DEVELOPMENT OF MINIATURE FILTERS FOR WIRELESS APPLICATIONS

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ABSTRACT

Miniature filters have been under development for wireless applications from 500 MHz to over 6 GHz using thin piezoelectric films on common substrates. Ladder filters have achieved insertion losses in the 3 dB range using aluminum nitride films for the piezoelectric and appropriate substrates such as silicon, sapphire, and glass. The ladder filters consist of interconnected series and shunt resonators forming a monolithic structure on a single die. This paper discusses recent results in the development of miniature filters with application to cellular phone, GPS, PCN, and other wireless systems.

I. INTRODUCTION

Most bandpass filters are composed of resonant elements whose dimensions are dependent upon a fundamental propagation mode. Because acoustic waves propagate approximately four to five orders of magnitude slower than electromagnetic waves, bulk and surface acoustic devices are much smaller than high permittivity based EM structures. For that reason considerable attention has been directed towards microwave acoustic filter development [1-4].

Filters that can be synthesized with acoustic resonators are shown in Fig. 1. In Figs. 1a and 1b are two classes of electrically connected resonator filters. These could be composed of bulk or surface wave resonators. The ladder filter, at low frequencies, generally uses shunt capacitors to control loop currents rather than resonators. Ladder filters fabricated on a common aluminum nitride membrane supported by a silicon substrate have been reported [2].

The lattice filter is suitable for balanced circuits and was once widely used at low frequencies. Such filters could be fabricated with thin films and then used in balanced integrated circuit networks.

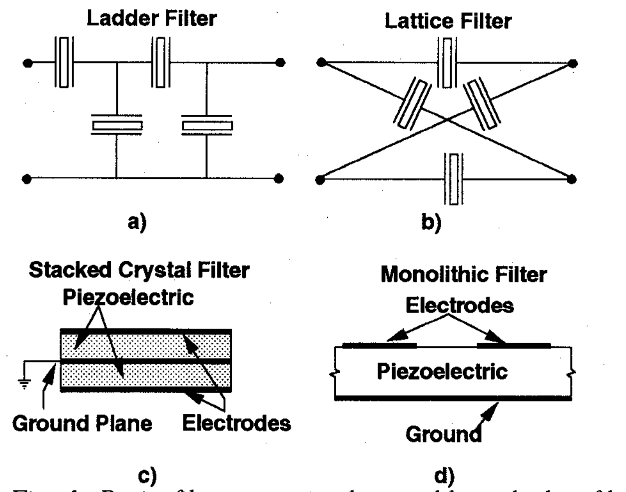

Fig. 1. Basic filter types implementable with thin film piezoelectric materials. a) electrically connected ladder filter, b) plate-wave monolithic filter, and c) stacked crystal filter.

Two forms of acoustically coupled resonator filters are shown in Figs. 1c and 1d. The monolithic filter is used in considerable volume at frequencies below 200 MHz while the stacked crystal filter (SCF) is most suited to higher frequencies where films can be grown to effect the proper bonds between the layers.

Variations of the SCF have been reported with operation as high as 7 GHz [3]. This device is suited for use in systems where the skirt selectivity of the ladder filter is not needed. Inductor tuning may be used to increase the bandwidth and reduce insertion loss. However, inductor tuning greatly increases the size of the filter.

The monolithic filter requires a degree of energy trapping for proper operation. Low frequency devices employ the energy trapping properties of plate waves in AT quartz

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4A

and other shear wave material cuts. Since the widths of the trapping electrodes are of the same order as the thickness of the piezoelectric plate, high resolution fabrication is required at microwave frequencies.

Resonators for use in electrically connected filters can be of several forms including SAW grating resonators. Of interest here are those resonators fabricated with thin films supporting the bulk thickness mode resonance of either shear or longitudinal waves.

In examining the bulk wave resonator types it is useful to define a resonator structure as one being bounded by extremes of impedance that tend to keep the waves confined within the desired volume. This is apparent from the fundamental one dimensional equation defining the electrical impedance of a bulk acoustic wave resonator [4]

$$Z = \frac{1}{j\omega C}\left[1 - K^2 \frac{\tan\phi}{\phi} \frac{(z_r+z_l)\cos^2\phi + j\sin 2\phi}{(z_r+z_l)\cos 2\phi + j(z_r z_l+1)\sin 2\phi} \right]$$

where z_l and z_r are normalized acoustic impedances at the boundaries of the piezoelectric plate. If the boundaries are composed of a low impedance material (like air or vacuum) the load impedances are zero and the electrical impedance reduces to;

$$Z = \frac{1}{j\omega C}\left[1 - K^2 \frac{\tan\phi}{\phi} \right]$$

This is the form of a simple acoustic resonator having the well known "crystal" impedance characteristic.

The resonator fabrication techniques suitable for using piezoelectric films and microelectronics processing are shown in Fig. 2. The resonators in Figs. 2a and 2b have low impedance material interfaces, after accounting for finite thickness electrodes, that approximate the above equation.

The configuration of Fig. 2a is a membrane type supported by the edge of the substrate. Typical fabrication involves deposition of a piezoelectric film followed by removal of all or a remnant portion of the substrate to free the membrane. Substrates such as silicon and gallium arsenide have been used with some success. However, strain in the film leads to breakage, and the approach is limited to substrates in which a VIA can be readily formed.

The second configuration involves fabricating an air gap under the resonator. This may be accomplished by first

BASIC RESONATOR CONFIGURATIONS

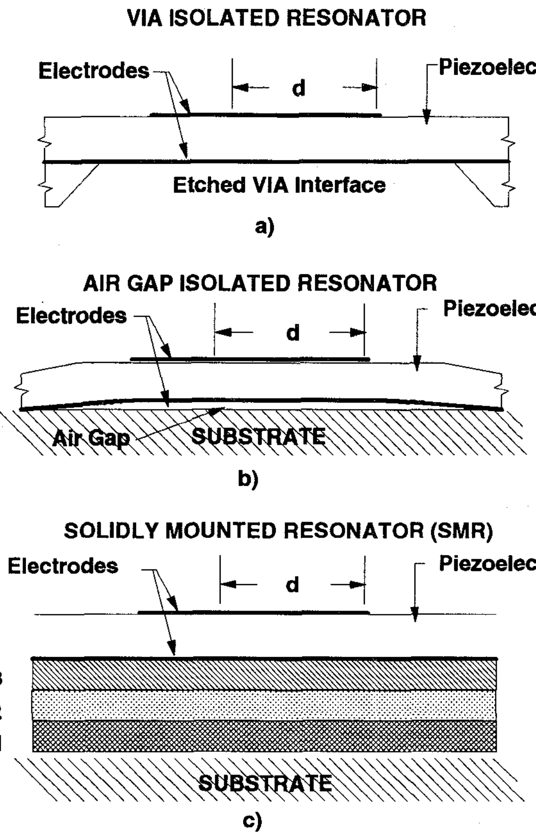

Fig. 2. Resonator types fabricated with thin films. a) Membrane or FBAR resonator, b) Air Gap resonator, c) SMR resonator using quarter wavelength reflector layers.

depositing a support film, forming the resonator on the support film, and subsequently removing the support film to leave a membrane supported at the edges but free from the substrate in the resonator region. The resulting membrane is fragile as in the case of Fig. 2a but is applicable to a larger number of substrates since a VIA is not actually formed.

The solidly mounted resonator (SMR) in Fig. 2c is of a slightly different form [5-7]. The top interface may be a real material, very low impedance, air interface while the bottom interface is an apparent zero impedance interface.

The SMR bottom interface is formed by a sequence of quarter-wavelength thick regions of differing mechanical impedance. Multiple reflections from the interfaces form a standing wave approximating a free surface reflection. If the layers are composed of altering low and high mechanical impedance materials, the reflections are large and the effect is to reduce the substrate impedance to near zero.

The operation of the reflectors is similar to that of the grating in a SAW resonator except that the magnitude of the reflections may be significantly larger without fear of exciting spurious modes.

The wave reflections are most pronounced at the quarter wavelength frequency. Well outside the center frequency the reflectors are less efficient and the resonator is more like a loaded transducer. The magnitude of the apparent mechanical impedance versus frequency for a number of layers is shown in Fig. 3.

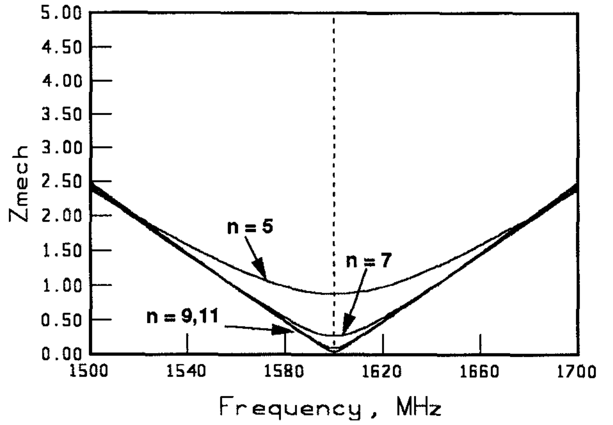

Fig. 3. Normalized mechanical impedance versus frequency around the quarter-wave frequency for various reflector layers.

The frequency bandwidth of the low impedance region of the reflection determines in part the series and parallel resonant frequencies of the resonator and, therefore, the bandwidth and insertion loss of the filter. The number of layers and the impedance discontinuity between adjacent layers determines the depth of the impedance transformation at center frequency.

The most significant advantage of the SMR resonator is that it can be fabricated on a wide variety of substrates With a sufficient number of layers the resonator fields do not interact with the substrate and, therefore, the acoustic properties of the substrate are not of real importance.

Equally important, the SMR structure is extremely rugged compared to membrane devices and are in much better thermal contact with the substrate. The rugged construction gives rise to a high device yield during manufacturing and the lack of a VIA allows the device die to be handled just as any other circuit die.

The fabrication of the SMR is more complex than in the membrane case because of the multiple layer deposition and material parameter controls required.

The absence of a VIA or any special substrate preparation shows considerable promise for direct integration onto active circuit wafers. It is necessary, in this case, to first passivate the IC's and then fabricate SMR devices, in areas provided, after all IC processing has taken place.

II. SMR FILTERS

Filters based on the SMR concept have been under investigation for a number of years. Results for a ladder filter composed of three series and two shunt resonators is shown in Fig. 4. Fig. 4a is S_{21} for the near-in frequency response and shows the deep notches that increase the filter skirt selectivity. The high frequency notch is due to parallel resonance in the series resonators and the low frequency notch is due to series resonance in the shunt resonators. Fig. 4b is the S_{21} wide band response showing a uniform level of out-of-band rejection due to the voltage divider formed by the resonators acting as capacitors.

One of the important features of the filter is the absence of apparent spurious plate wave resonances anywhere in the filter response. The third harmonic response of the filter shown in Fig. 4 is suppressed by the resonator and filter design. The result is an out-of-band rejection that is very favorable compared with high dielectric constant filters.

The deep notches on either side of the ladder filter are an advantage in the implementation of duplexer circuits where the transmit and receive filters are close in frequency. Duplexer circuits for cellular phone and PCN are now under development. Using the SMR approach a duplexer circuit for PCN frequencies (1900 MHz) would occupy an area of approximately 1 mm x 1.5 mm.

Techniques to improve the insertion loss of ladder filters are under investigation. Improvements are being made in film quality and thickness control. Some systems, such as GPS, front end filters require an insertion loss of less than 1.5 dB in order not to degrade the signal-to-noise ratio.

Low cost manufacturing requires a high device yield. The most important factor is to fabricate filters that are on frequency and which have a high degree of uniformity across the wafer to preclude the need for trimming filters to frequency. Shown in Fig. 5 is a uniformity map across a 100 mm diameter wafer. The filter center frequency is within +- 0.7% over the full wafer and the insertion loss is generally within +-0.15 dB. The average center frequency is 1670 MHz and the average insertion loss is 2.9 dB. The uniformity is a composite of the thickness and material properties of all the layers.

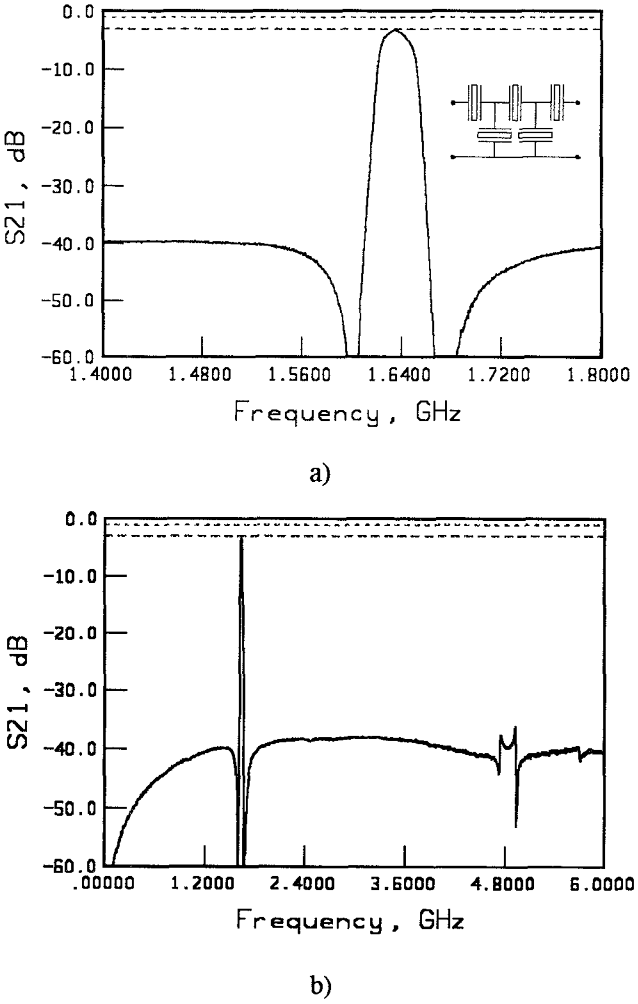

Fig. 4. Experimental results for a ladder filter fabricated on a glass substrate. The horizontal dashed lines are at 1 and 3 dB. a) Near in response, b) wide band response.

IV. SUMMARY AND ACKNOWLEDGMENT

Miniature filters have been demonstrated with insertion losses in the 3 dB range for application to wireless systems. These filters have been synthesized using a solidly mounted resonator that does not require a VIA in the supporting substrate. The resonators are isolated from the substrate using a sequence of quarter-wavelength thick layers that form an efficient reflector.

A high degree of uniformity has been shown for fabrication in the solidly mounted resonator configuration.

Efforts are now underway to improve filter insertion loss and to extend the concept to higher frequencies.

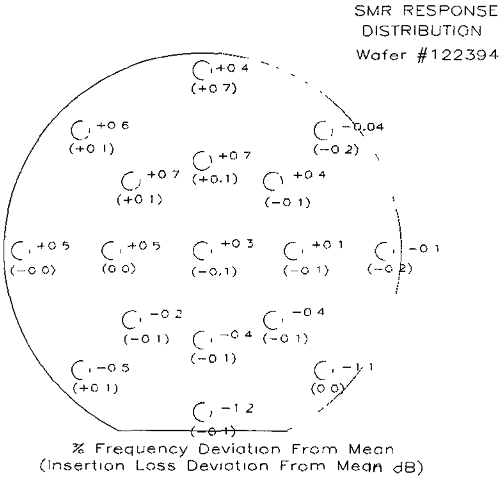

Fig. 5. Uniformity data across a 100 mm wafer for SMR filters. Center frequency is within +- 0.7% and insertion loss is within +- 0.1 dB approximately.

The authors wish to acknowledge contract support from the U.S. Army SBIR program, the U.S. Office of Research and Development, the U.S. Army Advanced Concepts and Technology program, DARPA SBIR program, and the U.S. Navy SBIR program.

V. REFERENCES

1. C. Vale, J. Rosenbaum, S. Horwitz, S Krishnaswamy, and R. Moore, "FBAR Filters at GHz Frequencies", 45 th Annual Symp. of Freq. Cont. Proc. pp.332-336
2. K.M. Lakin, G.R. Kline and K.T. McCarron, "Thin Film Bulk Acoustic Filters for GPS", 1992 Ultrasonics Symp. Proc., pp. 471-476.
3. R.B. Stokes and J.D. Crawford, "X-Band Thin Film Acoustic Filters on GaAs", IEEE Trans. Microwave Theory Tech. Vol. 41 no. 6/7, pp. 1075-1080, Dec. 1993
4. K.M. Lakin, G.R. Kline and K.T. McCarron, "High Q Microwave Acoustic Resonators and Filters", IEEE Trans. Microwave Theory Tech. Vol. 41 no. 12, pp 2139-2146, Dec. 1993
5. W.E. Newell, "Tuned Integrated Circuits - A State-of-the-Art Survey", Proc. IEEE, Vol. 52, Dec. 1964, pp. 50-52
6. W.E. Newell, "Face-Mounted Piezoelectric Resonators", Proc. IEEE, Vol. 53, June 1965, pp. 575-581
7. W.E. Newell, "Ultrasonics in Integrated Electronics", Proc. IEEE, Vol. 53, October 1965, pp. 1305-1309