Simulation of Thin High-Efficiency Photonic Power Converters Under 1310 nm Laser Illumination

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Abstract— **We designed and simulated highly efficient thin single-junction monochromatic photonic power converter (PPC) operating at 1310 nm for telecommunication applications. The PPC is designed using AlGaInAs lattice-matched to InP. To increase efficiency and minimize device thickness, we selected an inverted design structure with metallic back reflector and substrate removal. The cavity resonances enhance light trapping within the thin absorption layer. Opto-electrical simulations revealed significant improvement in figures of merit such as efficiency, open-circuit voltage, and short-circuit current. An efficiency of 51% is obtained under normal-incidence laser illumination at a wavelength of 1310 nm for this exemplary structure with an absorber thickness of 770 nm. This structure forms a single-junction for an intended higher-voltage multi-junction device yielding efficiencies in excess of 60%.**

Keywords— Photonic power converter, Photovoltaics, quaternary material, efficiency, back reflector, FDTD

I. INTRODUCTION

Unique features of power-over-fiber (PoF) such as immunity to electromagnetic interference make it one of the promising technologies with wide applicability ranging from telecommunication to biomedical and space. A typical PoF system consists of: a narrowband source such as laser or LED as a transmitter, an optical fiber as a transmission medium, and a photonic power converter (PPC) as a receiver to convert the photonic power to electrical power. For efficient power transmission PPCs with higher power conversion efficiency are required [1].

PPCs based on GaAs operating at wavelengths <870 nm and PPCs based on GaS and InGaAs/InP operating at longer wavelengths have been investigated extensively in the recent years [2-3]. Longer wavelengths allow accessing lower-attenuation regions within optical fibers to realize longer-distance or more efficient power transmission. Furthermore, thin photovoltaic converters have been received a significant attention due to lightweight, low cost and rapid growth procedure. However, reduction of absorption layer effects the optical absorption and degrades the PPCs conversion efficiency. Numerous designs such as texturized surface, back reflector (BR), surface and localized plasmonics have been proposed to boost up light trapping in the active layer of thin and ultrathin photovoltaic converters particularly solar cells.

In this study, we combine thin PPCs with BRs to design highly efficient thin PPCs at 1310 nm.

II. MODEL DESCRIPTION

$Al_xGa_yIn_{1-x-y}As$ on the InP with band-edge wavelength at 1430 nm is selected as a good candidate for PPCs at 1310 nm. The material has an absorption coefficient of 8×10^3 cm^{-1} at 1310 nm, requiring a 4.9 μm thickness to absorb 98% of incident light. Though selecting band gap closer to 1310nm could reduce thermalization losses and increase efficiency, this could increase the required device thickness [4]. We modeled thin PPC with active layer thickness of 770 nm and applied BR to enhance light trapping within this thin region. To fabricate a device with a BR, the structure should be grown inverted on the substrate. The BR is fabricated on the top layer of the inverted structure by depositing a layer of metal which also acts as the bottom contact in the final manufactured device. Next, the metal layer is bonded to a second substrate, which supports the device physically and allows us to remove the growth substrate inverting the structure.

In Table I and Table II we show the material, band gap energy, thickness and doping of each layer for conventional structure (upright) and proposed design (inverted) respectively.

TABLE I
DESIGN PARAMETERS FOR THE UPRIGHT STRUCTURE

Material	Band Gap (eV)	Doping (x 10^{18} cm^{-3})	Thickness (nm)
n-$In_{0.52}Ga_{0.48}As$	0.74	20	100
n-$In_{0.3}Al_{0.7}As$	1.926	2	10
n-$Al_{0.356}Ga_{0.117}In_{0.527}As$	1.25	5	400
n- $Al_{0.097}Ga_{0.371}In_{0.532}As$	0.864 eV	1	100
p- $Al_{0.097}Ga_{0.371}In_{0.532}As$	0.864 eV	0.02	670
p- $Al_{0.356}Ga_{0.117}In_{0.527}As$	1.25 eV	5	50
p- $In_{0.52}Ga_{0.48}As$	0.74 eV	20	100
p- $In_{0.52}Ga_{0.48}As$	0.74 eV	2	100
p-InP		10	625,000

TABLE II.
DESIGN PARAMETERS FOR THE INVERTED STRUCTURE

Material	Band Gap (eV)	Doping (x 10^{18} cm^{-3})	Thickness (nm)
p- $In_{0.52}Ga_{0.48}As$	0.74eV	20	25
p- $Al_{0.356}Ga_{0.117}In_{0.527}As$	1.25 eV	5	50
p- $Al_{0.097}Ga_{0.371}In_{0.532}As$	0.864 eV	0.02	670
n- $Al_{0.097}Ga_{0.371}In_{0.532}As$	0.864 eV	1	100
n- $Al_{0.356}Ga_{0.117}In_{0.527}As$	1.25 eV	5	400
n- $In_{0.3}Al_{0.7}As$	1.926 eV	2	10
n- $In_{0.52}Ga_{0.48}As$	0.74 eV	20	100
n- $In_{0.52}Ga_{0.48}As$	0.74 eV	2	100
n-InP		10	625,000

A. Optical Simulation

First optical simulations were performed with 2D finite-difference time-domain method (using FDTD: Electromagnetic Simulator by Lumerical) to calculate the absorbed power. The active layer and antireflection coating thicknesses are optimized to minimize the reflection loss at a wavelength of 1310 nm. The quaternary materials were modeled with refractive index parameters that were extracted experimentally

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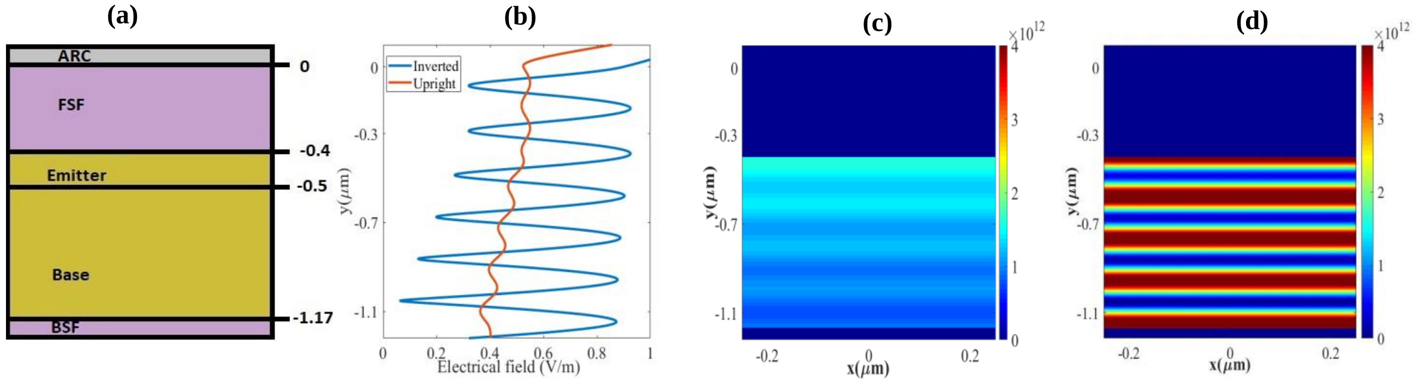

Fig. 1: Optical simulations with FDTD method for the structures in Table I and II: (a) Multilayer structure, (b) Electrical field versus position, (c) Absorbed power profile of upright design (note that substrate is not depicted), (d) Absorbed power profile of inverted design.

by ellipsometry measurements of samples of the same composition grown by molecular beam epitaxy. The multilayered structure was positioned on an InP substrate. Au is considered as metal contact and BR. Periodic and perfectly-matched layer (PML) boundary conditions are applied for the x (lateral) and y (growth) directions, respectively.

The ideal generation rate (g_{ideal}) is calculated over all wavelengths (λ) and positions (r), with the assumption that each absorbed photon generates an electron-hole pair and is therefore proportional to the number of incident photons:

$$g_{ideal}(\lambda) = \int g(\lambda, r)\, dr \qquad (1)$$

The electrical field versus depth and the absorbed power profiles for both structures are shown in Fig 1. Note that for comparison purposes the substrate of upright design is not depicted, although it was included in the simulations.

B. Electrical Simulation

Electrical simulations were carried out with finite element drift-diffusion method (using CHARGE: Charge Transport Simulator by Lumerical) to further investigate how much of the generated electron-hole pairs could be collected at contacts and yields to electrical current.

The $Al_xGa_yIn_{1-x-y}As$ quaternary alloy parameters (such as permittivity, mobility, effective mass, carrier lifetime) were determined by first combining InAs and AlAs to create the ternary alloy $In_{1-x}Al_xAs$ with the desired mole fraction (x). Next, this new model was combined with GaAs to create $Al_xGa_yIn_{1-x-y}As$.

In the next step, the ideal generation rate that was obtained from optical simulations is used as a source for electrical simulations. Device performance of both structures is evaluated in terms of current-voltage behavior parameters such as fill factor (*FF*), short circuit current density (J_{sc}), open circuit voltage (V_{oc}), and conversion efficiency. It is worth to mention that bulk recombination including Shockley read hall (*Rsrh*), Auger (*Rau*) and Radiative (*Ropt*) are considered in simulations.

III. RESULTS & DISCUSSION

We simulate the optical response of the nanostructure under a plane wave illumination with center frequency at 1310 nm, bandwidth of 20 nm and intensity of 100 mW/cm^2 at room temperature. The optical simulations demonstrated up to two times enhancement of the generation rate for inverted structure as compared to the upright design. As shown in Fig. 1, as the light passes through the structure, the electrical field (b) and subsequently the absorbed power (c and d) is descending while accompanied with resonances. The mild resonances in the upright design arises from refractive index difference between active layer and the superstrate and substrate materials. However, for the inverted design, the BR provides strong Fabry-Perot effect and boosts the absorption within the thin absorption layer. Main performance parameters from electrical simulations for both structures are summarized in Table III, showing improved figures of merit (especially the V_{oc}) for the proposed structure with BR.

TABLE III.
COMPARISON OF UPRIGHT AND INVERTED STRUCTURE PERFORMANCE

	J_{sc} (mA/cm^2)	V_{oc} (V)	*FF*	Efficiency (%)
Upright	47.1	0.51	0.78	18.9
Inverted with BR	96.9	0.65	0.8	51.7

In summary, we designed a thin PPC based on AlGaInAs on InP. The quaternary material composition in the absorption layer has been selected to have a strong absorption coefficient at the target 1310-nm wavelength to limit the thickness of material required to absorb the majority of incident light. We find that we can achieve high PPC conversion efficiency of 51% for the thin absorption layer due to large enhancement in J_{sc} and V_{oc} that was provided by applying BR. Improved accuracy of simulations is expected by taking into account surface and edge recombination as well as thermal properties.

The results in this paper imply a practical strategy for easily fabricated high efficiency thin photo-converters for entire telecommunication spectrum through proper choice of material and design optimization which could be embedded in multi-junction devices to achieve efficiencies over 60%.

[1] J. B. Rosolem, "Power-Over-Fiber Applications for Telecommunications and for Electric Utilities," in *Optical Fiber and Wireless Communications*, vol. 2, R. Roka, Ed. IntechOpen, 2017, pp. 255–278.

[2] M. Wilkins, C. E. Valdivia, A. M. Gabr, D. Masson, S. Fafard, and K. Hinzer, "Luminescent coupling in planar opto-electronic devices," *J. Appl. Phys.*, vol. 118, no. 14, 2015.

[3] N. Singh, C. Kin Fai Ho, Y. Nelvin Leong, K. E. K. Lee, and H. Wang, "InAlGaAs/InP-Based Laser Photovoltaic Converter at ~ 1070 nm," *IEEE Electron Device Lett.*, vol. 37, no. 9, pp. 1154–1157, 2016.

[4] D. Xia, M. M. Wilkins, S. S. Chahal, C. E. Valdivia, K. Hinzer. J. J. Krich,"Opportunities for increased efficiency in monochromatic photovoltaic light conversion," IEEE Photovoltaic Specialists Conference, 2018.*3688–3692, 2018.*