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Simulation assisted design of a gallium phosphide n–p photovoltaic junction

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ABSTRACT

A gallium phosphide photovoltaic junction is reported. Using a n–p structure, a gallium phosphide junction is grown on a gallium phosphide substrate by molecular beam epitaxy. Junction design is presented with measurements of the dark and light response. The light current was measured under an illumination of air mass (AM) 1.5. Without an anti-reflective coating, a V_{oc} of 1.53 V and a J_{sc} of 0.959 mA/cm^2 is achieved at one-sun AM1.5 global. A simulation of the junction is presented with best-fit parameters. Strategies for efficiency improvements are discussed which yield a simulated V_{oc} of 1.93 V and an AM 1.5 efficiency of 14% at 20 suns. Justification of a 51.3% efficient, ideal, multi-junction device is also presented.

1. Introduction

Alternative energy sources, such as solar photovoltaics, are regaining public attention. In order to reach efficiencies over 35%, solar cells must be multi-junction devices [1]. The overall efficiency of a multi-junction device depends heavily on the individual efficiencies of each junction for its portion of the spectrum. In the pursuit of higher and higher efficiencies, a suitable wide-bandgap junction must be designed that achieves maximum energy conversion efficiency in the realm of the blue-green to ultra-violet solar photons. Candidates for high-efficiency junctions were investigated, revealing gallium phosphide (GaP) as a good candidate.

GaP can be grown with diffusion lengths on the order of microns [2] on GaP substrates. Recent developments in growing III-V materials on Silicon and Germanium [3] provide a promising future for growing GaP on less expensive substrates. The band structure for GaP suggests that neither radiative recombination, nor auger recombination will be a dominating mechanism [4]. The band structure of GaP is such that the direct band edge is only 0.5 eV above the indirect band edge [5]. This yields high absorption coefficients for much of the spectrum of interest. Prior work from Sulima, et al. investigated AlGaP solar cells for space applications [6]. The ability to grow single-crystal on a GaP substrate, the ability to produce diffusion lengths on the order of microns, and the high absorption coefficients of GaP make it a promising candidate for a wide bandgap photovoltaic material.

2. Material and methods

2.1. Device growth and fabrication

The junction is grown by MBE. A highly doped buffer layer was grown on a GaP substrate (Fig. 1). A 4.5 μm p-type active region of GaP doped 1×10^{17} with Be. This was followed by a 0.5 μm n-type active region of GaP doped 1×10^{18} with Si. The structure was capped with a heavily doped 100 Å contact layer. No anti reflection (AR) coating was used at this stage.

An annealed Au/Ge/Ni contact was used for the n-type contact. A p-type Ni/Ti/Au contact was used for the back surface.

Cells were isolated by mesa etching to a depth of 2.2 μm in $HCl : HNO_3 : DI$ (1:1:10) at a rate of approximately 80 Å/s. The resultant cells have an area of 0.185 cm^2.

2.2. Device characterization

The light response measurement (Fig. 2) consisted of a Xenon lamp with an AM1.5 filter at concentration of 1 sun, verified by a silicon cell. The dark current is measured on the same setup as the light current. The internal quantum efficiency (IQE) is measured by filtering the Xenon lamp through a monochrometer, measuring the short circuit current per wavelength, and correcting for reflection and absorption. The spectrum power was measured with a thermopile optical power meter.

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n-GaP,	1E20, 10 nm
n-GaP,	1E18, 0.5 μ m (Si)
p-GaP,	1E17, 4.5 μ m
p-GaP buffer,	1E18, 0.2 μ m (Be)
p-GaP Substrate,	1E18 (Zn)

Fig. 1. Structure of the baseline GaP photovoltaic cell.

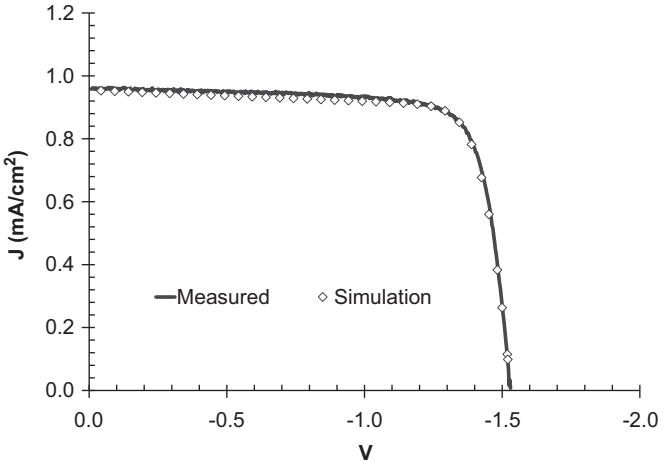

Fig. 2. AM1.5 response of the GaP cell. $V_{oc} = 1.53\,V$ $J_{sc} = 0.96\,mA/cm^2$.

2.3. Device simulation

To assist in device design, device simulation was conduced using a drift-diffusion based solar cell simulator, ADEPT-F [7]. Curve fitting was accomplished by starting with an assumed ideal device, and logically modifying various parameters to account for likely non-idealities.

3. Results

The n-type contact had a contact resistance of $6 \times 10^{-4}\Omega\,cm^2$ after annealing. The p-type contact had a contact resistance of $\approx 1\,\Omega\,cm^2$. Further investigation is needed to improve the p-type contacts.

The summary of the light response can be seen in Table 1. The light response curve can be seen in Fig. 2. There was no anti-reflective (AR) coating on the cell. The dark response curve can be seen in Fig. 4. The internal quantum efficiency (IQE) can be seen in Fig. 3.

The best fit parameters can be found in Table 2 where d is the layer thickness, ND or NA is the doping concentration, τ_{srh} is the minority carrier lifetime due to Shockley-Read-Hall recombination, and μ is the minority carrier mobility.

3.1. Comparison to state of the art

The idealized 20 suns simulation, extrapolated from the 1 sun model, can be dropped into the 6-junction stack designed by Barnett et al. [8] in place of the 2.4 eV cell. Their ideal target efficiency is 13.3% for the highest energy 2.4 eV cell. The simulated ideal GaP cell achieves 12.2% efficiency at 20× concentration without the use of a DBR. The limiting efficiency for single-junction GaP predicted by Henry [1] is approximately 15%. This drop from the ideal efficiency is partially due to the lack of absorption of most of the photons of energies between the direct and indirect band (2.78 and 2.26 eV, respectively) in the 5 μm GaP active region. If the photons between the direct and indirect bandgaps were reflected back into the GaP, the resulting efficiency can be expected to reach 14%, as seen in Table 4. For the purpose of this evaluation, we will assume the photons not absorbed on the first pass through the GaP are allowed to pass through to lower bandgap cells.

$$\eta_{bot} = \frac{\int_{2.26}^{2.4} \Phi(E)(1-e^{-\alpha_{GaP}(E)5\ \mu m})\,dE}{\int_{0.7}^{2.4} \Phi(E)\,dE} \quad (1)$$

$$\eta_{tot} = \eta_{top}\eta_1 + \eta_{bot}\sum_{i=2}^{6}\eta_i \quad (2)$$

To obtain a theoretical value for the maximum efficiency, we can make two observations. The first observation is that the 5 μm GaP cell is 1.1% less efficient than the optimal 2.4 eV cell over the whole AM1.5 spectrum. The second observation is that the spectrum available to the lower cells is reduced by 1.42%. Eq. (1) expresses this where $\Phi(E)$ is the AM1.5 spectral irriadiance as a function of energy. If we let η_i be the ideal target efficiency of each

Table 1
Measured AM1.5 light response.

V_{oc} (V)	J_{sc} (mA/cm^2)	FF	Efficiency
1.53	0.959	0.8	1.17%

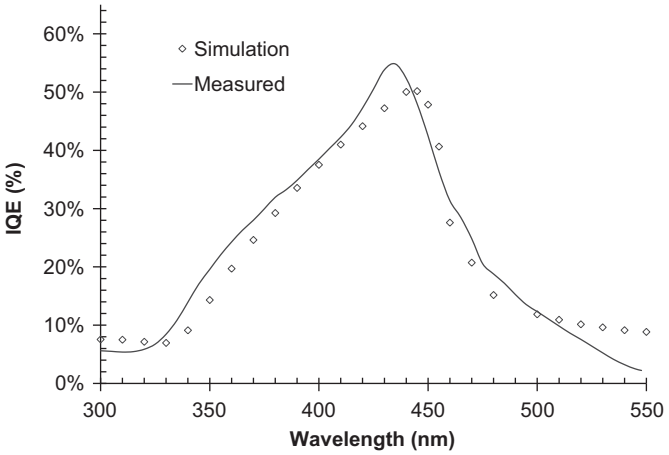

Fig. 3. Internal quantum efficiency of GaP cell.

Table 2
Best fit parameters.

Layer	d	ND or NA (cm)$^{-3}$	τ_{srh} (s)	μ (cm^2/V s)
n contact	150 Å	1×10^{19}	6×10^{-12}	78
n active	0.5 μm	$2.1 \times 10^{18} \rightarrow 0.7 \times 10^{18}$	12.57×10^{-6}	72→125
p active	4.5 μm	$0.73 \times 10^{18} \rightarrow 1 \times 10^{18}$	118.4×10^{-12}	64→59
p buffer	1 μm	2×10^{18}	1×10^{-12}	66
Series resistance	60 Ω			
Shunt resistance	40 kΩ			
$\chi_s - \Phi_m$	0.2 eV			