Effect of magnesium doping on the structural and piezoelectric properties of sputtered ZnO thin film

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Received 27 July 2007; received in revised form 12 December 2007; accepted 12 December 2007
Available online 23 December 2007

Abstract

Structural and piezoelectric characteristics of magnesium-doped ZnO films were investigated. Magnesium-doped ZnO films with a c-axis preferred orientation were deposited on ST-cut quartz by radio frequency magnetron sputtering. The crystalline structure and surface morphology of films were studied by X-ray diffraction, scanning electron microscopy and atomic force microscopy. The electromechanical coupling coefficient and temperature coefficient of frequency of the filters were then determined using a Love wave filter. A uniform crystalline structure and smooth surface of the ZnO films were obtained when magnesium dopant level was 1.5 mol%. The grain size of the ZnO film increased when magnesium doped. It has been found that the temperature coefficient of frequency declines to +0.44 ppm/◦C at 1.5 mol% magnesium-doped ZnO film.

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Keywords: Zinc oxide; Magnesium; ST-cut quartz; Love wave

1. Introduction

Zinc oxide belongs to the hexagonal wurtzite, 6-mm symmetric space group; it is an n-type wide band gap semiconductor material and has a variety of potential applications [1,2]. ZnO films also have extensively been applied as acoustic devices because of their strong piezoelectric effect [3,4]. Magnesium oxide is a nonpiezoelectric material with cubic rocksalt structure. Recently, magnesium zinc oxide has attracted increasing interest for use in ultraviolet optoelectronic applications [5]. Mg-doped ZnO film has been presented for surface acoustic wave (SAW) devices applications [6]. The electronic and optical characteristics of Mg-doped ZnO film can be tuned by adjusting the Mg doping level.

Surface acoustic wave devices have been utilized extensively in wireless communication systems in recent years. SAW devices must function at a high frequency, with low loss and high temperature stability. The piezoelectric material used in SAW filter applications must have a high phase velocity, high electromechanical coupling coefficient (K²) and low temperature coefficient of frequency (TCF). ST-cut quartz (42°45’ ) substrate is known for its excellent TCF for use in Rayleigh SAW devices. However, its phase velocity is as low as 3158 m/s and the electromechanical coupling coefficient is as small as 0.0014 [7]. On ST-cut quartz (42°45’ ) substrate for surface skimming bulk wave (SSBW) propagation (90°-rotated ST-cut (42°45’ ) quartz), the phase velocity increases to 5060 m/s, but the electromechanical coupling coefficient value is smaller than that of the Rayleigh wave, and the TCF value of SSBW reaches +30 ppm/◦C [8–13]. ST-cut quartz for SSBW filter applications is confined by the high TCF and low electromechanical coupling coefficient.

ST-cut quartz-based SSBW devices in the literature have a relatively high TCF of approximately +30 ppm/◦C, and the TCF can be reduced using a negative TCF ZnO layer [12,13]. Theoretical analyses and experimental results have demonstrated that the maximum electromechanical coupling coefficient of the Love wave filter depends on the optimal ratio of the thickness of the guiding layer to the wave length [13]. The thickness of ZnO film becomes too thin to reduce the positive TCF of the ST-cut quartz to zero, to maximize the electromechanical coupling coefficient. Emanetoglu et al. have found that the acoustic velocity increases, whereas the piezoelectric coupling decreases with increasing high Mg-dopant concentrations (over 10 mol%) [6]. But the influence of the TCF on the Mg-dopant levels was not

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doi:10.1016/j.sna.2007.12.007
investigated. This work studies the effect of the concentration of Mg in doped ZnO films on Love wave filter characteristics, to reduce the TCF of 90°-rotated ST-cut (42°-45°) quartz using a ZnO film of finite thickness.

2. Experimental details

ZnO films were deposited by radio frequency (RF) magnetron sputtering system using a ZnO target [2,14–18]. Mg-doped ZnO targets are prepared by adding MgCO₃ (99.5% Wako) and firing at 900 ºC for 3 h. In the film-deposition process, the sputtering power was maintained at 100 W; the sputtering pressure was 1.33 Pa; the O₂/Ar ratio was 0.75; the distance between the substrate and the target was 50 mm and the substrate was not heated. The deposition rates were controlled at approximate 0.55–0.6 µm/h. The crystalline structure and the orientation of the ZnO films were examined by X-ray diffraction (XRD, Rigaku Dmax 2000). The power of the XRD (Cu Kα radiation) was fixed at 40 kV and 30 mA and the XRD diffraction angles (θ) were measured from 20° to 60°. The surface morphology of the ZnO films was studied by scanning electron microscopy (SEM, Hitachi S-4700) and atomic force microscopy (AFM, Veeco Digital Instruments D3100). The voltage and current of the SEM were fixed at 15 kV and 10 µA. Veeco tip (OTR8-35) and contact mode were applied to measure the roughness of the ZnO films by AFM.

The Love wave devices were fabricated on 12 mm × 13 mm × 0.5 mm thick 42°-45° ST-cut quartz substrate with a propagation direction perpendicular to the crystallographic c-axis. The input and output interdigital transducers (IDT) consisted of 30 finger pairs with an electrode width of 10 µm and a separation of 10 µm, yielding a periodicity of 40 µm. The IDT aperture was 4 mm and the center-to-center of separation of the IDT was 6.2 mm. The IDTs were made of 200-nm sputtered aluminum. Three samples were fabricated with each Mg concentration and three measurements were made of each device. Error bars were obtained from the mean values of all measured results. A network analyzer (Agilent E5062A) was used for the device measurements. The center frequency of the SSBW filter made by 90°-rotated ST-cut (42°-45°) quartz without a ZnO film was 126 MHz. The thickness of the ZnO films in the experiments performed herein is fixed at approximately 2.0 µm to maximize K² [13]. The center frequencies of the filters were 112–114 MHz and the phase velocities were 4480–4560 m/s.

3. Results and discussion

3.1. X-ray diffraction

Fig. 1 shows the X-ray diffraction patterns of ZnO films with Mg-dopant concentrations: 0, 1 mol%, and 5 mol%. Wurtzite structure and single-phase c-axis (0 0 2) orientation were examined by all thin films. The full width at half maximum (FWHM) of 0, 1, 2, 3, and 5 mol% Mg-doped ZnO films were 0.29°, 0.23°, 0.27°, 0.32°, and 0.30°, respectively. At 1–2 mol% Mg-dopant levels, the ZnO films have a highly crystalline structure. It is interesting to find the (0 0 2) orientation intensities of the ZnO films increased when Mg is doped. The SEM images show that the grain size increases with increasing Mg-dopant concentration. The XRD intensities become higher because of more uniformly crystalline when a little Mg dopant is added (1–2 mol%).

3.2. SEM and AFM

Fig. 2 shows the SEM top view of ZnO films with various amounts of Mg dopants. At low concentrations of Mg dopant, the surface morphology of the films appears uniform, and Mg-dopant concentration can help ZnO grains grow. The grain size increases with increasing Mg-dopant level. The results of AFM analysis shown in Fig. 3 indicate that the arithmetical mean roughness of the films increases as the Mg-dopant concentration increases. The increased roughness is due to the grain size growth.

3.3. Electromechanical coupling coefficient

The electromechanical coupling coefficient was obtained from the IDT radiation resistance and susceptibility, respectively [19]. Fig. 4 plots the relationship between the electromechanical coupling coefficient and the concentration of Mg in doped ZnO films. The influence of Mg dopant at low level (below 5 mol%) on the electromechanical coupling coefficient is not obvious. Magnesium oxide is a nonpiezoelectric material; it is expected that the electromechanical coupling coefficient of Mg-doped ZnO film decreases with increasing Mg-dopant level. The expected results have been reported when the Mg-dopant concentrations are over 10 mol% [6]. But our XRD and SEM results reveal that the defects (grain boundary) of ZnO films are reduced by grain growth, the films become more uniformly crystalline when a little Mg dopant is added (1–2 mol%). Therefore, the electromechanical coupling coefficients are not weakening as using a small concentration Mg dopant.
3.4. Temperature coefficient of frequency

The temperature coefficients of frequency were calculated by substitution of the center frequencies at 30, 50, and 70 °C into the following equation:

$$TCF = \frac{F(70^\circ C) - F(30^\circ C)}{40 \times F(50^\circ C)}$$ (1)

4. Conclusions

Surface acoustic wave filter utilized in modern wireless communication technique must function at a high frequency, with low loss and high temperature stability. The effect of the concentration of Mg dopants on the crystalline structure of ZnO films was investigated. The electromechanical coupling coefficient and the temperature coefficient of frequency of Love wave filter with Mg-doped ZnO guiding layer were also examined. We found that the grain size of ZnO film will grow when Mg doped, and the crystalline structure will become more uniform.
and dense when the Mg-dopant level is below 5 mol%. Temperature coefficient of frequency of ST-cut quartz for Love wave filter applications, has been compensated for using 1.5 mol% Mg-doped ZnO films with +30 to +0.44 ppm/°C at the ratio of the thickness of the guiding layer to the wave length is 5.0%, and the electromechanical coupling coefficient has no any decay. The crystalline structure of ZnO film and the temperature coefficient of frequency of Love wave filter will be improved undeniably when magnesium dopant level is 1.5 mol%.

Acknowledgements

The authors would like to thank Prof. Sea-Fue Wang at National Taipei University of Technology and Prof. Jyh-Wei Lee at Tung Nan Institute of Technology for experimental support. This research was supported by the National Science Council of Republic of China, under grant NSC-93-2216E-236-002.

References


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