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Film thickness determination by laser ultrasonics

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The thickness of films deposited on substrates is crucial for their thermal, electrical, optical behaviour. These properties are essential in thin film applications, especially in the field of microelectronics. In this study, we are interested in thickness determination of silver and gold films deposited by evaporation on a silicon substrate by using an ultrasonic non-destructive technique. In particular, the well-known laser ultrasonic technique is used to generate and detect the surface acoustic waves. Results obtained by two complementary methods allowing a non-contact measurement in a large bandwidth (from 5 MHz to 200 MHz) are presented, and the dispersion of the Rayleigh wave propagation velocity is analyzed to determine the film thickness.

Keywords: Laser ultrasonics – Rayleigh wave – Film – Thickness

1 Introduction

The determination of sample thickness is important both in physical investigations and industrial applications. Indeed, thin films and coatings are widely used in manufacturing such as in microelectronic, biotechnology and aerospace industries. There are several areas of interest for the study of thin films deposited on substrates including the characterization of material properties. More precisely, the small thickness of the films induces some differences between the physical parameters of the layer and these of the massive structure [1-2]. Consequently, the determination of films thickness is very important.

Ultrasonic methods based on the use of piezoelectric transducers have found a wide range of applications in the field of non destructive testing. An alternative approach is the use of laser ultrasonics. This technique provides many advantages over the previous conventional ultrasonic methods. For example, it allows non-contact ultrasonic measurements at large distance even if the sample has a complex geometry.

In this work, two complementary laser ultrasonic methods have been applied to investigate the first Rayleigh mode propagation in thin films. Measuring the surface wave group or phase velocities as a function of frequency enables the film thickness to be determined.

In the first part, some fundamental properties of Rayleigh modes are quickly reviewed. Then, the samples and the measurement techniques are presented. To finish, the dispersion curves obtained are analyzed, discussed and exploited in order to estimate the film thickness.

2 Theoretical background

In coated materials, surface acoustic waves are dispersive [3-5] as shown in Fig.1 for a 2 µm gold film on a silicon substrate. When the frequency is increased, the penetration depth of the surface acoustic waves is reduced. At high frequencies the phase velocity of the first Rayleigh mode tends to the Rayleigh wave velocity in the film material. On the other hand, at low frequencies, this mode of propagation penetrates deeper into the sample and its propagation phase velocity tends to the Rayleigh wave velocity of the substrate. Moreover, when the frequency increases high order Rayleigh modes can also be observed. The second Rayleigh mode is often called Sezawa mode [6].

In this work, for the samples studied, when the frequency increases, the first Rayleigh mode velocity decreases. 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. This leads to a relationship between the phase velocity, the frequency, the film thickness and the elastic parameters of substrate and film. The knowledge of the elastic parameters and densities permits to determine the film thickness by comparing the theoretical dispersion curve to the experimental results.

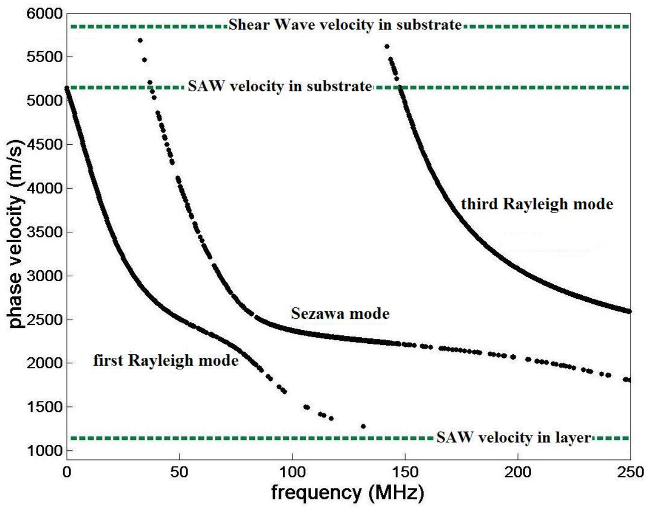

Fig.1. Rayleigh modes dispersion curves for a 2 µm gold film on a silicon substrate in direction (100).

3 Experimental setup

In this part, the samples are presented and the two complementary laser ultrasonic techniques are described.

3.1 Sample preparation

The thickness of the film, which was produced by physical vapour deposition (PVD), is strongly dependent on the temperature and the nature of the substrate, the deposition rate and the vacuum level. Fig.2(a) and Fig.2(b) present respectively the silicon substrate before and after deposition of different films. The thickness and diameter of the wafer are respectively 20 mm and 76.2 mm. Three films with different thickness deposited on the same silicon substrate are investigated: one gold film and two silver films designated by A and B.

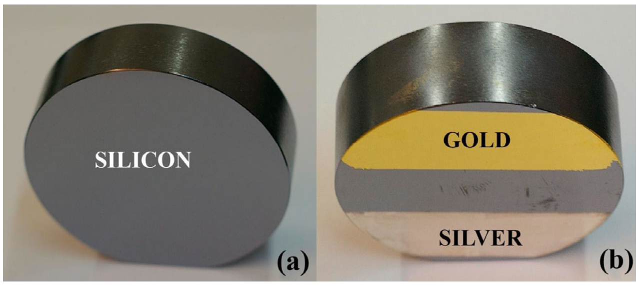

Fig.2. Silicon substrate without layer (a) and with gold and silver films (b).

3.2 Laser ultrasonic techniques

The first system used to generate the acoustic waves is schematically shown in Fig.3. A 10 ns duration Q-switched YAG laser pulse of 532 nm wavelength was focused at the surface of the sample as a line source of approximately 0.5 mm width and 10 mm length. The energy per pulse was about 6 mJ, which allowed us to work in the thermoelastic mode [7-8].

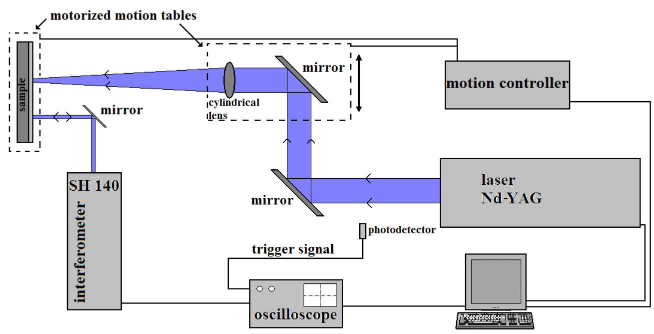

Fig.3. Experimental setup for the laser generation and detection of the first Rayleigh mode.

The normal displacement of the first Rayleigh mode was detected by a Mach-Zehnder type of interferometer with a power of 100 mW and a large bandwidth (200 kHz to 45 MHz). The received signals were sampled and averaged by a digital oscilloscope before acquisition. Each recorded signal corresponds to an average of 32 laser shots in order to improve the signal-to-noise ratio. Motorized motion tables permitted to move the laser source in order to detect the acoustic wave at several distances.

The second system, impulsive stimulated scattering (ISS) detection by heterodyne diffraction is particulary dedicated to the collection of short wavelength and thus high frequency data. In this method, SAW are generated by crossing two pulsed laser beams crossed at the surface of the sample (High-Q laser 10 ps, 1064 nm, 1 kHz rep. 30 µJ, 2x0.2 mm^2). Since the resulting interference pattern is made of a broad set of regularly spaced lines, laser light absorption takes place in the coating and the substrate with the same grating pattern, and thermo-elastically excites left and right traveling quasi-monochromatic acoustic waves at the surface of the sample, with wavelength given by the spatial repetition period of the optical interference pattern [9]. By tuning the beam crossing angle, one can control the acoustic wavelength λ, here in the range between 6 and 100 µm. These dynamic normal surface displacement ripples induced by the acoustic waves act in return as an optical grating, which moves at the SAW velocity, and diffracts a continuous laser beam that impinges on a fixed spot on the sample surface in their propagation path (Fig.4).

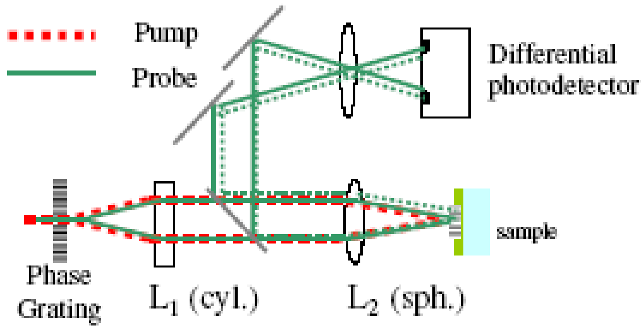

Fig.4. Optical layout of the heterodyne diffraction setup.

In the setup, the pulsed (pump) laser beam is split into two first order diffraction components by a phase grating and collimated onto the sample's surface in a parallel pattern of interferences. The CW probe is also split into two beams. On each of both photodetectors, the light of one respective beam that is dynamically diffracted by the SAW interferes with the other beam in an optical heterodyning process. The difference between the two detected dynamically varying intensities is measured.

This differential approach has two particular features that make it stable and suitable to detect small signals. The optical phase stability between the weak diffracted beams and the strong reference beams, necessary for efficient and stable optical heterodyne amplification, is ensured by using the same optics for all pump and probe beams. In addition, reference laser beam intensity variations are cancelled due to a modified differential implementation of the classical heterodyne diffraction scheme.

4 Results and discussion

The signals obtained by the first laser ultrasonic technique described previously are given below. Fig.5(a) shows the first Rayleigh mode for the gold film detected at several distances which are five millimeters apart from each other. Fig.5(b) and Fig.5(c) present this mode for the silver films A and B. In all cases, we observe that the velocities of the high frequency components of the Rayleigh mode are slower than the low frequency ones. This is in good agreement with the theoretical dispersion curves.

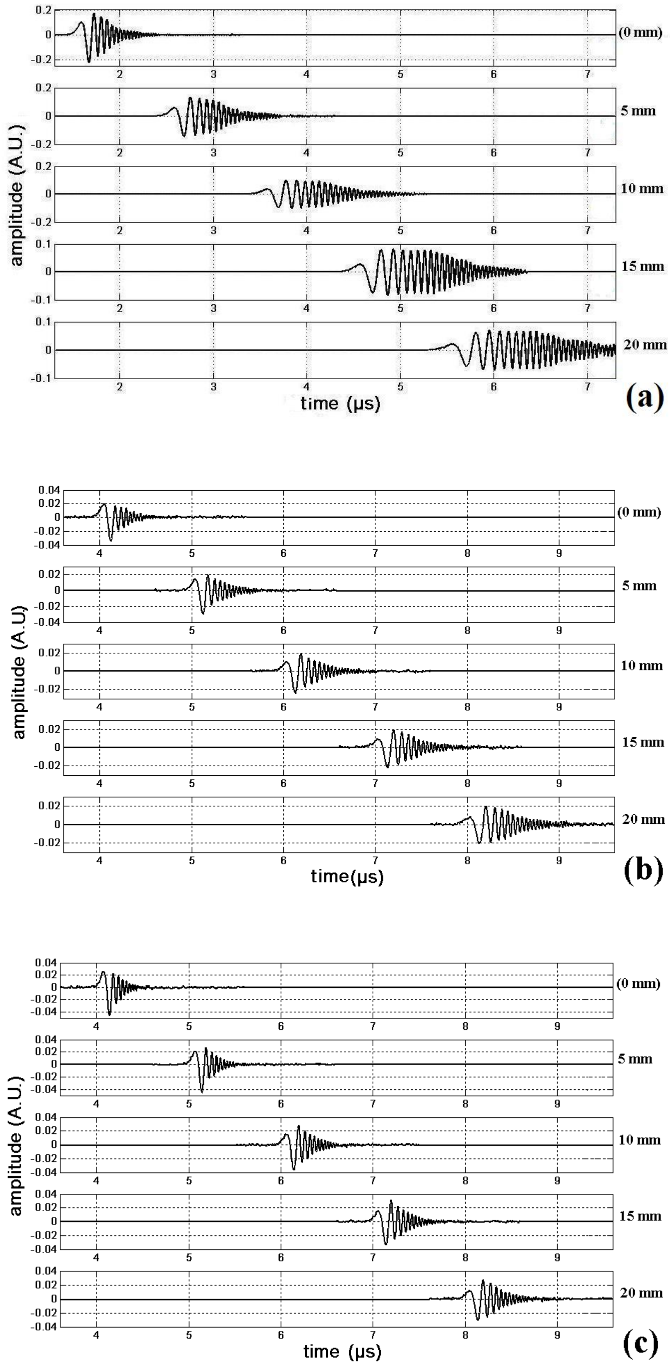

Fig.5. First Rayleigh mode detected at different distances in gold film (a), silver film A (b) and silver film B (c) deposited on the silicon substrate.

Time-frequency analysis using the pseudo-Wigner-Ville distribution (PWVD) was used to characterize the acoustic wave group velocity dispersion from the broadband acoustic signals measured by the first laser ultrasonic technique [10]. The group velocity dispersion curves for the gold film and the silver films are presented in Fig.6, for frequencies between 5 MHz and 20 MHz.

Fig.7 depicts the signal processing by the second laser ultrasonic method. By monitoring the optical phase variations of the diffracted beam in the all-optical heterodyne diffraction pump-probe scheme described above [11], the main signal (Fig.7(a)) frequency component f_0 can be determined from its Fourier transform (Fig.7(b)). Together with the imposed wavelength λ, the value of f_0 allows to determine the propagation velocity $c=\lambda f_0$ of the associated surface wave. In this way, points on the phase velocity dispersion curve are directly obtained (Fig. 8).

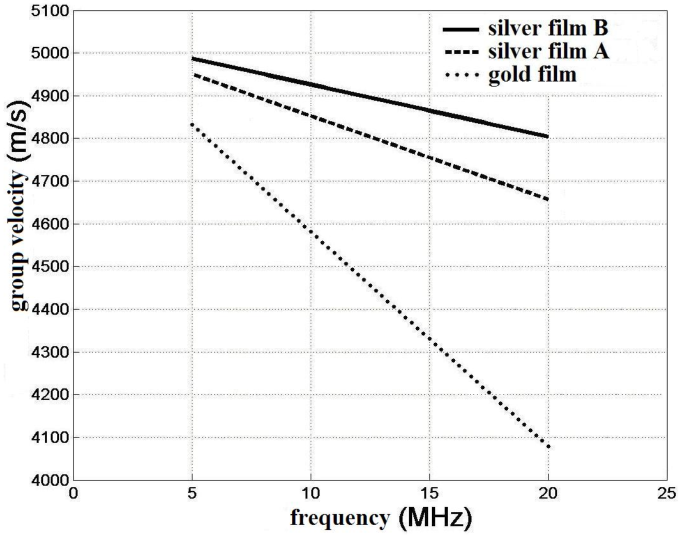

Fig.6. Group velocity dispersion curves of the first Rayleigh mode for gold and silver films.

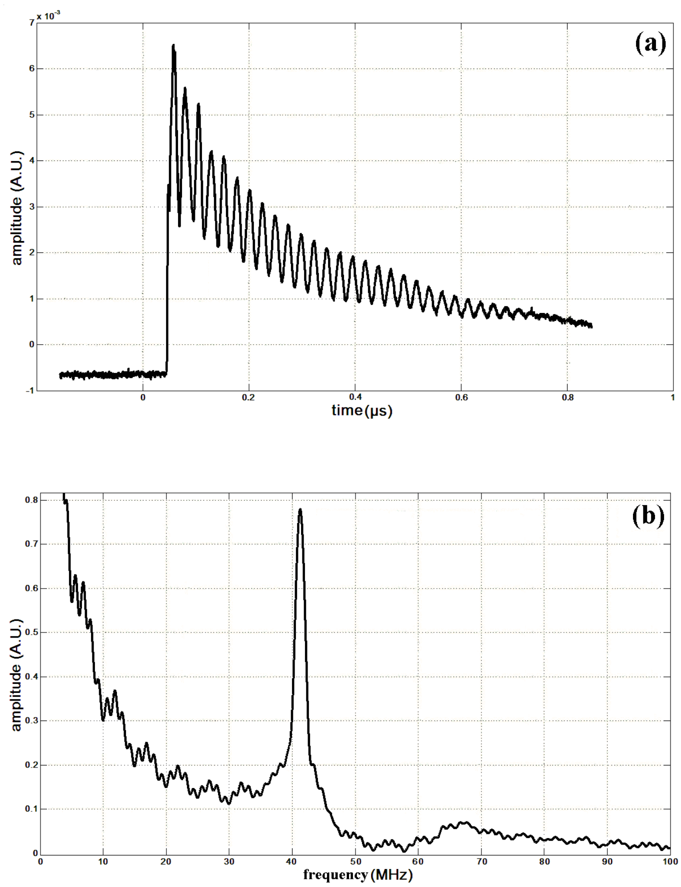

Fig.7. Heterodyne diffraction signal (a) and Fourier transform (b) for the gold film on the silicon substrate. Besides a displacement jump due to the laser induced thermal expansion grating, the time signal shows an oscillating component due to the moving SAW-induced grating.

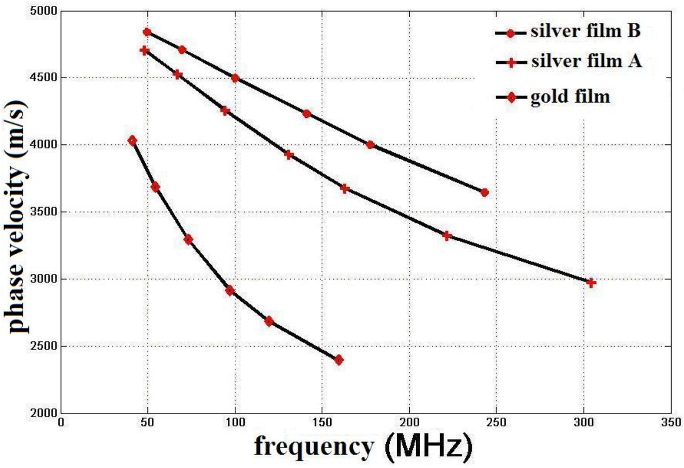

Fig.8. Phase velocity dispersion curves of the first Rayleigh mode for gold film and silver films.

Using the dispersion curves of the lowest Rayleigh mode and a fitting process, the film thickness can be determined. To obtain this one, the knowledge of the density and elastic parameters is necessary. The latter ones were obtained using the Voigt-Reuss-Hill approximation [12]. This is a useful scheme for calculating the elastic moduli of the isotropic polycrystalline film from the corresponding elastic constants of the massive material. The derived isotropic bulk and shear moduli respectively K and G of gold and silver films are given in Table 1.

Elastic moduli (GPa)	K	G
Gold	172.8	27.7
Silver	103.9	29.4

Table 1 Bulk (K) and shear (G) moduli of gold and silver films obtained by the Voigt-Reuss-Hill approximation.

The results obtained by using a least-squares-error method that determines the best fit between theoretical dispersion curve and the experimental one by varying the film thickness are given in Table 2.

	Thickness	
	Low frequency considered	High frequency considered
Gold film	1.55 µm	1.58 µm
Silver film A	1.24 µm	1.19 µm
Silver film B	0.78 µm	0.78 µm

Table 2 Thickness of gold and silver films.

The high precision of the numerical values in Table 2 indicates that the film thickness can be measured with a good approximation by fitting theoretical dispersion curve with the experimental results obtained by the two complementary laser ultrasonic methods. The measurement error on the film thickness is quite small because its value has a substantial effect on the shape of the SAW dispersion curve.

5 Conclusion

In this work, two complementary laser ultrasonics techniques were used to determine the thickness of gold and silver films deposited on a silicon substrate. First, the group and phase velocities of the first Rayleigh mode were experimentally obtained at low and high frequencies. Then, theoretical dispersion curves were calculated by varying the thickness in order to obtain the best fit with the experimental curves. Good agreement was found on thicknesses determined using the two techniques and for all the films.
Further work is however needed to evaluate simultaneously the thickness and the elastic constants of the film by exploiting the information in the dispersion curve of multiple modes of propagation.

Aknowledgements

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