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Modification-Scanning X-ray Microscopy of Semiconductor Structures Using Kumakhov Optics

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Abstract—A modification variant of scanning X-ray microscopy using Kumakhov optics has been realized for the first time. Using the proposed device, radiation tests of pressure sensors based on silicon-on-sapphire structures were performed under laboratory conditions. The source of ionizing radiation in the new device is an X-ray tube with a middle-focus polycapillary Kumakhov lens.

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A comparative analysis of the defect formation processes in metal–insulator–semiconductor (MIS) structures under the action of α and β radiation [1] showed that the mechanisms of direct atomic displacement on SiO_2 in the case of α particles do not significantly contribute to the generation of charged particles in SiO_2 and at the Si–SiO_2 interface. Investigations of the relaxation of mechanical stresses in Si–SiO_2 structures under the action of α and β particles are also indicative of the dominant role of ionization mechanisms in the defect formation in MIS structures. These facts suggest [1] that radiation tests on such structures for the analysis of changes in the charged state of insulators [2] or the surface density state in semiconductors [3] can be performed using more convenient sources of ionizing radiation—for example, X-ray tubes—rather than conventional α and β radiation sources.

In addition, X-ray radiation can be used in the electronic technology as a means of increasing certain useful properties, for example, increasing magnetic sensitivity of planar-diffusion semistor structures [5]. It was also reported that X-ray irradiation of silicon-on-sapphire (SOS) structures leads to modification of the surface microrelief, refractive indices, and optical absorption coefficients of both silicon and sapphire [6, 7].

The main factors determining the character of radiation effects in insulator–semiconductor systems include the presence of mechanical stresses in the system before irradiation and their transformation under the action of radiation [1]. It is possible to use X-ray radiation in the technology of such systems as a factor decreasing interlayer stresses, which can provide for an increase in the performance characteristics of devices. The proposed X-ray-stimulated modification can initiate changes not only in the electron structure of materials, but also in the character of physicochemical processes [1], which can probably lead to a decrease in the level of surface mechanical stresses at the interfaces. At present, this is usually achieved by means of cyclic thermal treatments. The use of high-intensity beams of nuclear radiations is hindered by the low availability of accelerators and reactors, high cost of such facilities, difficulties in using radionuclide sources, and the danger of induced radioactivity in the processed materials and devices. Thus, it would be expedient to study the influence of X-ray radiation on the mechanical stresses in semiconductor structures [8] in view of the use of such processing for the creation of stress sensors based on SOS structures and the development of related detectors and pressure transducers.

The well-known Kumakhov X-ray optics provides a means of obtaining local radiation densities under laboratory conditions on a level comparable to that of synchrotron sources ("laboratory synchrotron") [9]. Using the principles of Kumakhov optics, it is possible to transfer X-ray intensity over large distances from the source, which simplifies the optimum arrangement of equipment and helps eliminate the negative and dangerous factors.

This Letter presents the results of experimental investigations of the effect of X-ray radiation focused by a Kumakhov lens on the SOS-based resistance strain gauges used in microelectronic pressure sensors of the MIDA series [10]. The aim of this study was to evaluate the stability of the performance characteristics of pressure sensors under the action of ionizing radiation, to estimate the range of exposures and radiation power densities for nondestructive (nonmodifying) X-ray diagnostics (see, e.g., [11, 12]), and assess the possibility of using focused X-ray beams for the modification of the microelectronic structures under consideration [8]. All experiments were performed on a special setup designed and constructed for the investigation of Kumakhov optics [13, 14].

A medium-focus Kumakhov lens was manufactured at the Institute for Roentgen Optics (Moscow) and had X-ray optics characteristics analogous to those reported in [15, 16]. The input diameter of the lens was 3 mm, its length was 265 mm, and the front and back focal distances of the lens were 180 and 95 mm, respectively. An increase in the local intensity of radiation by means of the Kumakhov lens significantly reduces the time required for accumulating necessary doses, thus accelerating the technological procedures. The characteristics of pressure sensors used in the tests are described in detail elsewhere [10]. The X-ray radiation was focused on the accessible semiconductor structure arranged on the edge surface of the sensor device.

Initially, the samples were irradiated directly using the emission from an XTF 5011 X-ray tube (Oxford Instruments) with a mirror tungsten anode, without any additional X-ray optics. The samples were positioned at a distance of 1 cm from the beryllium foil window of the X-ray tube (which corresponds to a distance of $\approx$3 cm from the focal spot of the tube). The tube operated at a power of 50 W, in a maximum power regime at an accelerating voltage of 50 kV (upper limit) and a current of 1 mA, in which case the X-ray photon flux into a 4π solid angel was $\sim 10^{13}$ s^{-1}.

The state of the pressure sensor was characterized by monitoring the resistance of its bridge circuit. X-ray irradiation under the conditions described above produces only insignificant variations, which were caused predominantly by the thermal action of the heated metal case of the X-ray tube (this was checked by switching off the power source, whereby the changes were retained). When the sample was removed from the tube, the resistance relaxed to the initial value. Thus, for studying the effect of X-ray radiation on the sample, it was necessary to take additional measures for eliminating the thermal effects. It was possible either to remove the irradiated object from the X-ray tube to a distance sufficiently large to exclude the effect of heating or to use a thermal shield. In either case, the radiant flux density would be decreased.

The problem was solved with the aid of a medium-focus Kumakhov lens, which offers the advantageous transmission properties of the Kumakhov optics, makes possible local irradiation, and provides for an increase in the radiant flux density at the object. With this lens, the radiant flux density at a distance of 0.5 m from the focal spot of the X-ray tube was the same as that at a distance of several centimeters. It should be noted that the approach to the source in the case under consideration is limited by the X-ray tube design, in which the focal spot is spaced 2 cm from the beryllium window (this is typical of commercial X-ray tubes).

The experiments with X-ray irradiation via the Kumakhov lens were performed in various regimes, using different sections of the beam (from minimum to maximum) and the action sequential of focused radiation (scanning) on the entire surface of the microelectronic chip. The maximum duration of exposures was 3 h. The maximum radiant flux density on the sample surface was $\sim 10^{10}$ s^{-1} mm^{-2}, and the maximum total fluence reached $\sim 10^{14}$ mm^{-2} in the energy range from 5 to 50 keV.

The use of Kumakhov X-ray optics (capable of focusing the beam spot up to the micron level) in combination with a scanning facility that provides the possibility of sample modification can be considered as a new variant of scanning X-ray microscopy [12], namely, as modification-scanning X-ray microscopy of semiconductor structures. In this study, the proposed approach has been implemented for the first time.

Despite the action of X-ray radiation in the doses indicated above, the pressure sensors showed no significant changes in the technological and working characteristics, which was confirmed by delayed tests.

In conclusion, the use of a Kumakhov X-ray lens for radiation testing has proved to be a convenient and promising technique. The pressure sensor structure demonstrated high radiation stability. For the use of X-ray radiation in the technology of such (and similar) devices with the aim of electron structure modification, it is necessary to study the effect of even higher radiation intensities.

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