Bulk Acoustic Wave Devices – Why, How, and Where They are Going

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ABSTRACT

Bulk Acoustic Wave (BAW) devices have been researched for several decades with great promise and are now rapidly growing in the marketplace, migrating from the military and high-end industrial markets into consumer wireless applications. Although BAW devices can be fabricated for use below 500 MHZ, the economic sweet spot for BAW is above 1.5 GHz. At 1.8-1.9 GHz, BAW ladder filters become very competitive against Surface Acoustic Wave (SAW) devices with improved performance and against ceramic filters with significant size reduction in handset designs. The highest penetration for BAW devices has been in the area of PCS and UMTS duplexers. The cost of BAW devices has been reduced to the point of being very competitive with existing filter and duplexer technologies. The future of BAW devices will show migration to higher frequencies and potential integration with active integrated circuits.

OVERVIEW

Radio frequency (RF) filters are key components in any wireless system and as these systems continue to be miniaturized, the pressure on filter technology to shrink as well without compromising performance continues. Handheld systems and their associated volumes have generated strong interest in filter technologies that show promise for lower cost and smaller size. Surface Acoustic Wave (SAW) technology has long provided high performance RF filters with small form factors while showing a continuously declining cost structure. However, as requirements have increased, applications at the higher handset frequencies run up against the capability of conventional SAW structures. BAW devices provide the capability of addressing the frequencies at 1.8 GHz and above while hinting at the promise of a low cost structure competitive with SAW. Figure 1 shows the general space of mobile commercial applications and where the technology crossover occurs as SAW moves to temperature compensated SAW (TC-SAW) and on to BAW devices. BAW devices have the promise of the smallest form factor married with high performance. This and the capability to process BAW filters and duplexers in a silicon wafer fab makes this technology quite compelling.

BAW FUNDAMENTALS

The basic element of the BAW device is the thin film resonator which is very similar to the basic quartz crystal scaled down in size [1,2]. A piezoelectric film is sandwiched between two metal films as shown in Figure 2. The equivalent Butterworth/VanDyke circuit model consists of a fixed structure capacitance in parallel with a frequency dependant electro-mechanical resonant circuit.

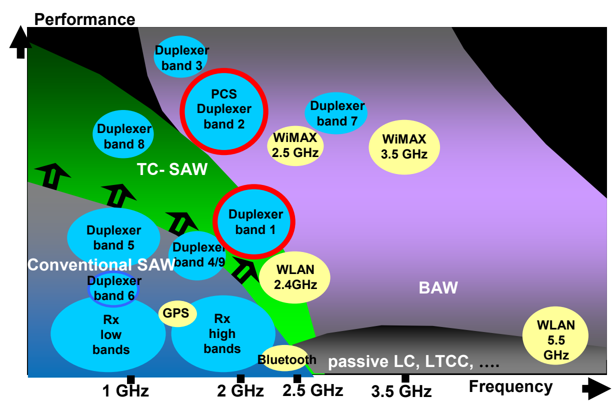
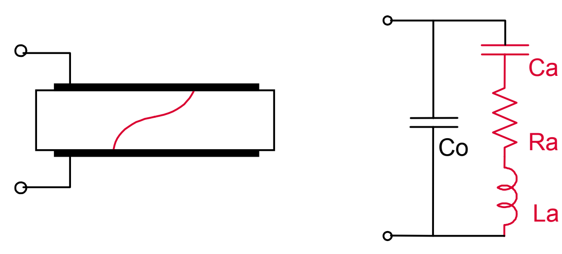


Fig 1. Mobile commercial applications mapped to SAW, temperature compensated SAW and BAW technologies.



a) b)

Fig. 2. BAW Resonator a) Cartoon BAW cross-section b) Butterworth/VanDyke equivalent circuit.

The key properties of the BAW resonator are set to store the maximum acoustic energy within the structure, achieving a high electrical Q. The boundary conditions outside of the metal films must maintain a very high level of acoustic reflection with vacuum being the ideal interface. The materials chosen must optimize both electrical and mechanical properties. Although there are many piezoelectric materials, AlN has been established as the best balance of performance, manufacturability, and reliability. The metal films range from Al, which offers the best performance with limited power handling to Mo or W which offer high power handling with the cost of additional resistivity losses. The resonant frequency is inversely proportional to the film thicknesses with both the metal and piezoelectric dielectric contributing to the resonant point.

The most common BAW filter is a ladder configuration consisting of series resonators with parallel resonator "rungs" shown in Figure 3. The shunt elements are tuned to a slightly lower frequency to achieve the bandpass function. The out of band rejection is set by the number of elements and the net capacitor divider. The more elements in the filter, the stronger the rejection will be but at the cost of increased insertion loss shown in Figure 4..

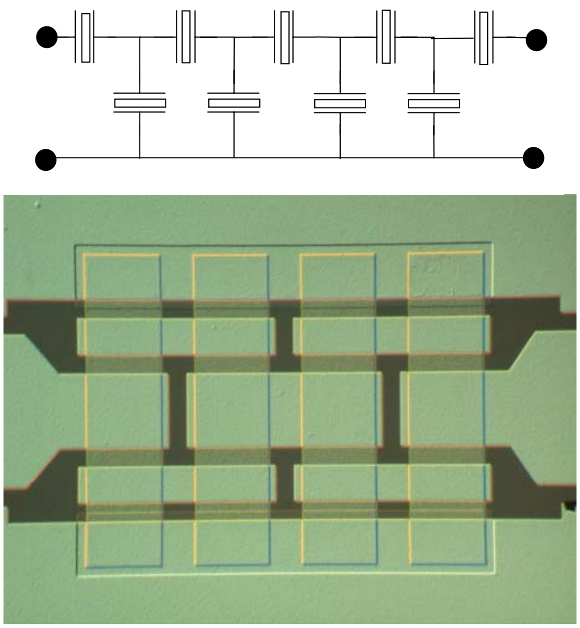


Fig. 3. Ladder filter schematic and die micrograph

DEVICE ARCHITECTURE

There are two common configurations of BAW architectures, Film Bulk Acoustic Resonator (FBAR) [3] and Solidly Mounted Resonator (SMR). The FBAR stays true to the fundamental concept of having free surfaces on both sides of the BAW resonator (Fig 5). The two common methods of creating an FBAR resonator film are to have a sacrificial support layer below the resonator that is removed late in the process to free the film. The other is to etch the substrate from the back of the wafer to the front surface creating the so called "pot hole" structure.

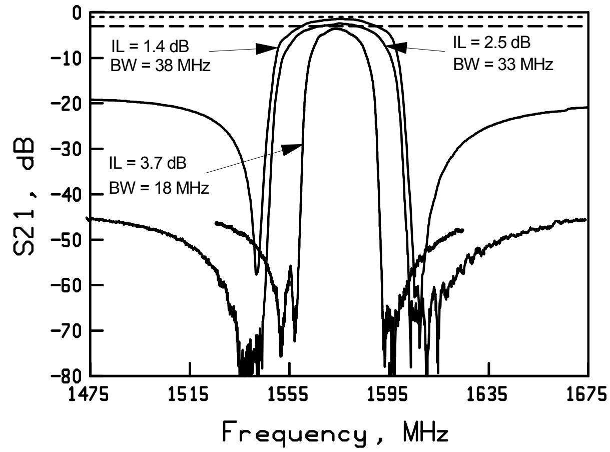


Fig. 4. Ladder filters passband responses. Three variants with tradeoffs of bandwidth, insertion loss and rejection (GPS L1)

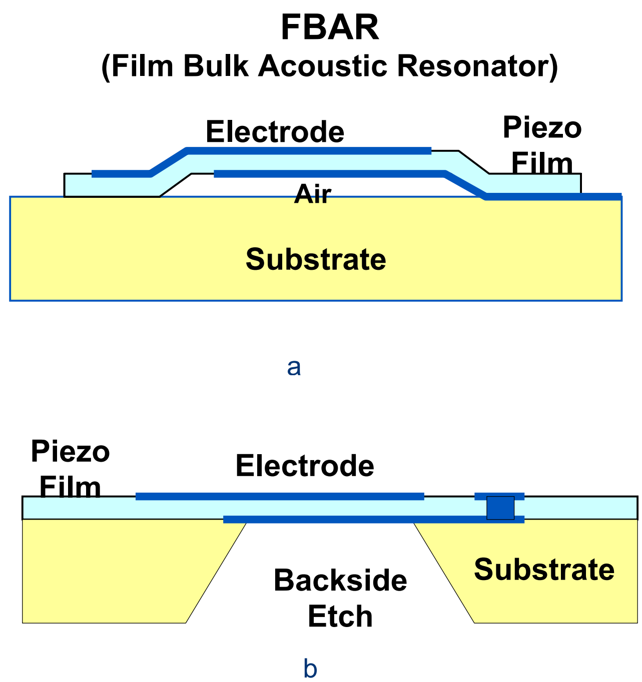


Fig 5. FBAR Cross-section. a) Sacrificial support layer b) Backside substrate etch

The SMR structure substitutes the free surface on the bottom of the resonator with a acoustic Bragg reflector shown in Figure 6. Alternating layers of differentiated acoustic velocity, ¼ wavelength in thickness, provides a reflectance approaching the performance of a free surface. The SMR structure offers advantages in fabrication and packaging but does compromise performance in Q as the acoustic mirror is not loss free.

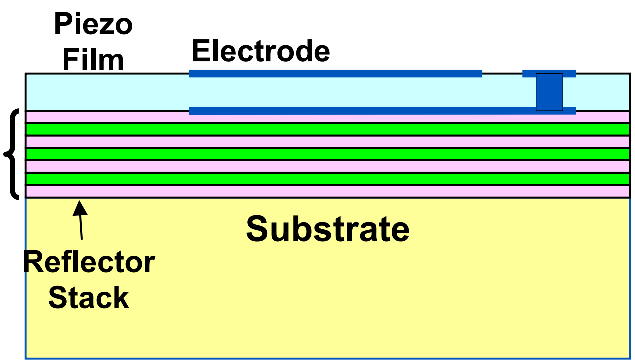


Fig 5. Solidly Mounted Resonator cross section

PROCESS ISSUES

The RF properties of the filter are directly related to the thicknesses and material properties of the thin films of the piezoelectric, dielectric and metal films. The fractional error allowed in the demanding handset filters are approximately 0.2%. Even the most advanced and optimized film deposition systems approach level of 1% and cannot achieve the required levels alone. These precise specifications are achieved in high volume and low cost with a successful marriage of optimized film deposition and direct write ion milling trimming algorithms based on electrical measurement feedback. The resonant frequency of the resonators can be adjusted upward by removing small amounts of the top layer film stack.

For all the difficulty in making the BAW filter the base substrate is not driven by any strong technological requirement. A variety of substrates have been used for BAW filters with the requirements more driven by basic fabrication constraints and economics. Quartz, glass, alumina, sapphire, and silicon have all been used successfully. For the volume wireless applications, high resistivity silicon is the material of choice for cost and compatibility with conventional processing equipment. Lithography is also an area of modest requirements for BAW devices. Most resonator structures are well over 1 µm in required dimensional fidelity.

The key film in the BAW stack is the AlN piezoelectric layer. This film must have a high level of crystal orientation to achieve the required level of K^2, the electrical-acoustic coupling coefficient. The AlN film is sputtered in specialized sputter chambers that have been developed to predispose the films to orient on the substrate. The initiation of the film growth and the surface the AlN is deposited upon are key process conditions that are carefully orchestrated and closely held.

ADVANCED STRUCTURES

The single resonator structure enables the construction of very effective filters in ladder and lattice configurations. However, more advanced BAW structures provide opportunities for an expanded range of filter properties.

The Stacked Crystal Filter (SCF) [4] is constructed with two resonators on top of one another (Fig 7). The two resonators work in concert, acting as a single resonator of the full thickness. The SCF has a narrow band frequency response with a shallower but eventually lower out-of –band rejection level (Fig 8). The SCF filter achieves the filter function with considerably smaller area than ladder filters. The SCF has some modest applications but is more important as the building block for a potent structure, the Coupled Resonator Filter.

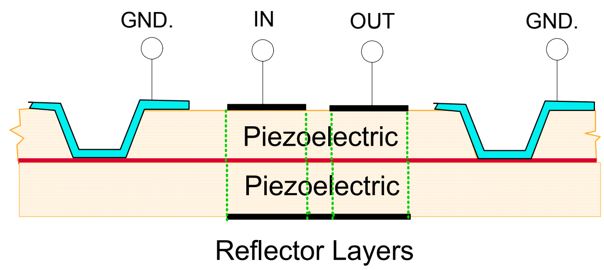


Fig 7 Stacked Crystal Filter (SCF) cross-section

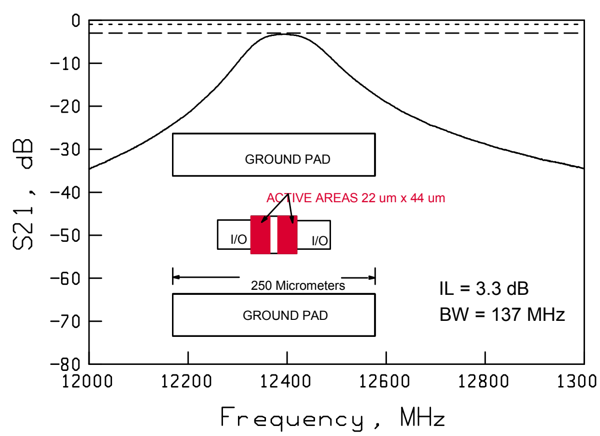


Fig. 8. Example Stacked Crystal Filter frequency response

The Coupled Resonator Filter is a more complex system that includes two stacked resonators with a series of decoupling layers in between (Fig. 9). The additional alternating layers of low and high acoustic velocity (similar to the reflector stack) are designed to allow partial coupling between the two resonators. This allows for much wider bandwidth filter responses (Fig. 10). With external matching inductors fractional bandwidths up to 25% can be realized.

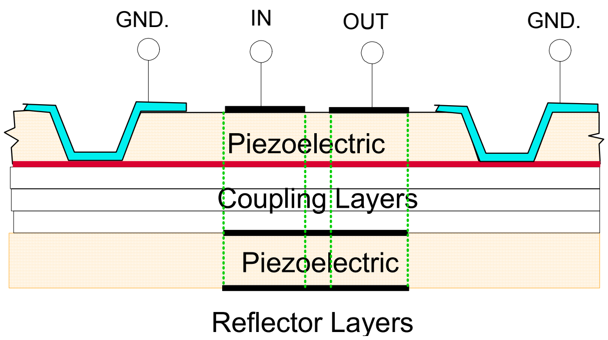


Fig 9 Coupled Resonator Filter (CRF) cross section

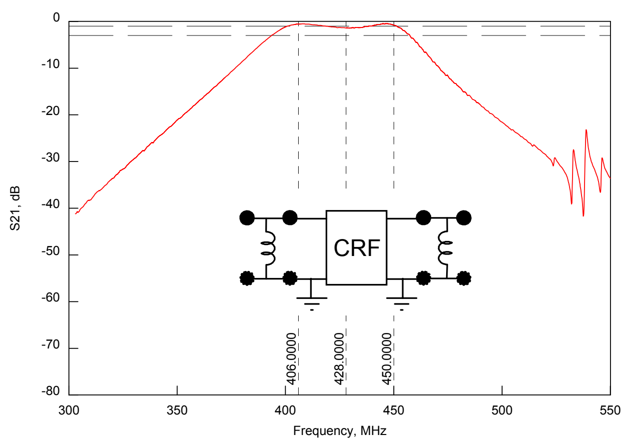


Fig 10. Coupled Resonator Filter – wide bandwidth filter with external matching inductors.

In the case of both the SCF and the CRF, the acoustic mirror used in the SMR architecture provides a non-obvious benefit. The SCF and CRF structures can allow many non-desired harmonic and spurious modes to occur due to the more complex structure. Although a very effective acoustic mirror for the frequency of design, the multi-layer reflector does have a finite bandwidth and acoustic modes that occur out of the reflector bandwidth are suppressed. These spurious modes are much more difficult to suppress in the FBAR structure.

INTEGRATION

Due to the intrinsically small size and the compatibility with silicon processing, the holy grail of BAW development has been the potential monolithic integration of BAW filters with mixed-signal silicon transceivers [5]. In the 1990s many of the large semiconductor companies initiated BAW integration development projects. Although integration demonstrations were achieved though innovative technology, several issues prevented commercialization. BAW processes, even at their current high maturity, have yield fallout significant enough that produces an unacceptable cost when compounded to the silicon yield. In addition, as multiple frequencies and modes in handset proliferate, the ever increasing filter count compounds the stacked yield problem. Most companies have either abandoned these programs or refocused them toward producing discrete BAW filters. As of 2007, BAW integration is limited to system-in-package applications such as front-end modules and radio modules.

CONCLUSIONS

BAW filters and duplexers are a growing presence in high volume mobile communication devices. The performance and size advantage for frequencies greater than 1.5 GHz have made it the emerging technology over SAW devices. As higher frequency WiMax and WiLAN devices proliferate, demanding the same performance/size/cost trade-offs as handsets, the market for BAW filters shows great promise for continued growth.

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ACRONYMS

RF	Radio Frequency
BAW	Bulk Acoustic Wave
SAW	Surface Acoustic Wave
TC-SAW	Temperature Compensated SAW
FBAR	Film Bulk Acoustic Resonator
SMR	Solidly Mounted Resonator
SCF	Stacked Crystal Filter
CRF	Coupled Resonator Filter
GPS	Global Positioning Satellite
PCS	Personal Communication Service
UMTS	Universal Mobile Telephone Service