FILM BULK ACOUSTIC WAVE RESONATOR AND FILTER TECHNOLOGY

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ABSTRACT

Film Bulk Acoustic Resonators (FBARs) are monolithically integrable with semiconductor devices, leading to small size and low cost, high Q rf circuit elements with wide applications in the EW, radar and communications area. We review in this paper recent developments in film resonator and the miniature monolithic filters based on these resonators.

INTRODUCTION:

Small, low loss microwave filters have become increasingly desirable for radar, communications and electronic warfare systems. The performance requirements of front-end filters, particularly those operating above 1 GHz, are increasingly difficult to meet with traditional approaches of lumped element, dielectric, or surface acoustic wave filters. Bulk acoustic resonator filters offer unique advantages since they are at least an order of magnitude smaller than dielectric resonators or lumped elements, and possess much lower insertion loss than surface wave devices.

During recent years, work has been progressing toward the development of UHF acoustic resonators that can be fabricated and utilized as stable, high Q, monolithic microwave integrated circuit (MMIC) elements.[1-10] The aim of these efforts is to simplify and improve performance of circuits associated with stable signal generation and narrowband signal sorting directly at UHF, reduce resonator volume, and fabricate in 100 % monolithic form. The FBAR is the only truly miniaturizable, low-loss monolithic filter available for microwave application. We review in this paper recent developments in miniature monolithic filters based on film bulk acoustic resonators.

Film Bulk Acoustic Resonators, fig.1(a), are fabricated by sputtering thin films of piezoelectric material such as aluminum nitride or zinc oxide onto semiconductor substrates such as silicon or gallium arsenide.

FBAR fabrication involves deposition of materials for the membrane, for the piezoelectric film, and electrodes. The material requirements, while common in some respect, are different for

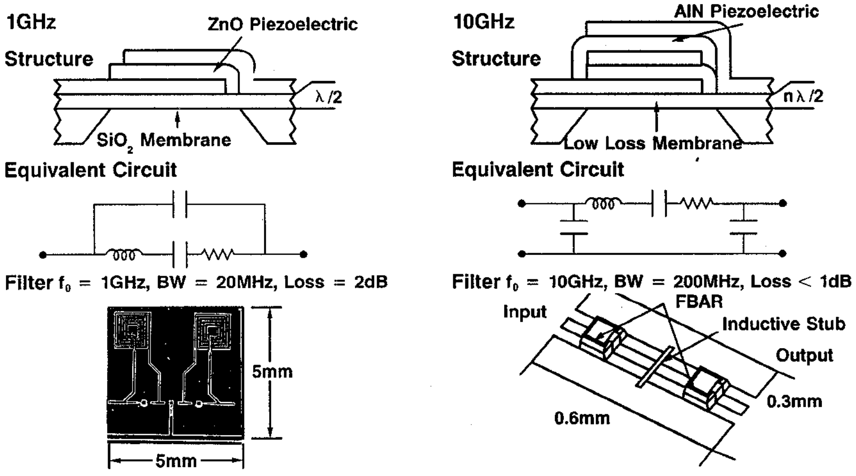

Figure 1. Schematic representation of FBAR structure, equivalent circuit, and filter configuration of (a) one-layer structure, and (b) stacked FBAR configuration. (a) also shows a photograph of two-pole monolithic filter using $ZnO/SiO_2/Si$ FBARs.

each of these layers. All these layers should have good adhesion, be smooth and dense. In the early stages of development an implanted p^+ Si layer was used as membrane material. Currently sputtered SiO_2 layers are being used for the membrane. Thin films of Si_3N_4, AlN, and epitaxially grown $MgAl_2O_4$ (spinel) have also been used as support material.

The requirements for the piezoelectric candidate materials are that they result in efficient large area devices and in turn this necessitates thin films (0.1 μm to 10 μm) with a high degree of orientation and large piezoelectric coupling. Additional materials requirements include high resistivity, good breakdown strength, and reproducibility of film deposition. Materials that satisfy a number of these requirements include CdS, ZnO, AlN, $LiNbO_3$, $LiTaO_3$, PZT, and PLZT. While it is difficult to obtain very high resistivity CdS films, thin film deposition of $LiNbO_3$ and $LiTaO_3$ suffers from stoichiometry control. Only recently have oriented films of PZT and PLZT been deposited and $LiNbO_3$ films have been deposited by molecular beam epitaxy (MBE) technique. Although all these materials have been investigated in the past few decades ZnO and AlN have attracted the most attention. ZnO and AlN films obtained by magnetron sputtering meet most of the material requirements described earlier and are primarily used for the piezoelectric layer.

Gold and aluminum have been the common materials used for the electrodes with the former used with ZnO based FBARs and the latter with AlN. In addition these layers serve as seed layers for orienting piezoelectric film. Orienting the second gold layer on top of the first piezo layer requires planarization of the piezoelectric layer. This is important for stacked FBAR fabrication.

APPLICATIONS

As mentioned earlier FBARs find wide range of applications in the fabrication of filters and stable oscillators. Oscillator results are briefly summarized here. We have fabricated hybrid oscillators using both ZnO as well as AlN based FBARs. We have demonstrated Pierce type oscillators operating at 300 - 700 MHz[5]. The FBAR stabilized oscillator phase noise performance (-110 dBc/Hz at 10KHz from the carrier) agrees with predicted values based on FBAR flicker noise and is comparable to that of SAW resonator oscillators. Tuning sensitivities of 800 KHz/volt with good linearity have been achieved. Burns and Ketchum[11] have demonstrated a similar oscillator using ZnO/Si FBARs. Burkland et al.[12], have integrated ZnO FBARs with bipolar junction transistor on silicon fabricating a 257 MHz oscillator which exhibits a phase noise of -90 dBc/Hz and a temperature stability of - 8.5 ppm/°C for 5 to 60 °C. Satoh et al.[4], have fabricated a fully integrated 400 MHz oscillator on a silicon chip using air-gap type FBAR with a phase noise of - 90 dBc/Hz.

FILTER APPROACHES

Multi-pole bandpass filters using FBARs can be grouped into three categories: a)monolithic crystal filters, b)conventional ladder filters, and c) stacked filters. The ladder filter, consisting of resonators electrically coupled to each other, has the advantage that all the resonators can be made identical to one another. Non-identical frequency (anharmonic) spurious responses are rejected by the cascade of resonators. The monolithic crystal filter (MCF) relies on acoustically coupling the resonators which are positioned so that there is an overlap of evanescent field regions. Thin film versions of the MCF support both shear and longitudinal mode propagation. In the stacked filter arrangement the two FBARs are deposited one over the other with a common ground plane separating them.

LADDER FILTERS

Recently we fabricated a completely monolithic version of a two-pole filter, shown in figure 2, that employs $ZnO/SiO_2/Si$ FBARs. Details of fabrication are presented elsewhere.[7]

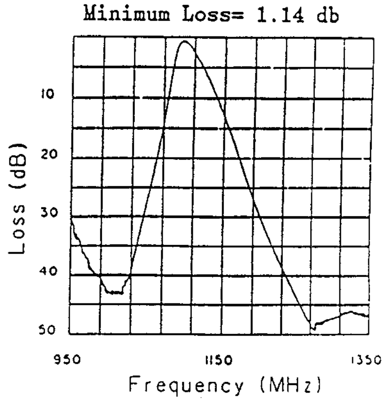

Figure 2. Typical response for a Two-pole Ladder Filter.

Figure 2 shows a typical S_{21} response for a two-pole filter. As can be seen from the figure the filter, operating at 1.093 GHz, has an insertion loss of 1.14 dB and a bandwidth of about 3%. Although the insertion loss is extremely low and the filter response has deep stop bands we observe some spurious responses in the pass band and on the upper stopband skirt. These spurious responses can be minimized by improving the filter processing and FBAR design. We have also fabricated a four-pole filter by cascading two two-pole filters. This filter showed a 100 dB stopband rejection and less than 4 dB insertion loss.

STACKED FILTER

When FBAR is used as a series element in a filter, the interelectrode capacitance limits the attainable bandwidth. An inductor can be used as a neutralizing element but there are an unwanted low-pass and high-pass responses. An alternate structure which has none of these characteristics is the stacked FBAR, shown in Figure 1(b).

The center electrode is connected to ground which provides high off-resonance isolation. The resonator in this two-port configuration provides better filtering action than a one port device because the capacitive elements connecting input to output are absent. Further, the need for inductors to tune out the parallel capacitance is eliminated. These inductors are typically an order of magnitude larger in area than the FBAR and dominate the monolithic filter chip. Thus the two-port arrangement significantly reduces the filter size and also eliminates unwanted high and low-pass responses that would otherwise be present in the simple FBAR. While the stacked filter configuration offers the advantage of smaller size it is more difficult to fabricate because two oriented piezoelectric layers have to be grown one over the other. Of course, the stacked configuration shown in figure 1(b) represents only a single resonator;two stacked resonators would be required to realize a two-pole filter.

We have recently fabricated a stacked filter operating in a overtone mode using $ZnO/SiO_2/Si$ FBAR structure. A typical response for a stacked FBAR resonator is shown in figure 3.

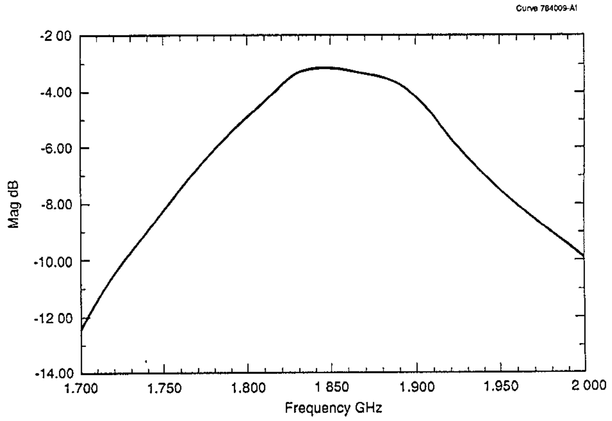

Figure 3. $ZnO/SiO_2/Si$ Stacked FBAR resonator response.

Measured S-parameter data was used in a computer simulation and it was possible to determine the minimum attainable loss for these devices. By adding ideal transmission lines and inductors the FBARs were matched to 50 ohms in the frequency range of the 1.8 GHz resonance. The resulting response is shown in figure 3 for the ZnO device. The minimum loss achieved was 3.57 dB. A similar exercise was conducted for the AlN devices. In that case, the minimum loss was 6.38 dB. We believe that with further process optimizations we will be able to reduce the filter loss, for both ZnO and AlN based devices, further down and even at higher operating frequencies. As can be seen from the figure the 3 dB band width for this device is about 10%. We have also observed overtone responses, for these FBARs, upto 5 GHz.

SUMMARY

FBAR development has progressed from VHF frequency to UHF frequency operation and FBARs have been combined not only in a hybrid fashion but also integrated monolithically with active circuit elements to form filters and oscillators. While most of the devices operate up to 1 GHz, we have recently developed FBARs that show resonances up to 5 GHz. We believe there is a growing need for extending the frequency of FBAR operation to X-band. This presents new challenges in the development of membrane and piezoelectric materials, new device configurations and advanced processing. Oscillator phase noise has to be improved by decreasing FBAR flicker noise. In the case of filters stop-band rejection has to be increased and the spurious responses in the pass band have to be minimized.

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