OPTIMIZATION OF RF-SPUTTERED ITO THIN FILMS FOR AUTOMOTIVE DISPLAY AND HEAD-UP DISPLAY APPLICATIONS

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ABSTRACT

Indium tin oxide (ITO) thin films are widely used as transparent electrodes in display technologies; however, automotive display and head-up display (HUD) applications impose additional requirements on optical stability, electrical reliability, and mechanical robustness. In this study, ITO thin films were deposited on glass substrates by radio-frequency (RF) magnetron sputtering, and the effect of sputtering power on their optical, electrical, and mechanical properties was systematically investigated. The RF sputtering power was varied from 40 W to 70 W while other deposition parameters were kept constant. Optical transmittance measurements show that all films exhibit high transparency exceeding 80% in the visible region, whereas changes in absorption edge position and optical constants indicate power-dependent microstructural evolution. Electrical characterization reveals a significant reduction in resistivity and sheet resistance with increasing sputtering power up to an optimal condition, beyond which electrical performance degrades due to defect formation. Residual stress analysis demonstrates that compressive stress strongly depends on sputtering power, with a pronounced minimum observed at an intermediate power level. Among the investigated conditions, an RF sputtering power of 60 W yields the most balanced performance, combining high optical transparency, low electrical resistivity, smooth surface morphology, and minimal residual stress. These results provide practical guidelines for optimizing RF-sputtered ITO thin films for automotive display and head-up display applications, where optical quality and long-term reliability are critical.

1. INTRODUCTION

The rapid evolution of intelligent vehicles has significantly increased the demand for advanced in-vehicle display technologies, including digital instrument clusters, center infotainment systems, and head-up displays (HUDs) (Das et al. 2023). These automotive display systems are required to operate reliably under harsh environmental conditions, such as wide temperature variations, mechanical vibration, and long-term thermal cycling, while maintaining high optical clarity and electrical performance. Consequently, the materials used for transparent conductive layers play a critical role in ensuring both functional performance and long-term reliability of automotive displays (Wang et al. 2025).

Indium tin oxide (ITO) is widely regarded as the industrial standard transparent conducting oxide (TCO) due to its excellent combination of high optical transmittance in the visible spectrum and low electrical resistivity. ITO thin films have been extensively employed in consumer electronics, including flat-panel displays, touch panels, and photovoltaic devices. In recent years, their application has expanded to automotive electronics, particularly in HUD systems and vehicle dashboards, where transparent electrodes must exhibit not only high optoelectronic performance but also strong mechanical stability to withstand automotive operating environments (Hossain et al. 2024).

Among various deposition techniques, radio-frequency (RF) magnetron sputtering has emerged as one of the most reliable and controllable methods for fabricating high-quality ITO thin films. This technique offers advantages such as uniform film thickness, good adhesion to glass substrates, reproducibility, and compatibility with low-temperature processing (Panaitescu and Antohe 2023). However, the properties of RF-sputtered ITO films are highly sensitive to deposition parameters, including sputtering power, working pressure, gas composition, and substrate conditions. In particular, sputtering power directly influences the kinetic energy of sputtered particles, thereby affecting film microstructure, packing density, surface morphology, and residual stress (Lunca-Popa et al. 2023).

Residual stress in ITO thin films is a critical yet often overlooked factor in automotive display applications. Excessive compressive or tensile stress can lead to film cracking, delamination, or optical distortion, especially when films are deposited on glass substrates subjected to thermal expansion mismatch and mechanical vibration. These issues are particularly severe in HUD and windshield-integrated display systems, where optical uniformity and mechanical reliability are paramount. Therefore, minimizing residual stress while maintaining high transparency and low electrical resistance is essential for vehicle-grade transparent electrodes (Patel et al. 2024).

Although previous studies have investigated the optical and electrical properties of ITO thin films deposited under different sputtering conditions, systematic studies focusing on the combined optimization of optoelectronic performance and residual stress for automotive display and HUD applications remain limited. In particular, the relationship between RF sputtering power and stress-induced reliability constraints relevant to automotive environments has not been sufficiently addressed (Sahoo, Au, and Pan 2024).

In this paper, RF-sputtered ITO thin films were deposited on glass substrates under different sputtering power conditions, and their optical transmittance, refractive index, electrical resistivity, surface roughness, and residual stress were systematically characterized. Special emphasis is placed on identifying a sputtering power window that achieves a balanced combination of high optical transparency, acceptable electrical conductivity, smooth surface morphology, and minimal residual stress. The results provide practical guidelines for optimizing ITO thin films intended for automotive display and head-up display applications, where both performance and long-term reliability are critical.

The main contributions of this work are threefold. First, the study systematically evaluates the influence of RF sputtering power on optical, electrical, and mechanical properties of ITO thin films under room-temperature deposition conditions. Second, unlike many previous studies that emphasize only transparency and conductivity, this work treats residual stress and surface smoothness as equally important optimization criteria for automotive display and HUD applications. Third, the study identifies an intermediate sputtering power of 60 W as the condition that provides the best overall balance between high transparency, low resistivity, and low residual stress, which is particularly relevant to vehicle-grade transparent electrode design.

2. RELATED WORK

Transparent conductive oxides for automotive displays and HUDs: Automotive display systems (instrument clusters, infotainment panels, and HUDs) require transparent electrodes that simultaneously provide high visible transmittance, low sheet resistance, and stable operation under harsh conditions such as temperature cycling, vibration, and prolonged sunlight exposure. Transparent conducting oxides (TCOs) are the dominant materials class used for this purpose because they enable optical transparency while maintaining electrical conductivity (Nguyen, Tran, and Bark 2023). Among available TCOs, indium tin oxide (ITO) remains the most widely adopted in commercial display stacks due to its mature processing, high optical quality, and strong compatibility with large-area glass substrates. For HUD and windshield-related optics, the transparent electrode layer must also maintain uniform optical properties to avoid haze, color shift, and distortion. Therefore, automotive-oriented research often evaluates not only transmittance and resistance, but also film uniformity, surface morphology, and long-term stability in conditions representative of vehicle operation (Cadenas et al. 2025).

Deposition approaches for ITO thin films: ITO thin films have been fabricated using multiple techniques, including sol–gel spin coating, spray pyrolysis, and electron-beam evaporation, each offering different trade-offs in film density, uniformity, process temperature, and scalability. Solution-based techniques are attractive for cost and simplicity, but may face challenges in achieving high density and low resistivity without high-temperature annealing (Sumayya et al. 2025). Physical vapor deposition methods, such as evaporation, can produce uniform films but often require careful control to balance optical quality and conductivity. In contrast, RF magnetron sputtering is widely used in industry because it provides excellent uniformity, reproducibility, adhesion, and compatibility with room-temperature or low-temperature processing. These advantages make RF sputtering highly relevant for automotive display manufacturing, where consistent quality across large panels is critical (Wang and Chu 2023).

Effect of sputtering power on optoelectronic properties: Within RF sputtering, the sputtering power is one of the most influential parameters because it directly affects the energy and flux of the arriving species on the substrate. Prior studies generally show that power can strongly modify film microstructure, which in turn impacts both refractive index and electrical transport (Carrasco-Hernández et al. 2025). As power increases, films may become denser and more conductive up to an optimum region; however, overly high power can introduce defects, increase roughness, or degrade optical quality, depending on the process window and gas composition. Because automotive displays and HUDs demand a balanced set of properties, it is not sufficient to optimize conductivity alone. Practical automotive-oriented optimization typically targets a combined figure of merit, seeking high transmittance, low sheet resistance, and stable optical constants (Nowsherwan et al. 2025).

Surface roughness and interface requirements in display stacks: Surface morphology plays a key role in display device performance. Rough ITO surfaces can lead to non-uniform electric fields, higher leakage currents, and increased defect density in adjacent functional layers. In OLED-based or multilayer optical stacks commonly used in advanced displays, higher roughness can accelerate degradation and reduce yield. Therefore, many works emphasize controlling ITO roughness through deposition conditions, where sputtering power, pressure, and oxygen fraction are among the most important levers. For HUD and automotive glass optics, low roughness also helps maintain high optical clarity and reduces scattering that can manifest as haze or unwanted stray light (Diletto et al. 2024).

Residual stress, mechanical reliability, and automotive relevance: Residual stress in thin films is a critical reliability factor, especially on glass substrates. Excessive compressive or tensile stress can lead to cracking, buckling, delamination, and gradual performance drift failure modes that become more likely under thermal cycling and vibration. In automotive environments, such stress-driven degradation is particularly concerning because components must maintain stable performance over long service lifetimes. Stress in sputtered films is known to depend on deposition energy, microstructure evolution, and defect incorporation (Petrovska et al. 2022). Since sputtering power strongly controls particle energy and film growth dynamics, it is frequently linked to stress variation. However, compared with studies focusing primarily on transmittance and resistivity, fewer works treat residual stress as a co-equal optimization target for automotive display/HUD electrodes. This creates a practical need for systematic studies that optimize optoelectronic properties together with stress (Alabdan et al. 2024).

Stress and roughness metrology for thin film optimization: Reliable optimization requires measurement methods capable of quantifying film stress and surface texture with high sensitivity. Interferometric techniques are commonly adopted to evaluate substrate curvature, surface profile, and thin-film-induced deformation, making them suitable for comparing films deposited under different sputtering conditions. By combining optical metrology with electrical probing and optical spectroscopy (UV–Vis, ellipsometry), researchers can build a comprehensive understanding linking deposition parameters → microstructure → performance and reliability (Seyhan and Kartal 2023).

Previous research establishes that RF sputtering is a practical route to high-quality ITO, and that sputtering power significantly influences optical constants, conductivity, and morphology. Nevertheless, for automotive display and HUD applications, there remains a need for systematic optimization that treats residual stress and surface roughness as core constraints alongside transmittance and sheet resistance. Motivated by this gap, the present work focuses on identifying a sputtering power window that achieves a balanced combination of high transparency, acceptable electrical performance, smooth surface, and low residual stress, which is essential for vehicle-grade transparent electrodes (Nisha and Sahu 2024).

3. METHODOLOGY

Materials and deposition procedure

ITO thin films were deposited on glass substrates using a radio-frequency (RF) magnetron sputtering system to evaluate their suitability for automotive display and head-up display (HUD) applications. Commercial B270 glass substrates were selected because of their high optical transparency and compatibility with vehicle-grade display systems. Before deposition, the substrates were sequentially cleaned in acetone, ethanol, and deionized water using ultrasonic agitation, followed by nitrogen drying to ensure a contamination-free surface.

A ceramic ITO target composed of 90 wt% In_2O_3 and 10 wt% SnO_2 with a purity of 99.99% was employed. The sputtering chamber was evacuated to a base pressure of approximately 2×10^{-6} Torr to minimize residual gas contamination. During deposition, argon was used as the primary sputtering gas, while a controlled oxygen flow was introduced to regulate film stoichiometry. The working pressure was maintained at 2.1×10^{-3} Torr, and all films were deposited at room temperature to ensure compatibility with automotive glass substrates. To investigate the effect of sputtering power, RF powers of 40 W, 50 W, 60 W, and 70 W were applied, while other parameters were kept constant to isolate the influence of power on film properties.

Assumptions and constraints

To ensure a controlled comparison of the effect of RF sputtering power, several assumptions and constraints were adopted in this study. First, all films were deposited on the same B270 glass substrate type to eliminate substrate-dependent variability. Second, except for sputtering power, all other deposition parameters, including chamber pressure, substrate temperature, target composition, and gas-flow conditions, were maintained constant. Third, the films were assumed to be laterally uniform over the measured region, allowing point-based measurements to represent the overall sample behavior. Fourth, the stress analysis was performed using Stoney's equation, which assumes that the film thickness is much smaller than the substrate thickness and that the substrate behaves elastically. Fifth, optical and electrical measurements were interpreted under the assumption that the deposited films were continuous and sufficiently homogeneous for comparative analysis. Finally, the automotive applicability discussed in this study is limited to material-level transparent electrode performance and does not yet include full device-level validation under environmental reliability tests.

The optical transmittance of the deposited ITO thin films was measured using a UV–visible spectrophotometer over the wavelength range of 300–1000 nm, covering the visible and near-infrared regions relevant to automotive display optics. The average optical transmittance T_{avg} in the visible region was calculated as (Cadenas et al. 2025):

$$T_{\text{avg}} = \frac{1}{\lambda_2 - \lambda_1} \int_{\lambda_1}^{\lambda_2} T(\lambda)\, d\lambda \tag{1}$$

In Equation (1), $T(\lambda)$ denotes the optical transmittance as a function of wavelength. The parameters λ_1 and λ_2 represent the lower and upper bounds of the wavelength range used for averaging. Optical measurements were conducted in the range of 300–1000 nm, while the visible region was mainly considered for evaluating the suitability of the films for automotive display and head-up display applications.

To further analyze the optical behavior, spectroscopic ellipsometry was employed to determine the refractive index nnn and extinction coefficient k of the ITO films. These optical constants are related to the complex refractive index $\tilde{n}$ by (Cadenas et al. 2025)

$$\tilde{n} = n + ik, \quad (2)$$

Where n reflects the film density and microstructure, while k is associated with optical absorption losses. Variations in these parameters provide insight into how sputtering power influences film compactness and optical quality.

Electrical properties were evaluated using a four-point probe method to measure sheet resistance and resistivity. The sheet resistance R_s was directly obtained from probe measurements, and the electrical resistivity ρ was calculated using (Cadenas et al. 2025)

$$\rho = R_s \cdot t, \quad (3)$$

Where t denotes the film thickness. Low resistivity and sheet resistance are essential for transparent electrodes in automotive displays to ensure efficient current spreading and stable luminance performance.

Surface morphology was characterized using a Linnik-type optical interferometric microscope combined with fast Fourier transform (FFT) analysis. The average surface roughness R_a was extracted from the height profile $z(x)$ according to (Hossain et al. 2024)

$$R_a = \frac{1}{L}\int_0^L |z(x)|\, dx, \quad (4)$$

Where L represents the evaluation length. Maintaining low surface roughness is critical for automotive display stacks, as excessive roughness can induce optical scattering and degrade adjacent functional layers.

Residual stress in the ITO thin films was evaluated using a Twyman–Green interferometer to measure substrate curvature before and after film deposition. The residual stress σ was calculated using Stoney's equation (Wang and Chu 2023):

$$\sigma = \frac{E_s t_s^2}{6(1-\nu_s)t_f}\left(\frac{1}{R}\right), \quad (5)$$

Where E_s and ν_s are the Young's modulus and Poisson's ratio of the substrate, respectively, tst_sts is the substrate thickness, t_f is the film thickness, and R is the radius of curvature induced by the film. Residual stress is a critical reliability parameter for automotive display and HUD systems, as excessive stress can lead to cracking, delamination, or optical distortion under thermal cycling and vibration.

Experimental setup and measurement conditions

The ITO thin films were deposited using an RF magnetron sputtering system equipped with a 99.99% purity ceramic ITO target with a composition of 90 wt% In_2O_3 and 10 wt% SnO_2. Commercial B270 glass substrates were used as deposition substrates. The base pressure of the chamber was approximately 2×10^{-6} Torr, while the working pressure during sputtering was maintained at 2.1×10^{-3} Torr. Argon was used as the primary sputtering gas, and oxygen was introduced at a controlled flow rate to regulate the film stoichiometry. The RF sputtering power was varied from 40 W to 70 W. Optical transmittance was measured using a UV–Vis spectrophotometer over the wavelength range of 300–1000 nm. The refractive index and extinction coefficient were determined using a PSA ellipsometer. The sheet resistance was measured by a four-point probe system. Surface roughness was characterized using a Linnik interferometric microscope with FFT-based analysis, while residual stress was evaluated using a Twyman–Green interferometer. The experimental conditions were kept unchanged except for sputtering power to ensure that the observed changes could be attributed primarily to the variation in deposition power

Experimental Workflow

The overall experimental workflow consists of five main steps. First, glass substrates were cleaned to remove contamination and ensure uniform film growth. Second, ITO thin films were deposited under different RF sputtering powers while maintaining constant chamber pressure and gas-flow conditions. Third, the deposited films were optically characterized by UV–Vis spectroscopy and ellipsometry. Fourth, electrical conductivity, surface roughness, and residual stress were measured using a four-point probe, a Linnik interferometric microscope, and a Twyman–Green interferometer, respectively. Finally, all measured parameters were comparatively analyzed to identify the sputtering power that provides the best balance between transparency, conductivity, smoothness, and low residual stress for automotive display applications

For each sputtering condition, measurements were repeated at multiple positions on the sample surface to evaluate repeatability and spatial uniformity. The values shown in Figures 2 and 3 are presented as mean ± standard deviation. The refractive index and extinction coefficient were extracted from ellipsometry fitting, while the residual stress was calculated from curvature measurements using Stoney's equation. The observed deviations are attributed to local thickness non-uniformity, small variations in film density, and measurement sensitivity associated with interferometric and optical fitting procedures.

4. EXPERIMENTAL RESULTS

The optical transmittance spectra of the RF-sputtered ITO thin films deposited at different sputtering powers are shown in the wavelength range of 300–1000 nm. All samples exhibit high optical transparency, with average transmittance exceeding 80% across the visible spectrum, which satisfies the basic optical requirements for automotive display and head-up display (HUD) applications. As the RF sputtering power increases from 40 W to 70 W, a gradual red-shift of the absorption edge is observed, indicating changes in film microstructure and carrier concentration. These results suggest that sputtering power plays a significant role in modifying the optical band structure and density of the deposited ITO films.

Spectroscopic ellipsometry measurements were used to extract the refractive index and extinction coefficient of the films as a function of sputtering power. The refractive index initially increases slightly when the power is raised from 40 W to 50 W, indicating improved film densification due to increased adatom energy. However, at higher powers, particularly at 60 W and 70 W, the refractive index decreases, suggesting the formation of a more porous microstructure or increased defect incorporation. The extinction coefficient exhibits a similar power-dependent trend, where moderate sputtering power enhances absorption due to increased carrier concentration, while excessive power leads to reduced optical quality. For automotive HUD systems, maintaining a stable refractive index and low extinction coefficient is critical to minimize optical distortion and absorption losses.

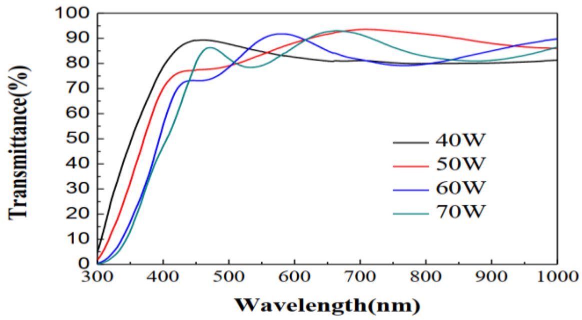

Figure 1. Schematic illustration of RF magnetron sputtering deposition of ITO thin films on glass substrates for automotive display applications.

Figure 1 shows the optical transmittance spectra of ITO thin films deposited at different RF sputtering powers in the wavelength range from 300 to 1000 nm. All samples exhibit high optical transparency, with visible transmittance exceeding 80%, confirming their suitability for automotive display and head-up display (HUD) applications. As the RF power increases from 40 W to 70 W, a gradual red-shift of the absorption edge is observed. This shift is attributed to changes in carrier concentration and microstructural evolution caused by increased kinetic energy of the sputtered species. Among the investigated conditions, films deposited at intermediate RF powers (50–60 W) exhibit more stable and uniform transmittance across the visible region, which is critical for reducing color distortion and ensuring uniform luminance in HUD optical paths.

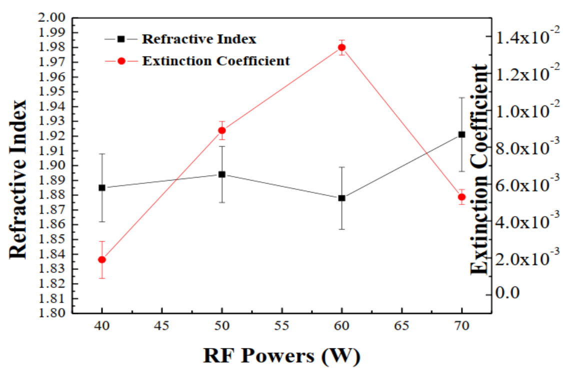

Figure 2. Application of RF-sputtered ITO thin films in automotive display systems, including instrument clusters and center infotainment panels.

The variation of refractive index and extinction coefficient with RF sputtering power is presented in the Figure 2. The refractive index increases slightly when the power is raised from 40 W to 50 W, indicating improved film densification and packing density due to enhanced adatom mobility. However, further increasing the power to 60 W and 70 W results in a decrease in refractive index, suggesting the formation of a less compact microstructure or the introduction of defects. The extinction coefficient shows a pronounced increase at 60 W, followed by a significant decrease at 70 W, revealing a trade-off between optical absorption and carrier concentration. Such variations in optical constants are particularly important for automotive HUD systems, where refractive index stability and low optical loss are essential to minimize ghost images and optical distortion.

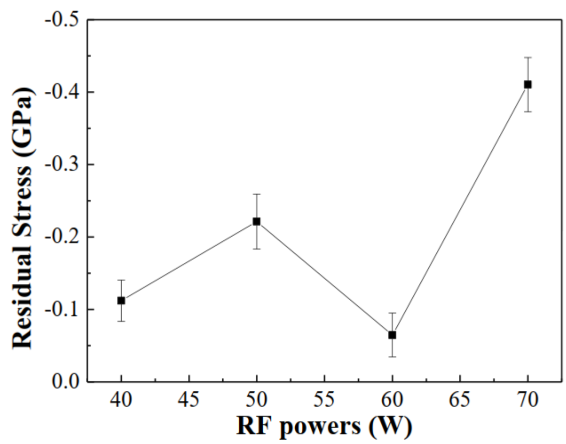

Figure 3. Conceptual diagram of head-up display (HUD) integration using transparent ITO electrodes deposited on automotive glass.

Figure 3 illustrates the dependence of residual stress on RF sputtering power. All deposited ITO films exhibit compressive residual stress, which is commonly associated with atomic peening effects in sputtered oxide films. The magnitude of compressive stress increases from 40 W to 50 W, decreases markedly at 60 W, and then increases sharply at 70 W. The minimum residual stress observed at 60 W indicates a balanced growth condition in which sufficient adatom mobility allows stress relaxation without excessive defect formation. This reduction in residual stress is highly advantageous for automotive applications, as it enhances mechanical stability and reduces the risk of cracking, delamination, and optical deformation under thermal cycling and vibration.

The error bars in Figure 2 indicate that the variation in refractive index is relatively small, suggesting acceptable optical uniformity among the deposited samples. The larger deviation observed at some sputtering powers may be associated with differences in film packing density and fitting uncertainty in the ellipsometry model. In Figure 3, the deviation in residual stress reflects the sensitivity of curvature-based measurement to local stress distribution and microstructural non-uniformity. The lowest stress obtained at 60 W is not only lower in magnitude but also indicates a more stable growth regime compared with the higher-stress conditions at 50 W and 70 W.

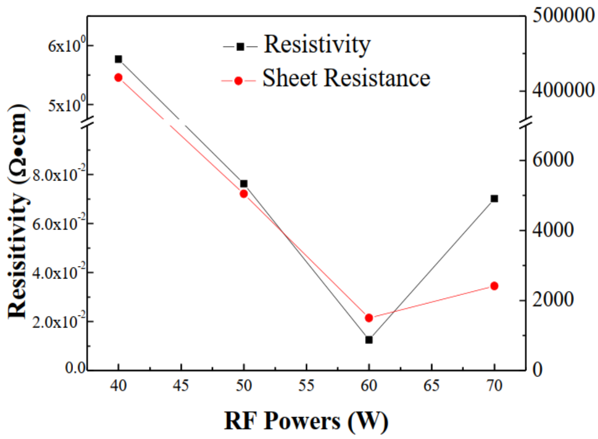

Figure 4. Key optimization targets of RF-sputtered ITO thin films for automotive displays, highlighting optical transmittance, electrical conductivity, and residual stress control.

The electrical resistivity and sheet resistance as functions of RF sputtering power are shown in the Figure 4. At low RF power (40 W), the films exhibit high resistivity and sheet resistance, which can be attributed to insufficient energy for effective film densification and carrier activation. Increasing the RF power leads to a significant decrease in both resistivity and sheet resistance, reaching minimum values at 60 W. This improvement is associated with enhanced crystallinity and increased carrier mobility. However, when the power is further increased to 70 W, electrical performance deteriorates, likely due to increased defect density and stress-induced scattering. The observed electrical trends highlight the existence of an optimal sputtering power window rather than a monotonic improvement with increasing power.

Figure 4 shows that both resistivity and sheet resistance decrease sharply when the RF sputtering power increases from 40 W to 60 W, indicating a rapid improvement in electrical transport in this power range. This steep slope suggests that increasing sputtering power initially provides sufficient particle energy to enhance film densification, reduce voids, and improve carrier mobility. However, when the power is further increased from 60 W to 70 W, the resistivity rises again, and the slope changes direction. This reversal indicates that the beneficial effect of increasing deposition energy is no longer dominant; instead, defect generation and stress-related scattering begin to degrade charge transport. Therefore, the electrical behavior is not monotonic, and the change in slope clearly identifies 60 W as the optimal operating point

The observed trends can be explained by the energy-dependent growth mechanism of RF-sputtered ITO films. At low sputtering power, the kinetic energy of sputtered particles is insufficient to promote dense packing and defect reduction, resulting in a porous microstructure, lower carrier mobility, and higher resistivity. As the sputtering power increases, enhanced adatom mobility improves film densification and electrical transport. However, excessive power also increases bombardment-induced damage and atomic peening effects, which generate defects and elevate compressive stress. Therefore, the optimum sputtering power is determined by a balance between densification and defect-induced degradation

The obtained results are consistent with the general trends reported in previous RF-sputtered ITO studies, where sputtering power strongly influences optical transparency, electrical conductivity, and film microstructure. In comparison with earlier works that mainly emphasize transmittance and resistivity, the present study additionally considers residual stress as a key optimization criterion. This is particularly important for automotive display and HUD applications, where thermal cycling, vibration, and glass–film mechanical compatibility significantly affect long-term reliability. Therefore, the present work extends the conventional optimization framework by incorporating optical, electrical, and mechanical criteria simultaneously

5. CONCLUSION

In this study, the effect of RF sputtering power on the optical, electrical, and mechanical properties of ITO thin films was systematically investigated with the aim of identifying suitable deposition conditions for automotive display and head-up display (HUD) applications. ITO thin films were deposited on glass substrates at different RF powers, and their optical transmittance, optical constants, electrical resistivity, surface roughness, and residual stress were comprehensively evaluated.

The experimental results demonstrate clearly that RF sputtering power has a significant influence on film performance. All deposited films exhibit high optical transparency exceeding 80% in the visible region; however, variations in absorption edge position, refractive index, and extinction coefficient reveal that excessive sputtering power may degrade optical quality. Electrical measurements show that increasing sputtering power improves conductivity up to an optimal point, beyond which electrical performance deteriorates due to defect formation and stress-induced scattering. Residual stress analysis further indicates that compressive stress is strongly dependent on sputtering power, with excessive stress observed at both low and high-power conditions.

Among the investigated parameters, an RF sputtering power of 60 W provides the most balanced performance, yielding high optical transparency, low electrical resistivity, smooth surface morphology, and minimal residual stress. This optimized condition is particularly advantageous for automotive applications, where transparent electrodes must maintain optical clarity and mechanical stability under thermal cycling, vibration, and long-term operation.

One of the primary challenges in optimizing ITO thin films for automotive applications lies in the conflicting effects of sputtering power. Increasing sputtering power can improve conductivity through enhanced densification and carrier transport, but it can also induce defect formation, higher optical loss, and elevated compressive stress. Therefore, the optimization process requires balancing multiple interdependent properties rather than maximizing a single performance metric.

Future work will extend this study in three main directions. First, thermal cycling, humidity exposure, and vibration tests will be conducted to evaluate the long-term reliability of the optimized ITO films under automotive environmental conditions. Second, the optimized films will be integrated into prototype automotive displays or HUD structures to verify device-level optical and electrical performance. Third, additional deposition parameters, such as oxygen flow rate, substrate temperature, and post-deposition annealing, will be investigated to further improve the balance between transparency, conductivity, and mechanical stability.

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TỐI ƯU HÓA MÀNG MỎNG ITO PHÚN XẠ RF CHO CÁC ỨNG DỤNG MÀN HÌNH Ô TÔ VÀ MÀN HÌNH HUD

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TỪ KHOÁ

Indium thiếc oxit (ITO);

Phun phủ magnetron tần số vô tuyến;

Màn hình ô tô;

Màn hình hiển thị trên kính chắn gió (HUD);

Tối ưu hóa ứng suất.

TÓM TẮT

Màng mỏng Indium Tin Oxide (ITO) được sử dụng rộng rãi làm điện cực trong suốt trong các công nghệ hiển thị; tuy nhiên, các ứng dụng màn hình ô tô và màn hình hiển thị trên kính lái (HUD) đặt ra những yêu cầu khắt khe hơn về độ ổn định quang học, độ tin cậy về điện và độ bền cơ học. Trong nghiên cứu này, các màng mỏng ITO đã được lắng đọng trên đế thủy tinh bằng phương pháp phún xạ magnetron cao tần (RF), đồng thời ảnh hưởng của công suất phún xạ lên các tính chất quang, điện và cơ học của màng đã được khảo sát một cách hệ thống.

Công suất phún xạ RF được thay đổi trong khoảng từ 40 W đến 70 W trong khi các thông số lắng đọng khác được giữ nguyên. Kết quả đo độ xuyên thấu quang học cho thấy tất cả các màng đều có độ trong suốt cao, vượt quá 80% trong vùng ánh sáng nhìn thấy; trong khi đó, những thay đổi về vị trí bờ hấp thụ và các hằng số quang học cho thấy sự biến đổi cấu trúc vi mô phụ thuộc vào mức công suất. Phân tích đặc tính điện cho thấy điện trở suất và điện trở mặt giảm đáng kể khi tăng công suất phún xạ đến một điều kiện tối ưu, vượt quá mức đó hiệu suất điện sẽ suy giảm do sự hình thành các khuyết tật cấu trúc.

Phân tích ứng suất dư cho thấy ứng suất nén phụ thuộc mạnh mẽ vào công suất phún xạ, với giá trị cực tiểu rõ rệt được quan sát thấy ở mức công suất trung gian. Trong số các điều kiện được khảo sát, công suất phún xạ RF 60 W mang lại hiệu suất cân bằng nhất, kết hợp được độ trong suốt quang học cao, điện trở suất thấp, hình thái bề mặt mịn và ứng suất dư tối thiểu. Những kết quả này cung cấp các hướng dẫn thực tế để tối ưu hóa màng mỏng ITO phún xạ RF cho các ứng dụng màn hình ô tô và màn hình HUD, nơi chất lượng quang học và độ tin cậy dài hạn là những yếu tố then chốt.