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PROPERTIES OF A SILICON SURFACE EXPOSED TO NANOSECOND LASER-RADIATION PULSES

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Results of the use of nanosecond laser pulses in the technology of production of very-large-scale integration circuits are presented. It is shown that, depending on the conditions of processing of silicon by these pulses, they can avoid mechanical failure of the silicon crystal lattice and form a gettering layer that cleans the silicon from impurities.

Introduction. One of the most promising methods of thermal treatment of silicon structures in the technology of production of submicron integrated circuits is the processing of them by radiation pulses. This method makes it possible to substantially decrease the time of thermal treatment of the silicon structure and, consequently, to decrease the number of defects arising in it in the process of long high-temperature treatment. It is advantageous to realize this method with the use of low-energy particles because the main effect arising in the process of their interaction with a solid body is a large release of heat from this body as a result of the excitation and relaxation of its electron subsystem during the electron or photon exposure.

At present, three universally adopted regimes are mainly used for heating of silicon structures [1]:

1) the adiabatic regime (lasting for 10^{-10}–10^{-6} sec) realized with the use of fairly short radiation pulses that do not cause transfer of heat from the layer in which radiation is absorbed into the bulk of the plate;

2) the heat-flow regime (10^{-6}–10^{-2} sec) realized under the conditions where, for the time of the pulsed photon treatment of a sample, the region of diffusion redistribution of heat becomes larger than the thickness of the layer in which radiation is absorbed but does not extend to the whole volume of the sample;

3) the thermal-balance regime (more than 10^{-2} sec) is established when the heat front reaches the nonradiated side of the sample and equalizes the temperature profile in its thickness.

In the case where a silicon plate is subjected to rapid thermal treatment, the adiabatic regime is considered as holding the greatest promise because it makes it possible to melt a thin surface layer of the plate with no change in the temperature of its substrate. This provides a means for obtaining supersaturated solutions, the removal of films of different materials, the cleaning of the surface layers from impurities, and the realization of the technology of production of very-large-scale integration circuits. This regime is realized with the use of different lasers irradiating pulses of duration 10^{-8}–$6 \cdot 10^{-7}$ sec.

The surface of an untreated silicon plate consists of pure-silicon regions, regions with a dielectric, and, in the case of formation of current-carrying layers, regions with a metal; because of this, on irradiation of it, these regions differently absorb photons, which leads to the appearance of temperature gradients on the plate and, as a consequence, to the formation of defects in the silicon and in the structure of the integrated circuit.

Results and Discussion. In the case where a silicon structure is subjected to rapid thermal treatment in the adiabatic regime with the use of a monochromatic or a coherent laser radiation, the radiation reflection coefficient depends on the radiation wavelength and the thickness of the dielectric on the silicon [2].

Our calculations have shown that, for a radiation wavelength of 1.06 μm (radiation of an YAG:Nd$^+$ laser) and thickness of the hydrated-silica plate equal to the half this wavelength, the radiation reflection coefficient reaches 30%. For a hydrated-silica plate of thickness equal to a quarter of the radiation wavelength, the coefficient of reflection of radiation from the dielectric decreases sharply and comprises less than 1%, i.e., practically all the incident radiation en-

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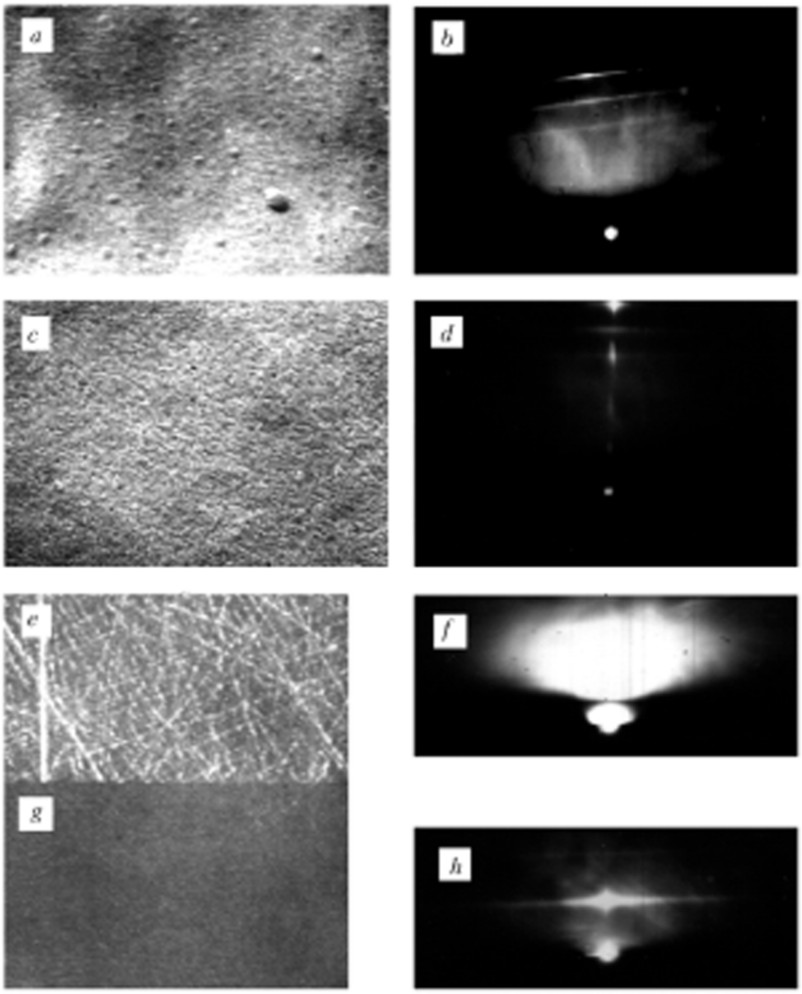

Fig. 1. Microrelief of the surface of a silicon plate and pattern of diffraction of radiation reflected from it in the case where the plate was subjected to chemical-mechanical (a, b) and mechanical (e, f) polishing and processing by laser-radiation pulses of nanosecond duration (c, d) and (g, h) respectively.

ergy is absorbed by the silicon. When the melting point of silicon is attained, this energy can be sufficient for erosion of the silicon under the oxide. This effect will manifest itself to a larger extent in the region of the wedge at the edge of the window in the oxide, the variations in the thickness of which leads to variations in the absorption of radiation and, as a result, to erosion of the silicon surface or to increase in the depth of occurrence of the *p*–*n*-junction under the wedge. This means that, in order for the radiation to be absorbed uniformly throughout the area of the silicon plate, its surface should be optically uniform.

The processing of a silicon structure by laser-radiation pulses can be used, depending on the pulse duration, for the cleaning of their working surface from impurities (10–30 nsec) and the formation of a gettering layer (100–150 nsec).

When laser pulses of duration 10–30 nsec are used, the depth of the local melting of the surface of a silicon reaches 1 μm; in this case, thermal stresses can arise in the silicon because of the appearance of a large temperature gradient at the boundary between the two phases: the liquid and the crystalline silicon. An investigation of silicon plates exposed to a laser beam of energy density 1.0–3.5 $\mathrm{J/cm^2}$ by the photoelasticity method has shown that thermal stresses and structural defects do not arise under the action of radiation with an energy density falling within the above-indicated range. This, evidently, is explained by the fact that, for the time of laser-radiation action, a plastic silicon flow has no time to form, and the thermal stresses arising in this case are purely elastic in character and disappear

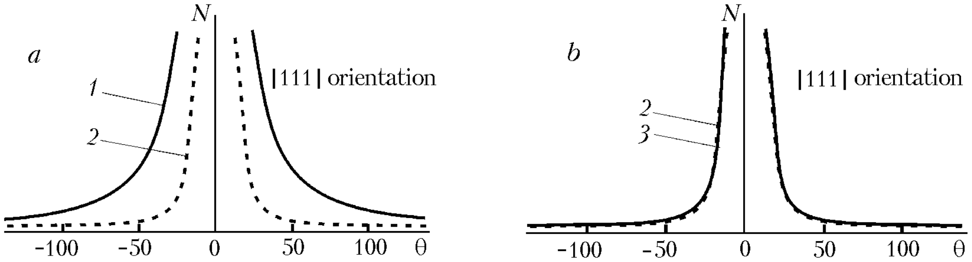

Fig. 2. Curves of diffraction reflection of radiation from the surface of a silicon plate subjected to the mechanical polishing (a) and then to processing by laser-radiation pulses of nanosecond duration (b): 1) before processing; 2) standard surface; 3) after processing.

when the treatment ends. At the same time, the mechanical stresses occurring in the plate decrease as a result of such a treatment, which is evidenced by the change in its deflection. This is supported by the following facts: if a silicon plate has an initial negative deflection, irradiation of its working side increases this deflection, and, in the case where a silicon plate has a positive deflection, this deflection decreases under the action of radiation. Such behavior of a silicon plate can be explained only by the fact that the deformed layer on the working side of the plate is removed under the action of irradiation as a result of its melting and subsequent recrystallization.

The examination of the working surface of the silicon plates, subjected to a final chemical-mechanical polishing (Fig. 1a), with the use of an electron microscope, has shown that this surface has a relatively smooth microrelief with irregularities of size not larger than 30 nm. The pattern of diffraction of the radiation reflected from these plates (Fig. 1b) shows that the crystallographic planes of their deep layers are predominantly parallel. The laser processing of the surface of the plates being investigated by laser pulses of energy density 2.5 J/cm^2 and duration 25 nsec (λ = 1.06 μm) significantly changed the morphology of this surface. The microrelief of the indicated surface became smooth and practically free of microasperities (Fig. 1c). In the electrograms presented in Fig. 1d, one can see the continuous vertical rods characteristic of an atomic-plane surface; these rods arise as a result of the two-dimensional diffraction of radiation reflected from the surface atomic layers of a silicon plate and suggest that laser processing of this plate leads to perfection of the crystal structure of its surface. This is also supported by investigations of the influence of laser processing on the crystal structure of the surface of silicon plates characterized by a lower quality of their preparation (polishing with diamond suspensions with grains of size 1–3 μm). The surface of such plates is covered by a dense net of differently directed marks having different lengths, representing the so-called "diamond background" (Fig. 1e). In this case, the structure of the surface layer of the silicon plate is deformed so that the electronogram "for the reflection" has the form of a diffuse halo (Fig. 1f). After the processing, the "diamond background" disappears (Fig. 1g) and Kikuchi lines appear in the electronogram (Fig. 1h). This is evidence that the crystallographic planes of the deep layers are not deformed and are strictly parallel.

These results are entirely supported by investigations carried out by the method of differential reflection curves. A comparison of the differential curves of the reflection of radiation from the surface of a silicon plate before and after the processing of it by laser radiation (Fig. 2) has shown that the broadening of the base of a differential reflection curve, characteristic of a deformed layer, disappears after this processing and the curve approaches the standard one characteristic of an ideal surface.

In the processing of the surface of a silicon plate by nanosecond laser pulses, the deformed surface layer, formed in the process of final chemical-mechanical polishing of the plate, is removed as a result of its melting to a depth comparable to the laser-radiation wavelength and the thickness of this layer.

The formation of a deformed layer on the surface of the silicon plate increases its free surface, and, consequently, the surface energy (the potential energy of the silicon atoms at the plate–air interface is two times higher than the energy in the bulk of the plate because these atoms are surrounded by silicon atoms only on the side of the plate bulk). In the region of the hemispherical scratches there arises a capillary pressure that serves to decrease the free energy and to form a stable equilibrium state of the plate with a minimum surface energy. As the temperature of the plate increases, the interacting force of atoms in the crystal lattice of the silicon decreases and, when it becomes equal

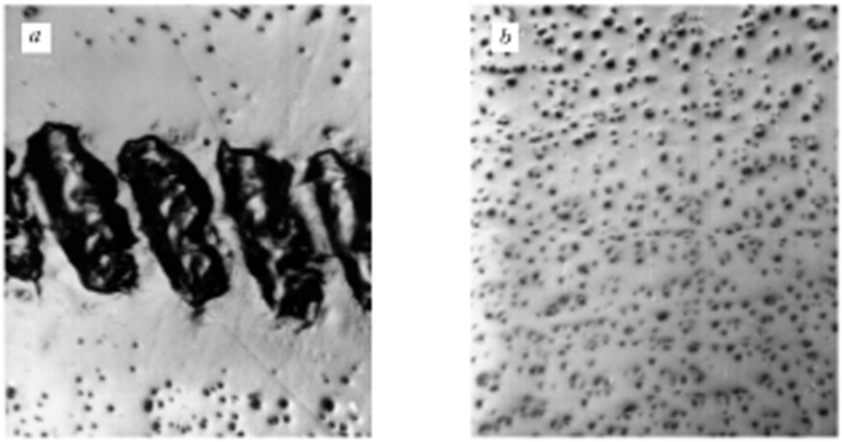

Fig. 3. Copper precipitates on the non-working side of a silicon plate in the region exposed to laser-radiation pulses (a) and outside it (b) after gettering.

to the capillary pressure, silicon atoms fill the region of the scratches. This process proceeds most intensively at the melting point of silicon. Since the process of recrystallization begins with the silicon having a perfect crystal structure, the structure of the silicon in the region of mechanical failures is completely restored.

The crystallization of the deformed surface layer of the silicon plate is enhanced when the absorption of laser radiation by it increases because, in this case, the surface layer is heated and two temperature gradients arise: the first temperature gradient appears at the boundary between the melted surface layer and the cold part of the plate, i.e., this gradient is directed along the normal to the surface of the plate, and the second temperature gradient, directed parallel to the surface of the plate, arises in the melt between regions with mechanical failure of the crystal lattice and regions free of these failures. This leads to the appearance of two crystallization fronts aiding in the removal of the regions with mechanical failures of the silicon crystal lattice. As a result of these processes, a silicon surface with a perfect crystal lattice is formed.

The processing of silicon plates with the use of laser-radiation pulses of duration 100–150 nsec makes it possible to form a gettering layer on the non-working side of the plate as a result of the destruction and evaporation of silicon in the region exposed to laser radiation. This leads to an increase in the free surface of the silicon and the appearance of thermal stresses around the indicated region due to the temperature gradient at the liquid silicon–crystalline silicon interface. Prolonged high-temperature processing of a silicon plate with the use of laser radiation leads to the formation of a dislocation net in the region exposed to laser radiation; this net serves as the sink for the rapidly diffusing impurities and point defects in the silicon.

The efficiency of this gettering layer in a silicon plate was determined in the process of experiments on the decoration of the centers gettered by copper deposited on the working side of the plate; the plate was subjected to thermal treatment at 800°C for 60 min in a nitrogen atmosphere. After copper was diffused, its precipitates on the non-working side were revealed by selective etching. As is shown in Fig. 3, these precipitates were distributed nonuniformly in the region of laser processing. Precipitates were absent on both sides of the scanning line in the bands of width 20–30 μm (Fig. 3a). In the central region between the two neighboring scanning lines, the density of the precipitates was increased and reached values characteristic of the silicon surface that was not exposed to laser radiation (Fig. 3b). The examination of angle lappings of the sample being investigated, subjected to selective etching, has shown that copper precipitates are absent both throughout the depth of the layer deformed by laser radiation and at a distance of up to 30 μm from it in the depth of the plate and sideways. These results point to the fact that the defects formed by laser-radiation pulses on the non-working side of a silicon plate are efficient sinks for point defects and rapidly diffusing impurities.

Conclusions. The processing of silicon plates with the use of laser-radiation pulses of duration 10–30 nsec makes it possible to remove mechanical failures of their surface layer at a depth of up to 1 μm. The use of laser-radiation pulses of duration 100–150 nsec for processing of silicon leads to the formation of defects of its crystal lattice, and these defects serve as efficient sinks for rapidly diffusing impurities.

NOTATION

N, number of pulses, pulse/sec; θ, angle; λ, wavelength, μm.

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