Design and Fabrication of Two-pole Monolithic Bulk Acoustic Filters

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ABSTRACT

A new class of miniature monolithic filters has been fabricated in the 1 to 1.5 GHz range. The devices are 2-pole ladder filters which incorporate two inductors, a coupling capacitor and two bulk acoustic resonators. They are characterized by small size and weight, low insertion loss (typically between 1 and 1.5 dB), narrow passbands (between 2 and 5%) and potentially very low cost. Filters have been fabricated on both high resistivity silicon and semi-insulating gallium arsenide substrates. Fabrication is completely compatible with all MMIC components and thus it is straightforward to integrate these devices with active components on the same wafer.

INTRODUCTION

The chief advantage of acoustic over electromagnetic devices is generally recognized as their small size due to the approximately five-order-of-magnitude reduction in the acoustic phase velocity. This property is utilized in the fabrication of surface acoustic wave filters, which can be made quite compact even at frequencies below 100 MHz. Because a wave must propagate between the input to output transducers, SAW filters suffer from relatively high insertion loss especially above 1 GHz.

Crystal ladder filters possess unique advantages [1]. Since there is no propagating wave, insertion loss is dramatically reduced. Devices using bulk quartz resonators have and discrete passive components have been fabricated for some years in the frequency range below 10 MHz. The FBAR (film bulk acoustic resonator) filter is a crystal ladder structure in which the acoustic resonators are composed of sputtered layers of piezoelectric films grown on semi-insulating substrates. The passive elements are fabricated using standard microelectronic techniques. These devices have the property of low insertion loss coupled with the added advantages of small size and possibility of integration with active circuitry.

CIRCUIT DESIGN AND ANALYSIS

The chip layout is shown in fig. 1.

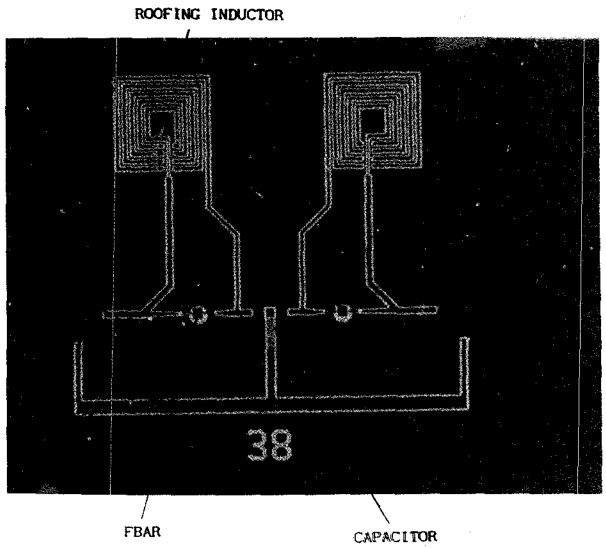

Fig. 1 Chip layout of a two pole FBAR monolithic filter showing the acoustic resonators, inductors and capacitor.

The most important components are the two film acoustic resonators. They consist of a four layer composite structure as shown in fig. 2.

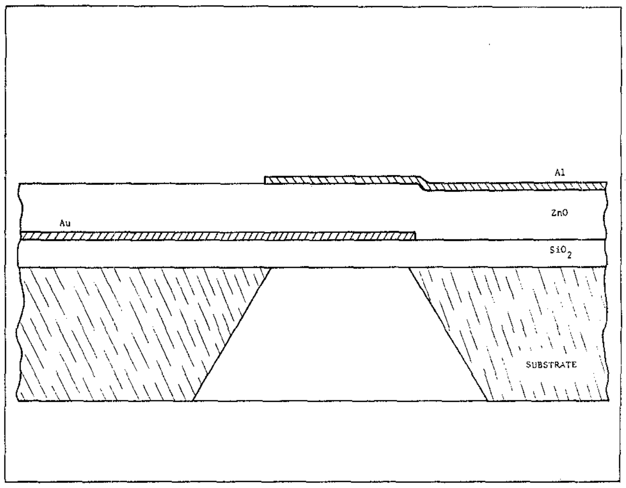

Fig. 2 Cross section of the composite structure of the acoustic resonator.

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The sputtered SiO_2 provides a rigid mechanical structure on which are grown the crystallographically ordered layers of gold and zinc oxide. The gold is vapor deposited in a manner which insures a <1,1,1> orientation. Properly ordered gold assures that the zinc oxide film will orient with the c axis parallel to the growth direction. This quasi-single crystal cut (the x and y axes are oriented arbitrarily in the wafer plane) is piezoelectrically active with coupling constant between .25 and .28 for the longitudinal mode and Q factors between 750 and 1000 at 1 GHz.

The external spiral inductors are known as "roofing inductors"; their purpose is to resonate out the clamped capacitance of the FBARs and thus provide a symmetric bandpass response. The inductance value depends on the dimensions and thickness of the piezoelectric resonators and typically falls between 10 and 25 nH. Finally, the coupling capacitor provides a means to adjust the filter bandwidth; typical values for this element are between 1 and 4 pF.

The circuit schematic is shown in fig. 3. The FBAR is represented by a clamped

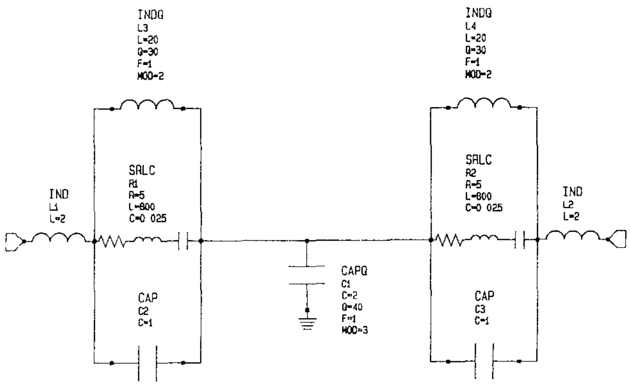

Fig. 3 Schematic circuit diagram of the two pole filter; the acoustic resonator is represented as series LRC in parallel with a clamped capacitance.

capacitor whose value depends on the FBAR dimensions and the electrical properties of the piezoelectric layer in parallel with a "motional arm" consisting of the series RLC. These component values depend on the lateral dimensions and the piezoelectric, electrical and acoustic properties of the four layers which make up the acoustic path [2]. The value of the roofing inductor is chosen to resonate the FBAR parallel capacitance at 1 GHz. The coupling capacitor value depends on the desired bandwidth. Increasing the capacitance, for example, reduces the bandwidth at the expense of increased insertion loss.

The filter insertion loss is the most significant factor in the overall performance. At series resonance all reactive components except the coupling capacitor are resonated out of the circuit leaving the two resistors and C_c.. The insertion loss depends on the values for the motional resistances according to (in a 50Ω system).

$$\text{I. L.} = 20\log_{10}\left(1 + \frac{2\ R_m}{100}\right)$$

The values of R_m in turn depend on resonator lateral dimensions and their figure of merit defined by:

$$\text{F.O.M.} = \frac{Q}{C_r}$$

where C_r, called the "C" ratio, is the ratio between the clamped and motional capacitances. The resonator Q depends on the acoustic attenuations of the four layers in the acoustic path. It is optimized by using the largest thicknesses of SiO_2 (which has the lowest attenuation) and minimum thickness of high attenuating gold. C_r is minimized by choosing the thicknesses of SiO_2 to ZnO layers which provides the greatest electromechanical coupling constant at a given frequency. Since optimal performance in the 1 to 2 GHz range requires that the resonators operate in a second harmonic mode, maximizing the coupling involves computer aided design using a one-dimensional Mason model [3,4]. This model predicts the values of the motional elements and the clamped capacitance as functions of the material properties and thicknesses of the various layers. While the device Q will not suffer, if the thicknesses are not chosen correctly C_r will be too high resulting in a larger than desired R_m, and increased insertion loss, even though the ZnO is strongly piezoelectric. For a given C_r and Q the values of the motional resistors can also be reduced by increasing the lateral dimensions of the FBARs. This has the effect of increasing the clamped and (for a constant C_r) of the motional capacitance as well. Since the Q and frequencies are constant the motional inductance must be correspondingly reduced. The disadvantage of this method design is that while the filter insertion is reduced so too is the out of band rejection. As the frequency is increased C_r does not increase but Q is inversely proportional to frequency. For constant lateral dimensions however the value of the motional resistance actually decreases with increasing frequency because the clamped capacitance increases. Thus, while it is possible to design a low loss filter at higher frequencies (above 2 GHz) the out of band rejection will be seriously degraded. Generally the insertion loss is expected to increase from the 1 dB range at 1 GHz to the 3-4 dB range at 3 GHz for a two pole filter.

The values and Q's of the other components also affect the filter performance but to a lesser degree than the FBARs. Since value of the roofing inductor is chosen to resonate with the clamped capacitance it will decrease as the lateral dimensions of the FBAR are increased. Reducing the size of this component results in a significant reduction in the chip dimensions since from fig. 1 it is obvious that the inductor dimensions ultimately determine the chip size. The Q of the inductors becomes significant as the overall insertion loss drops below about 1.5 dB. The inductor value and Q are also determined by using a computer aided design program [5]. At 1 GHz the design calls for a metalization thickness of at least 4μm to achieve a Q of approximately 33 which is compatible with filter insertion loss of just below 1 dB. At higher frequencies the inductor Q increases and thus does not become a limiting factor in determining device performance. The coupling capacitor Q can be quite poor before it limits the filter loss. The value of this element is chosen to be as low as possible consistent with filter bandwidth.

FABRICATION

The FBARs are the most critical component and their fabrication is the most difficult step. The ordered gold deposition is performed at critical temperature, rate and vacuum requirements. The zinc oxide will generally be strongly active if the gold is well ordered. The sputter deposition must be performed so that the ZnO film has the lowest possible mechanical stress consistent with piezoelectric activity. Low stress films are essential both for mechanical integrity and electrical performance. Compressive films bow upward and have been observed to shatter even with the slightest applied pressure. Stress also seriously degrades the resonator Q and increases insertion loss.

The roofing inductors and coupling capacitor are fabricated using standard microelectronic techniques. The capacitor dielectric consists of 2500Å of silicon nitride deposited using a plasma enhanced CVD process. The 4μm thick gold metalization is performed using E-B evaporation and the delineation of the inductors is done by either etching or lift-off. The inductor lines are broken and air bridges are fabricated over the center conductor as shown in fig. 4. Air bridges are also fabricated at the coupling capacitor connections. These bridges are quite sturdy and hold up well in subsequent processing.

Fabrication of the acoustic resonators requires that the substrate crystal be entirely removed under the resonating area. This is accomplished for both silicon and gallium arsenide by reactive ion etching the substrate the same way that via holes are formed in analog MMIC's. Using RIE allows the etching to be performed in a batch process (with up to 25 wafers at a time) without requiring protection of the front side of the wafer as in wet chemical etching. For gallium arsenide a chlorine based chemistry is used while for silicon sulfur hexafluoride gives excellent results. Etch rates of up to 8 mils per hour for silicon and 6 mils per hour for gallium arsenide have been achieved. Fig. 5 shows a typical well etched in silicon.

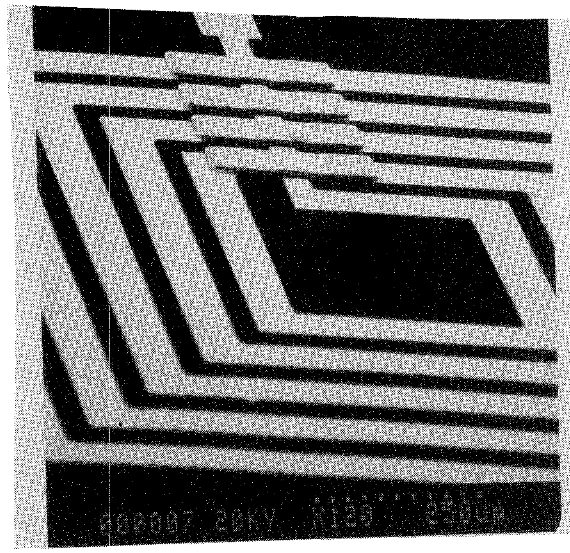

Fig. 4 Scanning electron photograph of an inductor with air bridges.

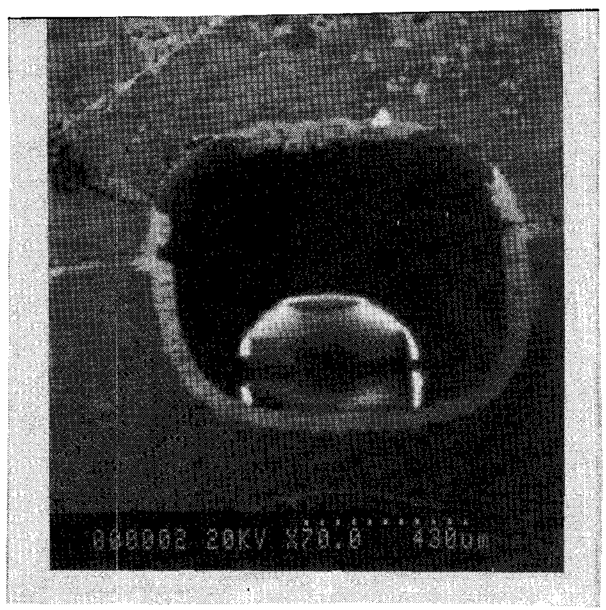

Fig. 5 Scanning electron photograph of a resonator "via"; the substrate thickness is 20 mils.

DEVICE PERFORMANCE

Fig. 6 shows a typical S_{12} (= S_{21}) response. For this value of insertion loss

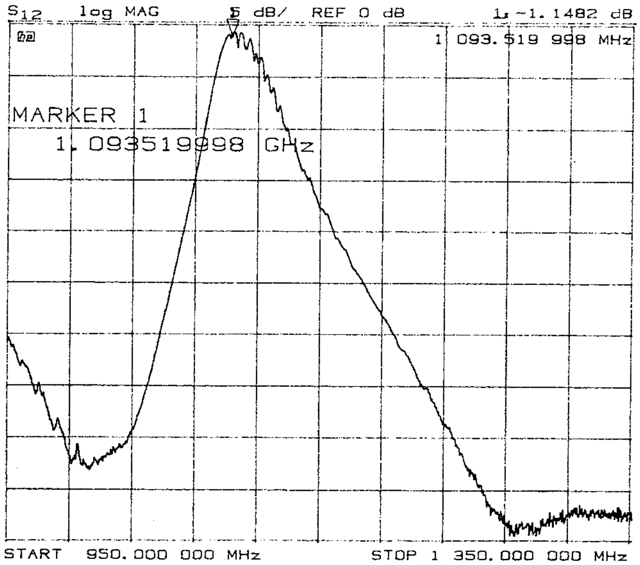

Fig. 6 Typical performance curve of low loss two pole filter.

the filter performance is primarily limited by the quality of the FBAR's. The small ripple in the pass band is due to the presence of spurious acoustic modes which are always present to some degree. Their effect can be minimized however, by improving the processing. The out of band rejection also depends on the quality of the FBARs as well as their dimensions and is typically greater than 50 dB. For the prototype filter the chip size was chosen for convenience of handling to be 300 mils per side. Using this oversized design there are 69 devices on a 3 inch wafer as shown in fig. 7. The size of the individual chips can be reduced by more than 50% without changing the basic design. Thus it should be possible to pack at least 150 devices into a 3 inch or nearly 300 devices into a 4 inch wafer. Increasing the FBAR dimensions reduces the inductor size allowing even more devices on a wafer.

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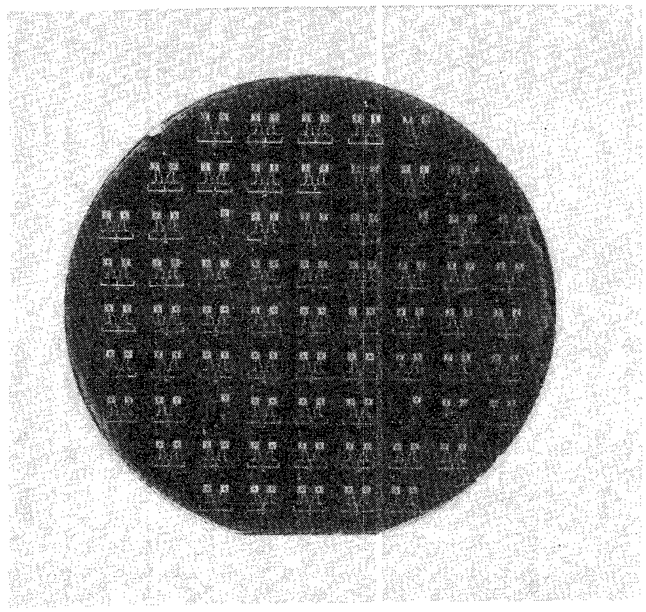

Fig. 7 Chip placement on a three inch wafer in the prototype design.