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# Light-Biasing Electron-Beam-Induced-Current Measurements for Multijunction Solar Cells

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# Light-biasing electron-beam-induced-current measurements for multijunction solar cells

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## ABSTRACT

Monolithic multijunction (MJ) solar cells consist of several single solar cells of different spectral sensitivity connected in series. These solar cells are current-limiting devices, and in order to measure the response of each individual cell, the junction to be measured should be current limiting. Electron-beam-induced-current (EBIC) measurements are particularly difficult because the excitation is restricted to an individual cell and current-limiting effects tend to cancel the EBIC. We have developed a technique to measure the EBIC of each individual cell while light biasing the MJ cell. Results using light-biasing EBIC are illustrated for dual-junction (DJ) InGaP/(In)GaAs solar cells.

## 1. Introduction

In space photovoltaics, the high-efficiency commercially available leading technologies are the dual-junction $In_{0.51}Ga_{0.49}P$/GaAs and triple-junction $In_{0.51}Ga_{0.49}P$/GaAs/Ge solar cells. The maximum practical efficiency for a solar cell (32.2% at 1-sun, AM1.5) has been achieved with a triple-junction device. Although the development of multijunction solar cells is mainly driven by space applications, terrestrial systems based on concentrators are indeed highly attractive for these devices. The design of MJ cells for high efficiency requires matching the current density of each individual solar cell to the solar spectral irradiance. Another requirement has been the use of lattice-matched semiconductors to prevent extended defects from forming in the epilayers. However, higher efficiency should be more attainable when the design is done without added requirements. Indeed, whereas the $In_{0.51}Ga_{0.49}P$/GaAs has no degree of freedom to suit the solar spectrum, this is not true for the InGaP/InGaAs tandem, where the indium content might be chosen to optimize the spectral sensitivity. Buffer engineering can then be applied to accommodate the lattice mismatch. This concept may be critical in expanding the triple-junction cell to quadruple- and quintuple-junction devices and so on. Electron-beam-induced-current (EBIC) measurements are well suited to investigate the electronic characteristics of defects and to estimate the diffusion lengths and surface recombination velocities of each component of the tandem. However, these measurements are particularly difficult because the beam excitation is restricted to an individual cell and current-limiting effects tend to cancel the EBIC. We have developed a technique to measure the EBIC on multijunctions by light-biasing the cell. Results using light-biasing EBIC are illustrated for dual-junction InGaP/InGaAs solar cells.

## 2. Experimental technique

Several dual-junction (DJ) solar cells have been investigated. One of them is the conventional DJ $In_{0.51}Ga_{0.49}P$/GaAs of *n-p* polarity commercialized by Spectrolab, where the InGaP top and the GaAs bottom cells are lattice matched. To explore mismatched systems, $In_{0.65}Ga_{0.35}P/In_{0.17}Ga_{0.83}As$ and $In_{0.49}Ga_{0.51}P/\ In_{0.03}Ga_{0.97}As$ DJ devices of *n-p* polarity were fabricated on GaAs substrates by metal-organic vapor-phase epitaxy [1].

For EBIC measurements, the cells were mounted on a modified stage with an optical fiber attached to it. The EBIC was detected using a low-input impedance picoamplifier. The optical fiber provided external illumination to the solar cell inside the chamber of the scanning electron microscope. Light-biasing EBIC measurements are then accomplished by a filtered light source. The measurements were made under short-circuit conditions.

## 3. Dual-junction model

The current densities for both the top and bottom cells are given by

$$J = J_s\left(e^{qV/k_BT} - 1\right) - J_{ph}\,, \qquad (1)$$

where $J_s$ is the saturation current density and $J_{ph}$ is the photocurrent density. The top and bottom cells are connected in series. Assuming superposition, the characteristics for the dual-junction cell are estimated by addition of the subcell voltages for each current density. In the short-circuited cell (V=0, $V_{top} = -V_{bot} = V_{sc}$), one of the cells is forward biased and the other is reversed biased. If the photocurrent density is higher in the top cell, this cell will be forward biased and,

$$J = J_s^{top}\left(e^{qV_{sc}/k_BT} - 1\right) - J_{ph}^{top} = J_s^{bot}\left(e^{-qV_{sc}/k_BT} - 1\right) - J_{ph}^{bot} \cong J_s^{bot} - J_{ph}^{bot} \cong -J_{ph}^{bot} \qquad (2)$$

the current will be limited by the bottom cell photocurrent. These solar cells are then current-limiting devices, and in order to measure the response of each individual cell the junction to be measured should be current limiting [2]. Cross-sectional EBIC measurements are particularly difficult because the excitation is restricted to an individual cell and current-limiting effects tend to cancel the EBIC. Only a residual current is measured when the electron beam crosses the interconnecting tunnel junction and both the top and bottom cells are excited.

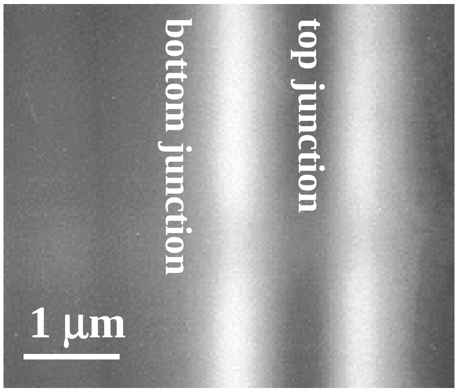


Figure 1. EBIC image of a DJ InGaP/InGaAs solar cell

## 4. Results and discussion

Figure 1 shows a cross-sectional EBIC image of the mismatched $In_{0.65}Ga_{0.35}P/In_{0.17}Ga_{0.83}As$ tandem cell. The cell was illuminated through the front surface by the optical fiber with non-filtered light. The photocurrent is then excited at both subcells. Thus, there is no current-limiting junction for the EBIC, because $J_{EBIC} << J_{ph}$. The lateral resolution of the EBIC is sufficient to resolve the top and bottom junctions. The diffusion lengths at the *p*-type $In_{0.65}Ga_{0.35}P$ and $In_{0.17}Ga_{0.83}As$ bases are estimated to be less than 0.5 μm. This is due to the mismatch. Otherwise, diffusion lengths are longer than 2 μm, as for the nearly matched $In_{0.49}Ga_{0.51}P$/ $In_{0.03}Ga_{0.97}As$ tandem. In that case, the resolution of the EBIC is not adequate to resolve the subcells (see Fig. 2). Illuminating the cell using a filter around 750 nm, photons are transmitted by the top cell and absorbed at the bottom cell. The current-limiting junction is then the top cell and the EBIC is generated there (see Fig. 2). Using a filter around 450 nm, photons are absorbed at the top cell and the EBIC is excited at the current-limiting bottom cell. Therefore, the lateral resolution of the EBIC has been improved by light biasing. Diffusion lengths and surface recombination velocities are estimated individually for each subcell.

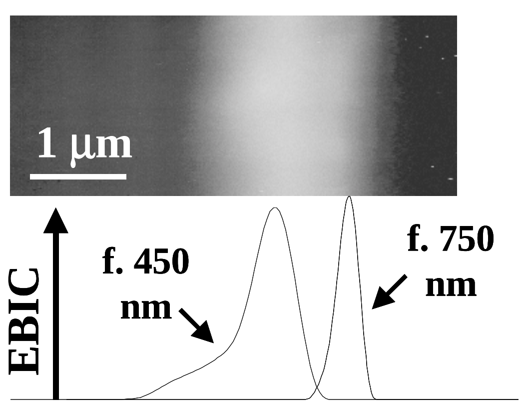


Figure 2. Light-biasing EBIC

This technique is particularly valuable in defect imaging. At electron-beam energies over 20 keV, the beam excites both cells, and an induced current arises. Fig. 3a is an EBIC image showing misfit dislocations at the mismatched interfaces for the $In_{0.65}Ga_{0.35}P/In_{0.17}Ga_{0.83}As$ tandem cell. However, at beam energies below 10 keV, the excitation is confined within the top junction. The bottom junction is current limiting and the EBIC is canceled. On the other hand, when light-biasing the front surface of the cell using a 750-nm filter, the current is limited by the top cell. An image of the defects present at the top cell is obtained; in this particular cell, threading dislocations extend across the InGaP epilayer (see Fig. 3b)

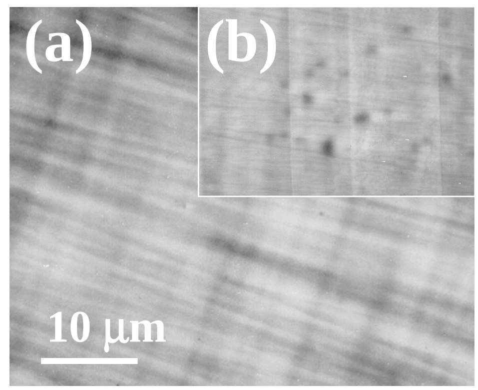


Figure 3. Defect imaging by EBIC: (a) bottom cell, (b) top cell

## 5. Conclusions

Light-biasing EBIC has proven to be very useful in measuring the individual cells of multijunctions. The estimate of diffusion lengths, surface (interface) recombination velocities, and defect recognition in each subcell are the most attractive capabilities of this method.

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