Photoacoustics in the Study of Micromechanical Structures

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Photoacoustics and Elastics – Micro-Electro-Mechanical-Systems (MEMS) technologies enable the production of compact, lightweight, highly sensitive transducers (sensors, actuators, detectors and converters), whose work is based on elastic deformations and vibrations of micromechanical structures (MMS). A particularly important group consists of the so-called optical MEMS transducers - Micro-Opto-Mechanical- Systems (MOMS), in which elastic deformations and vibrations are generated by the absorption of modulated optical energy. Photoacoustic (PA) and photothermal (PT) effects are important as driven mechanisms for MMS (MOMS). In addition, PA and PT methods are important for measuring and analyzing the elastic displacements (deformations) and elastic characteristics of MMS. The connection between the theory of elasticity and PA and PT science is briefly presented.

Micromechanical Structures – The production of MMS (MEMS) takes place on pre-prepared pieces (Si wafers) of monocrystalline silicon (c-Si), the most commonly used technological process - anisotropic etching. MSs produced by micromachining process have an anisotropic structure (cubic crystal structure), which requires complex analysis in the elastic (mechanical) domain. Depending on the application, MMS is made in very different shapes (3D structures mechanically coupled to the frame; typically frame and MMS form the mechanical part of the microelectronic chip). Analysis of mechanical properties of these microstructures (elastic deformations, displacements, vibrations, ...) is a very complex problem, which requires different methods of modeling and measurements.

Photoacoustic Effect in Micromechanical Structures – A general theoretical analysis of the transport processes in a semiconductor MMS is presented by modeling the complex system of the plasma, thermal and elastic wave phenomena. This theoretical treatment enables quantitative accounting of the amplitude and phase of the carrier density, temperature and elastic displacement and describes their functional dependence on the modulation frequency and thermal, elastic, and carrier transport properties of the MMS.

Photoacoustic (PA) effect in semiconductor MMS is based on the photogeneration of electron-hole pairs, i.e. plasma waves, generated by the absorbed intensity-modulated (time-varying; pulse, periodical) optical excitation. Depth-dependent plasma waves (the carrier-density or plasma field) contribute to the generation of space and time-varying heat (the temperature field) and mechanical vibrations (the elastic displacement field), i.e. thermal and elastic waves. Thermal waves can propagate to the surfaces of the sample, i.e. may cause temperature changes in the gas layer near the sample surface. Changes in gas temperature cause a change in gas pressure, i.e. acoustic response to optical excitation - PA signals. This is the so-called thermodiffusion (TD) mechanism of PA signal generation (thermal piston). On the other hand, the thermal and plasma waves in the MMS can cause elastic vibrations - the thermoelastic (TE) and plasmaelastic (PE) mechanism of PA signal generation. Vector sum of the TE and PE components forms mechanical PA signal (mechanical piston).

In linear elastic materials it is possible to use the principle of superposition, i.e. consideration of separate components of elastic displacement and their addition in order to find the field of total elastic displacements as a vector sum. For example, given the PA experimental configuration considered a uniformly optically excited square membrane. In mechanical point of view, the membrane is modeled as a thin elastic plate (Kirchhoff-Love plate theory). Two components of the elastic displacement of the thin elastic plate have significant influence on the measured PA signal. These two components are out-of-plane displacements and they defined separately as: a) pure elastic expanding W_E along thickness and b) pure elastic bending W_B of the uniformly optically excited plate.

In the PA solid-gas-microphone detection configuration, using the composite-piston model, the PA signal in Si MMS can be written as a vector sum of five components: one thermal - the thermodiffusion S^{TD}, and four mechanical: S_E^{TE}, S_E^{PE}, S_B^{TE} and S_B^{PE}, where S_B correspond to the elastic bending, and S_E to the elastic expanding.

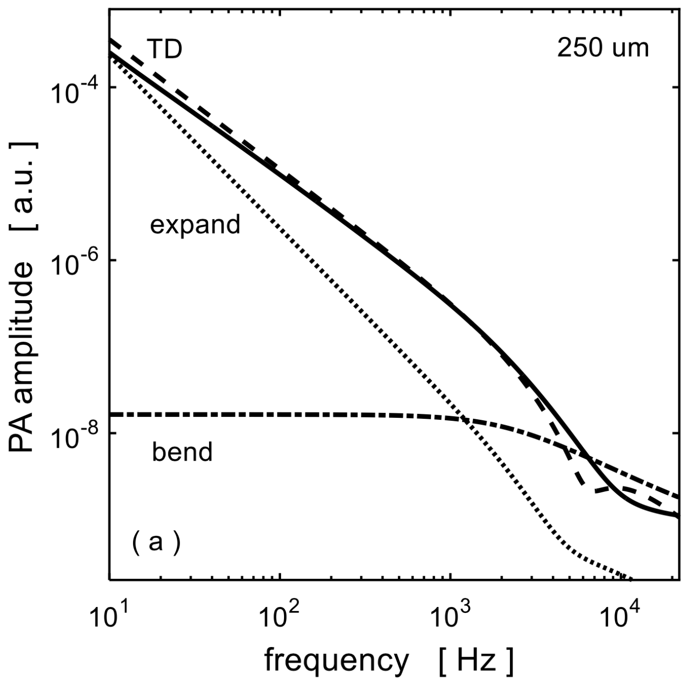

Fig. 1. PA amplitude of a Si micromechanical structure vs. frequency of modulation of the optical excitation. Micromechanical structure is Si chip with frame and square membrane (length L = 3000 and thickness h = 250 μm). In mechanical point of view, in this case the membrane is modeled as a thin elastic plate. PA components: (– –) TD; (···) expanding; (_._) bending.

The comparison of the experimental and theoretical PA spectra confirms the previously obtained results of the theoretical analysis and shows the possibilities of applying the PA method for testing the elastic characteristics of MMS. This research is important for many practical experimental situations (atomic force microscopy, thermal microscopy, thermoelastic microscopy, etc.) and sensors and actuators.