Structural and electrical characteristics of R.F. magnetron sputtered ZnO films

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Abstract

We investigated the effects of both bottom electrodes and processing parameters on the physical and electrical properties of ZnO films deposited by R.F. magnetron sputtering. We found that the preferential $c$-axis growth of deposited ZnO films depends on the type of bottom electrode: Both Al and Au bottom electrodes enhance the growth of $c$-axis orientation in ZnO films, while no clear evidence for any preferential growth was observed in case of Cu and Si. The resistivity of ZnO films deposited on Au and Al bottom electrodes was greater than $10^6$ $\Omega$ cm. The ranges of dielectric constant of Al/ZnO and Au/ZnO samples were 8–14 and 13–16, respectively. Dissipation factors change from 0.02 to 0.05. In general, as $c$-axis orientation enhances, dielectric constant and dissipation factor increase and decrease, respectively.

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1. Introduction

Film bulk acoustic resonator (FBAR) has been used for many communication applications including duplexer and resonator [1–3]. A thin layer of piezoelectric film located between top and bottom metal electrode, i.e., metal–insulator–metal (MIM), is used to convert electrical energy into mechanical energy, and vice versa. It is therefore important to find the proper piezoelectric material, which can improve the reliability and/or property of FBAR. Either ZnO or AlN has been a choice for piezoelectric materials for FBAR. Requirements for these materials are highly preferred $c$-axis orientation, stable dielectric constant, high resistivity, and low dissipation factor. In order to satisfy these conditions, ZnO thin films are deposited using several methods including chemical vapor deposition [4] and the sol–gel method [5]. However, when a sputtering method is used to form ZnO thin films, many researchers have reported that highly preferred $c$-axis orientation is influenced by the processing conditions including the type of the substrate [6], the substrate temperature [7,8], the input power [9], and the sputtering gas pressure [9,10].

In this article, we investigated the effects of deposition parameters and various bottom electrodes on the electrical and structural properties of ZnO thin film.

2. Experimental

The sample used in this work is a metal–insulator–metal (MIM) capacitor as shown in Fig. 1. To minimize the substrate effects, SiO₂ film (250 nm) was deposited on the Si substrate by the sputtering method.

In order to investigate the effects of bottom electrode, various types of thin metal films (i.e., Al, Au, Cu) were deposited directly on either Si/SiO₂ or Si using the sputtering method. Immediately after the deposition of bottom electrode, ZnO thin films were deposited by R.F.
magnetron sputtering using a sintered ZnO target (99.99%). The sputtering chamber was evacuated to $2 \times 10^{-5}$ Torr using a turbo-molecular pump. Sputtering was carried out in a mixture of Ar (50%) and O2 (50%), and at room temperature. Table 1 shows the sputtering conditions in more detail. For the structural analysis of ZnO thin films, $c$-axis preferred orientation was characterized by X-ray diffraction (XRD) $h/2h$ scans using a diffractometer (Rigaku Rotaflex D/MAX System, 30 kV, 100 mA). The thickness and cross-sectional image of films were observed by a scanning electron microscope (FESEM, JEOL, JSM6700F, magnification of 50,000). The RMS roughness and surface morphology of films were measured by an atomic force microscope (AFM Seiko, SPA-300 HV). For electrical analysis, the capacitance and dissipation factor of the films were measured using a Hewlett-Packard 4275 A multi-frequency LCR meter at the frequency of 100 kHz–4 MHz. The dielectric constant was calculated from the capacitance value. The gate area of MIM capacitor was $4 \times 10^{-4}$ cm². The electrical resistivity was measured using a CMT-SR1000N (Changmin).

3. Results and Discussion

In order to achieve high piezoelectric coefficient for the required thickness extensional mode, columnar ZnO grains with the $c$-axis perpendicular to substrate are strongly recommended [11,12]. The texture of sputtered ZnO films has been known to depend on the deposition conditions, the substrate surface, and the deposition rate. As a consequence, it is important to investigate the roles of bottom electrode on the deposition rate.

Fig. 2 shows the deposition rate of ZnO films as a function of sputtering conditions. The data shown in Fig. 2(a) indicate that the deposition rate rapidly decreases as the distance between the sample substrate and the ZnO target (i.e., target-sample distance) increases as expected. In addition, we found that the deposition rate is independent of bottom electrode except Al, which shows a slightly higher value as compared to the others. In Fig. 2(b), the deposition rate also decreases as the working pressure increases and is independent of bottom electrode except Au at this time. However, note that the growth rate of ZnO on Au in Fig. 2(b) was obtained with target-sample distance of 50 mm (i.e., 20 mm smaller than the others) to improve the crystallinity of ZnO film as we will discuss later in this paper. Therefore, the difference on the growth rate between Au and the others as shown in Fig. 2(b) is simply the effect of target-sample distance. Based on the data shown in Fig. 2, the effect of target-sample distance on the deposition rate is more severe than that of working pressure.

For acoustic devices, it is important to get both smooth interface and surface for all the individual layers of the resonators. Therefore, we investigated the RMS roughness and surface morphology of the films deposited under various conditions.

Table 1

<table>
<thead>
<tr>
<th>Deposition parameter</th>
<th>Conditions</th>
</tr>
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<tbody>
<tr>
<td>R.F. power</td>
<td>150 W</td>
</tr>
<tr>
<td>Ar/O2 gas ratio</td>
<td>Ar(50%)+O2(50%)</td>
</tr>
<tr>
<td>Base pressure</td>
<td>$2 \times 10^{-5}$ Torr</td>
</tr>
<tr>
<td>Substrate temperature</td>
<td>Unheated and no control</td>
</tr>
</tbody>
</table>
| Distance of target substrate | Al, Cu, Si: 50, 55, 60, and 70 mm  
                           | Au: 45, 50, 55, and 60 mm |
| Working pressure     | 7, 15, 25, and 35 mTorr |

Fig. 2. Deposition rate of ZnO films as a function of (a) target-sample distance with the working pressure of 25 mTorr and (b) working pressure during sputtering.
Fig. 3. The effects of (a) target-sample distance and (b) working pressure on the surface roughness of ZnO films.

(a) Target-Sample Distance: 50 mm  
(b) Target-Sample Distance: 70 mm

Fig. 4. AFM images of (a) Al, (b) Cu, (c) Au, (d) Si, (e) ZnO on Al, (f) ZnO on Cu, (g) ZnO on Au, and (h) ZnO on Si.

RMS: 3.21 nm  
RMS: 0.85 nm  
RMS: 1.39 nm  
RMS: 0.09 nm  
RMS: 3.928 nm  
RMS: 2.37 nm  
RMS: 7.826 nm  
RMS: 1.336 nm

Fig. 5. The effects of working pressure on the crystallinity of ZnO films deposited on (a) Al, (b) Cu, (c) Au, and (d) Si.
Fig. 6. The effects of target-sample distance on the crystallinity ZnO films deposited on (a) Al, (b) Cu, (c) Au, and (d) Si.

Fig. 7. SEM images of ZnO films deposited on Al, Cu, Au, and Si with the working pressure of 25 mTorr; (a) Si/SiO₂/Al/ZnO, (b) Si/SiO₂/Cu/ZnO, (c) Si/SiO₂/Au/ZnO, and (d) Si/ZnO.
roughness of ZnO films grown on the different types of substrate with various sputtering conditions. Fig. 3 shows the surface RMS roughness of the deposited ZnO films as a function of sputtering conditions. The surface roughness of ZnO films is dependent on sample-target distance (Fig. 3(a)), while no clear evidence for the roughness change due to working pressure is observed (Fig. 3(b)). In addition, bottom electrode also affects the surface roughness of ZnO films as shown in Fig. 3. Comparing the data shown in Figs. 2 and 3, we argue that the surface roughness is mainly decided by the growth rate. That is, the surface roughness increase as the growth rate of ZnO film increase, consistent with the previously published results [8].

In addition to the growth rate, the surface roughness of bottom electrode may affect the roughness values of ZnO films. Fig. 4 shows AFM images of the surface roughness of bottom electrodes (a–d) and ZnO films (e–h). The data shown in Fig. 4 indicate that there is a correlation between the surface roughness of bottom electrode and the one of ZnO film. More specifically, the RMS roughness values of Al (a) and Au (c) were greater than those of Cu (b) and Si (d). Furthermore, as shown in panels (e–h), the roughness of ZnO films deposited on bottom electrode is dependent on the surface conditions of bottom electrode. Therefore, we suggest that the surface roughness of ZnO film is decided by both target-sample distance and the surface properties of bottom electrode.

The XRD data shown in Figs. 5 and 6 show the effects of working pressure and target-sample distance, respectively, on the crystallinity of ZnO films deposited on various bottom electrodes. A comparison of XRD data shown in Fig. 5 indicates that c-axis preferred orientation is only observed from ZnO films deposited at 25 mTorr on Al (a) and Au (c): Note that the values of target-sample distance for ZnO film deposited on Al and Au were 70 and 50 mm, respectively. On the other hand, there were no clear evidences for the development of c-axis preferred orientation from ZnO film deposited on Cu (b) and Si (d). Based on the experimental results shown in Fig. 5, we suggest that the best choice for bottom electrode and working pressure are Al (or Au) and 25 mTorr, respectively, when target-sample distance has been fixed during the sputtering process. Fig. 6 shows the effects of target-sample distance on the development of c-axis preferred orientation from ZnO films deposited on Al (a) and Au (c): The working pressure was fixed at 25 mTorr in this case. As shown in Fig. 6, the relative intensity of c-axis preferred orientation from ZnO film was clearly distinctive only if bottom electrodes were either Al (a) or Au (c). As shown in Fig. 6, we found that the best choice for bottom electrode is either Al or Au. In addition, we were able to observe the best results in view of the crystallinity of ZnO films if target-sample distances were 50 and 70 mm for Au and Al, respectively. Based on the experimental results shown in Figs. 5 and 6, we suggest that the development of c-axis preferred orientation is dependent on the sputtering conditions (e.g., target-sample distance and working pressure) and bottom electrodes (e.g., Al and Au). These results are consistent with the previous work presented in reference [13].

Fig. 7 shows the SEM images of Si/SiO2/bottom electrode/ZnO films. In consistent with the experimental results shown in Figs. 5 and 6, the columnar structures were observed only in ZnO thin films deposited on Al and Au bottom electrode.

Fig. 8 represents the electrical properties of the MIM capacitor investigated in this work. The data shown in Fig. 8 indicate that the MIM capacitors consisted of Al bottom electrode results in the lower values of both dissipation factor and dielectric constant. As shown in Fig. 8(b), the range of dielectric constant of Al/ZnO and Au/ZnO samples with high c-axis preferred orientation was 8–14 and 13–16, respectively. In addition, dissipation factor measured at 2 MHz was low (e.g., 0.02–0.05), and the resistivity was greater than 10^6 Ω cm (not shown). Therefore, we suggest...
that ZnO films with high c-axis preferred orientation are suitable for the FBAR applications.

4. Conclusion

We investigated the effects of both bottom electrodes and processing parameters on the physical and electrical properties of ZnO films deposited by the R.F. magnetron sputtering method. We found that the development of c-axis preferred orientation is dependent on the sputtering conditions (e.g., target-sample distance and working pressure) and bottom electrodes (e.g., Al and Au). Furthermore, the MIM capacitor consisted of ZnO films with a high c-axis preferred orientation results in the good electrical properties for the FBAR applications.

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References