Effect of spectral changes on I-V parameters of triple junction solar cells

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Abstract. Characterisation of multi-junction solar cells presents more challenges compared to single junction solar cells due to the series connection of multiple subcells. In monolithically integrated solar cells, the subcells are epitaxially grown and internally connected in series through tunnel junctions with each subcell optimised to absorb a given range of wavelengths of the solar spectrum. However, changes in the spectral content of the incident beam may lead to changes in the photo-generated current from the subcells leading to current mismatch. This will affect the current-voltage (I-V) characteristics, the operating voltage and performance of the multi junction solar cell device. In this study, current and voltage values were obtained while simultaneously carrying out light beam induced current (LBIC) measurements on an InGaP/InGaAs/Ge triple junction solar cell under different spectral conditions to obtain point illuminated I-V characteristics. A curve fitting algorithm was then applied to obtain point I-V parameters under different spectral conditions. The extracted parameters showed large variation which could be attributed to changing recombination mechanism within the solar cell device and the effect of current mismatch between the subcells.

1. Introduction

Multi-junction solar cells (MJSCs) based on III-V semiconductors have attained conversion efficiencies of more than 40% under concentration [1, 2]. Their application in terrestrial concentrator photovoltaic systems is growing rapidly due to the demand for higher efficiency systems. The higher efficiencies attained is due to the reduction of thermalisation and transmission losses [3, 4] when multiple subcells, each tuned to absorb a given range of wavelengths of the solar spectrum, are used. The subcells can be mechanically stacked or monolithically grown on a single substrate. In monolithically grown solar cells, the subcells are connected in series through tunnel junctions to form a two terminal solar cell device. This implies that the individual subcells are not directly accessible, making characterisation of multi-junction solar cells quite challenging [5]. Due to the series connection of the subcells, the short circuit current (I_{sc}) for the solar cell device is determined by the subcell producing the lowest current [6]. The current generated by each subcell is in turn determined by its spectral response and the spectral content of the beam incident on it. The spectral response of InGaP/InGaAs/Ge triple junction solar cell (TJSC) showing the spectral response range of each subcell is given in **Figure 1**.

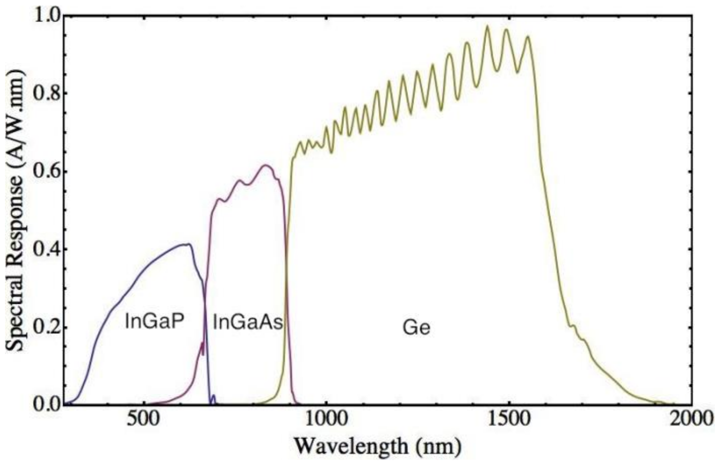

Figure 1. Spectral response of individual subcells of InGaP/InGaAs/Ge TJSC [7]

Any changes in the incident spectrum may result in current mismatch which will reduce the I_{sc} [8] and affect the I-V characteristics and performance of the solar cell device. Multi-junction solar cells are therefore very sensitive to changes in the spectral content of incident light compared to standard solar cells. In this paper, we studied the effect of change of the spectral content of the beam probe on the I-V parameters of a III-V triple junction solar cell. In particular, the InGaP/InGaAs/Ge triple junction solar cell manufactured by the Emcore Corporation [9] was investigated using a variation of the Light Beam Induced Current (LBIC) technique.

2. Experimental procedure

The InGaP/InGaAs/Ge triple junction solar cell evaluated in this paper is a 1cm^2 lattice matched solar cell device with two parallel connected bypass diodes across the terminals of the cell. To perform LBIC measurements, the cell was mounted on a raster scanning X-Y translation stage under a fixed light beam source. A 660nm wavelength laser and solar light were used as beam probes. The arrangement was put in a dark enclosure to eliminate any external light sources. For solar LBIC (S-LBIC) measurements, the system was mounted on a two axis sun tracker. At each measurement point the solar cell was dynamically biased from reverse bias to a voltage slightly higher than its open circuit voltage (V_{oC}) using an Agilent Function waveform generator at a voltage step interval of 0.01V and frequency of 10Hz. The current from the point illuminated cell was amplified using a SR570 low noise current preamplifier from Stanford Research Systems with a 50Ω output impedance. At each biasing voltage, the current and the corresponding voltage were simultaneously measured using a National Instruments simultaneous sample and hold data acquisition device interfaced with a computer. The translation stage, biasing and data acquisition were all controlled through a custom developed Labview programme. The measured induced current was then plotted as a function of position using the Labview programme to obtain a photo-response map. Localized I-V curves were obtained by plotting current versus voltage at a given measurement point on the cell surface.

3. Results and discussion

In this section, we present the results from the LBIC mapping technique carried out under different spectral conditions. The I_{sc} photo-response maps obtained by plotting I_{sc} as a function of position are presented from which current reducing features on the solar cell device are located. A curve fitting algorithm was performed based on the single diode equation to extract device and performance parameters. The single diode equation is given by

$$I = I_{ph} - I_0 \left\{ exp\left[q\left(\frac{V + IR_s}{nkT} \right) \right] - 1 \right\} - \frac{V + IR_s}{R_{sh}}$$

where I_{ph} is the photo-generated current, I_0 is the reverse saturation current, q is the magnitude of charge, T is the temperature, k is the Boltzmann's constant, n is the diode ideality factor, R_s and R_{sh} are the series and shunt resistances, respectively, while I and V are the current and terminal voltage, respectively. The extracted device and performance parameters are presented and discussed.

3.1 Photo-response mapping

LBIC measurements were performed on an InGaP/InGaAs/Ge triple junction solar cell manufactured by Emcore Corporation. An area of 7.1x7.1mm^2 was scanned using a 660nm laser. The results of the I_{sc} photo-response map are shown in Figure 2.

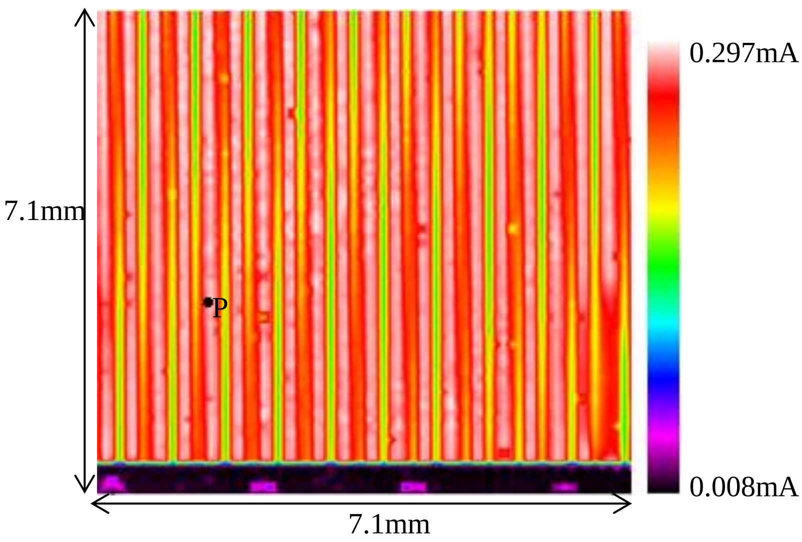

Figure 2. I_{sc} photo-response map for the TJSC using a 660nm wavelength laser. P shows a point where I-V curves were extracted at different spectral conditions

In Figure 2, we observe expected current reduction due to shading from the contact fingers and busbar metallisation. The current reduction contour adjacent to the metallisation (fingers and busbar) is due to the change in effective illuminated area while the light spot is moving over a shading finger or busbar. No other major current reducing defects are visible on the cell, an indication of the high quality of the MJSC device. When the TJSC device is illuminated with monochromatic laser light of wavelength 660nm, the top two subcells (InGaP and InGaAs) will be primarily activated since this wavelength lies within the spectral response range of the two subcells as shown in **Figure 1**. The Ge bottom subcell will not be primarily activated by the 660nm beam probe since its wavelength lies outside the spectral response range of the Ge subcell and will primarily not generate any current. Due to the series connection of the subcells, no current output will be expected from the TJSC device since the output current is determined by the subcell producing the lowest current. However, MJSCs made of III-V materials are made of high quality semiconductor materials and when forward biased, they undergo electroluminescence. The secondary luminescent photons may be absorbed by lower bandgap junctions through luminescent coupling, thus contributing to photocurrent generation of those junctions [10]. For the InGaP/InGaAs/Ge TJSC, the electroluminescence from the top subcell is visible to the naked eye as a red glow while the emission from the middle junction lies in the infrared region. The emitted luminescent photons from the top subcell may be absorbed by the middle subcell leading to an increase in the InGaAs subcell current generation. The luminescent photons emitted from the middle subcell may also be absorbed by the Ge subcell, thus enhancing photocurrent generation in the bottom subcell. Radiative coupling between the subcells may therefore play an important role in overcoming current mismatch and thus improving the performance of TJSC devices especially when they are operated under spectral mismatch conditions [11]. This could explain the current response observed when the TJSC is illuminated with a 660nm wavelength laser.

3.2 Effect of spectral content

In order to investigate the effect of spectral content on the device and performance parameters of TJSCs, the InGaP/InGaAs/Ge TJSC device was point illuminated with solar light to carry out S-LBIC I-V measurements. The spectral content of the solar beam probe was then changed using a long pass colour filter with a cut off wavelength of 610nm. In addition, a 660nm wavelength laser was used as a beam probe for LBIC I-V measurements. Current and voltage values obtained respectively under the three spectral conditions were plotted to obtain point I-V characteristics for the TJSC device. An interval division algorithm based on the single-diode solar cell model was then applied to extract point I-V parameters. Figure 3 shows representative measured and fitted point I-V curves at point P (Figure 2), an area of good photo-response, taken at the three spectral conditions.

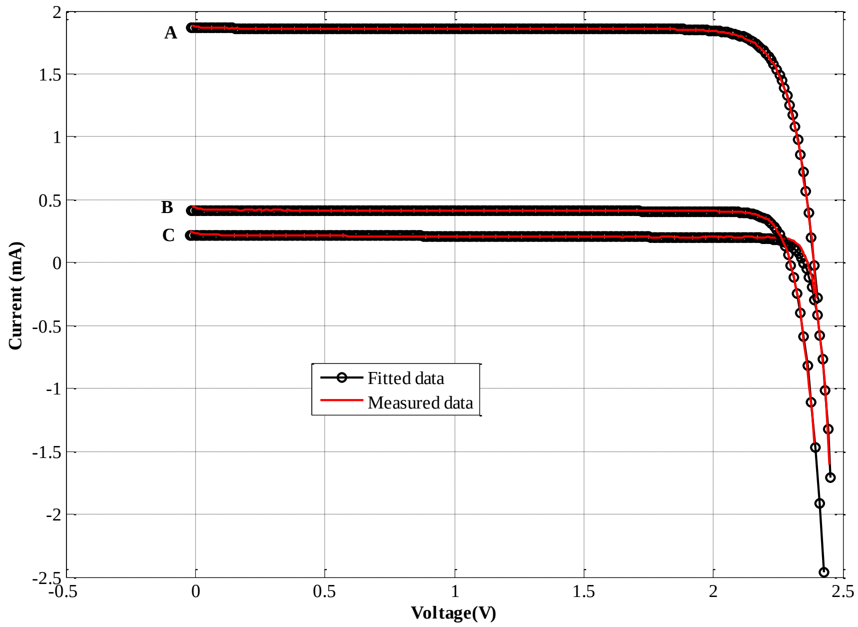

Figure 3. Measured and fitted I-V curves using **A**) Solar light, **B**) Solar light with a 610nm long pass colour filter, **C**) 660nm wavelength laser, as beam probes

The measured and the fitted I-V curves show good agreement, an indication that the single-diode model can, in general, under certain conditions model the I-V characteristics of a TJSC. Deviation between measured and the fitted data, especially at the "knee" is observed particularly for low current levels. This deviation could be attributed to the limitation of the single diode model in describing the cell behaviour at low illumination levels. The decrease in I_{sc} when a long pass colour filter is used is due to the decrease in the short wavelength radiation that renders the spectrum richer in red than blue wavelengths for a given intensity. This could lead to a decrease in current generated in the top subcell and hence a reduction in the device output current. Basic device and performance parameters were extracted from the fitted I-V curves at the three spectral conditions and are listed in Table 1. The parameters give a basic indication of the functioning of the solar cell device.

Table 1. Extracted parameters for the TJSC under different spectral conditions

			Parameters			
Source	n	I_o (mA)	R_{sh} (Ω)	R_s (Ω)	V_{oc} (V)	Isc (mA)
Solar	3.073	1.33×10^{-13}	310.61	4.08×10^{-4}	2.389	1.864
Solar with filter	1.838	2.83×10^{-22}	220.41	1.53×10^{-2}	2.298	0.416
660nm laser	1.726	2.04×10^{-22}	110.20	2.20×10^{-3}	2.350	0.219

When illuminated with solar spectrum, the TJSC device is characterised by high shunt resistance, high saturation current and ideality factor ~3, consistent with reported values [12, 13]. However, as the spectral content is changed, a decrease in the ideality factor, short circuit current and saturation current is observed, with lowest values obtained when the beam probe is monochromatic. The reduction in I_{sc} may be attributed to a reduction in irradiance by the introduction of the bandpass filter and when using monochromatic light. The decrease in diode ideality and saturation current may be attributed to changing recombination mechanisms taking place within the solar cell device. In addition, variability in the ideality factor could also be due to the effect of current mis-matching between the individual subcells at the different spectral conditions. The change in V_{oc} is due to changes in I_o and I_{sc} since V_{oc} varies logarithmically with I_o and I_{sc}. The effect of shunting is observed to increase (decrease in shunt resistance) when the filter is used, with the lowest shunt resistance obtained when monochromatic light is used as a beam probe. The low shunt resistance provides an alternative path to current flow leading to a reduction in the terminal current and voltage output from the solar cell device.

4. Conclusion

In this paper, the LBIC imaging technique was used to investigate the effect of spectral content on the I-V parameters of a TJSC. We explained that when a triple junction solar cell is illuminated with a monochromatic light source, current mismatch could be overcome by the effect of radiative coupling between the subcells when the device is forward biased. Point I-V characteristics obtained while performing LBIC measurements at different spectral conditions were curve fitted using an interval division algorithm based on the single diode model to extract I-V parameters. The extracted parameters showed large variation which could be attributed to changing recombination mechanism within the solar cell device. Variation in the diode ideality factor could be attributed to the effect of current mismatching between the subcells.

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