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Ultrasonic characterization of porous silicon using a genetic algorithm to solve the inverse problem

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ABSTRACT

This paper presents a method for ultrasonic characterization of porous silicon in which a genetic algorithm based optimization is used to solve the inverse problem. A one-dimensional model describing wave propagation through a water immersed sample is used in order to compute transmission spectra. Then, a water immersion wide bandwidth measurement is performed using an insertion/substitution method and the spectrum of signals transmitted through the sample is calculated using Fast Fourier Transform. In order to obtain parameters such as thickness, longitudinal wave velocity or density, a genetic algorithm based optimization is used.

A validation of the method is performed using aluminium plates with two different thicknesses as references: a good agreement on acoustical parameters can be observed, even in the case where ultrasonic signals overlap.

Finally, two samples, *i.e.* a bulk silicon wafer and a porous silicon layer etched on silicon wafer, are evaluated. A good agreement between retrieved values and theoretical ones is observed. Hypothesis to explain slight discrepancies is proposed.

1. Introduction

Analysis of ultrasonic waves which have been transmitted through a sample allows acoustic and hence mechanical parameters of the sample to be extracted. In most cases, signals are not overlapped and both time domain [1] and frequency domain [2,3] analyses can be used to determine parameters such as wave velocity, attenuation or density.

In some cases, the acoustic wave transmission coefficients in the frequency domain have been used in order to calculate these parameters [4,5].

When the thickness of samples is in the same order as the wavelength in the medium, or in the case of multilayer samples, overlapping can occur and direct measurements of parameters are not longer possible.

Nevertheless, ultrasonic non-destructive characterization of materials has been widely studied in the case of thin layers [6,5,7,8]. Given the complexity of received signals, model-based methods are proposed [8]. Using an inverse problem resolution, these parameters can be extracted [9]. However, most optimization methods need a guess of initial values [10]. In the case of material whose parameters have huge variations, it is difficult to guess initial values with sufficient accuracy to reach the correct solution.

In this study, a genetic algorithm based resolution is proposed to limit the impact of initial values. Indeed, this optimization method is known to converge towards the global solution [11] and to ensure unicity of solution. A 1-D wave propagation model is chosen to calculate the spectrum of the signal transmitted through a multilayer sample. This spectrum is dependent on geometrical and acoustical properties of each layer, such as thickness, wave velocity and density.

For validation purposes, the theoretical transmission spectrum of immersed aluminium plates is calculated and compared to experimental ones in order to retrieve acoustical parameters of the sample.

Then, a sample composed of a porous silicon (PoSi) layer etched on a silicon wafer is studied. Wave velocity and density of bulk silicon are known. The porous silicon layer is considered as homogeneous and its parameters are estimated by solving the inverse problem with genetic algorithm.

2. Porous silicon

2.1. Fabrication of the porous silicon layers

Porous silicon has found many applications in microelectronics. One can point out for example, the use of mesoporous Si as an

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isolating substrate for RF applications [12] or the application of the high specific surface of PoSi in sensors [13].

The PoSi layers were formed by the anodization in HF based solutions of highly doped (100) p-type Si (10–50 mΩ cm) samples with thicknesses varying between 650 and 700 μm. This type of silicon is known to produce mesoporous materials with pore diameters between 10 and 100 nm [14]. The etching process is highly anisotropic and pore direction is normal to the wafer surface as can be seen in Fig. 1. The electrochemical etching was performed in a double tank electrochemical cell developed by AMMT. The HF concentration is 30% and the surfactant used is acetic acid with volume ratios HF (50%):acetic acid:H_2O of 4.6:2.1:1.5. The anodization was performed in a galvanostatic mode. A current density of 28 mA/cm^2 was fixed to obtain an estimated porosity of 50%. Then, the duration determined the total thickness of the porous layers. In our case, a duration of 174 min lead to 200 μm. The average technological dispersion is in the range of 5–10%. Decontamination of samples is performed using several baths of pure water so that etching liquid is completely removed.

2.2. Materials specification

The samples used for this study are square-shaped crystalline silicon wafers on which a circular shaped PoSi layer with a one inch (2.54 cm) diameter is etched. This diameter is larger than the surface of the acoustic beam to ensure that all the ultrasonic signals pass through the porous medium. Porous silicon layer thickness has been measured using a destructive method in order to be compared with values retrieved using the inverse problem resolution. These values and the expected density are recalled in Table 1.

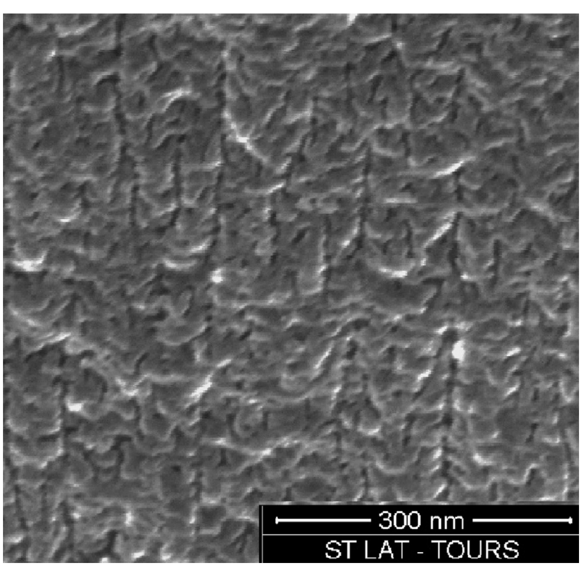

Fig. 1. SEM observations of a typical highly doped n-type mesoporous sample [12].

Table 1
Sample geometrical characteristics.

Sample number	Measured wafer thickness (μm)	Measured PoSi thickness (μm)	Expected PoSi density (kg m^{-3})
1	674 ± 1	0	–
2	675 ± 1	195–204	1650 ± 100

Table 2
Acoustical parameters of porous silicon, silicon and water.

Acoustical parameter @ 20 °C	Water	Silicon	Porous silicon variation range
Wave velocity (m/s)	1480	8430	1480–8430
Density ρ (kg m^{-3})	1000	2330	1000–2330

The physical parameters of the crystalline silicon and water used for this study are noted in Table 2 [15,16]. The ultrasonic wave velocity in water is strongly dependent on temperature [15]. In our study, the temperature of water is kept around 20 °C and is measured, allowing wave velocity in water to be corrected in calculations.

Porous silicon parameters are unknown and are the model inputs for optimization.

3. Inverse problem resolution

3.1. Model

The acoustic wave propagation model is based on the assumption of a 1-D plane wave propagation along the z-axis where the ultrasonic beam is normal to the surface and all the interfaces are parallel. Given that wavelengths in the considered bandwidth are more than 3 orders of magnitude larger than the pore size, the porous silicon layer is considered as a non-dispersive medium. In this study, all the measurements are performed using a water immersion method. Given the small deformation hypothesis, the acoustic velocity v in any one of the layers can be decomposed into a scalar and a vector potential field, respectively ϕ and ψ:

$$u = \nabla\phi + \nabla \wedge \psi \tag{1}$$

with

$$\phi = [a_+^L e^{jk_z^L z} + a_-^L e^{-jk_z^L z}]e^{-j\omega t} \tag{2a}$$

$$\psi = [a_+^S e^{jk_z^S z} + a_-^S e^{-jk_z^S z}]e^{-j\omega t} \tag{2b}$$

where a_-^U is the downstream amplitude, a_+^U the upstream amplitude and $k_z{}^U$ the complex wavevector (Eq. (3)) of mode U, which can either be shear (S) or longitudinal (L), and ω is the angular frequency

$$|k_z^L| = \frac{\omega}{c_z^L} \tag{3a}$$

$$|k_z^S| = \frac{\omega}{c_z^S} \tag{3b}$$

where $c_z{}^U$ is the wave velocity of mode U.

The matrix representation proposed by Cervenka and Challande [17] is used in this study. Each of the layers of the material can be either fluid or solid. In particular, the pseudo-fluid matrix proposed in his work allows the entire system to be represented by a single matrix. Since the sample is surrounded by water and the waves are normal to its surfaces, shear waves can be neglected, hence vector potential field ψ is null and displacement u can be written as follows:

$$u = \nabla\phi \tag{4}$$

Using the material characteristics of each layer (longitudinal wave velocity, attenuation, density, thickness), the propagation of ultrasonic waves can be computed. Taking into account the boundary conditions, waves in the output medium (A_t transmitted through the sample) and waves in the input medium (A_i the incident wave and A_r the wave reflected by the sample) are related