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METAMORPHIC AND LATTICE-MATCHED SOLAR CELLS UNDER CONCENTRATION

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ABSTRACT

Metamorphic III-V semiconductor materials offer access to bandgaps that span key portions of the solar spectrum, enabling new bandgap combinations in multijunction solar cells, and increasing both theoretical and practical efficiency limits for terrestrial concentrator cells. Experimental results are given for the quantum efficiency of metamorphic GaInAs solar cells with bandgap from 1.1 to 1.4 eV, and for metamorphic GaInP with both ordered and disordered group-III sublattices. Variable intensity J_{sc} vs. V_{oc} measurements are used to compare recombination components due to n = 1 and n = 2 mechanisms in metamorphic and lattice-matched GaInAs, GaInP, and 3-junction solar cells. A record efficiency metamorphic GaInP/ GaInAs/ Ge 3-junction solar cell has been produced with 38.8% efficiency independently confirmed (241 suns, AM1.5D, low-AOD, 25ºC), essentially equaling the performance of a lattice-matched 3-junction cell with 39.0% efficiency, the highest efficiency yet demonstrated and verified for a solar photovoltaic conversion device. With the combination of high-quality metamorphic materials that are increasingly less controlled by recombination at dislocations, and the higher efficiency limits afforded by freedom of lattice constant selection, practical terrestrial concentrator cell efficiencies well over 40% are expected in the near future.

INTRODUCTION

III-V multijunction photovoltaic cells in concentrator systems have become the highest efficiency technology for solar electricity generation in recent years [1-6]. The high efficiency of these cells stems from their ability to utilize a broad range of the solar spectrum, from 300 to beyond 1800 nm, while controlling the spectrum incident on each subcell to minimize the energy loss of photogenerated carriers as they thermalize to the band edges. Lattice-matched (LM) GaInP/ GaInAs/ Ge 3-junction terrestrial concentrator cells, with the upper two subcells lattice-matched to the Ge substrate, achieve a good but still imperfect division of the solar spectrum for maximum efficiency. The Ge subcell in particular, makes incomplete use of the higher energy photons (up to the 1.41 eV bandgap of the LM GaInAs subcell) as carriers that they generate relax to the 0.67-eV bandgap of the Ge subcell. Nevertheless, such cells are the most efficient photovoltaic converters of sunlight into electricity yet developed, demonstrating an independently confirmed 39.0% efficiency for an experimental cell under the concentrated terrestrial spectrum (AM1.5D, low-AOD, 236 suns, 25ºC) [1]. By dividing the photon flux available in the solar spectrum more evenly among the subcells, still higher efficiencies well in excess of 40% are possible in practice and expected to be achieved soon. This paper discusses the properties of lattice-mismatched, or metamorphic (MM) semiconductor materials with the bandgaps needed to optimally partition the solar spectrum, and describes experience with their integration into high-efficiency multijunction terrestrial concentrator cells.

HIGH-EFFICIENCY APPROACHES

Several options are available to address the problem of unequal photogenerated current in the subcells of lattice-matched GaInP/ GaInAs/ Ge cells. These include: 1) increasing the bandgap of the 3rd (bottom) subcell by using a different material than Ge [1,6]; 2) decreasing the bandgap of subcell 2 above the 3rd subcell, to capture and convert more high energy photons at the higher voltage of subcell 2 [1,2]; 3) dividing the terrestrial solar spectrum more finely using cells with 4, 5, or 6 junctions or even more [1]; 4) combinations of the above. The subcell bandgaps needed for these high-efficiency multijunction cell designs can be accessed most readily with III-V semiconductor materials that are not all at the same lattice constant. However, such lattice-mismatched materials typically have crystal dislocations that are effective

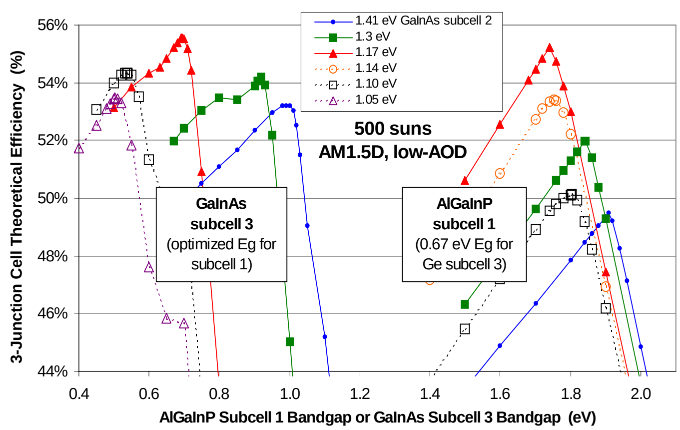

Fig. 1. Calculated ideal efficiency of 3-junction solar cells as a function of subcell 1, 2, and 3 bandgaps.

Shockley-Read-Hall recombination centers, reducing minority-carrier lifetime, voltage, and current collection in lattice-mismatched cells. The goal is to establish growth of metamorphic (meaning "changed form") semiconductor materials at a new lattice constant different from that of the substrate, with a minimum of lifetime-killing crystal imperfections.

Fig. 1 shows the theoretical efficiencies of 3-junction cells under the terrestrial AM1.5D, low-AOD spectrum at 500X, as a function of the bandgaps of subcells 1, 2, and 3. The familiar case of a lattice-matched GaInP/ GaInAs/ Ge cell can be seen in the right group of curves for which the (Al)GaInP top subcell bandgap is varied. From the curve for a 1.41-eV GaInAs subcell 2, the optimum bandgap for subcell 1 (top subcell) is 1.9 eV when subcell 3 (bottom) is Ge. The highest efficiencies are obtained for a subcell 2 bandgap of 1.17 eV, and a top subcell bandgap between 1.7 and 1.8 eV. In the left group of curves, for which the subcell 3 bandgap is varied and the subcell 1 bandgap is optimized for each point, the optimum subcell 3 bandgap is 1.0 eV for a middle subcell Eg of 1.41 eV, with a theoretical efficiency of ~53%. Interestingly, the ideal efficiency can be made higher, well over 55%, if a middle cell bandgap of 1.17 eV can be achieved. The optimum subcell 3 bandgap is then ~0.7 eV, very near that of germanium.

RESULTS AND DISCUSSION

A large part of the wide range of semiconductor bandgaps needed to span the solar spectrum and realize the high-efficiency cell architectures and bandgap combinations described in Fig. 1 can be reached using metamorphic GaInAs and GaInP materials. The ordering state on the group-III sublattice provides an additional lever for bandgap adjustment, and is a particularly strong effect in GaInP. Figure 2 shows measured internal quantum efficiency as a function of photon energy for metamorphic GaInAs solar cells out to a high lattice mismatch of 1.6% to the Ge substrate for 1.1-eV 23%-In GaInAs, and external quantum efficiency for ordered and disordered metamorphic GaInP solar cells. The GaInAs long wavelength response is nearly ideal out to the band edge of 1.12-eV GaInAs with 1.6% lattice mismatch, indicating long minority-carrier diffusion length in this metamorphic material. Disordered metamorphic GaInP with a lattice mismatch of 0.5%, corresponding to the lattice constant of 8%-In GaInAs, has an absorption edge in spectral response that is similar to that of ordered, lattice-matched GaInP, due to their similar bandgaps. The ordered GaInP bases were grown thinner in order to achieve the same current density as in the disordered bases, so their softer cut-on near the band edge is due primarily to lower photogeneration in the thin bases, rather than reduced carrier collection.

As mentioned above, lattice-matched GaInP/ GaInAs/ Ge 3-junction solar cells have demonstrated the highest independently confirmed efficiency of any solar photovoltaic conversion device, with 39.0% efficiency at 236 suns, AM1.5D, low-AOD, 25ºC. The illuminated light I-V curves of this cell are shown in Fig. 3, along with those of record efficiency one-sun cells.

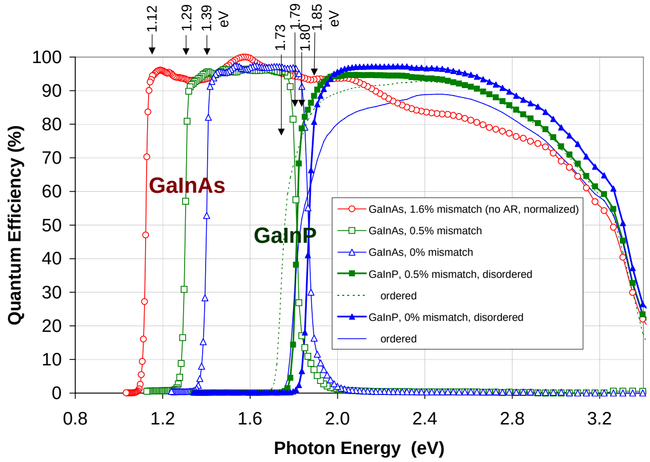

Fig. 2. Measured quantum efficiency for metamorphic and lattice-matched GaInAs and GaInP subcells. Both disordered and ordered cases for the group-III sublattice of GaInP are shown.

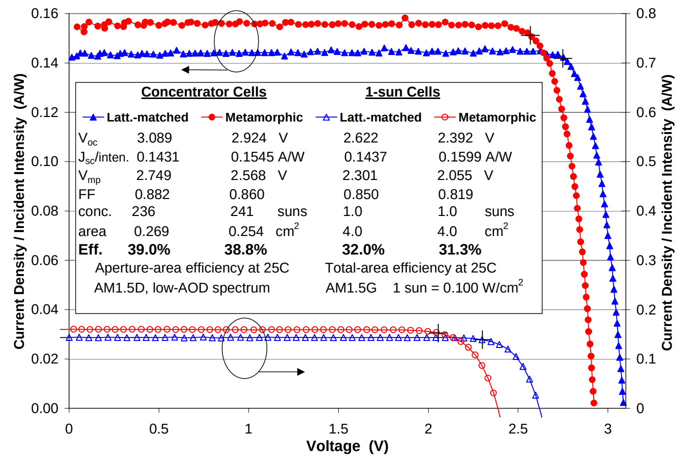

Fig. 3. Light I-V curves for record efficiency metamorphic cell with 38.8% efficiency, and record efficiency lattice-matched cell with 39.0%, under the concentrated AM1.5D, low-AOD terrestrial solar spectrum. Record efficiency MM and LM one-sun cells are also shown for comparison.

Perhaps even more remarkable is that a metamorphic 3-junction GaInP/ 8%-In GaInAs/ Ge cell built in the same fabrication run gave an efficiency that is nearly as high at 38.8%, essentially identical to the lattice-matched cell performance within experimental error. The light I-V curve for this MM 3-junction cell is also shown in Fig. 3. The fill factor FF is consistently observed to be lower in MM 3J cells than in the LM case. Here the record-efficiency MM 3-junction cell has a FF of 86.0% compared to 88.2% for the LM cell, but the MM cell makes up for this lower FF in the other light I-V parameters. The J_{sc}/intensity, or responsivity of the MM cells is naturally much higher than for the LM cells due to the lower bandgaps of the MM subcells. For this MM 3J cell, the responsivity is 8% higher with 0.1545 A/W compared to 0.1431 A/W in the LM case.

Efficiencies of experimental lattice-matched and metamorphic 3-junction cells measured at Spectrolab are shown in Fig. 4, as a function of the J-ratio, *i.e.*, the ratio of top subcell to middle subcell current densities. The light I-V measurements are steady-state, at intensities from 100- to 130 suns, using an X25 solar simulator in combination with a Fresnel lens, and using LM and MM GaInAs and GaInP reference cells calibrated at the National Renewable Energy Laboratory (NREL). The J-ratio is extracted by integrating the measured quantum efficiency of top and middle subcells, weighted by the standard AM1.5 Direct, low-AOD spectrum. The expected arch shape is seen for the upper edge of the efficiency data vs. J-ratio, with a broad peak centered on a J-ratio of 1.0. It is easier to achieve J-ratios > 1.0 for MM cells than for LM 3-junction cells. Efficiencies measured at Spectrolab with this setup tend to underestimate the official efficiency measured at NREL, by 0.5-2.5% in absolute efficiency, so that some of these cells with efficiency near 39% may in fact be over 40% efficiency once independently confirmed.

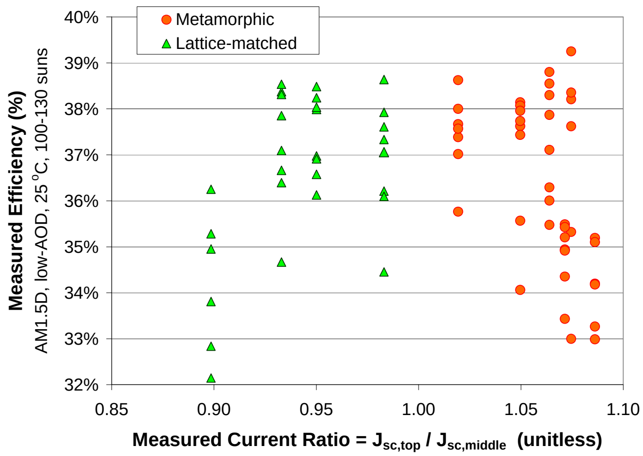

Fig. 4. Multijunction terrestrial concentrator cell efficiency at 100-130 suns, tested at Spectrolab using NREL-calibrated reference cells, plotted vs. current ratio.

Refering back to Fig. 3, the open-circuit voltage V_{oc} of the MM GaInP/ 8%-In GaInAs/ Ge cell, with 0.5% lattice-mismatch to the Ge substrate in the upper two subcells, is 2.924 V at 241 suns, only 165 mV less than the V_{oc} of the record efficiency lattice-matched cell, in spite of the ~200 meV difference in the sum of subcell bandgaps for the two cells. For the record efficiency one-sun cells, the difference in the LM and MM V_{oc} values is 230 mV, exceeding the ~200 meV bandgap sum difference. This indicates that while the defects controlling recombination in the MM materials may be more detrimental to cell performance at low incident intensities, their influence is significantly lessened at higher concentrations.

This voltage trend, in which the V_{oc} increases more rapidly with increasing light concentration in MM materials than in the LM case, is also evident in Fig. 5, which plots the efficiency, FF, and V_{oc} as a function of light concentration for the record-efficiency LM and MM 3J cells. After a 2.5-decade increase in incident intensity, the MM cell V_{oc} has increased by 598 mV, while the LM cell increased by only 554 mV. This can occur if one or more MM subcells has a larger n = 2 component of the diode saturation current density than their LM counterparts, where n is the diode ideality factor.

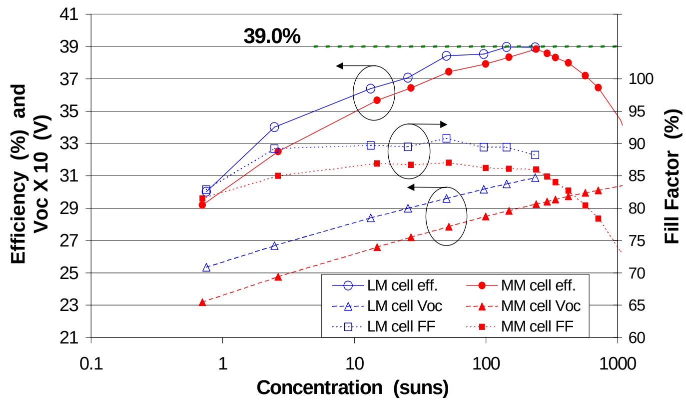

Fig. 5. Dependence of efficiency, V_{oc}, and FF on solar concentration ratio for record-efficiency metamorphic and lattice-matched 3-junction cells.

The current of a solar cell with an n = 1 recombination component, due for instance to recombination in the quasi-neutral regions in low-level injection in the emitter and base, as well as an n = 2 recombination component due to recombination in the space-charge region at the junction, is given by:

$$\begin{aligned} J &= J_{ph} - J_{rec,n=1} - J_{rec,n=2} - J_{shunt} \\ &= J_{ph} - J_{o1}\left(e^{q(V+J\rho_s)/kT} - 1\right) \\ &\quad - J_{o2}\left(e^{q(V+J\rho_s)/2kT} - 1\right) - \left(V + J\rho_s\right)\sigma_{sh} \end{aligned} \qquad (1)$$

where $J_{ph} \approx J_{sc}$ is the photogenerated current density, J_{o1} and J_{o2} are the diode saturation current density components corresponding to n = 1 and n = 2, ρ_s is the specific resistance in Ωcm^2, and σ_{sh} is the specific shunt conductance in $\Omega^{-1}\text{cm}^{-2}$. In forward bias, assuming shunting is negligible as it usually is, and choosing $J = 0$:

$$J_{ph} = J_{o1}e^{qV_{oc}/kT} + J_{o2}e^{qV_{oc}/2kT} = J_{o1}z^2 + J_{o2}z \qquad (2)$$

where $z \equiv e^{qV_{oc}/2kT}$. The coefficients of this quadratic equation, J_{o1} and J_{o2}, can be extracted from variable intensity light I-V (J_{sc} vs. V_{oc}). The J_{sc} vs. V_{oc} method is one of the most useful for extracting J_o components for concentrator cells, since it removes the effect of series resistance which is problematic in dark I-V analysis.

Figure 6 shows J_{sc} vs. V_{oc} curves for the GaInAs and GaInP subcells of MM and LM 3-junction cells, and for integrated MM and LM GaInP/ GaInAs/ Ge 3-junction cells. Fitting to concentrations greater than one sun yields the most reliable data, since it is less subject to any small shunts or recombination mechanisms that are significant only at very low light levels, and since the relevant intensity range for concentrator cells is greater than one sun in any event. However, it is important at these higher intensities to avoid cell heating by using a pulsed light source for the light I-V measurements, since the rise in cell temperature for steady-state testing lowers the V_{oc} and confounds the extraction of J_{o1} and J_{o2}.

J_{o1} and J_{o2} values were found in this way for MM GaInAs and GaInP subcells, and for LM GaInAs and

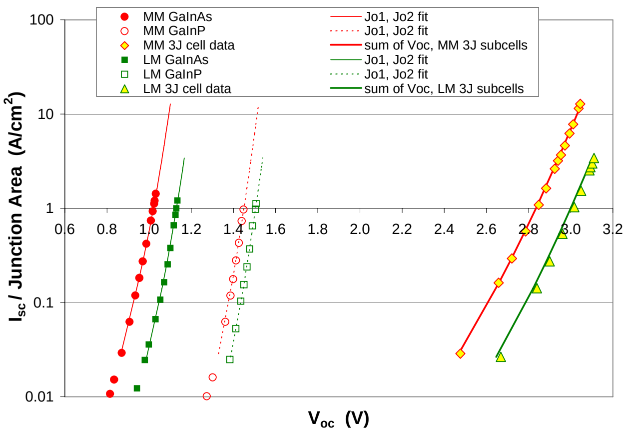

Fig. 6. J_{sc} vs. V_{oc} plots at varying intensities for metamorphic and lattice-matched GaInAs, GaInP, and 3-junction cells, and fits to the data using extracted J_{o1} and J_{o2} values.

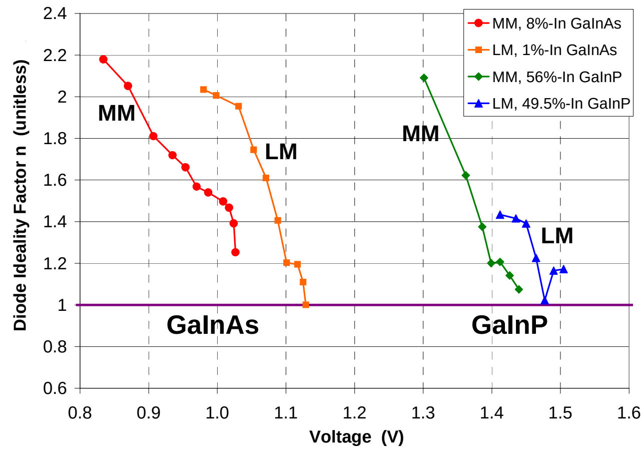

Fig. 7. Diode ideality factor n as a function of voltage for MM and LM solar cells.

GaInP subcells. The fit to the cell data is better using a J_{o1}, J_{o2} analysis than for a variable n analysis in which J_{on} and n are extracted in a single exponential, allowing a more physical interpretation of the recombination data (n=1 due to recombination in the quasi-neutral regions of the device, and n=2 recombination in the space-charge regions), and allowing more accurate extrapolation of the J_{sc} vs. V_{oc} data to higher concentrations. The sum of the open-circuit voltages of the individual subcells in the LM and MM cases agree well with the J_{sc} vs. V_{oc} data for the integrated LM and MM 3-junction cells, as shown in Fig. 6.

Because of the different exponential dependence of the J_{o1} and J_{o2} terms, if one does use a single-diode model instead, the diode ideality factor n will vary as a function of voltage. In this case, in forward bias:

$$J_{ph} = J_{on} e^{qV_{oc}/nkT} \;;\; \ln J_{ph} = \ln J_{on} + \frac{q}{nkT} V_{oc} \qquad (3)$$

$$n = \left(\frac{kT}{q} \frac{d\left(\ln J_{ph}\right)}{dV_{oc}} \right)^{-1} = \left(\frac{kT}{q} \cdot (\text{slope}) \right)^{-1} \qquad (4)$$

A plot of n with respect to voltage, as shown in Fig. 7, helps to show the difference between LM and MM cell behavior. A few trends can be observed. All cells show a striking drop in ideality factor (becoming more ideal as n approaches unity) with increasing concentration (higher voltage). The MM GaInAs cell has n ranging from 2.2 near one sun to ~1.25 at around 100 suns. The rapid drop in n for higher voltages may be an artifact due to cell heating. Over the same range of concentrations, n is ~0.2 lower for LM GaInAs cells than for MM GaInAs. MM GaInP has somewhat lower values of n than MM GaInAs, ranging from 2.1 at one sun to 1.05 at ~100 suns. The LM GaInP cell in Fig. 7 has a lower n than the MM GaInP, especially at one sun where n for the LM GaInP cell is 1.4.

SUMMARY

The quality of metamorphic III-V semiconductors has reached the point at which these materials may be used freely in high-efficiency solar cell designs, with performance essentially equal to that of the highest efficiency photovoltaic devices yet demonstrated. The greater flexibility in bandgap that the metamorphic approach offers for terrestrial concentrator solar cell design results in higher theoretical efficiency limits for multijunction cells, giving solar cell designers more headroom to increase multijunction solar cell efficiencies in practice. With these improvements, practical multijunction solar cells with well over 40% efficiency are likely to be achieved in the near future.

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