Design for Fabrication of High Efficiency 1310 nm Photonic Power Converter

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***Abstract*— Thin photonic power converter devices were designed for a power-over-fiber system operating at 1310 nm. Studies have shown that trapping light in a thin photonic structure can enhance the absorption. In this work, we simulate and compare the performance of a device with a conventional upright design to one that is grown inverted and fabricated with a back reflecting mirror to increase the absorption. Lumerical simulation shows that the short-circuit current is doubled and open-circuit voltage is enhanced from 0.51 V to 0.65 V. We also developed a microfabrication process to deposit a layer of Ti(15 nm)/Pd(15 nm)/Au(50 nm) as a back reflecting mirror on the inverted structure, for further experimental comparison with the conventional PPC design.**

Keywords—Photonic power convertor, Power-over-fiber, Inverted structure, Back reflector, light trapping.

I. INTRODUCTION

Photonic power converter (PPC) [1-3] devices convert photonic energy (light) directly into electricity via the photovoltaic effect after the light has travelled through free space or an optical fiber for a variety of applications. In power-over-fiber (PoF) [4] technology, high power monochromatic light is sent through a fiber and received via a PPC at the destination. PPCs can have one or more optically-thin pn junctions (segments) of the same absorber composition to split the photo-current into a monolithic series-connected multi-junction stack. Regardless of the number of segments, the total absorber thickness remains the same for all designs and can sum to several microns of epitaxially-grown material. Similar to solar cells, PPC performance can be improved via light management, such as through the implementation of a back-reflecting mirror to effectively double the optical path length [5]. Here we simulate the effect of back reflector on a single junction device which has been structured according to the intended design of one of the segments of a multi-junction PPC. This device is composed of AlGaInAs with a 0.864 eV bandgap to absorb the light coming from a high power 1310 nm laser.

II. ARCHITECTURE

The methodology for this design process is exhibited in Figure 1, which begins with the selection of material that is suitable for the 1310 nm PPC. After the material is grown, optical and material properties of each layer of the multi-layer structure are characterized. Next, we implement the properties into Lumerical to simulate the devices that are then fabricated and characterized. In our Lumerical model, parameters such as surface recombination, doping diffusion, contact size and resistivity parameters need to be taken into consideration to have more accurate results. Experimental results from material and device characterization are used to re-optimize the design in Lumerical. The steps are explained in more detail below.

A. Growth

High performance electro-optical components are epitaxially grown on an InP substrate to have good material properties along with physically supporting the device. Our devices are grown using molecular beam epitaxy (MBE). Absorbing layers are $Al_xGa_yIn_{1-x-y}As$ lattice matched to InP, with a band gap of 0.864 eV. In this work we have designed an optically-thin absorber with a thickness of 0.77 μm which is intended to absorb 50% of incident light at a wavelength of 1310 nm in a single pass. Other layers in the device including the front and back surface fields are composed of an AlGaInAs composition having a larger band gap to be transparent to the design wavelength. A strained AlInAs etch stop layer and an InGaAs cap layer help to form the front contact grid. This structure is referred to as the *upright* design.

To improve upon the performance of the conventional PPC design, it is feasible to remove the original substrate and fabricate the device on a reflecting layer to provide a light-trapping effect. In this scenario, instead of passing the light through the device just once, the reflecting layer on the backside of the device forces the light to pass the thickness of the device at least two times, increasing the light absorption. This process first requires the epitaxial growth to be sequenced in reverse order, creating an *inverted* design. Subsequently, a blanket metal layer which will act as the back reflecting mirror is deposited on top of the growth structure, then the metal surface is bonded to a second conductive substrate. The new substrate is a good physical support for the epitaxial device structure and allows us to remove the original substrate. Thereafter, we have a structure that is bottom up and bonded to a new substrate for handling.

B. Simulation

We used Lumerical software to simulate the thin upright structure and inverted structure with back reflector mirror. The performance of each structure was evaluated in two steps, as shown in Figure 1. First, the composition of the layers is defined in FDTD and optical and material properties obtained experimentally through material characterization of each layer are implemented. Lumerical FDTD is used to simulate the optical performance of the multi-layer structure and generates the optical power absorption of the device. Second, the same structure is simulated in the Lumerical device interface,

post-deadline paper

Financial support by: 1) TOP-SET, CREATE 497981-2017
2) PowerCom, STPGP 494090

inputting the absorbed power from FDTD, to determine the electrical behavior of the device; current-voltage behavior and efficiency are simulated.

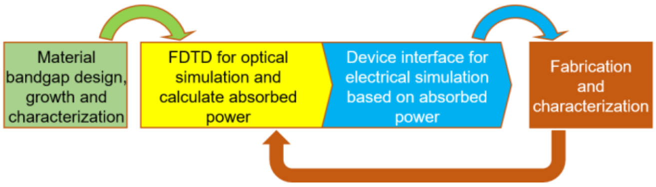

Figure 1. Methodology of the design process

C. *Fabrication process*

To compare the simulation results with real fabricated devices, we developed a process to manufacture the inverted structure with back reflector that is shown in Figure 2. First, the structure should be grown inverted on the substrate, Figure 2(a), to allow formation of the back reflector and subsequent removal of the substrate to reveal the light-incident side. The second step is to individualize the devices on the wafer using a citric acid-based wet etch (Figure 2b, mesa definition). Next, metal is deposited on the top surface of the inverted grown PPC structure (Figure 2c). This metal layer plays the role of a back reflector of the PPC as well as the bottom contact of the final device. The metallized surface will then be bonded to a conductive substrate. Later, one step chemical etch (wet or dry) removes the original substrate, stopping at the contact layer (Figure 2d). One photolithography process followed by metal deposition produces ohmic contacts on top of the device (Figure 2e). Finally, an antireflection coating is fabricated to passivate the device and minimize reflection of incident light from the surface of the device.

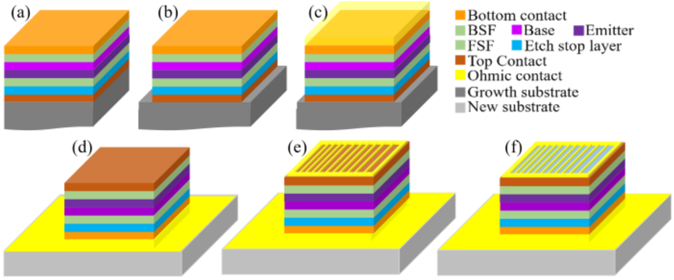

Figure 2. The schematic shows the back reflector fabrication process steps; (a) epitaxial growth, (b) wet etch to define individual devices, (c) metal layer deposition, (d) bonding to new substrate and old substrate removal, (e) top grid fabrication, (f) anti-reflection coating.

III. RESULTS AND DISCUUSION

Simulation results show absorption enhancement in the inverted structure with back reflector mirror compared to the upright device. Hence, the short-circuit current density (J_{sc}) which is directly proportional to absorption increases from 47.1 to 96.9 mA/cm^2 in the inverted structure. As shown in Figure 3, open-circuit voltage is 0.65 V in the inverted design which is higher than the 0.51 V in the upright structure. This improvement is due to the reflection from the substrate and increased absorption after applying the back reflecting mirror. In the simulation we apply a light source with 100 mW/cm^2 at 1310 nm. The simulated efficiency of the inverted structure is 2.5 times higher than upright device.

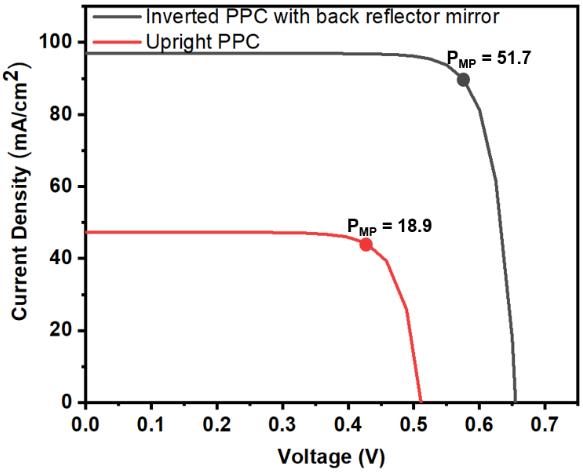

Figure 3. Current-voltage characteristic of the simulated upright design and inverted structure with back reflector. P_{MP} shows the maximum power point of each device.

To summarize, we use a methodology to design, simulate and develop a fabrication process of thin PPC with back reflecting mirror in order to improve the device performance. $Al_xGa_yIn_{1-x-y}As$ grown on InP is used as the absorber layer for 1310nm wavelength. Optical and material properties of the layers are introduced to the Lumerical FDTD interface for optical simulation and absorbed power generation. Subsequently, the generation rate of the simulated device is transferred to Lumerical device interface for electrical simulation which obtains short-circuit current, open-circuit voltage, and efficiency. We could achieve nearly two times improvement in short-circuit current and 27% improvement in open-circuit voltage in inverted structure compare to upright device which we attribute to the back reflection from the mirror and light trapping effect. We also developed a process to fabricate the back reflector for the inverted structure.

IV. ACKNOWLEDGMENT

We acknowledge the support of the Natural Sciences and Engineering Research Council of Canada (NSERC) STPGP 494090.

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