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*Research Article*

# Influence of Deposition Parameters of ITO Films on the Performance of HJT Solar Cells

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TCO (transparent conductive oxide) films are widely used in solar cells due to the characteristics of transparency and conductivity. In this paper, ITO (indium tin oxide) transparent conductive films are prepared on common slides by DC magnetron sputtering, and the preparation process and characteristics of ITO films are studied. The target for sputtering is ITO, with the mass ratio of $In_20_3$ and $Sn0_2$ was 90% : 10%. The sheet resistance, carrier concentration, and carrier mobility of ITO films are measured and analyzed by a UV-Vis spectrophotometer, four-point probe, and Hall effect measurement system. By changing the oxygen content, deposition temperature, and sputtering power to studied the effects on the light transmittance and electrical conductivity of the ITO films, further studied the effects on the HJT (heterojunction with intrinsic thin film) solar cells, and finally determined the appropriate preparation parameters. Results show that the resistance is $6.4^*10^{-4}\,\Omega$•cm, the light transmittance is beyond 90.6%, efficiency is 23.78%, and bifacial ratio is 84% when oxygen content is 2.2%, sputtering power is 3 kw, and deposition temperature is 190°C.

## 1. Introduction

In recent years, with the rapid iteration of solar cell technologies, HJT solar cells have attracted extensive attention due to their high conversion efficiency, high open circuit voltage, low temperature coefficient, low process temperature, and bifacial power generation. It is expected to become one of the mainstream high-efficiency solar cell technologies [1–3]. Its structure is shown in Figure 1. Using an n-type silicon wafer as the substrate and cleaning and texturing, intrinsic amorphous silicon film (i-a-Si:H) and N/P-type amorphous silicon film (n/p-a-Si:H) are sequentially deposited by plasma-enhanced chemical vapor deposition (PECVD) on the front and back sides to form a back surface field and P-N heterojunction to reduce the recombination of carriers. Then deposit TCO films by DC magnetron sputtering (SP) on the front and back sides as a carrier transport. Finally, print metal on the front and back sides of the solar cells by screen printing. Heterojunction with a double-sided symmetrical structure is formed that TCO layer/P-doped a-Si:H layer/intrinsic a-Si:H passivation layer/c-Si wafer/intrinsic a-Si:H passivation layer/N-doped a-Si:H layer/TCO layer [4]. But the emitter of HJT solar cells is amorphous silicon, so TCO films should be introduced between the amorphous silicon layer and the metal electrode to ensure the lateral transmission of current and reduce the disadvantage of high heat loss caused by poor lateral transmission performance of conventional solar cells. In addition, TCO films also have excellent light transmittance to maximize light absorption by the solar cells [5, 6].

Among many TCO films, ITO film is a heavily doped, highly degenerate n-type semiconductor transparent conductive oxide film with band gap greater than 3.5 eV and resistivity as low as $10^{-4}\,\Omega$ cm. It has unique optical properties such as UV cut-off characteristics, high visible light

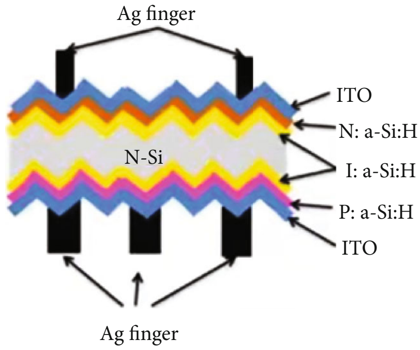


Figure 1: Structure diagram of HJT solar cells.

transmittance, and high infrared reflectivity. So, it is widely used in many fields such as flat panel displays, light-emitting diodes, and solar cells [7–10]. Due to its excellent optoelectronic properties, ITO films not only act as a key material for the collection and transport of photogenerated carriers in HJT solar cells but also act as an antireflection film. Its performance directly affects the photoelectric conversion efficiency of HJT solar cells. Therefore, in order to achieve high conversion efficiency, the ITO films need to meet the characteristics of high transmittance and low resistivity at the same time. Increasing the light transmittance of the ITO films can reduce parasitic absorption and improve the short-circuit current (Isc) of the solar cells. Low resistivity results in higher fill factor (FF), which in turn enables improved conversion efficiency.

Because the horizontal conductive characteristic of amorphous silicon is poor, ITO films play an important role in HJT solar cell. This paper focused on the preparation of ITO films with high electrical conductivity and high light transmittance by magnetron sputtering and the analysis of the relationship between its optoelectronic properties and the electrical properties of HJT solar cells.

## 2. Experimental

*2.1. Sample Preparation.* The glass used in the experiment was Corning 7095, and the n-c-Si wafer with a size of 166 cm and thickness of 165 um. The silicon wafer was successively cleaned and textured; PECVD equipment was used to prepare intrinsic amorphous silicon and doped amorphous silicon layers; PVD equipment was used to prepare ITO films; and finally, the printed metal grid lines formed HJT solar cells. The mass ratio of the ITO target, $In_20_3$ and $Sn0_2$, was 90% : 10%, and the target-base distance was 3 cm. The sputtering gases were $Ar_2$ and $O_2$, deposited temperature was 140-230°C, and the sputtering power was 2~4 kw. Presputtering for 30 min to remove the water vapor on the carrier plate and contaminants on the target surface.

*2.2. Sample Characterization.* The carrier concentration and mobility of the ITO films were tested by the nanometric Hall effect test system; the transmission spectrum of the ITO films was tested by the UV-Vis spectrophotometer; and the IV characteristics ($\eta$, FF, Isc, and Voc) of the solar cells were tested by the IV tester.

## 3. Results and Discussion

*3.1. Influence of Oxygen Content on the Electrical and Optical Properties of ITO Films and the Optoelectronic Properties of HJT Solar Cells.* In the process of preparing ITO films, oxygen content, deposition temperature, and sputtering power are key factors. Oxygen content is more sensitive to the transmittance and resistivity of ITO films. As shown in Figure 2, the change curves of carrier mobility, carrier concentration, resistivity, and transmittance of ITO films prepared with different oxygen contents, the conductivity of ITO films mainly depends on oxygen vacancies and heteroatom doping to provide carriers. The substitution of one $Sn^{4+}$ for $In^{3+}$ can provide one electron, and one oxygen vacancy can provide two electrons; however, the mobility is related to the scattering mechanism in films [9, 11, 12]. It can be seen from Figure 2(a) that the carrier concentration decreases with increasing oxygen content, which is caused by a decrease of oxygen vacancy. With the increase of oxygen content, mobility shows a trend of first increasing and then decreasing. When the oxygen content is 2.2%, the mobility reaches a maximum of 29.9 $cm^{-2}/V^{-2}{\cdot}s^{-1}$; however, the mobility decreases when the oxygen content is more than 2.2%. Abundant oxygen content makes the oxygen ions in the film become oxygen impurities. Therefore, the scattering of carriers becomes enhanced with the increase in oxygen content, which leads to the decrease in carrier mobility [11]. The resistivity increases with the increase in oxygen content. According to the following equation (1), the resistivity of the ITO films is related to carrier concentration and mobility and is inversely proportional to the product of carrier concentration and mobility. At the beginning, due to insufficient oxygen, there are many oxygen vacancies in ITO films, which leads to the higher carrier concentration and the lower resistivity. After that, with the increase in oxygen content, the carrier concentration and mobility in the film both decrease, and the resistivity increases [9].

$$\rho = \mathrm{N}\mu. \tag{1}$$

The transmittance of the ITO films is mainly related to two wavelength regions, which are the mid- and short-wave regions and the long-wavelength region. The transmittance in the mid- and short-wave regions is mainly related to the forbidden band width of the material, while the transmittance in the long-wave region is mainly related to the carrier concentration. Excessive carrier concentration will have a strong interaction with the incident light, thus affecting the transmittance of the film [13]. It can be seen from Figure 2(b) that the transmittance of the ITO films first increases and then decreases slightly with the increase in oxygen content. Because of the formation of high-valence compounds under the condition of high oxygen content, the transmittance of the film rises to more than 90%. When keep increasing the oxygen content lead to the light transmittance decreases again, which may be the result of the

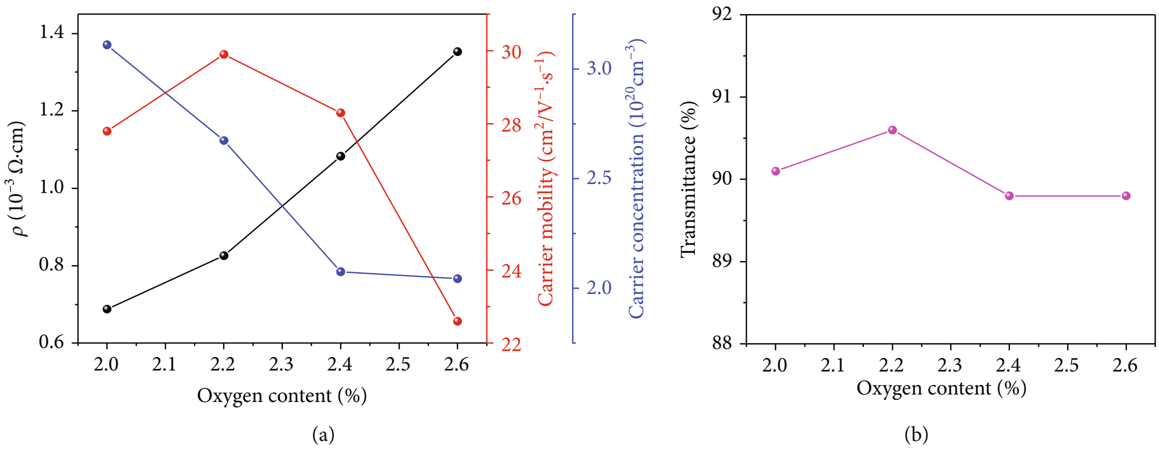


Figure 2: (a) Electrical properties and (b) optical properties of ITO films with different oxygen content.

absorption of excess oxygen ions at the grain boundary and defects in the sample that enhance the scattering of the sample [14].

ITO films play a crucial role in improving the efficiency of HJT solar cells. Hence, the performance of ITO films directly affects the efficiency of cells. As can be seen from Figure 3(a), the efficiency of the solar cells shows a trend of first increasing and then decreasing with the increase in oxygen content and reaches the maximum at 23.78%. FF shows an upward trend, shown in Figure 3(b), and Voc drops slightly, as shown in Figure 3(c) because the electric field direction of TCO and a-Si-n is the same as the electric field direction of the P-N junction. So, an increase in oxygen content leads to an increase of the work function of ITO films, which weakens the electric field of TCO and a-Si-N, and there is no gain to the built-in field of the P-N junction. The built-in field of the P-N junction will be weakened with increase work function, thereby Voc will decrease [15]. Isc shows a basically unchanged trend, as shown in Figure 3(d).

In conclusion, HJT solar cells has excellent optoelectronic properties when the oxygen content is 2.2%. The average efficiency of the back side of the cells is 19.95%, and the average bifacial ratio reached 84.75%.

*3.2. Influence of Deposition Temperature on the Electrical and Optical Properties of ITO Films and the Optoelectronic Properties of HJT Solar Cells.* The deposition temperature is also an important parameter, which mainly affects the performance of ITO films by changing its microstructure during the growth process. It can be seen from Figure 4(a), the carrier concentration increases first and then decreases with the increase in deposition temperature because $Sn^{4+}$ is more conducive to replacing $In^{3+}$ when the deposition temperature increases, thereby increasing the carrier [16]. The carrier concentration decreased when the temperature is 190°C, due to Sn can fully react with $O_2$ at high temperature to generate oxides with relatively complete composite stoichiometric ratios, leading to a decrease in carrier concentration. The temperature continues to rise, with little change. However, the mobility increases with the increase in deposition temperature and reaches the maximum at 270°C is $31.1\,cm^{-2}/V^{-2}\cdot s^{-1}$. The reason is that increase of deposition temperature improves the crystallinity, which is helpful in improving the mobility [17]. In conclusion, carrier concentration reaches the maximum of $3.439^{*}10^{20}\,cm^{-3}$ and the mobility is $28\,cm^{-2}/v^{-2}\cdot s^{-1}$ when the deposition temperature is 190°C.

As can be seen from Figure 4(b), the transmittance of ITO films increases with the increase in deposition temperature and reaches a maximum of 90.9% at 270°C. On the one hand, $Sn^{4+}$ is more conducive to replacing $In^{3+}$ at high deposition temperature, thereby generating less low-valance brown oxides so as to improve the visible transmittance [16, 18]. On the other hand, it can improve the crystallinity at high deposition temperature. However, the temperature in the HJT solar cells cannot be higher than 200°C; therefore, 190°C is more appropriate.

Figure 5(b) shows that the FF first increases and then decreases when the increase in deposition temperature because the crystallization of ITO films is improved at high deposition temperature, which is conducive to the FF of the cells increasing from 82.22% to 83.4%. In addition, when the deposition temperature is too high, the H element in the amorphous silicon layer of the cells will escape, which will worsen the passivation and then lead to the deterioration of FF.

It can be seen from Figure 5(c) that with the increase in deposition temperature, Voc increased from 0.743 V to 0.745 V and then decreased to 0.739 V. The reason is that when the temperature exceeds 190°C, the amorphous silicon layer will be destroyed, which increases its defects and worsens the passivation effect. The key factor in Voc is the interface contact characteristics of the N layer/ITO layer. The ideal performance of the N layer makes the built-in field of cells enhance, and it is easy to obtain higher Voc. However, the Isc increases with the increase in deposition temperature, as can be seen from Figure 5(d). In addition, the average efficiency of the back side of the cells is 19.87%, and the average bifacial ratio is 84.4%.

Comprehensive the above analysis, ITO films have ideal performance when deposition temperature is 190°C, and the increase of the deposition temperature is beneficial to the

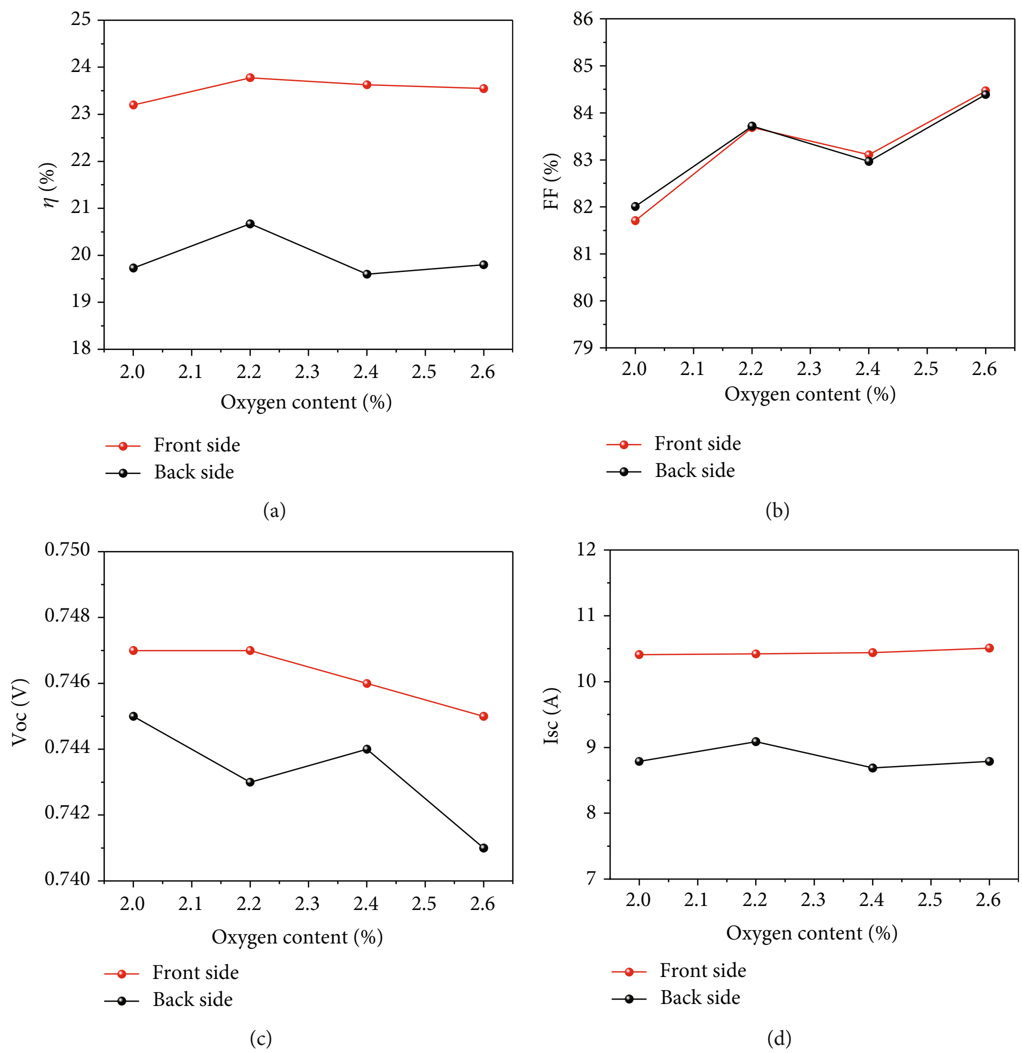


Figure 3: Optoelectronic properties of HJT solar cells with different oxygen content (a) $\eta$, (b) FF, (c) Voc, and (d) Isc.

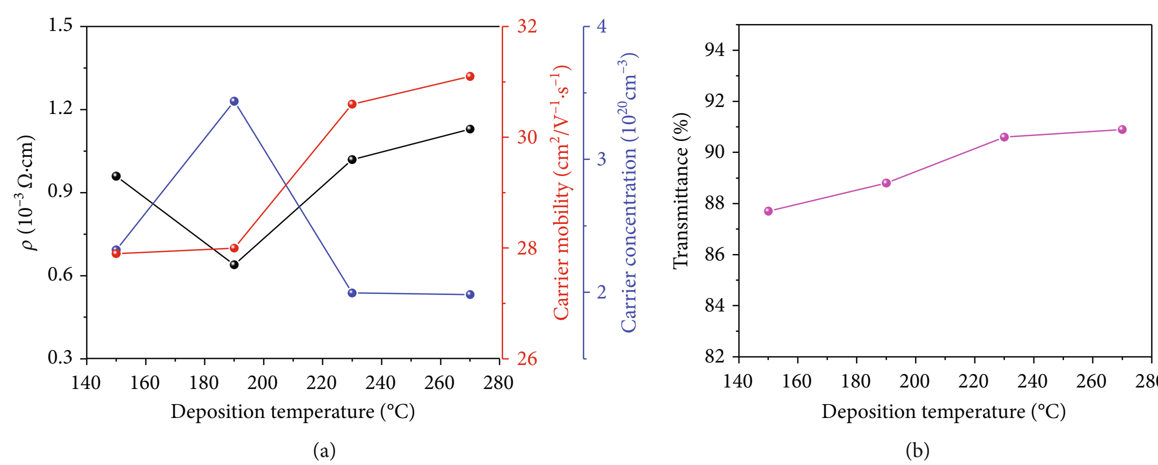


Figure 4: (a) Electrical properties and (b) optical properties of ITO films with deposition temperature.

improvement of the Voc, FF, and Isc of the solar cell. Therefore, we should mainly consider that the effect of deposition temperature on the solar cell's performance in the process of the preparation of ITO films. By adjusting the deposition temperature to obtain an ideal performance.

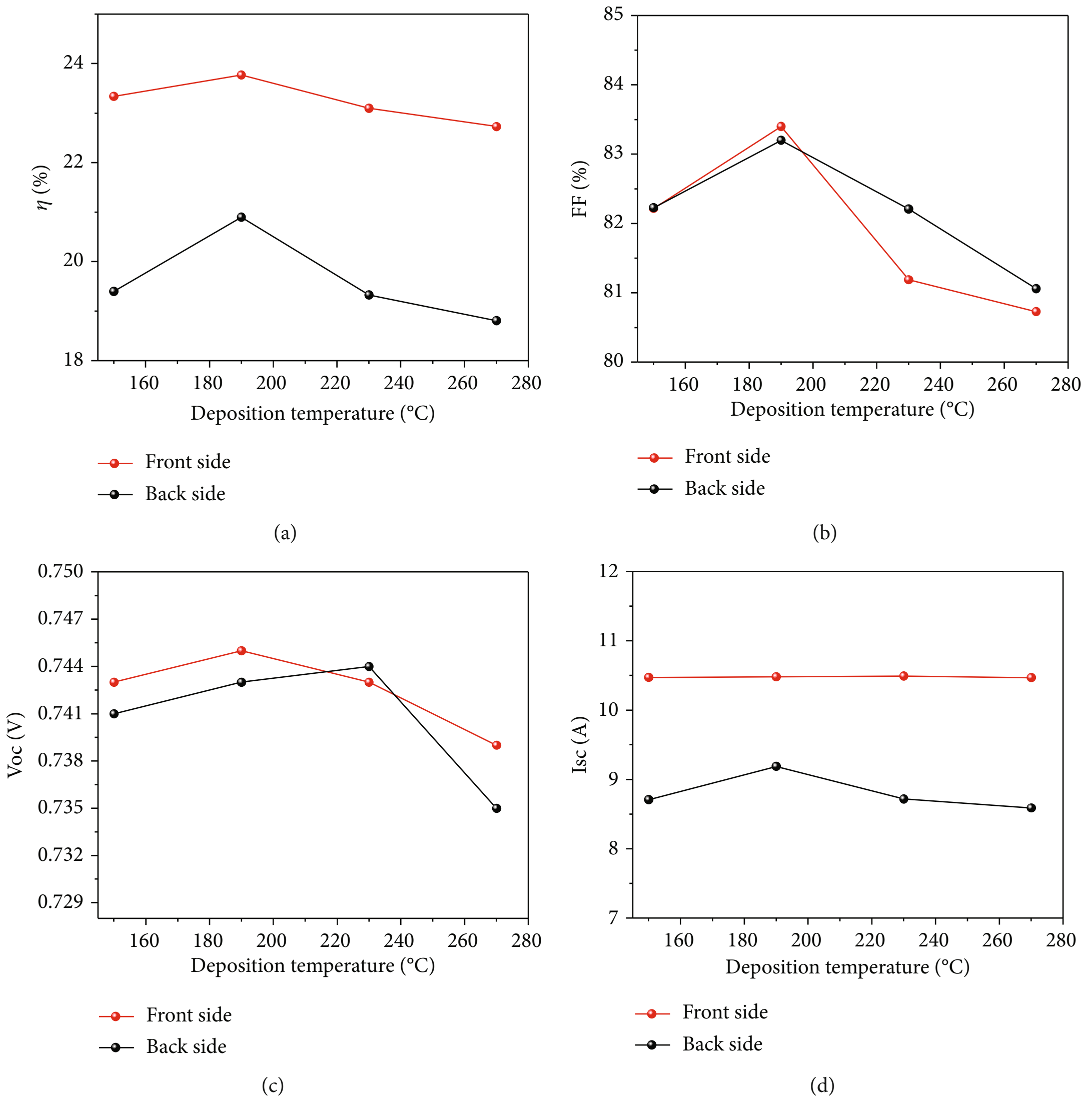


Figure 5: Optoelectronic properties of HJT solar cells with different deposition temperature (a) $\eta$, (b) FF, (c) Voc, and (d) Isc.

*3.3. Influence of Sputtering Power on the Electrical and Optical Properties of ITO Films and the Optoelectronic Properties of HJT Solar Cells.* The sputtering power also has a very important role in the conductive properties of ITO films and then affecting the ITO films compactness and adhesion between the silicon wafer by affecting the energy of sputtering particles. It can be seen from Figure 6(a) that the carrier concentration increases with the sputtering power. Because the higher sputtering power generates a lot of sputtering particles, the oxygen is insufficient to fully oxidize the sputtering particles under the same oxygen content, which increases the carrier concentration by $2.076^{*}10^{20}$ cm$^{-3}$ [19]. The mobility first increases and then decreases with the increase in sputtering power. It may be that the argon ions can obtain higher energy with the increase of sputtering power, which can conducive to improve the adhesion between ITO films and substrate, thus the crystal structure of the film is improved, and the carrier mobility is further increased to 38.9cm$^{2}$/v$^{-1}$·s$^{-1}$. However, the film will be damaged and carrier mobility will decrease when the sputtering power continues to increase to 5 kw, so the resistivity of the ITO films will first fall then rise with increase the sputtering power. In addition, sputtering power should not exceed the threshold value. On the one hand, if the sputtering power is too high, high-energy particles will cause damage to the film and further affect the conductivity of the film. On the other hand, the ceramic target is brittle, and with a high-power bombardment can easily lead to fracture.

As can be seen from Figure 6(b), the transmittance of ITO films first increases and then decreases slightly with the sputtering power. The sputtered particles are limited at low sputtering power, and the sputtering particles can be completely oxidized by oxygen to generate high resistance and transparent oxides; hence, the transmittance can reach more than 90%. However, the number of sputtering particles increases with increase of the sputtering power, and only part of the particles can be oxidized under the condition of unchanged oxygen content, leading to the decrease of the

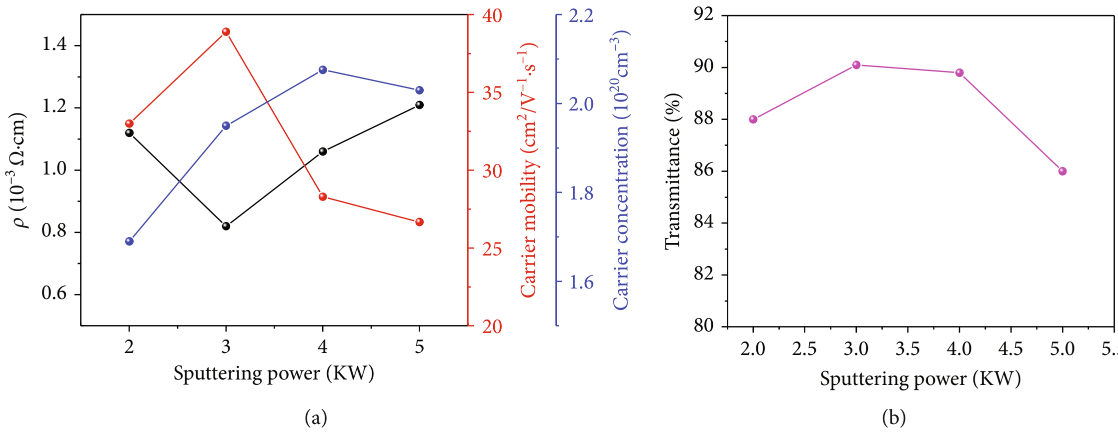


FIGURE 6: (a) Electrical properties and (b) optical properties of ITO films with sputtering power.

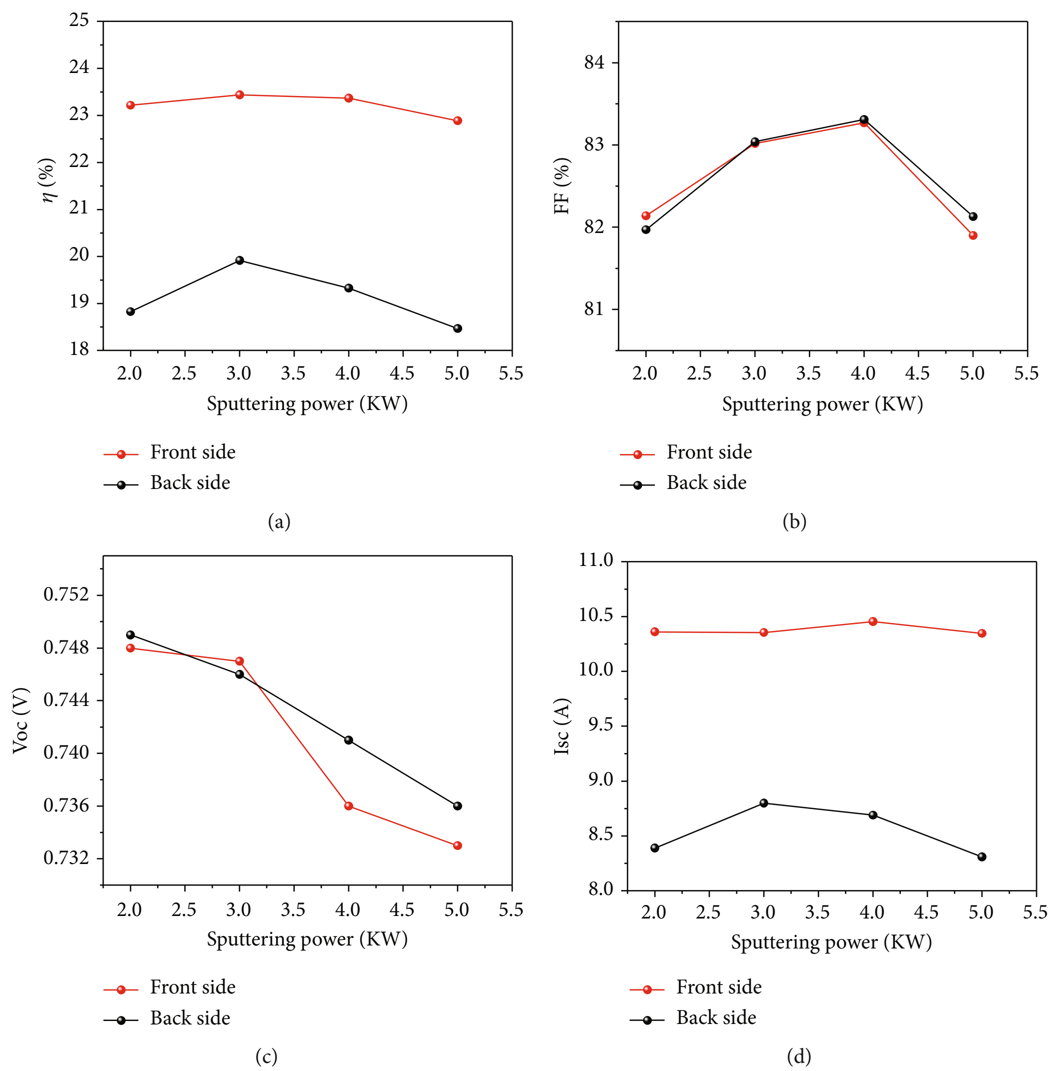


FIGURE 7: Optoelectronic properties of HJT solar cells with different sputtering power (a) $\eta$, (b) FF, (c) Voc, and (d) Isc.

transmittance of the ITO films. In addition, the carrier concentration reaches the maximum with the increase of sputtering power, resulting in a decrease in transmittance.

It can be seen from Figure 7 that the efficiency of the solar cells increases with the increase in sputtering power; FF rises and Voc falls due to the amorphous silicon layer being damaged by high-energy particle bombardment with the increase of sputtering power, which leads to the built-in field weakening of the P-N junction and then Voc dropping. At the same time, it is found that the minority carrier lifetime decreases with the increase of sputtering power after deposition of ITO films by PVD, and the Voc decreases. The Isc shows an upward trend with the increase of sputtering power. However, the bombardment on the amorphous silicon layer further increases when the sputtering power is higher than 3 kw, resulting in a decrease of efficiency. At the same time, the average efficiency of the back side of the cells is 19.36%, and the average bifacial ratio reaches 82.4%.

In conclusion, HJT solar cells has excellent optoelectronic properties when sputtering power is 3 kw. Increase sputtering power is conducive to the improvement of the FF and Isc of solar cells.

## 4. Conclusion

In this paper, ITO films are prepared by DC magnetron sputtering. The effects of oxygen content, deposition temperature, and sputtering power on the electrical and optical properties of ITO films and optoelectronic properties of HJT solar cells are studied. Results show that the properties of ITO films change with different process parameters. The resistivity of ITO films is very sensitive to oxygen content; the resistivity of ITO films increases with the increase of oxygen content; increasing deposition temperature helps to improve the transmittance of ITO films; and increasing the sputtering power causes the resistance of the ITO films to first decrease and then increase. Too high sputtering power will cause damage to the film, resulting in a serious decrease in the minority carrier lifetime. Therefore, ITO films have excellent electrical and optical performance when the oxygen content is 2.2%, the sputtering power is 3 kw, and deposition temperature is 190°C. Therefore, solar cells also exhibit excellent optoelectronic properties, such as a resistance is $6.4^{*}10^{-4}\,\Omega$•cm, light transmittance is beyond 90.9%, the efficiency is 23.78%, and bifacial ratio is beyond 80%.

## Data Availability

The data used to support the findings of this study are included within the article.

## Conflicts of Interest

The authors declare that they have no conflicts of interest.

## Acknowledgments

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