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A figure of merit to evaluate transparent conductor oxides for solar cells using photonic flux density

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ABSTRACT

We report an alternative method to evaluate transparent conductor oxides (TCO) from their photonic flux density (PFD(hυ)) to be used in solar cells. From the transmittance spectrum (T(hυ)) in the visible region, we calculate the PFD(hυ) and the solar photon flux-weighted transmittance (T_{SW}) of one specific TCO with potential application in solar cells. The photo-current density (J_{PH}) in mA/cm^2 of one specific TCO when exposed to white light is evaluated when PFD(hυ) is integrated over the whole solar electromagnetic spectrum. Finally, we define a figure of merit as J_{PH} over the TCO film sheet resistance to find the best equilibrium between the transmission and its electrical resistance. To carry out this work, a bibliographical search of investigations about development of TCOs was extensively made to evaluate its T(hυ), T_{SW}, PFD(hυ), J_{PH} and the figure of merit that we propose. From our results, we consider that the proposed method is a good tool for a fine comparison of transparent conductive films in solar cell development.

1. Introduction

In recent years, the discovery of several transparent conducting oxides (TCOs) of n-type has been reported. This renewed interest has arisen as a result of their applications as opto-electronic transparent devices and in the solar cell industry [1–3]. Common to all TCOs applications is the need to optimize the electrical and optical coating parameters. Depending on the type of device, the requirements as a transparent electrode, the optical transmission and the electrical conduction of the electrodes should exceed certain minimum values. Ideally, both parameters should be as large as possible, but their inter-relationship usually excludes the simultaneous achievement of both criteria [4]. In solar cells, the TCOs are used like front contact before the deposition of the window layer. Those TCOs must have a specific electrical and optical characteristic that enhances the transmission of the solar light on the material absorbent film.

The most studied TCOs in CdTe based solar cells are: SnO_2:F, ZnO:Al, In_2O_3:Sn and Cd_2SnO_4. These metallic oxides exhibit a very high n-type conductivity associated with an outstanding optical transparency, around 90% in visible and NIR radiation. These TCOs are generally semiconductor materials near to its degenerate state with a free carrier concentration from 10^{18} cm^{-3} to 10^{20} cm^{-3} with a resistivity $< 10^{-4}$ Ω-cm and mobility around 50 cm^2-V s. In order to use TCOs in solar cells, the sheet resistance (R_{Sheet}) must be ~10 Ω/sq., this implicates TCOs with thickness ~ 100 nm or more [2].

The most widely figure of merit used to compare the performance of TCOs is the figure of merit of Haacke [5], where the optical transmission is selected by taking its average around 500 nm (near solar spectrum maximum). In this context, the 500 nm region is an important one, but the use of a narrow band is not representative of the whole ability of the film to transmit photons.

The transmittance spectrum in the visible region (T(hυ)) is very important because it provides information of the photonic flux density (PFD(hυ)) and of the solar photon flux-weighted transmittance (T_{SW}). If the T(hυ) is integrated over the whole solar spectrum, it is possible to evaluate the photo-current density (J_{PH}) that a TCO will produce when it is exposed to white light, and then evaluate this integral PFD (IPF) over the R_{Sheet} of the film in order to find the best equilibrium between the transmission and resistance properties of those TCOs.

Consequently, instead of using a narrow band transmittance, we propose the use of the air mass 1.5 global (AM1.5g) photon flux spectrum to analyze the maximum photo-current density $(J_{PH})_{max}$ for a particular TCO. Where the $(J_{PH})_{max}$ must be obtained in the range of solar

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Table 1
Photonic characterization of TCOs.

TCOs characteristics					Haacke characterization		Photonic characterization		
Ref.	Material	Thickness	R_{Sheet}	Band Gap	T(500 nm)	Fig. Mer.	$(J_{PH})_{max}$		Fig. Mer.
		nm	Ω/sq.	eV	%	Ohm^{-1}	$mA\ cm^{-2}$	%	$mA\ cm^{-2}\ Ohm^{-1}$
[11]Fig. 10	$In_4Sn_3O_{12}$	500 nm*	4.3	3.50	76.291	0.0155	24.15	89.0**	5.61
		320 nm*	8.8	3.38	89.476	0.0374	24.06	89.6**	2.73
		140 nm*	32.0	3.44	91.417	0.0127	26.29	97.9**	0.82
		100 nm*	52.1	4.00	88.629	0.0057	24.92	92.8**	0.48
		70 nm*	86.5	3.95	81.258	0.0014	24.89	92.7**	0.29
[12]Fig. 4	$In_4Sn_3O_{12}$	330 nm*	13.1	3.78	77.47	0.0059	25.12	93.6**	1.92
		580 nm*	15.1	3.62	86.06	0.0147	22.60	84.2**	1.50
[13]Fig. 1	CTO	150 nm	11.9*	3.67	90.20	0.0299	25.53	95.1**	2.15
	ITO	135 nm	12.0*	3.79	88.12	0.0235	19.97	74.4**	1.66
	SnO_2	481 nm	9.7*	3.67	76.37	0.0069	18.76	69.9**	1.93
Tcurv.	CEC020B	–	20*	3.65	88.00	0.0139	24.79	92.4***	2.45
		330	16.7	3.51	89.89	0.0206	25.61	95.4**	1.51
		360	27.8	3.35	85.90	0.0079	26.13	97.3**	0.93
[14]Fig. 5	ZnO:Va	380	13.9	3.44	88.30	0.0207	26.02	96.9**	1.85

* Reported by author. In another case, estimated from author data.
** Of $(J_{ph})_{max} = 26.85\ mA\ cm^{-2}$ (ideal TCO on Corning 7059 glass).
*** Of $(J_{ph})_{max} = 26.82\ mA\ cm^{-2}$ (ideal TCO on PräzisionsGlas&Optik Float glass).

energy spectrum of absorber material band gap (E_G) to TCO band gap (E_{TCO}) used as the front contact in a solar cell. Then, the proposed figure of merit is defined by the ratio between $(J_{PH})_{max}$ and R_{Sheet}.

2. TCO characterization

In solar cells, a semiconductor PN junction converts radiation energy into electrical energy. The $(J_{PH})_{max}$ that the junction can provide to an external load is related to the number of photons with energy above E_G which cross the TCO used normally as transparent front contact of solar cells, for example TCO/CdS/CdTe.

The integral photonic flux (IPF), which represents the maximum photocurrent density of an ideal cell, is defined as:

$$(J_{PH})_{max} = e \int_{E_g}^{E_{TCO}} PFD(h\nu)\, d(h\nu) \quad (1)$$

where e is the electron charge, E_{TCO} is the band gap energy of the TCO layer, and E_G is the band gap energy of the absorption layer, $PFD(h\nu)$ is the photon flux density of energy $h\nu$. $PFD(h\nu)$ is defined as:

$$PFD(h\nu) = \frac{I_S(h\nu)\, T(h\nu)}{h\nu} \quad (2)$$

where $I_S(h\upsilon)$ is the irradiance of the standard AM1.5g solar spectra global and $T(h\upsilon)$ the transmittance spectrum of a particular TCO in the wavelength range 300–1200 nm. In thin film solar cells the figure of merit for a TCO performance is defined as the ratio of the electrical conductivity to the optical absorption coefficient of the film. The most widely figure of merit used, the one proposed by Haacke [6] defined by:

$$\varphi = \frac{T^{10}}{R_{Sheet}} \quad (3)$$

where T is the optical transmission average around 500 nm (near the solar spectrum maximum) and R_{Sheet} the sheet resistance. The Haacke's figure of merit has been used by many authors for transparent conducting film characterization in solar cell development [7–9]. The 500 nm region is important, but the use of such narrow band in the figure of merit definition is not representative of the whole ability of the film to transmit photons. Additionally, recent work on CdS/CdTe solar cells points out the need of increasing the absorption of photons with different energies to be converted into photocurrent [10]. Therefore, it is important to have a better criterion to describe the cell performance at a wider spectrum range.

Thereafter, instead of the transmittance near 500 nm and a narrow band, we use the $(J_{PH})_{max}$ of a particular TCO to define a figure of merit as:

$$\Theta_{PH} = \frac{(J_{PH})_{max}}{R_{Sheet}}. \quad (4)$$

This equation does not include any exponent, as the Haake's one, because $(J_{PH})_{max}$ has defined physical units and meaning. This figure of merit offers a better insight into the contradictory roll of optical and electrical properties of TCO in solar cell applications, since the ideal cell photocurrent is determined by the numerator of Eq. 4, while the Joule-effect losses are proportional to the denominator. Furthermore, it represents a numerical physically based value, easy to compute using standard measurements in TCO.