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THE IMPACT OF ELECTRICAL PROPERTIES OF FLUORINE-DOPED TIN OXIDE FILM ON THE PERFORMANCE OF DYE-SENSITIZED SOLAR CELLS

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Abstract
In this study, we assessed how the electrical properties of fluorine-doped tin oxide (FTO) layers affected the efficiency of dye-sensitized solar cells (DSSCs). The results demonstrated that the DSSCs' open-circuit voltage, fill factor, short-circuit current density, and energy conversion efficiency were severely affected by the electrical properties of the FTO films. The layer thickness of the FTO utilized to make dye-sensitized solar cells was around 2 micrometres. The samples were characterized using a profilometer, Hall Effect methods, and UV-visible Spectroscopy. Based on the Hall Effect measurements, the FTO has an electrical resistivity of 1.613 Ωcm, a sheet resistance of 8.065 X 103 Ω, and a conductivity of 6.200 X 10^-1 Ωcm. Consequently, the solar cell's transmittance within the visible wavelength spectrum decreases as the FTO's sheet resistance and resistivity rise with thickness. The converted efficiency of the dye-sensitized solar cells was 1.34%, 1.32%, and 2.88%, respectively, and their optical bandgaps were 2.6eV, 2.8eV, and 3.0 eV, respectively. In addition, the electrical properties of the FTO sheets had varying effects on the performance of the DSSC as a function of the components employed.

Keywords: TiO_2, electrical properties, Transmittance, FTO, Hall effect, Thickness

Introduction

Glassy tin oxide doped with fluorine is a common material for transparent electrodes in optoelectronic devices, a transparent conductive oxide (TCO). Tin dioxide (SnO_2) makes up the majority of its structure, with a trace quantity of fluorine (F) dopant integrated into the crystal lattice (Najafi & Rozati, 2017). Fluorine doping into tin dioxide changes the material's characteristics in several ways. First of all, it makes tin dioxide more electrically conductive, improving its electrical conductivity. Important for solar cells, touchscreens, screens, and LEDs (light-emitting diodes). Second, fluorine doping increases the tin oxide's stability and toughness. It increases the material's resilience to deterioration brought on by heat, moisture, and other external variables. This is crucial for applications where the material must withstand challenging circumstances or have long-term dependability (Malik et al, 2015). FTO transmits light with little absorbing or scattering since it is very transparent to visible light. For applications like display technology where light transmission through the material is necessary, this transparency is crucial. Fluorine doping level and deposition method adjustments may be made to customize the electrical and optical characteristics of FTOs. This makes it possible to tailor its performance for certain applications (Ogbonda & Amaechi, 2023). Typically, methods like spray pyrolysis, chemical vapour deposition (CVD), or sputtering are used to deposit FTO on a substrate (Rahal et al., 2014). Before its doping with fluorine, tin oxide (FTO) was extensively studied as a transparent conductive oxide (TCO) because of its wide bandgap, high optical transparency, low electrical resistivity (a few times 10^{-4} cm), and significant infrared reflectance. Its affordability, environmental robustness, and suitable electrical and optical properties make it a popular choice (Usami & Ozaki, 2001). Optoelectronic device manufacture, hybrid microelectronics, photo-thermal conversion, direct energy conversion, solar cells, and other applications utilize fluorine-doped tin oxide films (Ito et al., 2008). Many people consider films of fluorine-doped tin oxide to be a versatile material (Minami, 2000). Various deposition techniques, including sputtering, chemical vapour deposition, the sol-gel process, metal reactive evaporation in oxygen, the hydrothermal method, the ultrasonic spray pyrolysis (USP) method, the pneumatic spray pyrolysis (PSP) technique, the pulsed laser approach have all been covered in previous works (Gratzel, 2004: Banyyamin et al., 2014). When it comes to producing FTOs in large quantities, pneumatic spray pyrolysis (PSP) is the way to go (Shi & Xu, 2017).

Solar Cell

It is still a huge task to harness the power of solar energy and transform it into structures that people can use. The most prevalent way to harness solar energy is through photovoltaic devices, which convert light into electricity. Solar cells are a kind of photovoltaic technology that converts the intense light from the sun's rays into usable energy using the ageing process and a subsequent assortment of elementary particle gap sets (Hanif et al., 2015). There have been three distinct epochs in the history of solar-powered cell development and pricing. Despite their greater effectiveness, the original solar cells are more costly to produce. Using silicon and germanium, they are analogues of earlier generations of solar cells. The company's presentation is overseen by this generation. Amorphous silicon, cadmium telluride (CdTe), nanocrystalline silicon, copper indium gallium selenide (CIGS), and thin films of sunlight are the basis of the second age group of cells. They aren't as skilled, but they're cheaper to make and don't rely on as many outside sources (Flores-Carrasco et al., 2014). The third age of sun-oriented devices consists of cell kinds that were not created during the previous two eras. A sun-based cell that has been dyed is a third-era natural sun-based cell. Although most third-age innovations aren't yet marketable, there's a plethora of studies and investigations that are producing encouraging outcomes (Khan, 2013). Individuals with dye sensitivity Photovoltaic devices, or solar cells, can convert the visible light from the sun into energy. They work by using a thin layer of semiconductor oxide with a wide band gap that has been coloured (Chergui, 2015). While silicon sunlight-based cells have accomplished power restoration proficiencies going from 15% to 20%, the creation cost of colour-sharpened sun-oriented cells and third-age sun-oriented cells is essentially lower. Hypothetically and functionally, a smaller layer has been upheld to wedge the electron recombination through the helper channel. Recombination at the cathode/electrolyte connection point might be successfully forestalled by a compacted blocking store between the going with electron and the nano-translucent Titanium dioxide (TiO_2) layer (Ozuomba et al., 2015).

Materials and Methods

The monolithic design and fabrication method was adopted for this research work, which implies that all the different layers of each sample were deposited on a single Fluorine doped Tin oxide (FTO) glass substrate housing both the photoanode and counter electrode with Zirconium dioxide deposited on a large area as an insulating material between them.

The following were the labels applied to three FTO glass substrates;

- Glass substrates 1(sample without blocking layer),
- Glass substrates 2 (sample with Titanium dioxide (TiO_2) blocking layer),
- Glass substrates 3 (sample with Tin Oxide (SnO_2) blocking layer.

A square black tape was used to define the area where the blocking area was situated.

One of the key components that helps define the performance of dye-sensitized solar cells is the photoanode. This is made by preparing a layer of titanium dioxide (TiO_2) and a coating of tin oxide (SnO_2).;

- Fluorine-doped Tin Oxide coated glass substrate was cut into 2cm square pieces.
- Etching of samples; Each piece of fluorine-doped tin oxide glass substrate was shielded using a black-masked tape to isolate the area of the fluorine-doped tin oxide glass substrate to be etched, (etching is a process of cutting into the unprotected parts of the FTO glass substrate) and the etching was done using Electro-etching method with voltage set initially to 7.5volts and later to 15volts at the final stage of etching plus the addition of few drops of zinc acetate dehydrate (zinc oxide) to aid the etching process. Hydrochloric acid was used to remove both the zinc oxide and FTO, and finally, water was used to rinse the Hcl off the sample.
- A digital meter was used to confirm that the etching (separation of the masked taped area) was properly done.
- Blocking layer preparation; FTO glass substrate 1 has no blocking layer.

FTO glass substrates 2; Based on a 40 ml precursor containing 0.1 mM titanium isopropoxide, 0.4 mM acetylacetone, and methanol, the blocking layer was created via electrospinning and calcination. The FTO glass substrates 2 were turned dried for 20 seconds after two drops of the originator arrangement were applied to them.

FTO glass substrates 3; Electrospinning in addition to calcination was used to generate the 40 ml precursor, which included 0.1 mM Tin IV chloride ($Sncl_4$), 0.4 mM acetylacetone, and methanol, to form the blocking layer. After spin-drying for 20 seconds, a few drops of the precursor solution were applied to cover the space on the FTO glass substrates 3. With the black tapes removed, the three slides underwent a 30-minute annealing process at 450^0C. To prevent cracking, the FTO substrates were let to cool for approximately half an hour before being removed.

- Using the screen printing approach,' the three fluorine-doped tin oxide glass substrates were coated with titanium dioxide (TiO_2), which is typically applied as a paste. Applying a layer of screen printable paste (Solaronix Ti-Nanoxide D/SP) on top of the glass substrates and defining it on the active region was done using a squeegee. The annealing temperature was steadily increased for the samples from 150^0C to 300^0C and eventually 450^0C. After annealing to 150^0C, the samples were subjected to a 10-minute rest period, followed by annealing to 300^0C, another 10-minute dwell period, and lastly, annealing to 450^0C. The samples were let to cool for half an hour after annealing. As per Grant et al. (2002), this layer fills in as the adverse terminal for solid colour-sharpened sun-powered cells.
- A covering of Zirconium dioxide (Solaronix Zr-nanoxide Z/SP) screen printable glue was applied to the fluorine-doped tin oxide glass substrates utilizing the screen-printing process. To prevent the cells from short-circuiting, the area where the Zirconium dioxide was coated was increased to cover the preceding layer of TiO_2. The titanium dioxide mesoporous layer is shielded from the counter anode by this layer. Following a 30-minute annealing at 400^0C, the samples were given another 30-minute cooling period. To remove any remnants of the prior layer's deposit from the screen-printing machine, a mixture of propanol and cotton wool was utilized.

The following is the procedure for preparing the platinum (Pt) and Elcocarb that make up the counter electrode, an integral part of the monolithic dye-sensitized solar cell;

- Screen printing utilizing Solaronics plastisol T/SP glue, an impetus, was utilized to store a meagre layer of platinum onto the glass substrates, which were then strengthened at 400^0C for 30 minutes.
- A layer of screen-printable paste (Solaronix Elcocarb G/SP) was applied to the active region using a screen-printing process, covering the samples on top. Elcocarb, a simple conductive substance, was printed to connect the two conductive layers; it acts as a positive terminal for monolithic dye-sensitized solar cells and helps to transmit electricity to the rear layer. The samples were subsequently cooled to 100^0C after being annealed to 400^0C for 30 minutes, which activated the Elcocarb layer for operation. The manufactured DSSCs were sensitized with a dye solution and dried calyxes of Hibiscus sabdariffa. After a thorough washing with distilled water, the calyxes of the hibiscus sabdariffa (zobo) plant were brought to a boil in 40 cl of water to create the dye solution. After three hours of cooling, the cells were immersed in the dye extract and left to soak at room temperature overnight so that it could penetrate all of the cell layers. The cells were removed from storage and cleaned with water before being dried at 60^0C after 12 hours of being kept in the dark.
- The forward and switch associations of the solid colour sharpened sun-powered cells were checked to utilize copper conductive tape.
- Electrolyte (Solaronics Iodolyte AN 50) was applied in the active area, to start the cells working and it helped to regenerate the dyes.

The profilometer (Dektak 150 from Veco instrument TMCU.S. A.) was used to measure the active layers' surface thickness. A profilometer is a tool for quantifying surface roughness by measuring its profile. Surface topography is used to calculate critical parameters including step, curvature, flatness, and thickness (Gratzel, 2004).

The Hall Effect measuring equipment HMS-3000, Ecopia was employed to assess the electrical characteristics of the glass substrate doped with fluorine tin oxide (FTO). The results revealed many properties of the FTO, such as its sheet resistance (Rs), conductivity, bulk concentration, mobility, and resistivity.

The optical assessment of the cells was directed utilizing a UV-VIS-NI spectrophotometer (UV 752) from the Unified Realm, which works inside the frequency scope of 230 nm to 1100 nm. Various optical characteristics were measured and recorded using the spectrophotometer, including absorbance, reflectance, energy band gap, extinction coefficient, refractive index, and transmittance.

An I.V. meter from Keithley was used to obtain characteristics, and a Newport solar simulator (model 94043A) was used to estimate the simulated sun irradiation of the dye-sensitized solar cell. A 1cm x 1cm cell surface area was measured, along with short circuit current (Isc) and open-circuit voltage (Voc) readings taken from the Keithley 2400 source meter. Additional solar cell parameters, such as fill factor (FF) and efficiency, were also assessed.

Results

Measurement of the Fluorine doped Tin Oxide (FTO) Thickness

The profilometer was used to measure the thickness of the fluorine-doped thin oxide (FTO), which was transformed from 20,000 Angstroms to micrometres (2µm). According to Rahal et al. (2014), who discovered that the optical transmittance of FTO films decreased as the film thickness increased due to an increase in crystal size, this 2µm (micrometre) thickness will raise the sheet resistance and resistivity of the FTO and directly affect its transmittance. Light transmission and, by extension, the efficiency of dye-sensitized solar cells, are directly impacted by the FTO thickness.

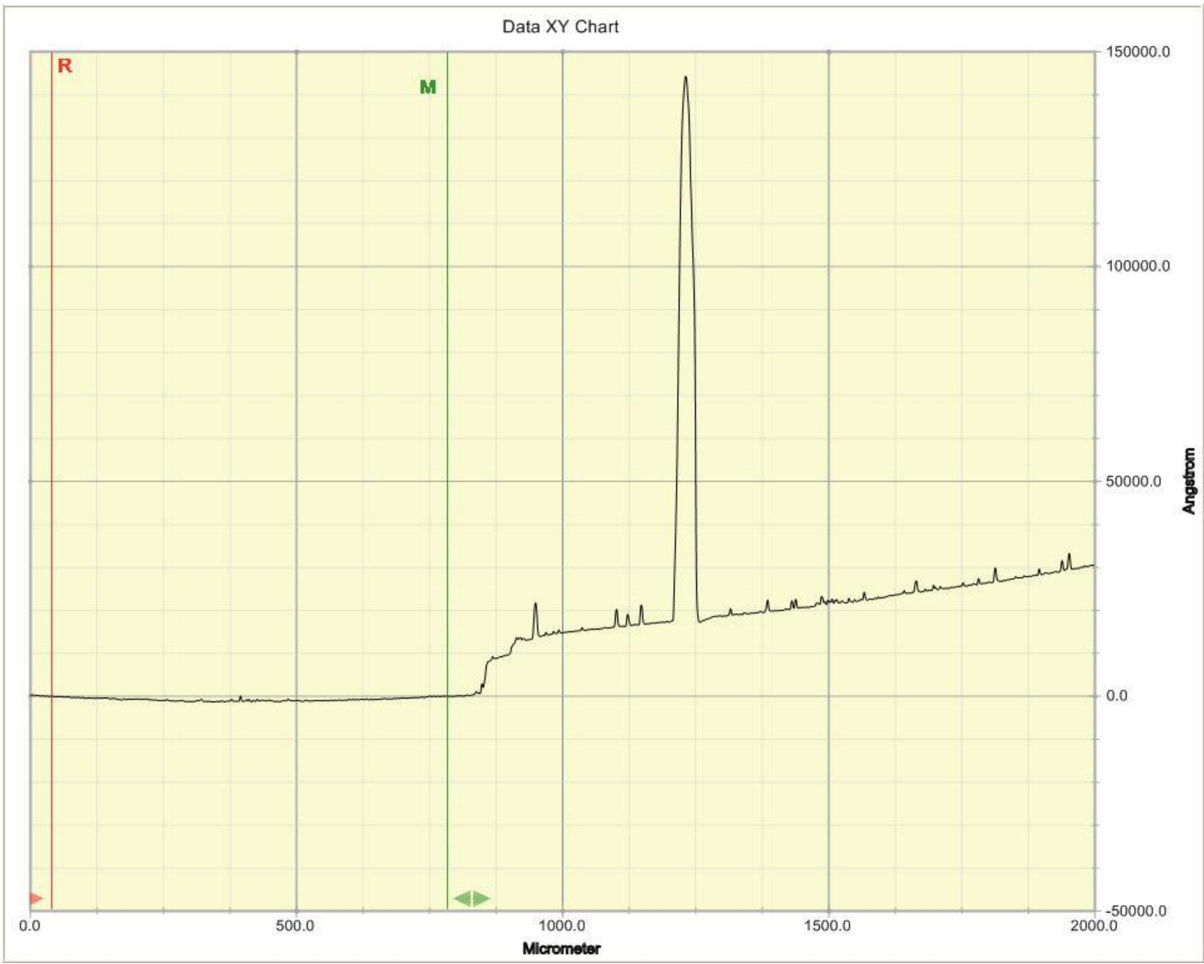

Figure 1: Picture capturing the thickness of the FTO glass substrate using profilometry

Electrical properties of the FTO Glass substrate

Through the use of the Hall Effect measuring device, the electrical characteristics of the FTO were examined. According to Table 1, the electrical resistivity, sheet resistance, and conductivity of the FTO used in this study were 1.613 Ωcm, 8.065 X 103 Ω, and 6.200 X 10^-1 Ωcm, respectively. The acquired characterization data demonstrate that the solar cell's transmittance around the visible wavelength spectrum decreases as the sheet resistance and resistivity of the FTO decrease with increasing thickness.

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Table 1: Result for electrical analysis of the Fluorine doped Tin Oxide coated glass (FTO) at Temperature 300k.

SAMPLE: Fluorine-doped tin oxide-coated glass substrate	
Bulk concentration (/cm^3)	5.775E+16
Mobility (cm^2/V$_5$)	6.701E+1
Sheet Resistance (Ω)	8.065E+3
Resistivity (Ωcm)	1.613
Sheet concentration (/cm^2)	1.155E+13
Conductivity (1/ Ωcm)	6.200E-1
Average Hall coefficient (cm^3/C)	1.081E+2
Magneto Resistance (Ω)	2.229E+2
The ratio of vertical/horizontal	3.993E-4

It was observed from the hall coefficient data that the FTO thin film exhibited p-type conductivity and bulk concentration was found to be 5.775 X 10^{16}/cm^3, and electron mobility as 6.701 X 10^1cm^2/Vs.

Optical characterization

Uv-vis evaluation of the samples as seen in the figures below revealed that transmittance presented an inflection point around 450 nm for the TiO_2 layer and TiO_2+dye layer respectively, and around 510 nm for the colourant.

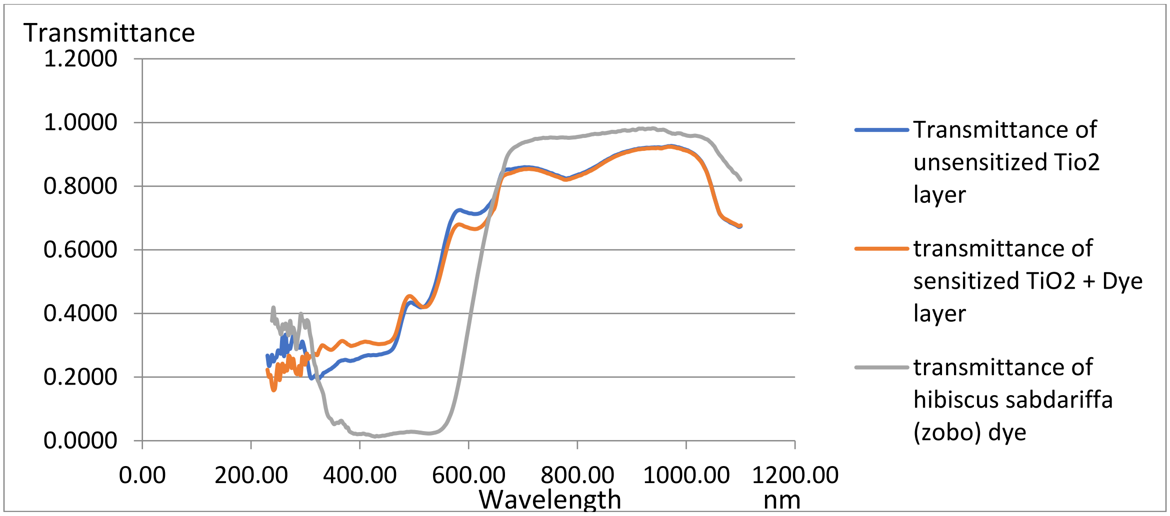

Figure 2: Uv-vis- Transmittance spectra of TiO_2 layer, TiO_2 + dye layer and Dye.

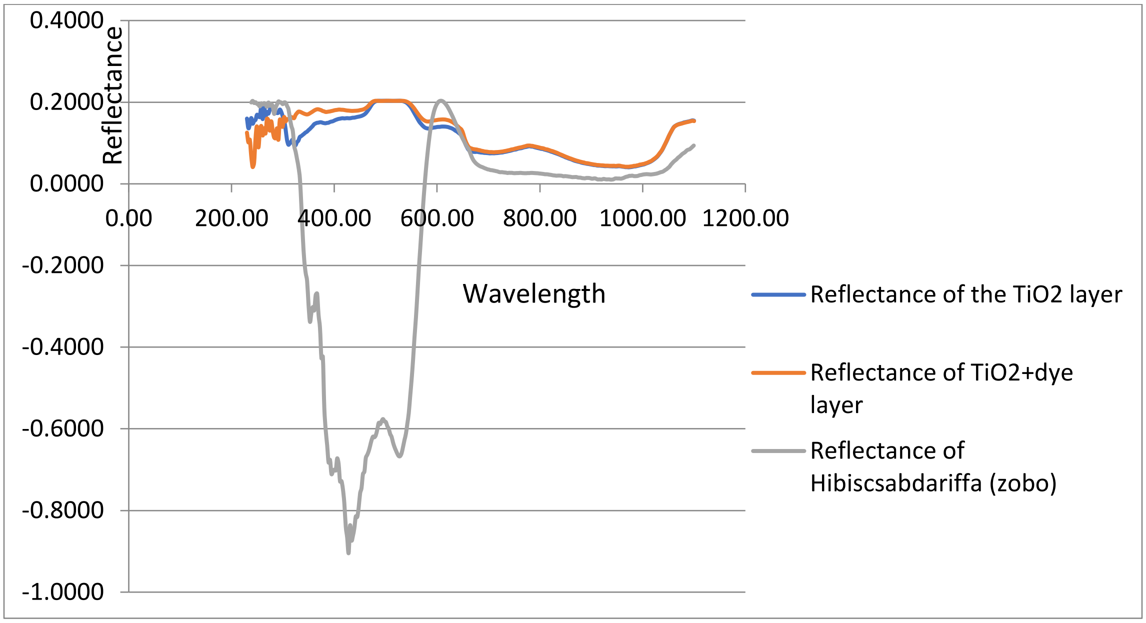

Figure 3: Uv-vis- Reflectance spectra of TiO_2 layer, TiO_2 + dye layer and Dye.

The value was extrapolated to 3.0 eV, as shown in Figure 4, which is the direct band-gap of TiO2 doped with hibiscus sabdariffa.

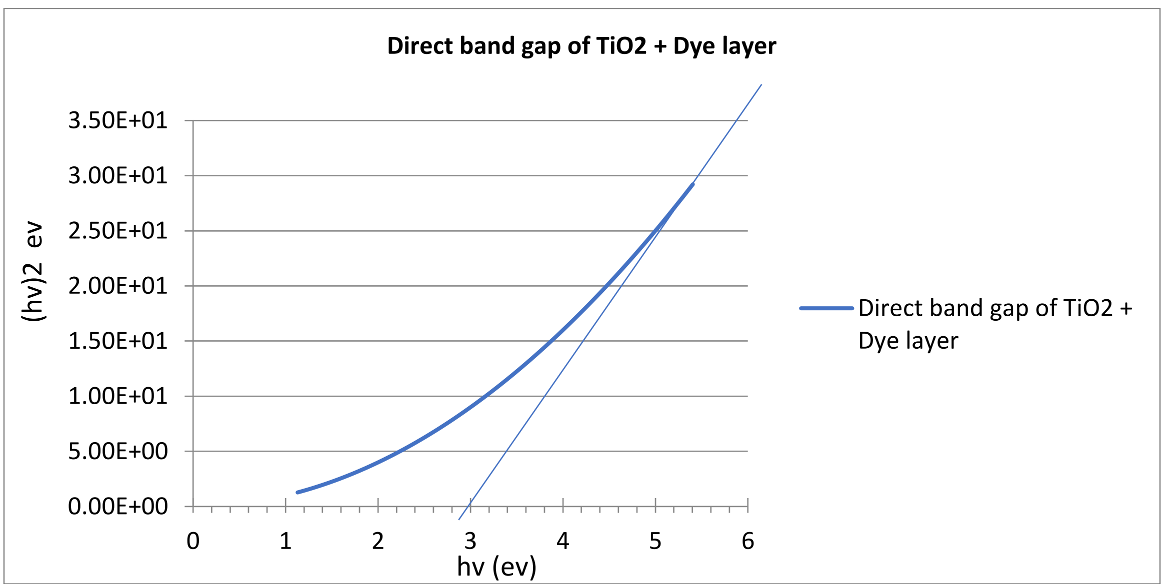

Figure 4. Direct band-gap of hibiscus sabdariffa-doped TiO_2

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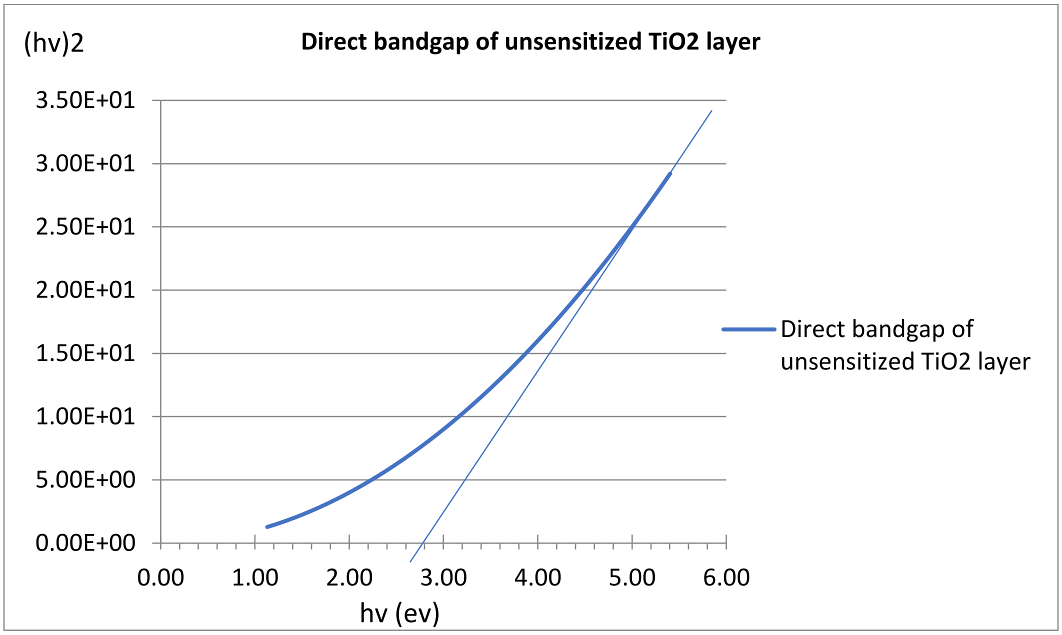

Figure 5. Direct band-gap of un-sensitized TiO_2 layer

Utilizing the straight part of the bend (hv)2 versus (hv), the direct optical band-gap for the unsensitized TiO_2 is settled to be 2.7ev.

Photovoltaic properties

All of these readings were taken using a 100 mW/cm2 light source. We measured the DSSC's performance by finding its short circuit current (Isc), open-circuit voltage (Voc), fill factor (FF), and conversion efficiency (ῦ). By intercepting the IV curve on the y-axis, we were able to ascertain the open-circuit voltage (Vm) and short-circuit current (Isc). The characteristics were used to determine the fill factor (FF) and conversion efficiency (ῦ). Table 2 presents the cell properties of the manufactured DSSCs. The DSSCs doped with Hibiscus sabdariffa (dye) are shown in figures 6, 7, and 8 in the I.V. visual depiction, respectively.

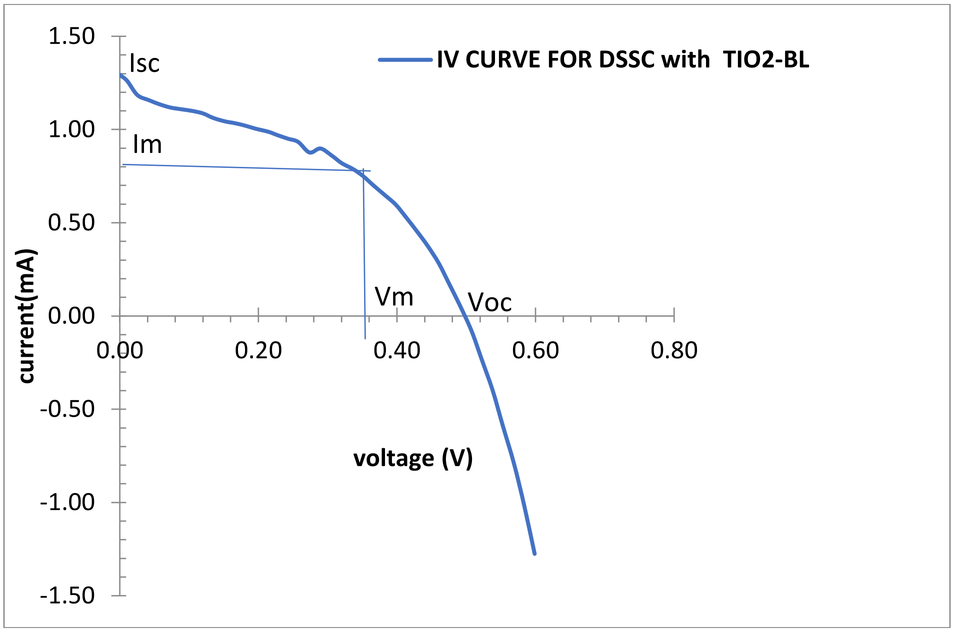

Fig 6. I/V curve for Sample 1 (DSSC without blocking layer)

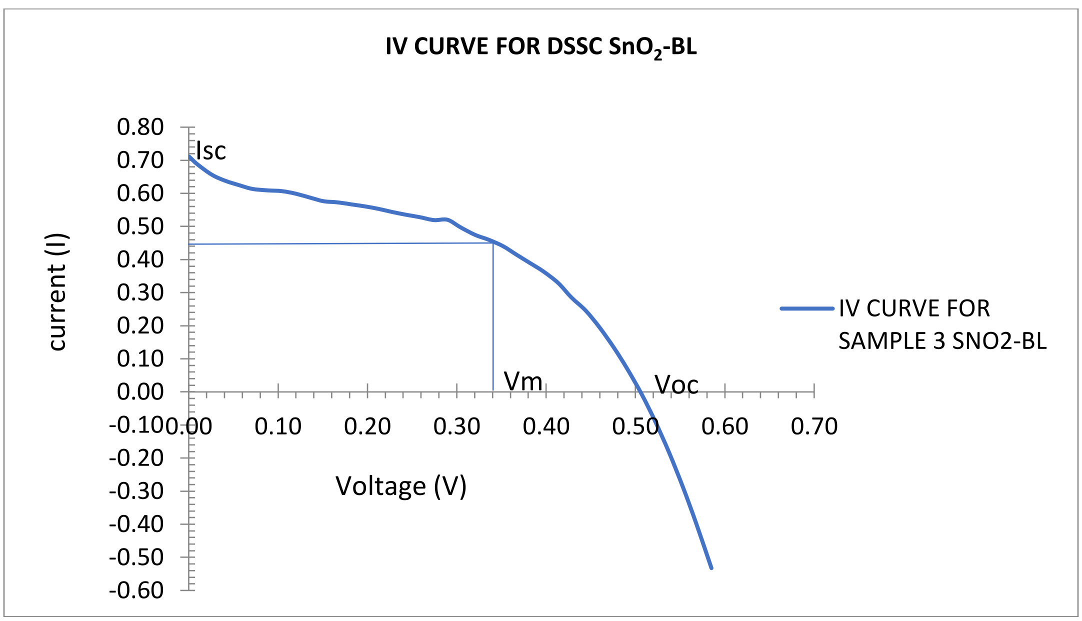

Fig 7. I/V curve for sample 3 (DSSC with SNO_2 blocking layer)

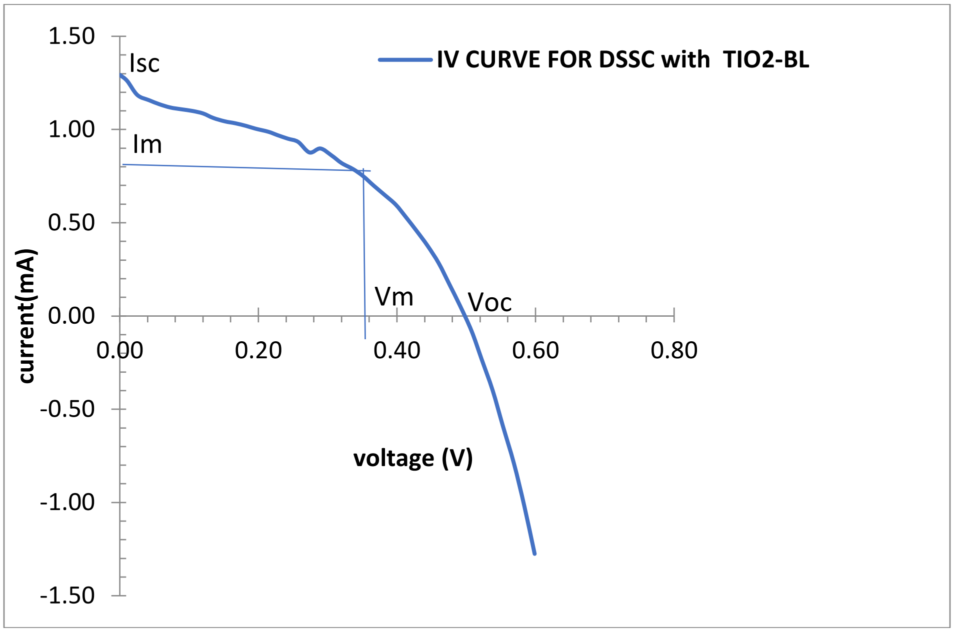

Figure 8: IV curve for Sample 2 (DSSC with TIO_2 blocking layer)

Table 2: H. sabdariffa-sensitized dye-sensitized solar cells (DSSCs) and their photovoltaic characteristics.

TiO_2 DSSC samples (cell)	Voc (V)	Isc (mA/cm^2)	Vm (V)	Im (mA/cm^2)	FF	ή %
Cell 1.	0.47	0.78	0.29	0.48	0.38	1.34
Cell 2.	0.50	1.3	0.36	0.8	0.44	2.9
Cell 3.	0.50	0.70	0.35	0.45	0.37	1.32

Discussion

The associations between the electrical qualities of colour-sharpened sunlight-based cells (DSSCs) and fluorine-doped tin oxide (FTO) layers are better grasped thanks to this study's outcomes. Key attributes including as open-circuit voltage, fill factor, impede thickness, and absolute energy change proficiency of DSSCs were studied to decide the impact of FTO films. Utilizing a profilometer, Hall effect strategies, and UV-noticeable Spectroscopy, the examination originally estimated the electrical qualities of FTO layers with a thickness of around 2 micrometers. The FTO's electrical resistivity was 1.613 Ωcm, sheet obstruction was 8.065 X 10^3 Ω, and conductivity was 6.200 X 10^-1 Ωcm, as shown by the Hall effect tests. The solid relationship between the electrical qualities of the FTO films and the productivity of the DSSCs is a significant finding. The sun-oriented cell's conveyance inside the apparent frequency range declined as the sheet opposition and resistivity of FTO rose with thickness. This gives additional proof that the electrical properties of FTO intensely impact the optical properties of DSSCs.

Results showed that different FTO electrical qualities impacted DSSC execution in various ways. Any modifications to the electrical qualities of the FTO films fundamentally affected the DSSCs' open-circuit voltage, fill factor, impede thickness, and energy change effectiveness. To work on the general productivity of colour-sharpened sun-oriented cells, advancing the electrical properties of FTO layers is essential. Furthermore, the exploration gave condition-explicit productivity evaluations for the DSSCs. The colour-sharpened sunlight-based cells had conversion efficiencies of 1.34%, 1.32%, and 2.88%, individually, with optical bandgaps of 2.6eV, 2.8eV, and 3.0 eV, respectively. This exploration adds to how we might interpret colour-sharpened sunlight-based cells by showing how significant FTO layers' electrical qualities are. To work on the presentation and effectiveness of DSSCs, the outcomes feature the meaning of unequivocally tuning these attributes. More powerful and dependable energy change might be accomplished with the assistance of colour-sharpened sun-based cells, and this study lays the foundation for such an undertaking.

Conclusion

Titanium dioxide (TiO_2), a semiconducting semiconductor, was successfully screen-printed onto an FTO substrate to create dye-sensitized solar cells (DSSCs). As a photosensitizer, we utilized an organic dye derived from the calyxes of the Hibiscus sabdariffa flower. The I-V properties of the DSSCs and absorption spectra of the TiO_2, TiO_2 + dye, and dye layers were measured. You may see the results of the calculations of the photovoltaic properties of the manufactured DSSCs up there. Finally, a UV-VIS-NI spectrophotometer (UV 752) was utilized to quantify the retention coefficient, refractive index, UV-vis absorbance spectra, conveyance spectra, and reflectance spectra of three colour-sharpened sunlight-based cell tests. To fabricate the colour-sharpened sun-powered cell, Ecopia's Corridor Impact estimation gadget HMS-3000 was utilized to test the electrical properties and thickness of the FTO. The sun-powered reproduction properties of the fabricated DSSCs were resolved utilizing a Keithley 2400 source meter and a Newport sun-oriented test system (Model 94043A). Utilizing a Keithley 2400 source meter, we estimated the surface region of the cells, which was 1cm X 1cm, the short circuit current (Isc), the open-circuit voltage (Voc), and different qualities of the sun-powered cells, including fill factor (FF) and proficiency. After concentrating on the FTO's electrical properties and surface thickness, specialists found that colour-sharpened sunlight cells made with FTO had a much lower power transformation effectiveness because of the material's thick 2μm (2000nm) layer, which is related to high resistivity and sheet opposition values.

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