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Solidly mounted resonators fabricated for GHz frequency applications based on $Mg_xZn_{1-x}O$ piezoelectric film

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ABSTRACT

Solidly mounted resonator is a type of film bulk acoustic resonator for microwave operation applications. ZnO piezoelectric films provide a choice to produce solidly mounted resonator, but show a low longitudinal acoustic velocity and a relatively low response. In this work, a ternary compound magnesium doped zinc oxide ($Mg_xZn_{1-x}O$) piezoelectric film is introduced and investigated, which has a flexible frequency response and a higher acoustic velocity. X-ray diffraction (XRD) θ-2θ coupled scans of the $Mg_xZn_{1-x}O$ films are investigated versus different RF magnetron sputtering deposition conditions. Residual stresses are studied to ensure a reliable fabrication of solidly mounted resonators. A typical device fabricated based on $Mg_xZn_{1-x}O$ piezoelectric film show a resonant frequency at 2.046 GHz with a return loss of −38.9 dB, a quality factor of 965 and a coupling coefficient of 2.5%. The calculated longitudinal acoustic velocity of a $Mg_xZn_{1-x}O$ film is 6854.1 m/s, faster than that of ZnO.

Film bulk acoustic resonator (FBAR), as a bulk acoustic wave (BAW) device, has attracted much attention due to its small size, high performance and promising potential applications in high-frequency and sensor areas [1–11], compared with SAW devices [12]. There are two different types of FBARs, one with a free-standing membrane, and the other Solidly Mounted Resonator (SMR) is composed of a piezoelectric thin film sandwiched between electrodes and a Bragg reflector consisting of alternating high and low acoustic impedance quarter-wavelength thick layers, which is demonstrated by Newell [13]. SMR is more robust than free-standing membrane FBAR significantly [14], but Bragg reflector layers must be carefully designed and precisely fabricated to reflect the desired resonant frequency. The surface roughness and film thickness are critical to the performance of the device, which determines the effective coupling coefficient $keff^2$, the mechanical loss, and in turn the quality factor Q. Both Zinc oxide (ZnO) and Aluminum nitride (AlN) thin films have been widely used as the piezoelectric layer for SMR. Filters based on AlN SMRs operate mainly in the low and medium gigahertz range, although they can also be used in high-frequency devices [15,16]. ZnO SMRs show additional prospects on biosensor applications and high-frequency applications [17,18]. Such sensors can be integrated onto Si substrate, compatible with small-size microwave antenna, hence used for remote wireless sensing. However, ZnO films have the drawback of low longitudinal acoustic wave velocity and low resistance. $Mg_xZn_{1-x}O$ is a ternary compound formed by alloying ZnO and MgO, which is relatively new in SMR fabrication. In another report, the SMR frequency response can be tailored by adjusting the Mg doping percentage [14]. Besides, piezoelectric $Mg_xZn_{1-x}O$ has higher acoustic velocity and resistance than that of ZnO [19].

As we know, ZnO is a member of the hexagonal wurtzite crystal group and has piezoelectric property, while MgO possesses a cubic rock salt structure and is non-piezoelectric. As to $Mg_xZn_{1-x}O$ film, the film is hexagonal phase or cubic phase with different Mg concentration x. During the phase transition Mg concentration in $Mg_xZn_{1-x}O$ is a determining factor, and the crystalline phase changes from hexagonal to cubic phase with x increasing from zero to 1. According to the report from Ohtomo et al. [20]. For $Mg_xZn_{1-x}O$ with $0 < x < 0.33$, only hexagonal phase was obtained. After that the crystalline structure transited from hexagonal phase to cubic phase gradually. MgO has higher acoustic velocity than ZnO, and the acoustic velocity of $Mg_xZn_{1-x}O$ increases with Mg content, while piezoelectric coupling decreases. The higher velocity of the material could be due to the suppressed acoustic transmission loss, so

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higher quality factor of the device can be achieved.

The purpose of this work is to investigate the performance of $Mg_xZn_{1-x}O$ SMR with the optimized fabrication conditions on different residual stress and growth orientation of $Mg_xZn_{1-x}O$ films. A sharp of c-axis orientation of the $MgxZn_{1-x}O$ films are essential to the bulk acoustic wave devices since the piezoelectric properties heavily depend on the crystallographic orientation of the film. Besides, residual stresses of the structural films have profound influence on the properties of multilayer films of SMR, in which high stress affects the mechanical stiffness of the resonator, which is directly related to the acoustic velocity and the resonant frequency [21].

Herein, films ($Mg_xZn_{1-x}O$/Ti/W) for SMR resonator were deposited by RF magnetron sputtering on <100> oriented high-resistance silicon (Si) substrates which has a layer of SiO_2 on it as an insulator. Residual stresses and XRD of multilayer films are measured. Based on deep analysis, better growth conditions for RF magnetron sputtering to obtain good $Mg_xZn_{1-x}O$ films are concluded. Frequency response of device fabricated at the better growth conditions is measured with probe station and Network analyzer.

Although other methods were reported for fabrication of $Mg_xZn_{1-x}O$ films [22], sputtering is the most industrialized. In this work the $Mg_xZn_{1-x}O$ films were deposited on Ti/W/Si substrates in RF magnetron sputtering system with a base pressure of around 5×10^{-4} Pa. Prior to the piezoelectric layer deposition, W and Ti films were deposited on <100> oriented silicon (Si) substrates as Bragg reflector detailed in our previous work [23]. Besides as Bragg reflector, the topmost Ti layer also came as the bottom electrode for high frequency coupling signal. Fig. 1(a) is a 3D-view of SMR and Fig. 1(b) is an across-sectional view of SMR's $Mg_xZn_{1-x}O$/Ti/W layered structure and the inset is the top electrode pattern. The Au top electrode was sputtering deposited with 50 nm Ti as a buffer layer. $Mg_xZn_{1-x}O$ ($x = 10\%$) was employed as target source material.

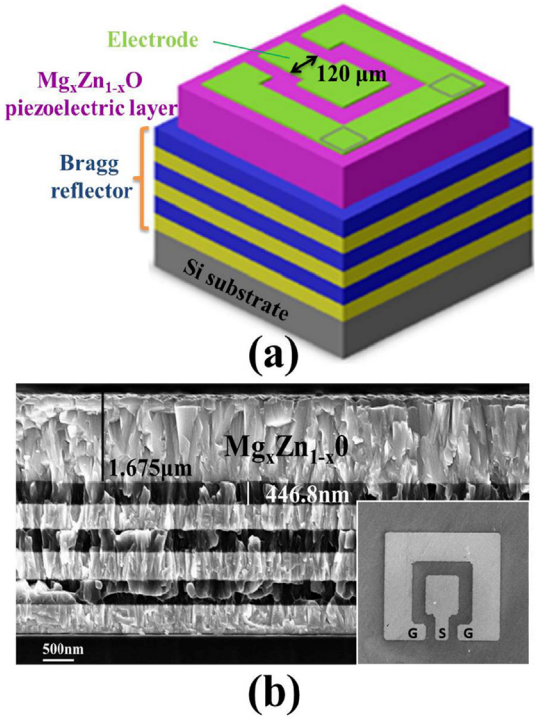

Fig. 1. (a) Side-view of acoustic Bragg reflector, electrodes, and piezoelectric layers of SMR. (b)Cross-sectional view of $Mg_xZn_{1-x}O$/Ti/W layered structure of SMR. The inset is GSG top electrode pattern.

A mixture of argon (Ar) (99.999%) and oxygen (O_2) (99.999%) was used as sputtering gas. The distance between target and substrate is around 70 mm and target diameter around 80 mm. During different films depositions, the substrate temperature is kept at 300 °C [23], while the ratio of Ar and O_2 can be varied from 40:0 to 10:30, sputtering pressure between from 1.5 Pa to 2.5 Pa, sputtering power from 100 W to 250 W. The sputtering conditions of all layers are detailed in Table 1. Analyzed by Energy Dispersive Spectrometer, the Mg concentration of $Mg_xZn_{1-x}O$ layers are kept around 10% in these sputtering conditions, so we neglect the influence of films composition in the following discussions.

The SMR device operation is based on the acoustic resonance technology which is based on transient acoustic reflections from layers and plates [24,25]. A GHz signal inputs to the piezoelectric layer through the GSG top electrode which was deposited with 150 nm Au layer shown in inset of Fig. 1(b). According to the piezoelectric effect and inverse piezoelectric effect, the electric signal and acoustic signal could be conversed mutually. The GHz acoustic signal impinging in the piezoelectric layer will be reflected from both the front interface with air and the back interface with Bragg reflector. For the frequencies where an integer multiple of the half wave length $\lambda/2$ matches the thickness of the piezoelectric layer d, the signal response will be resonant. For a given acoustic phrase velocity c and film thickness d, as to the bulk acoustic resonator, with the thickness extensional (TE) mode based on the longitudinal velocity, the resonance frequencies are given by:

$$f = \frac{c}{2d} \quad (1)$$

The films' structural texture were measured by X-ray diffraction (XRD, D/max 2200/PC), which used a Cu-Kα radiation. The cross-sectional structure of a fabricated SMR was observed by field emission scanning electron microscope (FESEM, Carl Zeiss Ultra 55). Frequency response of device fabricated at a better growth condition is measured with probe station and Network analyzer (Agilent 8714ET). The residual stress of the $Mg_xZn_{1-x}O$ thin films is estimated using the following formula [26]: $\delta = -233 \times 109(C-C_0)/C_0$ Pa, where $C_0 = 5.2065$ Å is the strain-free lattice constant, and C is the lattice constant of the structural films which is computed from XRD θ-2θ curves.

Fig. 2(a) shows the θ-2θ curves of the $Mg_xZn_{1-x}O$ films deposited on Ti/W/Si structure under different RF power, with Ar/O_2 ratio of 40:0, substrate temperature of 300 °C and pressure of 2 Pa. It can be seen that the preferential c-axis orientation appears with the RF power changing from 100 to 250 W, diffraction peaks at 2θ are around 34.4°, corresponding to the $Mg_xZn_{1-x}O$ <002> orientation. The $Mg_xZn_{1-x}O$ <002> diffraction peak becomes stronger and sharper with increasing RF power. The sample deposited under 200 W RF power exhibits a single and sharp <002> diffraction peak, which is a preferred c axis orientation with the full-width at half maximum (FWHM) of 0.48°. However, when the power increases to 250 W, the FWHM of <002> peak becomes relatively broader as is depicted in Fig. 2(d). The reason could be that the energy of atoms arriving at substrate is so low that the momentum of most atoms diffuses on the deposition surface. With the increasing of RF power,

Table 1
Sputtering parameters of all materials used in SMR structure.

Deposition parameters	$Mg_xZn_{1-x}O$	Ti	W
Base pressure (Pa)	$<5 \times 10^{-4}$	$<5 \times 10^{-4}$	$<5 \times 10^{-4}$
RF power (W)	100–250	180	100
Ar/O_2 flow rate (sccm)	40/0–10/30	40/0	20/0
Sputtering pressure (Pa)	1.0–2.5	2.5	2.5
Substrate temperature (°C)	300	300	300