A NOVEL APPROACH USING PICOSECOND ULTRASONICS AT VARIABLE LASER-WAVELENGTH FOR THE CHARACTERIZATION OF ALUMINIUM NITRIDE FILMS USED FOR MICROSYSTEM APPLICATIONS

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Abstract

We present the application of the picosecond ultrasonic technique to the characterization of the mechanical properties of piezoelectric thin films resonators. The measurements were made on real structures what let us investigate the AlN layer properties as used in realistic cases. Simultaneously, we get informations concerning the other layers of the structure. We also show that varying the laser wavelength let us extract further data on the same samples : in particular sound velocity and thickness can be deduced independently.

Introduction

In the current wireless systems, most of the functions are performed by microelectronics 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. Piezoelectric thin films resonators can replace SAW technology at high frequencies : thickness mode resonators with much reduced dimensions can be fabricated and connected in a ladder or a lattice network to build bandpass filters. One of the biggest advantages of Film Bulk Acoustic Resonators (FBAR) is that their resonance frequency is given by the piezoelectric film thickness, and not by the distance between the electrodes elements as it is the case for the Surface Acoustic Wave (SAW) Resonators. Using standard microelectronic processes, Bulk Acoustic Wave (BAW) resonators can be fabricated and integrated with active devices.

The basic structure of a Bulk Acoustic Resonator is a piezoelectric film sandwiched between two electrodes as presented in figure 1.

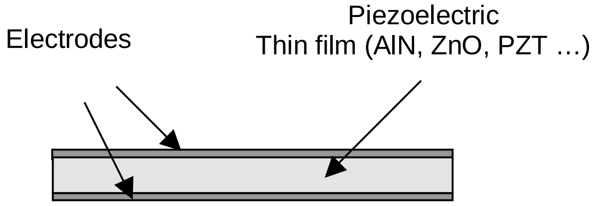

Figure 1 Bulk Acoustic Resonator

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 certain 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. So we need a measurement method so as to extract these parameters. Here we presents such results obtained with an original method called the picosecond ultrasonics.

In a picosecond ultrasonic experiment, a first optical pulse (the pump pulse) is incident at the sample surface where it is absorbed and 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. Such a mechanical pulse propagates into the sample at the longitudinal sound velocity (typically a few nanometers per picosecond), which explains how absorption can generate picosecond acoustic pulses. This pulse is reflected onto the film-substrate interface and the resulting echo comes back to the surface and modifies 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, attenuation and so on.

Here we report on picsoecond ultrasonics measurements performed at different laser wavelength in order to get as many as possible mechanical properties of the films of the BAW resonator.

Experimental details

The experiment is based on a conventional pump and probe setup associated with a tunable 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 the 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. Both beams are focused on the same point of the sample by a 60 mm lens. To improve the signal-to-noise ratio, the pump beam is chopped using an acousto-optic modulator and the output of the photodiode, which monitors the reflected probe, is amplified through a lock-in scheme.

Parasitic fluctuations in the probe intensity were normalized by splitting the probe into signal and reference beams and monitoring the difference between the signals detected in identical photodiodes.

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.

Figure 2 gives a schematic diagram of the studied sample. It is a three-layer film stack deposited on a silicon substrate. The 2000 nm AlN film is the piezo-electric layer. The 200 nm Al film is the bottom electrode. In order to insure a good adhesion of the Al film, a thin layer of Ti (50 nm) has been deposited on the substrate before the aluminum deposition.

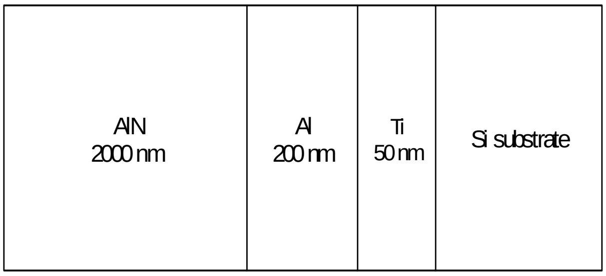

Figure 2 Schematic diagram of the sample. The piezoelectric layer is composed of AlN. The Al film is the bottom electrode and the Ti layer

First kind of experiments

Figure 3 reproduces the transient reflectivity signal measured in the sample. Both pump and probe pulses are centered at 770 nm. The signal is first composed of a jump at zero time that is the electronic contribution to the pump-probe signal. Few picoseconds later, the pump energy is converted into heat, which diffuses on a larger time scale. This leads to a slow decrease of reflectivity. Figure 3 also shows several acoustic echoes that are analyzed in three groups.

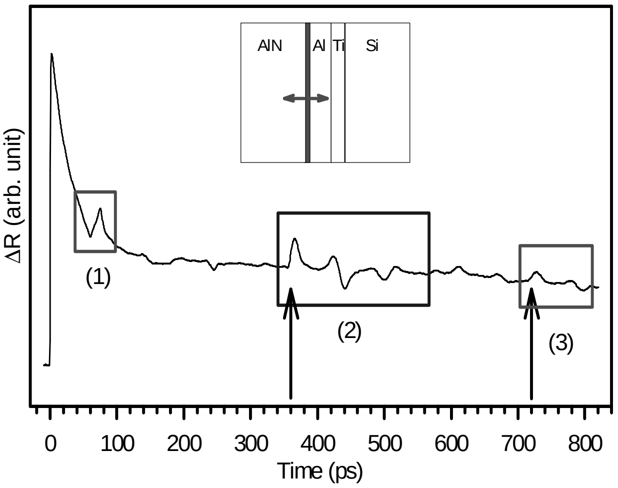

Figure 3 Pump and probe response of the AlN sample with a laser wavelength of 790 nm for both pulses.

The structures which appear in the group (1) correspond to echoes which have been reflected at the interfaces Al/Ti and Ti/Si. Their time of arrival give us the thicknesses of the metallic layers : assuming a sound velocity of 6400 m/s for Al and 6300 m/s for Ti one obtains respectively a thickness of 192 nm for the Al layer and 44 nm for the Ti layer. The opposite signs of the first two echoes are consistent with the acoustic impedances of the different layers : the Al/Ti interface has a negative reflection coefficient whereas it is positive at the Ti/Si interface.

In the group (2) we detect echoes which have first passed through the AlN layer. One first observes an asymmetric echo at t=360 ps. Usually in picosecond ultrasonics the strain pulse is generated at the sample surface in a thin metallic layer. In that case the strain pulse is described as composed of a positive and a nearly equal negative parts. At the detection a symmetrical echo results. Here as we are generating into the sample the strain pulse which propagates toward the surface in the AlN layer has only one sign component. This is the reason why the detection of its come-back in the aluminum layer has an asymmetrical shape. Other echoes are visible after this first structure. They are the replica of this wave after a reflection on the Al/Ti and Ti/Si interfaces.

The last group (3) near 700 ps contains echoes which have traveled twice time in the AlN layer. The comparison of the amplitudes of the first and second echoes can give the reflection coefficient at the AlN/Al interface : r=-0.31. (assuming that there are no acoustic losses in the AlN)

Second kind of experiments

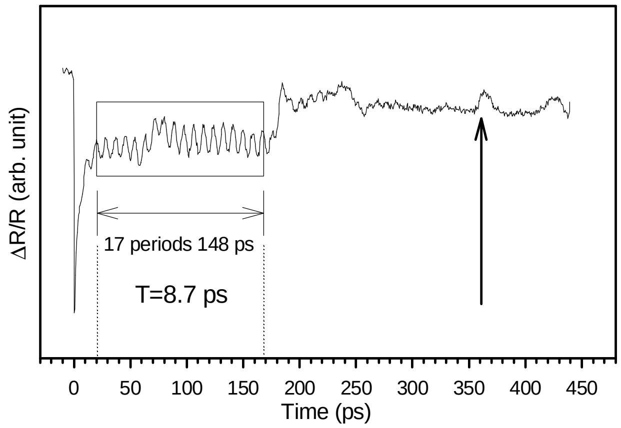

Figure 4 Transient reflectivity obtained using a red-infrared pump and a blue probe. The laser wavelength in that experiment was 800 nm.

Figure 4 reproduces the experimental signal obtained by performing a picosecond ultrasonic experiment in the same sample but using a blue probe instead of red-infrared one. One first remarks that many contributions have changed. One should also remark the detection of the first echo coming from the AlN layer at the same time 360 ps.

In the first 200 ps we also observe high frequency oscillations that were not visible in the previous experiment. During that time, a strain wave is propagating in the AlN layer. As we show in the following the origin of these oscillations may be found in the acousto-optic interaction in the AlN layer.

In fact, in the case of a layer which is transparent for the probe beam, an acousto-optic interaction may appear as soon as both acoustic and electromagnetic fields exist in the film [4]. In that case the acoustic pulse is detected in the probe intensity but the short acoustic pulse is replaced by an oscillation. The period of these so called Brillouin's oscillations may be written as :

$$T = \frac{\lambda}{2nv\cos\Theta} \qquad (1)$$

where λ is the probe wavelength, n is the index of refraction, v is the sound velocity and Θ is the angle of incidence. Due to the high value of its energy gap (near 6 eV [3]) AlN is a transparent layer for any wavelength greater than 210 nm. If the coupling between acoustic and electromagnetic fields is sufficient one can thus expect the observation of such a phenomenon as long as the strain pulse propagates in the AlN layer. One should notice that the measurement of their period permit the evaluation of the sound velocity independently of the thickness of the layer. Combined with the time of flight of an echo one can thus deduce both thickness and sound velocity for a transparent layer.

Taking an optical index value of 2.15 (reference ?) and a sound velocity of 11 nm/ps we obtain a period for Brillouin's oscillations detected with a probe beam centered at 400 nm of 8.5 ps. This value is very closed to the detected period 8.7 ps that supports the proposed interpretation.

To go further in the confirmation that the detected oscillations well result of an acousto-optic interaction in the AlN film, we have performed similar experiments at different laser wavelengths. On the Figure 5 we have plotted the period obtained in each case as a function of the probe wavelength. We have also superimposed the theoretical curve deduced from Eq. (1). There is an excellent agreement between experimental and theoretical data. That finishes to confirm the origin of the detected oscillations.

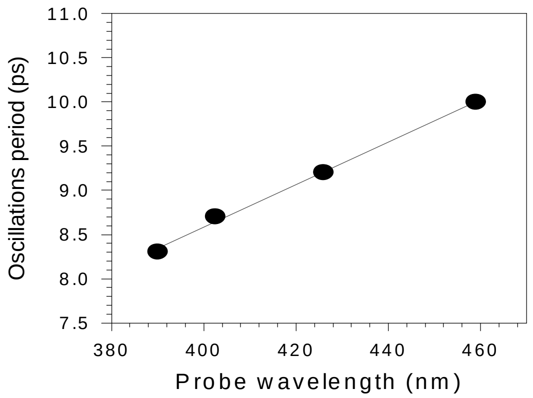

Figure 5 Dependence of the period of the oscillations detected in the transient reflectivity experiment performed using a blue probe.

Discussion

We now show how this let us deduce number of physical parameters of the studied structure.

First the sound velocity is deduced from the excellent agreement between experimental and theoretical periods presented on the Figure 5 on which the theoretical data correspond to a sound velocity of v=10760 m/s and an optical index n=2.15 [3]. From the time of flight obtained in the first experiment we can now estimate the thickness of the AlN layer : 10.76*360/2=1937 nm. Finally using the reflection coefficient and the sound velocity value we can get the density value of the AlN film : the reflection coefficient at the AlN/Al interface is given by :

$$r = \frac{Z_{Al} - Z_{AlN}}{Z_{Al} + Z_{AlN}} \qquad (2)$$

where Z_{Al} and Z_{AlN} are the mechanical impedances of respectively Al and AlN. Assuming the expected values for the sound velocity and density of aluminum we deduce Z_{AlN} from the value of r. As the impedance is the product of the sound velocity by the density we finally obtain the density of the AlN film : $\rho = 3.05$ g.cm^{-3}. This value is slightly lower than to the bulk value (3.2 g.cm^{-3}).

One has to notice that these results are all deduced from the index of refraction value. Unfortunately we have no measured value of *n* in the studied sample at the working wavelength.

One may also ask oneself why the Brillouin's oscillations detected in the second kind of experiments are not detected in the first. In fact AlN is transparent in both cases and the strain pulses should be identical since the pump wavelength is unchanged. The answer can be found in the piezo-optic coupling value. As we have shown in previous studies the coupling between the strain pulse and the probe beam can be very sensitive to the probe wavelength [5][6]. Here the observed results can be understood by assuming a smaller value of this coupling in the red-infrared range than in the blue one.

Conclusion

We have presented picosecond ultrasonics results obtained in a piezoelectric thin films resonator structure. This technique is contact less and can extract mechanical data on thin films in complex structures. Using different experimental conditions we have shown that we were able to extract mechanical properties of the AlN layer that are determining in the design of the resonator. More precisely we have measured both the thickness and the longitudinal sound velocity of the layer using different laser wavelengths. The same experiments have also given data about the electrodes which also impacts resonator response

In this scheme, the precision on the extracted values is directly related to the precision of the index of refraction of the AlN layer. Here we have used a literature value that is not much satisfactory since it can also be strongly dependent on the deposition process and on the wavelength. So in the next future we will improve this by completing these results with ellipsometric measurements performed in the same sample at precise wavelength.

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