs melt and melt depletion is used to grade to about 40% GaAs. At this point, the substrate is contacted with another melt to achieve the final GaAsP composition. Since melt depletion is used to grade the final two layers, the ending composition is determined by the final temperature. Modelling has been done to anticipate the temperature at which the final desired composition will be achieved. Table VI shows various expected vs. measured compositions.

Table VI

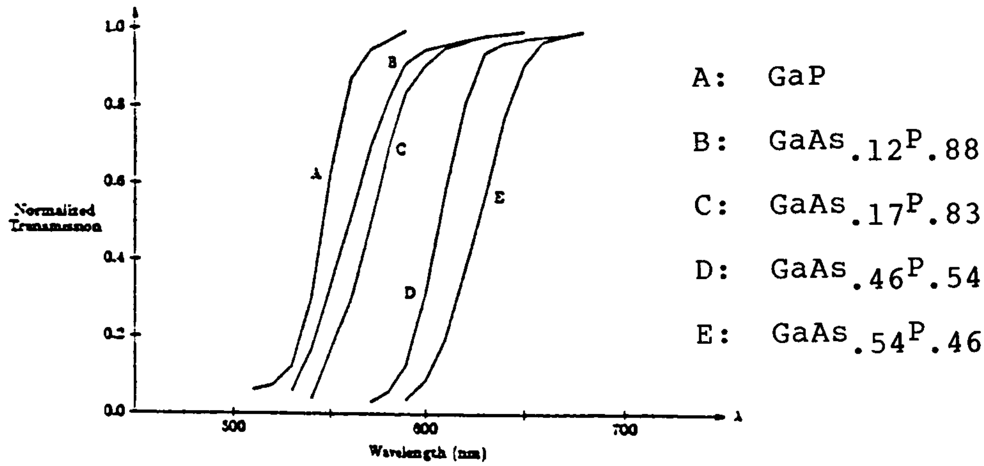
Comparison of Expected vs. Measured
Composition of Grown GaAsP

Sample	Design % GaAs	Energy Gap (eV) Expected	Measured
PT#66	50	2.01	2.01
PT#101	47	2.03	2.01
PT#104	79	1.69	1.69
PT#117	65	1.85	1.88
PT#193	54	1.97	1.98
PT#198	54	1.97	1.98
PT#200	54	1.97	1.96
PT#209	54	1.97	1.97

Since the LPE boat assembly has a graded well design (which allows easy access to the individual grown layers), optical transmission is used to determine the compositions of the grown layers. A typical structure determined by optical transmission is shown in Figure 2.

Figure 2

OPTICAL TRANSMISSION OF FOUR LAYER STRUCTURE



The preferred solvent for the GaAsP-GaP solvent system is gallium. When tin is used as a solvent, the grown layer is n-type with a carrier concentration of $6x10^{18}$/cc, which is too high for our solar cell design.

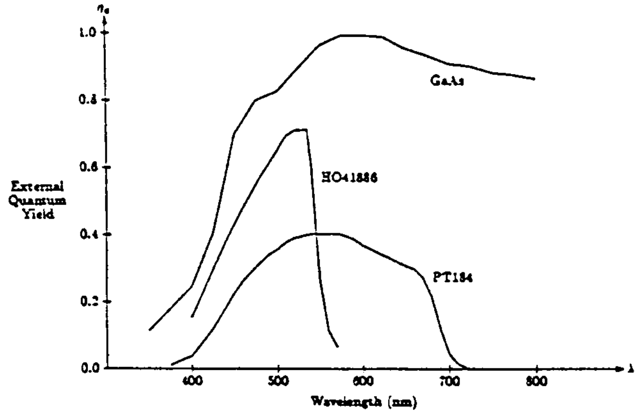
We are currently working on p/n structures, with the preparation of the thin emitter layers being accomplished by solid state diffusion techniques. This process was developed in our laboratory and is very similiar to diffusion from spin-on silica glasses (9). However, our process consist of a SiO_2 passivation layer to protect the crystal surface, a Zn_3P_2 layer for the zinc source, and a SiO_2 capping layer for the entire structure. The SiO_2 enhances the diffusion of a relatively low concentration of zinc (thereby minimizing wafer surface damage while facilitating high surface concentrations (10)). These diffusions are leading to open-circuit voltages in excess of 1.4 volts; however, the short-circuit current has been low.

Figure 3 shows the spectral response of two of our devices compared to a GaAs standard. Sample PT#184 has a 1.84eV composition, which shows a low quantum yield and a flat response. It is believed that part of this low yield is due to a dead layer resulting from the solid state diffusion process.

Sample H041886 has a 2.08eV composition and shows a more peaked response. This sample peaks in the region corresponding to the direct bandgap. Hence, some efficiency is lost in the indirect composition region. The poor blue response of H041886 is most likely due to a deep junction.

Figure 3

SPECTRAL RESPONSE OF TWO GaAsP DEVICES



To achieve the 71.8% quantum efficiency needed for the attainment of a 25% tandem solar cell, the flat response of PT#184 must be brought up to the level of the H041886 peak. We are currently investigating the spectral response of MIS devices and grown p/n junctions in order to achieve this.

The near term goal of a 25% efficient tandem solar cell requires a 13.5% efficient top solar cell. Table VII shows our best parameters to date.

Table VII

Best GaAsP on GaP Solar Cell Parameters

	Target	Actual
Transparency below Eg (%)	95	92.3*
Voc (volts)	1.46	1.43
Jsc (mA/cm^2)	14.9	14.6**
FF	.84	.84

*Single layer AR coating
**MIS Device

The first experimental two-junction, four-terminal tandem cells with GaAsP top solar cell on a conventional silicon bottom cell has been prepared. The top cell has an open circuit voltage of 1.397 volts and a fill factor of 0.81, although the current was low. Nonetheless, the tandem stack outperformed the conventional silicon solar cell by more than 10%. If the GaAsP top solar cell were stacked on a state-of-the-art silicon solar cell, an efficiency approaching 20% would have been achieved. A transparency of 95.0% has been achieved with this tandem structure - this includes grid shading but neglects busbar losses.

Conclusions

Preliminary results are encouraging for the achievement of high conversion efficiencies using a GaAsP top solar cell mechanically stacked on a conventional silicon solar cell. A realistic maximum of 29.4% is suggested when both the top and bottom solar cells are state-of-the-art. Practical system efficiencies greater than 25% are attainable in the near future with the use of a state-of-the-art bottom solar cell.

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