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Electrical Properties of Amorphous Indium Gallium Zinc Oxide Thin Films Prepared by Magnetron Sputtering (Postprint)

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Abstract

Amorphous indium gallium zinc oxide (IGZO) thin films were prepared using medium-frequency alternating current magnetron sputtering and characterized by XRD, XRF, Hall measurement, and other techniques. The influence of process parameters such as sputtering current and oxygen flow rate on their electrical properties was investigated. The results show that the prepared IGZO thin films all exhibited an amorphous structure, with compositions essentially consistent with the target material. The electrical properties were insensitive to the sputtering current, whereas changes in oxygen flow rate could significantly affect the carrier concentration and Hall mobility of the films. With increasing oxygen flow rate, the carrier concentration of the films first increased and then decreased, while the Hall mobility increased with increasing carrier concentration. The transmittance first improved with increasing oxygen flow rate and then stabilized above 90%.

Full Text

Electronic Properties of Amorphous Indium-Gallium-Zinc Oxide Thin Films Fabricated by Magnetron Sputtering

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Abstract

Amorphous indium-gallium-zinc oxide (a-IGZO) thin films were fabricated using mid-frequency AC magnetron sputtering deposition with variable oxygen flow rate and sputtering current. The influence of processing parameters on the electronic properties of the films was investigated by means of XRD and XRF analyses, as well as Hall effect measurements. The results show that all samples are amorphous with compositions roughly equal to that of the target. The change of sputtering current had no significant effect on the electronic properties. However, the carrier concentration of the samples exhibited an obvious change with increasing O_2 flow rate, initially increasing slightly then rapidly decreasing. The samples with higher carrier concentration exhibited larger Hall mobility. The average transmission of the IGZO thin films deposited with large O_2 flow rate is above 90%.

KEY WORDS inorganic non-metallic materials, IGZO thin film, amorphous semiconductors, magnetron sputtering, mobility

Introduction

With the rapid development of information technology, flat panel display technology is advancing toward higher resolution, faster response speed, lower power consumption, fully transparent devices, and flexible displays, which places higher demands on the performance of thin-film transistor (TFT) devices in active-matrix displays such as AMLCDs. Traditional amorphous silicon TFTs have low mobility (~0.5 $cm^2 \cdot V^{-1} \cdot s^{-1}$), which cannot meet the requirements for high-resolution, large-size LCD displays and severely limits their application in OLED displays [1]. In 2004, Nomura et al. first reported amorphous indium gallium zinc oxide (IGZO) thin films successfully applied to TFT devices with saturation mobility as high as 6–9 $cm^2 \cdot V^{-1} \cdot s^{-1}$ [2]. Since then, amorphous IGZO thin films have attracted attention from both academia and industry due to their advantages of high carrier mobility, high transmittance, and low processing temperature [1, 3–5].

Currently, the main preparation methods for IGZO thin films include vacuum and non-vacuum techniques, such as pulsed laser deposition [6, 7], RF magnetron sputtering [8–10], and solution methods [11–13]. Magnetron sputtering offers good process stability and high uniformity over large areas, making it suitable for industrial production. Therefore, this study employs mid-frequency AC magnetron sputtering to prepare IGZO thin films and investigates the effects of process parameters such as sputtering current and working gas on film properties.

1 Experimental Methods

IGZO thin films were prepared by magnetron sputtering using an $InGaZnO_4$ quaternary target measuring 360 mm × 80 mm × 5 mm with a composition

of In:Ga:Zn = 1:1:1. The substrates were soda-lime glass. The sputtering equipment was a reciprocating mid-frequency AC magnetron sputtering system with a turbo molecular pump achieving a base vacuum of 10^{-5} Pa. The target-to-substrate distance was 70 mm, and the substrate holder could reciprocate parallel to the target surface during sputtering to ensure uniform samples. A heater inside the substrate holder allowed for sample heating.

All samples were prepared at a base vacuum of 1$×10^{-3}$ Pa, with primary investigation of sputtering current and oxygen flow rate effects on IGZO thin film properties. When examining sputtering current effects, the working gas was high-purity Ar with zero oxygen flow, and sputtering currents of 0.50, 0.75, 1.00, 1.50, and 2.00 A were selected. For oxygen flow rate investigation, the sputtering current was fixed at 1.00 A with oxygen flow rates of 0, 0.25, 0.50, 1.00, and 1.15 sccm, while Ar flow was fine-tuned around 44 sccm to maintain a sputtering pressure of 0.7 Pa.

The prepared thin film samples had thicknesses controlled at approximately 200 nm. Film structure was analyzed using an X-ray diffractometer (D/max-RB). Composition was determined by X-ray fluorescence analysis (XRF-1800). Film transmittance, reflectance, and thickness were measured using a multifunctional thin film tester (SCI Film Tek 3000NIR). Resistivity, carrier concentration, and Hall mobility were measured using a Hall effect tester (HL5500 PC). To minimize environmental effects from oxygen and water, Hall measurements were completed within 30 minutes of film preparation at approximately 30% humidity.

2 Results and Discussion

2.1 Film Composition

Table 1 lists the atomic percentages of In, Ga, and Zn metal elements in IGZO thin films prepared under different sputtering currents. The results indicate that the composition ratio of metal elements in the sputtered films is essentially consistent with the target composition, close to 1:1:1. However, Ga content is slightly higher than 1/3, while In and Zn show slight losses, with In loss gradually increasing and Zn loss gradually decreasing as current increases.

2.2 Effect of Sputtering Current on Electrical Properties

Figure 1 [Figure 1: see original paper] shows the resistivity and carrier concentration of IGZO thin films prepared at different sputtering currents. The results demonstrate that changes in sputtering current have essentially no effect on the electrical properties of IGZO thin films, with carrier concentration remaining around 10^{19} cm^{-3} and resistivity at approximately 10^{-1} $\Omega \cdot cm$, showing no significant variation.

For crystalline semiconductor materials, increased sputtering current or power can improve film crystallinity, thereby altering electrical properties. This study

used XRD to examine film structure. Figure 2 [Figure 2: see original paper] presents XRD patterns of IGZO thin films prepared at different sputtering currents (0.5, 1, and 2 A). All three samples exhibit only an amorphous diffuse peak without strong crystalline diffraction peaks, indicating that the prepared IGZO thin films are amorphous [14]. Consequently, changes in sputtering current cannot alter the film crystal structure, and electrical properties remain essentially unchanged with varying sputtering current.

2.3 Effect of Oxygen Flow Rate on Electrical Properties

According to TFT device operation principles and performance requirements, IGZO thin films used as the active layer must possess appropriate electrical properties. Relevant calculations [15] indicate that IGZO thin films suitable for TFT devices should have resistivity in the range of 10^2-10^3 $\Omega \cdot$cm and carrier concentration controlled at 10^{14}-10^{15} cm^{-3}. Hall measurements show that the IGZO thin films prepared in this study are n-type conductors, with carriers primarily generated by oxygen vacancies. During sputtering, some oxygen is lost, so IGZO thin films prepared in pure Ar atmosphere exhibit excessively low resistivity and are unsuitable for TFT devices. Introducing oxygen into the sputtering gas should significantly influence IGZO thin film electrical properties, and controlling oxygen flow rate can produce films with appropriate electrical characteristics.

Figure 3 [Figure 3: see original paper] shows the resistivity and carrier concentration of IGZO thin films prepared at different oxygen flow rates. As oxygen flow rate increases, carrier concentration initially increases then gradually decreases, with corresponding resistivity first decreasing then gradually increasing. Under pure Ar atmosphere, sputtered IGZO experiences significant oxygen loss, resulting in numerous dangling bonds and defects, leading to structural disorder. Introducing oxygen during sputtering can fill some oxygen vacancies, improve film microstructure, and create more ordered local chemical bonds, thereby increasing carrier concentration and decreasing resistivity. However, as oxygen flow rate further increases, oxygen vacancies in the film continuously decrease. Since oxygen vacancies are shallow donor-type defects that provide electrons, their reduction inevitably leads to decreased carrier concentration and increased resistivity. At an oxygen flow rate of approximately 1.15 sccm, IGZO thin film carrier concentration can be controlled at around 10^{15} cm^{-3}, making it suitable for TFT device fabrication.

Figure 4 [Figure 4: see original paper] illustrates the relationship between Hall mobility and carrier concentration in IGZO thin films. The results show that mobility gradually increases with rising carrier concentration, which is a distinctive characteristic of IGZO thin films. For conventional semiconductor materials, increased carrier concentration enhances ionized impurity scattering, thereby reducing mobility. However, the electron transport mechanism in amorphous IGZO differs, with potential barriers existing above its mobility edge. When carrier concentration increases, these barriers decrease, leading to increased mo-

bility [16]. At low carrier concentrations, the Fermi level lies below the mobility edge within tail states, and only a few carriers captured by tail state defects can participate in conduction through thermal excitation to above the mobility edge, resulting in low mobility. When carrier concentration increases, tail states become filled with electrons, the Fermi level exceeds the mobility edge, and carriers have sufficient energy to overcome the barriers, thereby increasing mobility. Although the active layer requires low carrier concentration (10^{14}-10^{15} cm^{-3}) and IGZO mobility is at the 100 $cm^2 \cdot V^{-1} \cdot s^{-1}$ level, the gate voltage applied during TFT device operation causes carriers to accumulate near the insulator side, band bending occurs, and the Fermi level rises above the mobility edge, resulting in high mobility.

2.4 Oxygen Flow Rate and Film Optical Properties

As an oxide semiconductor, IGZO has a large bandgap and high transmittance. Figure 5 [Figure 5: see original paper] shows the transmittance curves of IGZO thin films prepared at different oxygen flow rates. To calibrate film transmittance, measurements were taken for both IGZO-coated soda-lime glass (T_1) and bare soda-lime glass (T_0), with the ratio T_1/T_0 used as the film transmittance. The results indicate that films prepared at low oxygen flow rates have relatively low transmittance, around 85% in the visible range (for 200 nm thickness). This is because significant oxygen deficiency creates numerous defects, incomplete metal oxidation, and even metal precipitation, reducing film transmittance. Increased oxygen flow fills oxygen vacancies, creates more ordered film microstructure, and increases transmittance to a stable level above 90%. This trend is consistent with the electrical property changes observed at low oxygen flow rates, where trace oxygen introduction improves film microstructure, resulting in lower resistivity and higher transmittance.

3 Conclusion

Using magnetron sputtering to deposit from $InGaZnO_4$ quaternary ceramic targets, amorphous IGZO thin films with stable composition, electrical properties suitable for TFT devices, and high transmittance can be prepared. IGZO thin film electrical properties are insensitive to changes in sputtering current. Increased oxygen flow rate improves the disorder in film microstructure caused by oxygen deficiency, creating more ordered local chemical bonds and thereby enhancing carrier concentration and Hall mobility to some extent. Further increase in oxygen flow fills oxygen vacancies, reduces carrier concentration, and increases film resistivity. Film Hall mobility increases with carrier concentration. At an oxygen flow rate of 1.15 sccm, the sputtered IGZO thin film exhibits a carrier concentration of 6.14$×10^{15}$ cm^{-3}, Hall mobility of 8.96 $cm^2 \cdot V^{-1} \cdot s^{-1}$, and visible light transmittance of approximately 90%, making its electrical properties suitable for TFT device fabrication.

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