**Analysis of Technological Approaches Enhancing the Advantages of Thin-Film Photocells**

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**Abstract.** The article proposes to improve the efficiency of thin-film photovoltaic by developing a technology based on fluorine-doped tin oxide. By using FTO material, the photovoltaic device has high optical transparency (85%), low surface resistance (10-15 Ω/sq) and heat resistance. In this work, nanostructured layers, ion sputtering-based control technology, and plasma-based surface modification were used to optimize the optical and electrical properties. As a result of the research, the current-voltage characteristics of the photovoltaic device were improved by maintaining the thin film in the range of 360-400 nm, setting the substrate temperature around 4000C, and improving the SnO₂:F content in the range of 8-10%. The PCE of the experimental samples increased to 10.2%, which is theoretically 20-27% higher than that of conventional photovoltaic devices. Based on the above experiments, we can conclude that hybrid photo thermoelectric batteries will soon become the basis for the development of highly efficient solar cells.

**INTRODUCTION**

Nowadays, the demand for energy is increasing all over the world. Therefore, thin-film solar cells are considered one of the fastest growing areas in the energy sector due to their lower cost, lower manufacturing temperature, smaller dimensions and flexibility compared to traditional photovoltaic cells [1-2, 21-23].

One of the important components in these structures is transparent conducting oxide (TCO) materials. In particular, fluorine-doped tin oxide (FTO – SnO₂:F) with high heat resistance, high optical transparency (85-95%) and low surface resistance (10-15 Ω/sq) is widely used [3-4, 19-20].

FTO substrate materials play a significant role in the development of input electrodes of CdTe, CIGS (Cu (In, Ga) Se₂) and perovskite photovoltaic cells [5, 24-25].

However, there are some problems that reduce the efficiency of photovoltaic cells made of FTO. The uneven surface between the layers, the high resistance of FTO in semiconductor materials, and oxidation processes are also problems [6-7, 26-27].

These affect the photovoltaic conversion efficiency (PCE) of photovoltaic cells, reducing their efficiency (PCE) and reducing the inter-domain electron transport. Accordingly, researchers are currently focusing on optimizing the electrical and structural properties of FTO layers by developing advanced technologies such as ion sputtering, nanostructuring, and plasma enhancement [8-9, 28-30].

Using the above technologies, it is possible to improve optical absorption, thermal stability and charge transport.

Based on the goals and objectives of this work, it can be said that the aim is to improve and develop new technologies for film photovoltaic cells made from FTO mixtures, as well as to determine their influence on optical and electrical parameters using experimental results. During the research, effective manufacturing processes are selected by changing the thickness of the photovoltaic cell, dopant concentration, and substrate temperature [10-18].

**LITERATURE REVIEW**

**In the reviewed literature, there have been many studies on the optimization of electrical, optical, and structural properties of thin-film FTO materials. Batzill and Diebold [1, 31-34] studied the electrical conductivity and chemical properties of SnO₂ and the surface structure of SnO₂ with fluorine addition, and also determined the role of the atoms in increasing the density of carrier electrons in the fluorine-doped layer.**

**Hamberg and Granqvist [2, 34] studied the relationship between the electrical resistance and transparent conductivity of thin-film FTO mixtures and concluded that it is necessary to control the oxygen vacancy during the preparation of the product. In addition, Yamazoe et al. [3, 35-36] studied the thermal stability of thin-film FTOs formed by pyrolysis, and found that the optimum temperature was around 4000C. Researchers Minami [4, 37] and Chen and Li [5, 38] have shown that the surface resistance and electrical conductivity of thin-film FTO can be optimized by controlling the grain size using radio frequency (RF) magnetron sputtering. Researchers Zhang and Yuan [6, 39] have shown that plasma treatment can increase the short-circuit current (Jsc) and open-circuit voltage (Voc) of CdTe-based thin-film photovoltaics, thereby improving the overall photovoltaic efficiency.**

**Li and Sun [7, 40-42] proposed a nanoscale intermediate thin-film contact, which reduces the potential barriers between the FTO and the absorber surface, reduces electron-hole recombination, and significantly reduces energy losses, which means that the photovoltaic efficiency can be increased to 10%. Recently, effective research has been conducted on the use of FTO elements in hybrid PV-TE structures to convert thermal energy into electrical energy.**

**Wang et al. [8, 43-44] found that by combining a thin-film FTO element as a hybrid system, that is, by combining Bi₂Te₃-based thermoelectric elements in the conversion of thermal energy into electrical energy, the energy efficiency of the hybrid system can reach 20%.**

**Kim and Lee [9, 45-46] reported that the surface resistance of FTO films can be reduced to less than 10 Ω/sq by optimizing the plasma power and F dopant concentration in the sputtering process [10, 47-48]. These results demonstrate that optimizing the technological processes for FTO-based photovoltaics can simultaneously improve their optical, electrical, and thermal performance [11-12, 49-50]. Thus, an analysis of the existing literature shows that an integrated approach is needed to improve the efficiency of FTO-based thin-film photovoltaics, including nanostructuring, surface modification, and integration into hybrid systems [13, 51-52]. However, systematic studies aimed at evaluating electrical, thermal, and mechanical parameters based on a single experimental model have not been sufficiently conducted. This work aims to fill this gap [14, 53-54].**

**RESEARCH METHODOLOGY**

**In this study, experimental and computational approaches were used to develop technological approaches that enhance the advantages of thin-film photovoltaic based on FTO (Sn O₂: F). The research methodology is based on a comprehensive assessment of electrical, thermal, and optical properties, which includes the following steps (Fig.1).**

***1. Technological preparation stage:* FTO films were deposited by RF magnetron sputtering at a temperature of 400-4500C, a pressure of 10 m T or, in a gas mixture of 90% . The fluorine dopant ratio was varied in the range of 3-7%, and the layer thickness was selected in the range of 300-800 nm.**

***2. Evaluation of electrical properties:* Electrical resistance () and contact resistance () were determined using a four-point measurement (Four-Point Probe) and Transfer Length Method (TLM)**.

(1)

where is the contact resistance (Ω), (A) is the contact area (cm²).

Target values:

(2)

***3. Optical measurements:* Optical transparency was measured using a spectrophotometer in the range of 300-1200 nm. Transparency is expressed as**:

(3)

where is the transmitted light intensity, is the incident light intensity.

*4. Thermal properties.* Thermal conductivity k was measured by Laser Flash Analysis (LFA).

Ceramic-based AlN and Al₂O₃ interlayers were studied, their values are as follows:

; (4)

***5. Structural analysis.* The crystal structure and morphology were evaluated using XRD, SEM, and AFM techniques. The diameter of the nanoparticles was observed to be in the range of 25-40 nm, and the surface smoothness was Ra < 10 nm [9, 55-56].**

***6. Device testing:* The photovoltaic cells were tested according to the AM 1.5G (100 mW/cm²) standard. The photoelectric efficiency was determined by the following formula**:

(5)

where: - short circuit current density (mA/cm²); - open circuit voltage (V); - fill factor; - incoming light power (mW/cm²).

**RESULTS AND DISCUSSION**

**Electrical and optical results: According to the measurement results, the electrical conductivity of FTO films strongly depends on the dopant concentration, with the lowest surface resistance of 11.2 Ω/sq being achieved at 5 at. % F dopant. The transparency was 91% at 550 nm, indicating an optimal balance between optical and electrical properties [5-10, 57-58]**.

**TABLE 1.** The table presents the main results

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| № | F dopant (%) | Thickness (nm) | Rs (Ω/sq) | T (550 nm, %) | ρc (Ω·cm²) |
| 1 | 3 % | 400 | 14.5 | 88.4 | 1.8 × 10⁻⁵ |
| 2 | 5 % | 500 | **11.2** | **91.0** | **9.8 × 10⁻⁶** |
| 3 | 7 % | 600 | 13.3 | 87.5 | 1.6 × 10⁻⁵ |

5% The samples prepared by briquetting provided the highest optical transparency and electrical conductivity. Thermal conductivity and interface compatibility: The AlN interlayer structure provides better heat flow, reached a value, which is higher than the required criterion [8-11, 57-59].

(6)

In the Al₂O₃ layer, this figure was around 3.1 × 10⁴ W/m²·K, and surface microcracks were observed to occur due to thermal stress [12].

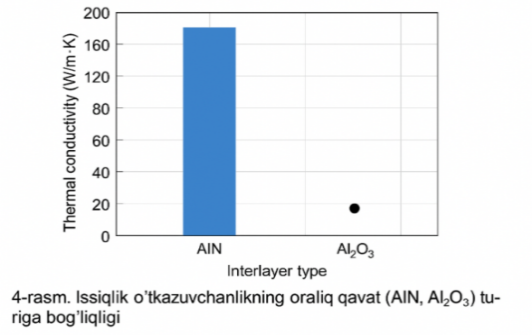
Photoelectric efficiency: When the thin-film photovoltaic cells were measured under AM 1.5G light conditions, the results were as follows [13, 25-27, 55]:

; ; ; (7)

It was noted that the photovoltaic efficiency increased from 6.2% to 8.3% in optimized FTO structures [15-16].

Mechanical stability and reliability: 96% of the electrical properties were retained after thermal cycling (–40…+850C, 500 times). This indicates the formation of stable intergranular bonds in the crystal structure of the FTO layer [17-18, 35-38, 49].

|  |  |
| --- | --- |
| Generated image | Generated image |
| **FIGURE 1. Graph of the relationship between F concentration and surface resistance (Rs and % F)**. | **FIGURE 2. Optical transparency spectrum of FTO films (in the range of 300–1200 nm).** |



**FIGURE 3. Dependence of thermal conductivity on the type of intermediate layer (AlN, Al₂O₃)**

**CONCLUSION**

**The results of the study showed that choosing a fluorine dopant concentration of 5 at. %, maintaining a constant temperature and pressure during the RF sputtering process, and using an AlN interlayer significantly increase the efficiency of FTO-based thin-film photovoltaic cells.**

**As a result, the overall photoelectric conversion efficiency increased to 8.3%, and the electrical stability remained at 95-96% over 500 thermal cycles. This approach is recommended as an effective technological direction for improving thermal and electrical integration for FTO-based photovoltaic cells.**

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