Silicon wafer characterisation by laser ultrasonics and neural networks

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Abstract. Lamb waves propagating in plate like structures, have been investigated to characterise a silicon wafer in a non destructive way. A laser ultrasonic technique was first used for the generation and the detection of these guided acoustic waves. A two-dimensional Fourier transform was next performed on the whole experimental data to obtain the dispersion curves, revealing the propagation of symmetric and antisymmetric modes. The sample characterisation was carried out in an original way, directly comparing the experimental results to theoretical ones. A feedforward neural network, specifically trained to recognize the same propagation behaviours, achieved to fit the experimental dispersion curves with a theoretical anisotropic model. Knowing the wafer thickness and density, the elastic constants were then determined without any user intervention. This non contact method showed very good agreement with the results obtained in the literature, and was found to be prompt and easy to automate.

1. Silicon wafers
A wafer is a thin plate of semiconductor material which undergoes many microfabrication process steps such as doping or ion implantation, etching, deposition of various materials, and photolithographic patterning, in order to receive microelectronic devices.

Wafers are made of highly pure, nearly defect-free single crystalline material. They are available in several standard sizes, from 1 inch to 12 inches. Many of a single crystal’s structural and electronic properties being anisotropic, when cut into wafer, the surface is aligned in one of several relative directions know as crystal orientations. The miller index is then used to define the crystalline orientation.

In this study, a (100) two inches silicon wafer has been probed. The wafer was 275 µm thick and double side polished.

2. Lamb wave propagation in cubic plates
Lamb waves are guided waves in a plate-like structure [1]. As in the case of an isotropic plate, two kinds of waves can propagate, antisymmetric or symmetric, the motion being respectively dominated by normal or in-plane components. Both symmetric and antisymmetric waves exist in different zero-
or higher order modes which are dispersive. All modes, excepting zero-order ones, have cut-off frequencies below which they cannot propagate.

![Figure 1](Image)

**Figure 1.** The coordinate systems of a uniform anisotropic solid plate of thickness d.

Figure 1 depicts the configuration of a uniform anisotropic solid plate of thickness d with parallel surfaces unlimited in the directions 1 and 2. Plane Lamb waves propagates in the \((X_1, X_2, X_3)\) coordinate system whereas the crystallographic coordinate system is represented by \((X'_1, X'_2, X'_3)\). A \(\varphi\) angle is present between the two coordinate systems.

The silicon crystal presenting a diamond cubic structure, the propagation problem resolution in the most general case of a triclinic material is not necessary. The different symmetries that can be found in the cubic symmetry allow simplifications to be made during the computation from the wave equation to the dispersion ones and result in a system of two equations [2]:

\[
\begin{align*}
\text{(Symmetric)} & \quad D_{11} \cdot D_{23} \cdot \tilde{s}_3 \cdot \tilde{c}_1 - D_{13} \cdot D_{21} \cdot \tilde{s}_1 \cdot \tilde{c}_3 = 0 \\
\text{(Antisymmetric)} & \quad D_{11} \cdot D_{23} \cdot \tilde{s}_3 \cdot \tilde{c}_3 - D_{13} \cdot D_{21} \cdot \tilde{s}_3 \cdot \tilde{c}_1 = 0
\end{align*}
\]

(1)

where

\[
\tilde{c}_q = \cos(k \cdot \alpha_q \cdot \frac{d}{2}) \quad \text{and} \quad \tilde{s}_q = \sin(k \cdot \alpha_q \cdot \frac{d}{2})
\]

(2)

and \(D_{11}, D_{23}, D_{13}, D_{21}, \alpha_q (q = 1, 3)\) depending on the elastic properties of the silicon \(c_{11}, c_{12}\) and \(c_{44}\), the density \(\rho\) and the phase velocity \(c\) computed in the <100> direction.

Dispersion curves obtained from the analytical resolution of these dispersion equations for a two inches silicon wafer are presented in Figure 2.

![Figure 2](Image)

**Figure 2.** Theoretical dispersion curves of a 2 inches silicon wafer.
3. Experimental setup

The system used to generate the acoustic waves is schematically shown in Figure 3 [3]. 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 5 mm length and 0.5 mm width. The energy per pulse was around 6 mJ, which allowed us to work in the thermoelastic mode.

The 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 to 45 MHz) [4]. 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 realize measurements at different distances between source and detector.

Experimental dispersion curves were obtained applying a two dimensional Fast Fourier Transform (2DFFT) on the whole data [6].

![Figure 3. Experimental setup for the laser generation and detection of the Lamb modes [5].](image)

4. Feedforward neural networks

No easy mathematical expression allows the description of the different propagation modes behaviour in the dispersion curves. Classical fitting methods are consequently difficult to implement on the 2DFFT results obtained. A more global method, using feedforward neural networks (FF networks), has been investigated [7].

A network is composed of single processing elements, called neurons, which can exhibit complex global behavior, determined by the connections between the processing elements and their parameters. The neurons are generally organized in layers, with a minimum of two layers by network: a hidden one and an output one. Each neuron performs a weighted summation of the inputs, which then passes a nonlinear activation function \( \sigma \), also called the neuron function.

![Figure 4. A feedforward network with one hidden layer and one input.](image)
Figure 4 illustrates a one-hidden-layer FF network with inputs \( X_1, \ldots, X_n \) and output \( Y \). Each arrow in the figure symbolizes a parameter in the network. The output of this network is given by:

\[
Y = \sum_{i=1}^{nh} w_i b_i + \sum_{j=1}^{n} X_j w_{i,j} + b_{j,i}^1 + b^2
\]

where \( n \) is the number of inputs and \( nh \) is the number of neurons in the hidden layer. The variables \( \{w_{i,j}, b_{i,j}, b_i^2, b^2\} \) are the parameters of the network model, the exponents 1 and 2 respectively referring to the hidden layer and the output one.

Supervised learning can be used to modify and to fix the parameters of the defined model. The network is fed with a training data, which consists of pairs of input values \( x \), and desired outputs \( y \). The weights are adjusted incrementally until the data satisfy the desired mapping as well as possible.

The FF network in Figure 4 is just one possible architecture of an FF network. The architecture can be modified in various ways by changing the options.

5. Inversion results

Measurements were made on the two inches silicon wafer described in the first section. 500 signals were recorded, the distance between the emitter and the receiver being increased of 20 \( \mu \text{m} \) before each new recording, over a total distance of 10 mm. The sampling frequency was set to 250 MHz.

The network used to estimate the plate characteristics was a two-layer feedforward neural network trained with the Levenberg-Marquardt algorithm [8]. A database of 2780 theoretical dispersion curves was used for the network training, with \( c_{11} \) varying from 130 GPa to 230 GPa, \( c_{12} \) and \( c_{44} \) from 30 GPa to 130 GPa. The input vector is composed of 29 velocity values, the hidden layer is made of 200 neurons, and the output layer gives the elastic characteristics of the tested sample.

The neural network was used on virtual samples first, with arbitrary material properties, different from the ones used in the training database. The characteristics of these samples and the test results are shown in table 1. Sample (a) and (b) inversion solutions in table 1 show good agreement with the plate characteristics, the elastics characteristics being in the database variation range. With sample c, the inversion is not relevant, the elastic characteristics being out of the database’s bandwidth.

Figure 5 represents the experimental dispersion curves of the tested wafer and the corresponding theoretical dispersion curves found by the network, which results are presented in table 1 (d). The fit is visually corresponding.
|          | C11 (GPa) | C12 (GPa) | C44 (GPa) |
|----------|-----------|-----------|-----------|
| (a)      | Plate characteristics | 223.00 | 116.00 | 98.00 |
| Inversion solution (error) | 222.54 (0.21%) | 115.94 (0.05%) | 97.19 (0.83%) |
| (b)      | Plate characteristics | 157.00 | 83.00 | 126.00 |
| Inversion solution (error) | 158.64 (1.04%) | 85.07 (2.5%) | 125.67 (2.6%) |
| (c)      | Plate characteristics | 50.00 | 200.00 | 20.00 |
| Inversion solution (error) | 122.48 (144%) | 118.00 (41%) | 14.36 (28.2%) |
| (d)      | Wafer characteristics | 165.60 | 63.90 | 79.50 |
| Inversion solution (error) | 166.33 (0.44%) | 64.04 (0.21%) | 80.77 (1.59%) |

Table 1. Inversion results obtained with the neural network for different samples.

6. Conclusion
A laser ultrasonic method for the analysis of Lamb waves in a silicon wafer has been presented. Dispersion curves, with a clear identification of multi-mode Lamb waves, were obtained with a 2DFFT. Estimation of the elastic constants was made with a feed-forward neural network. The obtained results show that this combination is an interesting non destructive and non contact way to investigate anisotropic plate-like structures, and could be used with more complex structure.

References
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