MULTILAYER THICKNESS EVALUATION OF SEMICONDUCTOR AND DISPLAY STRUCTURES BY PICOSECOND ULTRASONICS

1. INTRODUCTION

The product line JAX designed by Neta uses unique properties of femtosecond pulses and photo-acoustic effects to inspect thin films stacks. This 100% non-destructive optical method can be used to test and control multilayers which are typical from applications in the semiconductor or in the display industries.

Historically, acoustic waves were first generated with piezoelectric materials [1]. To increase the spatial resolution of these waves, it is necessary to increase their frequency. Whereas the frequency of the acoustic waves generated by piezoelectric transducers is still limited to a few hundreds of MHz [2], this frequency can extend up to several hundreds of GHz for acoustic waves generated by femtosecond lasers [3]. That means that the sample thickness can be typically evaluated from a few microns to several millimeters with high-frequency transducers and from a few nanometers to several microns with picosecond ultrasonics that is based on femtosecond lasers.
Regarding picosecond ultrasonics physics, the pump beam locally and suddenly heats the sample, which produces strains that give birth to an acoustic wavefront that propagates into the sample. When the top layer is opaque, the probe beam detects the wavefront that goes back to the surface after it encountered a boundary. With transparent or semi-transparent materials, the probe beam is reflected at the same time by the substrate and the wavefront that propagates into the transparent material, which produces the so-called Brillouin oscillations. Picosecond ultrasonics systems are well known in semiconductor field as a metrology tool for thicknesses monitoring.

In this paper, we will see how the embedded technology in Neta's system opens high resolution mapping or massive data acquisition. A mapping can be considered as a measurement only needs less than one second. This significantly improves the speed of acquisition and leads to much more data for control itself or potential inline inspection.

After illustrating how the thickness of a layer can be evaluated, this paper will focus on another possibility offered by Neta's system: to determine the acoustic velocity in the material. Two practical applications will then be detailed: a multilayer W-TiN-SiO_2 typical from MOS devices and a multilayer SiO_x-SiN_x typical from display components.

2. CONTEXT

As miniaturization expands, this implies ever more accurate ways of characterization. Some testing and evaluation methods exist, but a part of them have the main drawback to be destructive methods.
In order to perform non-destructive on-line inspection and control with at the same time accuracy, speed and repeatability, new characterization methods must emerge. This paper presents how Neta's system can fulfill the requirements imposed by the new characterization needs, thanks to its unique non-contact, non-destructive, fast and accurate features.

3. TECHNIQUE OF MEASUREMENT

The results presented in this paper have been obtained with Neta's system whose principle of measurement is illustrated on Figure 1.

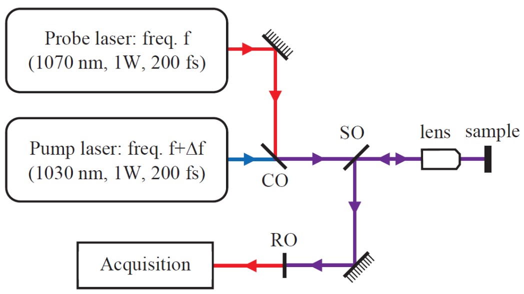

Figure 1. Heterodyne setup principle. CO: combining optics; SO: sampling optics; RO: rejection optics

Historically, the delay between the pump beam and the probe beam was historically managed by a translation stage, Neta's product line embeds two lasers whose delay is electronically managed [4].

Thanks to the electronic delay management between the two lasers instead of a mechanical delay line, considering the same signal to noise ratio and the same time span (typically 4 ns), heterodyne experiments are faster than homodyne experiments by a factor around 10 000 [5]. Typically, the total stack measurable ranges from few nanometers up to 20 µm and it usually takes less than one second to get an exploitable signal.

Please note that the system does not need a severe level of vibration control or clean room to operate. Particularly, measurements can be performed in a standard workshop environment.

4. APPLICATIONS

4.1 Thickness evaluation by echo detection

Knowing the acoustic velocity in the layer, the detection of the arrival time of acoustic echoes gives a direct estimation of the layer thickness:

$$e = \frac{V_{ac}.\Delta t}{2} \quad (1)$$

with e the layer thickness, V_{ac} the acoustic velocity and Δt the arrival time of the first echo or the difference in arrival time between two echoes. Time fly between coincidence and first echo is enough to extract the layer thickness. And even though it's not the focus of this paper but several echoes can give extra-information such as the relative adhesion between layers or interface quality.

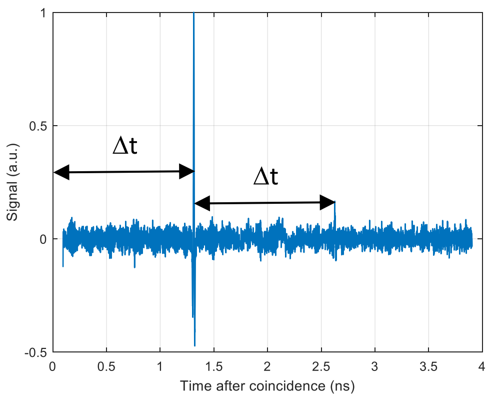

Figure 2. Typical signal showing 2 echoes in the case of a monolayer

Typical repeatability (standard deviation divided by the mean value) of this measurement is up to 0,33%. It has been obtained on a thin layer of tungsten (266 nm) on a silicon substrate.

In the case of a multilayer sample, echoes often overlap. To overcome this issue at first glance, Neta has developed additional analysis tools. First, a materials database allows to predict the approximate arrival times of the echoes corresponding to all the layers. Second, a simulation tool shows how each layer contributes to the acoustic signal and estimates accurately the thickness of each layer.

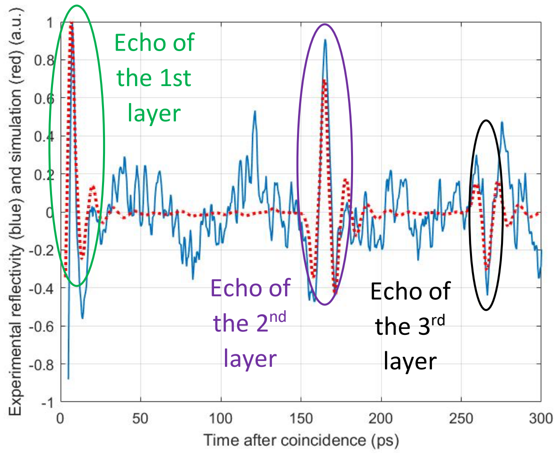

Figure 3. Typical experimental result (in blue) and simulation result (dotted red)

4.2 Acoustic velocity evaluation with Brillouin oscillations

When the material is transparent or semi-transparent and sufficiently thick (several hundreds of nanometers minimum), the acoustic waves generated on the substrate or on a thin top absorbing layer (called transducer) propagate in the transparent medium. The acoustic wavefront can then induce local changes in the reflectivity of the material.

The successively constructive and destructive interference between the part of the probe that is reflected on the substrate and the one reflected on the moving acoustic wavefront induces Brillouin oscillations with frequency:

$$f_{Brillouin} = \frac{2.n.V_{ac}}{\lambda} \quad (2)$$

with n the optical index for the probe beam, V_{ac} the acoustic velocity and λ the wavelength of the probe beam. Measuring the Brillouin frequency gives a direct estimate of the acoustic velocity, hence identifying the material.

4.3 Application on a semiconductor structure

The sample which is typical from a MOS device that is used in the semiconductor industry has the following structure from top to bottom:

- 20 nm of tungsten (W)
- 3 nm of titanium nitride (TiN)

- 130 nm of silicon oxide (SiO_2)
- A silicon substrate (Si)

These layers have been deposited with a PVD deposition process.

In order to evaluate the thickness of the first two layers, a set of simulations proved that the first two peaks of the signal spectrum were directly due to oscillations in the first two layers, respectively (see Figure 4).

To determine the thickness of the top W layer, the formula (1) has to be slightly modified by considering that the peak in frequency is due to regular echoes in the time domain:

$$e = \frac{V_{ac}}{2.f_{peak}} \quad (3)$$

with f_{peak} the frequency of the peak maximum.

To determine the thickness of the middle TiN layer, a set of simulation has been performed to define a direct relationship between the TiN thickness and the peak frequency around 350 GHz.

Regarding the third layer, another set of simulations proved that the SiO_2 thickness could be estimated via an indirect measurement of the exponential decay of the signal in time.

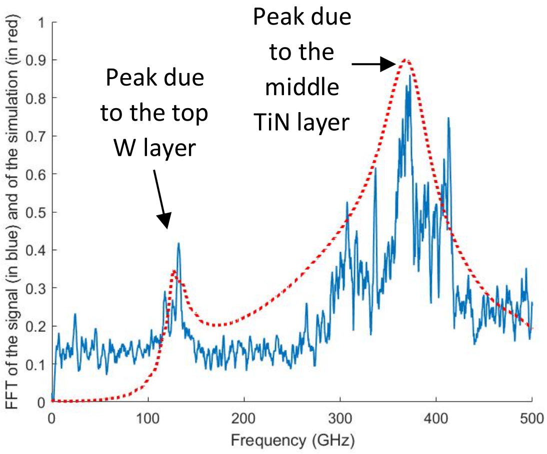

Figure 4. Typical spectrum of a measurement performed on the semiconductor structure (in blue) and simulation (dotted red)

A first set of 60 measurements on the same point gave the following relative standard deviation for the direct measurements:

σ_W = 0.387 % and σ_{TiN} = 0.645 %.

The thickness evaluation of the first two layers shows a very good repeatability, better than 1 % of the mean value.

A second series of experiments was performed on 30 x 30 points spaced by 100 µm, hence mapping on the sample an area 3 x 3 mm².

The total thickness of the 3 layers all together is represented on the graph below.

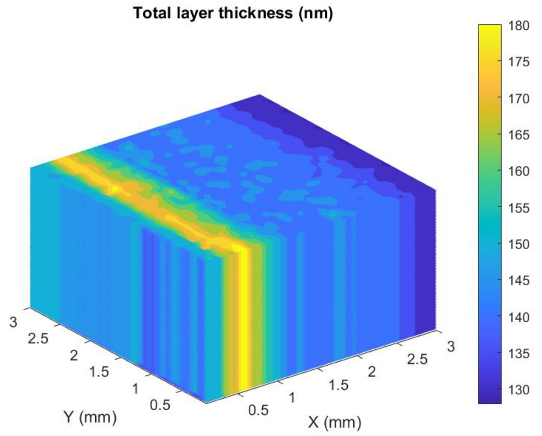

Figure 5. Thickness evaluation mapping of the total thickness of the three layers all together composing the semiconductor structure

In order to distinguish the influence of each layer on this total thickness, Figure 6 represents the thickness of each of these layers separately.

The values represented on Figure 6 deal with the layer thickness variation versus the mean value. The mean value for each layer is given on the Table below.

Layer	W	TiN	SiO2
Mean thickness value (nm)	18.96	3.21	124.78

Table 1. Mean thickness value of the mapping represented in Figure 6

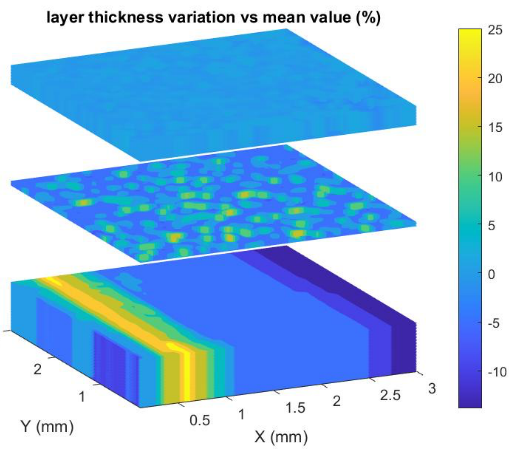

Figure 6. Thickness evaluation mapping of the three layers composing the semiconductor structure: W layer (top), TiN layer (middle) and SiO2 layer (bottom)

The top layer (the tungsten layer) shows very low variations on the mapped area. The middle layer (the titanium nitride layer) shows greater variations in percentage because of the low mean value. Regarding the third layer (SiO2), its thickness is much more steady regarding the Y axis but it shows big variations following the X axis. These variations may be due to a difference in the structure of the silicon substrate (such as a crack) that was smoothed by the silica deposition, or it may be due to physico-chemical local changes of the substrate that impacted the deposition efficiency.

4.4 Application on a display structure

The sample that is typical of display applications has the following structure, from top to bottom:

- 300 nm of silicon oxide (SiO_x)
- 300 nm of silicon nitride (SiN_x)
- A silicon substrate (Si)

These layers have been deposited with a CVD deposition process.

The measurements gave two kinds of information.

First, thanks to the signal spectrum, one can evaluate the Brillouin frequency in each layer: $f_{Brillouin(SiOx)}$ = 50.1 GHz and $f_{Brillouin(SiNx)}$ = 105.9 GHz. According to formula (2) above, the acoustic velocity in each layer can be deduced: $V_{ac(SiOx)}$ = 6 032 m.s^{-1} and $V_{ac(SiNx)}$ = 8 800 m.s^{-1}.

These acoustic velocities are now useful to determine the thickness of the two layers, thanks to echoes (see Figure 7).

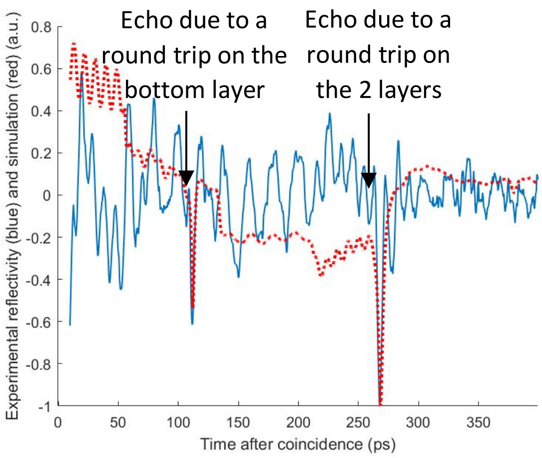

Figure 7. Typical signal obtained with the display structure (in blue) and simulation (dotted red)

The measurements have been performed on 30 x 30 points spaced by 100 µm, hence mapping on the sample an area 3 x 3 mm².

The total thickness of the 2 layers all together is represented on the graph below.

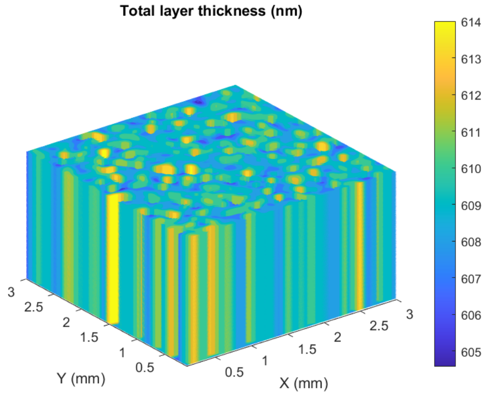

Figure 8. Thickness evaluation mapping of the total thickness of the two layers all together composing the display structure

In order to distinguish the influence of each layer on this total thickness, Figure 6 represents the thickness of each of these layers separately.

The values represented on Figure 9 deal with the layer thickness variation versus the mean value. The mean value for each layer is given on the Table below.

Layer	SiOx	SiNx
Mean thickness value (nm)	301.2	308.1

Table 2. Mean thickness value of the mapping represented in Figure 9

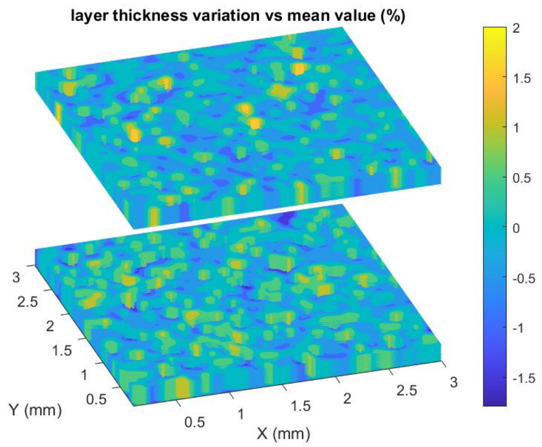

Figure 9. Thickness evaluation mapping of the two layers composing the display structure: SiO_x layer (top) and SiN_x layer (bottom)

The two layers have a thickness that is close to the mean value, except on some locations where impurities or local physico-chemical perturbations can have influenced the deposition process.

5. CONCLUSION

These results demonstrate the ability of Neta's system to evaluate both the total thickness of a multilayer structure and the thickness of each layer of samples typical of the semiconductor and of the display industry. In addition of

In addition of a good repeatability which the process is guaranteed near $\sigma = 0{,}5\%$, the mapping and the massive data available with Neta technology may enhance the analyze at nanoscale for the quality of electronic components, improve yields and reduce the cost of non-quality.

Nevertheless, multiple improvements are on the track, regarding both the hardware and the software with artificial intelligence implementation.

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