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Surface roughness of sputtered ZnO films

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Abstract
ZnO films are grown on Si and glass substrates by radio-frequency (RF) magnetron sputtering. The crystalline structures are investigated by x-ray diffraction (XRD). Moreover, the roughness characteristics of the films are examined by atomic force microscopy (AFM) and field-emission scanning electron microscopy (FE-SEM). All films exhibit strong (002) preferential orientation. The influence of the RF power and target-to-substrate distance (D_{ts}) on the properties of ZnO is studied. Under the optimized conditions of the RF power and D_{ts}, root-mean-square (RMS) surface roughnesses of <0.8 nm are achieved.

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1. Introduction

ZnO thin films present numerous remarkable characteristics because they have strong bonds, good optical quality, extremely stable excitons and excellent piezoelectric properties. Consequently, they have been actively examined in several fields, and have various potential applications in many technological domains, including surface acoustic wave (SAW) devices [1, 2], blue-, violet- and ultraviolet (UV)-light emitting diodes (LEDs), laser diodes (LDs) [3], optical-wave guides and transparent conducting coatings [4]. ZnO films can be prepared using different approaches, such as activated reactive or electron beam evaporation, spray pyrolysis [5], molecular beam epitaxy (MBE) [6, 7], metal-organic chemical vapour deposition (MOCVD) [8, 9], atomic layer deposition (ALD) [10, 11], filtered cathodic vacuum arc discharge [12], the sol-gel method [13, 14] and magnetron-beam-sputtering [15–19]. Among these processes, the sputtering technique has the greatest potential for depositing ZnO films. The benefits of sputtering are the simple apparatus required, high deposition rate, low substrate temperature, flat surface obtained, transparency and dense layer formation [20]. Furthermore, ZnO films grown on Si substrate enable the integration of devices with the mature Si integrated circuits. Many experimental data on sputtered ZnO films with various parameters have been reported. Most authors have focused on the effects of the radio-frequency (RF) power, the substrate temperature and the Ar/O_2 ratios on the quality of ZnO. However, the properties of ZnO with reference to D_{ts}, have seldom been studied. Moreover, the surface roughness is critical to the characteristics of the devices. Hence, this study proposes the growth of ZnO films on Si and glass substrates by RF magnetron sputtering. Various sputtering conditions, particularly in changing D_{ts}, have been examined to achieve optimum surface roughness.

2. Experimental procedure

In this experiment, ZnO films were deposited by RF magnetron sputtering using ZnO targets (99.99% purity). Corning 1737F glass and p-type silicon with a (100) orientation were adopted as the substrates. Both substrates were cut into ~20 mm × 20 mm samples. These substrates were ultrasonically cleaned in acetone (ACE) and isopropanol (IPA) for 10 min, rinsed in deionized water, and subsequently dried in flowing nitrogen gas before they were introduced into the sputtering system. Prior to deposition, the target was pre-sputtered for 10 min to remove any contaminants from the target surface and to enable equilibrium conditions to be reached. The chamber was pumped down to 2.6×10^{-6} torr using a diffusion pump before premixed Ar and O_2 sputtering gases were introduced into the chamber. The distances between the substrate and the target were varied from 25

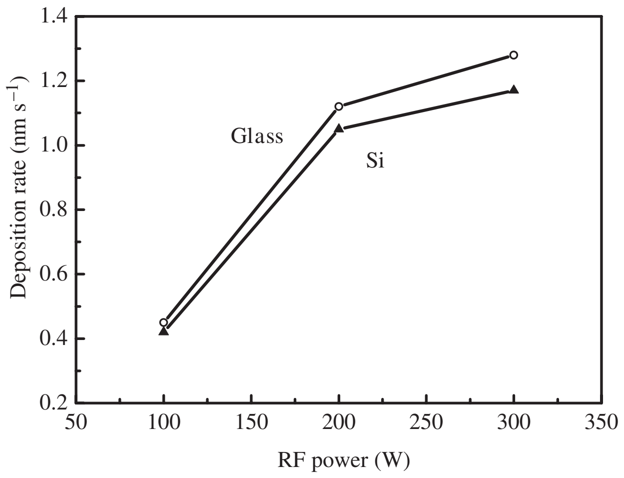

Figure 1. Dependence of the growth rates of the ZnO thin films on the RF powers.

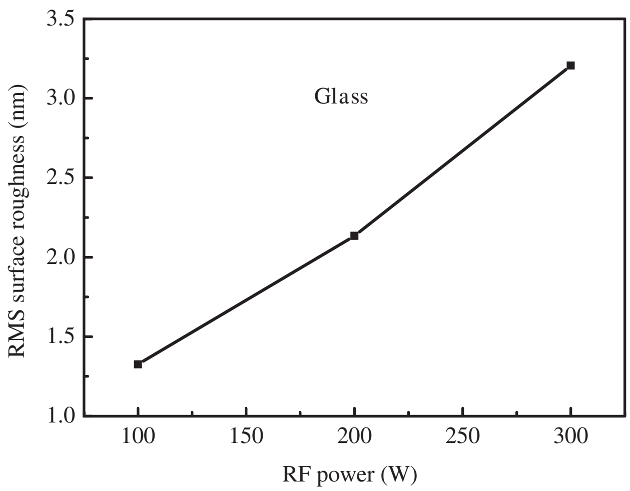

Figure 2. Surface roughness as a function of RF power for the ZnO thin films grown on glass substrates.

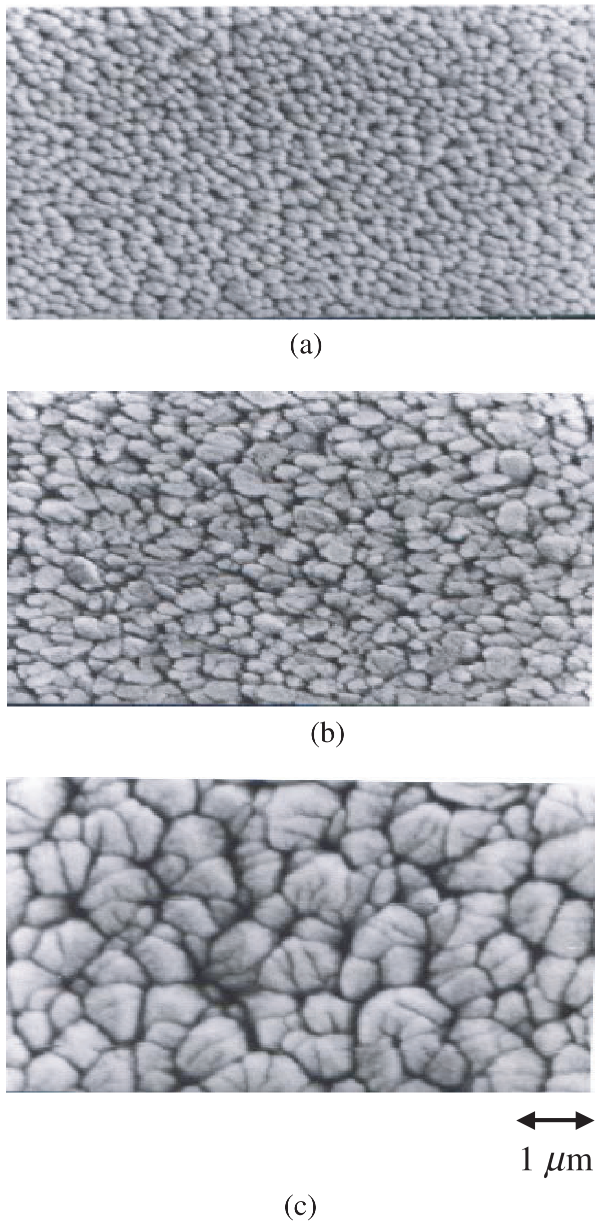

Figure 3. Top-view SEM images of the ZnO thin-film on Si substrates with different RF powers of (a) 100 W, (b) 200 W and (c) 300 W.

to 45 cm. All of the ZnO films were sputtered by supplying 100–300 W RF power at a frequency of 13.56 MHz. Moreover, the deposition pressures of all the films were held at 50 mtorr. Various sputtering conditions were applied by varying D_{ts} and RF power. The thickness of the film was measured using a conventional stylus surface roughness detector (Alpha-step 200). The crystallinity of the ZnO films was elucidated by plotting a x-ray rocking curve (XRC) for (0002) diffraction using a double-crystal diffractometer with Cu-K$_\alpha$ radiation ($\lambda = 1.540562$ Å). The surface morphology was monitored by atomic force microscopy (AFM) and field-emission scanning electron microscopy (FE-SEM).

3. Experimental results and discussions

Figure 1 plots the relationship between RF power and the deposition rate of the thin films. The deposition rate increases with the RF power, because the number of sputtered ZnO molecules on the target surface increased with the intensity of bombardment by argon and oxygen ions as the RF power increased. Notably, the thin-film deposition rates increase markedly with the RF powers from 100 to 200 W. Nevertheless, the deposition rate depends weakly on the RF power from 200 to 300 W. The experimental data reveal that the deposition rate stabilizes above 200 W. The root-mean-square (RMS) surface roughness of the ZnO films was measured on an area of 5 μm $\times$ 5 μm area using AFM. Figure 2 shows the RMS surface roughness as a function of RF power for the ZnO thin films. Notably, the roughness of the surface increases with the RF power. Figures 3 and 4 show the SEM photographs of the ZnO films deposited on Si and glass respectively, at RF powers of 100, 200 and 300 W under constant D_{ts}, sputtering time, ambient pressure and O_2/Ar ratio. Figures 3 and 4 clearly show that the size of the crystallized grains also increases with the power. The high RF power allows the deposited particles to grow as larger grains, improving the density of surface state. However, further

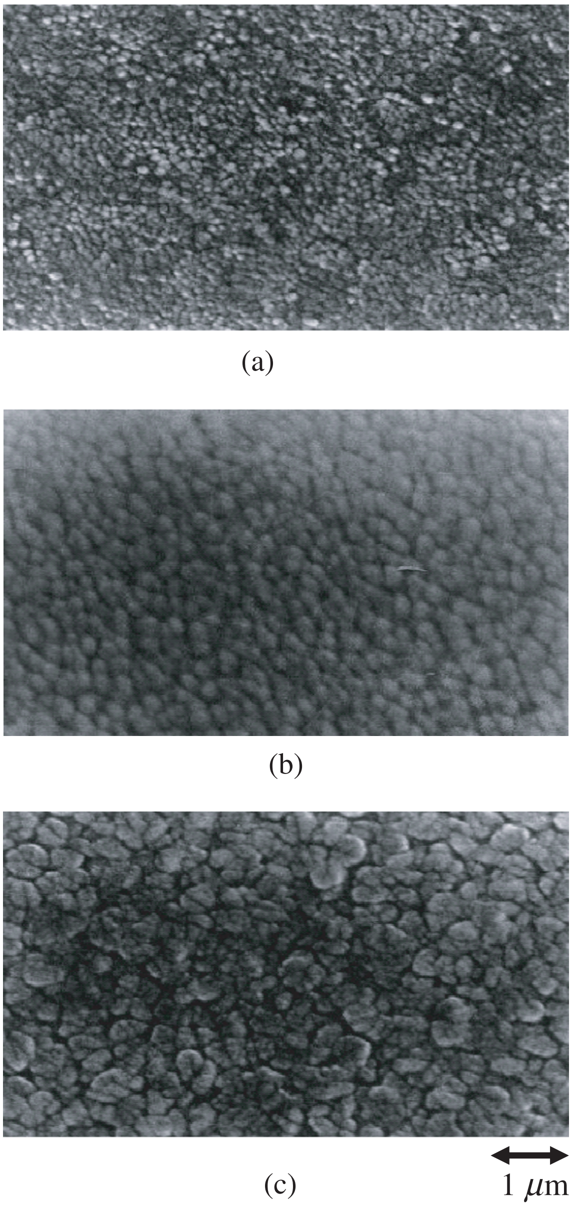

Figure 4. Top-view SEM images of the ZnO thin-film on glass substrates with different RF powers of (a) 100 W, (b) 200 W and (c) 300 W.

increasing the power to 300 W causes the surface to become ragged and the grains to tighten. These phenomena are associated with anti-sputtering. Increasing the RF power also causes the deposited particles to obtain more kinetic energy, tightening the thin films. So, the surface roughness of the thin-films also increases. When ZnO films are used in SAW device applications, their rough surface impedes wave transmission and increases propagation loss. X-ray diffraction (XRD) analyses were undertaken to determine the crystallinity and crystal orientations of the films. The films deposited at 100 and 300 W have a larger full-width at half-maximum (FWHM) than that at 200 W and so poorer crystallinity. These results indicate that the kinetic energy of the ZnO molecules that arrive at the surface of the substrate increases with the RF power, improving crystallinity by increasing surface mobility. However, the crystallinity of ZnO become worse as the RF power increases further, because the number of the sputtered ZnO molecules increases substantially.

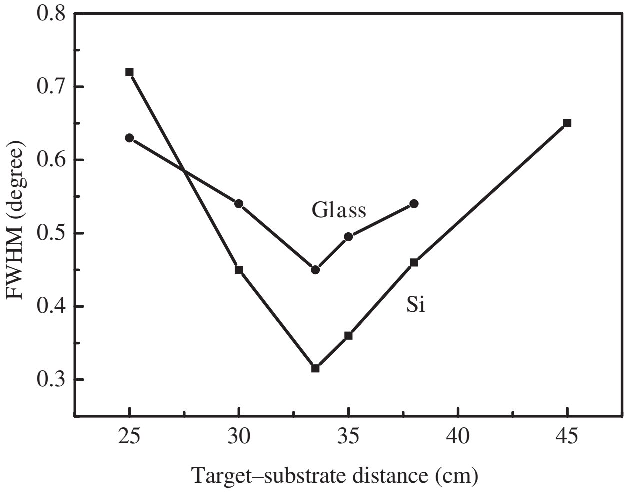

Figure 5. FWHM of XRD for the ZnO thin films grown on Si and glass substrates.

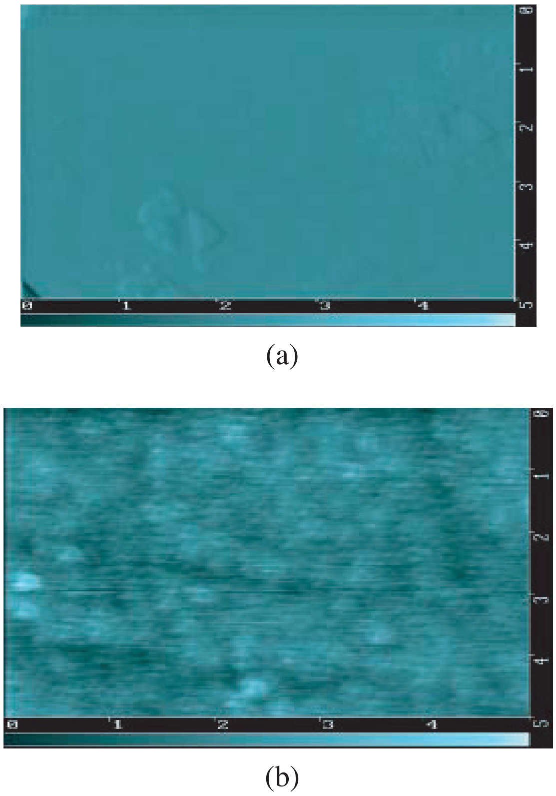

Figure 6. AFM images of ZnO on (a) Si and (b) glass substrates.

The different D_{ts} were used to explore the effect of D_{ts} on surface roughness. The effect of D_{ts} on the crystallinity of the (200) plane is studied. Both intensities of the (002) peak of ZnO films deposited on Si and glass increase with D_{ts}, before decreasing from the peaks. The ZnO films grown on glass at $D_{ts} = 45$ cm exhibit poor crystallinity and become amphorous. Figure 5 shows FWHM of XRD as a function of D_{ts} for the ZnO films grown on Si and glass substrates. The studied ZnO films exhibit the smallest values of FWHM when $D_{ts} = 33.5$ cm. The most intense (002) peaks and the smallest FWHM are observed when $D_{ts} = 33.5$ cm, suggesting better crystallinity. Figure 6 shows the AFM images of ZnO grown

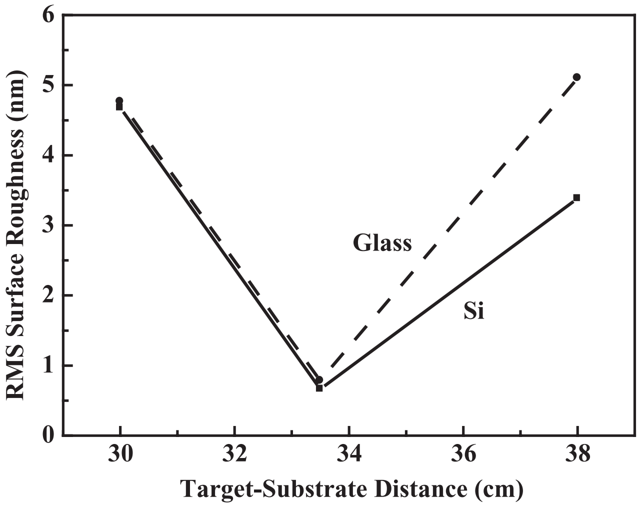

Figure 7. Surface roughness as a function of target–substrate distance for the ZnO thin films grown on Si and glass substrates.

on Si and glass substrates. Figure 7 shows the RMS surface roughness as a function of target–substrate distance. Notably, the ZnO films have the best surface roughness when D_{ts} = 33.5 cm. The best RMS roughness of the films grown on Si and glass was measured to be as low as 0.664 and 0.7852 nm respectively. These findings reveal that D_{ts} and the RF power are the key factors in determining the surface roughness.

4. Conclusions

ZnO thin films were grown on Si and glass substrates. Experimental results demonstrate the excellent surface roughness of ZnO films. Consequently, precisely controlling RF power and D_{ts} yield ZnO films of sufficiently high quality to be prominent candidates for use in device applications.

Acknowledgments

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