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Solidly mounted BAW resonators with layer-transferred AlN using sacrificial Si surfaces

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ABSTRACT

We present a new method to manufacture solidly mounted bulk acoustic wave resonators. This new process introduces the use of wafer bonding techniques and sacrificial surface removal to manufacture solidly mounted resonators having special properties. With the proposed process, Aluminum Nitride (AlN) thin films are obtained having exceptional *c*-axis crystal orientation with XRD rocking curve FWHM of 1.36° and material electromechanical coupling constant of 6.8% exceeding that of the epitaxial AlN electromechanical coupling constant. Fully functional single-mask resonators were successfully fabricated with this process working around 2.35 GHz and enjoying *Q*-values as high as 1300.

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1. Introduction

Filters based on bulk acoustic wave (BAW) resonators have gained significant interest for many RF applications. In comparison to surface acoustic wave (SAW) and ceramic filters, they offer superior performance (higher power handling and better temperature coefficient of frequency) and decisive advantages in chip size and processing costs, respectively [1]. Aluminum Nitride (AlN) is currently widely used as the piezoelectric material in the fabrication of all commercial BAW resonators. In order for BAW based filters to meet the challenging specifications (high *Q*-values with a wide enough bandwidth), the sputtered AlN thin film must show a high quality of crystal orientation. In this work, we introduce a new process to transfer high quality AlN thin films grown on 8-in. prime (100) Si wafer surfaces into a fully functional solidly mounted BAW resonator. The properties of the transferred layer are examined by X-ray diffraction (XRD), electron microscopy, and wafer-level RF electrical and temperature measurements.

2. Solidly mounted BAW resonators

The typical structure of a solidly mounted BAW resonator (SMR) is shown in Fig. 1. The active piezoelectric AlN layer is placed between two metal electrodes and mounted on top of an acoustic mirror. The acoustic mirror comprises of alternating layers of high and low acoustic impedance materials. The acoustic energy is prevented from leaking outside the device by means of the total acoustic reflection from the air interface with the top layer of the device (air has a negligible value for acoustic impedance, usually acoustically treated as vacuum with zero acoustic impedance), and by the high acoustic reflection of the acoustic mirror under the bottom electrode [2]. The acoustic mirror is designed to achieve high acoustic reflection around the operating frequency range of the device. In order to understand the role of the mirror, consider the acoustic impedance seen at the end of one layer of thickness t_n and characteristic impedance R_n where the other end is terminated by an impedance Z_{n+1}. The equation for this impedance is

$$Z_n = R_n \cdot \frac{1 - j\left(\frac{Z_{n+1}}{R_n}\right)\cot\frac{2\pi t_n}{\lambda_n}}{\frac{Z_{n+1}}{R_n} - j\cot\frac{2\pi t_n}{\lambda_n}} \tag{1}$$

At the frequency where $t_n = \lambda_n/4$ (quarter wave length condition), Eq. (1) reduces to:

$$Z_n = R_n \cdot \frac{R_n}{Z_{n+1}} \tag{2}$$

Alternating low and high acoustic impedance, starting with low acoustic impedance under the bottom electrode results in very small value for the acoustic impedance seen under the

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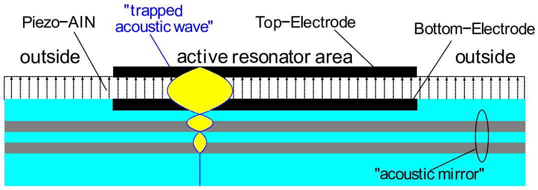

Fig. 1. Solidly mounted bulk acoustic wave resonator.

bottom electrode, the value decreases with the increase of alternating layers, and the reducing factor is the ratio between the high and low acoustic impedances. As a result, a very low acoustic impedance is experienced under the bottom electrode when looking into the mirror. Silicon dioxide is used as the low acoustic impedance material and tungsten is used as the high acoustic impedance material.

At the series resonance frequency (longitudinal mechanical resonance frequency) f_s, the impedance of the device attains its minimum, and it attains its maximum at the parallel resonance frequency (mechanical antiresonance frequency) f_p. f_p is mainly determined by the thickness of the piezoelectric layer, as well as by the electrodes and additional layers in which mechanical energy is stored (mirror layers, passivation layers, etc.). f_s is related to f_p through the effective coupling coefficient k_{eff}^2 given in percentage (%). It is defined as [3]

$$k_{eff}^2 = \frac{\pi}{2}\left(\frac{f_s}{f_p}\right)\cot\left(\frac{\pi}{2}\frac{f_s}{f_p}\right) \tag{3}$$

k_{eff}^2 is a key parameter, and it determines the bandwidth of BAW based filters. Achieving as high k_{eff}^2 as possible is usually a goal for BAW filter designers.

For a properly designed resonator layer stack, the limiting factor of k_{eff}^2 is the piezoelectric layer material electromechanical coupling constant (k_{mat}^2) which depends on the quality of the piezoelectric layer and is defined by:

$$k_{mat}^2 = \frac{e^2}{c^E \epsilon^S} \tag{4}$$

where e, c^E, and ϵ^S are the piezoelectric stress constant, stiffness at constant E field, and dielectric constant at a constant strain, respectively.

The quality of the deposited piezoelectric layer is usually investigated by X-ray diffraction (XRD). The full-wave half maximum (FWHM) of the rocking curve (RC) around the c-axis or (002) orientation normal to the substrate is the most commonly used figure of merit for the crystal quality of AlN films. Higher quality AlN films show smaller FWHM values.

It is evident that the layer on which AlN is deposited has a strong influence on the AlN quality [4]. High c-axis orientation of AlN on smooth crystalline surfaces such as Sapphire [5] and Silicon [4] has been reported. It is, however, not reported so far how a useful resonator can be made from these AlN thin films. A mechanism is needed to separate the AlN layer from the crystalline surface and transfer it into the resonator layer stack.

3. Processing and fabrication

Fig. 2 shows the process sequence for realizing the proposed solidly mounted BAW resonator. The sequence of material deposition is different from the conventional way; the process starts with the direct deposition of AlN on prime (100) Si wafer (Fig. 2a). The Si surface is smooth and its crystallinity is best suited to grow highly c-axis oriented AlN. The Si wafer acts as a sacrificial growth surface for the AlN to improve its growth quality and will be removed later on. The bottom electrode is then deposited on top of the AlN (Fig. 2b) followed by the deposition of the mirror layers (Fig. 2c). The deposited stack is then transferred onto the top of a carrier glass wafer (Fig. 2d) and the Si wafer is completely removed exposing the AlN surface for the deposition and structuring of the top electrode (Fig. 2e and f).

As a proof of concept, solidly mounted resonators are manufactured with the aforementioned processing steps. Aluminum is used for the electrodes, where a thin tungsten layer is deposited directly onto the AlN to enhance the effective coupling coefficient of the resonator while acting as part of the bottom electrode [6]. Using a single-mask approach [7], only the top metal layer is structured. Top electrodes with an area of $300 \times 300\ \mu m^2$ are surrounded by the rest of the top metal which forms a ground plane. The area of the ground plane is orders of magnitude larger than the top electrode area, and hence, the capacitance between the ground plane and the unstructured bottom electrode is large and can be considered as an AC short-circuit at the resonator frequency range of interest. With this single-mask approach, the resonator can be RF probed from the top metal layer without making contacts to reach the bottom electrode. The final resonator is shown in Fig. 3. The wafer is bonded to a glass carrier with a glue and a thermal release foil. A cross section of the solidly mounted resonator is shown in Fig. 4.

This approach provides several advantages compared to the usual method of depositing the AlN film onto the bottom electrode:

- Fig. 4 shows that the AlN/W interface is a uniform one. This comes from the fact that W is deposited on the AlN and not vice versa. In the conventional way, deposition of the W must come first. The surface of the deposited W layer is rough and must be treated with chemical–mechanical polishing (CMP) before AlN deposition. In our process, there is no need to CMP the W of the bottom electrode.
- The AlN exposed surface in Fig. 2e is the surface on which the AlN deposition has started. Deposition usually starts with a nucleation layer and then the growth is favored in the c-axis orientation. The material coupling constant of the nucleation layer is lower than that of the highly oriented bulk of the film. It is now possible to remove this layer. In the conventional way it is not possible to have access to this side of the AlN.
- Metal layers grow a native oxide in air. The thickness of this layer is hard to control [3]. In the conventional way, the bottom electrode must also be chemically treated to remove this oxide before depositing AlN. Otherwise, the native oxide will be inside the resonator active volume and will lead to reduction of coupling. In the process presented here, the native oxides are grown to the outside of the resonator, and hence no chemical treatment is necessary to remove the native oxide.
- The AlN is deposited directly on the Si wafer surface. Such surfaces have high degree of uniformity with inspected thickness tolerances. Directly depositing the AlN layer on such a flat surface ensures that the resulting layer has high thickness uniformity. This removes spurious modes arising near the resonance frequency in the working resonator. In the conventional process, even after applying CMP to the bottom electrode, thickness deviations across the resonator occur. As a result, resonators made with our process are expected to have better spectral purity than conventional resonators.
- This process allows the fabrication of novel BAW devices that are not possible to realize with the conventional process. For example, applying the aforementioned processing steps while using SOI wafer as the sacrificial wafer, and then removing the bulk silicon and the SiO_2 leaving the thin Si layer, implants

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