ACOUSTICS 2012

Characterization by laser-ultrasonics of thin film/substrate structure: application to the detection of microcracks

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Surface coatings are often used in electronic, microelectronic or optic and their characterization is usually a major issue. For example, thickness control of coated materials and microcracks detection are very important. In this work, the sample consists of a micrometric gold thin film deposited by evaporation on a silicon substrate. Surface acoustic waves generated and detected by laser are used for non destructive testing. This method has the advantage to be a contactless technique with a large bandwidth. In a first part, the film thickness influence on the first Rayleigh mode has been theoretically studied. Then, the effect of a film thickness variation has been highlighted. In order to predict the propagation of the first Rayleigh mode, a finite element method is also presented. Finally, the interaction of this mode with microcracks is theoretically and experimentally investigated.

Keywords: Laser-ultrasonics - Rayleigh mode - Thin film - Microcracks

1 Introduction

Thin films and coatings are widely used in microelectronic, biotechnology and aerospace industries. Particularly, thickness control and microcraks detection of coated materials is very important to ensure the structure functionality. Many non-destructive testing methods based on ultrasonics have been developed. The more classical technique is generally based on bulk waves and times of flight analysis. However this method needs to increase the acoustic frequency when the film thickness decreases. In certain cases, this is a limit for piezoelectric transducers.

Other solutions are to consider guided waves such as Rayleigh or Lamb modes. Indeed, the energy of surface acoustic waves is concentrated in a depth of the order of one wavelength [1]. For example, resonant ultrasound spectroscopy [2], surface Brillouin scattering [3], and acoustic material signature [4] are methods measuring the dispersion of these waves to characterize thin films without being required to use high frequencies as in the case of bulk waves. However laser-ultrasonics [5,6] has the advantage to be a contactless technique with a large bandwidth which is very useful for microelectronic materials characterization.

In this work, laser-ultrasonics is first used to excite the surface acoustic waves in order to highlight a film thickness variation. To predict the propagation of the first Rayleigh mode, a finite element method is also presented. Finally, the interaction of this mode with microcraks is theoretically and experimentally investigated.

2 Theoretical background

Surface acoustic waves propagate along the plane surface of an elastic solid and their amplitude decays rapidly with depth [1]. In coated materials, surface acoustic waves are dispersive and the wave velocity is a function of frequency f, layer thickness h, and elastic parameters [7,8].

Depending on the ratio of the shear waves velocities between the layer and the substrate, the initial slope of the dispersion curve of the first Rayleigh mode is either positive (stiffening effect) or negative (loading effect) and then the curve exhibits a turning point with slope reversal. In order to study the Rayleigh modes and their velocities, a homogeneous system of six equations can be derived from the elastic boundary conditions at the interfaces. It has solutions for certain eigenvalues obtained by equating the corresponding determinant to zero [7,8].

For materials combination which satisfies the conditions of stiffening effect only one Rayleigh mode can propagate and only for a limited range of frequency. As shown in Fig.1, phase velocity dispersion curve starts at the Rayleigh wave velocity of the substrate and increases monotonically with the frequency-thickness product until the substrate shear wave velocity is reached. The group velocity V_g follows first the evolution of the phase velocity V_p, and at a given frequency-thickness product it decreases until it is equal to the phase velocity.

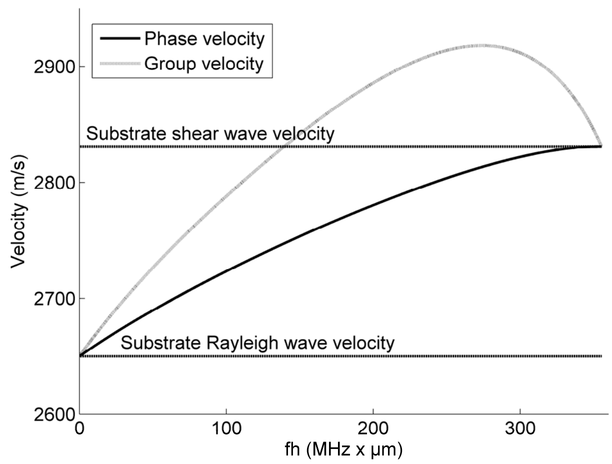

FIG.1. Rayleigh mode dispersion curves for 2 µm silicon thin film deposited on a zinc oxide substrate.

In the case of loading effect, an infinite number of Rayleigh modes can exist depending on the layer-substrate combination and the frequency-thickness product as shown in Fig.2.

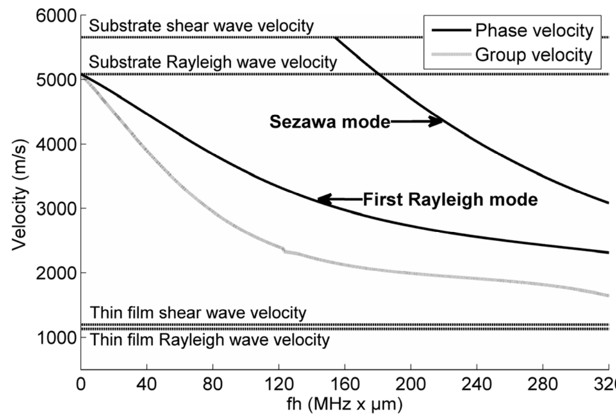

FIG. 2. Rayleigh modes dispersion curves for 2 µm gold thin film deposited on a silicon substrate.

The second Rayleigh mode is often called Sezawa mode [7]. For the first mode, the phase velocity dispersion curve starts at the Rayleigh wave velocity of the substrate, and as the frequency-thickness product increases the velocity monotonically decreases to asymptotically approach the Rayleigh wave velocity of the material layer. Each of the higher Rayleigh modes has a low-frequency cut-off at which the phase velocity is equal to the substrate shear wave velocity. These modes evolution is the same as the first Rayleigh mode. The group velocity V_g follows the evolution of the phase velocity V_p, and in high frequencies it tends to the phase velocity.

Using a finite element model based on tangential dipolar forces [9], the laser-ultrasonics excitation of Rayleigh modes in the structure can be simulated.

Temporal and spatial resolution of the finite element model is critical for the convergence of numerical results [10]. In general, an adequate integration time step is given by:

$$\Delta t = \frac{1}{20 f_{\max}} \quad (1)$$

Where $f_{\max}$ is the highest acoustic frequency of interest.

Usually the rule for elements size is that there are more than ten nodes in a wavelength. However, twenty nodes per wavelength are often recommended. This criterion can be expressed as:

$$L_e = \frac{\lambda_{\min}}{20} \quad (2)$$

Where L_e is the element length and $\lambda_{\min}$ is the shortest wavelength of interest.

Figures 3 and 4 show respectively the calculated normal displacement of the Rayleigh wave propagating on the silicon substrate and on the gold /silicon structure. The dispersion of the first Rayleigh mode is clearly observed in Fig.4.

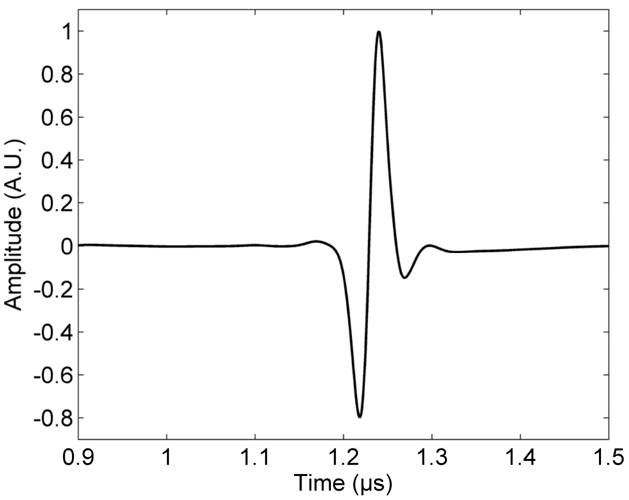

FIG.3. Normal displacement of the Rayleigh wave propagating on a silicon substrate.

The influence of the layer thickness on the phase velocity dispersion curves can also be analytically quantified.

The film thickness is varied separately by step of 100 nm with a maximum of +/- 500 nm in a frequency range up to 45 MHz. The initial value of the thickness is fixed to 2 µm. The result is presented in Fig.5. It appears that for the structure and the frequency range considered, the phase velocity of the first Rayleigh mode increases when the film thickness decreases.

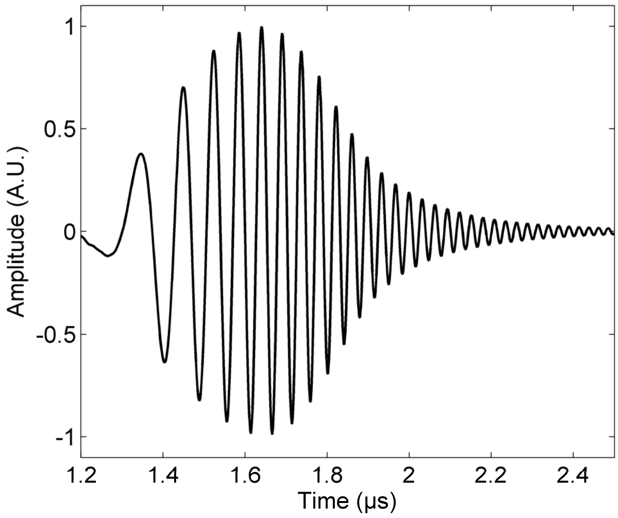

FIG.4. Normal displacement associated with the first Rayleigh mode obtained for a 2 µm gold thin film deposited on a silicon substrate.

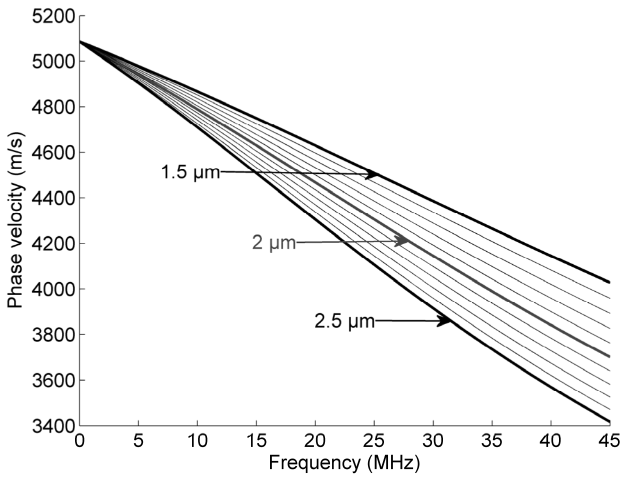

FIG.5. Variation of film thickness versus phase velocity.

3 Experimental setup

In this part, the sample is presented and the laser ultrasonic technique is described.

3.1 Tested sample

Fig.6 presented the layout of the sample. This one is composed of a silicon substrate with thickness and diameter equal to 0.79 in. and 3.00 in. respectively. A gold layer of 2 µm thickness was deposited on this substrate by means of physical vapor deposition. This combination corresponds to the loading effect described previously. At the maximum frequency-thickness product of 45 MHz only the first Rayleigh mode exists. On this film an area of 1 cm x 0.5 cm corresponds to a thickness variation of 100 nm.

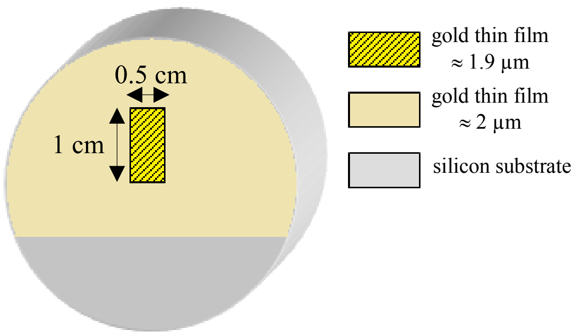

FIG.6. Studied sample layout.

3.2 Laser ultrasonic technique

The system used to generate the surface acoustic waves is presented in Fig.7. A 10 ns duration Q-switched Nd:YAG laser pulse of 532 nm wavelength was focused at the sample surface as a line source of about 6 mm length and 0.5 mm width [11]. The energy per pulse was around 6 mJ, which allowed us to work in the thermoelastic mode.

The surface waves were detected by a Mach–Zehnder type interferometer with a power of 100 mW and a large bandwidth. In order to improve the signal-to-noise ratio, eight laser shots were performed for each measurement. The signals received were sampled with a digital oscilloscope and averaged. Motorized motion tables allowed us to move the laser line source to perform measurements at different distances between the source and the receiver.

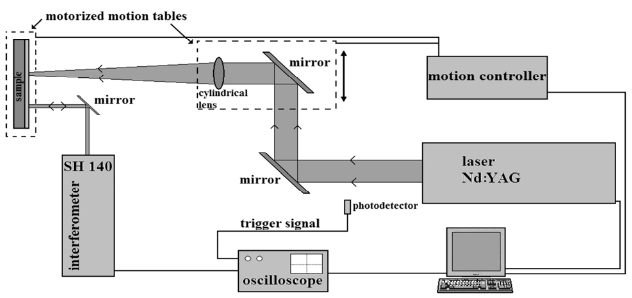

FIG.7. Laser-ultrasonics setup.

4 Results and discussion

In the direction of propagation studied, the sample can be considered as isotropic. Measurements on gold/silicon structure were performed by moving the laser source by step of 200 µm from the position Z = 0 mm to the position Z = 25.2 mm as shown in Fig.8. The distance D between source and detector was kept constant. The detected signals are presented in Fig.10. The normalized amplitude of the displacement is visualized with the color warmness: warm colors for high amplitude and cold colors for low amplitude. From this figure, two observations can be expressed. First, between the position Z = 5.2 mm and Z = 16.4 mm, the effect of the thickness variation on the first Rayleigh mode propagation is clearly observed. In this zone, the first Rayleigh mode is detected earlier. These results are in good agreement with the theoretical dispersion curves. Indeed, the phase velocity of the first Rayleigh mode increases when the film thickness decreases. Moreover, these curves show that the thickness variation is more visible for the higher frequency ranges, which was also verified experimentally.

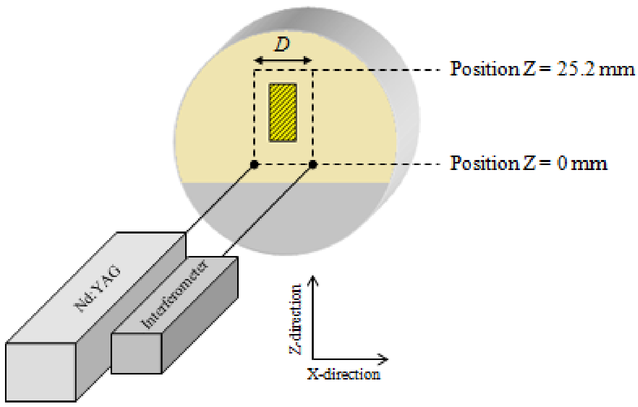

FIG.8. Configuration allowing to scan the sample.

In order to confirm these results, a finite element model has been used to simulate the first Rayleigh mode propagation on such a structure. In this simulation, the length of the propagation path is 7 mm and the width of the area with a thickness variation of 100 nm is 5 mm. Figure 9 shows the simulation results which are in good agreement with the effect observed experimentally.

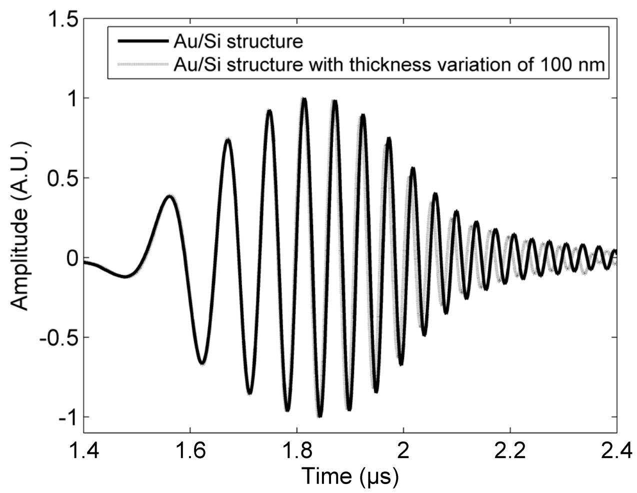

FIG. 9. First Rayleigh mode on Au/Si structure and on Au/Si structure with thickness variation.

The second observation is the detection of microcracks. By the presence of these defects, the first Rayleigh mode is detected earlier and the delay obtained depends on the size of the microcracks area in the propagation direction but also on the frequency component considered due to dispersion phenomena.

The dimensions of these microcracks were measured by a microscope and they are presented in Fig.10.

Additionally, these results have been confirmed by finite element method and are presented in Fig.11.

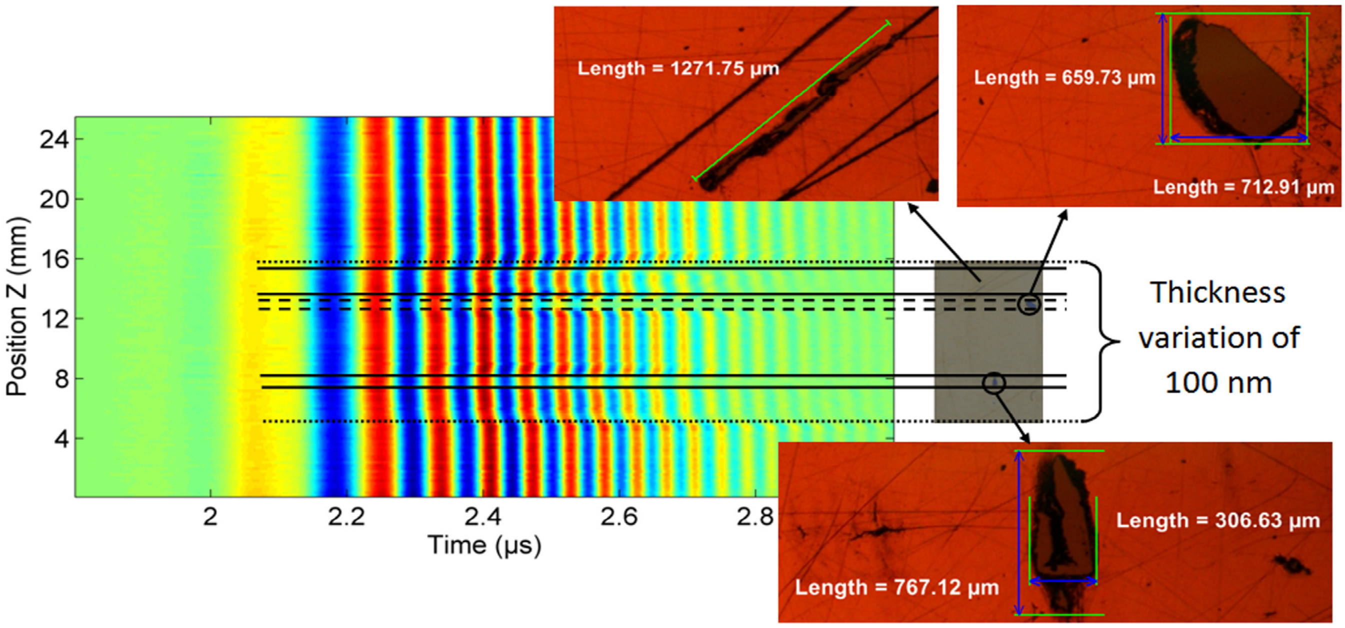

FIG.10. Rayleigh mode amplitude as a function of time for different Z-positions.

The length of the propagation path is 7 mm and the width of the microcrak is 500 µm. This figure confirms the experimental results: by the presence of this defect, the first Rayleigh mode is detected earlier and the delay obtained depends on the frequency component considered.

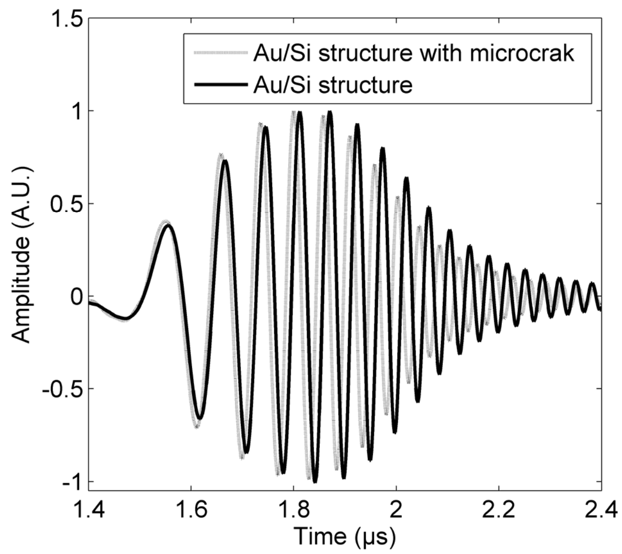

FIG. 11. First Rayleigh mode on Au/Si structure and on Au/Si structure with microcrak.

5 Conclusion

In this work, we used first laser-ultrasonics to excite surface acoustic waves in order to highlight a film thickness variation. Moreover, using these waves, the presence of microcracks has been clearly observed.

The experimental results have shown a good agreement with the theoretical models based on finite element method.

In the near future, we hope to study the influence of disbonds on the first Rayleigh mode propagation by laser ultrasonics.

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