Picosecond Ultrasonics: Characterization of Single Crystal Piezoelectric Materials for Advanced RF Filters

AM: Advanced Metrology

S. Gibb
Akoustis Technologies, Inc.
Huntersville, NC USA
sgibb@akoustis.com

R. Mair, J. Dai, P. Mukundhan
Rudolph Technologies
550 Clark Drive, Budd Lake, NJ 07828
priya.mukundhan@rudolphtech.com

ABSTRACT

I. INTRODUCTION

State of the art smartphones now contain upwards of 60 filters and the filter market has been identified as one of the fastest growing segment of RF MEMS with an estimated CAGR of 35% [1]. Multiple growth drivers include shift from 2G/3G, device manufacturers shifting from Surface Acoustic Wave (SAW) filters to 4G/LTE Bulk Acoustic Wave (BAW) filters, increased bands and carrier aggregation, foray into new spectrum, higher frequencies, and move to 5G. Not surprisingly, with the move to higher frequencies and 5G, the complexity of the devices is expected to increase as well as the performance requirements. At these higher frequencies, SAW filters require smaller width and pitch of the interdigital transducers, which limits their performance. Hence, BAW is the primary technology employed above 2.5GHz. Film bulk acoustic resonators (FBAR) [2] and solidly mounted resonators (SMR) [3] are the dominant technologies currently utilized in BAW RF filters due to their small footprint, high Q factor and good power handling.

Traditional SMR and FBAR resonators are constructed using polycrystalline thin film piezoelectric aluminum nitride (AlN) on silicon substrates. These polycrystalline films are deposited via physical vapor deposition (PVD) on top of metal films. In contrast, the AlN films used in this work are single crystal films grown epitaxially via organometallic vapor phase epitaxy (OMVPE) on silicon carbide (SiC) substrates. SiC is an ideal substrate for high frequency RF applications due to its excellent thermal conductivity and low loss. Single crystal AlN films grown on SiC have significantly higher crystalline quality compared to polycrystalline AlN. A comparison of (002) x-ray rocking curve FWHM clearly shows 0.028° for single crystal material compared to 1.5° degrees for PVD AlN.

FBAR performance is determined by the thickness and acoustic property of the AlN layer. Metrology techniques employed for characterizing these properties must meet the sensitivity, accuracy and stringent repeatability requirements. In this paper, we discuss the single crystal BAW filter technology and the application of picosecond ultrasonic technology for monitoring thickness and sound velocity simultaneously.

II. METHODOLOGY

A. *Epitaxial Growth of single crystal AlN films*

The single crystal piezoelectric layers were grown on 150mm diameter, c-plane (001) oriented 4H polytype SiC substrates via OMPVE using trimethylaluminum (TMAl) and ammonia (NH_3) as precursors. The growth temperature was maintained at approximately 1200ºC during film growth. Prior to measurement, a 150 Å titanium (Ti) was deposited via e-beam evaporation on the epitaxial film (no additional processing was performed on the film to reduce thickness non-uniformity). This layer served as a transducer layer for generating acoustics.

B. *Measurement of Metal Films*

Picosecond ultrasonic technology (PULSE™), as implemented in the MetaPULSE® G system, is a non-contact, non-destructive pump-probe laser acoustic technique for the measurement of metal film thickness. It is a proven work horse in semiconductor fabs around the world. A 0.1ps laser pulse (pump) is focused to a small (~ $5\times7\mu m^2$) spot onto a wafer surface to create a sharp acoustic wave. The acoustic wave travels away from the surface through the film at the speed of sound. At the interface with another material, a portion of the acoustic wave gets reflected and comes back to the surface while the rest is transmitted. The probe pulse detects this reflected acoustic wave as it reaches the wafer surface. Knowing the speed of sound in the material, and the arrival time of the echoes, thickness is readily extracted using first principles technique. Information on film density and surface roughness, depending on the application, can also be obtained by fitting the damping rate of the echoes and the width of the echoes, respectively.

C. *Measurements on semi-transparent and transparent films*

In the case of transparent or semi-transparent films on silicon or other metal transducers, the opaque substrate absorbs energy from the pump pulse, launching a sound wave that travels up through the transparent film at the speed of sound. The strain causes a local change in the index of refraction of the film. The partial reflection of the probe beam from the moving sound wave, combined with the partial reflection from the film surface, leads to destructive and constructive interference at the detector. As a result of this time-dependent interference, the measured signal oscillates with a period, τ, from which the sound velocity (V) in the material can be determined by:

$$V = \frac{\lambda}{2n\tau\cos\varphi}$$

where n is the index of refraction, λ is the wavelength, and φ is the angle of refraction.

III. RESULTS

In figure 1, raw data plot of change in reflectivity versus time is shown. Sound velocity is calculated from the period of the AlN oscillations using the equation described in the preceding section. AlN thickness is obtained from the round trip travel time. Refractive index of AlN, obtained from optical techniques, is used to improve the accuracy of the calculated sound velocity. Shown in figure 2, is a 49pt uniformity map of a 1µm AlN film. Average velocity is ~107.6 Å/ps and average thickness is 1.03µm. Within wafer uniformity is better than 99% for both thickness and velocity. During process development, obtaining detailed information regarding wafer uniformity and edge profiles is important. Small spot size of the technique enables measurements ~0.5mm edge exclusion. Radial scans from AlN/SiC are presented in figure 3.

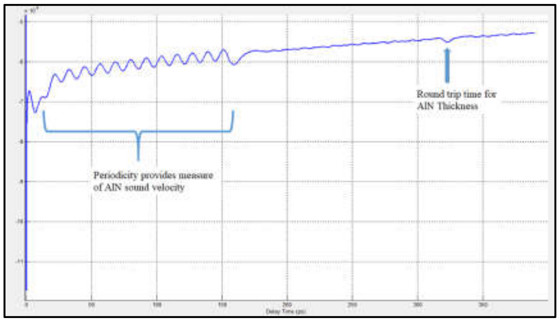

Fig 1. Raw data shows the periodic oscillations from AlN. Round trip time used for calculating AlN thickness

Accurate measurement of the film thickness and sound velocity is critical to the design of high performance RF filters as the resonant frequencies are directly related to these values. Site-level repeatability performance for both thickness and velocity is typically < 0.02% (1σ) for load/unload measurements. Sensitivity of the model to track the thickness and velocity (Table 1) was evaluated by depositing 4000-12000Å AlN films on SiC.

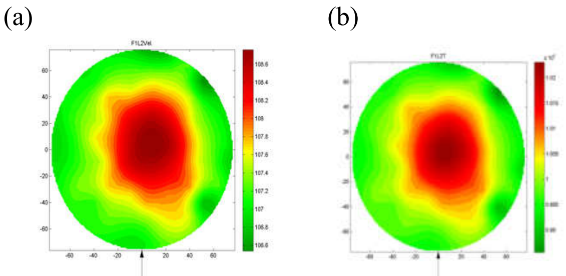

Fig 2. (a) AlN velocity and (b) thickness profiles across the wafer

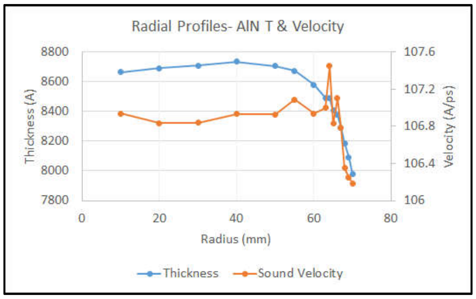

Fig 3. Radial profiles of thickness and velocity

Table 1. Average thickness and velocity from samples of varying thickness but similar acoustic properties

	Thickness (Å)	Velocity (Å)/ps
Sample 1	4425.2	106.08
Sample 2	8470.9	106.83
Sample 3	12454.4	106.99

Key Words: Picosecond Ultrasonics, Metrology, Single Crystal RF Filter, Piezoelectric

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REFERENCES

[1] MEMS Industry: RF is changing the game, Status of the MEMS Industry report (2017)

[2] R. Ruby, "Current Status, Future Growth for Filters used in Cell Phones..," Proc. Int'l Symp. On Acoustic Devices, Chiba, Japan, 2015, pp13-17.

[3] R. Aigner, G. Fattinger, A. Tajic, A. Volatier, F. Dumont, P. Stokes, M. AlJoumayly, "The Edge of Tomorrow in BAW: Innovate, Ramp, Repeat.," Proc. Int'l Symp. On Acoustic Devices, Chiba, Japan, 2015, pp7-12.