Using Measurements of Fill Factor at High Irradiance to Deduce Heterobarrier Band Offsets

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ABSTRACT

Using a 2D device simulation tool, we examine the high irradiance behavior of a single junction, GaAs concentrator cell as a function of the doping in the back surface confinement layer. The confinement layer is designed to be a barrier for both holes and electrons in the base of the solar cell. For a p-type base we show that the FF of the cell at high concentrations is a strong function of both the magnitude of the valence band offset and the doping level in the barrier. In short, for a given valence band offset (VBO), there is a critical barrier doping, below which the FF drops rapidly with lower doping. This behavior is confirmed experimentally for a GaInP/GaAs double heterostructure solar cell where the critical doping concentration (at 500 suns) in the back surface confinement layer is ~1e18 cm^{-3} for a VBO of 300 meV.

INTRODUCTION

It is well known that the fill factor and efficiency of a concentrator cell under high irradiance is a sensitive function of its series resistance, R_s. The R_s of the emitter/top contact of the cell usually receives the most attention. However, in III-V multijunction solar cells, heterobarriers, normally required for minority carrier confinement, can also be significant sources of R_s. This series resistance is associated with the reverse-bias, transport of majority carriers over the barrier. These barriers, if not properly designed, can reduce the FF and efficiency of the device, particularly at high irradiance levels. This problem is not unknown to the community[1, 2] but there is very little quantitative guidance available to the cell designer. In this paper, we focus on the back surface field (BSF) layer of a n-on-p GaAs solar cell. The key parameters in this effort are the valence band offset VBO between the base of the cell and the BSF layer and the doping in the BSF layer. Experimentally the VBO is fixed by the choice of the BSF layer material, e.g. AlGaInP, GaInP, or AlGaAs. While there is much known about the AlGaAs/GaAs heterointerface, our understanding of the GaInP/GaAs heterointerface is far from complete. It is complicated by the tendency of GaInP to order[3] and difficulties with forming an abrupt interface with GaAs.[4, 5] However, with the aid of 2D, finite-element, device simulation tool Apsys from Crosslight Software, Inc., we can numerically vary the value of the VBO and, in combination with the level of doping in the BSF layer, study its effect on the FF and efficiency of the device under concentrated illumination. In the following we show that by comparing the simulated results with experimental data we can deduce the magnitude of the VBO between GaInP and GaAs.

GaAs Cell Structure

A schematic of the GaAs device is shown in Figure 1. The BSF layer is nominally Zn-doped Ga$_{0.52}$In$_{0.48}$P with a band gap of 1.88eV. The doping in the window and emitter layers are set at 2e18 cm^{-3}. The doping in the base is set at 1e17 cm^{-3}. The emitter and BSF layer thicknesses are 0.1µm and the base is 2.5 µm think. The active area of a cell (total area less busbar area) is 0.100 cm^2. Grid width and pitch are 10 µm and 150 µm respectively. Cells are simulated/measured without antireflection coating. Details of the simulation conditions are similar to those published previously.[6]

N-GaInP 2e18 cm^{-3}	0.02 µm
N-GaAs 2e18 cm^{-3}	0.1µm
p-GaAs 1e17 cm^{-3}	2.5µm
P-BSF layer	0.1µm
P-GaAs	

Figure 1 Schematic of a GaAs concentrator cell with back surface field layer.

The simulation of the device in Figure 1 assumes thermionic transport of carriers across the heterojunction barriers. The composition and doping profiles at the interface between the p-GaAs base layer and the P-BSF layer are assumed to be abrupt. In practice abrupt interfaces are difficult to achieve. Without special precautions, the interface can be smeared or graded and the effective barrier height, which controls the carrier transport, can be substantially different compared to the ideal case. For this study, we use two techniques to mitigate this problem. First, we grow the GaAs solar cells (by MOCVD) in the inverted configuration[7] so that the last two layers grown are the P-BSF layer and the P-GaAs back contact layer. The total growth time for these two layers is less than 10 min. The growth temperature during this time is limited to less than 620˚C. These conditions

lead to less interdiffusion of the chemical constituents compared to the non-inverted case where the interface would be subjected to higher temperature (e.g. 650°C) for longer times (30 min or more).[4] Second, the interface between the base and BSF layer is formed using a simple stop growth procedure, where at the end of the base layer the Ga-source is first switched off to cease all growth for a total of 9 seconds. For the first 6 s of this stop growth, only the arsenic source (AsH_3) is flowing to the reactor. For the remaining 3 s only PH_3 and the p-type doping source (diethyl zinc) are flowing to the reactor. At the end of the 9-s stop growth, the Ga and In sources are introduced to initiate the growth of the GaInP BSF. This sequence ideally yields an interface layer of As-rich GaInAsP about 1 monolayer thick.[5]

The devices were processed in a manner described by Geisz et al.[7] The hole concentration in the BSF layers was determined from a set of Zn-doped calibration layers grown under similar conditions and deduced from electrochemical capacitance voltage measurements. The concentrator measurements were made using a Spectrolab HIPSS at 25°C.

RESULTS

Simulated IV Curves and Fill Factor

The JV curves of a GaAs heteroface solar cell at 500 suns (J_{sc} = 13 Acm^{-2}) were simulated as a function of the doping in the BSF layer and the VBO of the BSF layer with respect to the base of the GaAs cell. An example of a simulated JV curve is shown in Figure 2. Here the BSF interface is abrupt, the VBO is set at 300 meV and the doping in the BSF is set at N_A = 4.9e17 cm^{-2}. Figure 2 also includes a JV curve for the isolated GaInP/GaAs heterobarrier, a JV curve for a GaAs cell with a low VBO at the BSF interface. The curve labeled "composite" is the superposition of the first two. The JV curve of the heterobarrier exhibits a roughly linear behavior for $|J| < 6\,Acm^{-2}$. For larger positive currents (which correspond to hole transport from the base to the BSF), the effective resistance of the heterobarrier becomes much larger which is also reflected in the FF of the composite JV of the GaAs cell.

In Figure 3 we show a contour plot of FF vs hole concentration and VBO. (Here, to conserve computation time, we consider 1D current flow only. Hence there are no emitter resistance effects and the FFs are unreasonably high.) It shows that for a given VBO, there exists a critical hole concentration in the BSF layer below which the FF decreases rapidly with decreasing hole concentration. Above this critical concentration, the FF increases much more slowly with increasing hole concentration.
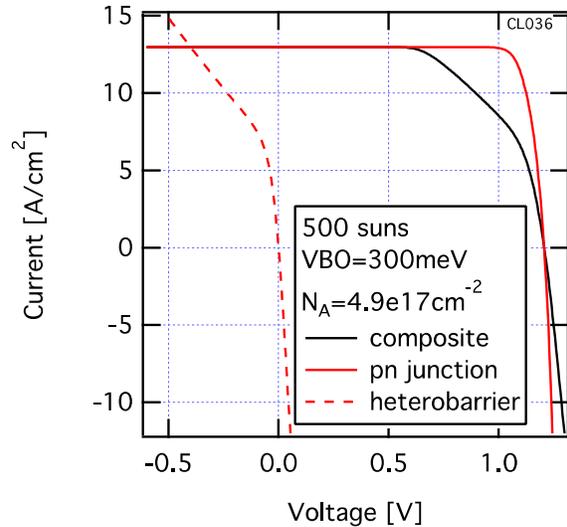

Figure 2 JV curves for an isolated GaInP/GaAs heterobarrier, a GaAs pn junction with a low VBO at the BSF interface and a composite of the two.
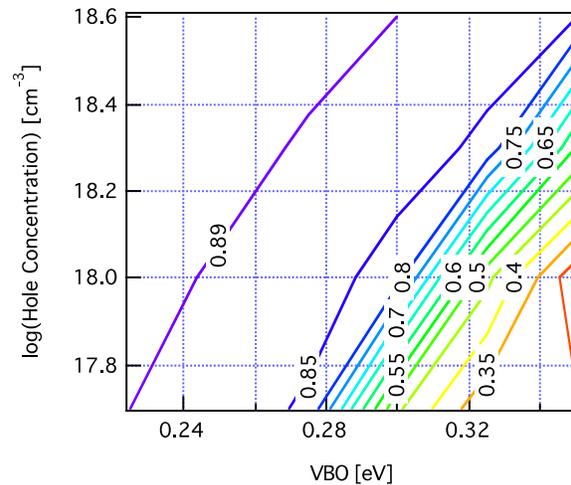
Figure 3 Contour plot of fill factor at 500 suns (J_{sc} = 13 Acm^{-2}) of a GaAs solar cell versus the hole concentration in the BSF layer and its VBO with respect to GaAs.

Experimental

The IV characteristics of the four GaAs devices with different Zn doping levels in the GaInP BSF were measured as a function of irradiance. The results at ~400 suns (J_{sc} = 11 Acm^{-2}) are shown in Figure 4. It is clear that the FF decreases, at first slowly and then more rapidly, with decreasing BSF layer doping. In Figure 5 we plot of the FF of the four GaAs devices (interpolated to J_{sc}=13 Acm^{-2}) as a function of the doping in GaInP BSF layer along with three simulated curves for VBOs equal to 275, 300 and 325 meV. The experimental curve lies

roughly between the curves for VBOs of 275 and 300 meV. The agreement between simulation and experiment is not perfect (compare the JV curves in Figure 3 and Figure 4). The simulated IV curves for the two lowest hole centrations only agree qualitatively with the measured IV curves. And the device with the lowest hole concentration in BSF layer has a higher FF (it is closer to VBO=275 meV than the other three samples). But the VBO that one infers from the experimental data would suggest that the VBO between GaAs and GaInP is close to 300 meV. This is consistent with most other reports.[8, 9]
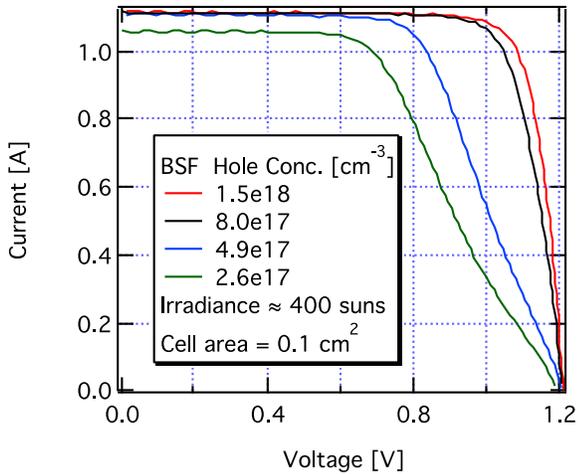

Figure 4 I-V curves of four GaAs solar cells with variable Zn doping in the GaInP BSF.
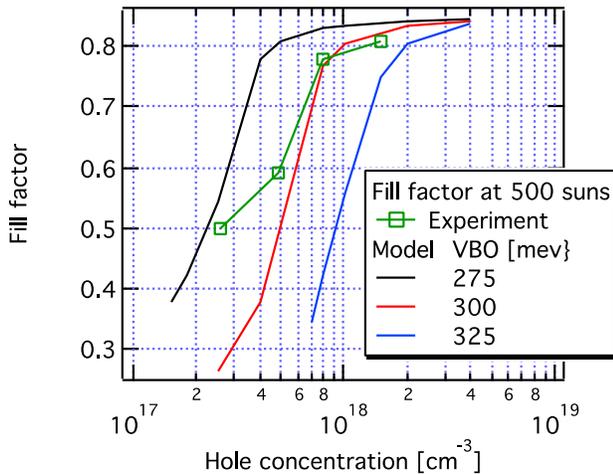

Figure 5 Modeled and measured fill factor of a GaInP/GaAs heteroface solar cell at ~500 suns and a function of the hole concentration in the GaInP BSF and its VBO with the GaAs base.

DISCUSSION

Knowledge and control of heterojunction band offsets are important for the design of high efficiency solar cells.

Traditional methods of measuring the band offsets at a semiconductor heterojunction include direct measurement of carrier transport using current-voltage measurements, capacitance-voltage profiling[10], and deep level transient spectroscopy[8, 11]. These all involve the fabrication of special (albiet relatively simple) test structures that may or may not represent the situation in actual solar cells. These methods are not totally consistent yielding band offset values for a given materials combination that vary widely.

One can also measure the IV curve of an <u>illuminated</u> cell as a function of temperature. In general one expects the effective resistance of any heterointerface to decrease exponentially with increasing temperature. The limitation of this technique is that the temperature dependence of the heterobarrier transport is confounded with that of other temperature dependent processes or parameters.

Due to the nonlinear behavior of the transport over the barrier, these effects are not necessarily observable at low current densities or in the dark. (See Figure 2.) At low current densities (near V_{oc} or at low irradiance levels) the barrier behaves like a simple resistor. This implies that the FF or maximum power loss associated with a heterobarrier cannot be deduced from a low current measurement of the effective resistance such as that proposed by King et al.[12] In the dark the majority carrier transport across the barrier is in the opposite/forward direction and not representative of the limiting mechanism under illumination.

The approach we use in this study is quite different: we use numerical simulation and experimental measurements of the FF as a function of dopant concentration on full devices to deduce the band offsets. The effect is isolated to the heterojunction where the doping is being altered and is not confounded by the doping level in other parts of the cell.

There are, however, several limitations of this technique:

- For low VBO, the critical dopant concentration may be lower than the background carrier concentration of the BSF layer. One can always try high irradiance levels, but this too will have its limits.
- The diffusion of the dopant, particularly at high concentrations, across the interface can promote interdiffusion of the heterobarrier constituents and a smearing or grading of the interface. This can artificially lower the critical dopant concentration. [13]
- As noted above, the simulations assume an abrupt interface between the BSF and base of the cell and special precautions were taken to achieve these conditions experimentally. Indeed, we find that simply growing the interface without a stop growth largely eliminates the large FF loss at low dopant concentrations. Such measures can introduce other problems. For example the "graded" layer between GaInP and GaAs may not be lattice matched and depending on "switching" time constants for the individual source gases it is possible to have a graded

layer that is "InGaAs"-rich leading to a low band gap region that could trap minority carriers.

- The technique requires the availability of device simulation software that can accurately treat heterobarrier transport.

CONCLUSIONS

We have presented an alternative method for measuring the band offsets associated with barrier layers in a single or multijunction solar cell. The method involves comparing simulated and measured JV curves at high irradiance levels as a function of doping level in the barrier layer. The techniques was applied to the valence band offset between GaInP and GaAs which forms the back surface field of a GaAs solar cell. We deduce a value for the VBO between GaInP and GaAs of ~300 meV that is reasonably consistent with literature values.

ACKNOWLEDGEMENT

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