Optik 166 (2018) 61–68

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

Original research article

Design optimization of multi quantum well solar cells

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A R T I C L E I N F O

Article history:
Received 15 November 2017
Received in revised form 6 March 2018
Accepted 2 April 2018

Keywords:
Solar cells
Multi quantum well
InGaN
GaN

A B S T R A C T

This study provides the optimized picture of multi quantum well (MQW) solar cell using Brennan method and Schrodinger equation. MQW solar cell is optimized by varying some parameters such as Indium composition of the 'well' and 'barrier'; band gap difference of 'well' and 'barrier'; number of quantum wells; the thickness of 'well' and 'barrier'. The photovoltaic parameters of optimized GaN/InGaN 12MQW solar cell are short circuit current density of ~2.10 mA/cm^2, open circuit voltage of ~0.85 V, fill factor of ~0.86 and conversion efficiency of ~8.92%.

1. Introduction

Multi quantum well (MQW) solar cell approach is based on the insertion of a MQW structure in the intrinsic region of p-i-n solar cells with a bunch of wider(barrier) and narrow (well) band gap semiconductor to improve the spectral response below the absorption edge of 'barrier' material. This idea was pioneered by Barnham et al. in 1990 [1]. The MQW structure improve the p-i-n solar cells efficiency and numerous researchers are working on this structure. This idea is developed by the Imperial College group [1–6]. The quantized energy levels in quantum structures become the driving force for more carrier generation [7]. Several theoretical models have been developed to explain the performance of the MQW solar cells [8–11].

In this paper a model is used for MQW solar cells, which is developed by Andersona et al. [10] and Cabrera et al. [12]. This model is used to study the dependence of photovoltaic parameters on the quantum 'well' and 'barrier' properties. Brennan method is used for optimization of well barrier thickness and Schrodinger equation solved for finite potential barrier. The open circuit voltage (V_{oc}), short circuit current (J_{sc}), fill factor (FF) and conversion efficiency (η) are simulated as a function of band gap difference of 'well' and 'barrier' under AM 1.5G illumination. The photovoltaic parameters of fabricated p-GaN/i-GaN-InGaN (5MQW)/n-GaN solar cell are compared with predicted results based on this model and found in high qualitative consistency. This work provides the most comprehensive and qualitative picture of MQW solar cell, and serve a useful guide for designing and interpreting the characteristic parameters of MQW solar cell.

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https://doi.org/10.1016/j.ijleo.2018.04.008
0030-4026/

2. Theoretical multi quantum well model

The used model in optimization of MQW solar cells is based on the following simplifying assumptions as

2.1. Depletion region approximation

Minority carrier's forward and reverse current treated as independence of the depletion region width.

2.1.1. Recombination model

Schockley-Read Hall (SRH) recombination, Auger, surface and radiative recombination are considered. Recombination rates throughout the structure including the depletion region are described by radiative coefficient (B_B) in 'barriers' and a separate radiative coefficient (B_W) is assumed for the 'wells'.

2.1.2. Quasi-equilibrium

Carrier distribution throughout the structure is described by non-degenerate Maxwell-Boltzmann statistics and quasi Fermi levels. This presumes that scattering processes is sufficiently efficient to keep the carrier subsystems in the 'well' and 'barrier' in quasi-equilibrium with themselves as well as capture and emission rates sufficiently rapid to keep the two subsystems in quasi-equilibrium with one another [10].

2.1.3. Finite mobility

Ohmic losses are assumed as experimental values. The quasi-Fermi levels are assumed to be flat throughout the intrinsic region and separated by the terminal voltage.

2.1.4. Polarization

The piezoelectric polarization can be manually changed by modifying the parameter, "degree of relaxation" from zero, i.e. with piezoelectric polarization to unity, i.e. without piezoelectric polarization [13]. The spontaneous polarization remains unchanged. In this paper, we have considered "degree of relaxation" as zero, i.e. with piezoelectric polarization.

MQW solar cell theoretical model is based on the following J–V relationship [10].

$$J_{QW}(V) = J_o\left[e^{\frac{qV}{KT}} - 1\right] - J_{G|W} - J_{G|B} + J_{R|W} + J_{R|B} \tag{1}$$

A fraction (f_W) of the intrinsic region is occupied by 'well' layers and $(1 - f_W)$ by 'barrier' layers.

$$f_W = tn_w$$

$$1 - f_W = 1 - tn_w$$

$$J_{QW}(V) = J_o\left[e^{\frac{qV}{KT}} - 1\right] - qW\left[f_W(R_W - G_W) + (1 - f_W)(R_B - G_B)\right) \tag{2}$$

where t is thickness of 'well', n_w number of 'well, q is electron charge, V is the terminal voltage, kT is the thermal energy, J_0 is the reverse saturation current density, $J_{G|W}, J_{G|B}, J_{R|W}, J_{R|B}$ are current densities correspond to the carrier generation and recombination, in the 'well' and 'barrier', respectively, and R_W, G_W, R_B, G_B are recombination and generation rate of 'well' and 'barrier' [12].

The J–V equation for the MQW solar cells become as,

$$J_{QW}(V) = J_o\left[1 + r_R\beta\right]\left[e^{\frac{qV}{KT}} - 1\right] - qW\left[f_W\left(G_W|_{opt}\right) + (1 - f_W)\left(G_B|_{opt}\right) \tag{3}$$

The Schockley-Read Hall recombination (r_{R1}) and radiative recombination (r_{R2}) are modeled as below

$$r_R = r_{R1} + r_{R2}$$

$$r_{R1} = \frac{pn - n_i^2}{\tau_p\left[n + n_i exp\left(\frac{Etrap}{kT}\right)\right] + \tau_n\left[p + n_i exp\left(\frac{-Etrap}{kT}\right)\right]}$$

$$r_{R2} = 1 + f_W[\gamma_B\gamma_{DOS}^2 \exp\left(\Delta E/kT - 1\right)$$

where, $Etrap$ is the difference between the trap energy level and intrinsic Fermi level, T is the lattice temperature in degrees kelvin and τ_p, τ_n are hole and electron lifetime. It represents the fractional increase of recombination in the intrinsic region at equilibrium condition due to the presence of the quantum 'well'. The J_{sc} and V_{oc} for MQW solar cell are expressed as below [10],

$$J_{scQW} = qW\left[f_W\left(G_W|_{opt}\right) + (1 - f_W)\left(G_B|_{opt}\right)\right] \tag{4}$$