Photothermal elastic vibration method: investigation of the micro-electro-mechanical-systems

D. M. Todorović, B. Cretin, Y. Q. Song, P. Vairac

1 Institute for Multidisciplinary Research, University of Belgrade, P.O.Box 33, 11030 Belgrade, Serbia,
2 FEMTO-ST, Université de Franche-Comté, CNRS, ENSMM, UTBM, Besançon, France
3 MOE Lab for Strength and Vibration, School of Aerospace, Xi’an Jiaotong University, P.R. China

E-mail: dmtodor@afrodita.rcub.bg.ac.rs

Abstract. The various types of micromechanical structures (the cantilevers, membranes and plates) were studied by the photothermal elastic vibration method. The amplitude and phase of the photothermal elastic vibration spectra (the elastic displacements vs. the frequency of modulation of the laser beam) were measured. The analysis of these spectra showed that the different characteristics of the micromechanical structures can be obtained. The photothermal elastic vibration spectra, for example, can be used to analyze how the technological processes change the characteristics of the micromechanical structures.

1. Introduction

The development of microsystem technologies (surface and bulk micromachining) resulted in the production of miniature sensors, actuators, resonators and electromechanical parts. The photoacoustic (PA) and photothermal (PT) science and technology extensively developed new methods for the investigation of micro (nano) – electro – mechanical - systems (MEMS, OEMS). The PA and PT effects can be important also as driven mechanisms for optically excited micromechanical structures.

The PT and PA effects in micromechanical structures are based on the photogeneration of electron-hole pairs, i.e. plasma waves, generated by the absorbed intensity-modulated excitation. The plasma waves contribute to the generation of periodic heat and mechanical vibrations, i.e. thermal and elastic waves. The thermal waves also cause elastic vibrations, i.e. the thermoelastic (TE) wave generation. On the other hand, the photogenerated carriers produce periodic elastic deformation in the sample – the electronic deformation (ED). The TE and ED mechanism are two main mechanisms of elastic displacement (elastic bending) generation in optically driven MEMS (NEMS), OEMS.

The analysis of the TE and ED effects in micromechanical structures consists in modeling a complex system by simultaneous analysis of the coupled plasma, thermal and elastic wave equations. Todorović et al. [1,2,3], theoretically and experimentally investigated the TE and ED effects in micromechanical structures. The PT elastic vibration method was presented in our previously published papers [4,5].
In this work, the PT elastic vibrations method is used to investigate the characteristics of three different types of MEMS.

2. Photothermal elastic vibration method
The PT elastic vibration method is based on the laser excitation of the micromechanical structure and detection of the elastic vibrations with a very sensitive optical probe. The optical probe [6,7,8] is a heterodyne laser interferometer designed to measure the very low amplitude vibrations (below 1 picometer magnitude in accurate adjustment conditions). This setup includes optical excitation (doubled Nd:YAG laser, 532 nm, 200 mW), and optical probe detection (HeNe laser, 633 nm, 0.5 mW). The excitation laser beam is modulated and the response signal was measured in the frequency range 3~120 kHz.

The amplitude and phase of the PT elastic vibration spectra (the displacements versus the frequency of modulation of the excitation laser) were measured and analyzed. Figure 1 shows the typical configuration for three different micromechanical structures.

![Figure 1](attachment:figure1.png)

**Figure 1.** PT elastic vibration method for three different micromechanical structures: (a) the cantilever, (b) the membrane for pressure sensor; (c) the rectangular simple supported thin plate.

3. Experimental PT vibration spectra

3.1. Microcantilevers
Silicon cantilevers with different lengths and thicknesses were fabricated using the chemical etching process. The elastic vibrations were detected at the free end of the cantilever (Figure 1). Figure 2 shows typical experimental amplitude elastic vibration spectra for two silicon (Si, n-type, 3-7 Ωcm) cantilevers with different dimensions. Obvious peaks can be observed in the amplitude signal.

3.2. Membranes
One of the main types of micromechanical structures are the membranes. The standard low-pressure sensors are typically with square membrane with a concentric boss. These sensors were fabricated by
standard microelectronic technology. In this work we measured and analyzed the samples for three different technological levels: (1) first technological level – poor Si; (3) third level – Si with SiO₂ layer; and (4) fourth level – Si, SiO₂, sputter oxide and Al layers. The thicknesses of SiO₂, sputter oxide and Al layers are smaller than the thickness of the membrane, but these layers have significant influence on the elastic (the stiffness) characteristics of the membrane.

Figure 3 shows the amplitude PT elastic vibration spectra for the pressure sensors membranes for three different technological levels. The vibration was generated by means of the modulated focused laser beam in the center of the membrane and the displacement of the membrane was measured with the laser probe at a point close to the spot of the excitation beam.

![Figure 3](image_url)

Figure 3. Experimental amplitude of the PT elastic vibration spectra for three different technological levels.

3.3. Thin plate
Due to their importance in microelectronic applications and as a tool in the analysis of other fundamental semiconductor physical investigations, the SiO₂/Si structure has been studied extensively. The formation of SiO₂ is of essential importance in the fabrication of Si devices because of its masking and passivating capabilities, its basic role in MOS structures, and its characteristics as dielectric in the formation of capacitors and multi-level interconnections.

The micro rectangular plates with a different type of the silicon-dioxide film on the silicon substrate were measured. The SiO₂ films were formed by wet thermal oxidation with O₂ gas bubbling through the water solution of NaCl by the anodic oxidation of Si. The properties of SiO₂ are very sensitive to impurity content and structure. Figure 4 shows the amplitude PT elastic vibration spectra for the SiO₂/Si rectangular plate (SiO₂ film, 0.69 µm thick).
Figure 3. Amplitude of the PT elastic vibration spectra for the pressure sensors membranes (311) for three different technological levels: (1) poor Si; (3) Si with SiO₂ layer; (4) Si, SiO₂, sputter oxide and Al layers.

4. Analysis and discussion

PT elastic vibration spectra for different type of micromechanical structures were analyzed. For example, it is interesting to analyze the resonant frequencies for different boss type membranes. Table 1 shows the measured resonant frequency (first resonance f₁) for two different boss types and three different technological levels. For these data, it is possible to see that in this case, the technological processes cause the decreasing of the resonant frequency of the microstructure. The explanation for this is that the technological processes change the characteristic of the membrane. After the first technological level, when the chemical etching process forms the membrane with boss, in the next processes the thickness of the membrane practically is not changed. However, during the next processes (the technological levels (3) and (4)), the elastic characteristics (the stiffness …) are changed significantly. On the other side, the shape and mass of the boss practically are not changed. It is possible to conclude that in this case, the technological processes decreasing the effective frequency.

| Technological level | Resonant frequency (measured) f₁ [kHz] |
|---------------------|---------------------------------------|
| Sample 311          | Sample CC                             |
| (1)                 | 54.6                                  |
| (2)                 | 49.6                                  |
| (3)                 | 38.6                                  |
|                     | 58.4                                  |
|                     | 57.0                                  |
|                     | 45.5                                  |
Conclusion
The various types of micromechanical structures were studied by the photothermal elastic vibration method. The amplitude and phase of the photothermal elastic vibration spectra were measured. These results showed that the PT vibration spectra are very convenient for investigating the mechanical characteristics of various types of micromechanical structures (the cantilevers, membranes, and plates). For example, for the membranes with a concentric boss and different technological levels of production, it is possible to detect the influence of the technological processes on the PT vibration spectra. The analysis of the PT elastic vibration spectra showed that the different characteristics of the micromechanical structures can be obtained.

Acknowledgement
The part of this work was performed in the frame of the project TR 11027, supported by grants from the Ministry of Sciences and Technology Development, Republic of Serbia.

References
[1] D.M.Todorovic, P.M.Nikolic, A.I.Bojicic, K.T.Radulovic, Phys.Rev.B, 55(23), 15631-15642 (1997).
[2] D.M.Todorovic, P.M.Nikolic, Ch. 9 in Semiconductors and Electronic Materials (A.Mandelis and P.Hess, Eds., SPIE Opt.Eng. Press, Belingham, Washington, 2000), p. 273-318.
[3] D.M.Todorović, “Photothermal elastic bending method”, Anal. Sci., 17, s141- s144 (2001).
[4] Y. Song, B. Cretin, D. M. Todorović, P. Vairac, J. Phys. D: Appl. Phys. 41, 155106 (8pp) (2008).
[5] Y. Song, B. Cretin, D. M. Todorović, P. Vairac, J. Appl. Phys. 104(10), (6pp) (2008).
[6] B. Cretin and P. Vairac, Applied Physics Letters, 1(15), 2082-2084 (1997).
[7] P. Vairac and B. Cretin, Opt. Commun., 132, 19-23 (1996).
[8] B. Cretin and P. Vairac, Appl. Phys. A, 66, S235-S238 (1998).

Figure 4. Amplitude PT elastic vibration spectra for the rectangular plate: ( . ) SiO₂ / Si; ( * ) Si substrate ( <111> ). The errors indicate the characteristic frequencies.