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Thin Solid Films 476 (2005) 59–64

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A statistical parameter study of indium tin oxide thin films deposited by radio-frequency sputtering

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Received 31 May 2004; received in revised form 18 August 2004; accepted 2 September 2004
Available online 30 October 2004

Abstract

In order to optimize the electrical and optical properties of indium tin oxide (ITO) thin films, a statistical analysis called Taguchi design was employed. It is shown that the sheet resistance and transmittance are inversely proportional to each other as a function of the process parameters. Additionally, the preferred orientation of crystalline ITO film is distinguishably changed with the increase of sputtering temperature and oxygen fraction (O_2/O_2+Ar) in the sputtering ambient. The change in crystallinity results from the content of incorporated oxygen, which significantly affects the electrical and optical properties of ITO films and causes a rearrangement of atoms to form preferred closed-packed plane orientation. Finally, the microstructure of the ITO films becomes denser with the increasing oxygen fraction. As a result of this work, we have successfully achieved low sheet resistance (7.0 Ω/□) and high transmittance (~90%) for 300 nm thick films.

PACS: 73.50.-h; 78.20.-e
Keywords: Indium tin oxide (ITO); Sputtering; Taguchi design; Transparent electrode

1. Introduction

Indium tin oxide (ITO) thin films are widely used as transparent electrodes in electronic displays [1]. In recent years, ITO has also been implemented in light-addressed intracellular biological probes [2,3]. Normally RF magnetron sputtering is used for the deposition of the film because it provides a low temperature deposition process and higher process efficiencies, higher throughput, and process reliability [1]. When using ITO transparent electrodes, there is a well-known trade-off between the sheet resistance and the transmittance, which is dominated by the number of oxygen vacancies in the films [4,5]. Oxygen vacancies are donor levels in ITO; consequently, when ITO is slightly oxygen-deficient, reasonable electrical transport can be realized. The transmittance however can be deleteriously affected if the films are too oxygen-deficient as they become more metal-like. Therefore it is important to determine the optimized deposition conditions in order to achieve high transmittance and low sheet resistance at the same time. In a typical RF magnetron sputtering system, normally there are four main factors that control the process; RF power, gas pressure, temperature, and gas composition. To optimize this wide parameter space in a serial manner is tedious and unwieldy and many parameter interactions can go undetected. To facilitate rapid process optimization and reduce the number of trials and analytical errors, statistical tools can be implemented. In this research, we describe a Taguchi design of experiment (DOE) for the purpose of optimizing the ITO deposition [6,7]. This DOE is normally used for optimizing a process condition that is completely unknown or in the initial stage of process development to determine the overall tendencies of process factors with less experiment trials [7]. The process targets for the ITO films are sheet resistance <10 Ω/□ and transmittance (at 488 nm) >85% for a nominal film thickness of 300 nm.

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doi:10.1016/j.tsf.2004.09.011

2. Experimental details

The specified description of the DOE is described in detail in Table 1. Our initial DOE was a three-level design (low, medium, high) for the four process factors, which included RF power, temperature, pressure, and O_2 fraction (for a Ar+O_2 ambient). The responses for the DOE included deposition rate, transmittance, sheet resistance, and etching rate. For the DOE analysis, a high deposition rate, high transmittance, low sheet resistance, and high etch rate were desirable. Consequently, to qualify how the factors affected our responses, the following illustrates our interpretation of the results: 'larger is better' for deposition rate, 'larger is best' for transmittance, 'smaller is best' for sheet resistance, and 'larger is better' for etching rate.

An AJA ATC2000 RF magnetron sputtering system was utilized for the deposition of ITO thin films on glass substrates. The sputtering target has a diameter of 50 mm and a thickness of 6 mm and consists of In_2O_3 and 10 wt.% SnO_2. The base pressure prior to the sputtering deposition was below 5.3×10^{-6} Pa and the total flow rate of argon used in the sputtering was fixed at 25 sccm for all conditions. The substrate is heated by quartz lamps and the temperature is controlled within ±1 °C.

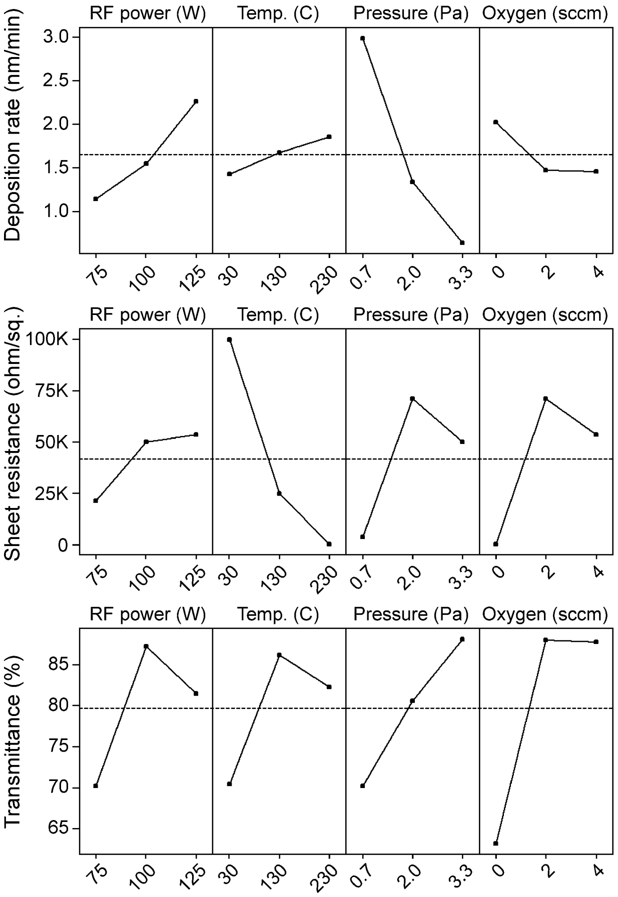

Fig. 1. Effects of RF power, temperature, pressure, and gas composition on the deposition rate, sheet resistance, and transmittance.

The transmittance of ITO thin films was measured using a calibrated Ar lamp and an Ocean Optics PC2000 spectrometer with a wavelength range 200–900 nm. The transmittance was fixed and normalized at 488 nm because our application is a light-addressed biological probe operated at that wavelength because silicon is the active layer and has a high absorption coefficient at 488 nm. The sheet resistance was analyzed via four-point probes (Veeco FPP-5000) and the reported value is an average of three measurements over the sample. The film thickness and etching rate were evaluated by using Surface Profiler (KLA Tencor Alpha-Step 500). The etchant was a solution of $HCl+CH_3COOH+H_2O$ (22%+6%+72%) and heated and maintained at 40 °C on a hot plate. The crystal orientation of ITO thin films was determined by a Phillips X-pert Pro X-ray diffraction

Table 1

DOE for optimizing ITO thin film deposited by RF magnetron sputtering: Taguchi design

No.	Factors				Responses			
	RF power, W (W/cm^2)	Temperature, °C	Pressure, Pa	O_2, sccm	D/R[a], nm/min	Tr[b], %	Rs[c], Ω/□	E/R[d], nm/min
1	75 (3.7)	30	0.7	0	2.63	35.1	262	>200
2	75 (3.7)	130	2.0	2	0.67	86.1	63,593	>200
3	75 (3.7)	230	3.3	4	0.14	89.5	391	<5
4	100 (4.9)	30	2.0	4	0.82	87.2	~150,000	>200
5	100 (4.9)	130	3.3	0	0.93	85.8	231	>200
6	100 (4.9)	230	0.7	2	2.91	88.9	343	424
7	125 (6.2)	30	3.3	2	0.84	89.2	~150,000	>2000
8	125 (6.2)	130	0.7	4	3.43	86.8	10,839	545
9	125 (6.2)	230	2.0	0	2.52	68.6	28	403

[a] D/R: deposition rate (nm/min).

[b] Tr: transmittance at 488 nm (%).

[c] Rs: sheet resistance (Ω/□) at 300 nm thickness films.

[d] E/R: etching rate in $HCl+CH_3COOH+H_2O$ (22%+6%+72%), 40 °C.