Dynamics of the growth and mechanism of formation of laser-induced ordered relief on a silicon surface under the influence of polarized radiation

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Our goal is to investigate the dynamics of relief formation, thermoluminescence, and reflectivity of a silicon surface as a result of laser irradiation near the melting point; a realistic mechanism of relief formation is deduced on the basis of the results of the study.

A diagram of the experimental apparatus is shown in Fig. 1. The mechanically polished (111) surface of silicon with a thickness of 4 mm was used in the experiments. The sample was heated by p-polarized radiation from a neodymium glass laser (λ = 1.06 μm) with a radiation pulse duration of 0.8 ms at the half-height points. The intensity of the thermal radiation from the heated surface was recorded in the spectral interval 0.4–0.9 μm. The diffraction and thermoluminescence signals were separated by mechanical modulation of the He–Ne laser probe beam (f = 60 kHz).

The dynamics of the surface thermoluminescence signal for various power densities q of the incident radiation is illustrated in Fig. 2. An approximately bell-shaped time dependence is observed for q = 114 kW/cm², with a maximum that increases smoothly as the power density of the beam is increased. For q = 120 kW/cm² an inflection point occurs near the peak of the curve (Fig. 2), but then as q is increased, the inflection point changes into a minimum (Fig. 2c), its depth and the distance between maxima increasing with q.

The dynamics of a typical signal produced by diffraction of the probe beam for structures with a period d = 2λ (0 ≤ θ ≤ 9°) is shown in Fig. 3a. Figure 3b illustrates the dynamics of λ structures not observed previously in the residual relief (the relief that remains after surface hardening). The presence of residual λ structures occupying only 5–10% of the irradiated zone is observed. The dynamics of λ and 2λ structures was recorded simultaneously in one irradiation phase in the same way as the d− and 2d− structures.

Figures 3c and 3d show the dynamics of the d− and 2d− structures (9 ≤ θ ≤ 30°) (Ref. 2), respectively, determined for q = 123 kW/cm² and λ = 1.06 μm. The experiments show that the existence of 2d− structures is associated with the existence of the d− structures: When the latter are formed, 2d− structures are formed as well. For low values of q the 2d− relief dominates the central part of the irradiated zone, whereas the d− relief occupies the peripheral zone. In the interval 95–170 kW/cm² the depth of the 2d− relief and the area occupied by it increase, with d− and 2d− structures emerging in the intermittent, spatially bounded regions. For q = 170–190 kW/cm² the observed decrease in the amplitude of the diffraction signal corresponding to residual 2d− structures is attributable to the decrease in the area occupied by them when a locally smooth melt zone is formed within the limits of a ring.

The dynamics of the variation of the surface reflectivity at λ = 0.63 μm was investigated by recording the intensity of specularly reflected radiation, making it possible to determine the melting initiation time and to find a lower bound for the fraction of melt formed on the surface (we note that part of the reflected radiation was lost through diffraction). The reflectivity varies both on account of the temperature dependence of the optical constants of silicon and because of the intrusion of the melt. Approximating the data of Ref. 3, we find that at T = T_mel the increase of the reflection factor at λ = 0.63 μm is ≈ 25%. An estimate shows that the maximum fraction of the surface melt for Fig. 4b does not exceed 20%. The times of onset of melting, determined from the inflection point of the thermoluminescence curve (Fig. 4c) and from the reflection curve (Fig. 4b), coincide when the temperature dependence of the optical constants is taken into account.

The depth of the residual relief is usually 0.1–0.2 μm. The profile of the relief in the transverse direction has a relatively flat bottom and an abruptly rising edge (Fig. 5).

We now discuss the data on the dynamics of the surface reflectivity. We note that the reflectivity of silicon in the solid phase is higher than that of the liquid phase. Indeed, the spectral emissivity e(λ) is given by the balance equation e(λ) = 1−ρ(λ)−τ(λ), where ρ(λ) and τ(λ) are the spectral reflectivity and transmissivity, respectively. For a silicon (metal) melt we have e_1(λ) = 0.2, since ρ(λ) = 0.8 and τ(λ) = 0. In the fundamental absorption region we have e_2(λ) = 0.7, since ρ(λ) = 0.3, τ(λ) = 0 (thick plate), and e_2/e_1 = 3.5.

The inflection point and the minimum appear on the thermoluminescence curve as a result of nonuniform melting of the surface. In fact, as q is increased, the fraction of melt on the surface increases, lowering the luminescence intensity. The increase in the luminescence intensity in cooling (the second maximum in Fig. 2c) is associated with crystallization of the melt, because e increases in this case. A comparison of the dynamics of the diffraction, reflection, and thermoluminescence signals shows that the surface corresponding to the first maximum represents the coexistence of regions of liquid and solid phases.

The values of the intensity on the thermoluminescence curve contain information about the melt fraction on the surface. Assuming that the surface temperature does not exceed
\[ T_{\text{melt}} \text{, we can estimate the fraction of the melt area on the surface } \left( S_x/S \right) : \]

\[ S_x/S = \left( 1 - e_2/e_1 \right)^{-1} \Delta/A, \]

(1)

where \( A \) is the amplitude of the second maximum, \( \Delta = A - B \), and \( B \) is the amplitude of the signal at a time in the existence of the partial melt, for example, at the minimum of the luminescence curve.

The estimation of \( S_x/S \) using the experimental value of \( \Delta \) corresponding to the start of growth of the resonance structures for small values of \( q \) gives \( S_x/S \approx 0.26-0.3 \).

We now discuss the mechanism underlying the formation of the \( 2\lambda \) and \( \lambda/(1-\sin \theta) \) structures. Two stages of the evolution of relief are discernible in the dynamics. The first is characterized by the onset of local melting, which is detectable by three criteria: the first appearance of an inflection in the thermoluminescence curve, an increase in the reflectivity of the surface, and the presence of residual microrelief. The formation of relief in this stage is attributable both to the increase in the density of silicon as it melts and to the effect of capillary forces in the local melt zones. As \( q \) is increased, the dimensions of the local melt zones increase, the relief becomes smoother, and a minimum emerges in the dynamics of the diffraction signal.