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Comparison of the electrical and optical properties of direct current and radio frequency sputtered amorphous indium gallium zinc oxide films

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ABSTRACT

The electrical and optical properties of direct current and radio frequency (RF) sputtered amorphous indium gallium zinc oxide (a-IGZO) films are compared. It is found that the RF sputtered a-IGZO films have better stoichiometry (In:Ga:Zn:O = 1:1:1:2.5–3.0), lower electrical conductivity (σ<8 S/cm), higher refractive index (n = 1.9–2.0) and larger band gap (E_g = 3.02–3.29 eV), and show less shift of Fermi level ($\triangle E_F$ ~0.26 eV) and increased concentration of electrons ($\triangle N_e \sim 10^4$) in the conduction band with the reduction concentration of oxygen vacancy (V_O). Although a-IGZO has intensively been studied for a semiconductor channel material of thin film transistors in next-generation flat panel displays, its fundamental material parameters have not been thoroughly reported. In this work, the work function (φ) of a-IGZO films is tested with the ultraviolet photoelectron spectroscopy. It is found that the φ of a-IGZO films is in the range of 4.0–5.0 eV depending on the V_O.

1. Introduction

Due to the high carrier mobility, on/off current ratio and excellent optical transmittance, the amorphous indium gallium zinc oxide thin film transistors (a-IGZO TFTs) are considered as promising device for application in next-generation active-matrix flat panel display backplanes [1]. The a-IGZO channels are usually deposited by direct current (DC) [2,3] or radio frequency (RF) [4] sputtering, but the film quality of a-IGZO deposited in the same apparatus by these different sputtering methods is seldom compared. The RF sputtered films have better stoichiometry but with low deposit rate. The DC sputtering is often used for mass production of oxide films.

The O content in a-IGZO influences the electrical and photosensitive characteristics and the reliability of a-IGZO TFTs [5]. It is known that the O in a-IGZO body affects the concentration of electrons (N_e) in a-IGZO [6], the oxygen-related trap states (acceptor-like) or oxygen vacancy-related trap states (donor-like) at the a-IGZO/gate dielectric interface [7], and the sub-gap density of states [8] or defects [9]. In ZnO film the Fermi level (E_F) can be easily changed depending on the oxygen vacancy (V_O) [10]. When the E_F is raised from valance band to conduction band, the defect formation energy of V_O and oxygen ions (O^{2-}) is varied from −0.5 to 4 eV and from 8.5 to 4 eV [11] with the increase concentration of N_e. However, in a-IGZO film there are no reports about the effects of V_O on E_F.

The work function (φ), one of the fundamental electronic structure parameters for oxide semiconductor films, affects the energy barrier height at the heterojunction interface [12] and the reliability of TFT [13]. The φ of many oxide semiconductors, such as In_2O_3, ZnO, $Zn_2In_2O_5$ and $GaInO_3$, has been tested by ultraviolet photoelectron spectroscopy (UPS). It is found that the φ is impacted by film composition or surface treatment [14]. In a-IGZO TFT, the a-IGZO composition is easily changed by deposition process or plasma treatment [15–17]. However, the φ of a-IGZO film has not been tested.

In this study, the properties of DC or RF sputtered a-IGZO films are compared, the E_F and φ of a-IGZO films are tested, and the relations of the energy band parameters with the properties of films are discussed.

2. Experimental details

The a-IGZO thin films in our experiments were deposited by DC or RF magnetron sputtering with power of 80 W respectively, in varied ratios of Ar:O_2 flow rates and the oxygen partial pressure (P_{O2}) varied from 0, 9% to 17%. Deposition time was 10 min for all films. The $InGaZnO_4$ target was used for sputtering at room temperature. The electrical resistance of a-IGZO films was tested by four probe methods. The optical transmittance of a-IGZO films were measured with a Lambda 900 spectrometer. The films were characterized by X-ray photoelectron spectroscopy (XPS) and UPS (Thermo-Fisher ESCALab 250) with a mono-chromated Al Kα (energy 1486.6 eV) X-ray source. The X-ray spot size was 500 μm and the measurement was taking at chamber pressure of 10–9 mbar. The XPS spectra were collected in the

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Table 1
The depositing rates and electrical properties of a-IGZO films.

Sample	P_{O2} (%)	r (nm/min)	$R_{\square}$ (Ω/□)	σ (S/cm)
DC a-IGZO1	0	33	4.8E+2	62.9
DC a-IGZO2	9	21	3.8E+3	12.1
DC a-IGZO3	17	18	4.8E+4	0.9
RF a-IGZO1	0	11	1.1E+4	8.3
RF a-IGZO2	9	9		
RF a-IGZO3	17	8		

condition with pass energy of 20 eV and a 0.05 eV/step for high-resolution scans. The low-energy electron flood gun (−3 V, 200 μA) was applied to compensate for charging effects due to the poor conductivity of a-IGZO films. The spectra were calibrated using the absorbed C1s at peak 284.8 eV. This experiment didn't use sputtering ion beam. The spectra were fitted by Avantage software. A Smart mode was used to calculate the background and the spectra were fitted with Gaussian–Lorentzian curve, whose shape of all peaks was assumed to be 80% Gaussian and 20% Lorentzian. The UPS spectra were recorded using a He I radiation ($h\nu = 21.22$ eV) from an unfiltered gas discharge lamp with step size of 0.025 eV. The work function φ was determined by the following equation: $\varphi = h\nu - {}^{\Delta}E$, where ${}^{\Delta}E$ is the energy difference between Fermi level and secondly electron cutoff. During UPS measurement, the samples were biased at −7.5 eV to observe the secondary electron cut off and moreover the Fermi edge location of each sample was estimated with silver as reference.

3. Results and discussions

Table 1 compares the depositing rates and electrical properties of a-IGZO films. It is found that the RF a-IGZO films have lower depositing rate (r), higher resistance ($R_{\square}$) and lower conductivity (σ) compared with the DC a-IGZO films deposited in the same P_{O2}. The $R_{\square}$ of RF a-IGZO2-3 films is out of the limit (1E+5 Ω/□) and cannot be tested. The depositing rate can also be deduced from the optical transmittance of films, as seen in Fig. 1(a) and (b). The film thickness and refractive index (n) of the film can be calculated from the transmittance spectra by the envelop method [18]. The n of the RF a-IGZO films is 1.9–2.0, higher than those of the DC films (n: 1.6–1.8), which indicates that the RF a-IGZO films have higher packing density and low depositing rates. The band gap (E_g) of films can also be calculated from the transmittance spectra by the Tauch method [5]. It can also be found that the RF a-IGZO films have larger E_g (3.02–3.29 eV) than those of the DC films (3.05–3.10 eV), as shown in Fig. 1(c) and (d). With the increase of E_g, the electrons in the valence band (VB) are difficult to inject into the conduction band (CB), and the intrinsic N_e in CB decreases and the σ of film decreases. The N_e, E_g and σ are in the following relations [19]:

$$N_e = (N_c N_V)^{1/2} \exp\left(-\frac{E_g}{2k_B T}\right), \tag{1}$$

$$\sigma = N_e q \mu, \tag{2}$$

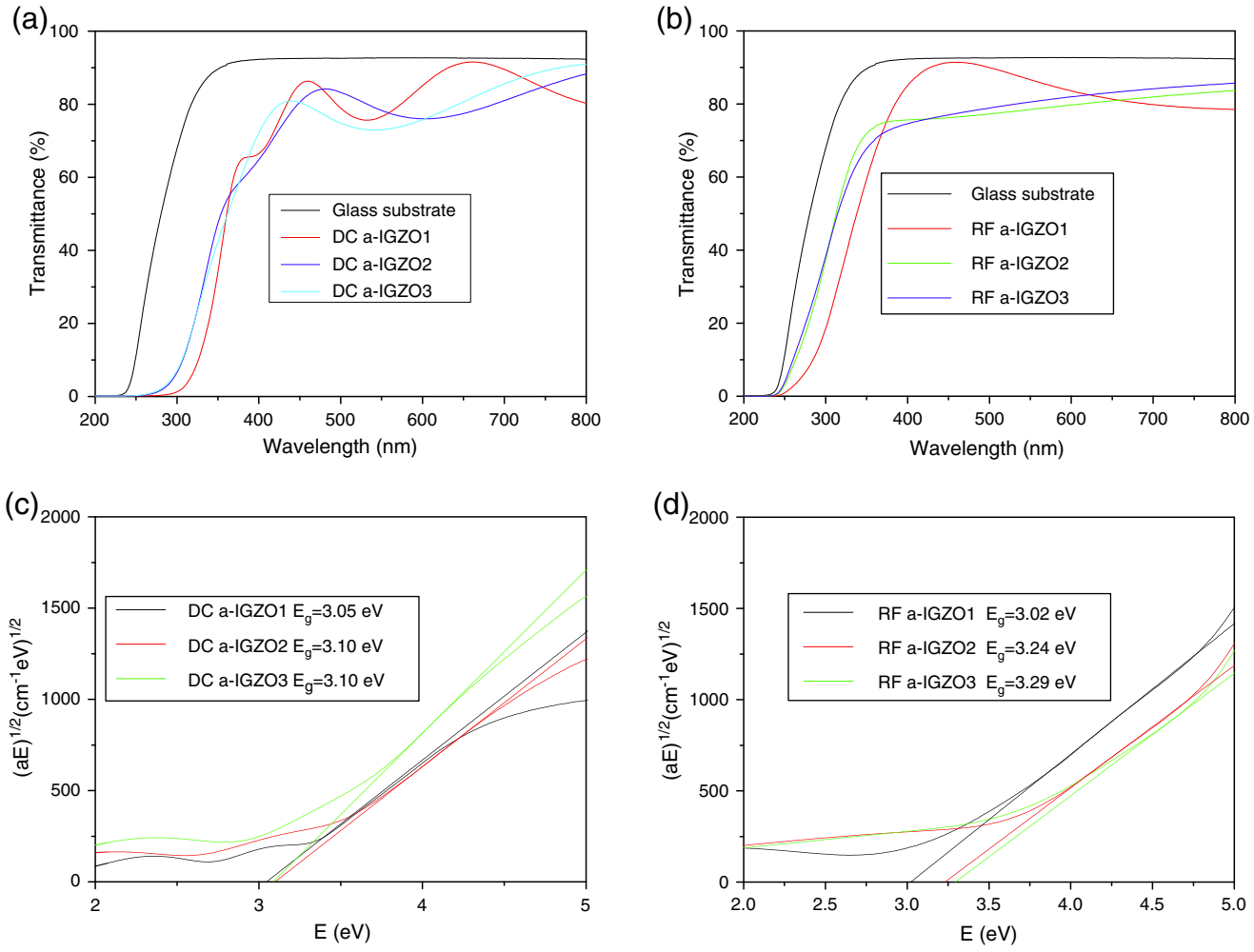

Fig. 1. The transmittance and band gap (E_g) of a-IGZO films.