Bulk-Acoustic-Wave Filters: Performance Optimization and Volume Manufacturing

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Abstract — **Performance parameters of BAW devices are reviewed and ranked corresponding to their importance for RF-filters in mobile phone applications. The most important performance parameters – such as resonator bandwidth and Q-values - critically depend on the quality of the piezolayer and other relevant layers in the acoustic stack. The design of the complete layer stack in a Solidly Mounted Resonator (SMR) concept in combination with a proper design of lateral resonator-boundaries will be revealed to be extremely important for the suppression of spurious resonances. Challenges in manufacturing of BAW filters will be briefly reviewed. Examples of state-of-the-art in BAW filters in production and ramp-up status will be presented.**

I. Introduction

Bulk-Acoustic-Wave (BAW) respectively Film-Bulk-Acoustic-Resonator (FBAR) filters are determined to replace conventional RF-filters in the mobile phones as they have now evolved in performance beyond SAW filters and can be manufactured in a very cost competitive way using standard IC manufacturing.

All mobile phones need RF-filters to protect the sensitive receive (Rx) path from interference by transmit (Tx) signals from other users and noise from various RF sources. The minimum Rx signal strength at which a phone must still operate can be 120 dB lower than the strength of interfering signals. No affordable preamplifier will generate sufficiently small intermodulation effects to deal with such a situation. Highly selective RF-filters between antenna and preamplifier make sure that only signals from the correct Rx band will be amplified. The frequency bands allocated to mobile phone systems can vary from country to country, in general they are in a range of 400 MHz to 2.2 GHz. The bandwidth is typically 20 to 75 MHz. The Tx band is located below the Rx band but only with a gap of 20 MHz in between. Within this narrow transition range of 20 MHz an Rx filter should change from >15 dB attenuation at the upper edge of the related Tx band to < 3 dB insertion loss at the lower edge of the Rx band. In order to achieve such steep filter skirts the filter elements must have extremely low losses respectively high Quality factors, $Q \geq 400$ for the reactance elements is mandatory. Selective RF-filters are also needed in the Tx path of a mobile phone as regulations forbid to emit RF-power outside the specified band. These Tx filters take care that the power amplifier will not amplify noise and tones at frequencies outside the Tx band. The European GSM phone system works in a time multiplexed mode with timeslots reserved for Rx and Tx. The antenna in a GSM phone is switched between Rx and Tx path using an RF-switch. Due to this switching the receive and transmit signals are relatively easy to isolate from each other inside a GSM phone. In contrast to this the CDMA and W-CDMA systems used in USA and the 3rd Generation (UMTS) standard in Europe work in full duplex mode, meaning that the phone receives and transmits simultaneously. This kind of operating mode enforces the use of a so called antenna-duplexer which consists of highly selective filters for receive and transmit bands and makes sure that as little power as possible from the power amplifier ends up in the Rx path and that the Rx signals from the antenna are guided to the preamplifier with little losses. Duplexers are challenging to make with SAW filters because they need to handle up to 2 Watts transmit power and must be able to maintain proper operation at elevated temperatures which occur due to self heating effects.

BAW filters serve these mobile applications very well because they offer excellent Q-values up to 1500, they can handle power levels up to several Watts and the temperature coefficient of frequency is significantly lower than in SAW filters.

II. Processing of SMR type BAW devices

Similar to [1] but in contrast to [2] we decided to use the Solidly Mounted Resonator (SMR) BAW concept because it offers excellent mechanical robustness and simplifies

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wafer-handling, dicing and packaging considerably as compared to membrane BAWs.

Processing of the SMR type BAWs to be discussed here is done on standard Si-wafers utilizing a 6 inch BiCMOS manufacturing facility. All processes are 100% compatible to CMOS in terms of thermal budget and contamination issues. Only 5% of the equipment needed is dedicated to BAW-processing.

In the sequence of processing several µm of Plasma-Oxides will be built up and therefore a strongly tensile LPCVD Nitride for stress compensation is deposited first. The layers used for the acoustic mirror are two pairs of CVD Tungsten and Plasma-Oxide. The main advantage of this mirror type is the excellent ratio of acoustic impedance (≈ 7) which allows to achieve 99.98% reflectivity with just 2 pairs of λ/4 layers. Due to the high impedance ratio the acoustic energy decays quickly within the mirror layers. This reduces the acoustic energy stored outside the active resonator layers and helps to maintain excellent resonator bandwidth. The Tungsten used in the mirror necessitates a patterning of the mirror because electrically connected mirrors of neighboring resonators would generate excessive parasitic coupling. The patterning of the complete mirror is done in an efficient way using a novel process we call "multi-CMP". Only one lithography step is required to pattern all layers at once. Similar to a "Damascene" processes for Cu-interconnects in advanced IC processes we first deposit all mirror layers into a recess that was etched into a Plasma-Oxide layer. The recess defines the size of the mirror regions. In step two we polish down the Oxide and Tungsten layers sub-sequentially by altering the CMP conditions in order to avoid dishing and achieve selective removal of Oxide and Tungsten. After "Multi-CMP" the wafers are perfectly

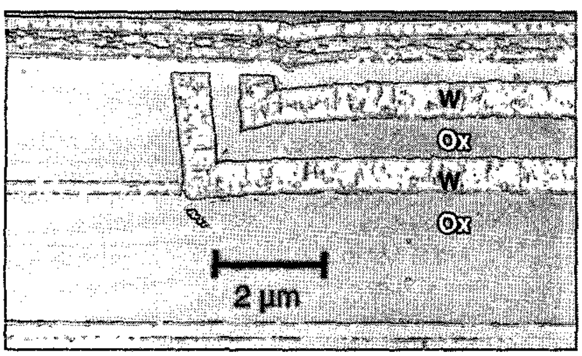

Fig. 1. SEM cross-section of 2-pair Tungsten/Oxide acoustic mirror made with Infineon's patented "multi-CMP" process. Picture only shows the edge region of mirror-region which extends far to the right side.

planar which means excellent starting conditions for the build-up of the active resonators consisting of bottom-electrodes, piezolayer, top-electrodes and additional layers.

For ladder type BAW filters two sets of resonators at different frequencies are required. An auxiliary metal layer for the shunt resonators is deposited on the top-electrode in order to shift frequency down by approximately 60% of the required filter bandwidth.

Infineon's BAW process features a thin passivation layer on top of the resonators in order to avoid frequency shifts and degradation of resonator performance in humidity and other harsh environmental conditions. This particular advantage allows to package our BAW devices in non-hermetic (low cost) plastic packages.

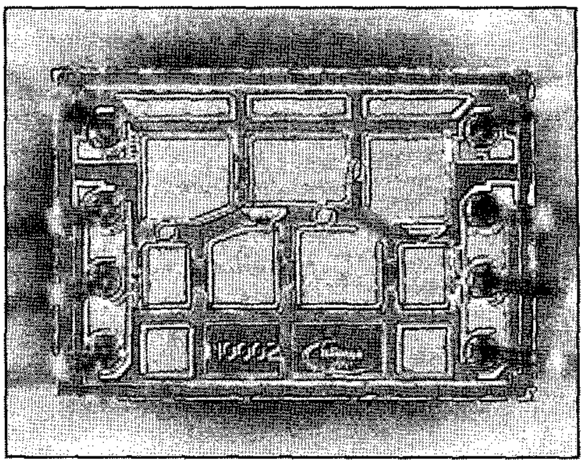

Fig. 2. 3.5 stage ladder BAW filter for DCS/PCN1800 Rx (1805 to 1880MHz). Chip-size: (0.6 x 0.9) mm², active area 45%.

III. PERFORMANCE PARAMETERS OF BAWS

One of the prerequisites for a BAW filter for mobile phone applications is to achieve sufficient resonator bandwidth respectively sufficiently large *effective coupling coefficient* k_{eff}^2 for the resonators,

$$k_{eff}^2 = \frac{\pi^2}{4} \frac{f_p - f_s}{f_p},$$

where f_s and f_p denote the resonator series and parallel resonance frequency. The most important ingredient for large k_{eff}^2 is an excellent piezo-layer, which means high c-axis orientation of the cristallites and little contamination. However, all the layers outside the piezo-layer represent an acoustic load that can – if properly chosen – increase

k_{eff}^2 but if not properly chosen dramatically decrease coupling [3].

From a modeling point-of-view k_{eff}^2 is well understood, since its behaviour is dominated by the main lateral resonance in the layer stack. Therefore, the dependency of k_{eff}^2 on the thickness and material parameters of the various layers in the FBAR stack is well described by the (1-dimensional) Mason-model [4]. Once a certain layer stack of the FBARs has been derived (typically from manufacturability considerations as described in sec. II), the optimization of the various layer thicknesses with respect to k_{eff}^2 can be achieved by wrapping a numerical optimizer around the Mason-model which maximizes k_{eff}^2 while the correct resonance frequency of the stack is used as a constraint.

The second important parameter is resonator *Q-value* which can be derived from the phase steepness of the resonator impedance plot at f_p and f_s. For most applications *Q*-values above 400 will be required to meet typical specifications for insertion loss and steepness of the filter skirts, whereas certain mobile phone standards like e.g. US-WCDMA necessitate Q>1000.

In order to optimize resonator-Q, various sources for energy loss must be minimized. This amounts to keeping ohmic series resistances of electrodes and interconnects below approx. 500mΩ/resonator, to minimize vertical acoustic energy leakage through the bragg-reflector by choosing the proper materials and number of mirror-pairs and to optimize lateral acoustic energy trapping. This last point is to our experience the most critical point in FBAR optimization since a good acoustic energy trapping on one hand increases resonator-Q but on the other hand also increases the spurious mode contribution to the resonator impedance characteristic. Spurious modes arising from lateral plate wave resonances in the active area of the resonator contaminate the filter response, especially in the pass band. A method to effectively deal with these unwanted vibrational modes is described in [5]. This principle relies on the modification of mechanical boundary conditions at the resonator edge to achieve a displacement profile of the main resonance that closely matches the driving force of the constant electric field. In practice this boundary condition matching is achieved by manufacturing a narrow border region having different acoustic properties – e.g. different resonance frequency - at the periphery of the resonator. The efficiency of this method can be seen in fig. 4.

Further parameters of significant importance are temperature coefficient of frequency TCF, efficiency of heat dissipation, resonator size at a given impedance level and ESD-robustness of the device.

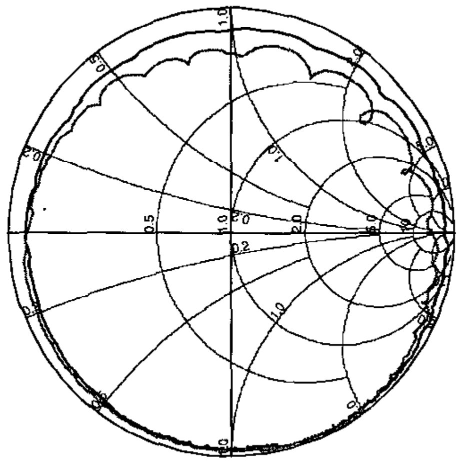

Fig. 4. Using a correct border region results in almost perfectly smooth resonator response. Grey: no border matching, black: proper border matching.

IV. Volume Manufacturing of BAWs

Even though prototype BAW resonators may finally show the desired performance there are difficult problems to solve before manufacturing in large volumes will be feasible. The first challenge is to achieve the required quality of the piezolayer on a regular basis. There is usually no margin to loose coupling coefficient. The second challenge is to hit the right frequency on more than just a few spots on a wafer. The resonance frequency of a BAW is determined by the thickness of the piezolayer and the neighboring layers. The required tolerance for the resonance frequency is around ±0.1% for typical mobile phone filters which translates into a thickness tolerance in the same range. These extreme thickness tolerances can not be met by standard tools for semiconductor processes which typically offer 5% accuracy. Even if the run-to-run variations can be optimized to meet a tighter specification there is still a big problem regarding thickness uniformity across the wafer to be solved. An efficient method of frequency trimming is therefore mandatory to achieve satisfying yields >80%. Infineon's trimming method corrects run-to-run deviations as well as uniformity problems by using localized processing of wafers. High throughput and extremely tight frequency distributions are achieved as is shown in fig. 5. A yield-map is shown in fig. 6. Fig. 7 shows the insertion loss and the voltage standing wave ratio of a DCS/PCN1800 Rx BAW filter.

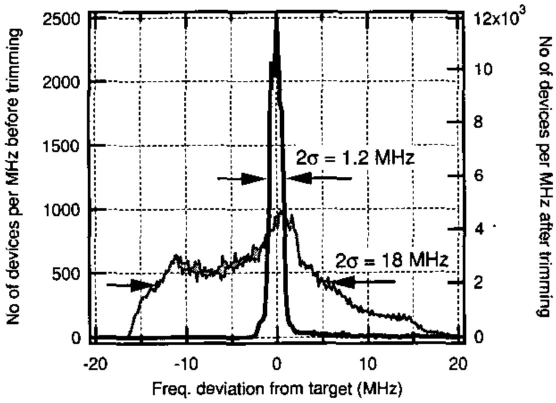

Fig. 5. Frequency distribution on a typical productive wafer before (grey) and after trimming (black).

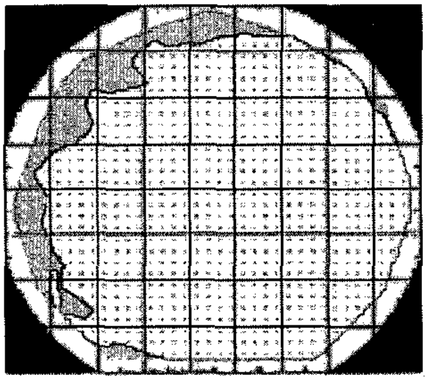

Fig. 6. Yield-map of a BAW filter for DCS/PCN1800 Rx as shown in fig. 2. White are good dies, dark grey are fail dies. Light grey are dies outside testing area.

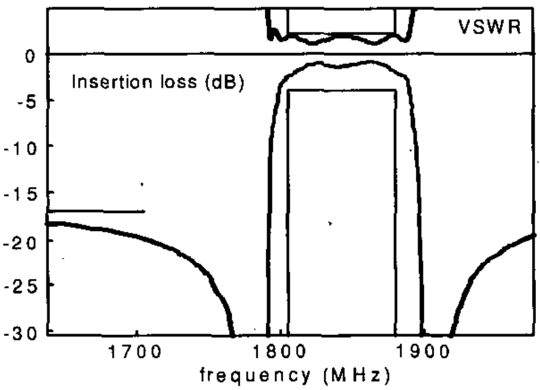

Fig. 7. Performance of a DCS/PCN1800 Rx BAW filter in production at Infineon.

V. Conclusion

BAW Filters are able to beat SAW-filters in all performance parameters and can replace ceramic filters in duplexer applications. The breakeven in performance was achieved when we managed to make resonators with an effective coupling of k_{eff}^2 of 6.5 % and push resonator Q-values well above 500. This results in improved insertion loss and steeper filter skirts. The use of acoustic mirror allows to reduce the temperature coefficient of frequency (TCF) to –22 ppm/K which is clearly better than in SAWs. Chip-size is at least a factor 2 smaller for 1.8 GHz filters. ESD robustness is superior. Power-handling up to 3 Watt is feasible even above 2 GHz which makes BAW filters an ideal replacement for ceramic filters in duplexer applications. The figure of merit (Q . k_{eff}^2) for the typical resonators we manufacture is (900 . 0.067) = 60.

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