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Uniformity Improvement Techniques for IGZO Thin Film Transistors

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Abstract. This study focuses on key technical strategies for enhancing the uniformity of indium gallium zinc oxide (IGZO) thin-film transistors (TFTs), a critical factor for their industrial scalability. A comprehensive comparison is made between conventional vacuum-based deposition methods, such as sputtering, atomic layer deposition (ALD), chemical vapor deposition (CVD), and emerging solution-based technologies, including spin coating, inkjet printing, and spray pyrolysis. The analysis identified precursor formulations, deposition parameters, interface engineering, and post-treatment methods, such as laser or plasma annealing, that play decisive roles in improving microstructural quality and electrical uniformity. This paper compared the effects of vacuum deposition and solution techniques on IGZO thin-film transistors, found that material composition, deposition conditions, and post-treatment processes are the keys to improving device uniformity.

Keywords: IGZO; TFTs; Uniformity.

1. Introduction

Thin film transistors (TFTs) as core components of modern electronic devices, are widely used in liquid crystal displays (LCDs), organic light-emitting diode displays (OLEDs), and flexible electronic devices. In recent years, Indium Gallium Zinc Oxide (IGZO) has emerged as an ideal semiconductor material for the new generation of display technology over traditional amorphous silicon (a-Si) and poly-Si due to its high electron mobility, excellent transparency, low leakage current, and good electrical stability.

Currently, the mainstream IGZO thin film preparation techniques include traditional vacuum deposition methods such as sputtering, chemical vapor deposition, and atomic layer deposition, as well as emerging solution-based techniques including spin coating, inkjet printing, spraying, and dip coating.

Although the vacuum deposition method can produce high-quality films, it suffers from problems such as complex and expensive equipment, cumbersome operation process, and high processing temperature. These factors make it difficult to maintain the film thickness and property consistently over a large area of the substrate and thus create a more serious uniformity problem. In contrast, the solution process has gradually received extensive attention from academia and industry due to its simple equipment, process flexibility, lower processing temperature (generally below 300°C), and reduced cost. However, since the solution method is affected by multiple factors such as precursor solution composition, coating conditions, drying, and annealing process, it is still a big challenge to obtain films with uniform and stable thickness and properties in actual production. In conclusion, both methods need to address the issue of uniformity control. Therefore, deeply exploring the uniform growth mechanism of thin films during the solution preparation process is one of the key scientific issues for achieving high-performance device manufacturing.

To systematically solve the uniformity problem in IGZO thin film transistors, this paper thoroughly investigates the causes of non-uniformity and evaluates corresponding solutions within mainstream fabrication techniques. This paper first analyzes the key factors contributing to the non-uniformity of IGZO films prepared by both vacuum-based and solution-based methods and proposes the process methods and routes that can effectively improve the uniformity of IGZO films. Finally, a critical evaluation was conducted on the practical effects and economic advantages of various membrane preparation techniques in enhancing uniformity, and a solution most suitable for industrialization was obtained.

2. Principles and Structure of IGZO Thin Film Transistors

2.1. IGZO-based TFTs Structure

IGZO-based TFTs may be bottom-gate or top-gate with an apparent impact on device performance and integration. Bottom-gate TFTs are simpler to fabricate, while top-gate designs provide better protection from the environment. Additionally, a hybrid and self-aligned architecture has been proposed for improved functionality [1].

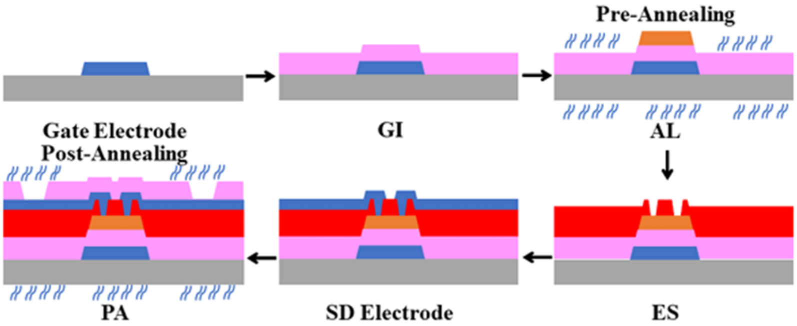

Fig. 1 Schematic fabrication process flow of an a-IGZO TFT, highlighting pre- and post-annealing steps, active layer formation, and electrode deposition [1].

2.2. IGZO Deposition Techniques

Depending on the deposition technique, IGZO thin films can be fabricated using physical and chemical vapor deposition methods, atomic layer deposition, or solution techniques. RF magnetron sputtering, a physical vapor deposition (PVD) technique, is extensively used in industry due to its excellent control over film thickness and high uniformity across large-area substrates. For instance, parameters such as gas composition, substrate temperature, and sputtering power employed during deposition directly affect the stoichiometry and electronic properties of the films. Meanwhile, vacuum-based methods like ALD and CVD provide superior uniformity and atomic-level control, but with higher capital and processing costs.

In contrast, solution-based methods like spin coating, inkjet printing, and spray pyrolysis offer inexpensive and scalable fabrication routes, making them particularly attractive for flexible electronics and rapid prototyping. These methods enable direct patterning on polymer substrates and improve compatibility. However, solution-processed IGZO films still suffer from challenges such as grain boundary formation, microstructural inhomogeneity, and stoichiometric variation, despite their economic and processing advantages.

Such imperfections can lead to random dopant fluctuations, threshold voltage fluctuation, subthreshold slope degradation, and reduced carrier mobility due to grain boundaries and inhomogeneities, resulting in incomplete conduction within the substrate. In addition to improvements in deposition methods, researchers have increasingly explored hybrid approaches, where low-cost and low-density films are first deposited, followed by post-treatment techniques such as thermal or laser annealing and plasma exposure. These post-treatments enhance film densification and reduce defect densities, thereby mitigating the inherent limitations of solution-based methods.

2.3. Influencing Factors of IGZO Film Uniformity

Several parameters critically influence the uniformity of IGZO TFTs, including oxygen vacancy concentration, precursor purity, deposition temperature, annealing conditions, and substrate surface roughness. Oxygen vacancies act as electron donors and must be carefully controlled to ensure stable electrical properties [2]. Thermal annealing, particularly multi-step annealing processes, has proven effective in minimizing threshold voltage shifts and enhancing the device stability [3]. Furthermore, factors such as interface state, passivation layers, and exposure to ambient environments significantly influence the long-term reliability of the devices [1].

3. Processing techniques for IGZO film stability

The IGZO thin film preparation technology is divided into vacuum deposition and solution process. The former has high precision but high cost, while the latter is flexible and adaptable but relies on the optimization of precursors. By combining post-treatment and structural optimization to enhance performance, the two technologies work together to promote the large-scale application of IGZO-TFT in flexible displays.

3.1. Vacuum-based Deposition Techniques

Vacuum deposition technology achieves high-precision IGZO thin film preparation through RF magnetron sputtering, ALD, and CVD. RF is suitable for large-scale mass production, ALD considers low temperature and complex surface film formation, and CVD is fast but requires temperature control. Overall, although the precision is excellent enough, the high cost and complexity of processes still need to be optimized.

3.1.1. RF Magnetron Sputtering

Radio frequency magnetron sputtering is a widely adopted process in industry for IGZO deposition. By adjusting the sputtering power, argon gas flow rate and substrate temperature, highly uniform and defect-free IGZO layers can be obtained. This approach enables control over the thickness, composition, and uniformity of the thin film [3]. It is also suitable for large-sized substrates, making it highly attractive for commercial applications such as OLED and LCD panels.

3.1.2. Atomic Layer Deposition

Atomic layer deposition, as a thin film preparation technology based on self-limiting surface chemical reactions, is crucial for depositing uniform IGZO films on high aspect ratio or complex surfaces due to its ability to produce films with atomic-level precision and conformal coatings. Due to its compatibility with low-temperature processes, ALD is also often the ideal choice for flexible electronics and back-end-of-line (BEOL) integration.

As to improve electrical performance and stability of ALD-grown IGZO films, some recent works have focused on compositional engineering approaches, incorporating alloying elements such as lanthanum and yttrium–while, to the best of our knowledge, no studies have yet considered magnitude of vertical conductivity and its influence in the performance of an yttrium-doped film over a ferroelectric dielectric oxide. These dopants also exhibited good properties such as lowered interface trap density along with better carrier mobility and bias stability [4].

3.1.3. Chemical Vapor Deposition

Chemical Vapor Deposition methods, such as plasma-enhanced CVD (PECVD), tend to have higher deposition rates than the ALD ingredients and thus can be used for large-area processing. Processing temperatures are generally higher, restricting compatibility with temperature-sensitive substrates. Chemical vapor deposition parameters like gas flow rates, reaction pressure and precursor reactivity have a significant effect on the nature of the deposition. Recent studies have found that optimizing these parameters can significantly enhance the uniformity and electrical properties of IGZO films. PECVD variations using nitrogen or oxygen plasma have been specifically successful in removing defects and improving the density of the films [5].

Large-area uniform deposition by scaling CVD for ultra-large panels, for example, requires an accurate precursor delivery system and dynamic control of gas flow. Although there have been challenges, developments around low-temperature and remote plasma CVD variants have increased the number of compatible substrates, which nonetheless allow IGZO to be integrated into wearable and conformal electronics.

3.2. Solution Processing Methods

3.2.1. Inkjet Printing

Inkjet printing is a digital, maskless patterning technique particularly well suited for large-area electronics. After inkjet deposition, post-treatment processes are often employed to enhance film performance. Optimal ink formulation, printing parameters, and substrate surface treatment can significantly reduce the coffee-ring effect, enabling the formation of highly uniform films [6].

3.2.2. Spin Coating Method

Spin coating is a widely adopted technique in laboratories for depositing thin, uniform films. Key parameters such as spinning speed, precursor concentration, and solvent volatility influence film thickness and homogeneity [7]. Recent studies have demonstrated that, with the incorporation of dual-step annealing and solvent engineering, spin-coated IGZO films can achieve carrier mobility and threshold voltage stability comparable to those prepared via vacuum-based methods [8].

3.2.3. Spray Pyrolysis Technique

Spray pyrolysis is frequently utilized as a solution-based method for depositing films on large-area and irregularly shaped substrates. This method atomizes a solution containing metal precursors into tiny droplets and sprays them onto the surface of a heated substrate, causing the droplets to rapidly evaporate at high temperatures and undergo thermal decomposition reactions, thereby depositing a uniform IGZO film on the substrate. Film thickness can be effectively controlled by tuning parameters such as the spray rate and the concentration of the precursor, allowing for the fabrication of functional films with gradient thickness distributions. Such gradient structures are advantageous for improving the electrical and interfacial properties of the films, thereby enhancing overall device performance [9].

3.2.4. Additive-assisted Solution processing

Incorporating small-molecule additives into the precursor solution is an effective method for regulating film quality. These additives can form stable complexes with metal ions, inhibit metal aggregation during atomization and deposition processes, and thereby enhance the stability of the precursor solution. After subsequent heat treatment, the additive facilitates uniform decomposition of the precursors and promotes smooth film formation, improving surface morphology and flatness. In the long term, this approach enhances electrical properties, such as carrier mobility, also improves the operational stability of the resulting devices.[7].

3.2.5. Dip Coating Technique

Dip coating is a simple yet effective technique for fabricating uniform thin films. Film thickness can be finely controlled by adjusting the withdrawal rate and solution viscosity. Dip-coated IGZO films have exhibited comparable performance to spin-coated counterparts with optimized annealing. Further, the roll-to-roll processing is highly flexible for dip coating, thus serving as a possible route for printed electronics. Due to the compatibility with flexible substrates and the capability of continuous coating over long lengths with an economical process, X-ray backlight technology can be highly suitable for low-cost display manufacturing. However, retaining meniscus stability and film-drying behavior is still a technical challenge. Recent advances in dynamic withdrawal strategies and solvent engineering demonstrate how to minimize inhomogeneous edge effects [9].

3.3. Post-treatment Techniques

The advantage of post-processing technology lies in improving the uniformity of IGZO devices by repairing microscopic defects in the thin film and optimizing interface characteristics. Thermal annealing technology can effectively reduce threshold voltage shift, while laser annealing technology improves carrier mobility through local crystallization. Plasma treatment can help prevent surface defects and suppress leakage current. These methods have been verified for reliability in practical applications and provide key technical support for the large-scale production of flexible displays [4].

3.3.1. Thermal Annealing Optimization

Thermal annealing is a key process for enhancing the crystallinity of thin films and reducing defect density. Research shows that a staged temperature control strategy is highly effective: first, a low-temperature pre-treatment at 200°C is used to relieve the thermal stress of the substrate, followed by high-temperature annealing at 350°C to promote grain growth, which can reduce defect density by more than 40%. This two-step method improves the yield of flexible OLED devices and stabilizes the threshold voltage fluctuation within 0.3 volts, making it a widely adopted standard process in industrial mass production. [3].

3.3.2. Laser Annealing Techniques

Laser annealing is a non-contact method at high speed for improving the film. It can decrease defect density without thermal damage by applying high-intensity pulsed energy. The method was empirically validated in a series of recent studies that confirmed a better uniformity and mobility for IGZO films treated this way [10]. Laser annealing heats the material locally in a highly rapid manner, resulting in low thermal budget processing. It is ideal for flexible substrates and can activate IGZO without disturbing underlying layers [10].

3.3.3. Plasma Treatments

Plasma treatments following metal deposition (especially with oxygen and nitrogen species) efficiently passivate surface states and reduce defect formation. This helps to stabilize the IGZO film and reduce the fluctuation of threshold voltage [1]. In addition to standard O2 and N2 plasmas, fluorine and argon-based plasmas are being investigated to differentially clean surface contaminants and modify band alignment at interfaces. These treatments are typically applied alongside ALD passivation to maximize performance advantages. In production environments, parameters such as RF power, pressure, and exposure time are optimized in real-time monitoring systems, so these make this technique suitable for high-throughput manufacturing. Such plasma treatments are generally performed at the end of the processing workflow in high-throughput applications, predominantly after solution deposition, e.g., after inkjet printing.

3.4. Advanced Structural Design Approaches

3.4.1. Multi-layer IGZO Structures

IGZO layers with controlled interlayer interfaces may be stacked to reduce defect propagation and improve transport charge. Multi-layer structures, like HTL, BN, or BHJ, have been shown to improve performance consistency across large-area devices [11].

3.4.2. Channel Patterning and Edge Control Techniques

Use of photolithographic or inkjet-defined channel geometries allows control over edge effects, reducing leakage currents and improving field-effect mobility. This patterning is critical for scaling TFT dimensions [6]. Whereas conventional photolithography spurs intense interest, other complementary patterning approaches to defining submicron IGZO features with high fidelity, such as nanoimprint lithography (NIL), laser direct writing, and electrohydrodynamic jet printing, are also under exploration.

3.4.3. Interface Engineering with Passivation Layers

In addition to defect suppression, advanced interface engineering allows for the use of novel dielectric stacks, including Al2O3/HfO2 bilayers. These structures allow for maintained leakage current limitations at enhanced capacitance. For next-gen IGZO TFTs [used in biomedical sensing and IoT edge devices [5], hybrid passivation methods by combining organic self-assembled monolayers with inorganic barriers come under exploration.

In addition, the passivation layer deposition method like ALD, PECVD, or spin-on dielectric, can influence final device reliability and should be tuned according to the needs of the application. Deposition of passivation layers such as Al2O3 or SiNx by atomic layer deposition or plasma enhanced chemical vapor deposition, linked to environmental degradation, leading to stabilizing the threshold voltage. By significantly suppressing interface trap densities, these materials also improve subthreshold characteristics [5].

3.4.4. Additional Insights on Processing Integration

The combined strategy of deposition technique and post-treatment/patterning technique determines the overall performance and scalability of the IGZO TFTs. With the industry advancing toward heterogeneous integration and wearable electronics, the combination of deposition method, post-treatment, and device architecture becomes progressively vital. Conventional fabrication lines are often combinations of different deposition techniques, high-resolution lithography, and in-line annealing steps, designed together to ensure that uniformity, yield, and performance targets are all met at once [1].

4. Conclusion

This study systematically addresses the challenge of enhancing IGZO-TFT film uniformity, a critical bottleneck limiting their large-scale application in advanced display and flexible electronic technologies. Through a comparative analysis of vacuum-based and solution-based deposition techniques, the key determinants of film thickness consistency, microstructural homogeneity, and electrical stability are identified, including precursor composition, deposition dynamics, interfacial engineering, and post-deposition treatments.

A comprehensive evaluation of various IGZO thin film fabrication methods reveals that the ALD process, with its self-limiting growth mechanism, enables the formation of ultrathin, high-quality films on complex surfaces and has been successfully applied to OLED backplane manufacturing by leading companies such as LG Display, significantly improving the process yield and manufacturing controllability. In contrast, the CVD process is highly sensitive to temperature and pressure, requiring a delicate balance between film densification and thermal stress management. The inkjet printing method demonstrates excellent pattern control and process flexibility and is suitable for the large-scale and low-cost preparation of flexible electronic devices. Notably, post-deposition treatments play a crucial role in improving the microstructure and electrical uniformity. Furthermore, structural design offers additional avenues for the enhancement of device performance. Overall, the vacuum process has more advantages in terms of high precision and stability, and is suitable for the industrial production of high-performance IGZO TFT. Conversely, solution-based methods, due to their low cost and flexible adaptability, show broad application prospects in the future printed electronics field. Further advancements in low-temperature processing and heterogeneous integration are required to accommodate fragile, flexible substrates. Additionally, the development of intelligent process control systems, potentially guided by machine learning, may help minimize performance variability. Parallel efforts should focus on the use of environmentally benign materials and recyclable manufacturing schemes to support the sustainable development of IGZO-TFT technology within the broader context of green electronics.

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