MICROMACHINED CELLULAR FILTERS

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Abstract

Bulk wave Acoustic Resonators using thin piezoelectric films have the potential to become useful filters for telecommunication markets. These devices has been variously referred to as a thin film resonator (TFR) (1) or a film bulk acoustic wave resonator (FBAR) (2). Typically, the piezoelectric material is a sputter-deposited film of aluminum nitride or zinc oxide. Processing techniques such as the use of KOH or ethylene diamine pyrocatechol (EDP) to etch silicon or the use of sacrificial materials to form "air gap" structures (3) are needed to isolate the acoustic cavity from the underlying substrate. These same techniques are also part of the micromachinists' "tools-of-the-trade" and are becoming better understood as well as becoming a part of an accepted processing infrastructure.

Introduction

As the telecommunication market continues to grow, the various aspects of the components have changed. There is more integration of discrete devices and at the same time, the cost of these components have gone down. One component that has not materially changed and at the same time has become one of the larger cost items is the filter. Typical filters used in the rf front-end for commercial telecommunication units (i.e. cordless and cellular phones) are SAWRs and ceramic resonators. Ceramic resonators have certain attractive features including cost (about one dollar a pole), stability, robustness, and reasonably low insertion losses. Surface acoustic wave resonators (SAWR) have a strong niche in the IF portion of the radio block diagram, however, they have relatively high insertion losses at the rf frequencies and poor power handling capabilities.

The markets presently occupied by these resonators are certainly one attractive reason to investigate FBAR devices; another is that FBAR devices can be integrated with active devices. The attraction of this approach is the elimination of on/off chip interconnects.

Device Description

A thin film bulk-wave acoustic resonator (FBAR) consists of a single piezoelectric material (aluminum nitride, in our case) sandwiched between two metal electrodes. A stacked thin film bulk-wave acoustic resonator (SBAR) is made of two FBAR devices back-to-back(4). Here, the middle electrode electrically isolates the input electrode from the output electrode. The naturally formed two-port filter uses the acoustic coupling between the two FBAR resonators to create a band-pass for selected frequencies.

For either an SBAR or FBAR device to work, there must be two essential ingredients; the first is the acoustic cavity. The second ingredient is a mechanism by which electrical energy is converted into acoustic energy. The FBAR device accomplishes the latter by using a piezoelectric material (such as AlN or ZnO). The first ingredient is satisfied by having a large acoustic impedance mismatch two interfaces, thus "trapping" the energy.

Figure 1a shows a simulated Log[Magnitude] Plot (S11) vs. frequency for a single composite FBAR device (as shown in Fig. 3) with some series resistance.

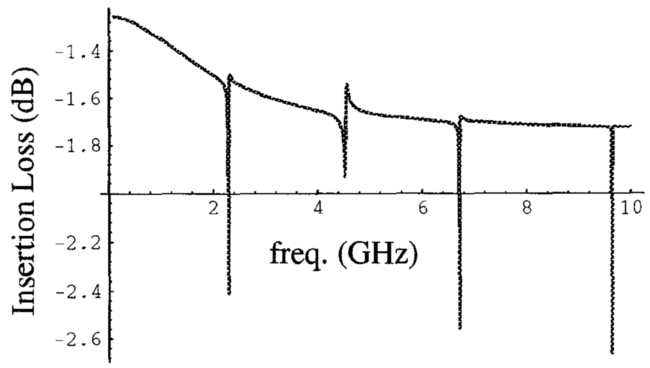

Fig. 1a Log[S11] vs. Frequency

Filters built from FBAR elements can be implemented in a ladder or lattice structure, where the designer uses FBARs with different thicknesses to selectively place poles and zeros at appropriate values of frequency.

Another approach uses the two-port SBAR device which has one pole in the pass band. Figure 1b shows the complex transfer function V_{out}/V_{in} as a function of frequency. [Note: the transfer function, when looked at head on, is just S21 as measured by a network analyzer.]

The points in Fig. 1b are simulations using a physical model that takes as its inputs, physical properties such as mass density, stiffness coefficients, piezoelectric stress coefficients, dielectric permittivity, and geometrical constants of each physical layer. The continuous line is a simulation from an electrical analog model based on the Butterworth-Van Dyke circuit consisting of an LRC resonating circuit sandwitched between two plate capacitors. The red dots were used to determine the best fit of the coefficients of the polynomial equation for the electrical analog model to the physical model.

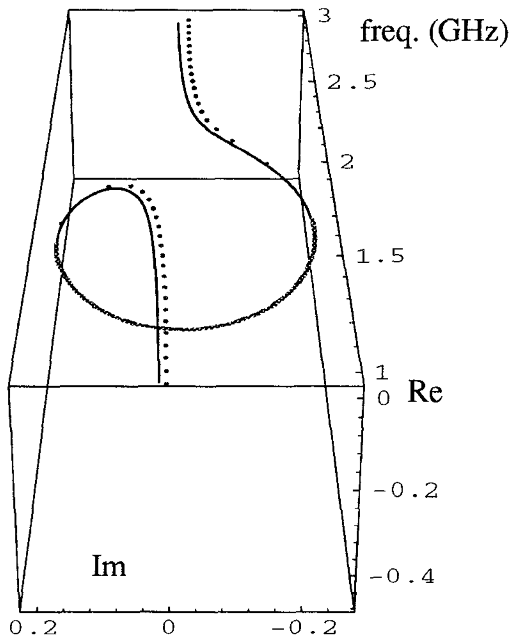

Fig. 1b Transfer Function vs. Frequency

By cascading several SBARs together, a multipole filter is formed. Figure 2 plots the insertion loss in dB vs. frequency for a 1,2,3 & 4 pole SBAR ladder filter.

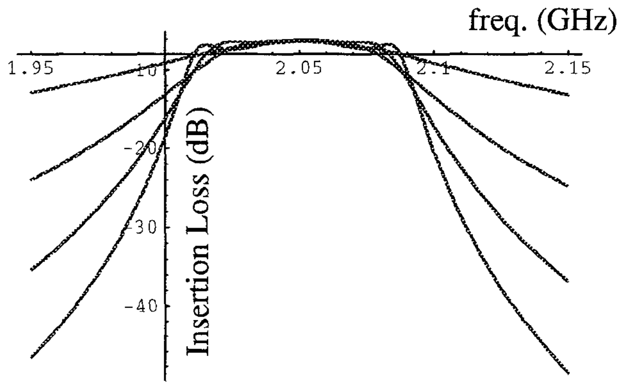

Fig. 2 Insertion Loss vs. Frequency for 1,2,3, and 4 pole SBAR Filter

Micromachining Tools

FBAR devices first appeared on the scene in 1980 having been nearly simultaneously invented in 3 places (1,2,6). At the same time, micromachining was developing as a field in its own right. Not surprisingly, the tools developed for micromachining are useful for building FBAR devices. It is not the intent of this paper to cover all of the techniques developed by the micromachining community. However, I will highlight several of these techniques as they apply to the production of FBAR devices.We start with the cross-section of an single FBAR device made at HP (Fig. 3).

The first obvious feature is the cavity formed underneath the active area.This cavity is one of several ways to form a "crystal-air" interface. [Note: another way of trapping energy uses acoustic Bragg reflectors on one side. This device is referred to as a Solidly Mounted Resonator (7)].

For devices made on silicon, etches such as EDP or KOH are well understood and characterized.

The next feature is the silicon nitride layer. This is used as an etch stop for the silicon etch and also becomes part of the acoustic path. A further property on the silicon nitride that has been developed and exploited by the micromachining community is that the membrane is low stress. This guarantees flatness of the membrane, and for the FBAR device, a strong support structure as well as a useful silicon etch stop layer.

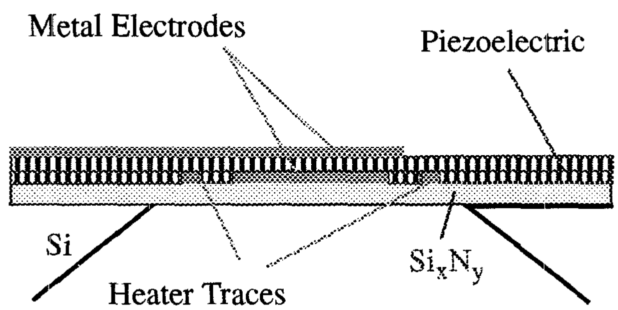

Fig. 3 Schematic of an FBAR Device

Measurements of devices using this layer structure have yielded measured unloaded Q's of 2300 and coupling coefficients, k_t^2, as high as 6% (5). The best Figure of Merit (FOM = Q k_t^2) measured was about 70 at ~4 GHz (Fig. 4 shows a typical resonance of our device. A serious parasitic resistance term, since eliminated, degrades the resonance as shown in Fig. 4) .

In comparison, FOMs of 40 are found for SAWR devices on lithium niobate(8). It is clear from the measured values that the Si_xN_y portion of the acoustic cavity is not degrading the performance. Low stress Si_xN_y was first developed for X-Ray mask technology but later used for a variety of devices (9).

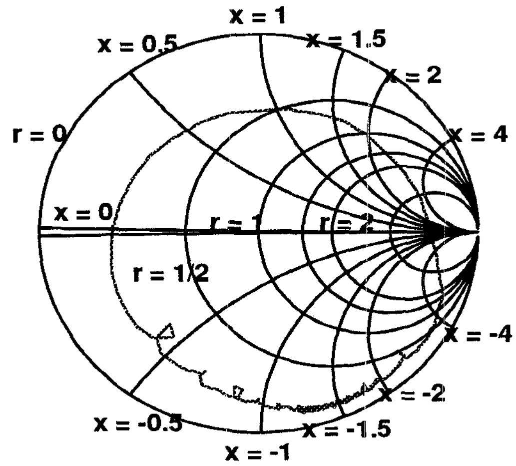

Fig. 4 S11 measurement of an FBAR Resonance

The low stress, silicon rich nitride membranes are deposited via CVD at deposition temperatures in the range of 900 C. Film thickness's can range from several hundreds of nanometers to microns.

The next thing to notice about Fig. 3 is the placement of heater resistors on the same membrane as the active piezoelectric layer. Figure 5 plots temperature of the heater versus power applied. The data is measured in the form of I vs. V (shown in inset). From bulk values of the thermal coefficient of resistance, one can convert the change in resistance into change in temperature as a function of power. Amazingly, we have been able to heat the membrane up to 600 C. The heater resistor snakes around the perimeter of the membrane effectively surrounding the active resonator area.

The ability to place on-chip heaters opens up two possibilities. The first application is in temperature tuning. We have observed temperature tuning ranges as large as ~ 2%. Of course, the FOM of the device degrades as the center frequency is pulled.

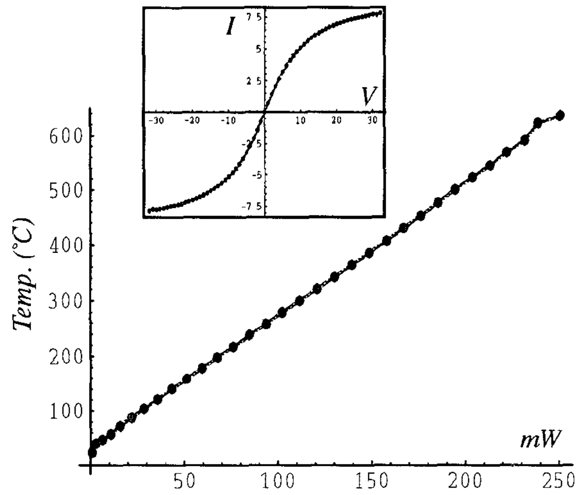

Fig. 5 Heater Temperature vs. Power
(Inset: the measured IV curve)

Another use of these heaters is to temperature stabilize the resonator analogous to the oven-controlled quartz crystal applications (10). Unlike the state-of-the-art oven-controlled quartz resonators that use watts of power to keep a constant temperature, these membranes need only milliwatts.

Not shown in Fig. 3 would be any advances made in micromachining on novel packaging paradigms and further integration of FBAR devices with other active microwave and millimeter wave devices.

Conclusions

There has been no attempt to exhaustively survey the micromachining literature and report on all accomplishments. Rather, it is hoped that there can be seen a synergy between the advances in the field of micromachining and bulk acoustic resonators and filters.

References

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