LATTICE-MATCHED AND METAMORPHIC GaInP/GaInAs/Ge CONCENTRATOR SOLAR CELLS

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ABSTRACT

Recent developments in epitaxial III-V multijunction solar cell technology have allowed concentrator and 1-sun cells to reach new heights in efficiency under the terrestrial solar spectrum. The bandgaps of the GaInP and GaInAs subcells are controlled by varying indium content, up to 12% indium in the GaInAs middle cell, or 0.8% lattice mismatch. Shockley-Read-Hall recombination at dislocations in such metamorphic cells has been restricted to lower levels than previously achieved, and is compared to the lattice-matched case. Terrestrial GaInP/GaInAs/Ge 3-junction cells have been produced at Spectrolab with record efficiencies independently verified at NREL, of 31.3% for metamorphic 1-sun cells and 32.0% for lattice-matched 1-sun cells (25°C, AM1.5G, 4.00 cm^2), and 35.2% for lattice-matched concentrator cells under the AM1.5 Direct, low-AOD spectrum (25°C, 66 suns, 0.26 cm^2).

INTRODUCTION

The need for ever higher photovoltaic cell efficiencies requires incorporation of new multijunction device structures in lattice-matched solar cells[1-3], as well as exploration of subcell bandgap combinations possible only in lattice-mismatched solar cells[3-6]. Fig. 1 illustrates the tradeoff between available photon flux in the terrestrial AM1.5G solar spectrum, and GaInP/GaInAs/Ge 3-junction cell voltage, with varying GaInAs middle cell bandgap. These competing effects result in optimum theoretical efficiency at lower GaInP and GaInAs bandgaps than at lattice match to the Ge substrate, corresponding to ~14%-In GaInAs in the absence of dislocations. However, dislocations have historically limited the efficiency of such lattice-mismatched, or metamorphic cells to significantly less than that of lattice-matched cells. Recent developments in the growth of lattice-mismatched systems have drastically reduced the effect of dislocations on Shockley-Read-Hall recombination in the active subcells, and have allowed metamorphic cell efficiencies nearly as high as those of the best lattice-matched cells. Coupled with developments such as high-bandgap tunnel junctions and control of GaInP group-III sublattice disorder, both lattice-matched and metamorphic GaInP/GaInAs/Ge 3-junction cells have reached new heights in terrestrial concentrator and 1-sun efficiency.

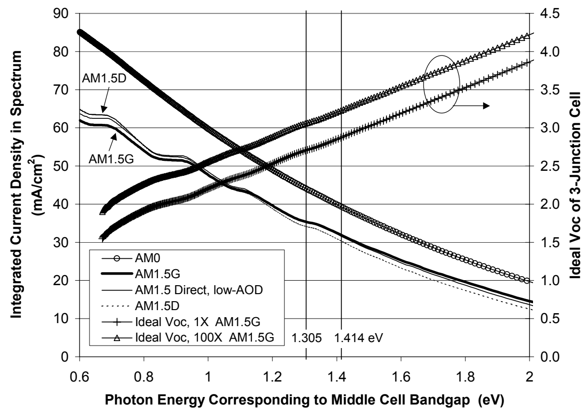

Fig. 1 Current density available in the AM0 space, and AM1.5G, AM1.5 Direct low-AOD, and AM1.5D terrestrial spectra as a function of bandgap, showing the tradeoff with cell voltage. The GaInAs middle cell bandgaps measured for LM and MM cells in Fig. 2 are indicated.

EXPERIMENT

Lattice-matched (LM) and metamorphic (MM) 3-junction GaInP/GaInAs/Ge solar cells were grown by metal-organic vapor-phase epitaxy (MOVPE), to be current-matched for the concentrated terrestrial spectrum. Most metamorphic subcells were grown with compositions of 8%-In GaInAs and 56%-In GaInP with a nominal lattice constant of 5.686 Å, though some single-junction cells were grown with up to 12%-In GaInAs in the base. A variety of growth conditions were explored, influencing sublattice disorder and bandgap in GaInP, tunnel junction bandgap, and dislocation propagation from the step-graded buffer of the metamorphic cells.

GaInP/GaInAs/GaInP and AlGaAs/GaInP/AlGaAs double heterostructures (DHs) were also grown, both lattice-matched and mismatched to the Ge substrate. The DHs were grown with base compositions of 1%- and 8%-In GaInAs, and 49.5%- and 56%-In GaInP, in order to directly measure minority-carrier lifetime in these materials, which mirror the base compositions of the solar cells.

Until recently, the AM1.5G (E 892-87) [7] spectrum has been found by the National Renewable Energy Laboratory (NREL) to be a closer match than AM1.5D (E 891-87) [8] to the actual spectrum in most concentrator applications[9,10]. More recently, the AM1.5 Direct, low-AOD spectrum has been adopted by NREL as the standard reporting spectrum for concentrator cells[11]. The record concentrator cell efficiency results reported in this paper were independently verified under this spectrum at NREL. One-sun cell results were also independently confirmed at NREL, using the AM1.5G (E 892-87) spectrum.

External quantum efficiency (EQE) and room-temperature wavelength-resolved photoluminescence (PL) were measured for the LM and MM cells, to characterize subcell bandgap and minority-carrier collection properties. A 488 nm Ar ion laser was the excitation source for wavelength resolved PL. Minority-carrier lifetimes in the DHs were measured directly by time-resolved photoluminescence (TRPL) at NREL, using a rhodamine 6G dye laser at 580 nm, a multichannel plate photomultiplier tube, and an overall 30 ps response time.

RESULTS AND DISCUSSION

Epitaxial Layer and Subcell Characterization

The EQE and photoluminescence spectra of LM and MM cells are plotted in Fig. 2. The energy of the PL peak, a reasonable estimate of the subcell bandgap E_g , is indicated in the figure. The shift of ~80 meV downward for the GaInP top cell, and ~110 meV for the GaInAs cell is readily apparent for the metamorphic case, resulting in higher available current density. The offset between bandgap voltage E_g/q and open-circuit voltage V_{oc} of a subcell limited by radiative recombination is roughly independent of E_g [3], so the metamorphic 3-junction cell voltage can be expected to be ~190 mV lower than that of the LM cell in Fig. 2, even in the absence of additional recombination due to dislocations. Figure 3 plots the measured dependence of V_{oc} on bandgap of LM and MM single-junction GaInAs cells as the composition is varied from 0% to 12%-In. The offset E_g/q - V_{oc} is approximately constant at ~400 mV, indicating that the change in voltage is due almost entirely to the varying bandgap, not to additional SRH recombination at dislocations in the MM cells.

The similarity in SRH recombination rates that can be achieved in lattice-matched and mismatched GaInAs is shown in Fig. 4, plotting the minority-carrier lifetime measured by TRPL in double heterostructures. The effective lifetime shown is a lower limit for the bulk lifetime in the base material. Measured lifetimes are shown for not-intentionally-doped (nid) GaInP with an ordered group-III sublattice (lower bandgap than disordered for a given GaInP composition), GaInP with a disordered sublattice (higher bandgap), and GaInAs bases from a previous experiment[3]. The lifetimes from recent measurements of 1%- and 8%-In nid-GaInAs DHs are also shown, with a phenomenally long lifetime of 600 ns in the metamorphic $Ga_{0.92}In_{0.08}As$ base, compared to 1120 ns in the lattice-matched $Ga_{0.99}In_{0.01}As$ case. The measured lifetime in these recent metamorphic $Ga_{0.92}In_{0.08}As$ samples is approximately 60 times longer than in earlier MM 8%-In GaInAs DHs.

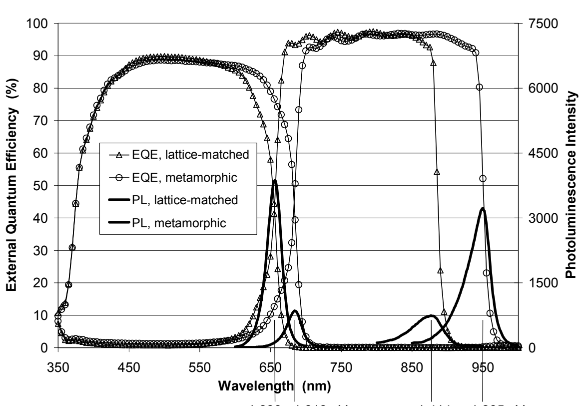

Fig. 2 External quantum efficiency and photoluminescence measurements made on 3-junction lattice-matched and metamorphic GaInP/GaInAs/Ge cells, showing the shift in top and middle cell bandgaps in the two cases.

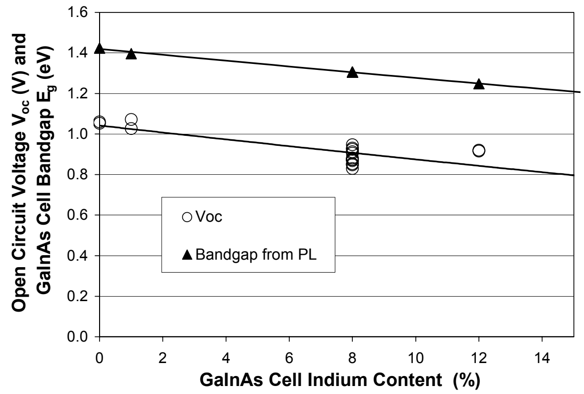

Fig. 3 Measured V_{oc} and bandgap from room-temperature PL of GaInAs single-junction cells with 0%- to 12%-In composition, showing the nearly constant offset of ~400 mV between E_g/q and V_{oc} .

Lattice-Matched and Metamorphic 3-Junction Cells

Figure 5 plots light I-V measurements for two new record efficiency terrestrial cells produced at Spectrolab. The lattice-matched 3-junction cell in the chart has an efficiency of 32.0% (AM1.5G, 0.100 W/cm^2, 4.0 cm^2, 25^{o}C), making this the highest independently confirmed solar cell efficiency at one-sun. The metamorphic GaInP/GaInAs/Ge 3-junction cell in Fig. 5 has nearly as high efficiency at 31.3%. This is not only a record efficiency for a metamorphic solar cell, but is also higher than the previous record one-sun efficiency of 31.0% for a

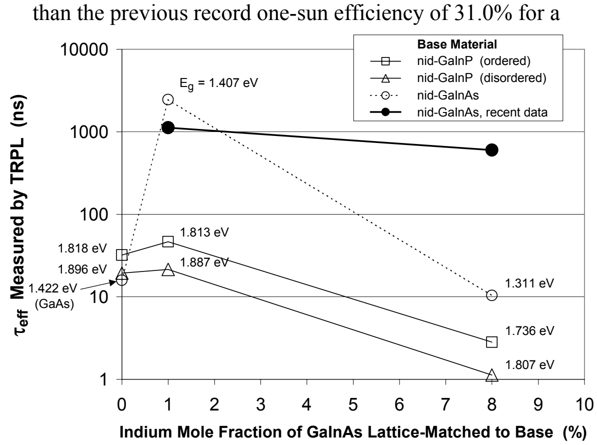

Fig. 4 Minority-carrier lifetime in LM and MM double heterostructures with GaInAs and GaInP bases, showing the very high lifetimes achieved in recent 8%-In GaInAs samples due to optimized metamorphic growth conditions.

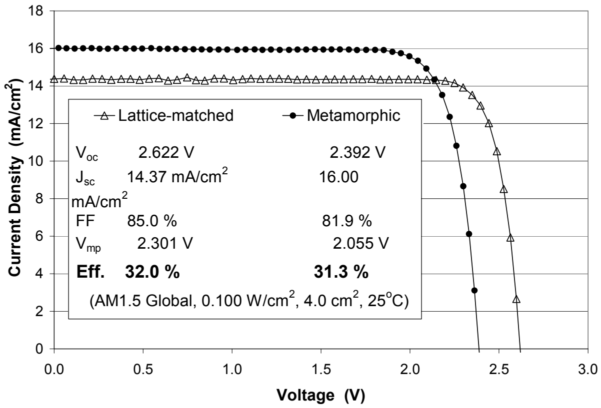

Fig. 5 I-V curves of lattice-matched and metamorphic 3-junction cells processed at Spectrolab, with record one-sun efficiency independently measured at NREL.

cell < 1 cm^2, or 30.3% for a 4.0-cm^2 cell[12]. The higher current and lower voltage of the MM cell design are evident in comparison to the LM cell in Fig. 5.

In these cells, only ~130 mV of the 230 mV difference in V_{oc} between LM and MM cases is accounted for by the difference in the sum of the subcell bandgaps. The remaining 100 mV portion may be due to increased SRH recombination, particularly in the MM GaInP top cell. As this voltage difference becomes smaller with further experimentation in metamorphic cell growth, and as we learn the mechanisms controlling the relatively low fill factor (FF), we expect that the efficiency of the metamorphic cells can reach and surpass that of the best lattice-matched cells.

These one-sun solar cells were fabricated using a mask set with grid patterns optimized for 1 to 1000 suns on the same wafer, in an experimental concentrator cell run. Concentrator 3-junction solar cells from this run have also demonstrated record performance under the concentrated solar spectrum. Figure 6 plots the efficiency, V_{oc}, and FF of a lattice-matched 3-junction cell grown and processed at Spectrolab, and measured at NREL to have an efficiency of 35.2% at 66 suns (AM1.5 Direct, low-AOD, 6.6 W/cm^2, 0.266 cm^2 aperture area, 25°C).

The open-circuit voltage of this 3-junction cell is seen to increase by ~250 mV per decade in concentration from the 2.504 V measured at one sun, and the FF for this

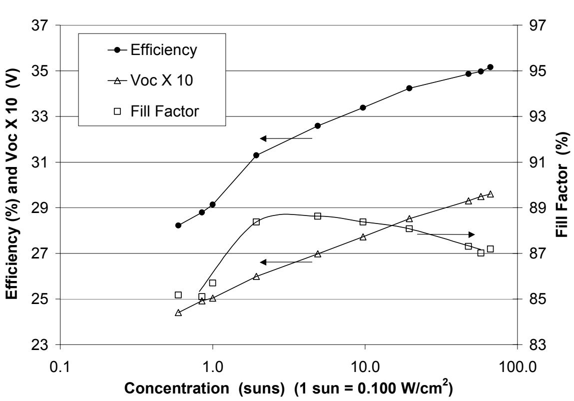

Fig. 6 Dependence of lattice-matched 3-junction concentrator cell performance on incident intensity.

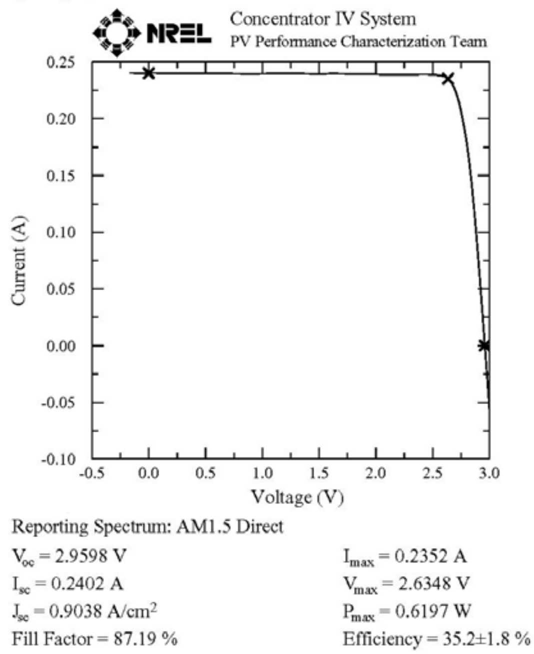

Fig. 7 I-V curve of record 35.2%-efficient Spectrolab concentrator cell measured at NREL under the AM1.5 Direct, low-AOD spectrum.

lightly-gridded concentrator cell peaks at only ~3 suns. However, the efficiency has still not peaked by the time it reaches 35.2% at 66 suns incident intensity. This was the highest intensity at which this cell was tested in these steady-state measurements at NREL using an X25 solar simulator. The I-V curve of the 3-junction lattice-matched cell at the 35.2%-efficiency point is plotted in Fig. 7.

Relationship Between Lifetime and Cell Parameters

For a cell limited by radiative lifetime τ_{rad} and Shockley-Read-Hall (SRH) lifetime τ_{SRH} , a simple expression for the saturation current density J_o is given by Eqn. (1) below, where n_i is the intrinsic carrier concentration, and w and N_A are the thickness and doping concentration, respectively, of the solar cell base. The J_o can be determined experimentally for the LM and MM single-junction component subcells grown, from their measured V_{oc} and J_{sc} , and the expression $J_o = J_{sc}\, e^{-qVoc/kT}$, for unity diode ideality factor. Using the relationships $\tau_{rad} = 1/BN_A$, where B is the radiative recombination coefficient, and $n_i^2 = N_C N_V\, e^{-Eg/kT}$, where N_C and N_V are the effective densities of states in the conduction and valence bands, respectively, one obtains Eqn. (2) for τ_{SRH} :

$$J_o = \frac{qwn_i^2}{N_A}\left(\frac{1}{\tau_{SRH}} + \frac{1}{\tau_{rad}}\right) \tag{1}$$

$$\frac{1}{\tau_{SRH}} = N_A\left(\frac{J_o}{qwN_C N_V e^{-Eg/kT}} - B\right) \tag{2}$$

For the measured 1-sun V_{oc} values of 1.010 V for the LM middle component cell, and 0.856 V for the MM GaInAs middle cell, and measured values of E_g from PL and N_A , one can determine the characteristic lifetime of SRH recombination mediated by deep levels at interfaces and dislocations in the crystal lattice, separated from the radiative component. This analysis yields very long lifetimes of 430 ns for τ_{SRH} in the LM case, and is only slightly shorter at 180 ns in the metamorphic GaInAs cell, reflecting the very low dislocation densities in these cells. Within the uncertainty in the method, the long lifetimes in both the LM and MM solar cells are consistent with the similarity between recombination lifetimes measured in lattice-matched and metamorphic double heterostructures, as plotted in Fig. 4.

SUMMARY

Recent developments in epitaxial III-V multijunction solar cell technology have allowed concentrator and 1-sun cells to reach new heights in efficiency under the terrestrial solar spectrum. The bandgaps of the GaInP and GaInAs subcells are controlled by varying indium content, up to 0.8% lattice mismatch. Shockley-Read-Hall recombination at dislocations in such metamorphic cells has been restricted to lower levels than previously achieved, comparable to the lattice-matched case, as determined from solar cell parameters as well as direct measurement of minority-carrier lifetime by time-resolved photoluminescence. The 31.3% one-sun efficiency measured for such metamorphic cells is greater than the previous efficiency record, and would have been the highest one-sun efficiency yet measured had it not been exceeded by a 32.0% lattice-matched 3-junction cell in the same fabrication run. A new record concentrator cell efficiency of 35.2% under the AM1.5 Direct, low-AOD spectrum has been achieved in this work.

ACKNOWLEDGMENTS

The authors would like to thank Donna Senft and Clay Mayberry of the Air Force Research Laboratory; Dean Marvin of the Aerospace Corporation; Martha Symko-Davies, Tom Moriarty, James Kiehl, Brian Keyes, Dan Friedman, Jerry Olson, and Sarah Kurtz at NREL; and Dimitri Krut, Mark Takahashi, Anastacio Paredes, and Greg Glenn, and the entire multijunction solar cell team at Spectrolab. This work was supported in part by the Air Force Research Laboratory (AFRL/VS) under DUS&T contract # F29601-98-2-0207, in part by the Department of Energy through the NREL High-Performance Photovoltaics program (NAT-1-30620-01), and by Spectrolab.

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