High Frequency SAW Devices

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This paper will discuss some of the technology approaches currently being pursued to extend the SAW device operating frequencies to the 1-6 GHz range. This range of frequencies has become commercially interesting in the past few years due to the large increase in wireless applications, especially cellular and mobile communications. This range of frequencies is challenging because it pushes the limits of the currently available technology implementations. In order to achieve the higher frequencies, research and development continues on the improvement of current SAW components and the development of new structures, examining new types of wave propagation, and exploring new materials.

Introduction

SAW devices are currently being manufactured in high volume in the frequency range from 100 MHz to approximately 1 GHz. It has been demonstrated previously in the research environment that SAW can be successfully generated and detected up to 20 GHz [1]. Therefore, it appears at this time that there is no fundamental reason SAW devices can not penetrate the higher frequency markets. The upper frequency range is limited by the device wavelength determined by fundamental material parameters, photolithographic line resolution and manufacturing tolerances. Current line widths of approximately 0.5 microns are achievable in high volume manufacturing for SAW devices. Although device line widths may be reduced further, photolithography gains are not enough to push the use of SAW devices into the 5 GHz range.

The following sections will discuss some of the recent approaches and developments in the areas of materials, acoustic modes and transducer structures for the purpose of extending the operating frequency of SAW devices. Although advances in any one of the areas are important, integration of several technology advancements has the greatest potential to meet the new high frequency market requirements.

SAW Transducer Structures

One approach to high frequency operation is to modify the SAW transducer structure such that a higher fundamental operating frequency can be achieved. Conventional transducers are typically fabricated using either eighth- or quarter-wavelength electrodes. Eighth wavelength electrodes provide reflectionless transduction within each period which is important for a wide class of transversal filters while quarter wavelength electrodes yield both transduction and reflection within a transducer period which can be useful for resonators and classes of single phase unidirectional transducers. In both of these embodiments there is usually a ratio of metal to free surface regions within a period that is nominally 50:50. There are new types of electrode structures which strive to achieve a nearly 100% metallized transducer with no free surface regions. There are several approaches to this class of transducers and they can be grouped under the heading of narrow gap (NG) types.

Yamanouchi is first credited with the introduction of the NG transducer structure [2]. The narrow gap structure has an electrode periodicity of one-half wavelength. The goal is to have the electrode or metallized region occupy as near to 100% of the period as possible, i.e., to make the gap between adjacent electrodes as small as possible. There are a number of approaches to achieving a narrow gap transducer structure which include advanced photolithographic processing, anodic oxidation of the electrode edges, directional metallizations, multilevel transducers, and combinations of one or more techniques. The advantages of the NG transducer is that it provides the widest electrode possible per period, reflectionless transduction, and low resistivity per electrode when compared to the conventional transducer. The disadvantages are a high electrode capacitance and difficult fabrication.

A NG transducer can be produced by several different fabrication processes and can have several different embodiments. Figure 1 shows a schematic view of a typical single level narrow gap SAW transducer. Three different embodiments will be presented. The first

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technique produces a transducer which has a very narrow gap region between adjacent electrodes; an actual pattern

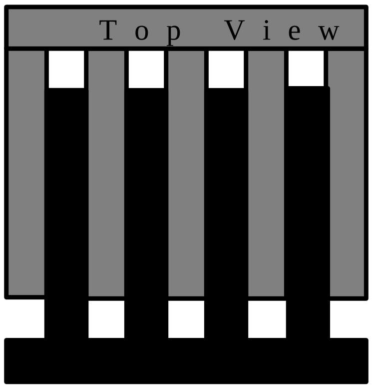

Figure 1. Schematic view of a single level narrow gap SAW transducer structure. The actual adjacent electrodes have a small gap between each other.

is shown in Fig. 2a[3]. The fabrication technique used involves producing a series of metal electrodes having one wavelength periodicity, followed by a photoresist level, backside exposure and liftoff of a second metal. By proper photoresist exposure and developing, a narrow gap between the first and second metal deposition can be obtained between adjacent electrodes. Through use of backside exposure, the process is self aligned in the critical geometry areas. The second technique uses a relatively thin aluminum oxide at the electrode edges to separate adjacent electrodes, shown in Fig. 3[3,4]. The aluminum oxide is grown through anodization and proper masking. The complete process requires several masking levels, and a chemical oxidation process. The third technique uses a thin dielectric film to separate adjacent electrodes. The technique requires two metallizations, a dielectric layer deposition and multiple masking levels, shown in Fig. 4[5].

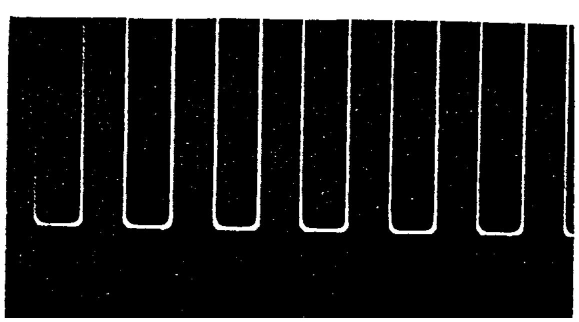

Figure 2. A microscope photo of a back lit narrow gap transducer. Period is approximately 2.4 microns and gap is approximately 0.1um.

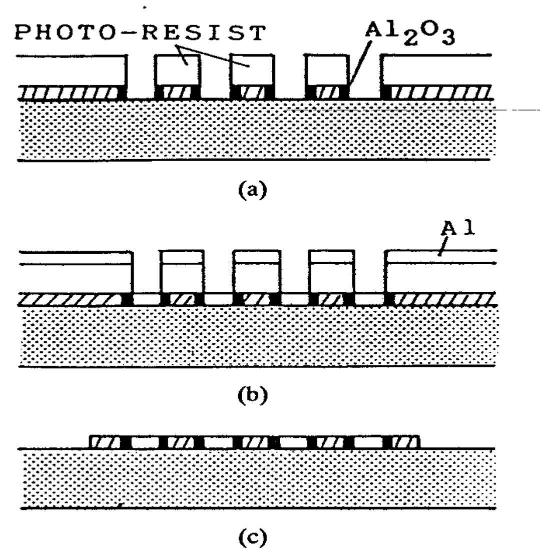

Figure 3. A narrow gap transducer process using anodic oxidation of aluminum to separate adjacent electrodes, from [2].

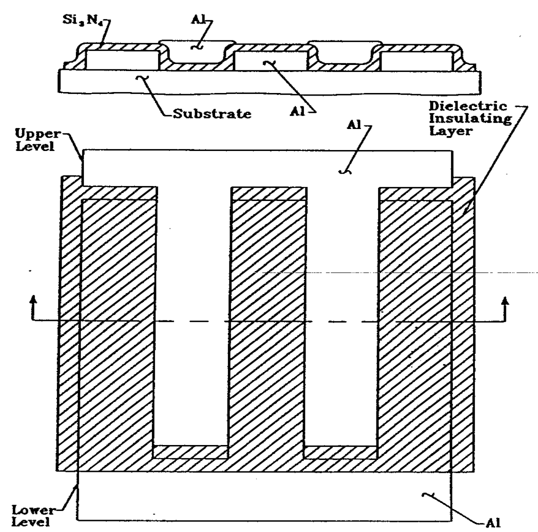

Figure 4. Cross sectional view of a multilevel narrow gap transducer structure.

Fig. 5 shows the predicted and measured filter response for a 1.8GHz NG multilevel transducer filter as described in Fig. 4. The filter is composed of two unweighted NG transducers fabricated on YZ lithium niobate. The filter insertion loss is dominated by the electrical mismatch loss.

In order to predict NG device performance adequately, the effects of having very close adjacent fingers in the transducer must be modeled. A number of investigators have previously examined the effects of the

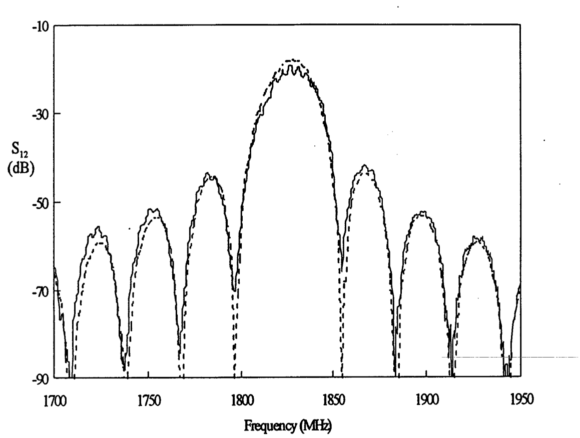

Figure 5. Frequency response of an unweighted 1.83 GHz multilevel narrow gap filter. Solid line is experimental results and dashed line is theory using a transmission line equivalent circuit model [5].

electrode duty on the device parameters. Morgan finds that as the duty factor approaches 100%, the coupling factor increases to its maximum value [6]. For the 2 electrode per wavelength transducer, the normalized center frequency conductance is given as

$$G_a(f_0,\eta) = G_{a0} * \sin(\tfrac{\pi}{2}\eta)$$

where G_{a0} is the maximum center frequency conductance and η= electrode duty factor This relationship is valid for all η. However, as the duty factor approaches 100% the inter-electrode capacitance increases rapidly. The normalized capacitance is approximately given by

$$C_t = C_{t0} * \frac{1.382}{(1-\eta)^{.19}} \quad \text{for} \quad .9 \le \eta \le .99$$

where C_{t0} is the capacitance for $\eta = .5$ A plot of the normalized conductance and capacitance is shown in Fig 6 for single level NG transducers. Since the conductance is approximately constant for narrow gaps, the NG gives rise to an increase in the transducer electrical Q. The Q is inversely proportional to available bandwidth at a given

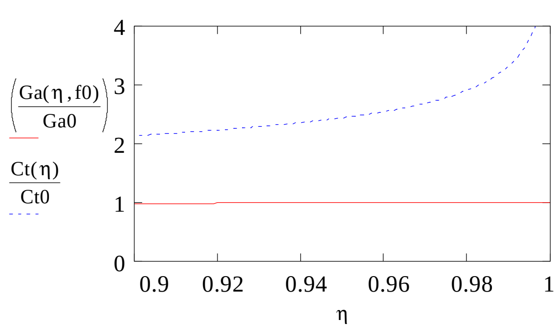

Figure 6. Normalized transducer conductance and capacitance for $.9 \le \eta \le 1$.

insertion loss level; this means that the NG transducer has a narrower achievable bandwidth when compared to a conventional transducer geometry.

The multilevel transducer has a more complicated geometry which must also be modeled. The effect of the dielectric layer is to decrease the effective coupling into the SAW since the electric fields must penetrate the dielectric layer before entering the substrate, as well as to modify the effective inter-electrode capacitance and Q value. The coupling factor can be reduced by a factor of 2 or more depending on the design constraints which include fabrication reliability of the thin film. Typically the dielectric film is 2% or less of a wavelength thickness and as thin as possible to maintain good coupling while ensuring good step coverage and uniformity over the electroded areas of the transducer.

Materials Considerations

The standard single crystal wafers for SAW include lithium niobate, lithium tantalate and quartz. It would be highly desirable to find new materials which have a higher velocity while still maintaining a high coupling coefficient and low temperature coefficient of delay TCD). Some new single crystal substrate materials currently being investigated include lithium tetraborate (LBO), langasite and langanite, gallium arsenide, berlenite and others. Of these, only LBO offers significant promise as a new material for high frequencies since it has a higher coupling coefficient (~1%) and velocity (~3500 m/sec) than ST quartz with a moderate TCD [7].

In addition to single crystal materials, thin film layered materials are also under investigation. The materials studied include zinc oxide, aluminum nitride, lithium niobate and lithium tantalate, diamond, sapphire, silicon dioxide and silicon nitride. The non piezoelectric films are being studied for intermediate layers for crossovers or multilayer transducers, overlays for passivation and waveguides, and substrate TCD adjustment. Multilayer composites consisting of a substrate material and multiple layers of dielectric and piezoelectric can form a high velocity material with desirable characteristics. The ZnO/diamond/Si substrate is very interesting since it has the highest wave velocities (~10,000 m/sec) reported to date, can have coupling in the 2-5% range, and may ultimately provide device integration in the future [8]. The diamond velocity is 2.5 times faster than YZ $LiNbO_3$ which is extremely significant for high frequency applications. These structures also offer new challenges in analysis and design due to velocity dispersion, and complications in fabrication/manufacturing due to the multiple material structure and film thickness tolerance issues.

New Types of Waves

The most widely studied wave has been the surface acoustic (SAW) or Rayleigh wave. This wave is trapped within one wavelength of the crystal surface and is easily tapped by a transducer at the surface. There are also other types of waves which have different particle motion and associated wave characteristics and are trapped near the substrate surface (although they are not the Rayleigh wave mode). These types of waves include the shear waves and the high velocity pseudo (HVP) SAW [9]. These waves typically penetrate further into the bulk than the Rayleigh mode and can have velocities nearly twice that of the SAW since they are in a stiffer substrate environment. New modes are of great interest due to the higher frequency achieved for a given line resolution and often have a higher coupling coefficient than their SAW counterparts for a given transducer structure. An excellent review of the HVP SAW is presented by ca Cunha [9]. He shows that these modes can exist on all the common SAW substrates which include lithium niobate, lithium tantalate, lithium tetraborate, quartz and gallium arsenide. As an example, the HVP SAW on 41^0 $LiNbO_3$ has a velocity of 8,314 m/sec compared to YZ $LiNbO_3$ which has a SAW velocity of 3,488 m/sec.

Conclusion

Research and development continues in all of the fundamental SAW technology areas. Promising results in new SAW transducer structures and materials presented indicate the possibility of higher frequency acoustic devices for the future. In the next few years, practical, manufacturable SAW devices may be realized at frequencies exceeding 3GHz.

References

1. K. Yamanouchi, H. Odagawa, T.Meguro, Y. Wagatsuma and K. Yamamoto, "Nano-meter electrode fabrication technology using anodic oxidation resist and application to 20GHz-range SAW devices," Proc. IEEE Ultrasonics Symposium, pp. 1263-1266, 1993.
2. K. Yamanouchi, T. Meguro and K. Matsumoto, "New electrode separation technology using anodic oxidation technology and application to SAW interdigital transducers," IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, Vol. 39 No. 3, pp. 447-452, 1992.
3. N. Sakairi, S. M. Richie, K. J. Casey, and D. C. Malocha, "Characteristics and fabrication of a narrow gap transducer," Proc. IEEE Ultrasonics Symposium, pp. 143-146, 1992.
4. K. Yamanouchi, T. Meguro and K. Matsumoto, "New electrode separation technology using anodic oxidation technology and application to SAW interdigital transducers," IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, Vol. 39 No. 3, pp. 447-452, 1992.
5. J.H. Hines, High Frequency Low Loss Surface Acoustic Wave Filters, Ph.D. dissertation, University of Central Florida, 1996.
6. D.P. Morgan, *Surface Wave Devices for Signal Processing*, *Elsevier*, New York, 1985.
7. N.M. Shorrocks, R.W. Whatmore, F.W. Ainger, and I.M. Young, "Lithium Tetraborate-A new Temperature Compensated Piezoelectric Substrate material for Surface Acoustic Wave Devices", Proc. IEEE Ultrasonics Symposium, pp 337-340, 1981.
8. H. Nakahata, A. Hachigo, S. Shikata, and N. Fujimori, "High Frequency Surface Acoustic Wave Filter Using ZnO/diamond, Si Structure", Proc. IEEE Ultrasonics Symposium, pp. 377-380, 1992.
9. M.P. da Cunha, "High Velocity Pseudo Surface Wave (HVPSAW): Further Study", IEEE Ultrasonics Symposium, to be published, 1996.