Modification of polished silicon under exposure to radiation of nanosecond ultraviolet laser

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Abstract. The polished surface of monocrystalline silicon was exposed to radiation of nanosecond ultraviolet laser (λ = 355 nm, pulse duration - 10 ns, pulse energy - up to 8 mJ, pulse repetition rate - up to 100 Hz). Then the samples were examined by scanning electron microscopy and multibeam optical profilometry. The optical damage threshold accompanied by the appearance of a plasma torch near the surface and crater formation was 1.2 J/cm². Microbreakdown centers on processing defects were observed at an energy density more than 0.2 J/cm². In the range 0.2 - 1.2 J/cm² traces of surface lifting were observed.

1. Introduction
Silicon is actively used in modern microelectronics and optics [1, 2]. Laser technologies are often used for silicon processing. Therefore, understanding the processes of interaction of radiation with the material is necessary for the successful implementation of the technological process. Many works are devoted to the study of these phenomena, for example, [3-12]. After detecting lifting on a polished copper surface under subthreshold exposure to a nanosecond ultraviolet (UV) laser pulse [13], it was decided to conduct a similar experiment with silicon, the mechanical properties of which differ significantly from copper. Silicon was chosen due to the thorough study of this material, which facilitates the interpretation of the obtained results. Earlier deformation effects in the material under the action of subthreshold nanosecond radiation were not observed, although theoretical studies of the kinetics of nonlinear deformation waves excited in solids by a powerful laser pulse were carried out [14, 15]. In this work we studied the effect of a nanosecond UV laser on a polished silicon surface.

2. Experimental technique
Samples of n-type silicon single crystal with a resistance of 1 kOh·cm were polished using traditional optical technology [16]. Before exposure the initial surface roughness was 50 - 60 Å. The laser exposure was carried out with a setup described in detail in [13, 17-19]. The radiation source was a solid-state Nd:YAG laser (third harmonic, wavelength λ = 355 nm, pulse duration is 10 ns, pulse energy is up to 8 mJ, pulse repetition rate (f) is up to 100 Hz, laser beam diameter is 3 mm, divergence is 1-2 mrad).

The modes of sample irradiation were as follows:

- the radiation spot was stationary (30 pulses, f = 10 Hz);
• a scanning spot, where the laser beam moved along the sample over a raster trajectory ("snake").

Distance between horizontal lines was near 30 μm (f = 100 Hz, “snake” length - 4 mm). Partial overlapping of spots took place. The overlap coefficient \( k \) (≥ 99%) is defined as the ratio of the area treated with two radiation pulses to the area of one spot:

\[
k = \left( \frac{S_i \cap S_{i+1}}{S_i} \right) \times 100\% ,
\]

where \( S_i \) - is the surface area treated by the pulse \( i \).

After exposure the surface of the samples was examined by Zygo NewView 7300 optical profilometer and a JEOL JSM 6610LV scanning electron microscope (SEM).

3. Experimental results and discussion
The optical resistance threshold of the polished silicon surface in our experiment was 1.2 - 1.3 J/cm². It is usually accompanied by the appearance of a plasma torch in the air near the sample and the formation of a crater on the surface. However, in our experiment we could detect earlier signs of radiation exposure. Figure 1 shows the results of the impact of radiation on the silicon surface (30 pulses; energy density is 0.7 J/cm²; repetition rate is 10 Hz). In the irradiation zone numerous point formations on the surface were observed. Their characteristic size is about 1 μm in width and several micrometers in height.

![Figure 1](image)

**Figure 1.** Surface of silicon single crystal after exposure to 30 laser pulses (Nd:YAG laser, third harmonic, \( \lambda = 355 \) nm, pulse duration is 10 ns, \( f = 10 \) Hz, energy density is 0.2 J/cm²): a) optical micrograph (Zygo NewView 7300); b) surface profile at the center of the studied area, c) 3D image.

The elemental composition of the irradiated zone was investigated using an attachment to the JEOL JSM 6610LV (figure 2). The composition was measured in three regions of the irradiated zone (figure
2). Table 1 shows the data in atomic percentages. It can be seen, that in the region of liftings the silicon is oxidized, and the formed oxides contain up to 30% oxygen. In region 2, according to measurements, up to 5% oxygen is present, although no visible traces of damage were observed.

![Figure 2. SEM micrograph of the irradiated surface of a silicon single crystal ($\lambda = 355$ nm, 30 pulses of 10 ns duration, $f = 10$ Hz, energy density is 0.7 J/cm$^2$). The figure shows the areas, in which the elemental composition was measured.](image1)

**Table 1.** Spectral composition of the irradiated silicon region (in atomic percents).

| Region         | O  | Si  |
|----------------|----|-----|
| Area 1 (general) | 17.97 | 82.03 |
| Area 2 (clean)    | 4.98  | 95.02 |
| Average          | 30.69 | 69.31 |

When exposed to a scanning spot of radiation at an energy density of 0.2 J/cm$^2$ ($f = 100$ Hz), damages were fragmentary. Traces of micro-breakdowns with a characteristic size of several micrometers, which may have arisen on defects in the optical surface treatment, were observed. With an increase in the energy density the distance between the spots decreased, the size of the spots increased, and at energies of 0.6 - 0.7 J/cm$^2$ a continuous field of damage was formed (figure 3).

When examined with an atomic force microscope, it was found that the surface is covered with a fine-grained layer of silicon particles. Their size was 150 – 400 nm.

![Figure 3. Results of scanning laser beam processing of the silicon surface (energy density is 0.7 J/cm$^2$, $f = 100$ Hz): a) SEM micrograph; b) surface profile.](image2)

**4. Conclusions**

Exposure to the surface of a silicon single crystal by ultraviolet laser pulses ($\lambda = 355$ nm, $\tau = 10$ ns, $f = 10$ Hz) at an energy density of $\geq 0.2$ J/cm$^2$ leads to the appearance of microbreakdown centers on
processing defects. Traces of uncontrolled surface lifting are also observed. At an energy density more than 1.2 J/cm² a threshold of optical damage with the formation of a plasma torch and a crater on the surface were obtained. When irradiated with a scanning laser beam at an energy density of 0.2 J/cm², microbreakdowns with a size of several micrometers appear on the surface. An increase in energy density causes an increase in the size of microbreakdowns, and at energies near 0.7 J/cm² the exposure to the scanning beam forms a continuous damage zone.

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