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Laser ultrasonics and guided waves for the thickness estimation of thin layers

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The dispersion of guided waves has been probed to estimate the thickness of a thin gold layer deposited on a two inches silicon wafer. Ultrasonic waves were generated and detected in a non-destructive and non-contact way using a laser ultrasonic setup. The guided waves dispersion curves were experimentally obtained with a two-dimensional Fourier transform, revealing the propagation of several modes. The development and the study of an analytical model allowed the determination of the most sensitive modes to the layer thickness. Using these modes the gold layer thickness was determined with no exact prior knowledge of the substrate and layer elastic characteristics. This method was found to be fast and easy to implement, with a suitable measurement error.

1 Introduction

Silicon wafers are widely used in microelectronics as substrate to receive microelectronics devices. They undergo many microfabrication process steps such as doping or ion implantation, etching, photolithographic patterning, thin layer deposition, etc.

In recent years, growing interest and concern for thin layer deposition has been observed. Numerous methods have been developed to characterise such films, using for example nanoindentation [1], X-ray reflectivity [2] or laser ultrasonics [3, 4].

In general, picosecond or femtosecond lasers are used to generate bulk waves with very short wavelength in order to estimate the properties of thin films [3, 4].

In this paper, a non contact and non destructive thin film thickness gauging method, involving reduced equipment costs, is proposed. Only guided waves generated by a nanosecond laser were used to determine the thickness of a thin gold layer deposited on a two inches silicon wafer. To this end, the dispersion curves were experimentally obtained by means of a two dimensional spectral analysis and the observation of the two first propagating modes allowed the direct measurement of the layer thickness, without exact knowledge of the substrate and layer elastic properties.

A good agreement between the experimental and analytical [5] results has been observed.

2 Lamb wave propagation in anisotropic bilayered structures

The transfer matrix method [6] has been used to describe the propagation of guided waves in a bi-layered plate-like structure. Such a structure is depicted in Fig. 1, where the exponents (1) and (2) refer to the different

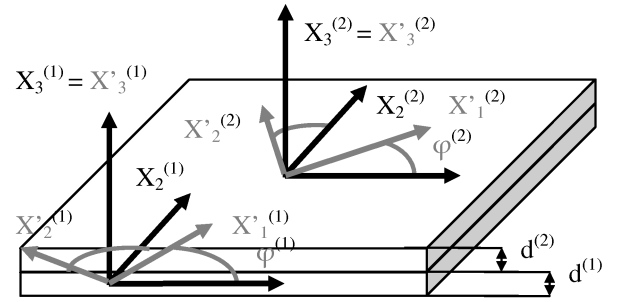


FIG. 1 – The coordinate systems of a plate composed of two anisotropic layers of thickness $d^{(1)}$ and $d^{(2)}$.

layers whereas the indices 1, 2 and 3 refer to the different directions.

In this method, for each layer, the displacements and stresses of a same surface are expressed in a vector P such as

$$P^{(k)} = \begin{bmatrix} u_1^{(k)} \\ u_2^{(k)} \\ u_3^{(k)} \\ T_{33}^{(k)} \\ T_{13}^{(k)} \\ T_{23}^{(k)} \end{bmatrix} \quad (1)$$

where $u_{i=1,2,3}^{(k)}$ are the surface displacements and $T_{ij=33,13,23}^{(k)}$ are the surface stresses of the layer k ($k = 1$ or 2). A link can be found between the P_+ vector of the top layer surface and the P_- vector of the bottom surface of the same layer

$$P_+^{(k)} = A^{(k)} \cdot P_-^{(k)} \quad (2)$$

A_k is called the transfer matrix of the anisotropic layer k . The use of continuity conditions for the displacements and the stresses at the interface between the two layers

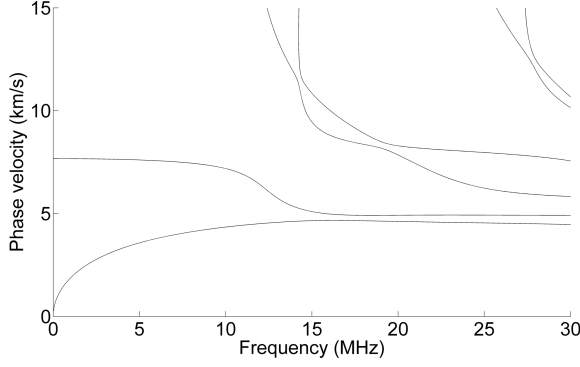


FIG. 2 – Theoretical dispersion curves for a 2 in. silicon wafer with a 1 μm thick gold layer.

$$P_+^{(1)} = P_-^{(2)} \quad (3)$$

leads to the expression of the global transfer matrix A . A links the surface vector $P_-^{(1)}$ of the first layer to the surface vector $P_+^{(2)}$ of the second layer

$$A = A^{(1)} \cdot A^{(2)} \quad (4)$$

The appliance of free boundary conditions to $P_-^{(1)}$ and $P_+^{(2)}$ permits to obtain

$$\begin{bmatrix} u_1(d^{(2)}) \\ u_2(d^{(2)}) \\ u_3(d^{(2)}) \\ 0 \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{13} & A_{14} & A_{15} & A_{16} \\ A_{21} & A_{22} & A_{23} & A_{24} & A_{25} & A_{26} \\ A_{31} & A_{32} & A_{33} & A_{34} & A_{35} & A_{36} \\ A_{41} & A_{42} & A_{43} & A_{44} & A_{45} & A_{46} \\ A_{51} & A_{52} & A_{53} & A_{54} & A_{55} & A_{56} \\ A_{61} & A_{62} & A_{63} & A_{64} & A_{65} & A_{66} \end{bmatrix} \times \begin{bmatrix} u_1(-d^{(1)}) \\ u_2(-d^{(1)}) \\ u_3(-d^{(1)}) \\ 0 \\ 0 \\ 0 \end{bmatrix} \quad (5)$$

Solutions for this equation can be found if and only if

$$\begin{vmatrix} A_{41} & A_{42} & A_{43} \\ A_{51} & A_{52} & A_{53} \\ A_{61} & A_{62} & A_{63} \end{vmatrix} = 0 \quad (6)$$

This problem has been solved in the case of a 1 μm thick gold layer deposited on a 2 in. silicon wafer. The formulation employed to express the components of the different transfer matrixes was the one of Nayfeh [7]. The silicon having a diamond cubic structure, which imply an anisotropic behavior, the resolution has been made in the 100 direction. The results are presented into dispersion curves that can be seen in Fig. 2.

3 Experimental setup

The system used to generate the acoustic waves is schematically shown in Fig. 3. A 10 ns duration Q-switched Nd-YAG (yttrium aluminum garnet) laser pulse of 532 nm wavelength was focused at the sample surface as a line source of about 5 mm length and 0.5 mm width [8]. The energy per pulse was around 6 mJ, which allowed us to work in the thermoelastic mode. The

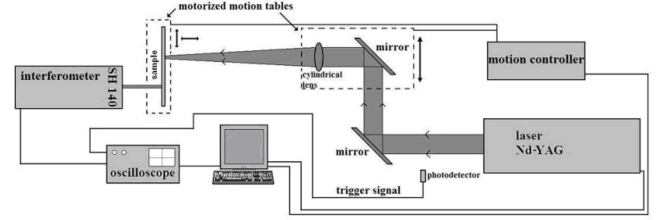


FIG. 3 – Experimental setup for the laser generation and detection of guided modes.

normal displacement of each Lamb mode was detected by a Mach-Zehnder type interferometer with a power of 100 mW and a large bandwidth (200 kHz – 45 MHz). The received signals were sampled and averaged by a digital oscilloscope before acquisition. Each recorded signal corresponded to an average of sixteen laser shots in order to improve the signal-to-noise ratio. Motorized motion tables allowed us to move the laser line source to perform measurements at different distances between source and detector.

Measurements were made with this experimental setup on a 2 in. silicon wafer on which a layer of 1.3 μm of gold has been deposited. 500 signals were recorded, the distance between the emitter and the receiver being increased of 20 μm before each new recording over a total distance of 10 mm. The sampling frequency was set to 500 MHz. The time signals obtained are shown in Fig. 4.

4 The two-dimensional spectral analysis

The experimental study revealed the propagation of several guided modes. The data posttreatment by a fast Fourier transform (FFT) did not allow us to distinguish these different modes. A 2DFFT technique [11], involving both spatial and time transformations, was consequently used. To describe the surface displacement $u(x_1, t)$ of a guided wave propagating along a plate in the X_1 direction, the next analytic expression was assumed

$$u(x_1, t) = A(\omega) \cdot e^{i \cdot (k \cdot x_1 - \omega \cdot t - \varphi)} \quad (7)$$

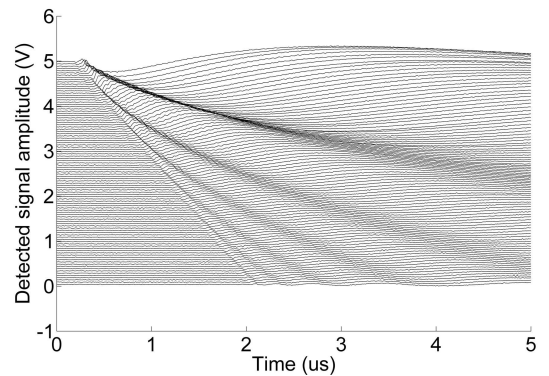


FIG. 4 – Representation of 100 time signals recorded each 100 μm on a 2 in. silicon wafer with a 1.3 μm thick gold layer.

where $A(\omega)$ is the frequency dependent amplitude and denotes the phase. The 2DFFT can provide the wave amplitude as a function of wavenumber and frequency

$$H(k, f) = \iint u(x_1, t) \cdot e^{-i \cdot (k \cdot x_1 - \omega \cdot t)} \cdot dx_1 dt \quad (8)$$

The 2D spectral analysis was applied to the experimentally obtained time signals (normal displacement) and the results are presented as contour plots of amplitude versus wavenumber and frequency in Fig. 5.

5 Layer thickness estimation with guided waves

The gold layer influence on the guided waves propagation has been theoretically probed. Several dispersion curves were obtained with different layer properties. The results are plotted in Figs. 6–8. In Fig. 6, only the layer thickness was changed between each computation, the other parameters being fixed to the gold characteristics or the silicon ones. It can be seen that the dispersion curves are significantly modified when the thickness layer increases. At high frequency, an interesting velocity gap between the two first propagating modes is present and is amplified when the thickness layer is increased. In Figs. 7 and 8 respectively, the layer thickness was kept constant to $1 \mu\text{m}$ but the layer Poisson ratio and the Young modulus were respectively increased. The influence of these two parameters on the dispersion curves is negligible.

The dispersion curves sensitivity to the layer thickness has been employed to measure the thickness of the gold layer deposited on the silicon substrate. The velocity gap between the two first modes was probed. To avoid an exact determination of silicon and gold elastic parameters, computations of this gap with several layer/substrate configurations were made. Assuming the characteristics presented in Table 1 for silicon and gold, 750 samples with characteristics in the range of 2.5% of these characteristics were used to compute the velocity gap at a frequency of 25 MHz. The results are plotted in Fig. 9.

The error made concerning the elastic parameters for each computation is presented as error bars. Despite

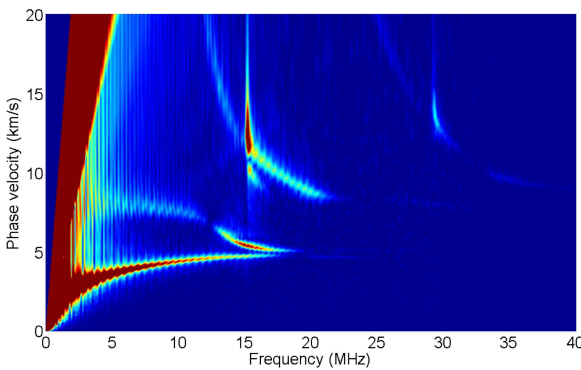


FIG. 5 – Contour plot of the 2DFFT results for the experimentations made on a 2 in. silicon wafer with a $1.3 \mu\text{m}$ thick gold layer.

these errors, it is still possible, knowing the gap value between the two modes, to determine the layer thickness with an accuracy of $\pm 0.07 \mu\text{m}$. This error represents less than 10% for layer thicknesses higher than $0.70 \mu\text{m}$.

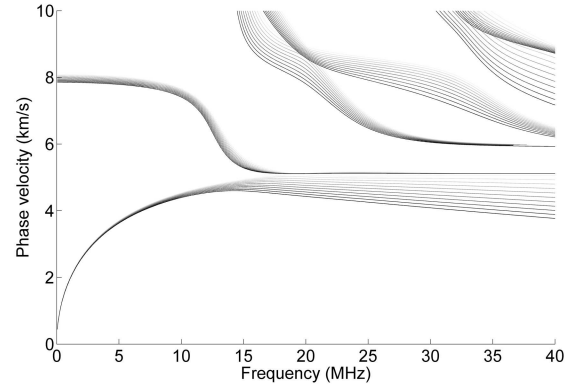


FIG. 6 – Influence of the layer thickness on the dispersion curves for the gold/silicon structure. The thickness is increased by $0.2 \mu\text{m}$ from $0.1 \mu\text{m}$ (light gray curves) to $2.1 \mu\text{m}$ (black curves).

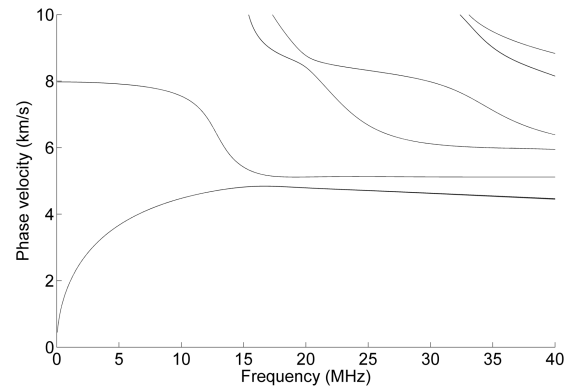


FIG. 7 – Influence of the layer Poisson ratio on the dispersion curves for the gold/silicon structure. The Poisson ratio is increased by 0.02 from 0.2 (light gray curves) to 0.45 (black curves).

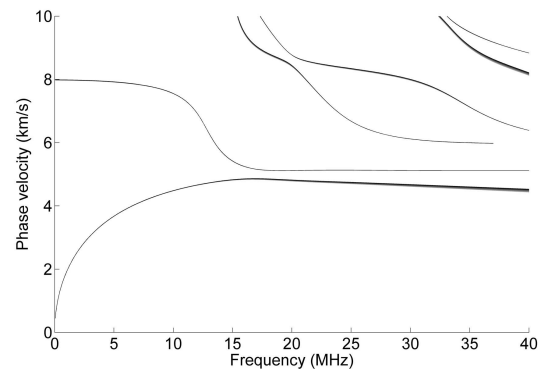


FIG. 8 – Influence of the layer Young modulus on the dispersion curves for the gold/silicon structure. The Young modulus is increased by 10 GPa from 50 GPa (light gray curves) to 150 GPa (black curves).

2 in. silicon wafer characteristics				
Thickness (μm)	Density (kg/m^3)	C11 (GPa)	C12 (GPa)	C44 (GPa)
275	2150	165.6	63.9	79.5
Gold layer characteristics				
Thickness (μm)	Density (kg/m^3)	Young modulus (GPa)	Poisson ratio	
1	19300	78	0.42	

TAB. 1 – The mechanical properties of the theoretical sample

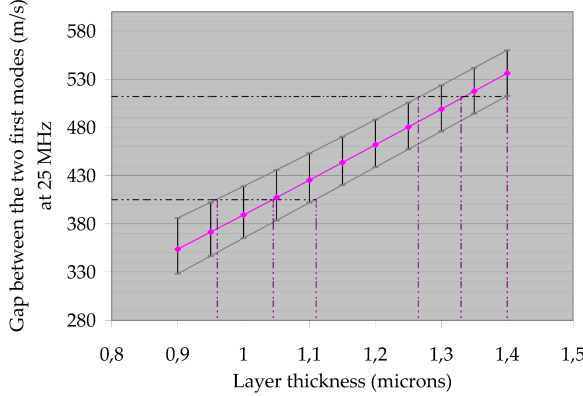


FIG. 9 – Mean velocity gap at 25 MHz between the two first propagating modes for different layer thicknesses. The mean was obtained after 750 computations with elastic properties close to the gold/silicon bilayered structure.

Here are presented results at 25 MHz, some others were obtained at different frequencies with the same conclusion but are not discussed here. This frequency was kept to facilitate the measurement of the experimental gap. Moreover, to validate the results obtained, a second thickness measurement was made with a high precision contact profilometer. These results are depicted on Fig. 10. The gold thickness obtained with this method was $1.30 \pm 0.04 \mu\text{m}$. This last measurement is in agreement with the result presented earlier.

6 Conclusion

A laser ultrasonic method for the analysis of guided waves in an anisotropic bilayered structure has been presented. Dispersion curves, with a clear identification of multimode guided waves, were obtained with a 2DFFT. Estimation of the layer thickness was made without exact knowledge of the layer/substrate elastic parameters and with only two modes. A good agreement between the finite element method simulation and the experiments has been obtained.

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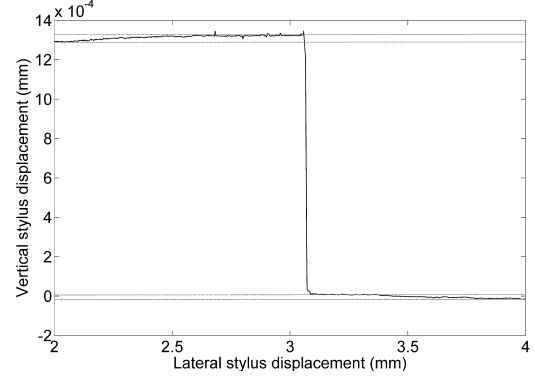


FIG. 10 – Profilometer results for the 2 in. silicon wafer with a deposited gold layer.

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