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Improving InGaN heterojunction solar cells efficiency using a semibulk absorber

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ABSTRACT

We demonstrate enhanced short circuit current density and power conversion efficiency in InGaN heterojunction solar cells using a semibulk absorber (multi-layered InGaN/GaN structure), with 8% indium concentration. The semibulk absorber shows peak external quantum efficiency of 85% and short current density of 0.57 mA/cm^2 under AM 1.5 G, i.e. almost four times higher than the typical InGaN solar cells based on single thick InGaN absorber. The power conversion efficiency is around 0.39% under AM 1.5 G, almost three times higher than state of the art for 8% indium incorporation. The improvement in power conversion efficiency is attributed to the enhancement in structural quality of the InGaN absorber. Simulations and experimental results are presented for an in depth investigation of the parameters limiting the power conversion efficiency of the solar cell. The semibulk absorber is an elegant solution for the realization of highly efficient InGaN-based PIN heterojunction solar cells.

1. Introduction

The InGaN material system, with its bandgap from 0.7 to 3.4 eV spanning the entire visible spectrum, enables the design of multi-junction solar cells of maximum efficiency. The high energy radiation resistance and high absorption coefficient (10^5 cm^{-1}) makes InGaN a potential candidate for high efficiency concentrated photovoltaic (PV) devices [1]. The power conversion efficiency (PCE) of InGaN PIN heterojunction solar cells is strongly dependent on the crystalline quality of the InGaN absorber layer, which must be larger than 100 nm thick in order to absorb 90% of incident above-bandgap light [2]. Despite its high optical absorption coefficient, the ability of InGaN to collect photogenerated carriers has been hindered by poor crystalline quality. It is unsurprising that thick InGaN layers exhibit poor optical performance since the critical layer thickness (CLT) for a fully strained high quality InGaN with high In content is only a few nanometers [3]. For instance, InGaN CLT is estimated to be 15 nm for a high quality fully strained epitaxial layer with 20% of In concentration. Above this thickness the crystalline quality and optical performance are degraded. The literature data reports that for InGaN layer thickness exceeding 100 nm with an In concentration above 10%, distinct sublayers of InGaN are observed with distinct In compositions and strain states [4,5]. Close to the InGaN/GaN interface, the film is two-dimensional (2-D), homogeneous and fully strained on the GaN template substrate. As the growth proceeds, spatial fluctuations of the composition are observed and an accumulation of In arises especially around threading dislocation (TD) terminations leading to 3-D In-rich domains embedded in the 2-D InGaN matrix [6].

Most bulk $In_xGa_{1-x}N$ heterojunction solar cells reported in the literature have very low PCE, compared to what is expected theoretically. For instance, Wu et al. [7] reported an experimental PCE of 0.51% and 0.3% for 10% and 14% of In content compared to their simulated PCE of 1.8% and 2.27% respectively. The large decrease in PCE with increase in In content of the InGaN absorber from 10% to 14% was attributed to a degradation of the higher In content absorber. Concurrently, Zheng et al. [8] reported that when they increased a 10%

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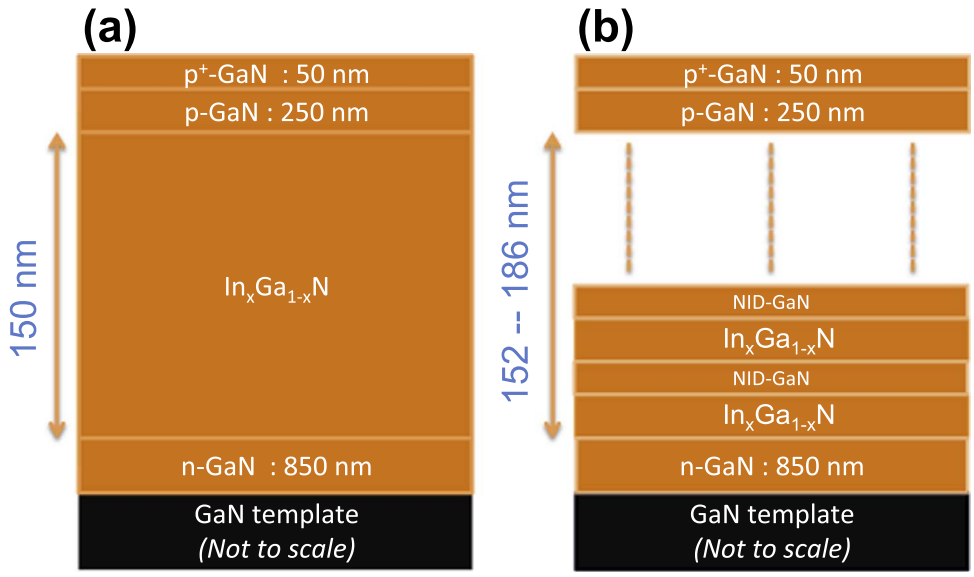

Fig. 1. Comparison of (a) bulk and (b) semibulk InGaN solar cell structures.

Table 1
CLT for InGaN epilayer used in simulation for semibulk structure.

InGaN (nm)	# of periods	In content (%)
75	2	5
30	5	10
21.4	7	15
15	10	20
12.5	12	25

In content InGaN absorber layer from 150 nm to 250 nm the PCE of the solar cell went down. This effect was attributed to poorer crystal quality of the thicker InGaN layer caused by the relaxation of the layer exceeding the InGaN/GaN heterojunction CLT [8].

We have previously demonstrated that replacing the thick InGaN absorber layer with a semibulk absorber may overcome the challenge of growing high crystalline quality, single phase absorber layers [9]. Semibulk structures consist of thin GaN interlayers inserted by stopping the In precursor flow during the InGaN growth (see Fig. 1(b)). The presence of thin non-intentionally doped (NID)-GaN interlayers absorb excess In that accumulates at the heterojunction surface and contribute to InGaN relaxation [4]. High structural quality for absorber layers using the semibulk approach has been demonstrated with In contents up to 14% [10]. In a recent study by Broeck et al. [11] the density of V-pits is reduced by using semibulk approach instead of bulk InGaN layers. These interesting results lead us to investigate the use of a semibulk absorber for the realization of heterojunction solar cells..

2. Design of the solar cell

Achieving a good PV performance using a semibulk absorber layer is not a trivial task. The CLT for the InGaN layers as a function of In composition, and the thickness of the NID-GaN interlayers were both factors that we had to consider in the solar cell design. InGaN epilayers exceeding the CLT would result in poor crystalline quality. Also the GaN interlayers need to be thick enough to absorb/desorb the excess In that promotes InGaN relaxation. However, the GaN interlayers also provide a barrier to electronic carriers and must be made thin enough so that tunneling through them can occur [12]. Using a previous study [3] based on the model proposed by Fischer et al. [13] and validated for the InGaN epilayer thickness dependence on the In content, we calculated the CLT of InGaN on GaN template. According to that model, the CLT h_c is

$$\frac{h_c}{\ln\frac{h_c}{B}} = \frac{B\times\cos\lambda}{0.0836\times x}\times\left(1+\frac{1-\frac{v}{4}}{4\pi\times\cos^2\lambda\times(1+v)}\right) \quad (1)$$

where B is the Burger's vector magnitude, λ the angle between the Burger's vector and the interface, x the Ga content of the $In_xGa_{1-x}N$ layer, and v is Poisson's coefficient. The values of Burger's vector are taken from the literature [14] and are equal to 0.324 nm and 0 degrees for the magnitude and the angle respectively. The CLT results are reproduced in Table 1 and indicate that the CLT decreases significantly for materials with a high In concentration.

To ensure the same amount of light absorption during simulations, the thickness for bulk InGaN absorber is kept at 150 nm regardless of In concentration. However, the growth of high quality 150 nm thick bulk InGaN absorber with In concentration exceeding 12% is very challenging. To assess our device design we utilized Silvaco software. Fig. 1 shows a schematic of two solar cell structures that were modeled.

Each has identical doping concentrations, and thicknesses. The only difference between the two structures is that one is a conventional bulk InGaN absorber and the other a semibulk absorber. The physical parameters required for the modeling of InGaN are widely available and were obtained from the previous studies [15,16]. The doping concentrations for the different epitaxial layers used during the simulations are, $3\times10^{17}\,cm^{-3}$, $1\times10^{17}\,cm^{-3}$, $6\times10^{16}\,cm^{-3}$, $5\times10^{16}\,cm^{-3}$, $6\times10^{18}\,cm^{-3}$ for p^+-GaN, p-GaN, NID-GaN, i-InGaN and n-GaN respectively. The model included doping concentration dependent mobilities based on the Caughey-Thomas model [16]. Both radiative and non-radiative recombination models were included in the model. The bandgap for $In_xGa^{1-x}N$ were calculated using Vegard's law, and the absorption coefficient of InGaN was calculated as a function of the bandgap energy and In composition and bowing parameter [3]. Fig. 2 shows the simulated dependence of the PCE versus the concentration of In for both bulk and semibulk structures with 150 nm total InGaN thickness and varying GaN interlayer thicknesses..

The GaN interlayer thickness does not significantly effect the PCE for In concentrations <10%. This is because for In concentration <10%, the current transport is dominated by thermionic emission. At high In concentrations (> 10%), the barrier height increases leading to current transport via tunneling. The increase in the thickness of GaN interlayers causes difficulty in tunneling of carriers, that results in reduction of the PCE. Thus for this study, we propose the fabrication of a