Deposition of ZnO Films for FBAR Device Fabrication

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Abstract—The effects of the deposition temperature on the growth characteristics of the ZnO films were studied for film bulk acoustic wave resonator (FBAR) device applications. All films were deposited using a radio frequency (RF) magnetron sputtering technique. It was found that the growth characteristics of the ZnO films have a strong dependence on the deposition temperature from 25 to 350°C. The ZnO films deposited below 200°C exhibited reasonably good columnar grain structures with a highly preferred c-axis orientation while those above 200°C showed very poor columnar grain structures with a mixed-axis orientation. This study seems very useful for the future FBAR device applications.

Index Terms—FBAR, ZnO Film, Temperature region, Critical temperature, FWHM, C-axis preferred growth

I. INTRODUCTION

Recently, film bulk acoustic wave resonator (FBAR) device has attracted a great attention as a new technology for the radio frequency (RF) filter applications, mainly because in addition to its small size, high performance, it can be compatibly integrated with the current manufacturing semiconductor technology. From the manufacturing point of view, the FBAR technology seems to be a unique candidate that can meet the rigorous requirements of the future wireless communications systems because it may enable the current off-chip RF filters to be realized in microwave monolithic integrated circuits. [1,2] From the FBAR operation point of view, an acoustic wave propagating through a piezoelectric film sandwiched between top and bottom metal electrodes generates the resonance. And the resonance characteristics depend on the degree of the preferred orientation of the crystal grain growth. Thus, the quality of the piezoelectric film cannot be overemphasized. In general, two piezoelectric materials (ZnO and AlN) have been frequently adopted for the FBAR devices. The ZnO appears to have some advantages compared with AlN due to its large piezoelectric constant and high film quality. [3] Recently, several studies on ZnO films and their growth characteristics on Al/Si (aluminum deposited on silicon) substrates have been reported. [4,5] However, few comprehensive studies have been reported on the effects of the various deposition temperatures on the preferred orientation or grain growth behaviors. A more comprehensive investigation on the effects of the deposition temperature on the ZnO crystal growth needs to be made, particularly from the processing standpoint.

In this paper, we present a comprehensive study on the effects of the deposition temperature on the growth characteristics of the ZnO films deposited on Al/Si substrates in comparison with those on Si substrates. The ZnO films were deposited using an RF sputtering method by varying the deposition temperature from room temperature to 350°C. The growth characteristics of the deposited ZnO films are shown to have a strong dependence on the deposition temperature. Overall, the ZnO films deposited below 200°C show a highly preferred orientation of c-axis where the FWHM value of the x-ray diffraction rocking curve is 14.0~14.4°.

II. EXPERIMENT

In this experiment, we investigated how the ZnO film characteristics depend on the deposition temperatures when the ZnO films were deposited on either Si wafer with Al (Al/Si substrate) or Si wafer without Al (Si substrate). The ZnO films were deposited at various temperatures (room temperature to 350°C) under the RF power of 320W, the deposition pressure of 10mTorr, and the O_2 concentration of 25%. Prior to the ZnO film deposition, the base pressure of $< 2.0\times10^{-6}$ Torr was maintained to remove any impurities in chamber as much as possible. Then, the reaction gas of high purity was injected into the chamber and the ZnO films were deposited on Si or Al/Si substrates with the substrate rotating at 6 rpm while the distance between the substrate and target was set 6.5cm. The ZnO target (Cerac Co. Ltd) has a diameter of 4 inch, thickness of 1/8 inch, and purity of 99.999%. The second one was to determine the deposition temperature at which the ZnO film can have a good crystal property and highly

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preferred growth characteristics. The crystal properties and preferred growth characteristics of the ZnO films were analyzed using a Rigaku D/max-RC x-ray diffractometer (XRD) with CuK_α radiation at 30kV and 60mA. The microstructures and preferred crystal planes paralleled to substrate were evaluated by the θ-2θ scan method with rotating x-ray detector by 2θ and sample by θ. But this method cannot determine the arrangement of the specific planes paralleled to substrate that indicate the degree of the c-axis preferred orientation growth. Instead, the rocking curve technique can solve this issue. In the case of ZnO films, it can calculate the FWHM values of Gaussian distribution obtained by performing the θ scan of samples around 17.21° with the x-ray detector fixed at position of 2θ value (34.42°) of the (002) plane, observed at θ-2θ scan. The smaller FWHM value indicates the higher degree of the c-axis preferred orientation growth. The Akashi DS-130C scanning electron microscopy (SEM) measurements were also done to analyze the morphology and thickness of the deposited thin films. In addition, Auger electron spectroscopy (AES) depth profiles were obtained from the samples in order to see any effects of the oxidation of the bottom Al electrode on the growth characteristics of ZnO films. The multilayer formation for the FBAR devices includes a piezoelectric ZnO film sandwiched between top and bottom Al electrodes and an acoustic wave reflector between the bottom electrode and silicon substrate. The acoustic wave reflector is formed by alternately depositing silicon dioxide (SiO_2) and tungsten (W) on a silicon substrate. [6,7] The W and SiO_2 films have one-quarter wavelength thickness of the resonance frequency and the ZnO film has half wavelength thickness of the resonance frequency. [6,8] Similarly, the top Al electrode was deposited on top of the ZnO film. Each thickness of SiO_2, W, and ZnO are 6000, 5500 and 13200Å, respectively. More process details are summarized in Table 1.

Table 1 Deposition condition for ZnO, SiO_2, W, and Al films

Film	ZnO	SiO_2	W	Al
Deposition system	RF sputtering		DC sputtering	
Power (W)	320	360	125	150
Pressure (mTorr)	10	5	15	20
Gas flow	Ar+O_2 (25%)	Ar		
Substrate temperature (°C)	200	Room temperature		
Target-substrate distance (cm)	6.5	4.8	6.5	6.5
Deposition time (min)	98	36	30	32
Deposition rate (Å/min)	134.3	146	175	40.5

III. RESULTS AND DISCUSSION

Fig. 1 shows the XRD θ-2θ scan results of the ZnO films deposited on two different Al/Si and Si substrates at various temperatures. In the case of the Si substrate, the intensities of the (002) peaks increase with increasing the deposition temperature up to 250°C. This is attributed to the improvement in the degree of the c-axis preferred growth of the deposited ZnO films. However, the intensity of the (002) peak decreases significantly at 350°C, as shown in Fig. 1(c). This can be explained by the fact that below 250°C, the sputtered atoms are allowed to move to their more stable sites due to their mobility improvements on the substrate surfaces while at higher temperature, the reduction in the degree of the preferred growth towards c-axis may cause an evaporation of the deposited films rather than enabling the Zn and O atoms to move to their stable sites. [9]

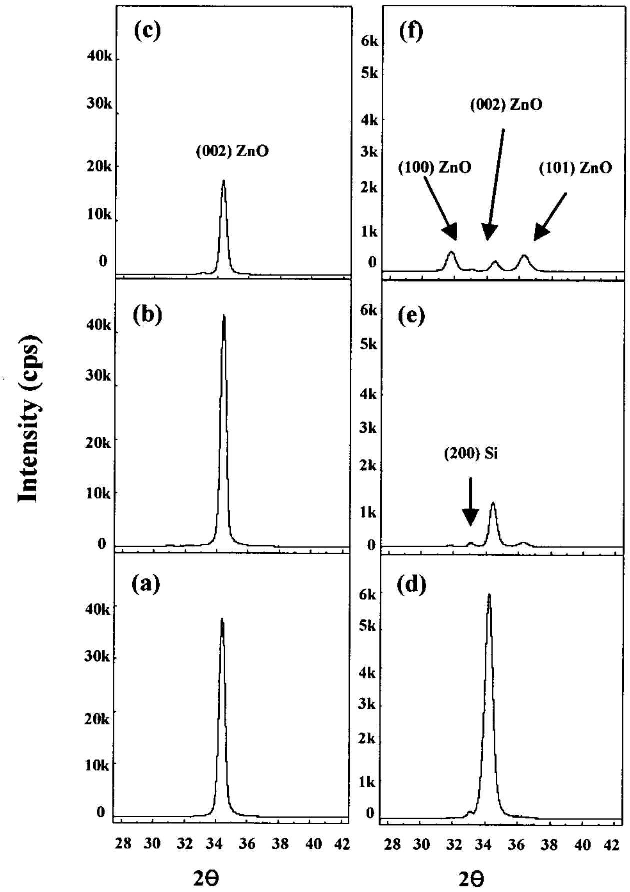

Fig. 1 XRD θ-2θ scan results of the ZnO films deposited at (a) 200, (b) 250, (c) 350°C on Si substrates and at (d) 200, (e) 250, (f) 350°C on Al/Si substrates.

Particularly on the Si substrate, the (002) preferred growth is observed at all temperatures, as shown in Fig. 1 (a)~(c). Unlikely, on the Al/Si substrate, the growth characteristics of the ZnO films are more dependent on the deposition temperatures. As the intensity of the (002) peak remarkably decreases, a small peak at (101) is observed at 250°C and the film begins to deviate from the c-axis preferred orientation growth, as shown in Fig. 1(e). The intensity of the (002) peak becomes small and the intensities of (100) and (101) peaks become large as the temperature increases to 350°C. Thus, the films show a mixed-axis orientation growth at this temperature, as seen in Fig. 1(f). The ZnO films deposited on the Si substrates show the c-axis preferred orientations at all temperatures while on the Al/Si substrate the deposited ZnO films show a change in their growth behavior from the c-axis to the mixed-axis orientation with increasing the deposition temperature. Thus, to grow the ZnO films with a highly preferred c-axis orientation on the Al/Si substrate seems more difficult than that on the Si substrate. Based on the SEM measurements and the FWHM of the rocking curves obtained from the ZnO films deposited at 250°C on the Si and Al/Si as shown in Fig. 2 (a)~(d), the rocking curve of the ZnO films deposited on the Si substrates show a Gaussian distribution profile (Fig. 2(c)) while that on the Al/Si substrate deviates significantly from the Gaussian distribution (Fig. 2(d)).

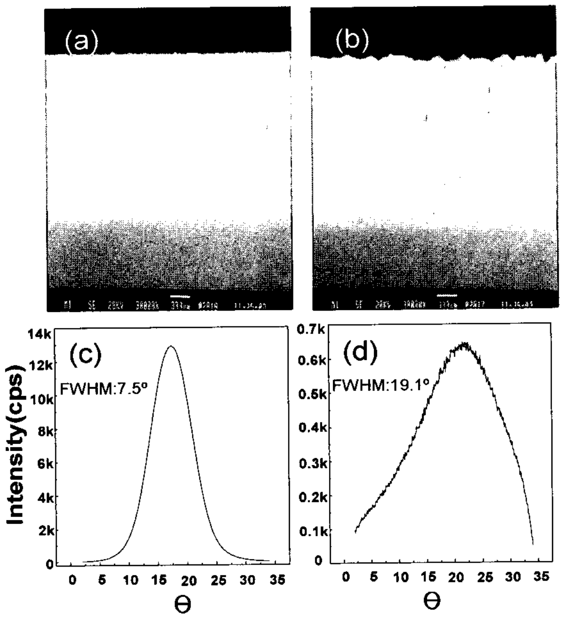

Fig. 2 SEM images of ZnO films deposited at 250°C on (a) Si substrate and (b) Al/Si substrate, and XRD rocking curves of the ZnO films deposited at 250°C on (c) Si substrate, and (d) Al/Si substrate.

The FWHM values of the ZnO films deposited at 250°C on Si and Al/Si substrates are 7.5 and 19.1°, respectively. It is noted at this point that since it is necessary to grow a high quality ZnO film on the Al bottom electrodes for the FBAR device applications, it seems desirable to observe the higher quality of the ZnO film on the Al/Si substrate. Several researchers have done some studies on the deposition temperature effects of various ZnO films deposited on the Si substrates. [9-12] But few comprehensive investigations on the deposition temperature effects on the ZnO films deposited on the Al/Si substrates have been reported. In this work, a more comprehensive study on the effects of the RF power and deposition temperature on the ZnO films was done when the films are deposited on the Al/Si substrates. First, several ZnO films were deposited on the Al/Si substrates under the RF powers of 160, 240 and 320W at two different temperatures of 200 and 350°C. As the RF power increases from 160W to 320W at 200°C, the intensity of the (002) peak increases with the increase in RF power, whereas the characteristics of the (002) preferred orientation growth remain almost unchanged, as shown in Fig. 3(a). In contrast, at 350°C, the ZnO films show a mixed-axis orientation growth behavior, including (100), (101) and (102) in addition to (002) orientation, as shown in Fig. 3(b). The ZnO films deposited at 200 show the (002) preferred orientation while those at 350°C show the mixed-axis orientation for various RF powers applied. This indicates that the growth characteristics of the ZnO films appear to be dominated by the deposition temperature rather than by RF power. For more clarity, the SEM and XRD measurements were made as shown in Fig. 4. The deposition temperature can be divided roughly into three regions (regions 1, 2, 3).

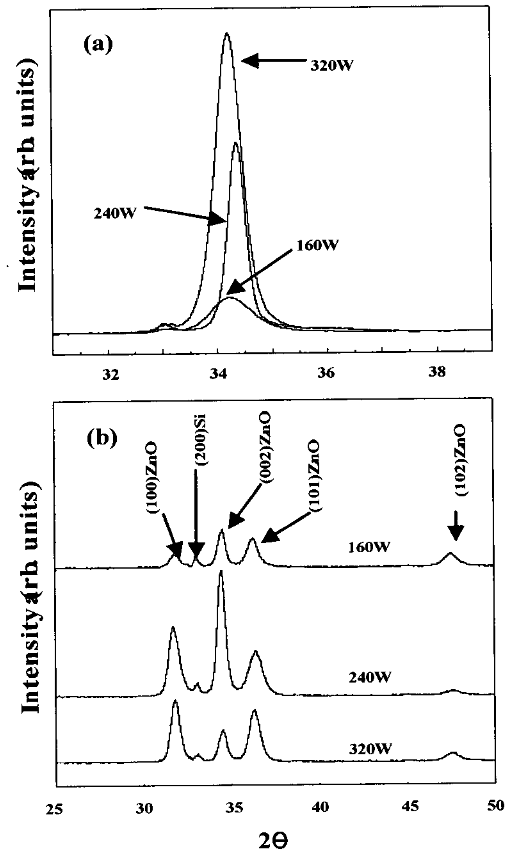

Fig. 3 XRD θ-2θ scan results of the ZnO films deposited at RF power of 160, 240 and 320W under two different temperatures of (a) 200 and (b) 350°C.

It is clear that the ZnO films deposited at three different temperature regions show three different growth behaviors, as shown in both SEM images (Fig. 4 (a)~(e)) and XRD measurements (Fig. 4 (f)~(j)). In the region 1 (23~200°C), the (002) peak observed in 2θ scope shows a very large intensity, as shown in Fig. 4 (f) and (g). The large intensity of the (002) peak indicates that the ZnO films deposited at this temperature range strongly may orient towards the c-axis, perpendicular to the substrate surface. Furthermore, the SEM images (Fig. 4 (a) and (b)) show the ZnO films with a highly preferred orientation towards the c-axis. In the region 2 (250~300°C), the intensity of the (002) peak seems remarkably diminished, and small peaks at (101) and (102) are additionally observed, as shown in Fig. 4 (h) and (i). This means that the ZnO films begin to deviate from the preferred c-axis orientation growth, thus leading to have a mixed-axis orientation. The SEM images show that the ZnO films have a less preferred orientation towards c-axis. In the region 3 (> 350°C), the

(100), (002), (101) and (102) peaks were detected in the displayed 2θ scope, as shown in Fig. 4(j) where the relative intensity of the (002) peak is smaller compared with the other peaks at (100) and (101). Clearly, the SEM images also show a randomly grown grain microstructure at this high temperature region.

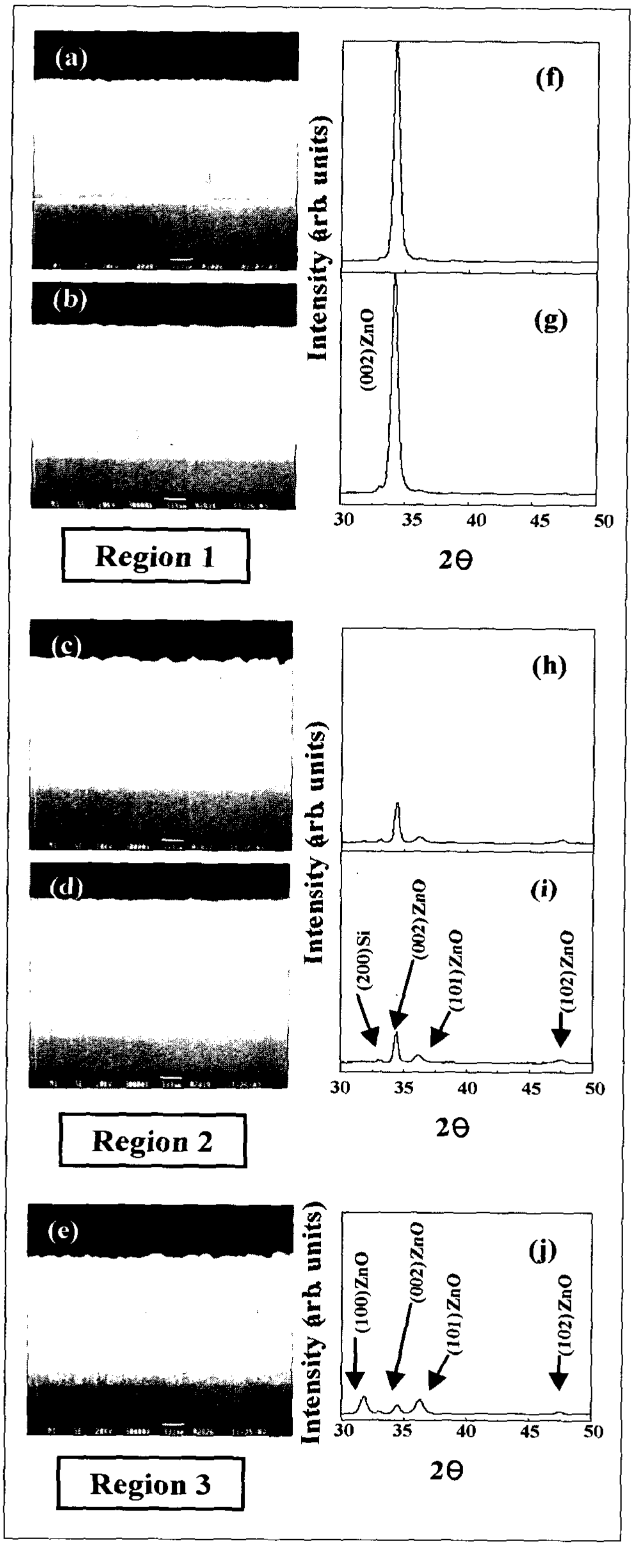

Fig. 4 SEM images of the ZnO films deposited at (a) 23, (b) 200, (c) 250, (d) 300, and (e) 350°C, and XRD θ-2θ scan results of the ZnO films deposited at (f) 23, (g) 200, (h) 250, (i) 300, and (j) 350°C

The positions of 2θ values of (100), (002), (101) and (102) planes observed at the θ-2θ scan are 31.77, 34.42, 36.25 and 47.54°, respectively, and the distances of the plane intervals are 2.814, 2.603, 2.476 and 1.911 Å, respectively.

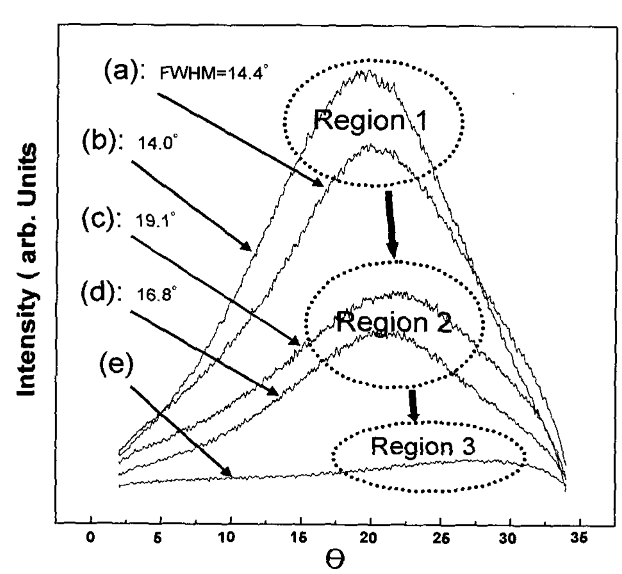

Fig. 5 XRD rocking curves of the ZnO films deposited at (a) 23, (b) 200, (c) 250, (d) 300, and (e) 350°C.

Overall, as the deposition temperature increases, the growth characteristics of the ZnO films seem to change from a highly preferred orientation growth to a completely mixed-axis orientation growth, mainly because more random crystal growths along (100), (002), (101) and (102) planes proceed together at relatively high temperature. In this experiment, it was found that the growth characteristics have a strong dependence on the deposition temperature, not much on the RF powers applied. For more clarity, the XRD rocking curves of the ZnO films deposited at various temperatures are extracted and compared, as shown in Fig. 5. The growth behaviors are clearly divided by three temperature regions with two critical temperatures. The FWHM values of the XRD rocking curves in the region 1 and region 2 are 14.0~14.4 and 16.8~19.1°, respectively. Unfortunately, in the region 3, it was not possible to calculate the FWHM value because the rocking curve does not show the Gaussian distribution, as shown in Fig. 5(e). The growth characteristics of the ZnO films deposited on the Al/Si substrates are shown to have a significant dependence on the deposition temperature. Finally, to investigate any possible oxidations of the Al film in Al/Si substrates during the ZnO deposition at high temperature, AES depth profiles were measured on the samples, consisted of the ZnO film/Al film/Si substrate. Fig. 6(a)~(c) show the depth profiles of the ZnO films deposited on the Al/Si substrates at 200, 250 and 350°C, respectively. As shown in the profiles, the amount of oxygen (O) atoms relative to the aluminum (Al) atoms (in term of the O/Al ratio) at/near the Al film significantly increases for the ZnO films deposited at higher temperature, indicating a more oxidation of the Al layers at higher temperature. In addition, the amount of the Zn atoms seems to increase at the Al film, possibly due to the Zn atoms diffusion at the high deposition temperature. During the ZnO depositions, it seems that both oxidation of the Al layer and the diffusion of the Zn atoms into the Al layer may occur. Eventually, the oxidation of the Al film occurring simultaneously during the ZnO deposition may suppress a high quality columnar grain growth with a highly preferred c-axis orientation, particularly when the film is deposited at the high temperatures such as 250 and 350°C. Table 2 summarizes the FWHM values, the degree of the c-axis preferred orientation, the observed crystal planes of the ZnO films and the orientation characteristics according to the deposition temperatures. Consequently, below 200°C, the ZnO film deposition results in the columnar grains with a highly preferred c-axis orientation. It is noted that the FWHM value is found the smallest of 14.0° for the ZnO film deposited at 200°C. This means that the ZnO film is strongly oriented to the c-axis perpendicular to the substrate surface. In this work, the critical deposition temperature of the ZnO film appears to be around 200°C below which a high quality ZnO film can be deposited for the FBAR device applications.

IV. CONCLUSION

In this paper, the effects of the deposition temperature on the growth characteristics of the ZnO films deposited on the Al bottom electrode are presented. The growth characteristics of the ZnO films appear to have a strong dependence on the deposition temperature. According to the distinguishably different micro-crystal structures and the c-axis preferred orientation, the deposition temperatures can be divided into 3 temperature regions and 2 critical temperatures in-between. Overall, the ZnO films deposited at/below 200°C seem to have good columnar grains with a highly preferred c-axis orientation. This study will be a useful reference for the ZnO film deposition process, particularly for the future FBAR device applications.

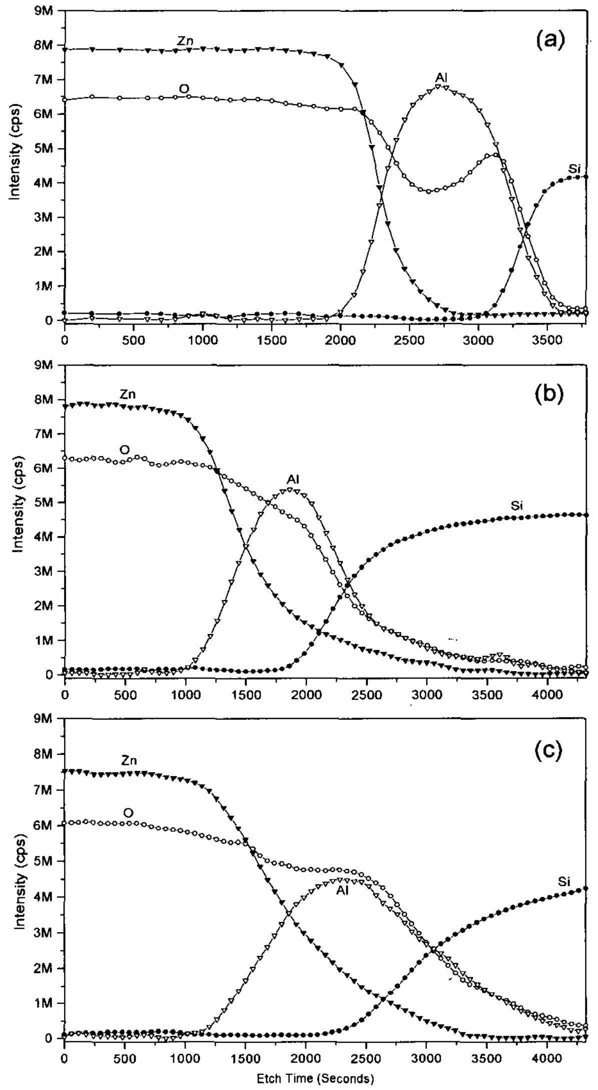

Fig. 6 AES analyses of the ZnO/Al/Si layers where the ZnO films were deposited at (a) 200, (b) 250, and (c) 350°C.

Table 2 Growth characteristics of ZnO films deposited at various temperature

Classification / Temperature region		FWHM (deg)	Temperature (°C)	Degree of c-axis preferred orientation	Planes observed	Orientation property
Region 1	23	14.4	23-200	High	(002)	Highly preferred c- axis
	200	14.0				
Critical temperature			Between 200 and 250			
Region 2	250	19.1	250-300	Middle	(002), (101), (102)	Start of mixed axis
	300	16.8				
Critical temperature			Between 300 and 350			
Region 3	350	Cannot be calculated	> 350	Low	(100), (002), (101), (102)	Completely mixed axis

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