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Fundamental Efficiency Losses in Next-Generation Multijunction Solar Cells

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Multijunction III-V photovoltaic cells for terrestrial concentrator systems are the highest efficiency solar cell technology yet demonstrated, with conversion efficiencies over 40% since 2006. These high efficiencies are extremely leveraging for reducing the cost of solar electricity, since they reduce all area-related costs of a photovoltaic system – balance-of-system costs like encapsulation, support structures, concentrating optics and trackers, as well as the area and costs of the cells themselves – needed for a given power output.

As high as III-V multijunction efficiencies are presently, practical cell efficiencies of 50% and higher are possible with new solar cell architectures having theoretical efficiencies of 70% and above. The increase in efficiency from 40% to 50% is an extremely important range, corresponding to a tipping point at which concentrator PV becomes the most economic solar electricity option, and is competitive with conventional electricity generation in many geographic areas even without government subsidies. In this paper, we quantify the controlling efficiency losses in next-generation multijunction cell designs, using both theoretical and experimental input, to evaluate the real potential of transformative cell architectures capable of 50% efficiency and above.

Fundamental physical principles dictate some of the directions necessary for reaching higher efficiencies than today's state-of-the-art cells. Incorporation of four and even more junctions is important to reduce the carrier thermalization losses that occur as electrons and holes relax back to their respective band edges, as illustrated in Fig. A1. Cells with 4 and more junctions have the added, highly significant benefit of lowering current density and I^2R series resistance power losses, especially important for concentrator cells. High quality subcells in the 2.0-eV and 1.0-eV band gap ranges are needed to avoid excessive carrier thermalization losses, while low band gap subcells in the 0.7-eV range are needed to capture as much energy as possible from the broad solar spectrum. Higher optical concentrations are favored as they narrow the gaps between the quasi-Fermi levels and their respective band edges, bringing the cell voltage closer to that defined by the band gap.

Solar cells with four or more junctions are not without technical challenges, which work against their theoretical efficiency advantages. Additional tunnel junctions to connect the added subcells in series makes parasitic light absorption in the tunnel junctions a greater concern. The finer division of the solar spectrum in a cell with more than 3 junctions can cause greater susceptibility to a single subcell limiting the current of the overall stack, as the solar spectrum changes over the course of the day and year due to atmospheric attenuation. This paper will quantify these non-ideal effects in high-efficiency next-generation multijunction cells, together with their fundamental efficiency advantages, in order to determine the net benefit in efficiency and energy production in terrestrial concentrator systems.

These advances in understanding are beginning to have an impact on experimental solar cell efficiencies. Upright metamorphic 3-junction GaInP/GaInAs/Ge concentrator cells, of the type that were first to reach over the 40% efficiency milestone, are now being inserted into production as the C4MJ cell. Pilot production runs of the C4MJ terrestrial concentrator cell have demonstrated average efficiency of 39.4%, nearly an absolute efficiency point higher than the previous cell generation, and are expected to reach 40% average efficiency in production. Inverted metamorphic terrestrial concentrator cells with a more advantageous band gap combination have been built and tested, and the latest measurement results will be presented in the paper. Lattice-matched GaInP/GaInAs/Ge cells built at Spectrolab have demonstrated an independently confirmed efficiency of 41.6% under the standard terrestrial spectrum at 364 suns (36.4 W/cm2) concentration as shown in Fig. A2, the highest efficiency yet demonstrated for any type of solar cell. These next generations of multijunction concentrator cells, capable of 45% or even 50% efficiency, have the potential to transform the economics of solar electricity generation.

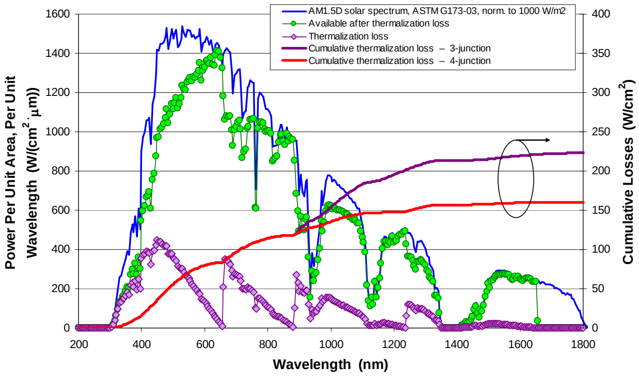

Figure A1. Thermalization losses in an advanced 4-junction solar cell, showing lower cumulative thermalization loss for this 4-junction case than for 3-junction cells. Fundamental losses and non-ideal losses are quantified in the paper, to illuminate the realistic potential of next-generation solar cells.

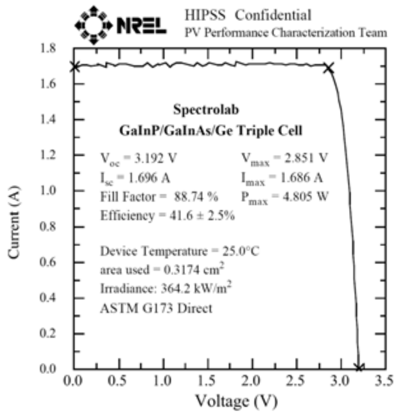

Figure A2. Light I-V characteristic for the record 41.6%-efficiency concentrator solar cell, the highest efficiency yet reached by any type of solar cell. This 41.6% cell was built at Spectrolab with a lattice-matched 3-junction cell structure, and has been independently verified at NREL.

Fundamental Efficiency Losses in Next-Generation Multijunction Solar Cells

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1 INTRODUCTION

Multijunction III-V photovoltaic cells for terrestrial concentrator systems are the highest efficiency solar cell technology yet demonstrated, with conversion efficiencies over 40% since 2006 [1-4]. These high efficiencies are extremely leveraging for reducing the cost of solar electricity, since they reduce all area-related costs of a photovoltaic system – balance-of-system costs like encapsulation, support structures, concentrating optics and trackers, as well as the area and costs of the cells themselves – needed for a given power output.

As high as III-V multijunction efficiencies are presently, practical cell efficiencies of 50% and higher are possible with new solar cell architectures having theoretical efficiencies of 70% and above. The increase in efficiency from 40% to 50% is an extremely important range, corresponding to a tipping point at which concentrator PV becomes the most economic solar electricity option, and is competitive with conventional electricity generation in many geographic areas even without government subsidies. In this paper, we quantify the controlling efficiency losses in today's state-of-the-art cells, using both theoretical and experimental input, to evaluate the real potential of transformative cell architectures capable of 50% efficiency and above.

2 MULTIJUNCTION CELL MODELING

Fundamental physical principles dictate some of the directions necessary for reaching higher efficiencies than in today's cells. Incorporation of four and even more junctions is important to reduce carrier thermalization losses as electrons and holes that are excited far into their respective bands by high energy photons relax back to the band edges. Cells with 4 and more junctions have the added, highly significant benefit of lowering current density and I^2R series resistance power losses, especially important for concentrator cells. Efficient subcells with 2.0-eV band gaps and higher are needed to avoid thermalization loss in the top subcell. High quality subcells with band gaps in the 1.0-eV range must be incorporated in low cost multijunction designs, to avoid high thermalization loss in the Ge bottom cell of today's 3-junction cells, while subcells with low band gaps in the 0.7-eV range must continue to be used in order to capture as much energy as possible from the broad solar spectrum. Finally, higher optical concentrations are favored as they narrow the distance between the quasi-Fermi levels of each carrier type and their respective band edges, allowing the cell voltage to come closer to that defined by the band gap.

Figure 1 plots the AM1.5 Direct ASTM G173-03 terrestrial solar spectrum, and the thermalization losses convoluted with the solar spectrum for a 4-junction concentrator solar cell with a 1.88/ 1.40/ 1.00/ 0.70 eV band gap combination, graphically showing the severity of this fundamental loss as a function of wavelength, with respect to the subcell band edges, and the intensity available in different parts of the solar spectrum. The cumulative thermalization losses are plotted for the 4-junction design, and compared to a standard 3-junction GaInP/GaInAs/Ge cell, showing the substantially lower theoretical thermalization losses for the 4-junction cell.

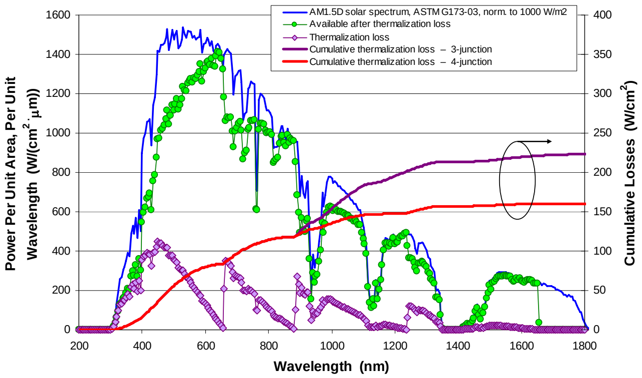

Fig. 1. Thermalization losses in an advanced 4-junction solar cell, and power available in the direct, terrestrial solar spectrum after thermalization losses as a function of wavelength. This 4-junction cell exhibits much lower cumulative loss from carrier thermalization to the band edges than in a typical 3-junction GaInP/GaInAs/Ge cell.

These and other fundamental aspects of new high-efficiency cell designs will be treated in the paper, such as the band gap-voltage offset $(E_g/q) - V_{oc}$ in the ideal detailed balance model and empirical models [1,5,6], series resistance and grid shadowing, and absorption from non-current-producing layers in the cell and impact on quantum efficiency, as for the experimental 4-junction cell quantum efficiency plotted in Fig. 2.

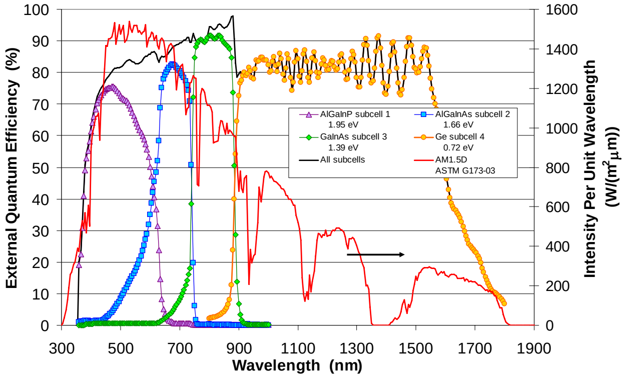

Fig. 2. Measured external quantum efficiency for the individual subcells of a 4-junction terrestrial concentrator AlGaInP/ AlGaInAs/ GaInAs/ Ge lattice-matched solar cell. The intensity per unit wavelength of the standard AM1.5D, ASTM G173-03 spectrum is plotted, to show available power in the response ranges of each subcell.

Solar cells with four or more junctions are not without technical challenges, which work against their theoretical efficiency advantages. Additional tunnel junctions to connect the added subcells in series makes parasitic light absorption in the tunnel junctions a greater concern. The finer division of the solar spectrum in cells with 4 or more junctions makes it more likely for a single subcell to limit the current of the entire multijunction cell stack, as the spectrum changes over the course of the day and year due to atmospheric attenuation, as illustrated in Fig. 3.

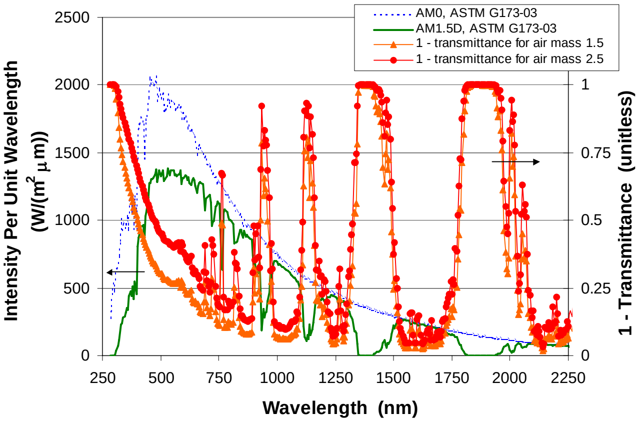

Fig. 3. Attenuation of light intensity due to the atmosphere, for air mass 1.5 and 2.5 [7].

Energy production from photovoltaic power plants has been gaining increasing attention from researchers for all types of solar modules, since it is the kilowatt-hours of electricity produced that has the most direct impact on the cost effectiveness of a solar electricity installation. It is a particularly salient topic for multijunction cells, since a shift in spectrum affecting the current of one subcell not only reduces the output of that subcell, but can limit the current of all the other subcells as well, even though they may have ample photogeneration. As shown in Fig. 4, preliminary modeling indicates that this effect may indeed cause a crossover in 3-junction and 4-junction efficiencies for very high air masses, *i.e.*, in the very early morning or very late afternoon when there is limited solar insolation available anyway, but that the higher efficiency of the modeled 4-, 5-, and 6-junction cells over the majority of hours in the day outweighs this effect, giving a significantly higher energy production over the day for the cell designs with more than 3 junctions [7].

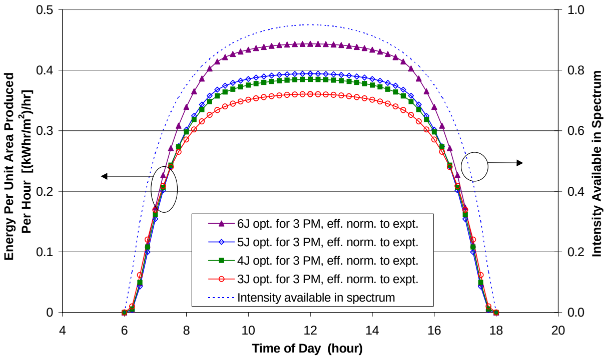

Fig. 4. Energy production of multijunction cells with 3 to 6 junctions, with cell efficiency normalized to correspond to experimental values. The energy production increases with each additional junction, for the cases shown, due to reduced series resistance and thermalization losses [7].

This paper will expand on these studies to quantify crucial non-ideal effects in high-efficiency next-generation multijunction cells, such as current imbalance due to spectrum variation and elevated temperature under operating conditions, together with their fundamental efficiency advantages, in order to determine the net benefit in efficiency and energy production in terrestrial concentrator systems.

3 EXPERIMENTAL RESULTS

These advances in understanding are beginning to have an impact on experimental solar cell efficiencies. Upright metamorphic 3-junction GaInP/GaInAs/Ge concentrator cells, of the type that were first to reach over the 40% efficiency milestone, are now being inserted into production as the C4MJ cell. A schematic cross section of this type of metamorphic cell is shown on the right side of Fig. 5, compared to a lattice-matched 3-junction cell on the left.

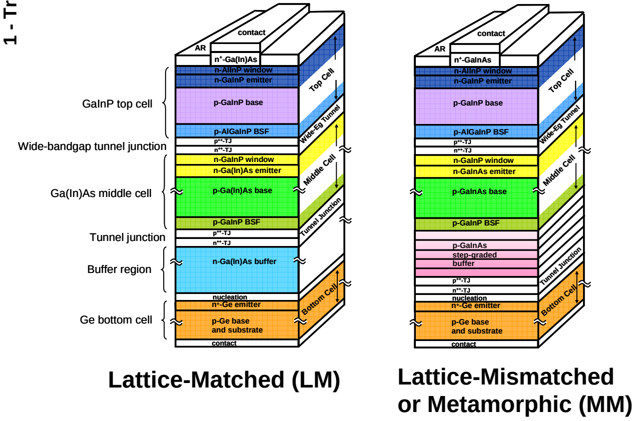

Fig. 5. Schematics of the layer structures of lattice-matched and upright metamorphic 3-junction solar cells.

As shown in Fig. 6, pilot production runs of the C4MJ terrestrial concentrator cell have demonstrated average efficiency of 39.4%, nearly an absolute efficiency point higher than the previous C3MJ cell generation, and are expected to reach 40% average efficiency in production. Inverted metamorphic terrestrial concentrator cells with a more advantageous band gap combination have been built and tested, and the latest measurement results will be presented in the paper.

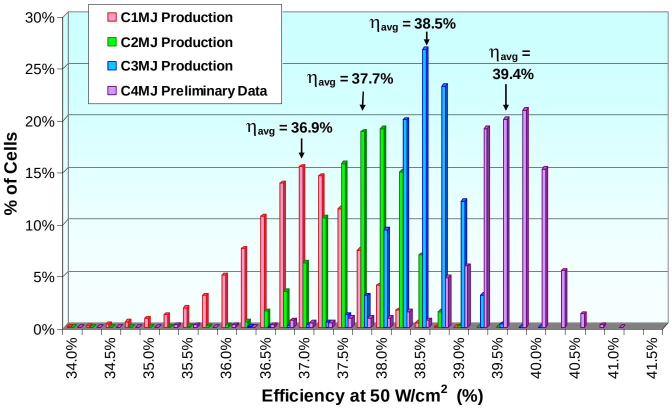

Fig. 6. Efficiency histograms of four generations of Spectrolab terrestrial concentrator cell products, from the C1MJ cell with 36.9% average production efficiency, C2MJ with 37.7%, C3MJ with 38.5%, and preliminary data for the next generation C4MJ cell, with 39.4% efficiency in early pilot runs. Average efficiency for the C4MJ cell is anticipated to reach 40%.

Lattice-matched GaInP/GaInAs/Ge cells built at Spectrolab have demonstrated an independently confirmed efficiency of 41.6% under the standard terrestrial spectrum at 364 suns (36.4 W/cm2) concentration, the highest efficiency yet demonstrated for any type of solar cell [6]. The illuminated I-V characteristic of this record cell, as verified by the independent test lab at the National Renewable Energy Laboratory (NREL) is plotted in Fig. 7, with measured V_{oc} = 3.192 V, J_{sc}/intensity = 0.1468 A/W, FF = 0.8874 , and efficiency = 41.6 % at 364 suns.

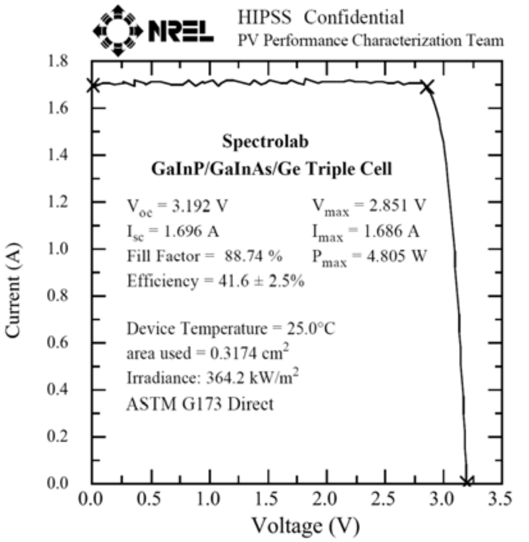

Fig. 7. Light I-V characteristic for record efficiency 41.6%-efficiency concentrator solar cell, built at Spectrolab with a lattice-matched 3-junction cell structure, and independently verified at NREL [6].

The dependence of the performance of this record 41.6%-efficient cell on varying incident intensity is shown in Fig. 8. The efficiency, V_{oc}, and FF of this record cell are plotted at concentrations from 0.9 to 940 suns. The efficiency peaks at 41.6% at 364 suns and drops for higher concentrations due to series resistance, but is still over 40% at 820 suns, and is 39.8% at 940 suns. The fill factor shows a broad plateau over ~2 decades in incident intensity, rising rapidly between 1 and ~4 suns due to increasing excess carrier concentration, and decreasing above ~400 suns due to series resistance. The V_{oc} increases at an average rate of ~80 mV per decade in incident intensity, per junction, in the intensity range from 1 to 10 suns. From 10 to 100 suns this rate is 75 mV per decade, while from 100 to 1000 suns it drops to 61 mV per decade. Thus over the 100 to 1000 sun range of interest, the average V_{oc} increase with concentration is fit fairly well by using diode ideality factor n = 1 for each of the 3 subcells.

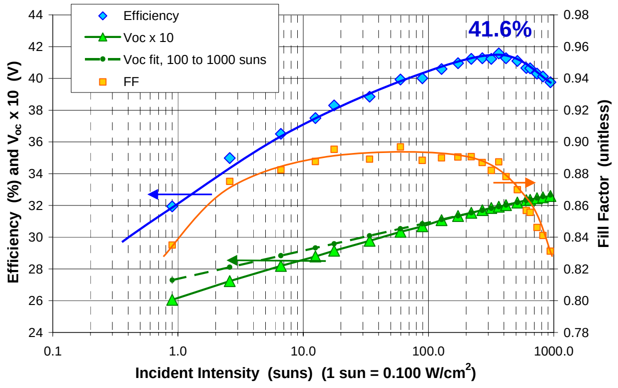

Fig. 8. Measured light I-V parameters of the 41.6%-efficient solar cell as a function of incident intensity. The cell is still over 40% efficient at 820 suns, and has 39.8% efficiency at 940 suns [6].

In Fig. 9, the illuminated I-V curve of a prototype 4-junction terrestrial concentrator cell is plotted, showing its high-voltage, low-current characteristics which lead to lower resistive power loss compared with 3-junction cells [6]. These early prototype 4-junction concentrator cells have reached up to 36.9% efficiency at 500 suns (50 W/cm^2) at Spectrolab in unconfirmed measurements. The independently confirmed light I-V curves of the earlier record 40.7%-efficient metamorphic 3-junction cell [1], the present record 41.6%-efficient lattice-matched 3-junction cell at 364 suns [6], and the same cell measured to have 40.1% efficiency at 822 suns, are also plotted for comparison.

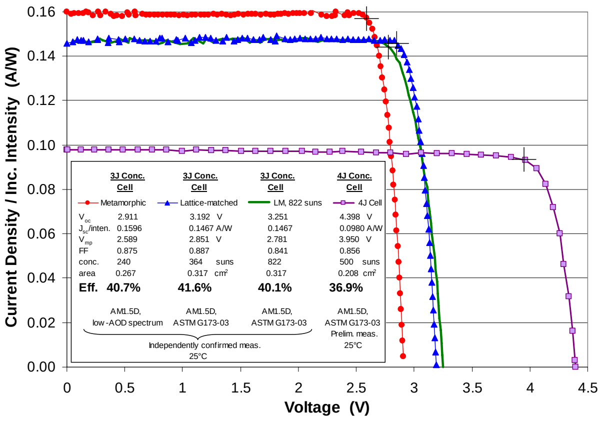

Fig. 9. Light I-V measurements for a 4-junction terrestrial concentrator cell with *Voc* of 4.398 V, and preliminary efficiency of 36.9% at 500 suns. An earlier record 40.7% MM 3J cell [1], the present record 41.6% LM 3J cell at 364 suns, and a cell with 40.1% measured efficiency at 822 suns, are plotted for comparison [6].

4 SUMMARY

By analyzing the fundamental efficiency losses in multijunction cells, this paper aims to form a bridge between today's state-of-the-art solar cells and future designs. Identifying the loss mechanisms that are fundamental and dictated by laws of physics, and those that are not fundamental and can therefore be reduced, allows one to make informed decisions on research directions, leading to advanced cell architectures that maximize efficiency and energy production. The next generations of multijunction concentrator cells, capable of 45% or even 50% efficiency, have the ability to transform the economics of solar electricity generation.

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