Formation of microconical structures on Si surface under the action of pulsed periodic Yb-fiber laser radiation

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Abstract. In this paper the results of microstructuring of monocrystalline silicon by series of nanosecond Yb-fiber laser pulses are presented. It is shown that nanosecond Yb-fiber laser can be successfully applied for creation of microrelief consisting of microcones arrays. Obtained relief provides a reduction of the reflection coefficient below 10% in visible range of the spectrum. It is also established that for creation of microconical relief by nanosecond Yb-fiber laser it is advisable to use “short” nanosecond pulses with pulse durations from several nanoseconds to several tens of nanoseconds.

1. Introduction
Laser structuring of Si surface can be applied for annealing of ion-implanted layers [1, 2], creation of superhydrophobic/superhydrophilic reliefs [4, 5] or antireflective reliefs [5–7]. The last application is important in a context of the problem of increasing of efficiency of solar cells, since the antireflective relief allows to reduce the optical losses. Currently, several methods are used to increase the absorptivity of silicon: chemical etching [8], reactive ion etching [9] and surface structuring using a laser radiation [5–7]. The laser methods allow to effectively reduce reflectivity and do not require to use any toxical gases or chemicals. Disadvantage of laser methods is that its performance is not high enough. In addition commonly used for creation of antireflective relief femtosecond lasers are difficult to operate, and they still not widely used as a technological tool. In opposite to femtosecond lasers nanosecond Yb-fiber laser is already widely used in manufacturing and has a number of indisputable technological advantages such as high efficiency factor, high reliability and stability of parameters, high processing speed caused by the possibility of operation at high pulse repetition rates (up to 100 kHz and higher). However the opportunities of Yb-fiber laser for creation of antireflective microrelief on silicon surface investigated insufficiently.

So the aim of this work is investigation of geometrical and optical properties of microrelief formed on silicon surface under the action of nanosecond Yb-laser pulses.

2. Description of the experiment
In our experiments we used nanosecond pulses-periodic Yb-fiber laser operated at fundamental wavelength 1.07 μm. Irradiation was carried out by line scanning across the square area 2x2 mm with different pulse durations \( t_p \) (4, 30 and 200 ns) and numbers of scan cycles \( N \). The distance between scan lines was 10 μm. The laser beam had a Gaussian profile with a diameter 50 μm at \( e^{-1} \) level. The beam movement over the surface was carried out by two-axis galvanometric scanner. Scanning speed
was 100 mm/s, pulses repetition rate was 50 kHz. The single pulse intensities were chosen close to the melting threshold and were about $6.7 \times 10^8$ W/cm$^2$, $1.3 \times 10^8$ W/cm$^2$ and $2.3 \times 10^7$ W/cm$^2$ for 4, 30 and 200 ns pulse durations respectively. The scheme of experimental setup and beam motion patterns are shown at Fig. 1.

![Figure 1. Scheme of experimental setup and beam motion pattern](image1)

![Figure 2. General view of treated sample](image2)

The plates of n-type (100) monocrystalline silicon were used as experimental samples. The experiments were conducted in air under normal conditions. After irradiation the samples were washed in ultrasonic bath. Obtained microreliefs were studied by the methods of optical and atomic-force microscopy (AFM). The reflection spectra were measured by spectrophotometer with an integrating sphere. The structural properties of threated surface were studied by Raman spectra measurements.

3. Results and discussion

The general view of sample treated by pulses with $t_p = 30$ ns is shown at Fig. 2. It can be seen that antireflective relief is formed. Typical types of microreliefs obtained by treatment with nanosecond pulses with different pulse durations are shown at Fig. 3. It can be seen that in case of irradiation by pulses with durations 4 and 30 ns the relief consisting of arrays of microcones is formed. The typical height of cones is about $4 – 6 \mu m$ for $t_p = 4$ ns pulse duration and about $14 – 16 \mu m$ for $t_p = 30$ ns. The base diameter of microcones is about $10 – 12 \mu m$ for $t_p = 4$ ns and $25 – 30 \mu m$ for $t_p = 30$ ns. So the aspect ratio in both cases is approximately the same. Note also that increasing of numbers of scan cycles $N$ doesn’t allow to significantly increase the aspect ratio of obtained microcones. The studies of Raman spectra of the treated samples did not reveal the presence of amorphous areas in the surface layers. It can be seen from Fig. 3 that when irradiation is carried out by “long” nanosecond pulses with $t_p = 200$ ns the microconical relief is not formed. The obtained in this case relief consist of “microcracks” oriented along the crystallographic directions (100), and some other types of surface periodic structures. That result indicates that the role of the processes of generations and accumulations of dislocations is much important for irradiation by “long” nanosecond pulses. So the processing mode with “long” nanosecond pulses is not suitable for formation of the relief consisting of microcones.

The dependences of reflection coefficient $R$ of obtained samples on wavelength in the range of 300 – 1500 nm are shown at Fig. 4. It can be seen that after laser structuring by the pulses with $t_p = 4$ ns and $t_p = 30$ ns significant reduction of reflection coefficient occurs. The reflection coefficient falls
approximately 3-4 times in the visible range of the spectrum in comparison with the initial one, and in the near UV there is a decrease by a factor of 5-6. Since the aspect ratio of microconical structures obtained in cases of structuring by the pulses with durations 4 and 30 ns differs insignificantly the reduction of reflection coefficient for this cases in approximately the same. The relief obtained by structuring with "long" nanosecond pulses practically has no antireflective effect.

Figure 3. Optical and AFM images of microrelief obtained by processing with laser pulses with different pulse durations (number of scan cycles $N = 40$ for $t_p = 4$ ns and $t_p = 30$ ns, $N = 30$ for $t_p = 200$ ns)

Figure 4. Reflection spectra of obtained samples
The comparison of absorptivity \( (A = 1 - R) \) of monocrystalline silicon processed by different methods shown at Fig. 5. It can be seen that the absorptivity of the samples structured by nanosecond Yb-fiber laser radiation exceeds the absorptivity of the samples structured by etching in NaOH solution. Absorptivity of femtosecond treated samples is a few percent higher than in case of nanosecond Yb-fiber laser structuring. However the processing speed is several times higher for Yb-fiber laser structuring in comparison with typical femtosecond experiment [7].

Figure 5. Comparison of absorptivity of silicon samples threatened by different methods

4. Conclusions

It is shown that under the action of pulsed periodic radiation of nanosecond Yb-fiber laser it is possible to create microreliefs consisting of microcones array. It is established that for creation of such type of microrelief it is advisable to use “short” nanosecond pulses with durations from several nanosecond to several tens of nanoseconds. Formation of the microconical relief by nanosecond radiation of Yb-fiber laser lead to a decreasing of reflection coefficient in visible range of spectrum in 3 – 4 times. At the same time the using of nanosecond Yb-fiber laser makes it possible to increase the processing speed several times in comparison with structuring by femtosecond lasers.

References

[1] Godbole V P, Chaudhari S M 1988 Bull. Mater. Sci. 11 97
[2] Yang Q et al 2014 Nano Lett. 14 1769
[3] Zorba V, Persano L, Pisignano D, Athanassiou A, Stratakis E, Cingolani R, Tzanetakis P, Fotakis C 2006 Nanotechnol. 17 3234
[4] Vorobyev A Y, Guo C 2010 Opt. Express 18 6455
[5] Vorobyev A Y, Guo C. 2011 Opt. Express 19 A1031
[6] Kontermann S, Gimpel T, Baumann A L, Guenther K M, Schade W 2012 Energy Procedia 27 390
[7] Kabashin A V et al 2010 *Nanoscale Res. Lett.* **5** 454
[8] Liu S et al 2014 *Solar Energy Materials & Solar Cells* **127** 21
[9] Kim J, Inns D, Fogel K, Sadana D K 2010 *Solar Energy Materials & Solar Cells* **94** 2091