Detailed Balance Efficiency of 1310 nm Multijunction Photonic Power Converters

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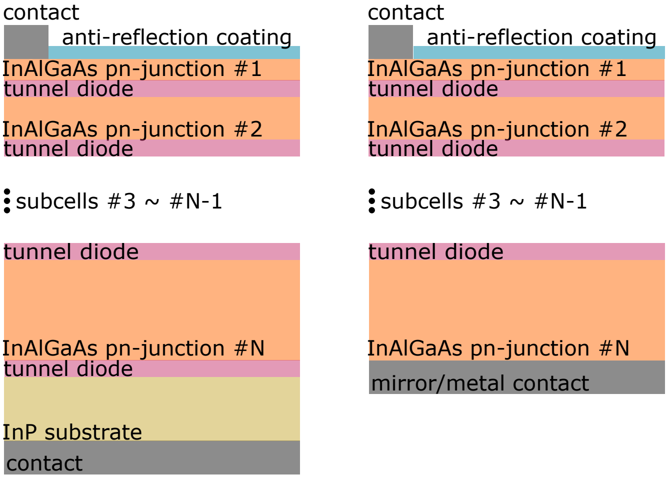
***Abstract*—We present modeled detailed balance efficiency of multijunction photonic power converters operating at 1310 nm at a laser intensity of 5.88× 10^5 W/m^2, corresponding to our test laser power and cell size, in two scenarios: (1) with an absorbing substrate and (2) with a perfect specular back reflector. We show that, in the radiative limit, efficiency increases as a function of number of junctions in the case of an absorbing substrate. In this case, efficiency can reach as high as 69% with 15 junctions. In the case of a perfect specular back reflector, efficiency reaches more than 75% and is not sensitive to the number of junctions. This insensitivity allows freedom in future device design.**

I. INTRODUCTION

Photonic power converters are photovoltaic (PV) devices that convert narrow-band light into electricity. They can be used to power micro-electronic circuits with optical energy sources, such as lasers. An optically powered system is immune to electromagnetic disturbance in the surroundings, and is spark-free. Applications include electric vehicles, telecommunication systems, electronics, etc. The development of a high efficiency photonic power converter operating at a suitable wavelength and outputting a high voltage has been the focus of our investigations. We have previously made a record efficiency GaAs-based 5-junction device converting light at 830 nm [1]. For long-distance power-over-fiber systems, we require operation in the telecommunications wavelength regime, at 1310 nm for example, for a low attenuation rate of 6.7% over 1 km [2].

Targeting operation in the 1310 nm band, In$_x$Al$_y$Ga$_{(1-x-y)}$As is used for the absorber material. It was previously shown that monochromatic conversion efficiency increases as input power[3][4], so we use a high power 14.7 W laser illuminating a cell area of 0.5 cm × 0.5 cm. High-voltage operation, which reduces series resistance loss, can be achieved through a multijunction design. A GaAs-based 20-junction device has been previously fabricated and has reached a conversion efficiency of more than 60% [5]. Motivated by previous success of GaAs devices, we propose two InAlGaAs multijunction structures, with (1) a substrate and (2) a perfect mirror at the back. Then we present the modeled detailed balance efficiency of these proposed structures.



(a) (b)

Fig. 1: Schematics (not to scale) of the InAlGaAs multijunction photonic power converters with (a) a substrate (b) a mirror at the back. The InP substrate is thick compared to the active region of the cell. The active region of the structure with a perfect mirror is half the thickness of the structure with substrate, in order to keep the total absorbance the same between the two structures.

II. MULTIJUNCTION INALGAAS ARCHITECTURE

We propose two multijunction structures consisting of In$_x$Al$_y$Ga$_{(1-x-y)}$As pn-junctions, series connected by tunnel diodes. The schematics are presented in Figure 1. In both structures, we limit the total thickness by allowing a 98% total absorbance. The absorbance is calculated using the Beer-Lambert Law. In the case of a thick substrate, we make a conservative estimate of photon-recycling effects and assume all photons entering the substrate are lost. The mirror structure has an active region thickness half that of the no-mirror case, to ensure both structures have identical vertical absorbance. Furthermore, thicknesses of the junctions are chosen so each junction absorbs the same number of incoming photons, to ensure proper current-matching in the series-connected architecture. For the mirror structure, thicknesses to ensure

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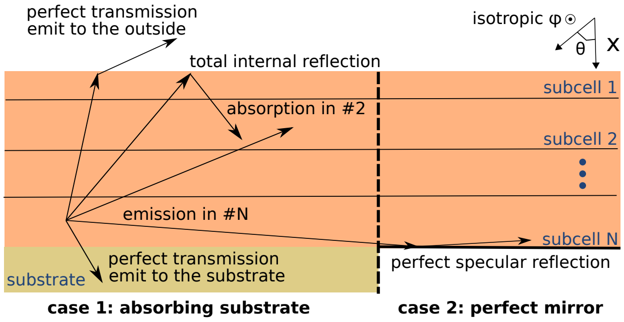

Fig. 2: Ray tracing between junctions to take into account luminescent coupling effects following an emission event in subcell N. Photons reaching the air-cell interface at an angle less than the critical angle are reflected; all others are transmitted. With a substrate, photons reaching the substrate are considered lost.

two-pass absorption matching are computed numerically.

III. MULTIJUNCTION DETAILED BALANCE EFFICIENCY

The thermodynamic efficiency limit of a PV device can be calculated using the detailed balance formalism. We extend Green's detailed balance theory for single-junction monochromatic PV conversion [3] to include effects of thermalization loss and multiple junctions including luminescent coupling and photon-recycling. We make the standard detailed balance assumptions that one photon creates one electron-hole pair and the emission rate in each junction is determined by the modified Planck spectrum, which depends on that junction's quasi-Fermi level splitting, μ_i [6]. We assume that μ_i is uniform across each junction. We also assume that all recombination events are radiative and there is no series resistance loss, in order to calculate the limiting efficiency. With these assumptions, the current in each junction can be written as [7]:

$$J_i = \dot{N}_i^{in} - \dot{N}_i^{rad}\left(\mu_i\right) \tag{1}$$

where $\dot{N}_i^{in}$ is the rate of photon absorption in junction i and $\dot{N}_i^{rad}\left(\mu_i\right) \propto \int_{E_g}^{\infty} E^2/\left[\left(E-\mu_i\right)/kT-1\right]$ is the rate of photon emission in junction i. $\dot{N}_i^{in}$ includes both photons from the external source, and photons emitted from other layers. This rate of photon absorption is calculated using a ray-tracing method, demonstrated in Figure 2. We assume perfect tunnel diodes with no reflections, absorption or series resistance. Equating J_i in each junction allows us to solve for a set of μ_i. The efficiency of the entire device is then $\eta = \frac{J\sum_i \mu_i}{P_s}$, where P_s is the input power.

Using this model, we predict the maximum efficiency as a function of number of junctions for the two proposed structures. In the calculations, we use a bandgap of 0.864 eV, which is measured on a test single-juncton InAlGaAs device using spectroscopic ellipsometry, and is confirmed with quantum efficiency measurements. For external flux, we use the measured emission spectrum of our DILAS fiber-coupled infrared laser. The spectrum centers at 1319 nm (0.940 eV) with a linewidth of 8.9 nm and operates at a maximum power of 14.7 W.

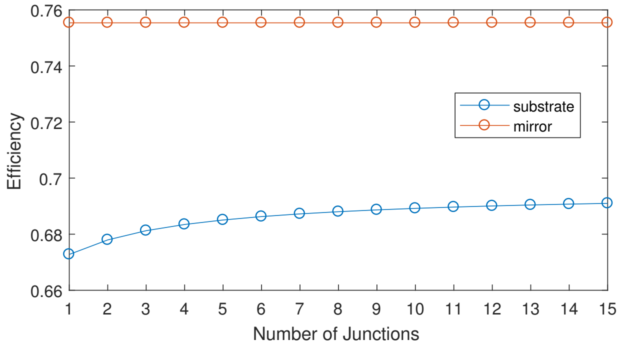

Fig. 3: Detailed balance efficiency as a function of number of junctions in the cell.

Figure 3 shows detailed balance efficiency as a function of number of junctions for each of the two cases. In the case of a substrate, the limiting efficiency is approximately 69% for a 15-junction device. In this case, efficiency increases with number of junctions, even though no series-resistance effects are included in this model. On the other hand, an addition of a perfect mirror at the back increases the efficiency by >6% absolute to more than 75% due to photon-recycling effects. In this case, the efficiency increases minimally with number of junctions, within 10^{-5}% absolute.

In conclusion, a back reflector not only reduces the total amount of material by half, but also significantly increases the limiting efficiency.

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