1st International Symposium on Laser Ultrasonics: Science, Technology and Applications
July 16-18 2008, Montreal, Canada

Picosecond Ultrasonics: a Technique Destined for BAW Technology

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Abstract
Since the 80's, Bulk Acoustic Wave (BAW) resonators technology has been seeing a rapid expansion, due to its potentials in terms of performances and integration for Radio-Frequency (RF) filtering. The control of the frequency is a challenging question for the mass production of such devices, and passes through an accurate control of mechanical properties of the whole stack. The picosecond ultrasonics technique is well-suited for the characterization of such a component. Using a colored setup (i.e. various probe wavelengths), it allows the measurement of several acoustic parameters (longitudinal acoustic phonon velocity, density, acoustic attenuation, thermal expansion and temperature dependence of sound velocity) of complex thin films stacks. Moreover, picosecond ultrasonics is prepared for on product process control measurements, and fits the requirements of a metrological support for BAW production.
Keywords: BAW resonators, Picosecond ultrasonics, elastic constant, thin films, trimming

1. Introduction

In the current wireless systems, most of the functions are performed by microelectronic components fabricated on silicon or gallium arsenide. However, radio frequency (RF) and intermediate frequency (IF) filters are usually surface acoustic wave (SAW) components, which are not compatible with CMOS or BiCMOS process. Using standard microelectronic processes, Bulk Acoustic Wave (BAW) resonators can be fabricated and integrated with active devices and can replace SAW technology at high frequencies. Bulk acoustic resonances excited by piezoelectric thin films were demonstrated in the early 1980s [1]. Using thin films whose thickness falls in the range 0.5–2 μm one can easily cover the 1 to 10 GHz range using the first longitudinal thickness mode. Aluminum nitride (AlN) has been taken as the favorite piezo-electric material in BAW technology [2].

The basic structure of a BAW is a piezoelectric film sandwiched between two electrodes (Figure 1). When an electrical signal is applied between the two electrodes, an acoustic wave is launched in the structure by the inverse piezoelectric effect and a resonance can occur at particular frequencies. We can show that the electrical resonance is linked to the thickness of the layers and especially to the piezoelectric film thickness and to its elastic properties.

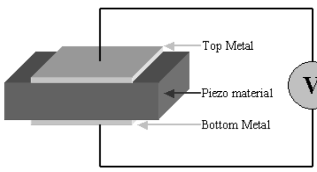

Figure 1. BAW resonator basic structure: a piezoelectric layer sandwiched between two electrodes

Furthermore the control of the resonant frequencies of such devices requires a very precise control of the active layer thickness. Large scale commercial applications require high-quality thin-piezoelectric layers with uniform thickness. BAW filters are thus a particularly demanding application regards to the metrology of thin layers.

Here we present application of the so-called picosecond ultrasonics technique to this delicate measurement problem. In picosecond ultrasonics one uses femtosecond laser pulses to generate and detect very high frequency acoustic waves. Contactless and non destructive the technique has been shown to be well-adapted to the characterization of thin layers even in complex stacks [3]. Here we show that the high requirements of the BAW application need an improvement of the technique concerning both the number of measured parameters and the measurement accuracy for the design and modeling of the devices. Moreover, the use of its clean-room version can assist the metrological strategy needed for an efficient realization process.

2. Picosecond ultrasonics

A schematic diagram of a picosecond ultrasonic experiment is shown in Figure 2. A first optical pulse (the pump pulse) is incident on the sample surface where it is absorbed. The resulting dilatation generates a strain pulse whose extension is related to the absorption length. In the particular case of a metal, absorption can be very strong, giving a length of a few nanometers. As this dimension is much smaller than the spot size (typically a few tens of microns in diameter) one can consider basically that only longitudinal waves are excited by the pump pulse. The resulting pulse propagates in the film at the longitudinal sound velocity of typically a few nanometers per picosecond that explains how absorption can generate picosecond acoustic pulses. The strain pulse is reflected onto the film-substrate interface and the resulting echo returns to the surface and modifies in this way the dielectric constant of the film. These changes can be detected by another optical pulse (the probe pulse) whose reflection or transmission is affected by the presence of the strain wave. By adjusting the delay between pump and probe pulses it becomes possible to monitor the successive echoes due to the strain generated by the pump pulse. Usually, these echoes are used to measure thicknesses of thin films, sound velocities and density [3], [4], [5].

The experiment is based on a conventional pump-probe setup associated with a tunable

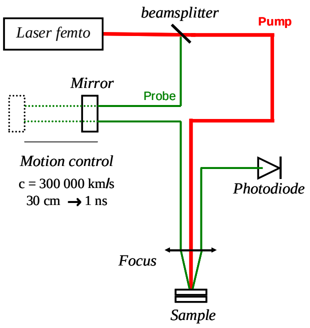

Figure 2. Schematic diagram of the experimental setup

titanium:sapphire oscillator which produces 120 fs optical pulses with a repetition rate of 76 MHz centered at a wavelength tunable between 700 nm and 990 nm. The laser output is split to provide pump and probe beams with crossed polarizations. The probe pulse can be delayed with respect to the pump pulse by an optical delay line based on a translation stage. Complementary experiments were also performed with a blue probe obtained by focusing the laser beam into a BBO crystal to generate the initial second harmonic.

It has been shown that the detection effects are connected with the choice of the probe wavelength [6] [7]. For our experiments, the tunability of the laser source can be used to perform measurements at various probe wavelengths: from picosecond ultrasonics to colored picosecond ultrasonics.

3. BAW resonators requirements

In order to work properly, a BAW resonator has to be decoupled from its substrate. Indeed, the mechanical vibration of the piezoelectric sandwich is running away through the substrate and induces energy losses. The SMR-type (Solidly Mounted Resonator, Figure 3) solution that consists on the deposition of an acoustic Bragg mirror between the piezoelectric sandwich and the substrate [8], is the choice made by most of the BAW manufacturers for its robustness and integration potentials.

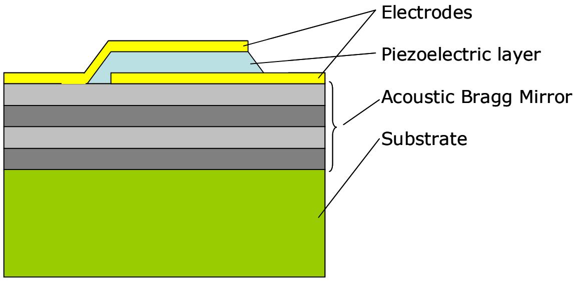

Figure 3. Cross section of an SMR-type resonator. The piezoelectric sandwich is at the top, then the acoustic Bragg mirror consisting on alternating layers of high and low acoustic impedance, and the substrate.

A BAW resonator is then a complex stack of different materials (piezoelectric, metals, dielectrics, semi-conductor…) in thin films (from 10 nm to 1 µm). At this point BAW manufacturers are facing two metrological challenges:

- the mechanical characterization of materials in thin films for the design and optimization of the components,
- the on-wafer products measurements for an efficient fabrication process.

As picosecond ultrasonics is probing the longitudinal acoustic propagation in thin films stacks, we identified it as the appropriate technique to study the BAW resonators. We will see that the use of a colored setup enables the measurements of the decisive mechanical parameters of a BAW resonator, then that the industrial version of the classical technique can be advantageously used to enhance the realization process.

4. Material characterization

The decisive parameters of a BAW resonator can be identified through the 1-D Mason's model [9]. These are the following:

- longitudinal sound velocity,
- mass density,
- attenuation coefficient,
- temperature dependence of thickness and sound velocity.

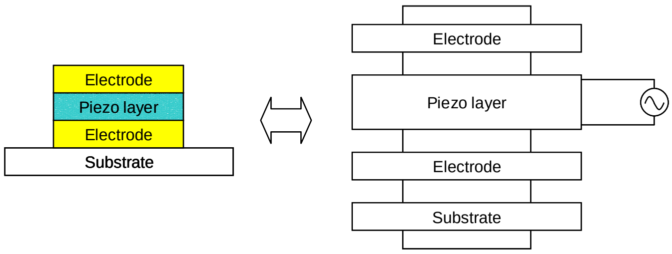

Figure 4. Electric model of a BAW resonator. On the left a BAW structure, on the right its equivalent circuit. Each layer is represented by a quadripole depending on the layers' parameters.

Sound velocity and density measurements are the standard use of the picosecond ultrasonics technique. However, a colored setup provides a better accuracy for sound velocity and density measurements in transparent materials [10]. Parallel to these developments, we still took advantage of the wavelength effects to set up new methods that enables access to the additional parameters (attenuation coefficient, temperature dependence of thickness and sound velocity) [11], [12]. From these experiments, we realize a database of the BAW materials (AlN, Mo, SiO2, W, SiN, SiOC…)

5. On-wafer Product Measurements

BAW resonators are promising for high volume applications in cell-phones and require an efficient realization process on standard 200 or 300 mm wafers. One of the major problems encountered during the process is the non uniformity of the deposited thicknesses (Figure 5). At first order, the resonant frequency f_r of a BAW resonator is given by the ratio $f_r=c/2e$ where c is the sound velocity of the piezoelectric material and e its thickness. However, all the stack's layers are contributing to the position of the resonant frequency. The impact of each layer dispersion is drastically reducing the yield, because of the strict specifications on the resonant frequencies for filtering applications.

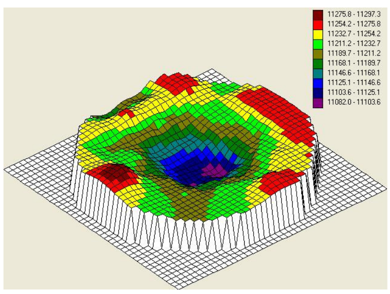

Figure 5. Typical thickness dispersion of an AlN layer (angströms).

To solve this problem, a correction strategy has been set up: the "trimming strategy". The idea is to etch the acoustic loading of a device as a function of its frequency offset. The trimming tool is an ion cluster beam with a 1 cm spot size that can be moved over the wafer to realize a non-uniform etching. This strategy requires as inputs:

- the resonant frequencies,
- the sensibilities (i.e. impact of the etching on the resonant frequency), to calculate the etching profile.

Up to now, these inputs are obtained with RF-tests for the frequencies and assumed for the sensibilities. The choice of RF-tests as the metrological support for the trimming tends to make a heavy strategy (RF-tests are contact measurements, and the assumed sensibilities require a second step of measurement). Here we demonstrate the capability of picosecond ultrasonics to predict the resonant frequency and sensibility of a BAW stack through thickness measurements. This skill can then be used for an efficient support of the trimming strategy (non-contact measurements and a unique metrological step).

The problem here is to validate the capability of picosecond ultrasonics for frequency prediction. As we brought up earlier, the resonant frequency of a BAW stack is determined by the thicknesses of the stack's layers. Thus, using the Mason's model and the database of the material parameters, the thickness metrology can predict both inputs (frequencies and sensibilities) for the trimming strategy.

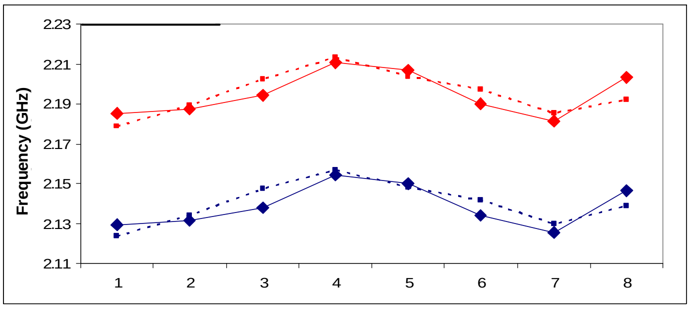

Figure 6. Measured (dotted) and simulated (line) resonant frequencies: fr in blue and fa in red, of a series of resonators (1 to 8) on a 200mm wafer (fa is an anti-resonance, at this frequency the resonator can be considered as an open circuit).

The results presented in Fig. 6 have been obtained on structures deposited on a 200 mm wafer. RF-tests and thickness measurements have been performed on the sample. The thickness measurements have been performed with a MetaPulse (clean-room version of the picosecond ultrasonics technique by Rudolph Technologies for opaque materials thickness control [13]). The figure shows that thickness metrology enables frequency prediction, and thus sensibility prediction (since sensibility represents the evolution of the frequency with respect to the etched thickness), which was the issue for RF-tests replacement.

5. Conclusion

In conclusion we have presented on original way of using the picosecond ultrasonic technique in a BAW stack. This technique uses a femtosecond laser to generate and detect very high frequency acoustic waves which suits very well the characterization of thin films in complex stacks. We have shown that using a laser source whose wavelength can be tuned we can improve the measurement technique by measuring more parameters with an increased accuracy compared to the classical technique. These developments enable the realization of a database of the decisive parameters for the BAW materials. Then we propose an efficient metrological support, able to replace RF-tests, based on a MetaPulse for the trimming strategy. Both of these results lead to the following statement: picosecond ultrasonics is a technique destined for BAW technology.

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