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ALL-OPTICAL ELASTIC CHARACTERIZATION OF SILICON WAFERS AND CANTILEVER BEAMS BY VIBRATION MODES

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ABSTRACT. An all-optical technique is developed to determine elastic parameters of both semiconductor wafers and cantilever beams through optical excitation and detection of vibration modes. Resonance frequency measurements of these modes are used to determine the materials Young's modulus and Poisson's ratio. The technique is remote, non-destructive and works on-line, making it an attractive inspection tool for use in semiconductor foundries and MEMS industries. Experimental results are compared with the values calculated by the theory of elasticity.

Keywords: Optical detection, vibration analysis, Silicon wafers, cantilever beams, MEMS, Young's modulus, Poisson's ratio.

PACS: 42.62 Eh; 43.58.+z; 46.40.-f; 42.62 Cf; 43.40.+s

INTRODUCTION

A phenomenological observation on the behaviour of resonance modes in Silicon (Si) wafers having two different crystallographic planes, namely $\langle 100 \rangle$ and $\langle 111 \rangle$ planes, led us to develop an experimental and analytical procedure to measure the corresponding in-plane and out-of-plane Young's modulus, E , and Poisson's ratio, σ . The motivation to investigate $\langle 100 \rangle$ and $\langle 111 \rangle$ single crystal Si wafers arises from their importance as component substrates in the electronic and MEMS (micro-electromechanical systems) industries [1]. The procedure is based on laser generation and detection of vibration modes in circular plates. This all-optical technique is completely non-destructive, require no sample preparation, and work on-line, rendering the full inspection of Si wafers at semiconductor foundries a simple and rapid routine. In fact, it is a generalization of the well-established resonance method for isotropic circular plates [1].

An all-optical technique has also been developed to generate and detect resonance modes in cantilever beams built on MEMS board. A novel and simple method to excite vibration modes is proposed. The generation laser pulse is directed to the opposite face of the Si substrate of the MEMS board. Acoustic excitation of the whole Si board then forces the cantilevers to vibrate in an effective way, as a variety of resonance modes are simultaneously excited. Measurements of the first resonance frequency can then be correlated to the effective Young's modulus of the cantilevers. To date, one of the most difficult parameters to measure in thin structures, such as the cantilevers considered here, has been the Young's modulus [2]. Our all-optical technique, which is non-destructive in nature, proved to be reproducible and easily implemented.

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Theoretical background

The vibration theory of isotropic circular plates under different boundary conditions is well documented [1]. In particular, if the circular plate is free, *i.e.*, held along its nodal lines or laid down on a soft and porous rubber pad, the resonance frequencies of the first pure torsional and flexural modes can be used to determine the Young's modulus, E , and Poisson's ratio, σ . In this case, owing to the invariance of both E and σ , rotation of the plate around the centre will not affect the measured frequencies of the modes generated and detected by the point probes indicated by Fig. 1. For anisotropic plates, however, this simple formalism cannot be applied, since the in-plane and out-of-plane E and σ are in general different, being the in-plane parameters also location dependent. Here we will describe an optical instrument capable of generating and detecting several resonance modes in Si wafers in an effective, robust and non-destructive way. Then, we will demonstrate that resonance frequency measurements of vibration modes in Si wafers can be predicted fairly well if we take into account the angular dependence of E and σ in the frequency equation of isotropic circular plates, resulting in [1]

$$f_{n,s}(\theta) = e_{n,s} \frac{h}{4\sqrt{3}\pi r^2} \sqrt{\frac{E(\theta)}{\rho[1-\sigma^2(\theta)]}}, \quad (1)$$

where $e_{n,s}$ is the mode eigenvalue, and h , r and ρ are the width, radius and density of the circular plate, respectively. The subscripts n and s stand for the number of nodal diameters and circles.

Experimental setup

The basic components of the experimental setup are illustrated in Fig. 2. Vibration modes in Si wafers were generated using a pulse from a frequency-doubled Q -switched Nd:YAG laser. Vibration modes were detected using a commercial heterodyne Mach-Zender interferometer (Ultra-Optec OP35-O) [3]. The interferometer is coupled to a demodulation unit that converts the photodetector output into an electrical signal proportional to the surface displacement. The wafers were laid down upon four tiny rubber pins mounted on a rotating table with a resolution of 1 degree. Further details about the experimental setup are found in [1].

Figure 1. Nodes and anti-nodes of the first pure torsional and flexural modes in free isotropic circular plates. G and D refer to the laser generation and laser

Figure 2. Experimental setup to generate and detect vibration modes in Si wafers. M is a mirror.

detection probes, respectively.

Experimental results, data analyses and discussion

The Si wafers employed in this work were commercial p-type, single side polished, <100> and <111> crystallographic planes. The diameters and thickness of these wafers were, respectively, 76.2 mm (3 inches) x 400 μm for the <100> Si wafer and 50.8 mm (2 inches) x 310 μm for the <111> Si wafer.

Fig. 3 illustrates the measurement procedure. Initially, each wafer was deposited on the four-pin support with the detection laser beam impinging upon a crystallographic axis of the polished surface. Then, the wafer was rotated 90 degree-clockwise at steps of 5 degrees, and signals were acquired.

Fast Fourier Transform (FFT) performed on typical resonance waveforms obtained in the <100> Si revealed that several modes could be effectively generated and detected, as shown in Fig. 4. It was also observed that, when flexural vibration modes were preferably induced by striking the wafer at the centre, the resonance frequency of the first pure flexural mode, $f_{0,1}$, slightly changed with rotation. For this mode, the variation on the frequency measurement was random and less than 1 %. On the other hand, by striking the wafer at the edge to favour torsional vibration modes, the resonance frequency of the first pure torsional mode, $f_{2,0}$, varied continuously and symmetrically with a 90-degree rotation. In this case, the variation on the frequency measurement was approximately 19 % and should be regarded as physical related.

Figure 3. Procedure to measure the resonance frequencies of torsional and flexural modes. Si wafers are rotated 90 degree-clockwise at steps of 5 degrees, while the detection probe D is kept fixed. The angle θ is defined as the line joining the center of the wafer to the detection point and a crystallographic axis.

Figure 4. Fast Fourier Transform (FFT) performed on resonance waveforms obtained in <100> Si wafers. The effect of in-plane anisotropy on the resonance frequencies of certain vibration modes is clear: a) generation beam directed at the wafer's edge to induce torsional vibration modes; b) generation beam directed at the wafer's center to induce flexural vibration modes.

Remembering that $\langle 100 \rangle$ Si wafers exhibit in-plane anisotropy with respect to E and σ , and that this anisotropy follows a 90-degree symmetry [1], we could correlate the resonance frequency measurements of the first torsional mode to the in-plane E and σ parameters. Solving Eq. (1) for $E(\theta)$ and $\sigma(\theta)$ (θ varying from 0 to 90 degrees), with the eigenvalue $e_{2,0}$ of the first torsional mode [1], and comparing these results to the direct measurements of resonance frequencies at different angles, a good agreement was found, as shown in Fig. 5a. Discrepancies were within 1.5 %. The resonance frequency of the first flexural mode could similarly be correlated to the out-of-plane E and σ parameters. With θ varying from 0 to 90 degrees, we measured $f_{0,1} = 883.6 \pm 3.8$ Hz. This value is consistent with $f_{0,1} = 887$ Hz obtained from Eq. (1), using E and σ pertaining to the crystallographic axis perpendicular to the $\langle 100 \rangle$ plane (*i.e.*, $E = 130.2$ GPa and $\sigma = 0.2783$), and the eigenvalue $e_{0,1}$ of the first flexural mode [1]. For solving Eq. 1 we used as density $\rho = 2300$ kg/m³ for Si.

Figure 5. Resonance frequency of a) the first pure torsional mode with respect to a 90 degree rotation of the $\langle 100 \rangle$ Si plane around the center and b) the first pure torsional mode with respect to a 90 degree rotation of the $\langle 111 \rangle$ Si plane around the center.

The procedure described above was repeated for the $\langle 111 \rangle$ Si wafer, where the in-plane E and σ parameters are supposed to be isotropic. Values found in the literature are $E = 168.9$ GPa and $\sigma = 0.2624$ [1]. Resonance frequency measurements for the first torsional mode, however, indicated a variation of approximately 3 % over a 90-degree rotation. This result, shown in Fig. 5b, confirms that the degree of anisotropy in $\langle 111 \rangle$ Si wafers is much less than in $\langle 100 \rangle$ Si wafers. Resonance frequency measurements for the first flexural mode resulted in $f_{0,1} = 1702.8 \pm 6.9$ Hz, which is also consistent with the value of $f_{0,1} = 1765$ Hz computed from Eq. (1) with E and σ referred to the axis perpendicular to the $\langle 111 \rangle$ plane (*i.e.*, $E = 187.5$ GPa and $\sigma = 0.1815$).

The inverse problem

Inspection of Fig. 4 reveals the modes effectively generated and detected by our setup as well as the effect of the wafer's anisotropy on the variation of the resonance frequencies. Experiments have demonstrated that these four modes, namely, the first pure torsional, the first hybrid, the first pure flexural and the second pure flexural are generated and detected with good SNR, and their frequency response to the rotation of the wafer is consistent with the in-plane and out-of-plane parameters as computed by Eq. (1).

Following the standard method to determine elastic parameters of thin and free isotropic circular plates [1], we propose a more general method equally valid for anisotropic circular plates. This novel method relies on the use of the curves shown in figures 6 and 7. Details about derivations of such curves and how to use them for elastic characterization purposes are thoroughly described in [1]. For an arbitrary orientation (θ) on a Si wafer, the procedure to determine the in-plane and out-of-plane E and σ parameters can be summarized as follows:

In-plane measurement:

- i) excite both the first torsional and first hybrid modes, and measure $f_{2,0}$ and $f_{2,1}$;
- ii) use the curve of Fig. 11 to find $\sigma(\theta)$ from the ratio $f_{2,1}/f_{2,0}$;
- iii) use the curve of Fig. 2 to find $e_{2,0}$ from $\sigma(\theta)$;
- iv) use Eq. (5) and $\sigma(\theta)$ to obtain $E(\theta)$ from the pair $(f_{2,0}, e_{2,0})$.

Out-of-plane measurement:

- i) excite both the first and second flexural modes, and measure $f_{0,1}$ and $f_{0,2}$;
- ii) use the curve of Fig. 12 to find σ from the ratio $f_{0,2}/f_{0,1}$;
- iii) use the curve of Fig. 2 to find $e_{0,1}$ from σ ;
- iv) use Eq. (3) and σ to obtain E from the pair $(f_{0,1}, e_{0,1})$.

Figure 6. Relation between the resonance frequency ratio of the first hybrid (torsional and flexural) modes ($f_{2,1}/f_{2,0}$) and the Poisson's ratio (σ) in free thin circular plates.

Figure 7. Relation between the resonance frequency ratio of the second and first pure flexural modes ($f_{0,2}/f_{0,1}$) and the Poisson's ratio (σ) in free thin circular plates.

To demonstrate the method, the in-plane and out-of-plane E and σ parameters were determined from the frequency measurements and then compared to the expected values of $\langle 100 \rangle$ and $\langle 111 \rangle$ Si wafers. Results for the in-plane characterization are shown in Figs. 8 and 9, and for the out-of-plane characterization, in Table 1. The reader is invited to refer to [1] for additional information.

Figure 8. Comparison of expected values as calculated by the theory of elasticity (solid curve) with inverse results (dots) for the $\langle 100 \rangle$ Si plane: a) in-plane Young's modulus; b) in-plane Poisson's ratio.

Figure 9. Comparison of expected values as calculated by the theory of elasticity (solid curve) with inverse results (dots) for the <111> Si plane: a) in-plane Young's modulus; b) in-plane Poisson's ratio.

TABLE 1. Out-of-plane mechanical parameters for <100> and <111> Si wafers.

Mechanical parameters	E (GPa)	σ
<100> Si wafer		
Measured	125.6	0.2986
Calculated	130.2	0.2783
<111> Si wafer		
Measured	180.7	0.2301
Calculated	187.5	0.1815

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Sample and experimental setup

Figure 10 shows an optical coherence tomography (OCT) image of the MEMS board and cantilever beams investigated in this work. The board (ICBPMAT5), has been developed by the École Polytechnique de Montréal for medical applications [3,4]. Typical dimensions for the cantilever beams are: length = 970 μm , thickness = 4.7 μm and width = 120 μm .

The experimental setup is sketched in figure 11. Resonances were excited optically by means of a pulsed Nd:YAG laser incident on the board. The optical excitation technique on the board itself rather than upon the cantilevers is novel and has shown to be very effective. An important advantage of this excitation technique is that the level of energy and probe location are easily adjusted, making it suitable for on-line and non-destructive inspection. A homodyne Michelson interferometer aligned with respect to an individual cantilever beam then senses the resulting mechanical vibration of the beam. More details about sample and experimental setup will be soon published elsewhere.

Figure 10. Optical Coherence Tomography (OCT) imaging showing of the ICBPMAT5 board .

Figure 11. Experimental setup for optical generation and detection of resonance modes in cantilevers.

Results and discussions

Figures 12.a and 12.b show resonance modes obtained on cantilevers #1 and #2, respectively. Four modes could be easily detected. Although the cantilever beams under investigation have a fairly complex geometry and material combination (several layers), the identification of modes could be accomplished by using the simple model of a rectangular isotropic cantilever beam for which the frequency equation is [4?]:

$$f_k = \lambda_k \frac{t}{l^2} \sqrt{\frac{E}{\rho}}, \quad (2)$$

where f_k is the mode frequency, λ_k is the mode eigenvalue ($\lambda_1 = 0.162$), and t , l , E and ρ are the thickness, length, Young's modulus and density of the cantilever, respectively. Assuming a rectangular cantilever beam 970 μm -long and 4.7 μm -thick made of SiO_2 ($E = 69 \text{ GPa}$, $\rho = 2203 \text{ kg/m}^3$), equation (2) gives the following values, in kHz, for the resonance frequencies of the first four modes: $f_1 = 4.529$, $f_2 = 28.38$, $f_3 = 79.48$ and $f_4 = 155.8$. In Table 2, one can compare the calculated and experimentally measured resonance frequencies of the first four modes for cantilever#1 and cantilever#2. It is interesting to note that equation (2) could be successfully used to predict the first mode resonance frequency (maximum discrepancy of 5%). For superior order modes, however, discrepancies can be as large as 28% [2].

Figure 12. Fast Fourier Transform of resonance signals obtained in a) cantilever#1 and b) cantilever#2.

TABLE 2. Calculated and experimentally measured resonance frequencies of the first four modes for cantilever#1 and cantilever#2.

Theoretical calculation (equation (1))	Measurement (cantilever#1)	Measurement (cantilever#2)
$f_1 = 4.529 \text{ kHz}$	$f_1 = 4.272 \text{ kHz}$	$f_1 = 4.456 \text{ kHz}$
$f_2/f_1 = 6.267$	$f_2/f_1 = 4.801$	$f_2/f_1 = 6.793$
$f_3/f_1 = 17.55$	$f_3/f_1 = 15.10$	$f_3/f_1 = 16.82$
$f_4/f_1 = 34.39$	$f_4/f_1 = 34.34$	$f_4/f_1 = 31.01$

From equation (2), the resonance frequencies of the first mode of each cantilever beam can be used in order to calculate the effective in-plane Young's modulus, E_{eff} . First, however, the effective density, ρ_{eff} , of the cantilevers must be determined. From the material properties of the cantilever beams of the ICBPMAT5 board listed in Table 3, the effective density is calculated using the following equation [2]:

$$\rho_{eff} = \sum \rho_i \frac{t_i}{t}, \quad (3)$$

where ρ_i and t_i are the density and thickness of each layer of the cantilever beam, and t is the total thickness of the cantilever beam ($t = 4.7 \mu\text{m}$). Equation 3 leads to $\rho_{eff} = 2389 \text{ kg/m}^3$. Hence, the effective Young's moduli for cantilever#1 and cantilever#2 are $E_{eff1} = 66.6 \text{ GPa}$ and $E_{eff2} = 72.4 \text{ GPa}$, respectively.

TABLE 3. Material composition of the cantilever beams of the ICBPMAT5 board [4].

Values for densities were obtained from [5].

	material	thickness (μm)	density (kg/m^3)
layer1	SiO_2	2.5	2203
layer2	SiO_x	0.7	2203
layer3	Si_xN_y	0.7	2887
layer4	Al	0.8	2700

CONCLUSION

We have developed an experimental and analytical procedure to measure the in-plane and out-of-plane Young's modulus, E , and Poisson's ratio, σ , of Si wafers with arbitrary crystal orientations. The approach is based on optical generation and detection of vibration modes in non-transparent circular plates. The obvious advantage of such an all-optical system is that it can be configured to be remote, non-destructive and work on-line.

An all-optical technique for generation and detection of vibration modes of cantilever beams built on MEMS was also developed. Vibration excitation was accomplished by a pulsed laser incident directly on the MEMS board rather than upon the cantilevers. Optical generation of vibration modes is desirable because the excitation energy and probe location are easily adjusted, making it suitable for on-line and non-destructive inspection. From measurements of the first resonance frequency of multi-layer cantilever beams, the effective Young's modulus could be calculated.

Further experiments and analyses have to be carried out on a larger number of similar samples in order to assess the accuracy of the all-optical technique proposed herein.

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