METAMORPHIC GaInP/GaInAs/Ge SOLAR CELLS

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ABSTRACT

High-efficiency, metamorphic multijunction cells have been fabricated by growing GaInP/GaInAs subcells that are lattice-mismatched to an active Ge substrate, resulting in GaInP/GaInAs/Ge 3-junction (3J) cells. The efficiency dependence of this 3J cell on lattice-constant of the top two cells and on sublattice ordering in the GaInP top cell is presented. A variety of composition-graded buffers have been explored through X-ray diffraction reciprocal space mapping to measure strain in the cell layers, and transmission electron microscopy to minimize misfit and threading dislocations. Quantum efficiency is measured for metamorphic 1.3-eV $Ga_{0.92}In_{0.08}As$ (8%-In GaInAs) cells and 1.75-eV $Ga_{0.43}In_{0.57}P$ cells grown on a Ge substrate, as well as for the 3J cell based on 4%-In GaInAs. Three-junction $Ga_{0.43}In_{0.57}P/Ga_{0.92}In_{0.08}As/Ge$ cells with 0.50% lattice-mismatch to the Ge substrate are measured to have AM0 efficiency of 27.3% (0.1353 W/cm^2, 28°C), similar to high-efficiency, conventional GaInP/GaAs/Ge 3-junction cells based on the GaAs lattice constant.

INTRODUCTION

GaInP/GaAs multijunction (MJ) solar cells have a history of being the highest efficiency photovoltaic cells in both the space and terrestrial arenas[1-4], with over 29% AM0 efficiency demonstrated for lattice-matched 3-junction (3J) cells[5]. However, the GaInP/GaAs bandgap combination is still far from optimum for the AM0 and AM1.5D spectra, and even higher efficiencies are possible by increasing the indium composition of the GaInP and GaAs subcells. This lowers the bandgap of each material, thereby tuning the resulting GaInP/GaInAs dual-junction cell for more efficient conversion of either the space or terrestrial spectrum[6-7]. This paper describes theoretical and experimental work to reach still higher efficiency by growing this GaInP/GaInAs subcell combination on an active, lattice-mismatched Ge substrate, resulting in a GaInP/GaInAs/Ge 3-junction cell. A variety of composition-graded buffers were explored in this work, in order to transition from the Ge lattice constant to that of the metamorphic GaInAs and GaInP subcells, with a minimum of threading dislocations extending into active cell regions.

THEORY

A number of researchers have plotted the theoretical efficiency of dual-junction cells for various combinations of the subcell bandgaps[7-9], often as efficiency contour plots on axes of cell 1 (top cell) bandgap E_{g1}, and cell 2 bandgap E_{g2}. For GaInP top cells and GaInAs middle cells with the same lattice constant, not all combinations of bandgaps are possible for cells 1 and 2, corresponding to a line of allowed bandgap pairs through E_{g1} , E_{g2} space. While this line does not go through the maximum efficiency point of the dual-junction contour plots, it does pass much closer than the ~1.85eV/1.424eV bandgap combination of GaInP/GaAs. Note that there is ~0.1eV latitude in the bandgap selection of GaInP due to ordering phenomena on the group-III sublattice. All other factors being equal, the higher bandgap resulting from group-III sublattice disordering is predicted to give the highest efficiency for a given GaInP composition. If a quaternary AlGaInP top cell is used[5] as in an AlGaInP/GaInAs multijunction (MJ) cell lattice-mismatched to Ge, still higher top cell bandgaps can be achieved and the theoretical optimum bandgap combination can be reached.

If the third Ge subcell is now included, the GaInP/GaInAs/Ge triple-junction cell efficiency can be calculated as a function of the lattice constant of the top two cells, as shown in Fig. 1. Use of Ge for the bottom cell and substrate not only provides one of the active

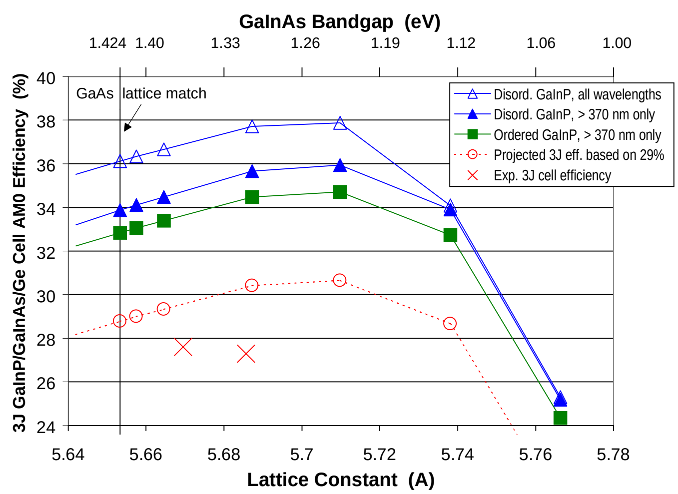

Fig. 1. Theoretical and experimental AM0 efficiencies for 3-junction GaInP/GaInAs/Ge cells as a function of lattice constant of the top two cells.

subcells in the triple junction stack, but it is also a far stronger and less expensive substrate than GaAs. Ge also has a slightly larger lattice constant than GaAs, requiring less lattice mismatch to a given composition of GaInAs and correspondingly fewer dislocations. The model uses: absorption coefficients for each subcell that are functions of the GaInP and GaInAs bandgaps at each lattice constant; the upper limit of open-circuit voltage V_{oc} assuming only radiative recombination and its dependence on subcell bandgap; and fill factors based on diode ideality factors of one.

Fig. 1 shows the increase in GaInP/GaInAs/Ge triple-junction cell efficiency for the AM0 spectrum, from the 5.6533 Å of GaAs to ~5.71 Å for $Ga_{0.38}In_{0.62}P$ and $Ga_{0.86}In_{0.14}As$. Efficiencies up to 38% are theoretically possible under these ideal conditions. The GaInP and GaInAs subcells are current matched in the model by adjusting their thicknesses. Due to the light filtering of the GaInAs cell, the current in the Ge cell limits the 3J cell current for lattice constants greater than ~5.71 Å, causing the efficiency to drop rapidly. The modeled curves serve to point out the effects of bandgap tuning of the top two cells (~2% gain in absolute efficiency); GaInP top cell disordering (~1% abs. efficiency gain); blue response and top layer transmittance that allows use of wavelengths < 370 nm (~2% abs.efficiency gain); current limiting by the Ge bottom cell (constrains lattice constant to < 5.71 Å). An extrapolation of the 29% AM0 efficiency achieved on lattice-matched cells[5] is shown in Fig. 1, as well as experimental efficiencies for the 3J cells with 4%- and 8%-In GaInAs middle cells described below.

EXPERIMENT AND DISCUSSION

The greatest barrier to realization of higher theoretical efficiencies of the metamorphic GaInP/GaInAs/Ge cell is naturally the dislocation density that results from the lattice mismatch between the top two cells and the Ge substrate. These dislocations act as recombination centers, as sites of preferential dopant diffusion and shunting paths in the cells. Studies of various buffers with step-graded GaInAs composition have resulted in cell structures in which the misfit dislocations are well localized to the beginning of the step grade, as shown in the transmision electron microscopy (TEM) image in Fig. 2. The step grade shown here sucessfully converts threading dislocations to misfit dislocations, preventing their propagation into the active upper layers of the device. The GaInAs middle cell (MC) base and GaInP top cell (TC) were dislocation-free as imaged by TEM.

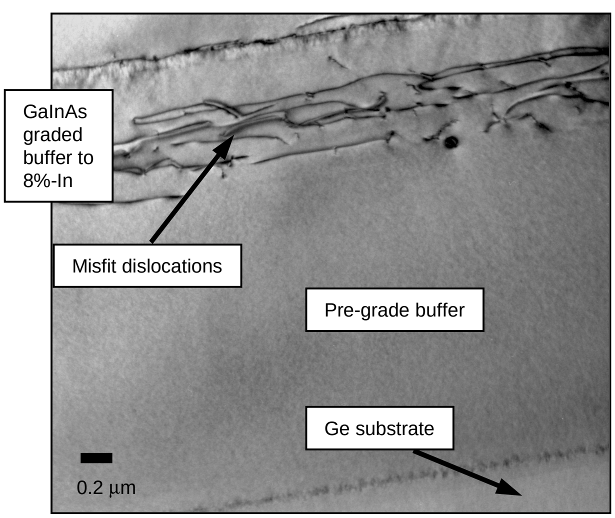

Fig. 2. Cross-sectional TEM image of lattice-mismatched GaInP/GaInAs/Ge structure.

The buffer structures are evaluated by high-resolution X-ray diffraction (HRXRD) and comparison to single- and dual-junction GaInP/GaInAs cell results. Fig. 3 shows triple-axis x-ray rocking curves in which the peaks corresponding to the lattice constants of the Ge substrate, GaAs buffer, the individual layers in the step-graded GaInAs buffer, and the metamorphic 8%-In GaInAs and GaInP cell layers can be seen clearly. The reciprocal space map in Fig. 4 gives the degree of strain in each layer of the structure. This has step-graded buffer layers and metamorphic subcell layers that are almost completely on the line of 100% relaxation, while the GaInPtop cell is strained with respect to the 8%-In GaInAs middle cell. Interestingly, we have found that buffer

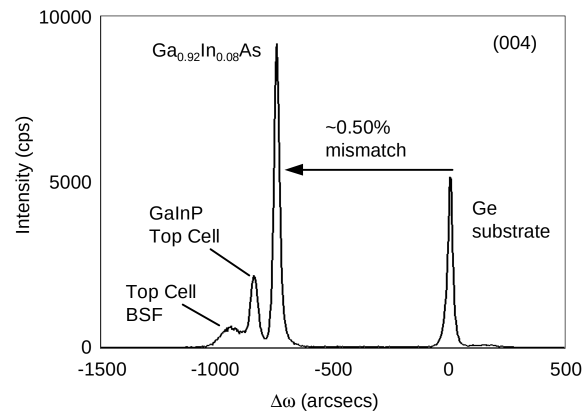

Fig. 3. (004) reflection XRD rocking curve of lattice mismatched GaInP/GaInAs/Ge structure.

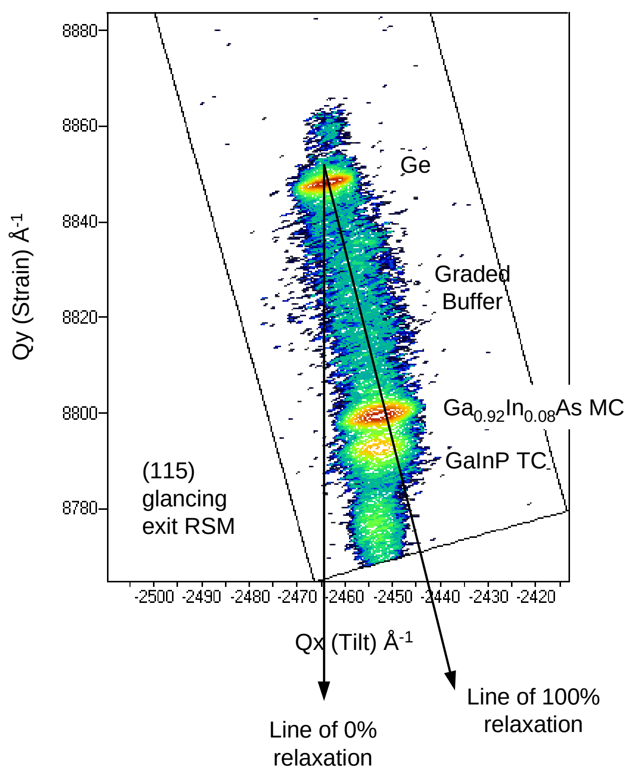

Fig. 4. (115) glancing exit XRD recriprocal space map of lattice-mismatched GaInP/GaInAs/Ge structure.

structures with some strain remaining in the layers give better metamorphic GaInP/GaInAs cell performance than for layers that are nearly 100% relaxed.

The shifts in bandgap for varying indium composition of metamorphic GaInP and GaInAs cells can clearly be seen from the wavelength of the peak photoluminescence (PL) signal on 3-junction cells with 0%-, 4%-, and 8%-In GaInAs middle cells in Fig. 5. The signals from the GaInAs are low due to the absorption of much of the excitation beam (at 488 nm) before it reaches the middle cells. The bandgaps from PL agree well with E_g from external quantum efficiency (QE) curves as shown in Fig. 6, extracted from the energy-axis intercept in plots of $(QE)^2$ *vs.* photon energy. The peak QE is at approximately the same level for each indium composition, with the primary change being a wavelength shift in photoresponse, indicating that the minority-carrier diffusion length has not been seriously degraded in the metamorphic cells by the lattice mismatch to the substrate.

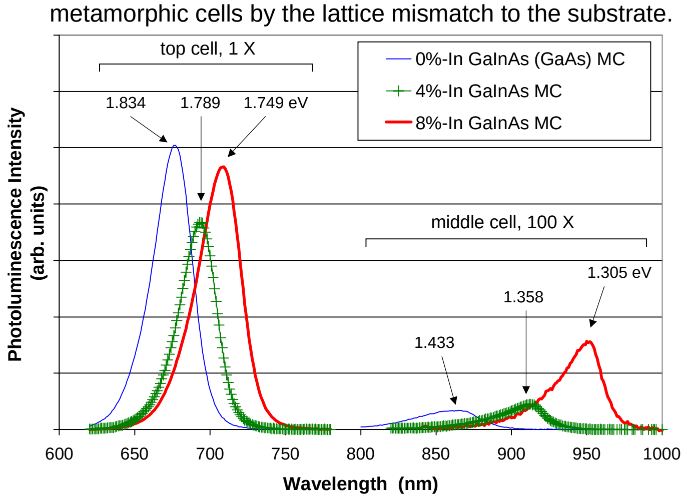

Fig. 5. Photoluminescence peaks measured on finished metamorphic 3J cells with varying In composition.

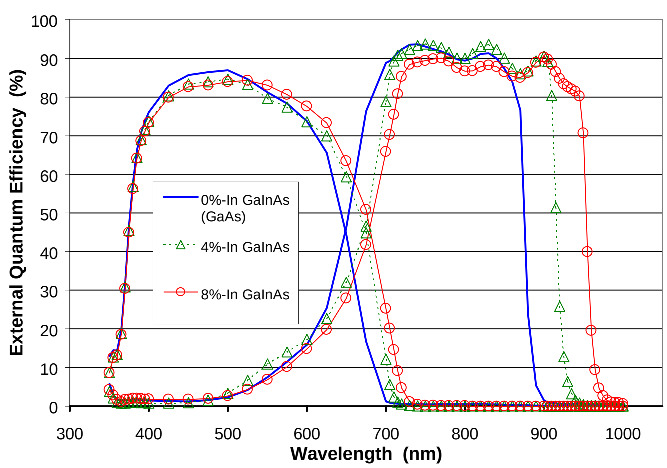

Fig. 6. Measured external QE for metamorphic 3J cells with 0%-, 4%-, and 8%-In GaInAs in the middle cell.

In spite of the challenges posed by dislocations, 3-junction metamorphic GaInP/GaInAs/Ge cells have achieved very respectable efficiencies, as shown in Fig. 7. AM0 efficiency was 27.3% for a 4.0-cm^2 3J cell with a 8%-In GaInAs MC (AM0, 0.1353 W/cm^2), and 27.6% for 4%-In GaInAs, both actually higher than the 27.0%-efficient 3J cell in Fig. 7 with a similar device structure and a 0%-In GaInAs (GaAs) middle cell. The V_{oc} can be seen to drop and the J_{sc} climbs with increasing In composition as expected, due to the decreased E_g of both the GaInP and GaInAs subcells.

The high efficiency of these metamorphic cells is very reproducible, as evidenced by the efficiency distribution in Fig. 8 of of over 90 3J cells with 8%-In in the middle cell base. The average AM0 efficiency for this experimental group of lattice-mismatched cells is over 26%.

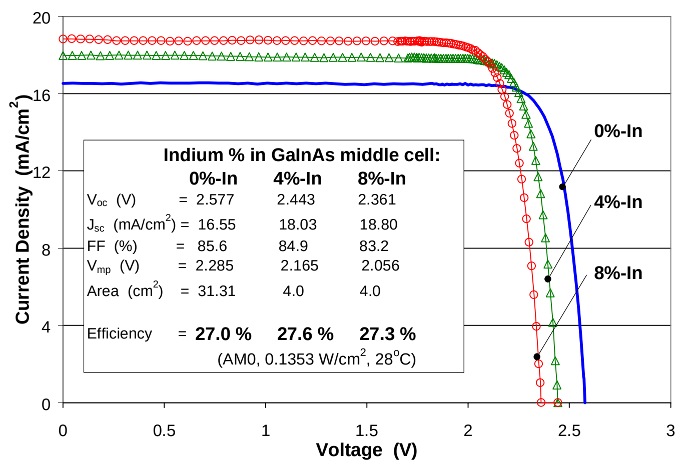

Fig. 7. Light I-V curves for metamorphic 3-junction GaInP/GaInAs/Ge cells with record AM0 efficiency.

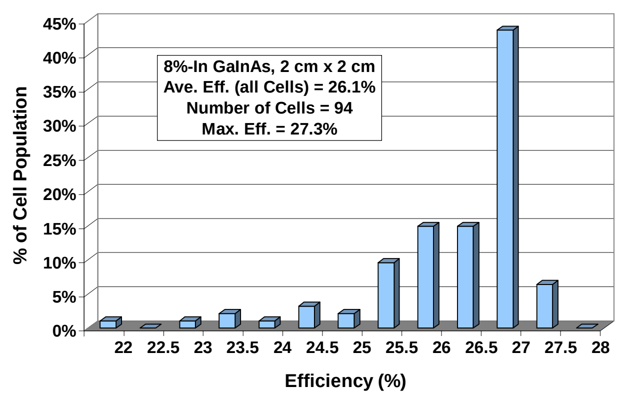

Fig. 8. Distribution of efficiencies for over 90 3-junction metamorphic solar cells.

Metamorphic cells may benefit from the high incident intensities in concentrator cell applications, as recombination centers due to dislocations in the subcells become saturated by the large concentration of photogenerated minority-carriers at hundreds of suns. Measurements of a concentrator metamorphic 3J cell with an 8%-In GaInAs MC, that is current matched to the AM0 spectrum, are shown in Fig. 9. The area of the cell is 1 cm X 1 cm. Spectral response measurements were used to determine the incident intensity, by integrating with respect to the AM0 and AM1.5D spectra to find the one-sun shortcircuit current densities on the top (GaInP) subcell J_T, and the middle subcell J_M. The response of the cell was assumed to be linear, so that the intensity is proportional to the J_{sc} measured at each light level.

The current through the multijunction stack is determined by the smallest of the current densities J_T and J_M, called J_{min} . However, by current-matching the cells for a particular spectrum, *e.g.*, by tuning the thickness and bandgap of the GaInP top cell, the MJ cell should be able to achieve a J_{sc} of approximately $(J_T + J_M)/2$.

Somewhat over 29% AM0 efficiency was reached by the lattice-mismatched cell in Fig. 9 over a wide intensity range from 20 to 70 W/cm^2. The AM0 efficiencies for intensity calculated using J_{min} (closed circles) are similar to those using $(J_T + J_M)/2$ (open circles), because this metamorphic cell is well current-matched for the AM0 spectrum. Although this cell was grown with a top cell base that is too thin to current match in the AM1.5D spectrum, having a current ratio of J_T/J_M = 0.78 in this terrestrial spectrum, the projected AM1.5D efficiency is over 32% for the range of 200-700 suns (open triangles) upon current matching this $Ga_{0.43}In_{0.57}P/Ga_{0.92}In_{0.08}As/Ge$ 3-junction cell.

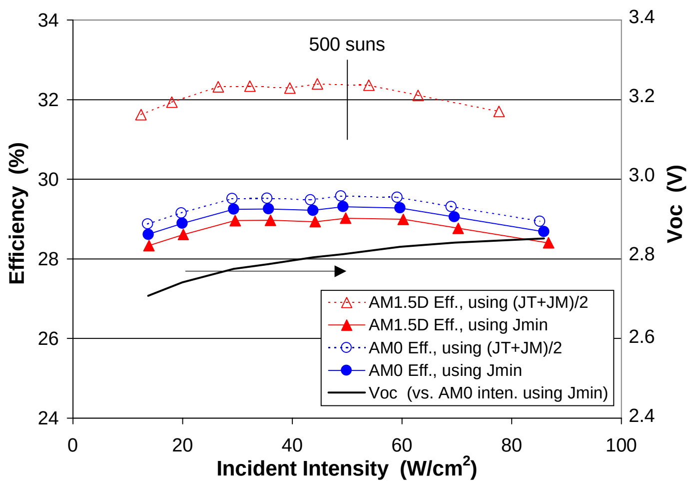

Fig. 9. Measured 3J cell efficiencies (closed symbols) and current-matched projections (open symbols) for a metamorphic 3J cell with a $Ga_{0.92}In_{0.08}As$ middle cell, for AM0 and AM1.5D spectra in the ~100-700 sun range.

SUMMARY

Theoretical and experimental work has been carried out to explore the potentially high-efficiency approach of growing GaInP/GaInAs subcells lattice-mismatched to an active Ge substrate, resulting in a GaInP/GaInAs/Ge triple-junction cell. The efficiency dependence of this 3J cell on lattice-constant of the top two cells and on sublattice ordering in the GaInP top cell is calculated. The Ge subcell strongly limits the multijunction cell current for top and middle cell lattice constants larger than ~5.71 Å, because of the lowered bandgap of the GaInAs cell, which must transmit light used by the Ge subcell. Efficiencies of 38% are ideally possible with this 3J cell configuration.

A variety of composition-graded buffers and cell growth conditions were explored in this work to minimize dislocations in the active cell regions, as determined by high-resolution XRD peak widths, strain measured by reciprocal space mapping, and optoelectronic properties of solar cells fabricated on the grown layers.

An AM0 efficiency of 27.3% (AM0, 0.1353 W/cm^2, 28°C) was measured for a 4.0-cm^2 metamorphic 3-junction $Ga_{0.43}In_{0.57}P/Ga_{0.92}In_{0.08}As/Ge$ cell with subcell bandgaps of 1.749 / 1.305 / 0.67 eV as measured by PL. Average efficiency for a population of over ninety 4.0-cm^2 3J cells with 8%-In GaInAs middle cell bases was over 26%. Measured AM0 concentrator cell efficiencies are over 29% for 8%-In-MC lattice-mismatched 3-junction cells, over the incident intensity range from 20 to 70 W/cm^2. On the basis of these measurements, metamorphic $Ga_{0.43}In_{0.57}P/Ga_{0.92}In_{0.08}As/Ge$ 3-junction concentrator cells are projected to have over 32% AM1.5D efficiency in the same intensity range, if the top cell thickness and group-III sublattice disorder is tuned for current match under this spectrum.

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