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Thin film piezoelectric property considerations for surface acoustic wave and thin film bulk acoustic resonators

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Abstract

We report on the optimisation of thin film piezoelectric ZnO for production of resonant acoustic MEMS devices (SAW and FBAR/BAW). The ZnO was deposited by RF sputtering, and conditions were optimised to promote uniform polycrystalline orientation, high resistivity and smooth surface morphology. Both surface acoustic wave and thin film bulk acoustic resonators exhibited high Q values with low insertion loss (3–5 dB).

1. Introduction

Piezoelectric materials are usually incorporated into RF MEMS devices in thin film form. Thin film materials that have been investigated for surface acoustic wave (SAW) and bulk acoustic wave (BAW) resonators include aluminium nitride (AlN) and zinc oxide (ZnO). Over the last two decades,[1] ZnO thin films have been successfully applied to delay line surface acoustic wave filters. However, over the last 5 years there has been a resurgence of interest in these materials for the acoustic material in thin film bulk acoustic wave resonator (FBAR) filters.[2] Such filters are strong candidates for duplexer filters in mobile phones. Furthermore ZnO and AlN surface acoustic wave devices are also of interest for high frequency remote sensing applications.[3]

Although ZnO can be grown as a thin film using a wide variety of techniques including spray pyrolisis,[4] MOCVD growth[5] and pulsed laser deposition,[6] for device applications it is usually deposited using RF sputtering. However, the sputtering process is a reactive one and so the properties of the thin film produced are strongly dependent on the sputtering conditions. For different conditions a wide range of surface and bulk morphologies are obtained for which the dielectric and acoustic properties vary considerably. For both high frequency SAW and FBAR devices it is important that the polycrystalline piezoelectric thin film is optimised with respect to orientation (which directly determines the piezoelectric coupling coefficient and should have high the c-axis perpendicular to the substrate) and dielectric loss (which determines the "*Q*" factor of the resonator). Furthermore, since these devices are electromechanical in nature it is important that the film possesses a high degree of morphological uniformity.

2. Experimental

The substrates used for deposition were high resistivity [100] oriented Si wafers. Coatings of SiO_2 and Au, with thicknesses of 200 and 100 nm, respectively, had been deposited previously. The one exception to this was the case of the SAW resonator, which was deposited on a fused quartz wafer coated with 100 nm Au. ZnO deposition was performed using an SVS (Scientific Vacuum Systems Ltd.) V2400 RF Sputter Box Coater. The target was ZnO supplied by Cerac Inc. Two modes could operate during sputtering; flow controlled or chamber pressure controlled. The latter was used, so that the gas flows of O_2 and Ar was automatically regulated to achieve the desired chamber pressure. The O_2/Ar mix employed was in all cases 17% O_2; it is well known[7] that oxygen concentrations lower than this can lead to reduced resistivity making the films unsuitable for resonant devices. Two other parameters changed were RF sputtering power and temperature of the substrate heater. Film thicknesses were in most cases 1 micron, with the exception of wafer K in which the film was 3.8 microns thick in order to create a sub-1GHz FBAR device. The runs are summarised in Table 1. In

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Table 1
Parameters for SVS materials wafer runs

Sample	Gas pressure (mTorr)	Substrate temp. (°C) resistance/resistivity	RF power (W)	Note
A	2	375 500 Ω/258 Ωcm	500	Open grains FWHM = 1.8 ε = 31.5 Loss = 10%
B	40	375 18 kΩ/362 Ωcm	500	Large grains FWHM = 1.1 ε = 16.5 Loss = 2%
C	40	RT 7 kΩ/1199 Ωcm	500	Packed grains FWHM = 10.4 ε = 9.5 Loss = 0.8%
D	2	RT 13 MΩ/5.4 MΩcm	500	Small dense grains FWHM = 2.4 ε = 10.4 Loss = 0.1%
E	2	375 8000 Ω	350	Medium grains FWHM = 1.6 ε = 11.9 Loss = 3.2%
F	20	150 78 kΩ/24 kΩcm	500	Inter-grown platelets FWHM = 4.1 ε = 12.2 Loss = 0.1%
G	2	150	350	Small densely packed grains FWHM = 1.9 ε = 9.9 Loss = 0.001%

Table 2, runs which were performed on silicon FBAR device wafers and one fused quartz SAW resonator device wafer (L) are summarised. Samples were analysed using a Siemens D5005 X-ray diffractometer and a Philips XL30 S-FEG Scanning electron microscope. The X-ray diffractometer was used to perform a 34° rocking curve analysis of the ZnO. The full width half maximum (FWHM) value of this peak gives a measure of the uniformity of *c*-axis orientation; the smaller the FWHM the more consistently *c*-axis oriented the ZnO is. To measure electrical properties, contact holes were etched through the ZnO to the Au base layer, and an Au top electrode deposited. A HP 4192A LF Impedance analyser and probe station were used to perform the low frequency (1–100 kHz) electrical measurements of loss and dielectric constant. Target values for the dielectric constant and resistivity are 9.9 (bulk value) and 2.5×10^6 Ωm (reported in a polycrystalline film) respectively.[8]

3. Results and discussion

The ZnO thin film most desirable for applications is with good c-axis orientation (low FWHM value) and high resistivity. A smooth surface is also highly desirable, especially in the case of SAW resonators where it directly influences the insertion loss of the device. It can plainly be seen from Table 1 and Fig. 5 that a wide variety of ZnO morphologies can be produced by varying the temperature and pressure of sputtering. Polycrystalline orientation was in all cases dominantly *c*-axis, although there was substantial variation in rocking curve FWHM. Au is known to encourage good *c*-axis orientation in ZnO.[9] A combination of low deposition temperature and high pressure appears to lead to lowest FWHM (wafers C and F). The 'best' quality material (wafer G as seen in Table 1) was deposited at relatively low pressure (2 mTorr), with intermediate temperature (150 °C) and power (350 W). This produced fine grained material with very low loss and high resistivity, as well as a dielectric constant equal to the bulk value of 9.9. It is interesting to note the formation of randomly oriented platelets at higher pressures in wafers I, H and F. It is possible that these could be caused by nucleation and crystal growth on microfragments of target material falling from the ZnO target (the system used was in a sputter-down configuration). The extreme surface irregularity of these platelets (especially since their diameter is of the order of the film thickness) is likely to make the film unsuitable for use in a piezoelectric resonator.

Figs. 1–4 show S_{11} reflected signal responses from assorted FBAR and SAW devices (The FBAR resonators were measured in two port configuration whereas the SAW resonator was a one port device so the S_{11} parameters are used in all cases to enable comparison). As can be seen, the best device response in terms of difference between series and parallel loss is from wafer I. Both wafers I and J were grown in identical conditions. As can be seen from the SEM images in Fig. 5, these conditions lead to a polycrystalline surface of medium (~100 nm) grain size with intermittent platelets. ZnO on wafers K and L was deposited using the same conditions as wafer G, which gave the smoothest surface

Table 2
Parameters for SVS device wafer runs

Sample	Gas pressure (mTorr)	Substrate temp. (°C)	RF power (W)	S_{11} resonator response
H	20	220	200	No response
I	40	150	500	Poor response (see Fig. 1)
J	40	150	500	Good response (see Fig. 2)
K	2	150	350	See Fig. 3
L	2	150	350	See Fig. 4

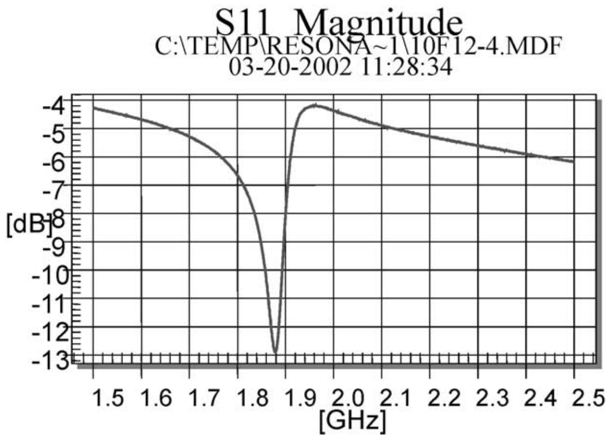

Fig. 1. S_{11} response from FBAR resonator device wafer I.

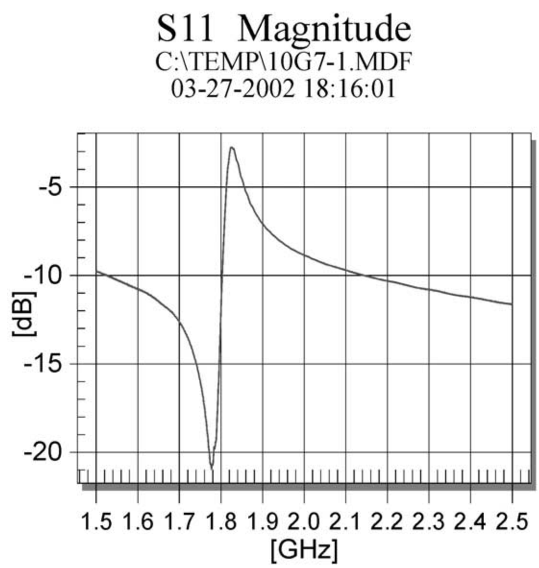

Fig. 2. S_{11} response from FBAR resonator device wafer J.

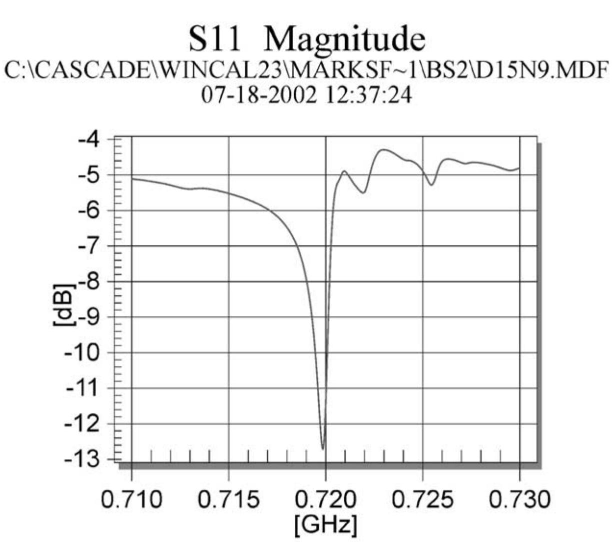

Fig. 3. S_{11} response from FBAR resonator device wafer L.

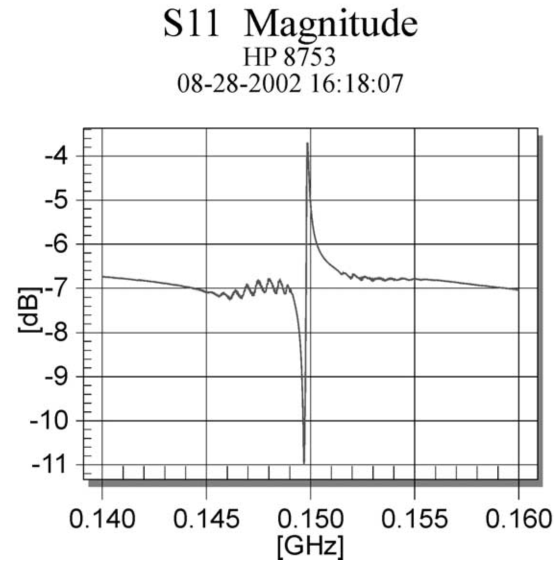

Fig. 4. S11 response from SAW resonator on wafer M.

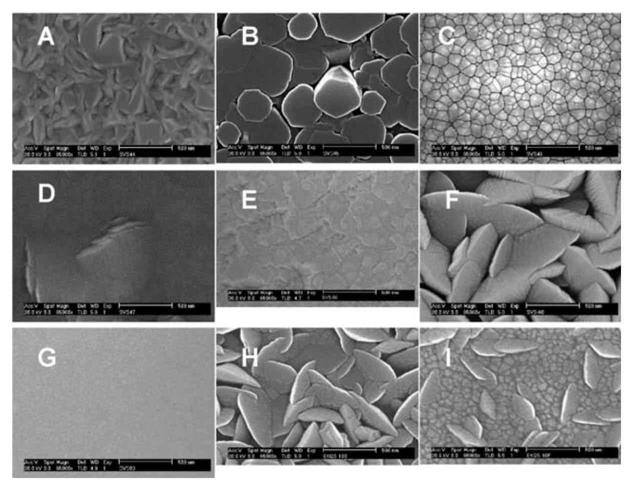

Fig. 5. SEM images from wafers A–I.

with small grains and low loss. A simple estimation of device "Q" value can be obtained by dividing the resonant frequency by the 3 decibel bandwidth. This gives Q values of 60, 59, 900 and 500 for the devices shown in Figs. 1–4 respectively.

4. Conclusion

Within the regime of a fixed fractional oxygen content, optimal conditions for smooth, well oriented ZnO have been established. Functional devices of reasonably high Q factor and low insertion loss have been fabricated. Further work is needed, including cross sectional SEM and stress analysis, to study the phenomenon of platelet formation. Also possible benefits of further increasing the fractional oxygen content need to be explored.

Acknowledgements

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