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Research of mechanical stresses in irradiated tin-doped silicon crystals

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ABSTRACT

An optical method of registration of mechanical stresses in undoped and tin-doped silicon samples is offered. Influence of electron irradiation on energy 5 MeV and high-temperature treatment at a 723 K on residual stresses in a silicon lattice was analyzed in the paper. The proposed method is based on a modulation of polarization of laser radiation transmitted through the anisotropic area and the definition of its anisotropy parameters by means of this modulation. The modulation polarimetry technique is an express method with high detection and resolution. The method allows identifying residual stresses in samples in absolute units with a resolution of $1{\cdot}10^{-4}$ MPa.

1. Introduction

Silicon (Si) is the basic material for numerous microelectronic, photovoltaic and sensor devices [1–4]. Its electronic properties are known to be significantly affected by the presence of impurities and defects, which play an increasingly important role with the miniaturization of devices. One of the promising silicon parameter control methods is doping by isovalent impurities [5,6]. Influence of isovalent impurities on Si properties is determined primarily by internal elastic deformations of a lattice. These deformations are due to a difference of atoms covalent radii of a matrix and impurity. Presence of local internal stresses can significantly influence on processes of defect-impurity interaction, as at a growing crystal, and under various external influences [7].

Therefore, even small changes of mechanical stresses arising in the silicon under influence of various external factors (radiation, heat treatment) [8,9], may lead to changes in electrical properties of the material. Several mechanical stress analysis techniques have been developed for silicon integrated circuits, substrate and device inspection. The most common techniques measure changes in elastic properties (e.g., micro-Raman spectroscopy, infrared grey-field polariscope, x-ray diffraction, acoustic microscopy) or stress-induced curvature of a device or structure (e.g., reflected laser, interferometry, coherent gradient sensing). Micro-Raman spectroscopy [10] is a technique for the study of local stress in silicon. It has the advantage of being non-destructive, one can control the probed depth by changing the wavelength of the exciting laser, and the spatial resolution is fairly good. Several studies are going on to improve this spatial resolution, for example by near-field optics, using optical fibers, or by decreasing the wavelength. One can measure on the sample surface, or, if more information on the variation of the stress with depth is required, on a cleaved surface, as for example near trench structures. Although it takes a good instrument and some knowledge about factors that may influence the Raman peak position, such as temperature, laser stability and outlining, the technique is relatively simple. One measures the silicon Raman peak at different positions and one monitor the position of this peak. This directly provides important information on the local stress variations in the sample.

Infrared grey-field polariscope [11] has been developed to provide rapid, full-field stress analysis for infrared-transparent materials. The capabilities of this scientific tool are proven using standard sample geometries fabricated from single crystal silicon substrates and the general applicability of the instrument demonstrated on bonded devices and silicon wafer geometries. Stress resolution in silicon wafers is 0,1 MPa at wafer inspection speeds of 10 s for a 100 mm wafer. Initial applications of the infrared grey-field polariscope have shown that the tool provides improvements in defect detection and stress quantification when compared to conventional infrared transmission imaging.

X-ray diffraction [12] offers the highest sensitivity and is widely used in both industry and academia. This non-destructive, single-point technique measures changes in the crystal lattice spacing to determine residual stresses. Incredibly high strain sensitivities on the order of 10^{-8} can be obtained for large Bragg angles and sensitivity on the order of 10^{-5}–10^{-4} is possible for angles of approximately 45°. Though highly sensitive, the small spot sizes and long inspection times render x-ray diffraction unsuited to real-time inspection in an industrial setting.

Scanning acoustic microscopy is a full-field, non-destructive technique capable of detecting changes in elastic properties of solids [13]. Compared to X-ray topography, this technique is relatively quick and

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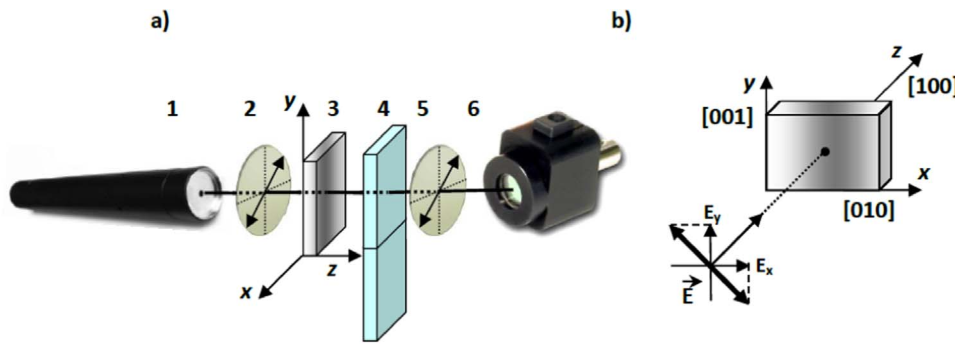

Fig. 1. The optical schema for measurements of birefringence (**a**): 1 – Ge-Ne laser; 2, 5 – linear polarizers; 3 - sample; 4 - photoelastic polarization modulator; 6 – photodetector; **b**) geometry of the experiment and crystallographic directions in the silicon crystal.

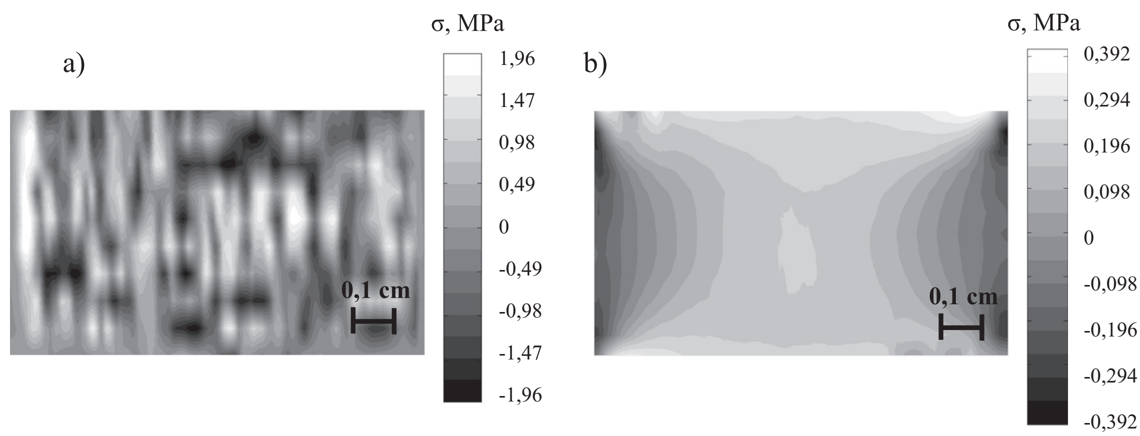

Fig. 2. Distribution of residual stresses in the tin - doped silicon sample (a); not tin - doped silicon sample (n-type) (b).

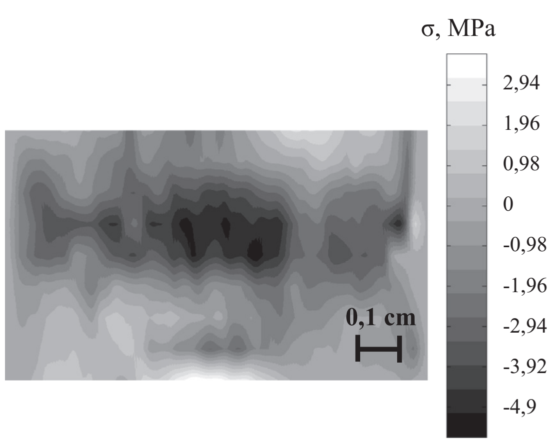

Fig. 3. Distribution of residual stresses in the tin - doped silicon sample after heat treatment at 723 K.

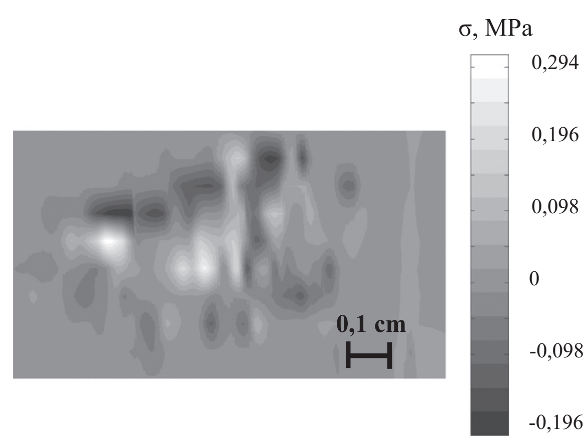

Fig. 4. Distribution of residual stresses in the tin - doped silicon sample after irradiation $Si(Sn)_{ir}$ and isochronal annealing.

inexpensive and is applicable to both crystalline and amorphous materials. An important drawback of acoustic microscopy is that measurements must be carried out in a coupling liquid and the sample must be rastered in order to present two-dimensional images, again rendering this technique unsuitable to real-time, on-line inspections.

The main drawbacks of described and mentioned methods of mechanical stress registration are the following. Either the resolution is too small, or they are destructive, or they have to go hand in hand with complex modeling, or they can be applied only to a certain class of materials, or they are costly and unsuited to real-time inspection.

A technique that has shown promise for providing very sensitive residual stress measurement is photoelastic stress analysis. This method has recently evolved and is related to a category of non-destructive. However, it is not the only version of the method described in classical monographs. There is a new its version, which allows us to find low residual stresses in Zerodur kind materials where these stresses usually considers as absent [14]. In this case, we deal with the technique of the modulation polarimetry (MP) whose detectivity is unsurpassed for registration of the birefringence caused by a directed strain. MP technique described in detail in [14–16]. The method is based on the well-established principles of photoelasticity with the addition of the polarization modulator in the optical scheme. In this article, we introduce the developed optical scheme and modulation polarimetry technique for high-precision and fast measurement of mechanical stresses in silicon samples. This method demonstrates the defect location in semiconductors using several samples (initial and after heat/radiation treatment).