High Frequency Thin Film Acoustic Ferroelectric Resonators

Paul Kirbya, Qing-Xin Sua, Eiju Komurob, Masaaki Imurab, Qi Zhang, and Roger Whatmorea
aNanotechnology and Microsystems group, School of Industrial and Manufacturing Sciences, Cranfield University, Cranfield, Bedford, MK43 0AL, UK
bTelecom Technology Development Centre, TDK Corporation, 2-15-7, Higashi-Ohwada, Ichikawa-shi, Chiba, 272-8558 Japan

ABSTRACT:
Both ZnO and PZT Thin Film Bulk Acoustic Resonator filters were fabricated, tested and modeled in this study. The development of an accurate Mason model allows the effect of particular parasitic components on the microwave s-parameters in the region of the series and parallel resonances to be identified. The parasitic components that limit the performance of our ZnO and PbZr0.3Ti0.7O3 Thin Film Bulk Acoustic Resonator filters are analysed. From an analysis of PbZr0.3Ti0.7O3 Thin Film Bulk Acoustic Resonator measurements values for the longitudinal acoustic velocity and electromechanical coupling coefficient can be derived. Measured PbZr0.3Ti0.7O3 Thin Film Bulk Acoustic Resonator filter responses confirm that the larger electromechanical coupling coefficients in this material compared to ZnO give wider filter band-widths.

INTRODUCTION:
There is a great commercial interest in decreasing the size of microwave 1-3 GHz filters to allow more functions to be incorporated in future mobile phones [1]. Presently there are two types of filters being developed to meet this need, ceramic filters based on electromagnetic modes and acoustic filters. The typical dimensions of both types of microwave filters are similar to the wavelength at the operating frequency. By using the piezoelectric effect to generate acoustic modes wavelengths and dimensions can be reduced by about four orders of magnitude compared to electromagnetic modes.

There are two types of acoustic filters considered contenders for future generations of mobile phones, both based on piezoelectric materials: surface acoustic wave (SAW) devices and Thin Film Bulk Acoustic Resonators (FBAR). The piezoelectric effect has been widely used in bulk acoustic resonators, such as single crystal quartz for many years. Recently by careful thinning or etching the quartz plate operation up to 200 MHz can be achieved but the low acoustic velocity of quartz and the resulting fragility of thinned substrates means that this technology cannot progress to higher frequencies. In SAW devices that direction of propagation is in the plane of the wafer while for FBAR it is perpendicular to a substrate surface. For FBAR operation the piezoelectric film thickness must be of the order of the acoustic wavelength at the desired operating frequency. In this paper we compare two candidate thin film piezoelectric materials, ZnO and PbZr0.3Ti0.7O3 (PZT) that have different acoustic properties. Although there has been considerable previous work on ZnO FBAR [2] and ZnO FBAR filters [3] there has only been a few reports on PZT FBARs [4]. In particular, the electromechanical coupling coefficients

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of the two materials are very different. The higher values of electromechanical coefficient of PZT compared to ZnO should allow wider band-width filters to be fabricated.

In FBAR devices the electrical and crystallographic quality of the piezoelectric thin film is often determined by the structure of the layer on which growth takes place. ZnO thin films with the desired C-axis orientation can be grown on Au and Al [5]. For PZT the situation is more constrained since the only metal on which high quality material can be grown is platinum [6]. Unfortunately Pt has low conductivity compared to Al and Au so higher electrode parasitic resistance effects could result.

EXPERIMENT

A schematic cross-section of the FBARs fabricated is shown in Figure 1. The thin film membrane is created by wet etching away the silicon. For both ZnO and PZT FBARs a Si3N4 (200 nm) layer served as a support membrane. PZT layers deposited on Si3N4 were found to have poor surface morphology, including cracks, so a thin layer (50nm.) of TiO2 layer was inserted between the Si3N4 and PZT to avoid this cracking. The TiO2 was formed by the oxidation of titanium. The sputtered metal layers were 100 nm thick. For the RF sputtered ZnO films used in this study only one orientation, C-axis perpendicular to the substrate, was observed by X-Ray diffraction. A sol gel preparation route [6] was used for the PZT films. For the FBAR configuration adopted, both ZnO and PZT layers were processed as blanket layers and the only patterning required for these layers was the opening of large contact hole areas using wet etching to allow access of the microwave probes. ZnO FBAR structures were prepared with Cr/Au electrodes while Pt was used for PZT FBARs.

MODELLING

One dimensional models were used to model the impedance data measured on fabricated FBARs. The full model used for the membrane supported FBAR structure is shown in figure 2. The piezoelectric layer is represented by one electrode and two acoustic ports. Multi-layers are taken into account by linking the acoustic ports in series. The non-piezoelectric electrode and support layers simply consist of acoustic ports. The terminations at the surface are simple.
resistors with values equal to the radiation impedance of the surrounding medium, which is equivalent to ~400 ohms for air.

Additional components have been added to account for the non-ideal properties of the piezoelectric layer and electrodes. $R_{\text{dielectric}}$ represents the dielectric loss, which can be frequency dependent, placed in parallel with the clamped capacitance of the device. The $R_{\text{ohmic}}$ term is included to model conduction losses due to free carriers in the piezoelectric material. Electrode resistances are represented by $R_{\text{e}}$.

It is possible to use different regions of the resonance curves to identify the effects of different loss mechanisms. Figure 3a and 3b shows the modelled S-parameters of a single FBAR when the electrode resistance and the dielectric loss in the piezoelectric material is varied. Platinum has about five times the resistivity of gold [7]. The effect of lowering the electrode resistance is to reduce the magnitude of $S_{11}$ at series resonance frequency, $S_{11\text{min}}$, but has little effect on the $S_{21}$ response, as shown in figure 3a. It is expected that a change in the acoustic loss of the piezoelectric material will have the same effect. Changes in the dielectric loss are observed as changes in the depth of the parallel resonance of $S_{11}$ and $S_{21}$. A lower dielectric loss increases

![Figure 3(a). Modelled S-Parameters versus frequency (1-2 GHz) for Pt (SA$_{11}$ and SA$_{21}$) and Au (SB$_{11}$ and SB$_{21}$) electrodes.](image)

the depth of the $S_{21}$ response and reduces the insertion loss of $S_{11}$, as shown in figure 3b. Changes in the resistivity of the piezoelectric material has similar effects. Higher resistivity dielectric films will increase the depth of the $S_{21}$ response and reduce the insertion loss of $S_{11}$. It

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is very difficult to distinguish between the effects of dielectric and resistivity losses. However, it is likely that the main loss mechanism is dielectric loss for PZT and DC loss for ZnO FBAR.

Figure 4 shows that by using the Mason model of figure 2, good agreement can be achieved between measured and modeled data. This gives confidence that the derived component values can be used to design filters. Although literature reports on the dielectric loss of ZnO thin films are limited, our own measurements at lower frequency (100kHz) suggest that the loss is very low. We believe therefore that the limited depth of the parallel resonance (in S21) measured in our material can be improved by increasing the ZnO dc resistivity, as mentioned above. This is also suggested by the insertion loss of the S11 parameters at parallel resonance being less than 3 dB. Figure 3(b) shows that the parallel insertion loss increases with increasing dielectric loss.
Figure 5 shows recorded S-parameters from a fabricated PZT FBAR having an area of 45\,\mu m^2. The PZT was poled at high temperature prior to etching the silicon substrate. The parallel resonance S11 insertion loss measured for PZT is greater than for ZnO FBAR. We associate this with the relatively high dielectric loss (~1-3\%) observed in sol gel prepared thin film PZT layers. We believe that dielectric losses currently limit the performance of our PZT FBARs.

![S-Parameters versus frequency of a PZT FBAR](image)

**Figure 5.** S-Parameters versus frequency of a PZT FBAR

The material properties deduced from analysis of ZnO and PZT FBARs measurements are shown in table 1. The deduced electromechanical coefficients for both materials are very close to bulk material values.

**Table 1.** Material parameters deduced from ZnO and PZT FBARs

<table>
<thead>
<tr>
<th></th>
<th>ZnO</th>
<th>PZT</th>
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</thead>
<tbody>
<tr>
<td>Electromechanical Coupling Coefficient, $k_e$</td>
<td>7%</td>
<td>19.8%</td>
</tr>
<tr>
<td>Q-values</td>
<td>350</td>
<td>54</td>
</tr>
<tr>
<td>Acoustic velocity (m/s)</td>
<td>6340</td>
<td>4500</td>
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**FBAR FILTERS**

Based on the analysis of measured impedance data obtained from single FBAR structures we have designed ZnO and PZT FBAR ladder filters. For a ZnO FBAR ladder filter having two series and two parallel FBAR elements the measured behaviour is to close to the modelled performance. A pass-band insertion loss of 3-4dB was measured with out of band rejection better than 25 dB. A 3dB band-width of 60 MHz was measured.

The designed performance and measured response for a 2x2 PZT filter is shown in figure 6. The measured insertion loss is ~6.5 dB compared to the predicted 2.5dB. This difference is thought to be due to the difference from the designed thickness of the series and parallel FBAR that make up the ladder filter. Another contribution will be the losses that arise from the
presence of spurious modes that are present in small area PZT FBARs. A 3 dB band-width of 100 MHz was measured consistent with the high electromechanical coupling coefficient.

CONCLUSIONS

This study has shown that the large electromechanical coefficient expected in PZT thin films leads to large separation between the series and parallel resonances in single FBARs and wide band-width FBAR filters. By inclusion of electrode resistances, piezoelectric dielectric loss and dc resistivity components within a Mason model it is possible to identify their influence on the microwave responses. For ZnO FBAR filters improved performance will result from the development of ZnO with higher resistivity while for PZT material with lower dielectric loss is required.

REFERENCES