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Scientific Research

Light Soaking Induced Increase in Conversion Efficiency in Solar Cells Based on $In(OH)_xS_y/Pb(OH)_xS_y$

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ABSTRACT

Light soaking characterization on complete SnO_2:F/TiO_2/$In(OH)_xS_y$/$Pb(OH)_xS_y$/PEDOT:PSS/Au, eta solar cell structure as well as on devices which do not include one or both TiO_2 and/or PEDOT:PSS layers has been conducted. Additionally, studies of SnO_2:F/$In(OH)_xS_y$/$Pb(OH)_xS_y$/PEDOT:PSS/Au solar cell have been performed. The power conversion efficiency and the short circuit current density have been found to increase with light soaking duration by a factor of about 1.6 - 2.7 and 2.1 - 3, respectively. The increase in these two parameters has been attributed to the filling up of trap states and/or charge-discharge of deep levels found in $In(OH)_xS_y$. These effects take place at almost fill factor and open circuit voltage being unaffected by the light soaking effects.

Keywords: Eta Solar Cell; Light Soaking; Conversion Efficiency; TiO_2; $In(OH)_xS_y$; $Pb(OH)_xS_y$

1. Introduction

Extremely thin absorber (eta) solar cell is a photovoltaic device proposed a few years ago [1,2] and is modeled on dye sensitized solar cell concept [3,4]. Unlike its dye sensitized solar cell counterpart where light absorption occurs in a monolayer of organic/or metalorganic dye molecule, in eta solar cell, the dye is replaced with a solid state inorganic sensitizer which is sandwiched between two wide band gap semiconductor materials, one n-type and the other one p-type. The photovoltaic effect of this type of device is due to charge carrier injection from the sensitizer material.

Since the eta concept inception, the conversion efficiency of this type of device has remained very low. A number of techniques have been proposed over the years towards improvement of the solar cell characteristics of this type of device. Some of the methods which have successfully been used so far include: insertion of a very thin insulating oxide to act as a tunneling or as passivation layer material such as MgO, Al_2O_3·ZnO, ZrO_2, and Y_2O_3 [4,5], engineering of the absorber material [6-9], use of buffer layers as recombination barrier [6,7,9], and recently use of ultra-thin devices whose charge transport is anticipated to be within solar wavelength [10,11]. In this work, we report on light soaking technique as one of the method for improving the conversion efficiency of the eta solar cell and other devices, by prolonged light exposure.

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2. Experimental Details

2.1. Sample Preparation

The solar cells samples were prepared on glass substrates coated with 15 Ω/ν sheet resistance SnO_2:F from Förschungzentrum Jüllich. Different solar cell structures were produced by coating thin films via various techniques with the following procedures being followed for a full solar cell structure of the type SnO_2:F/TiO_2/$In(OH)_xS_y$/$Pb(OH)_xS_y$/PEDOT:PSS/Au: A 2 μm thick titanium dioxide, TiO_2, thin film was coated by sol-gel technique at SgLux GmbH company using tetra-isopropyl orthotitanate ($Ti(C_3H_6OH)_4$) mixed with commercial grade solution of isopropanol ($CH_3CH(OH)CH_3$) as precursors. On top of TiO_2, an 80 nm thick indium hydroxyl sulphide, $In(OH)_xS_y$, was deposited at 70˚C for 30 minutes by chemical bath deposition (CBD) technique using

aqueous solution containing $InCl_3$ (0.025 M), thioacemide (0.1 M), and HCl (0.005 M), and repeated 3 times, after every cycle the sample was rinsed in distilled water before the next coating, following procedure as reported by Bayon *et al*. [6,7,12] and Musembi *et al*. [12]. the CBD method was also used in depositing $Pb(OH)_xS_y$ using aqueous solution containing $Pb(CH_3OOH)_2$ (0.05 M), NaOH (0.2 M), triethanolamine (0.05 M), and thiourea (0.05 M) at 40˚C for 10 minutes using a procedure as reported elsewhere by Gavrilov *et al*. [13]. The last layer, an undiluted poly(3,4)ethylenedioxythiophe doped with polystyrene sulfonate acid, type Baytron PH from Bayer GmbH, was then spin coated ontop of $Pb(OH)_xS_y$. The front and back contacts of the solar cell were coated by resistive vacuum evaporation of Au wire, using a special mask which gave solar cells of 0.126 cm^2 areas. The other solar cell structures were realized by eliminating a layer from the complete structure and these included: SnO_2:F/$In(OH)_xS_y/Pb(OH)_xS_y$/Au, SnO_2:F/$In(OH)_xS_y/Pb(OH)_xS_y$/PEDOT:PSS/Au and SnO_2:F/TiO_2/$In(OH)_xS_y/Pb(OH)_xS_y$/Au.

2.2. Characterization of the Samples

The current density-voltage (J-U) characteristics measurement were performed at room temperature using a DC source meter type Keithley™ 237 high voltage source unit connected to an Hewlett-Packard™ 34401A multimeter. A halogen lamp from General Electric™ (120 V, 300 W) type L268 was used as light source of the calibrated solar simulator (AM 1.5, 100 mW/cm^2 = 1 sun).

The analysis of soaking effects were done by first taking J-U characteristics of as-prepared solar cell, and then leaving it exposed to the solar simulator light for 180 minutes continuous. During this duration, the soaking effects were being monitored by taking J-U measurements after interval of 20 minutes.

External quantum efficiency measurements were used to study degradation of the solar cell after 180 minutes soaking effects for one of the solar cell structures. The analysis was done for as-prepared solar cell, then after 180 minutes light soaking, subsequently after 24 hours and 96 hours. One week old cell was also analyzed to study soaking effects.

3. Results and Discussion

3.1. J-U Characterization during Soaking

The performance of SnO_2:F/TiO_2/$In(OH)_xS_y/Pb(OH)_xS_y$/Au eta solar cell soaked in solar simulator light for 120 minutes is shown in **Figure 1**. Its photovoltaic parameters, fill factor (FF), open circuit voltage (U_{oc}) and efficiency (eff) as a function of light soaking duration in minutes are given. The solar cell showed an exponential increase in conversion efficiency, from eff = 0.13% for as-prepared solar cell to as high as eff = 0.33% representing increment factor of 2.5, while on the other hand, short-circuit current density showed an increment by a factor of 2.8 from J_{sc} = 2.1 mA/cm^2 to 5.9 mA/cm^2.

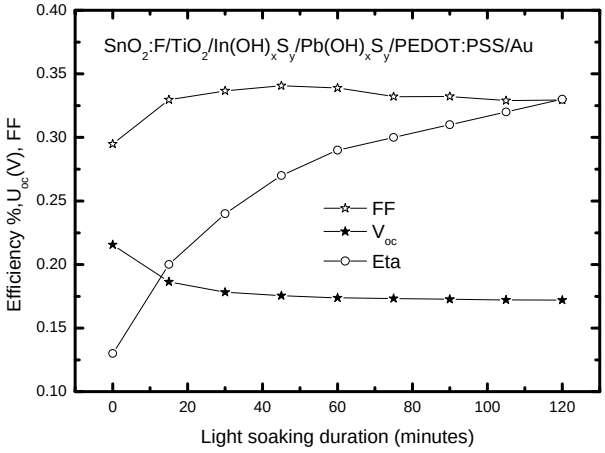

Figure 1. Light soaking characteristics for SnO_2:F/TiO_2/ $In(OH)_xS_y/Pb(OH)_xS_y$/PEDOT:PSS/Au solar cell.

The effect of light soaking for similar device but without TiO_2 window layer is shown in **Figure 2**. The SnO_2:F/$In(OH)_xS_y/Pb(OH)_xS_y$/PEDOT:PSS/Au solar cell device, after soaking for extended duration of 180 minutes, the conversion efficiency increased from 0.29% to 0.78% representing an increment factor of 2.7, while short circuit current density reached a maximum value of J_{sc} = 10.1 mA/cm^2 from a minimum value of J_{sc} = 3.4 mA/cm^2 for as-prepared solar cell for the same duration representing an increment factor of about 3. The U_{oc} of this type of device was observed to decrease with soaking duration similar to that of complete eta solar cell shown in **Figure 1**, while fill factor, there was a slight increment and after 30 minutes of soaking, it started to decrease for the rest of duration the sample was soaked.

The next experiment tested on the effect of light soaking on a reduced type solar cell which has either the polymer material removed or both TiO_2 and the polymer material. The fill factor and open circuit voltage of SnO_2: F/TiO_2/$In(OH)_xS_y/Pb(OH)_xS_y$/Au solar cell both showed a decrement of between 0.01 and 0.03 respectively, as shown in **Figure 3**. The short circuit current density, J_{sc} and conversion efficiency, (eff) both increased by a factor of about 2.1 and 1.6 respectively after soaking the solar cell for 180 minutes. The initial value was J_{sc} = 4.7 mA/cm^2 for as-prepared solar cell and increased to J_{sc} = 9.9 mA/cm^2 after light soaking, while the conversion efficiency reached 0.56% from the initial value of 0.36%.

Lastly, the solar cell device to be studied was the simplest p-n heterostructure consisting of SnO_2:F/$In(OH)_xS_y$/ $Pb(OH)_xS_y$/Au, this is shown in **Figure 4**.

For this type of device in **Figure 4**, the open circuit voltage and fill factor behaviour was similar to that

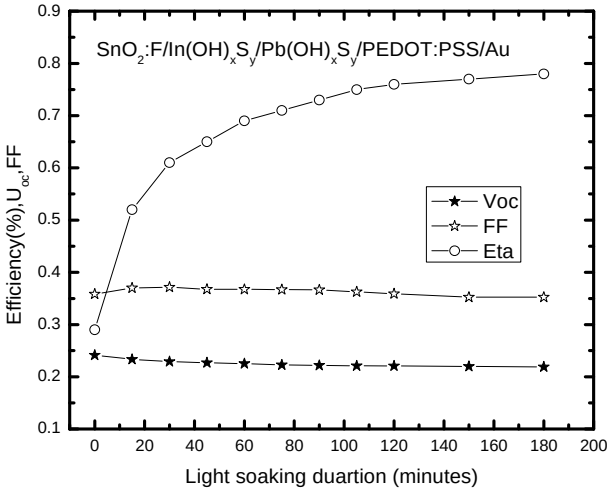

Figure 2. Light soaking characteristics for SnO_2:F/$In(OH)_xS_y$/ PEDOT:PSS/Au solar cell.

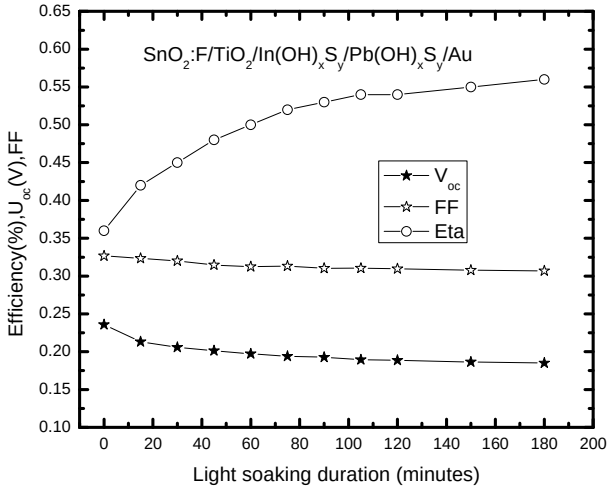

Figure 3. Light soaking characteristics for SnO_2:F/TiO_2/ $In(OH)_xS_y$/$Pb(OH)_xS_y$/Au solar cell.

displayed by the sample given in **Figure 3**. That is, there was a general decrease with increasing light soaking duration. On the other hand, conversion efficiency and short circuit-current density changed by a factor of about 2.0 and 2.5 respectively. The final value of J_{sc} = 14.3 mA/cm^2 after light soaking for 180 minutes from an initial value of about J_{sc} = 5.7 mA/cm^2, while the conversion efficiency, the value for as-prepared solar cell was 0.60% and increased up to 1.19% after light soaking for 180 minutes.

From the preliminary results of light soaking experiments for full eta solar cell with buffer layer and simplified solar cell devices realized by eliminating some layers, it can be deduce that light soaking improves the solar cell overall conversion efficiency and short circuit current density. The parameters have been observed to improve with light soaking duration since after 180 minutes

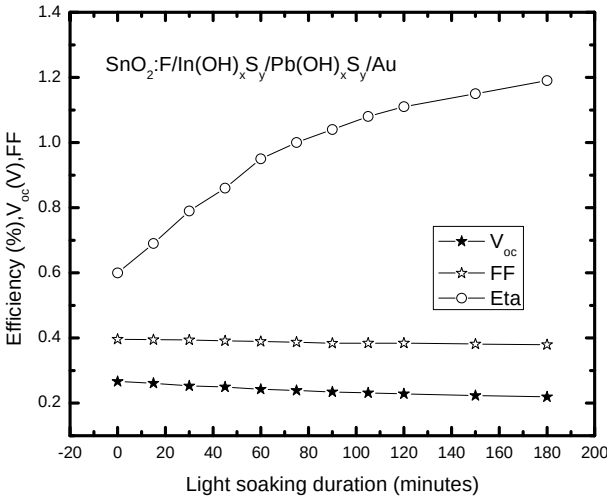

Figure 4. Light soaking characteristics for SnO_2:F/$In(OH)_xS_y$/ $Pb(OH)_xS_y$/Au solar cell.

of samples exposure to solar simulator light, both efficiency and short circuit current density increased by a factor of between ~2 and 3 which is a very big change given the initial values of as-prepared solar cells. Clearly, it can be observed that all samples containing PEDOT: PSS as a hole conductor had the highest gain in overall conversion efficiency of the solar cell, compare devices **A** (SnO_2:F/TiO_2/$In(OH)_xS_y$/$Pb(OH)_xS_y$/PEDOT:PSS/Au) and **C** (SnO_2:F/TiO_2/$In(OH)_xS_y$/$Pb(OH)_xS_y$/Au in **Table 1** against devices **B** (SnO_2:F/$(OH)_xS_y$/$Pb(OH)_xS_y$/PEDOT: PSS/Au) and **D** (SnO_2:F/$In(OH)_xS_y$/$Pb(OH)_xS_y$/Au).

Another interesting observation is that, when TiO_2 layer is removed for samples of similar structure, that is devices containing PEDOT:PSS layer and those without, as shown by pairs of samples **A**, **C** and **B**, **D**; the absence of TiO_2 layer in both cases results into increment of short circuit current density and therefore the overall conversion efficiency. This shows that PEDOT:PSS acts as a protective layer to the $Pb(OH)_xS_y$ and prevents Au back contact from diffusing into the bulk of the material thus increasing surface states leading to higher recombination rate. On the other hand, although TiO_2 improves the optoelectrical properties of the respective solar cell because of its highly structured porous surface, its presence together with the $In(OH)_xS_y$ layer material, tends to increase the space charge region such that recombination loss can set in, but when TiO_2 is absent the distant of the charge travels is shorter and thus resulting to higher short circuit-current density and conversion efficiency as a result for as-prepared sample. On the other hand, the increment in conversion efficiency of the solar cells can be attributed to the filling of trap states hence resulting to less recombination losses and this translates to higher conversion short circuit current density and conversion efficiency as the sample is soaked under illumination.

Table 1. Changes in solar cell parameters of eta solar cell and that of simplified devices, d represents decrease in value, i-d represents increase then decrease in value.

device PV	J_{sc}	V_{oc}	FF	Eff
A	2.8	d	i-d	2.5
B	2.1	d	d	1.6
C	3.0	d	i-d	2.7
D	2.5	d	d	2.0

3.2. Degradation Studies after Light Soaking

Degradation studies after soaking was performed for a device of similar structure to solar cell device **C** shown in **Table 1**. The external quantum efficiency first was measured before light soaking and found to be about 17% at peak wavelength of about λ = 505 nm for as-prepared sample, this is as shown in **Figure 5**. Then the sample was exposed to solar simulator light for 180 minutes (3 hours), the external quantum efficiency was again measured and found to have increased to 25% at peak wavelength of about λ = 514 nm.

Henceforth, the sample was kept in inert gas filled chamber, and subsequent measurement were taken after 24 hours and 96 hours and found external quantum efficiency to have dropped to 23% (at peak wavelength of about λ = 513 nm) and 21% (at peak wavelength of about λ = 510 nm) respectively. The drop in external quantum efficiency after soaking can be attributed to charge-discharge effects of the deep levels present in $In(OH)_xS_y$ layer as reported elsewhere in the literature [9,13]. The samples have also been found to be resilient to light soaking (figure not shown), 1 week old sample was found to regain both short circuit current density and conversion efficiency by a factor of about 1.3 and 1.2 respectively.

4. Conclusion

Light soaking has been performed for the first time in eta solar cell device. The effects of light soaking on eta solar cell with the following layers: SnO_2:F/TiO_2/ $In(OH)_xS_y/Pb(OH)_xS_y$/PEDOT:PSS/Au and other reduced devices derived from this structure, have been investigated. It has been found that conversion efficiency and short circuit current density can be increased by light soaking in solar cell devices having $In(OH)_xS_y/Pb(OH)_xS_y$ heterostructure. The increase in efficiency and short circuit current density has been attributed to the filling of trap states and/or charge-discharge of deep levels in $In(OH)_xS_y$. The question about the specific layer/s or interface responsible for the observed light soaking effects is still not completely clear and therefore necessitates further investigation.

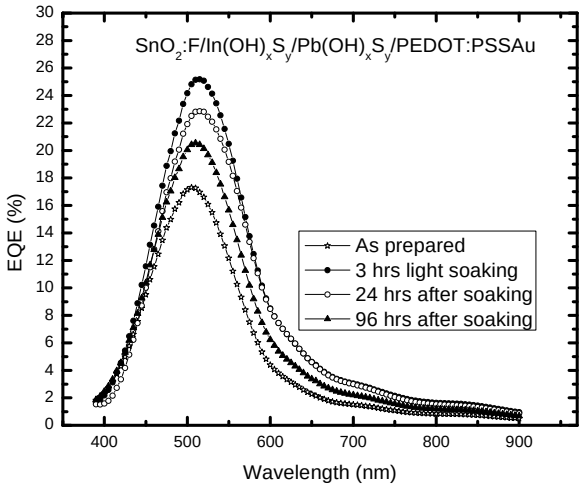

Figure 5. Degradation studies using external quantum quantum efficiency for SnO_2:F/$In(OH)_xS_y/Pb(OH)_xS_y$/PEDOT: PSS/Au solar cell.

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