C-axis Oriented ZnO Piezoelectric Thin Films Prepared by RF Magnetron Sputtering for Saw Filters

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***Abstract*-Well-crystallized ZnO thin film with high (002) orientation was prepared by RF magnetron sputtering on Pt/Ti/SiO2/Si substrates. Interdigital transducer (IDT) electrode with 40μm wavelength was fabricated by lift-off method based on photolithograph techniques. The thickness of the Al electrode was about 200nm. The orientation of the film was studied using X-ray diffraction. The surface morphology was investigated using scanning electron microscopy (SEM). SAW filter was measured by Network Analyzer. To improving the quality of ZnO film and the property of SAW filter, Mn-doped ZnO films were deposited and the structural and electrical properties of the films han been characterized.**

Keywords-ZnO films, SAW, lift-off, IDT

I. INTRODUCTION

ZnO is a direct wide bandgap (about 3.3eV) semiconductor with the hexagonal crystal structure. And ZnO is a versatile material for many applications due to its structural, electrical and optical properties. Especially, it can be used for making low-loss surface acoustic wave (SAW) filters operating at high frequency because of the high piezoelectric coupling coefficients. Compared with single-crystal substrate based SAW filters, high quality piezoelectric thin film based SAW filters lead to low power consumption, reduction of cost and circuit miniaturization through integration with mainstream MMIC technology. The study of piezoelectric thin film materials like ZnO will accelerate the development of future wireless communication.

Many deposition techniques have been employed for ZnO thin film deposition, including sputtering[1], sol-gel[2], and pulse laser deposition[3]. Among all, RF magnetron sputtering has many advantages, such as low substrate temperature, large area deposition, good adhesion of films on substrates and so on. The sputtering technique, which has been used for high quality orientation growth of various semiconductors and oxides, is the ideal production technology for growth of (002) orientation ZnO thin films. In this paper, (002) orientation ZnO thin films with high quality was fabricated by RF magnetron sputtering, and the microstructural and SAW characteristic are presented.

II. EXPERIMENTAL

ZnO thin film was deposited in a 13.56 MHz, 0-300 W RF magnetron sputtering system (JPG-560Ⅱ) with 7.5 cm diameter cathode. ZnO ceramic target was prepared by the standard ceramics process with high purity ZnO (99.9%) powder. The substrate was rinsed in acetone, ethanol and distilled water with ultrasonic vibration before deposition, and the chamber was pumped to a base pressure of 1×10-4 Pa and then the target was pre-sputtered for at least 30 min in an argon atmosphere to eliminate the surface pollutions. A mixed gas of high purity oxygen (99.99 %) and argon (99.99 %) with a ratio of 1:2 was used as the sputtering gas with a total pressure of 2.73 Pa. The target-to-substrate distance was fixed at 5 cm and the deposition power was 120 W. ZnO thin film was deposited on Pt/Ti/SiO2/Si substrate at room temperature and then annealed at 400℃ in an O2 atmosphere for 2 hours. The growth conditions were optimized initially through a series of process experiments by growing ZnO thin films on P-Si(100) substrates. At the above conditions, well-crystallized (002) orientation ZnO thin film, with high quality for SAW filter, was fabricated.

The crystallinity was characterized by X-ray diffraction (XRD) operated at 35KV, 25 mA using Cu Kα (λ=1.5405 $\AA$) radiation. The intensity determined with 2θ from 20º to 60º in a 0.02 degree step size. The microstructure and the cross section were observed by field emission scanning electron microscopy (FESEM, JOEL JSM 6700F). The frequency response of the device was measured using a network analyzer.

III. FABRICATION OF THE SAW DEVICE

Figure 1 showed a fabrication flow chart of the SAW device. The design of IDTs was common and not weighed. The concrete processes are as follows: (1) Cleaning the substrate — clean the substrate using an organic solvent to remove the surface contamination and use de-ionized water to remove the organic particles; then dry the surface. (2) Photoresist coating— pre-bake the substrate for 2 minutes at 100℃; spin with the photoresist and soft bake one minute at 105℃.

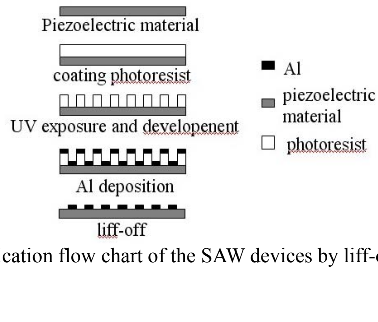


Figure 1. fabrication flow chart of the SAW devices by liff-off technology

(3) deposure and development —expose using a mask, develop and hard bake. (4) Sputtering — after photolithography, sputter the Al electrode to a thickness of 200nm using RF magnetron sputtering. (5) Lift-off — dip in the acetone.

Figure 2 presened the top view IDTs photographic of the fabricated SAW device.

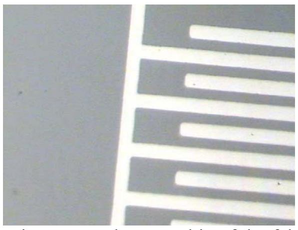


Figure 2. the top view IDTs photographic of the fabricated SAW device.

IV. RESULTS AND DISCUSSIONS

Figure 3 showed the XRD pattern of ZnO thin film fabricated on Pt/Ti/SiO2/Si substrate at room temperature and annealed at 400 ℃ in O2 atmosphere. It's obvious that the film exhibit only two peaks around 34.4°and 40°, related to (002) plane of hexagonal phase and Pt (111) peak, respectively. It showed that the ZnO thin film exhibited a strong preferential (002) orientation. The FWHM of the 34.4°peak was only 0.34°, indicating that the ZnO thin film was well-crystallized.

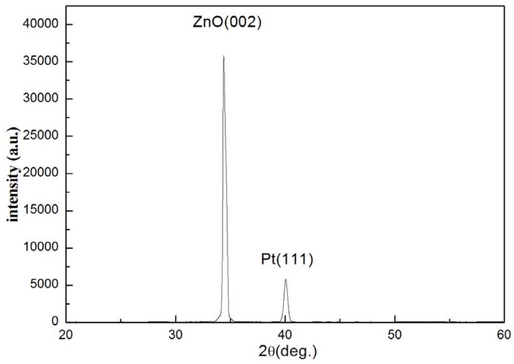
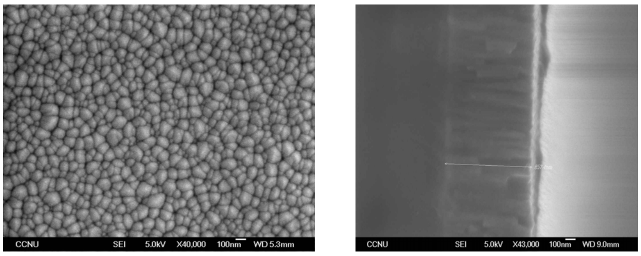


Figure 3. the XRD pattern of ZnO thin film

Figure 4 was the SEM spectra of the ZnO thin film. It can be seen, from the surface micrograph, that the grain of the ZnO film was spheric, and the grain size was small and uniform. There was no visible pores and defects over the film. In addition, the surface was smooth and densely packed. It's can be observed, from the cross-section image, that the ZnO film had a columnar crystal structure, indicating that the film had been crystallized and exhibited c-axis preferential growth characteristic. A dense interface structure also can be observed, indicating strong interface bonding.

Figure 5 showed the 3D AFM image for ZnO film grown on Pt/Ti/SiO2/Si substrate at room temperature and annealed at 400 ℃ in O2 atmosphere. The image indicated that the film grew with densely packed columnar structures, as can be seen in Figure 3. The surface root-mean-square roughness (rms) is 7.78nm, showing smooth surface structure of the ZnO film.



(a) (b)

Figure 4. the SEM spectra of the ZnO thin film
(a) surface morphology (b) cross-section image

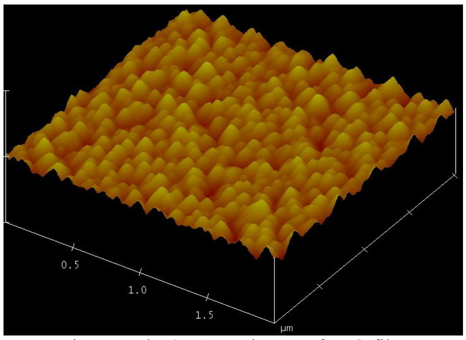


Figure 5. the 3D AFM image of ZnO film

The center frequency of a conventional SAW filter is determined by the width of the IDT finger and the phase velocity which excite the SAW on the piezoelectric materials.

$$V_s = \lambda f = (4d)f \qquad (1)$$

Where Vs is the phase velocity of the SAW, λ is the wavelength of the SAW, f is the center frequency of the SAW filter and d is the one finger width of IDT. In our study, the one finger width of the IDT is 10μm, so the wavelength of the SAW filter is 40μm, the center frequency of 146.8MHz can be seen from the frequency response of the SAW filter, showing in the Figure 6. So according to the formula (1), the phase velocity of the SAW is about 5872m/s. Thus, the SAW filter with a center frequency of GHz can be fabricated on the ZnO/Pt/Ti/SiO2/Si by using advanced 0.13μm ULSI technology.

V. MN-DOPED ZNO FILM

As can be seen in Figure6, the insertion loss was large and the bandwidth was narrow of that SAW device fabricated using pure ZnO thin film. To improve the frequency performance of the device, 0.1wt% and 4wt% Mn-doped ZnO thin films was faricated by RF magnetron sputtering and the structural and electrical properties were studied.

Figure7 showed the XRD pattern of Mn-doped ZnO thin films fabricated on Pt/Ti/SiO2/Si substrate at room temperature and annealed at 400 ℃ in O2 atmosphere. It's obvious that 0.1wt% Mn-doped ZnO film exhibit only one peak around 34.4°, related to (002) plane of hexagonal phase. It showed that the film exhibited a strong preferential (002) orientation and was well-crystallized. On the other hand, 4wt% Mn-doped ZnO film exhibit two other peaks around 32°and 56°, related to ZnO(100) and MnO2(402) peak, respectively. It's probably because when MnO2 largely doped into ZnO, some MnO2 gathered at the grain boundary. So 4wt% Mn-doped ZnO film was poor-crystallized and the preferential (002) orientation was damaged. Comparing the XRD results, 0.1wt% Mn-doped Zno film was better than 4wt% Mn-doped ZnO film for SAW device, concequently, the electrical characteristic of 0.1wt% Mn-doped ZnO film was further studied.

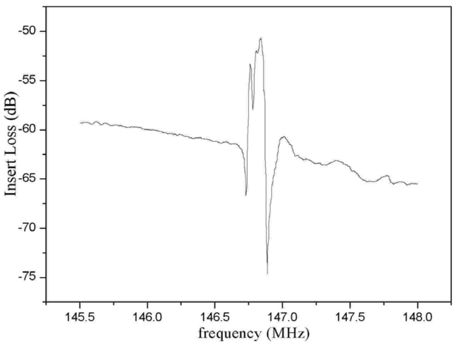
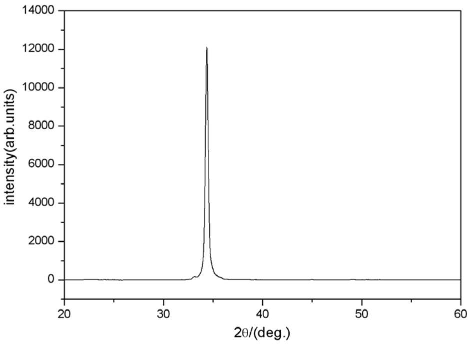
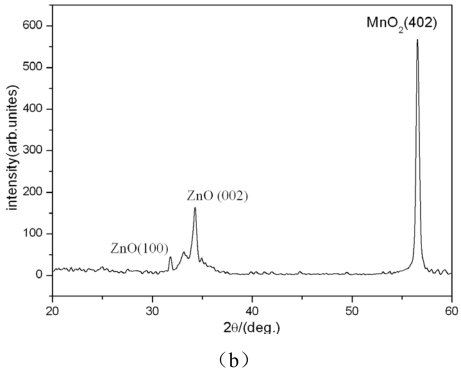


Figure 6. the frequency response of the SAW filter



（a）

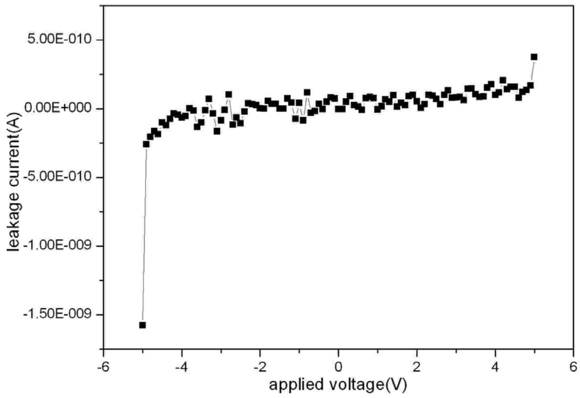


（b）

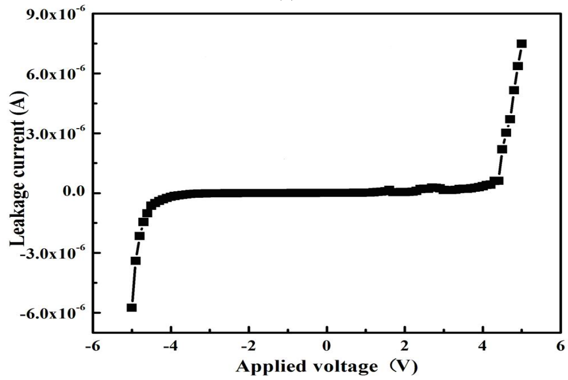
（a）0.1wt％ Mn－doped，（b）4wt％ Mn－doped

Figure 7. XRD patterns of Mn-doped ZnO films

Figure8 showed the I-V curves of pure and 0.1wt% Mn-doped ZnO film. To facilitated comparison, the thickness and the top electrode area of 0.1wt% Mn-doped ZnO film was the same as the pure one. It showed that the leakage current was sharply decreased when doped with Mn. The applied voltage varies from 0 to 5 V, the leakage current of 0.1wt% Mn-doped ZnO film was smaller and kept at about 10-13 order of magnitude. When the applied voltage increases above 4 V, the leakage current increases rapidly but still kept at about 10-9 order of magnitude.



(a)



(b)

(a) 0.1wt% Mn-doped ZnO film, (b) pure ZnO film

Figure 8. I－V curves of pure and 0.1wt% Mn-doped ZnO films

ZnO thin film is n-type semiconductor, and the electric conductivity was relevant on the oxygen vacancies and interstitial zinc atoms. When doped with Mn, the migration rate of oxygen vacancies in grain boundary decreased, on the contrary the barrier of grain boundary increased. Therefore, the resistance of the film increase.

VI. SUMMARIES

C-axis orientated ZnO thin film was prepared by RF magnetron sputtering on Pt/Ti/SiO2/Si substrates. And the SAW filter was also fabricated with the wavelength of 40μm. The structural of ZnO thin film and the frequency response of the SAW filter was studied. The XRD result revealed that the ZnO thin film was strong C-axis oriented, and well-crystallized. The SEM images indicated that the surface of the ZnO thin film was smooth and densely packed, and the growth of the ZnO film had a columnar crystal structure.

The frequency response of the filter indicated that the center frequency of the device was 146.8MHz and the phase velocity of the SAW was 5782m/s. When doped with Mn, the stuctural and electrical properties of film were impoved and higher frequency SAW device can be achieved and used in practice by 0.1wt% Mn-doped ZnO film in the future.

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