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On the mechanism of local melting on the surface of monocrystalline semiconductors under intense light irradiation

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Abstract. The dynamics of anisotropic local melting of monocrystalline semiconductors irradiated by intense pulses of coherent and incoherent light is studied. The time dependences of the size and the density (per unit area) of local melting region obtained *in situ* are interpreted using a model of a short-lived metastable state characterised by superheating in the solid phase. Experiments are discussed required to provide the final answer to the problem of the mechanism of the effect revealed.

1. Introduction

The interaction of intense optical radiation with matter arouses considerable scientific and practical interest. One of the effects observed upon irradiation of semiconductors by coherent and incoherent light pulses is an anisotropic local melting of the surface. A study of this effect permits us, on the one hand, to optimise the regimes of pulsed light annealing of implanted semiconductors and, on the other hand, to obtain new data on the physics of nucleation and on the special features of structural and phase transitions on semiconductor surfaces under transient conditions.

Anisotropic local melting consists in the following. Upon uniform irradiation of semiconductors by intense coherent and incoherent light pulses of length $\tau_p \sim 0.2$ ms – 10 s, local melting regions (LMRs) separated by regions of unfused material are produced on the sample surface. The LMR shape is uniquely related to the crystallographic orientation of monocrystalline silicon (Fig. 1).

The basic features of the effect are independent of what kind of radiation source is used — lasers or incoherent light sources. The anisotropic local semiconductor melting was first observed upon irradiation by the pulses of Nd : YAG and Nd : glass lasers operating in the free running mode (with pulse lengths of 0.2 and 1.5 – 6 ms, respectively) and also by 1-s pulses of a CO_2 laser [1, 2]. With the application of incoherent light sources to annealing ion-implanted layers, there appeared papers dedicated to studies of the mechanism of the effect employing different lamps: halogen lamps (pulse length $\tau_p \sim 10$ s [3]), flashlamps used to pump lasers ($\tau_p = 10$ ms [4, 5]), and flashlamps operating in the stroboscopic mode [6].

Several physical models of the effect have been proposed to date. For instance, Heinig [4] assumes that LMRs are formed upon superheating monocrystalline semiconductors by several tens of degrees. The superheating is required because of the existence of a barrier for the nucleation of a local liquid phase at the interface between silicon and natural silicon oxide. Heinig [4] proposed two possible mechanisms of nucleation of the local liquid phase — homogeneous and heterogeneous.

In the opinion of authors [7, 8], local melting can be described by a deformation-vacancy mechanism of formation of point defects with their subsequent clusterisation. Laser radiation produces point defects in the near-surface semiconductor layer. The defect clusterisation begins after irradiation for a certain period of time, when the concentration of point defects reaches a threshold value. Due to a high compressive stress inside a vacancy cluster, the melting temperature of the silicon surface inside a cluster lowers by approximately 100 K. Accordingly, the regions containing clusters melt before the onset of melting of the regions that do not contain defects.

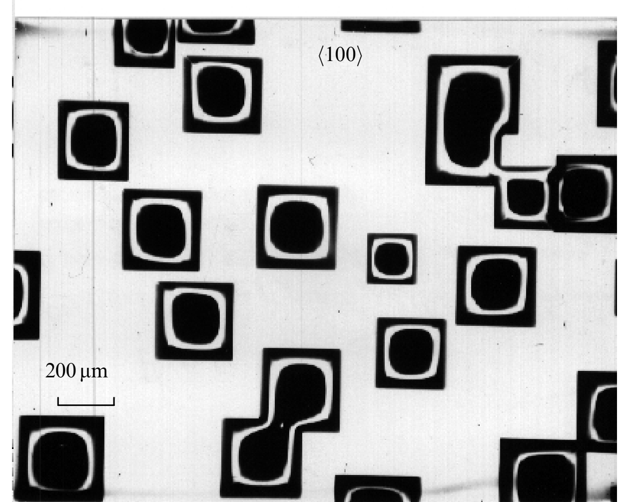

Figure 1. Microphotograph of the surface of monocrystalline silicon with the (100) orientation irradiated by light pulses in the regime of local melting.

Therefore, the threshold melting time (for a given irradiation intensity) is equal to the time taken to reach the critical

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concentration of point defects. It is noted that light-induced point defects accumulate primarily near initial inhomogeneities of the impurity crystal, initial dislocations, and other defects, which increase either the rate of generation of point defects or the probability of defect clusters formation.

In the opinion of Veiko et al. [9], the structures related to crystal orientation are formed due to the thermal deformation in near-surface layers heated by light. The resulting plasticity of silicon is accompanied by production of dislocations, which initially proceeds in a random way. Local melting can occur at surface dislocations.

The nature of liquid phase nucleation centres remains unknown: Is nucleation in a defect-free sample homogeneous, or does nucleation take place at defects that existed prior to pulsed light irradiation or at defects produced by the radiation itself?

Therefore, it is clear that, despite a rather large number of papers [1 – 11], there is no consensus on the physical mechanism and the main features of the effect. In this connection we set ourselves the task to obtain the *in situ* time dependences of the density and the sizes of the LMRs directly during the action of the light pulse. In our opinion, it is the *in situ* experiments combined with theoretical calculations that can provide answers to the controversial questions. We are aware of only one work [10] where this effect was studied in dynamics. However, only the formation dynamics of the specific profile of the visible LMR part was studied theoretically and experimentally in Ref. [10].

2. Experimental

The pulsed light irradiation of semiconductor samples in the regime of local melting was carried out on a UOL.P-1 setup employing the emission of three xenon flashlamps operated in the stroboscopic mode. The irradiation intensity was adjustable continuously from 20 to 2000 W cm^{-2}. The overall duration of irradiation τ_p was varied from 20 ms to 20 s by accumulating the corresponding number of pulses (shots).

We studied polished plates of *n*- and *p*-type monocrystalline silicon with diameters of 76 and 100 mm, specific resistance of 1 – 10 Ohm cm, and a surface orientation along the (100) and (111) planes.

The dynamics of nucleation and growth of the LMRs during and after the light pulse was recorded employing a specially designed long-focus microscope and a high-speed SKS-1M-16 camera with a frame frequency up to 3000 s^{-1}.

3. Results and discussion

We performed the first high-speed micrography of the nucleation and the growth of LMRs directly during irradiation by light pulses ranging from 50 ms to 10 s in duration. The experiment reported below was carried out as follows. A diamond needle was used to make a scratch on the surface of monocrystalline silicon to initiate local melting in precisely this region [4]. Hence, we observed heterogeneous nuclei of the liquid phase of two types: those at defects introduced by the scratch and those at defects caused by the sample growth technology and surface processing.

Fig. 2 illustrates typical surface photomicrographs of monocrystalline silicon obtained at different moments during a 1.74-s light pulse. The first LMRs were detected 1.019 s after the onset of the light pulse; after a point in time $t = 1.208$ s (Fig. 2), no new LMRs were observed. Therefore, we found that the nucleation of LMRs occurs primarily within a relatively narrow time interval ($\sim$ 190 ms).

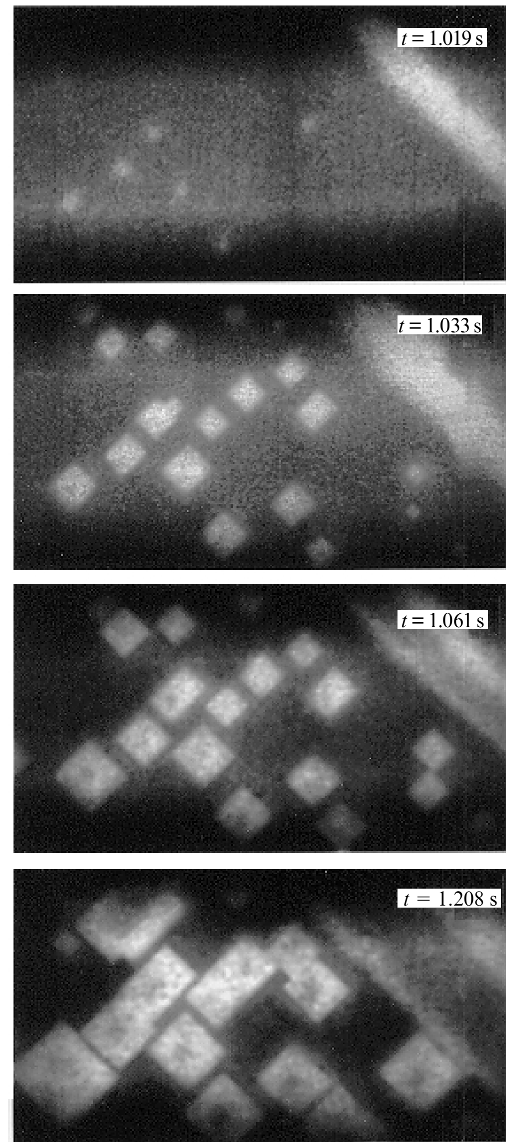

Figure 2. Microphotographs of the surface of monocrystalline silicon with the (100) orientation at different moments during a 1.74-s light pulse recorded with a high-speed SKS-1M-16 movie camera at a frame frequency of 1800 s^{-1}.

Fig. 3 shows the *in situ* time dependences of the dimensions of three individual melting regions during the light pulse. One can see that the first and second LMRs originate almost simultaneously but their dimensions are significantly different (by approximately 30%). We succeeded in revealing the cause of the difference in their dimensions owing to the *in situ* experiments. At the instant $t \approx 1.12$ s, the first LMR coalesces with the adjacent small third LMR. The coalescence and formation of a new LMR of a regular square shape occur rather rapidly, in 34 ms.

Earlier [6], we also studied the density of LMRs as a function of the light pulse duration for the fixed radiation intensity. The dependence obtained (a sharp increase, beginning with some characteristic duration, with a subsequent plateau) was the main argument in favour of the superheat model that we adopted.

Here, in order to refine the model and investigate the specific features of LMR origination in greater detail, we recorded the *in situ* time dependences of the LMR density during one light pulse (Fig. 4). It is evident that, for a 1.74-s light pulse, the rise of the LMR density from zero (at the instant of origination for $t = 1.019$ s) to the maximum value proceeds in 73 ms. The average LMR dimensions also increase appreciably within this time interval.

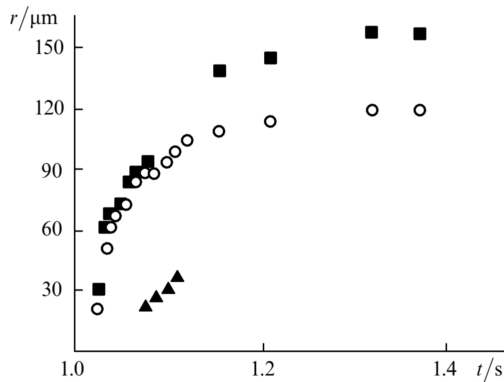

Figure 3. *In situ* time dependences of the dimensions of the first (■), second (○), and third (▲) local melting regions individually observed during a 1.74-s light pulse.

The above results agree well with the previously proposed model of anisotropic local melting based on the assumption of superheating of a solid-phase semiconductor during this short time period [4, 6]. In this case, the LMR density depends on the superheat [6] – the higher the intensity of radiation is used to heat the semiconductor, the greater the overheat and the greater the number of defects that become nucleation centres of the local liquid phase. Moreover, the greater the overheat, the earlier the first LMR nuclei appear. The overheating model is also confirmed by the fact that the growth of adjacent LMRs slows down as soon as their thermal 'radii of influence' begin to overlap.

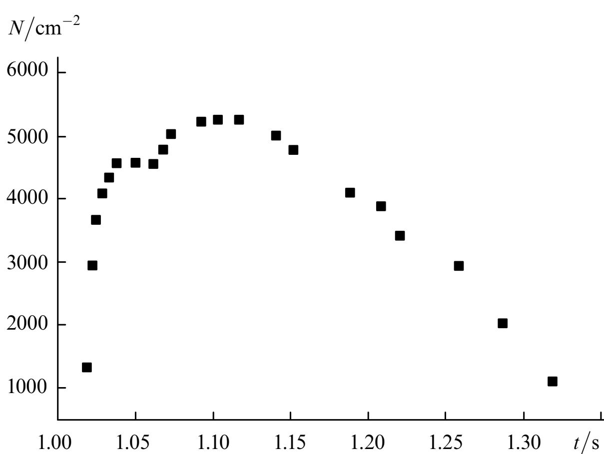

Figure 4. *In situ* time dependence of the LMR density during 1.74-s light pulse irradiation.

The superheat energy is spent to overcome the nucleation barrier, i.e., the production of a nucleus with dimensions exceeding the critical dimension. The existence of a barrier may be caused by the following reasons. First, this may be the stress at the interface between the monocrystalline silicon and the natural oxide [4]. Second, this barrier may be caused by an incomplete wetting of silicon by its own melt [12, 13]. The superheat depends on the light pulse duration and may be as high as $\sim 10^3$ K in the pico- and nanosecond duration ranges [13].

Taking into account the results of these studies, the model of LMR formation may be conceived as follows [13]. Upon pulsed light irradiation, a large amount of heat is transferred to the semiconductor surface. Owing to the transient character of the process, a redistribution of heat has no time to come to completion. As a consequence, a short-duration metastable state is initially produced, in which the entire semiconductor surface turns out to be superheated in the solid phase relative to its equilibrium melting temperature. Two stages may be distinguished in the subsequent melting process: the period of nucleus expectation and the period of the growth of its dimension caused by heat absorption from the surrounding superheated regions.

According to the data of Karpov et al. [13], the nuclei are produced due to fluctuations in a homogeneous defect-free semiconductor, i.e., they are homogeneous. However, our results [6] and the data of several authors [4, 11] testify that the nucleation centres of the liquid phase are mostly the defects present in the surface and in the near-surface semiconductor layer even prior to light pulse irradiation. The probability of homogeneous nucleation will increase as the quality of surface finish of industrial semiconductor platelets will improve.

At the same time, note that the light pulse itself produces new liquid phase nucleation centres in addition to the existing ones. These defects are dislocations produced in response to mechanical stress in the sample arising from the pulsed character of irradiation. This is supposedly the dominant mechanism of LMR formation when employing small-sized samples or lasers with irradiation spot dimensions comparable with the heat diffusion length for a given pulse duration.

At the second stage, the resultant nuclei grow primarily through the absorption of heat of the surrounding superheated regions. They develop independently until their surface density is $N \leqslant 1/L_t^2$, where L_t is the heat diffusion length. On reaching the density $N \simeq L_t^{-2}$, the thermal fields of individual centres overlap and new LMRs are no longer formed. The temperature of the entire semiconductor surface lowers to the equilibrium melting temperature. The amount of heat, which continues to arrive during the light pulse, becomes equal to the amount of heat radiated by the plate and also to that absorbed by LMRs from the surrounding superheated regions. The semiconductor surface temperature can no longer reach the superheat temperature. Some growth of the LMR dimensions now is due to the arrival of heat from the light pulse.

Therefore, the results of our *in situ* studies are consistent with the superheat model introduced in Refs [4, 6]. However, to establish the mechanism of anisotropic local melting unambiguously, additional *in situ* experiments for different duration of the light pulse and irradiation intensities are required. These experiments will allow the nucleation rate to be determined for different rates of semiconductor heating. Theoretical calculations invoking different models [2, 4, 6, 7, and 9] are also called for.

4. Conclusions

The investigations of the dynamics of anisotropic local melting of semiconductors exposed to intense light pulses allowed us to obtain the *in situ* dependences of the density and the dimensions of local melting regions on the surface of monocrystalline silicon. The results are consistent with the effect model involving formation of a short-lived state, which is characterised by superheating of the material in the solid phase relative to the equilibrium melting temperature. Planned for the future are experiments with different heating rates and, accordingly, with different rates of nucleation of the liquid phase, as well as theoretical calculations with recourse to alternative nucleation models.

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