Influence of Texture Depth and Layer Thickness of Crater-like Textured ZnO on the Efficiency of Thin Film Solar Cell

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***Abstract*—The application of zinc oxide (ZnO) thin film as transparent conductive oxide (TCO) layer in thin film solar cells (TFSC) has high potential because of the various advantages of ZnO over other TCO materials. In this paper, the influence of the crater-like texture of ZnO layer on the optical properties and performance of the solar cell is investigated. Using the commercial simulation software RSoft Fullwave and RSoft Solar Cell Utility, we designed solar cells with crater-like textured ZnO layers as TCO and varied the crater depth along with overall ZnO thickness. It was found that, the crater-like textured ZnO layer provides better light trapping with increased crater depth as well as higher conversion efficiency near the IR region in the solar spectrum.**

***Index Terms*—Thin Film Solar Cells (TFSC), Transparent Conductive Oxide (TCO), Zinc Oxide (ZnO), front electrode, crater type texture, light trapping, Nano-materials, RSoft fullwave simulation**

I. Introduction

Zinc Oxide (ZnO) thin film is gradually becoming very important for its potential application as Transparent Conductive Oxide (TCO) in solar cells, LEDs, flat panel displays, electro-chromic windows, and gas sensors. The commercial TCO material at present is Indium Tin Oxide (ITO) which is popular for its low dc electrical resistivity (10-4) and high visible transmittance (80%) [1], [2]. But the element Indium makes ITO expensive due to its scarcity in nature. Search for an alternative TCO material has been going on over the last decade. ZnO has received attention due to its abundance in nature, non-toxicity and good stability in hydrogen plasma process.

In this paper, we investigated the optical effect of texture and thickness of ZnO thin film TCO on the performance of solar cells. We selected crater-like textured ZnO surfaces for this study. The solar cell simulation was performed using RSoft simulation software. Thin films with varying thicknesses of textures were applied as the front electrode of the solar cell. The conversion rate of the cells were investigated using RSoft Solar Cell Utility and their quantum efficiencies analyzed with respect to the wavelength range of 300 nm to 1200 nm.

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II. Background

Thin film solar cells can lower the material cost of Photo-Voltaic (PV) systems significantly, but with compromised efficiency, as the number of photons absorbed in the active region (Si) goes down. To enhance the light absorption in the active region (Si) of TFSCs, effective light trapping scheme is necessary. Textured Transparent Conductive Oxides (TCO), applied as front electrodes in TFSCs, can help achieve improved light trapping through high transparency and scattering of light inside the active region. A suitable texture can efficiently scatter and effectively elongate the path length of light in the active region. ZnO is an excellent candidate as a TCO material with its intrinsic n-type semiconductor nature and a wide bandgap of 3.37 eV [3]. Besides the light trapping effect, the texture and thickness of ZnO thin film has a direct effect on the optical transmission and the conductivity of ZnO layer when applied as a TCO. Increased thickness of the film obviously decreases the optical transmission, but also reduces the sheet resistance [4].

III. Device Design

For our study, we followed the features of crater type textured ZnO surface from the work of Berginski *et al* [5]. In that work, ZnO thin films were prepared from RF magnetron sputtering followed by wet chemical etching. For low doping and high substrate temperature, a film surface almost entirely filled with equal sized craters was developed. The crater-like surface topography of ZnO had lateral length scales of 1 to 3 μm and depths of about 150 to 400 nm. The after-etching thickness of the film was about 650 nm. The Si layer thickness was 1μm.

We used Rsoft CAD to design a solar cell with the textured ZnO thin film as TCO. The cross-sectional view of a reference thin film solar cell is shown in Fig. 1. Incident light first passes through the glass (SiO_2) layer and then crosses the transparent front contact layer of ZnO. The photons arriving in the active region, the Si layer, are used to generate the electron-hole (e-h) pairs to produce PV current which can be collected from the back contact (Al) and the front contact (ZnO).

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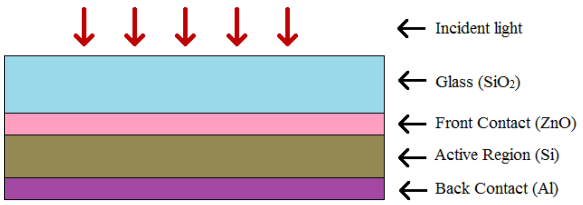


Figure 1. Cross-sectional diagram of solar cell with its different layers as modeled in our design.

In our simulation design, we take crater width as 1 µm. We start with the ZnO layer thickness of 150 nm and crater depth of 120 nm for our first cell design. Then we gradually increase the ZnO thickness and crater depth in several steps and observe the absorption in Si layer and solar cell performance.

Table I outlines the basic device parameters for the solar cell in our designs.

TABLE I: BASIC DEVICE PARAMETERS FOR THE SOLAR CELL

Device length	12 [µm]
Thickness of glass (SiO_2) cover	500 [nm]
ZnO layer thickness*	150 [nm] (initial)
Thickness of the amorphous Si layer	1 [µm]

*According to quarter wavelength design rule, considering free space wavelength as 600 nm

IV. SIMULATION OF SOLAR CELLS WITH TEXTURED ZNO THIN FILMS APPLIED AS TCO LAYER

Fig. 2 shows the solar cell design in RSoft CAD window for ZnO thickness t_{ZnO} = 150 nm (bottom to peak). The crater depth in this case is 120 nm and crater width is 1µm.

A. Excitation Field

Now we apply an excitation field to illuminate the solar cell. To mimic direct sunlight, we used a power density of 1 kW/m^2. The polarization of the incident light is Transverse Electric (TE), e.g., electric field is perpendicular to the direction of propagation from left to right along the x-axis.

The excitation field is shown in Fig. 2 as an orange colored bar having an arrow directed towards the solar cell. This indicates the direction of the incident light falling normally on the top of the cell.

B. Monitors

We apply a monitor (in green) in Fig. 2, which collects data in the absorption layer of the solar cell and is able to measure the absorbed part of incident light on the cell. The green rectangle in the Si layer is the monitor used to measure the absorbed spectrum of incident light in the Si layer. From the photon count in the selected area of the monitor, the quantum efficiency is calculated over the solar spectrum by the solar cell utility application. The observed field in the monitor is E_y.

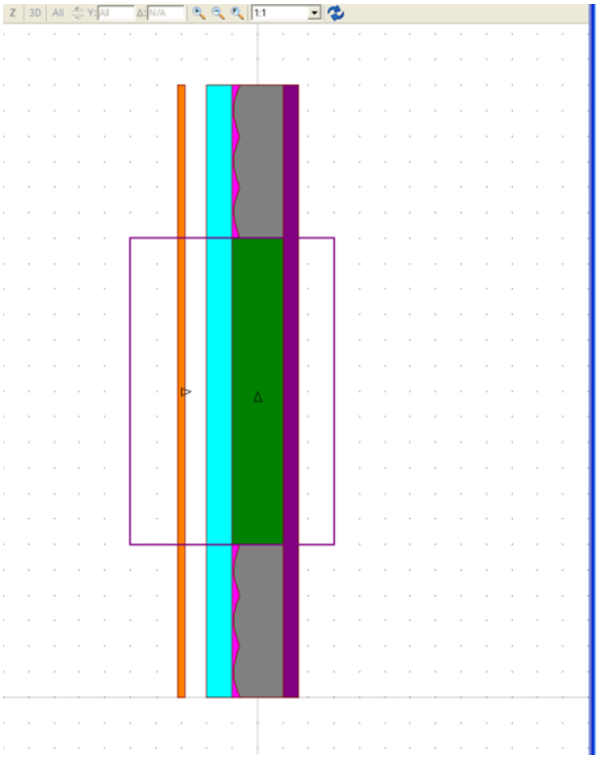


Figure 2. Simulation setup for solar cell having ZnO layer of crater type texture and 150nm thickness

We used CAD Grid size of 0.5 µm, solar cell length and the excitation field length of 12 µm and monitor length of 6µm.

C. Simulation Parameters

The default parameters in the Solar Cell Utility match the AM 1.5 criteria. A default solar spectrum of 300 nm to 1200 nm is chosen to mimic sunlight. The refractive index of ZnO was taken as n = 1.99 [6]. For the lower limit of the spectrum, free space wavelength, λ_{free} = 300 nm. After entering the ZnO layer, the wavelength becomes: $\lambda_{material}$ = 300 nm/n = 300 nm/ 1.99 = 150.754 nm.

For stability requirement, the FDTD spatial grid size should be < ($\lambda_{material}$/ 10). That is, grid size should be <15 nm. To ensure that the grid resolution is small enough, the grid points making up the mesh are set to 10 nm, which is smaller than the smallest crater depth.

The open circuit voltage is set to a constant 0.7824 V.

The basic equations and solar cell parameters used by the Solar Cell Utility are listed in Table II.

TABLE II: BASIC PARAMETERS AND EQUATIONS OF SOLAR CELLS USED FOR THIS SIMULATION [7]

External quantum efficiency (EQE) at a certain wavelength λ, $EQE(\lambda) = n_{e\text{-}h}(\lambda)/ n_s(\lambda)$	Here, $n_{e\text{-}h}(\lambda)$ = Number of electron-hole pairs generated at wavelength λ and collected by electrodes, $n_s(\lambda) = S(\lambda)/ E(\lambda)$ = The total number of incident photons at a certain wavelength λ, $E(\lambda) = h\nu = h(c/\lambda)$ [eV]= Single photon energy at a certain wavelength λ, $S(\lambda)$ [W/m^2. Nm] = Incident spectrum, which refers to energy density per unit wavelength.

Short circuit current density, $J_{SC} = eN_{e\text{-}h}$ [A/m^2].	Here, $N_{e\text{-}h}$ =, $N_{e\text{-}h}$ (λ) dλ = The total number of electron-hole pairs for the whole spectrum and collected by electrodes.
Open circuit voltage, $V_{OC} = (kT/e) \ln [(J_{SC} / J_{SO}) + 1]$ [V]	Here, e = charge of electron, k, Boltzmann's constant = 8.6173×10^{-5} [eV/K], T [K] is absolute temperature in kelvin, J_{SO} [exp(V/kT) - 1] is reverse saturation current density (A/m^2), for an ideal diode situation
Current generated in a solar cell, $J = J_{SO}$ [exp(V/kT)-1] + J_{SC} [A/m^2].	
Solar cell conversion efficiency, $\eta = J_{SC} V_{OC} \Gamma_f / P_{in}$	Here, Γ_f is the filling factor, obtained from the device J-V curve. P_{in} = the filling fac^2] = is the total incident power.

V. Simulation Results and Discussion

We start with ZnO layer thickness of 150 nm in the first design and gradually increase the ZnO thickness (t_{ZnO}) up to 500 nm in four steps. The crater depth (d_{Cr}) is increased as well.

The five cases we studied are listed in Table III.

TABLE III: ZINC OXIDE LAYER THICKNESS AND CRATER DEPTH COMBINATIONS USED IN THE SIMULATIONS

	Case 1	Case 2	Case 3	Case 4	Case 5
t_{ZnO}	150 [nm]	225 [nm]	300 [nm]	375 [nm]	500 [nm]
d_{Cr}	120 [nm]	180 [nm]	240 [nm]	300 [nm]	400 [nm]

In Fig. 3, a contour plot of E_y field is shown where the propagation direction of light is from left to right. Some scattering effect is observed near the edges of craters.

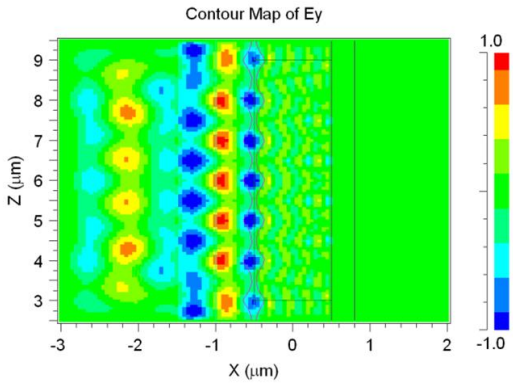


Figure 3. Contour plot for solar cell having ZnO layer of crater type texture and 150nm thickness

The simulation result in Fig. 4 showing the J-V curve of the cell gives out a conversion efficiency of 19.7799%.

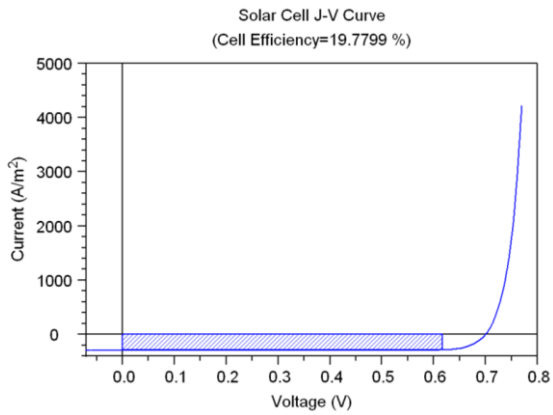


Figure 4. J-V curve for solar cell having ZnO layer of crater type texture and 150 nm thickness.

Now we gradually increase the ZnO thickness and crater depth, and perform simulations for the next four designs of solar cells. Fig. 5 shows a closed view of four cells with increasing ZnO thickness.

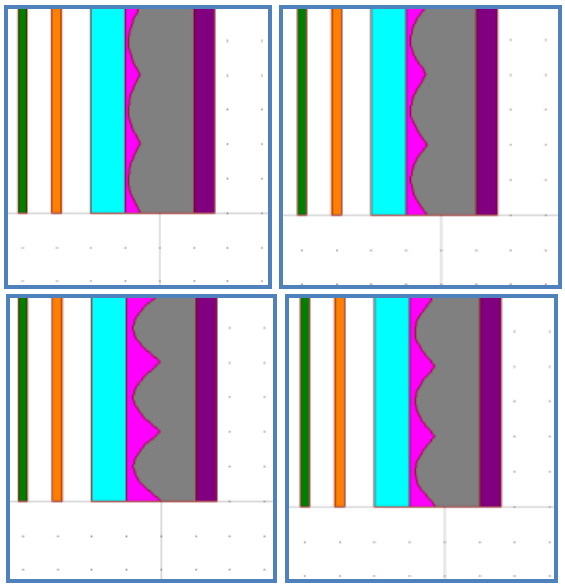
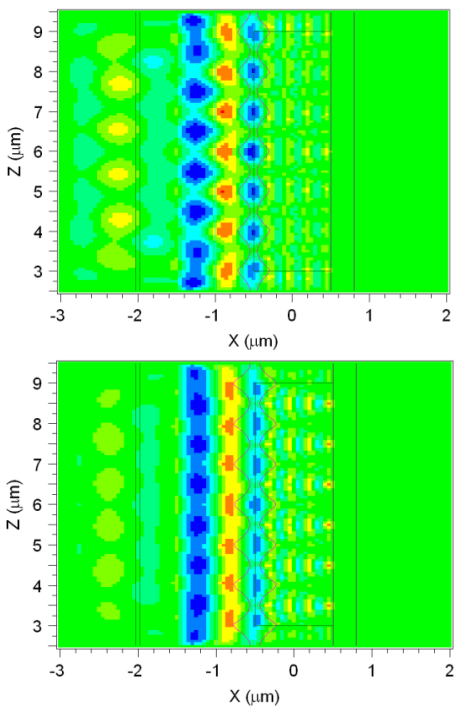


Figure 5. Close view of one end of the solar cells with crater type texture and increasing ZnO layer thickness. Clockwise from top left (t_{ZnO} and d_{Cr}): Case 2 (225 nm, 180nm); Case 3 (300 nm, 240nm); Case 4 (375 nm, 300nm); Case 5 (500 nm, 400nm).

The Ey contour maps for the respective cells are given in Fig. 6.



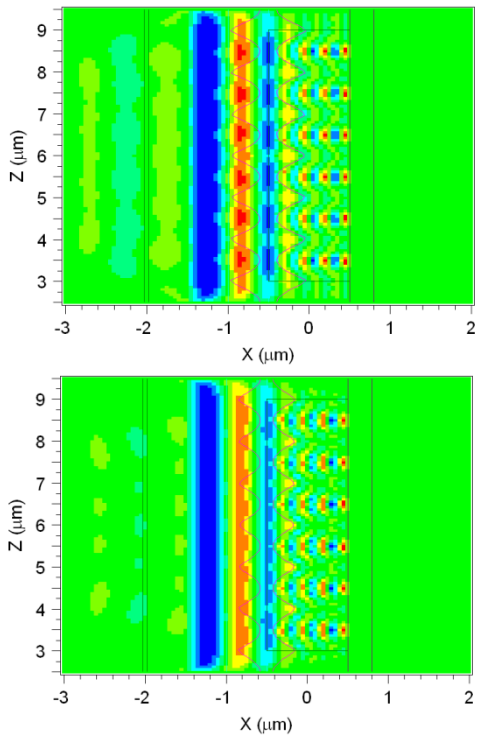


Figure 6. Simulation showing the contour map of E_y field as a function of spatial distance on the cross-sectional plane of the solar cell. From the top (t_{ZnO} and d_{Cr}): Case 2 (225 nm, 180nm); Case 3 (300 nm, 240nm); Case 4 (375 nm, 300nm); Case 5 (500 nm, 400nm).

It is observed from the contour plots in Fig. 6 that for shallower craters there is more scattering effect, whereas the deeper craters provide better light trapping effect and less reflection of light.

Hence we find that, although the transmission of light is supposed to decrease with increased ZnO thickness, the deeper craters with the thicker TCO can provide more efficient light trapping and result in increased number of absorbed photons in the Si layer.

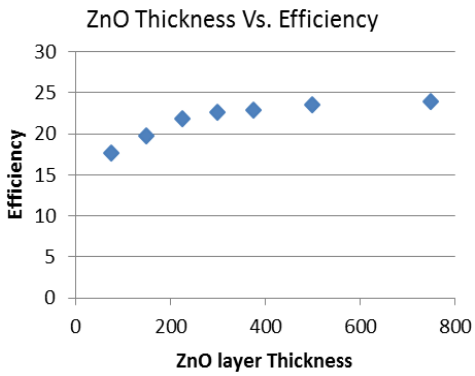


Figure 7. Comparison of conversion efficiencies of solar cells having crater-like textured ZnO layers of thicknesses 75nm, 150 nm, 225 nm, 300 nm, 375 nm, 500 nm, and 750 nm.

The plotting of J-V curve and calculation of cell current was performed for each of the solar cells. We obtained the values of conversion efficiencies for all of the solar cells. Fig. 7 shows a plot of conversion efficiency vs. ZnO thickness to compare the performance of solar cells for different thicknesses (from 75 nm to 750 nm) of crater-like textured ZnO layer. It is observed that, as we increased the ZnO layer thickness and crater depth, the conversion efficiency increased. The rise in efficiency is steep from the thickness of 75 nm to 300 nm, and it slows down after 375 nm.

Fig. 8 shows the change in quantum efficiency over the solar spectrum for varying thicknesses (from 150 nm to 500 nm) of crater type textured ZnO layer. The quantum efficiency gets improved with increasing thickness of ZnO layer. The improvement in the region of 900 nm to 1150 nm wavelength is noticeable for getting more stable values along the spectrum. In particular, the external quantum efficiency jumped significantly from 55% to 85% around the wavelength of 1100 nm where the single junction, thin film solar cells with plane surfaced TCOs show the lowest energy conversion along the range of the solar spectrum. So the most significant enhancement of efficiancy of the textured ZnO TFSC is seen near 1100 nm wavelength and energy harvesting in the infra-red (IR) region is thus increased.

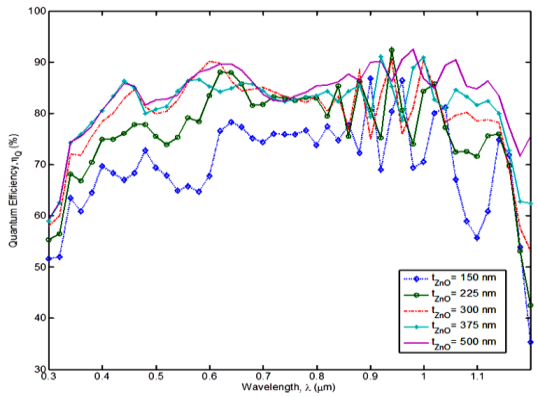


Figure 8. Quantum efficiency vs. Wavelength for five thicknesses of crater-like textured ZnO layer. The thicknesses are: 150 nm, 225 nm, 300 nm, 375 nm, and 500 nm.Conclusion and Future Work

In this paper, we compared solar cells with different ZnO layer thickness and crater depths. Simulations were performed to study the effect of texture depth and thickness on the solar cell performance. The conversion efficiencies show improvement with increased ZnO thickness in case of crater-like textured ZnO layer. External quantum efficiencies are also improved with increased ZnO thickness. Through analysis of transmission spectra we can also apply various kinds of ZnO thin films as TCOs in other applications, such as semi-transparent solar cells, displays, white LEDs and different colored LEDs. We are hopeful that with the development of low cost manufacturing processes and application of nano-materials, optimal design of textured TCOs will enhance the performance of thin film based solar cells, LEDs and displays to a great extent and also lower the cost [8]. This development in opto-IR energy harvesting using environment-friendly materials will accelerate the transition to green energy, low energy houses and sustainable architecture.

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