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Influence of oxygen/argon reaction gas ratio on optical and electrical characteristics of amorphous IGZO thin films coated by HiPIMS process

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ABSTRACT

High power impulse magnetron sputtering (HiPIMS) is a novel physical vapor deposition technique, especially for a low-temperature process application. In this study, the InGaZnO (IGZO) ceramic target (In:Ga:Zn:O = 1:1:1:4 in atomic ratio) was used to deposit amorphous IGZO thin film on quartz glass around 40 °C–50 °C under unipolar mode of HiPIMS. Influence of oxygen/argon reaction gas ratio with a fixed duty cycle of 3% on the amorphous IGZO thin films was investigated. During deposition process, target voltage and current were recorded. The crystal structure and surface morphology of the obtained amorphous IGZO thin films were investigated by using scanning electron microscopy and atomic force microscopy, respectively. The crystal characteristics of IGZO thin films were investigated using the transmission electron microscopy and a grazing incidence X-ray diffractometry. Compositions and chemical bonding state were analyzed using X-ray photoelectron spectra. The optical and electrical characteristics of the amorphous IGZO thin films were investigated by using UV/Visible light-absorbing detector and Hall-effect measurement instrument, respectively. In this study, it was demonstrated that HiPIMS system provides a smooth thin film coating at a low processing temperature around 40 °C–50 °C. The results revealed that the amorphous IGZO thin films grown by HiPIMS have higher optical and electrical properties and can help to better understand on the effect of argon/oxygen reaction gas ratio for the depositing characteristic of IGZO transparent conductive thin films.

1. Introduction

Transparent conducting oxide semiconductors (TCOSs) have attracted much attention owing to applications of thin-film transistors (TFTs) in mobile electronics, optoelectronics, and military fields. Amorphous TCOSs films, as an active layer of thin film transistors, have attracted great attentions for replacing conventional semiconductors such as Si, GaAs, InP and GaN in applications of flat-panel displays (FPDs) including liquid crystal displays (LCDs), organic light-emitting-diode displays (OLEDs), and electronic papers [1–8].

The use of TCOSs have shown advantages of using low-cost glass substrate and low temperature fabrication which are compatible for flexible substrate. In addition, TCOSs exhibit excellent structure uniformity to prevent grain boundary problems (short-range non-uniformity) and have stable electrical properties with high carrier mobility [9–11]. Several TCOSs have been reported as TFTs channel materials, including amorphous In—Ga—Zn—O (*a*-IGZO) [4,5,11], In–Zn–O(IZO) [6,7], Zn—Sn—O [12], and In—Sn—O [13]. Among these materials, *a*-IGZO thin film have high transparency, large energy band gap (more than 3.05 eV), low processing temperature, excellent uniformity over large area, and much higher field effect mobility that exceeds 10 $cm^2/V \cdot s$, have attracted considerable attention owing to their potential applications to flexible and transparent display devices. It is now commonly deposited using vacuum deposition techniques such as pulse laser deposition and magnetron sputtering method [14,15] while solution-based process such as sol-gel method has also been investigated [16–18].

Thin film deposition by magnetron sputtering is a wide spread method for industrial coating technology and research since 1970s. Compound films deposition such as metal oxides are commonly deposited using an insulating compound target via radio frequency (RF) magnetron sputtering. However, the deposition rate is low because of the lower sputtering yield of the compound material relative to metal, especially in metal oxide. Also the sputtering efficiency in RF discharges is low. A relative novel short-pulse high-power plasma physical vapor deposition method called as high power impulse magnetron sputtering (HiPIMS) has been introduced by Kouznetsov et al. [19,20]. HiPIMS is an alternative technique for compound film deposition with potentially

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higher deposition rates than RF magnetron sputtering. In reactive HiPIMS of metal oxides, there are also improved film properties as compared to films deposited by conventional magnetron sputtering. The deposited films show superior properties such as excellent adhesion, denser structure and higher hardness than films deposited by conventional PVD. Since then, TCOSs layers and/or nitride coatings have been tensely deposited by using HiPIMS for investigation [21–24]. The advantages of HiPIMS include low processing temperature, well-adherent coating, better films quality and droplet-free. By inputting high power short pulses to the target, HiPIMS provides higher gas dissociation and highly ionized plasma and therefore the target is not only sputtered but also ionized during the deposition process. As a result, plasma density with three orders higher in magnitude than conventional magnetron sputtering yields a smoother and denser thin film [25–27]. Lately, HiPIMS systems have achieved better stability of deposition process, suppression of arcing, increase of ion flux and improvement of thin film properties [28,29]. Enhanced film properties have also been demonstrated in oxide and nitride thin films. The effects of various parameters on the optical and electrical performances of IGZO films have been examined [30,31]. Amorphous IGZO thin films deposited using reactive HiPIMS techniques have been investigated only for purposes such as plasma diagnostics, and study of microstructures, mechanical properties etc. In this research, amorphous IGZO thin film was deposited near room temperature (around 40 °C–50 °C) via HiPIMS technique to investigate the effects of oxygen/argon reaction gas ratio with a fixed duty cycle of 3%. Not only were the microstructure characteristics, but the optical transmittance and electrical properties of amorphous IGZO thin films were also studied.

2. Experimental methods

An In—Ga—Zn—O (IGZO) ceramic target with In:Ga:Zn:O atomic ratio of 1:1:1:4 was used to deposit a-IGZO thin film on super clear glass and silicon wafer substrates using an unipolar HiPIMS process, which was performed in a modified STAR-2 PVD system, manufactured by Daedalus Precision Engineering Co., Ltd. A DC power supply (Advanced Energy, MDXII, max. 1000 V and 15 kW) connecting to a pulse power controller (SPIK 2000 A-20H, 0–50 kHz, $\pm$1000 A) was used to power the IGZO ceramic target to 1000 W. The target size was 6 in. in diameter with a thickness of 8 mm. The magnetic track area of the target is 83.3 cm^2. Schematic diagram of the HiPIMS deposition system as shown in Fig. 1. A uni-polar mode with a constant pulse-on time of 400 μs with a pulse frequency of 50 Hz in a fixed duty cycle of 3% was applied while a target-to-substrate distance was fixed at 100 mm. The substrate was continuously biased at -30 V without any additional

Table 1
Deposition conditions of IGZO coated by HiPIMS.

Item	Parameter
Target	IGZO ceramic target (99.99 wt%) (In: Ga: Zn: O = 1:1:1:4)
Target diameter (inch)	6
Working pressure (m Torr)	4.38, 4.55, 4.73, 4.82, 5.01
O_2/Ar ratio(%)	0, 5, 10, 15, 20
Input power (W)	1000
Substrate bias (V)	-30
Duty cycle (%)	3
Pulse width (μs)	On-time: 400 Off-time: 19,600
Mode	Unipolar
Deposition time (min.)	2
Pulse frequency (Hz)	50

substrate heating. The substrate temperature was measured near the substrate surface by a thermocouple. For all deposition conditions, the substrate temperate was all below 50 °C. The process parameters were shown in Table 1. In this study, the effects of reaction gas ratio on the deposition of IGZO film was investigated by varying the oxygen/argon reaction gas ratio from 0% to 20%. Before the deposition, the chamber was first evacuated to a base pressure of 5×10^{-6} Torr. While the O_2/Ar reactive gas flow rate ratio were introduced from 0% to 20%, the chamber working pressure were increased from 4.38 m Torr to 5.01 m Torr. Besides, the crystal structure, surface morphology, optical and electrical properties of the IGZO thin film were also investigated.

During the deposition, a digital oscilloscope (DSO-X-2012 A, Agilent Technologies) was used to monitor and record the target voltage and target current which were measured by a high voltage differential probe (*SI*-9010, Sapphire Instruments) and a passive probe (N2862B, Agilent) respectively. Thickness and surface morphology of the obtained amorphous IGZO thin film was measured using scanning electron microscopy (SEM, JEOL-JSM7000F) while surface roughness with area size of 10×10 μm^2 were investigated by atomic force microscopy (AFM, Veeco-DI 3100) under a tapping mode. Crystallinity and microstructures were investigated using the transmission electron microscopy (TEM, JEOL, JEM-ARM200FTH) and grazing incidence X-ray diffractometry (GIXRD, PANalytical-X'Pert PRO MRD) with an incident angle of 0.5° and a scanning speed of 0.04°/*sec*. The compositions and chemical bonding state were analyzed using X-ray photoelectron spectra (XPS, Thermo Scientific K-Alpha XPS) with a micro-focused Al Kα monochromatic X-ray after surface cleaning by 120 s of Ar$^+$ bombardment. UV/VIS spectrometer (JASCO V-570) was used to measure the

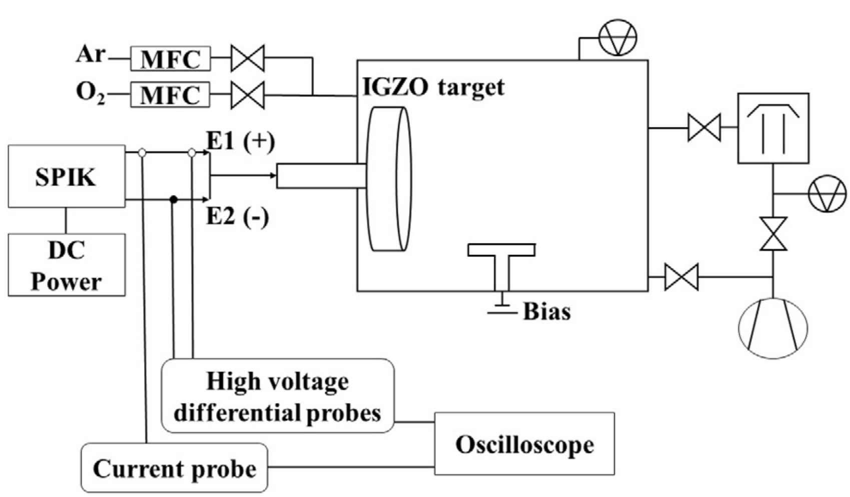

Fig. 1. Schematic diagram of the HiPIMS deposition system.