ZnO film for application in surface acoustic wave device

X.Y. Du[1], Y.Q. Fu[1*], S.C. Tan[1], J.K. Luo[1,2], A.J. Flewitt[1], S. Maeng[3], S.H. Kim[3], Y.J. Choi[3], D.S. Lee[3], N. M. Park[3], J. Park[3], W.I. Milne[1]

[1]Electrical Engineering Division, Department of Engineering, University of Cambridge, 9 JJ Thomson Ave, CB3 0FA, UK

[2] CMRI, University of Bolton, Deane Road, Bolton, BL3 5AB, UK

[3]Electronics and Telecommunications Research institute (ETRI), 161 Gajeong-dong, Yuseong-gu, Daejeon, 305-700, KOREA

Abstract. High quality, c-axis oriented zinc oxide (ZnO) thin films were grown on silicon substrate using RF magnetron sputtering. Surface acoustic wave (SAW) devices were fabricated with different thickness of ZnO ranging from 1.2 to 5.5 μm and the frequency responses were characterized using a network analyzer. Thick ZnO films produce the strongest transmission and reflection signals from the SAW devices. The SAW propagation velocity is also strongly dependent on ZnO film thickness. The performance of the ZnO SAW devices could be improved with addition of a SiO_2 layer, in name of reflection signal amplitude and phase velocity of Rayleigh wave.

1. Introduction

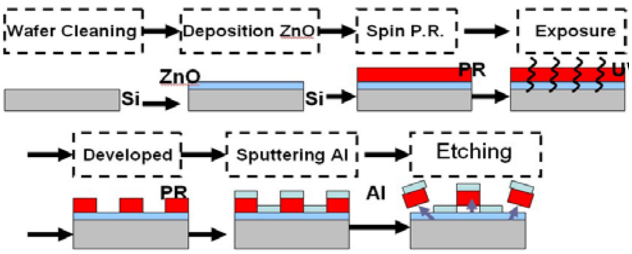
There has been an increased interest in zinc oxide (ZnO) thin films in terms of potential applications in transducers and sensors. One particularly application using ZnO materials is the fabrication of ultra-high frequency surface acoustic wave (SAW) devices for communication applications, which makes use of the piezoelectric properties of this material to generate and detect SAW signals [1]. Quartz is the dominant material for the SAW devices at the moment [2]. However it is expensive and, most importantly, it is difficult to produce on substrates such as silicon, thus limiting its applications, particularly with microelectronics. ZnO has good piezoelectric properties and a high electro-mechanical coupling co-efficiencient. It can be grown in thin film form by rf magnetron sputtering on a variety of substrates, including silicon, making it the most promising material to be integrated with control electronic circuitry. Other advantages of using ZnO films for SAW devices include easy integration with microsensors and microactuators on the same substrate; excellent bonding with various substrate materials, in particular silicon; high temperature stability [4]; and low cost of deposition. Modern microfabrication technology has allowed the production of SAW devices using ZnO films with high resonant frequencies. Grate *et al.* has fabricated

* Corresponding author: yf229@cam.ac.uk

ZnO SAW devices, grown of diamond substrates, with operation frequencies up to the GHz region with large acoustic velocities [3]. Many technologies have been developed to deposit ZnO thin films, including laser ablation, sputtering and metal organic chemical vapor deposition [5]. Of these, RF magnetron sputtering is attractive due to the simplicity of the process and low equipment cost. The key issue for ZnO film deposition by this technique is to improve the film crystal quality and hence the piezoelectric properties. This increases the SAW signal transmission and to lowers the internal acoustic energy loss [6]. The objective of this research is to develop and optimize the deposition of ZnO thin films with good piezoelectric properties allowing the fabrication of high performance SAW devices on silicon substrates at low cost.

2. Fabrication of SAW devices

The process flow to fabricate the SAW device is shown in Fig. 1. P-type Si (100) substrates were thoroughly cleaned using solvents to remove any organic contamination, and rinsed with deionized water. ZnO films with different thicknesses were deposited on both Si wafers and silicon dioxide (1μm thick) coated Si wafers using RF magnetron sputtering from a zinc target. The chamber was evacuated to less than 6×10^{-6} Torr before a mixture of argon (30 sccm) and oxygen (10 sccm) gas was introduced into the chamber and an RF power of 200W at 13.56 MHz applied to the target. The distance between the target and substrate was 11cm. The Zn target was pre-sputtered for 10 minutes prior to deposition on the sample to stabilize the oxidation state of the target surface. The deposition rate is 0.55 μm/min. The cross-section morphology of the deposited films were characterized using scanning electron microscopy (SEM). The surface morphology and roughness of the film were characterized using atomic force microscopy (AFM). The crystallinity and crystal orientation of film were investigated using X-ray diffraction (XRD).



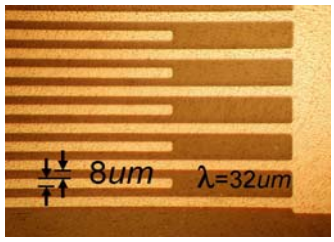


Figure1. *Process flow diagram for SAW devices and Al IDT fabricated*

The samples were patterned with a 1.5 μm thick layer of AZ5124E photoresist using conventional photolithography. The input and output interdigitated transducers (IDTs) of the SAW delay lines (see Fig. 2) consist of 30 or 60 pairs of fingers either 3200 μm or 4800 μm long, with a spatial periodicity of 32 μm, which defines the operational wavelength, λ, and an aperture of 4900 μm. These IDT electrodes were fabricated from aluminium using a lift-off and sputtering process. The Al film thickness is ~150nm, which is less than 0.5% of the λ of the SAW; therefore the effect of mass loading due to the Al layer is minimized. An HP8711A RF network analyzer was used to measure the resonant frequency and signal amplitude of the

SAW devices. The propagation of the SAW was studied through the analysis of the scattering parameters on two configurations: S_{11} and S_{22} (reflection) and S_{21} and S_{12} (transmission).

3. Results and discussions

Fig. 2 is a cross-sectional SEM micrograph showing the columnar morphology of a 2.2 μm thick ZnO film. The surface morphology measured by AFM of the film of 1.2 μm thickness is shown in Fig. 3. The root mean square (RMS) surface roughness values for all the films with different thickness were measured, and they increase from a few nanometres to 40 nm when the thickness of the films was increased from 0.55 μm to 5.5 μm. XRD also shows that the grain size also increases as the films get thicker with a preferred orientation of (002) for all the deposited films (Fig. 4). This is in agreement with Refs.[7, 8]. A large shift in the peak positions compared with the (002) ZnO reference peak indicates the existence of a large compressive stress in the deposited films which increases from 1.23 to 3.2 GPa with as film thickness increases from 0.14 to 2.5 μm.

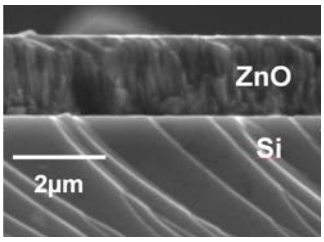


Figure 2. *Cross section SEM image of ZnO film*

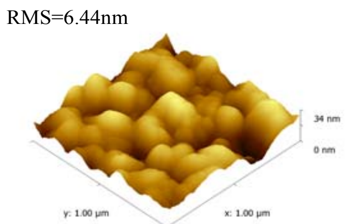


Figure 3. *AFM image of the ZnO surface morphology*

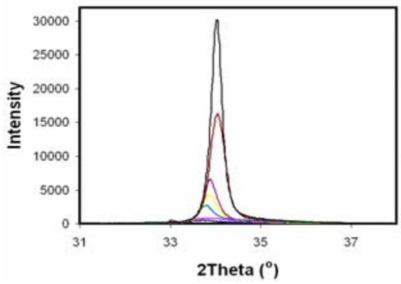


Figure 4. *XRD spectrum of different thickness ZnO film*

Figure 5 shows the measured reflection signals from the ZnO/Si SAW devices (with ZnO film thickness of 5.5 and 6.6 μm) using the network analyzer. The ratios of ZnO thickness, h to λ for these two films are 17.2% and 20.6%. Two peaks are observed: the first one (mode 0) at low frequency range is rather weak and is attributed to a Rayleigh mode wave [9], whereas the one at the higher frequency (mode 1) is quite strong and attributed to a Sezawa mode wave. When $h/\lambda < 0.15$, the Rayleigh mode wave appears to dominate the reflection and transmissions of the SAW signals. The Sezawa mode wave (mode 1) has a higher acoustic velocity compared with the Rayleigh mode, and it is normally observed if $h/\lambda > 0.15$ [10]. The phase velocities of both the Rayleigh and the Sezawa waves are simply calculated from $v = \lambda f_0$, in which v is the wave velocity and f_o is the measured resonant frequency, and shown in Fig. 6 (a). The peak frequencies of the Sezawa waves for the 5.5 and 6.6 μm ZnO SAW devices are 175 and 160 MHz, corresponding to acoustic velocities of 5600 and 5120 m/s, respectively, whereas those of the Rayleigh mode for the two films are 3721 and 3360 m/s. The reflected signal of the Sezawa mode is observed to be much stronger than that of the Rayleigh mode (Fig. 5), and the phase velocity of Sezawa wave is much higher. For the 5.5 μm ZnO/Si SAW devices with different numbers of finger pairs and lengths, the measured resonant frequencies of the Sezawa mode waves ranges from 176 to 178 MHz corresponding to phase velocities of 5569 to 5697 m/s, indicating good repeatability and reproducibility.

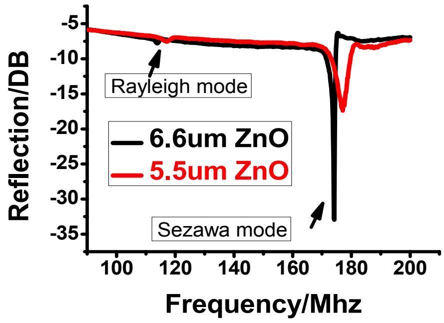
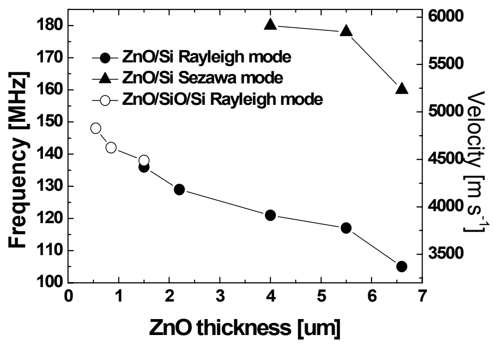
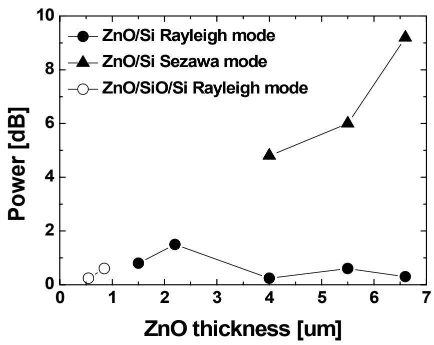


Figure 5. *Reyleigh and Sezawa modes wave*



(a)



(b)

Figure 6. *Frequency and velocity (a) and power amplitude (b) of SAW devices as a function of ZnO film thickness*

For the SAW devices on Si substrates with the ZnO film thickness below 1.5 µm ($h/\lambda <$ 0.05) only the Rayleigh mode is observed, as the film is too thin to generate high velocity Sezawa wave modes [10]. The resonant frequency of Rayleigh mode wave on the 1.5 µm ZnO films ranges from 136 to 139 MHz, corresponding to velocities of 4355 to 4470 m/s. Whereas, the Rayleigh mode resonant frequency of 5.5 µm ZnO SAW device ranges from 114 to 117 MHz, corresponding to a phase velocity of 3648 to 3721 m/s, respectively. It is apparent that the Rayleigh mode resonant frequency decreases by about 16% when film thickness increases from 1.5 to 5.5 µm. For the 6.6 µm ZnO SAW device, the resonant frequency of Rayleigh wave dropped even further, to ~104 MHz.

The measured resonant frequencies and the calculated velocities of the Rayleigh and Sezawa waves for the SAW devices on both the Si and SiO_2/Si substrates are shown in Fig. 6(a). It is apparent that the frequencies and velocities gradually decrease with increasing the thickness of ZnO film. In another words, the SAW velocity increases with the decrease of the h/λ ratio. The reasons behind these findings are not so clear. With increase in film thickness, the film compressive stress increases dramatically, and the surface roughness also increases significantly. These could be harmful for the SAW propagation, thus causing the decrease in SAW frequencies and velocities.

For the SAW devices on Si substrates with the ZnO film thickness below 1.5 µm ($h/\lambda <$ 0.04) no peaks in the reflected signals could be detected. Since the active layer thickness for SAW devices is within one wavelength, there will be substantial acoustic energy loss into the non-piezoelectric Si substrate through the wave penetration for these very thin ZnO films [11, 12]. Fig. 6(b) shows the measured reflection amplitude of the resonant frequency peaks (for both Raleigh and Sezawa modes) using the network analyzer. The peak amplitudes from the 5.5µm ZnO devices are in a range from 4.4 to 18 dB, whereas that for the 1.5µm ZnO device is in a range from 0.3 to 2.0 dB. As shown above, the grain size of the ZnO film increases with film thickness and the crystal quality and the piezoelectric properties could be improved with increase in film thickness. These could cause the larger amplitude of the reflection signal in a SAW device with a thicker ZnO layer.

It is expected that for thin ZnO films, the surface acoustic wave could be easily reflected through the film/substrate interface, thus there could be an enhancing effect to the propagating waves if the reflected signals are combined with the propagating wave signals. From Fig. 6(a), the reflection signal of the ZnO SAW device on the SiO_2/Si substrate can be detected if the ZnO film thickness is only 0.55 µm (although the reflection signals are much weaker, with amplitude around 0.3 dB. Whereas, the reflection signal can only be detected if the ZnO film thickness is above 1.5 micron on a Si substrate. As shown in Fig. 6(a), the resonant frequency of the Rayleigh mode on the ZnO/SiO_2/Si structure is slightly larger than that of the ZnO/Si structure with the same thickness of the ZnO film. The reason may be attributed to the higher acoustic speed on silicon oxide layer than that on Si substrate. The propagating wave within the ZnO film can be reflected by the SiO_2 layer and thus enhanced during the propagation, resulting in an increased propagation speed of the acoustic wave on the SiO_2 substrate. In ref. [13, 14, 15], results showed that the SAW velocities could approach the acoustic speed of the substrate materials when the piezoelectric layer thickness is significantly reduced with respect to the wavelength [9]. Although in this study, the thickness of ZnO layer on the SiO_2/Si substrate is too thin to generate the Sezawa mode wave, it is expected that for a thick ZnO film, the velocity of Sezawa mode wave is larger on the devices with ZnO/SiO_2/Si structure than those on the ZnO/Si structure.

Conclusion

High quality, c-axis oriented ZnO thin film were grown using RF magnetron sputtering. Epitaxial quality of the films was verified using XRD, SEM and AFM measurement. The reflection responses of SAW devices with variety of ZnO thickness were measured. The SAW propagation velocity is strongly dependent on ZnO thickness. Both the Rayleigh mode and Sezawa mode can be obtained with h/λ ratio larger than 0.15. The reflection signal amplitude and phase velocity of Rayleigh wave have been increased with with addition of a SiO_2 layer.

Acknowledgement

Experimental help from Mr. S. Pisana and Dr. M. Kataoka is acknowledged.

References

[1] S.J. Pearton, D.P. Norton, K. Ip, Y.W. Heo and T. Steiner, *J. Vac. Sci.& Technol. B* **22** (2004) 932.

[2] D.M. Bagnall, Y.F. Chen, T. Yao, S. Koyama, M.Y. Shen, T. Golo, *Appl. Phys. Let.,***70** (1997) 2230.

[3] W.J. Grate, S.J. Martin, R.M. White, *Anal. Che.,* **65** (1993), 940.

[4] S.Petroni, G.Tripoli, C.Combi, B.Vigna, M.De Vittorio, M.T.Todaro, G.Epifani, R.Cingolani, *Superlattices and Microstr.,* **36** (2004) 825.

[5] Jean Pierre Atanas,Roy Al Asmar, Antonio Khoury, Alain Foucaran, *Sensors and Actuators,* **127** (2006) 55.

[6] S.J.Pearton, D.P.Norton,K.Ip,Y.W.Heo,T.Steiner, *Process in Mat. Sci.* **50** (2005) 293.

[7] Stdfany Jacesko, Jose K Abraham, Taeksoo Ji, Vijay K Varadan, Marina Cole and Julian W Gardner, *Smart Mat. and Str.* **14** (2005) 1010.

[8]IvanStoyanov,MichaelTewes,Michael Hock,Markus Lohndorf, *Microelectronic Eng.* **83** (2006). 1681.

[9] S.Petroni,G.Tripoli, C.Combi,B.Vigna,M.De Vittorio,M.T.Todaro,G.Epifani,R.Cingolani, *Superlattices and Microst.* **36** (2004) 825.

[10]Y.Takagaki, P.V Santos, E.Wiebicke, O.Bramdt, H.P.Schonheer, K.H.Ploog, *Appl. Phy. Lett.* **81**, (2000) 14

[11] Showko Shiokawa, Yoshikazu Maysui, Yoyasaka Moriizumi, *Jpn. J. Appl. Phy.* **28**, (1989) 126.

[12] G. Mchale, M.K.Banerjee, M.I.Newton, *Phy. Rev. B* **59** (1999) 377.

[13] S.H.Lee, H.H.Jeon, SB.Bae,J.H.Lee, *IEEE Trans. Electron. Devices*, **48** (2001),524

[14] G.D.O'Clock, M.T.Duffy, *Appl. Phy. Lett.* **23** (1973) 55

[15] H.H.Jeong, S.K.Kim, Y.C.Choi,J.H.Lee, *Phy. Status Solidi*, A **188** (2001) 247.

[16] N.W.Emanetoglu, C. Gorla, Y. Liu, S. Liang, Y. Lu, *Mat. Sci. in Semicond. Proc.*, **2** (1999) 247.