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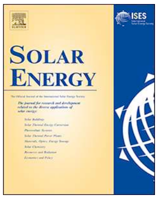

Degradation analysis of 3J InGaP/InGaAs/InGaAsN solar cell due to irradiation induced defects with a comparative study on bottom homo and hetero InGaAsN subcell

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ABSTRACT

The influence of irradiation induced traps in the triple junction $In_{0.49}Ga_{0.51}P/In_{0.01}Ga_{0.99}As/In_{0.30}Ga_{0.70}As_{0.98}N_{0.02}$ solar cell was studied using finite element analysis. The total 3J solar cell structure was simulated separately with homo and hetero InGaAsN structure as the third or bottom subcell. The higher efficient 3J InGaP/InGaAs/InGaAsN solar cell with bottom InGaAsN heterostructure was analyzed by including irradiation induced trap levels. The trap levels correspond to 1 MeV electron irradiation with fluence range of 1×10^{14}–1×10^{16} in electrons/cm^2 at room temperature. We realized that the traps in the middle cell cause more degradation, followed by bottom cell and then top cell. The onset of degradation of solar cell parameters (J_{sc}, V_{oc} and η) starts at trap concentration 1×10^{13} cm^{-3}, while more degradation occurs beyond 1×10^{16} cm^{-3}. At trap concentration of 1×10^{16} cm^{-3}, the solar cell design was optimized for achieving current matching among the subcells. While we obtained 36% conversion efficiency at 1-sun (AM0 spectrum) using bottom heterostructure, the introduction of 1×10^{16} cm^{-3} trap concentration and 10^4 cm/s surface recombination velocity simultaneously in all subcells resulted in 20.8% conversion efficiency which increased to 24.3% after current matching.

1. Introduction

III-V based multi-junction solar cells are the main choice today for powering space satellites. The state-of-the-art GaAs based multi-junction solar cells yielded an efficiency of 31% under AM0 (1 sun) (Zhang et al., 2017) and 46.0% under AM1.5D concentrated (508 suns) (Green et al., 2018) solar radiation spectrum.To improve the efficiency, the incident light spectrum should be effectively utilized for increasing the performance of multi-junction solar cells. Photons with wavelength range (200–670 nm), (500–900 nm), and (900–1800 nm) will create electron-hole pairs for current generation in InGaP, GaAs, and Ge cells respectively. Adding a material which uses the photons in the range (873–1240 nm) (Tan et al., 2011) with band gap ~1 eV and lattice matched to GaAs will increase the light absorption and increase the efficiency of the space solar cells. Due to the large difference in band gap energies of GaAs and Ge (~0.75 eV), energy is lost to Ge subcell in the form of heat (Kurtz et al., 2001). Hence there is a need for 1 eV band gap material to bridge the energy gap between GaAs and Ge subcell. This throws light on quaternary alloy InGaAsN which can be studied further for incorporating in satellite power systems. Kurtz et al. (1997) shows the variation of three junctions solar cell efficiency, as a function of third cell band gap, using InGaP, GaAs as top and middle cells. Third cell band gap values in the range of 0.95–1.05 eV for AM0 are close to optimum efficiency value. $In_{0.30}Ga_{0.70}As_{0.98}N_{0.02}$ is an optimal candidate that has a band gap of 1 eV and is lattice-matched to GaAs substrate (Kurtz et al., 1999). World record efficiencies have been demonstrated by incorporating dilute nitrides in multi-junction solar cells (Green et al., 2013; Ochoa et al., 2017). Addition of a small amount of N to (In) GaAs helps in tailoring the band gap in the range of 1– 1.2 eV. However, it also introduces acceptor-like defect at $E_c - 0.2$ severely affecting the diffusion length of minority carriers (Khan et al., 2007). Lee et al., has shown that sufficient photocurrent of around 14 mA/cm^2 can be achieved by keeping the trap density lower than 1×10^{16} cm^{-3} (Lee et al., 2015). Annealing the sample was found to be one way of improving the solar cell properties by reducing trap concentration (Khan et al., 2007). Recently, chemical beam epitaxy has been identified as a promising approach for high quality dilute nitride material growth compared to MBE (Lee et al., 2015). When using InGaAsN as the third subcell, GaAs substrate was found to be more beneficial compared to Ge substrate. This is due to increased photon path length and bottom surface reflection when using GaAs as substrate (Wilkins et al., 2013). As stated in reference Kurtz et al. (1999), defects are generated in

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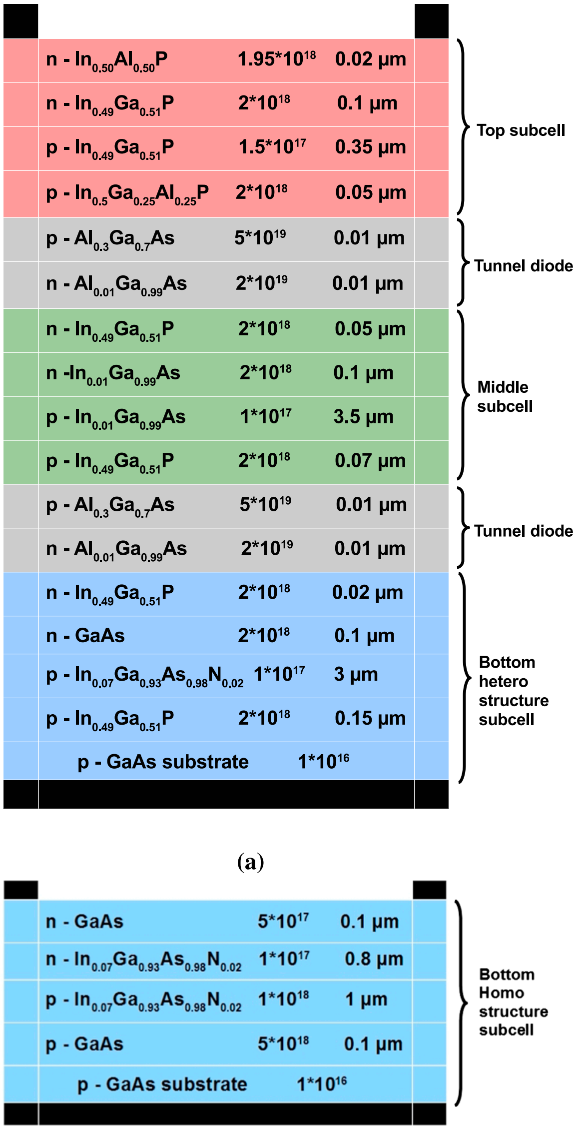

(a)

(b)

Fig. 1. (a) 3J InGaP/InGaAs/InGaAsN solar cell structure with bottom InGaAsN heterostructure (b) 1J bottom InGaAsN homostructure (doping values in cm^{-3}).

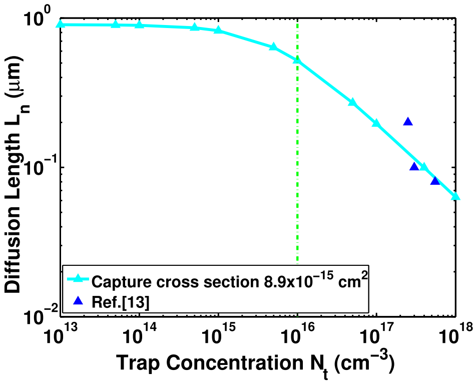

Fig. 2. Simulation model showing diffusion length variation with trap concentration at capture cross section for p-InGaAsN material $8.9 \times 10^{-15} cm^2$.

InGaAsN material due to Nitrogen incorporation that limits the performance of the solar cell. Minority carrier lifetime in the base layer is an important parameter that defines the efficiency of solar cell. The solar cells used in space are subjected to high energy electron irradiation environment which results in the formation of defects or traps. These traps act as non-radiative recombination centers and reduce the minority carrier lifetime. This, in turn, reduces the efficiency of the solar cell. It has been experimentally verified that electron traps with energy levels $E_c - 0.2$ in InGaAsN (Khan et al., 2006) are mainly responsible for solar cell degradation due to radiation. There were a few studies and analyses made on individual InGaAsN p-n junction as hetero and homo structure (Kurtz et al., 2005; Li et al., 2000). However, there was no analysis made on how the hetero or homo structure would perform in the overall 3J solar cell. The schematic illustrations of complete 3J solar cell structure with InGaAsN p-n heterojunction is shown in Fig. 1a and InGaAsN homojunction bottom subcell is shown in Fig. 1b. Characteristics of the 3J solar cell have been modeled using AM0 radiation. Further, the solar cell parameters such as short circuit current density (J_{sc}), open circuit voltage (V_{oc}) and efficiency (η) were analysed to investigate the irradiation influence by defining multiple trap levels in the top, middle, and bottom subcells (Khan et al., 2006; Danilchenko et al., 2008; Khan et al., 2002). Research has been carried out to study and model radiation effects on space photovoltaic systems (Schiavo et al., 2012; Mazouz et al., 2013; Stievenard et al., 1986). However, no research has been published on the degradation analysis of 3J InGaP/InGaAs/InGaAsN solar cell due to irradiation induced defects. In this paper, we performed simulations to assess the degradation of solar cell considering trap levels in *p*-base layers of InGaP, InGaAs, and InGaAsN materials. Specifically for InGaAsN, we have used the simulation model that shows the influence of trap concentration on minority carrier diffusion length in the base layer at a particular capture cross-section. Based on the model, we have plotted the variation in diffusion length with respect to trap concentration for InGaAsN layer. From Fig. 2, at $1 \times 10^{16} cm^{-3}$ trap concentration the diffusion length obtained is around 0.52 µm. The solar cells are usually exposed to 1 MeV electron irradiation with fluence varying between $1 \times 10^{14} - 1 \times 10^{16}$ in electrons/cm^2 (Danilchenko et al., 2008). According to these fluence values, a range of trap concentrations from $1 \times 10^{13} cm^{-3}$ to $1 \times 10^{18} cm^{-3}$ are considered in the simulation model (Khan et al., 2006; Khan et al., 2002; Mazouz et al., 2015). The trap concentration N_t varies proportionally with fluence ϕ and are related by $N_t = k\phi$, where k is the introduction rate of non-radiative recombination centers in cm^{-1}. The degradation parameter k is not specifically known for all the materials, but it can be roughly estimated from the published results. For example, in reference Makham et al. (2010) 1 MeV electron irradiation with 1×10^{16} electrons/cm^2 fluence introduces $1 \times 10^{16} cm^{-3}$ defects in GaAs indicating a k value of around 1.

In this paper, 3J InGaP/InGaAs/InGaAsN solar cell structures with heterojunction and homojunction InGaAsN bottom cells were created using layer builder and simulated using Apsys software from CrosslightInc., which is based on finite element analysis. To increase the absorption of the solar cell, anti-reflective coating layers MgF_2 and ZnS with a thickness of 90 nm and 52 nm were considered (Jiang Lin et al., 2013). These thickness values were optimized to 110 nm and 62 nm to increase the efficiency of the solar cell. AlGaAs tunnel junctions were used between subcells for better efficiency (Özen et al., 2015). The main objective of this paper is to: (i) understand the influence of defect level in InGaAsN layer on the overall performance of 3J solar cell and (ii) come up with suitable InGaAsN bottom subcell structure that gives better results when combined with total solar cell.

2. Simulation model

Table 1 shows the material parameters of InGaAsN considered for the simulation model. Traps defined in the base region of each subcell act as recombination centers and reduce the lifetime of minority carriers. These traps are characterized by capture cross section which is