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LETTER TO THE EDITOR

Real-time observation of local molten-phase nucleation on a semiconductor surface under powerful light irradiation

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Abstract. The first results of a dynamics investigation of the effect of anisotropic local melting of semiconductors observed under irradiation by powerful light pulses are presented. *In situ* time dependences of the sizes and density (quantity per cm^{-2}) of local molten regions are interpreted in the framework of the following model: the existence of a short-lived metastable state, characterized by superheating in the solid phase. The experiments and theoretical calculations crucial to clarifying the mechanism of the effect in question are discussed.

1. Introduction

Interaction of powerful light irradiation with matter is arousing great interest. One of the effects observed on irradiation of semiconductors with pulses of coherent and incoherent light is the effect of anisotropic local melting of the surface. On the one hand, the study of this effect allows one to optimize the regimes of pulsed light annealing of implanted semiconductors; on the other hand, it allows one to obtain new data on the physics of nucleation, and on the features of structural and phase transitions on the semiconductor surface under nonstationary conditions.

The essence of this effect is that as a result of homogeneous irradiation with powerful light pulses with durations of about 0.2 ms–10 s, the melting has an inhomogeneous character: local molten regions (LMRs) are formed on the surface of the semiconductor (figure 1). They are separated by regions of unmelted material. The regular geometric shape of the LMRs is unambiguously connected with the crystallographic orientation of the monocrystalline silicon [1–3]. The main features of the effect do not depend on the light source—lasers or incoherent light sources. At present, several physical models of the effect are available.

The question of the nature of the nuclei of the local molten regions remains under discussion—homogeneous nucleation in a defectless semiconductor or nucleation at defects present before the light pulse irradiation.

The many publications in this field have not led to an unambiguous understanding of the mechanism of this physical effect. Thus additional investigations are needed to establish it. The aim of this work is to obtain the *in situ* dependences of the sizes and densities of the LMRs on time directly during the light pulse. In our opinion, the *in situ* experiments and theoretical calculations allow us to clear up some remaining questions.

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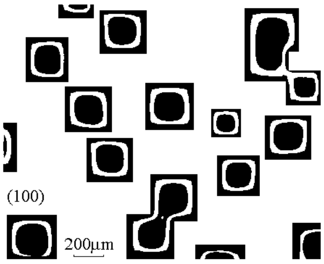

Figure 1. Micrographs of the surface of monocrystalline silicon, subjected to local melting. Surface orientation: (100).

2. Experimental procedure

Polished monocrystalline silicon wafers with diameter 100 mm, of n- and p-type conductivity, 1 to 10 Ω cm specific resistivity, and with surface orientation (100) and (111) were used in the studies.

Light pulse irradiation of the semiconductor wafers in the regime of the LMR formation was carried out by three xenon-filled flash lamps, operating in the stroboscopic regime. The radiation power density I_0 was regulated in the range from 20 to 2000 W cm^{-2}. The total pulse duration of the light irradiation ranged from 50 ms to 15 s.

The dynamics of the nucleation and growth of the LMRs during and after the light pulse are registered with a special hand-made long-focus microscope and a high-speed camera, SKS-1M-16, having a frame frequency of up to 3000 s^{-1}.

3. Results and discussion

The first results of the *in situ* investigation of the nucleation and growth of local molten regions directly during irradiation by light pulses with durations in the region of 50 ms–15 s are given. In figure 2, typical micrographs of the monocrystalline silicon surface are shown for different times during the light pulse. These micrographs were obtained with a high-speed camera, SKS-1M-16, having a frame frequency of 1800 s^{-1}. The light pulse duration was $\tau_p = 1.74$ s. The appearance of the first LMRs was registered in $t = 1.019$ s from the beginning of the light pulse (figure 2(a)). Formation of new LMRs was not observed after $t = 1.208$ s (figure 2(d)). Thus, it was proved that LMRs are predominantly created during a relatively small time interval. In our regime of irradiation, this interval is of about 190 ms—that is, less than 11% of the light pulse duration $\tau_p = 1.74$ s.

The dependences of the sizes of three different local molten regions on the time t during the light pulse irradiation are presented in figure 3. One can see that LMRs number one (curve 1) and number two (curve 2) appear almost simultaneously. However, their sizes differ by approximately 30% up to the end of the light pulse. The reason for this great difference in the size was established, due to the *in situ* experiment having sufficient time resolution. It was found that at time $t = 1.12$ s, LMR number one coalesces with a small neighbouring third LMR. The coalescence of two LMRs and formation of a new LMR with an exact geometrical (rectangular) shape take place relatively quickly, in 34 ms.

The time dependences of the LMR density N were measured to provide a more detailed understanding of the regularities of the LMR formation (figure 4). Previously [3], on the basis of the analysis of *ex situ* $N(t)$ dependences we made a supposition regarding the mechanism of

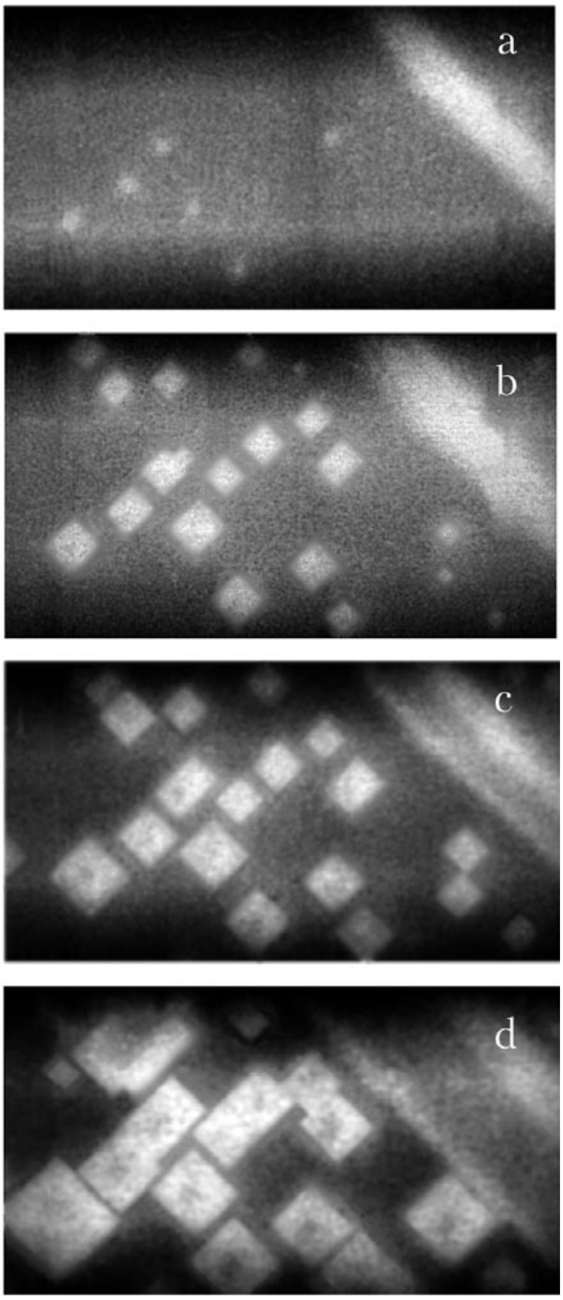

Figure 2. *In situ* micrographs of the silicon monocrystal surface (100) during exposure to a light pulse, with $\tau_p = 1.74$ s, at different times t: (a) $t = 1.019$ s, (b) $t = 1.033$ s, (c) $t = 1.061$ s, (d) $t = 1.208$ s. The frame frequency of the high-speed camera, SKS-1M-16, is 1800 s^{-1}.

this effect. This mechanism should be checked—by studying *in situ* dependences $N(t)$. One can see that the LMR density increases from the value $N = 0$ at $t = 1.019$ s to the maximum value very quickly: in 73 ms for the given light pulse duration $\tau_p = 1.74$ s. The average

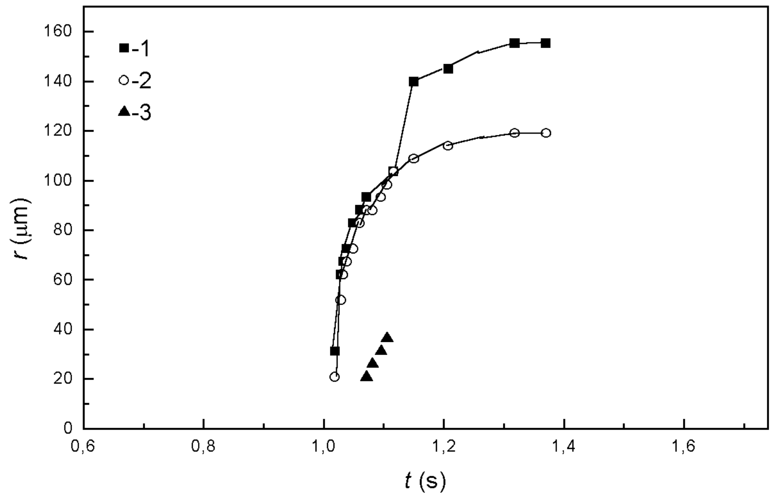

Figure 3. *In situ* time dependences of the sizes of three different local molten regions (1, 2 and 3) during a light pulse lasting $\tau_p = 1.74$ s.

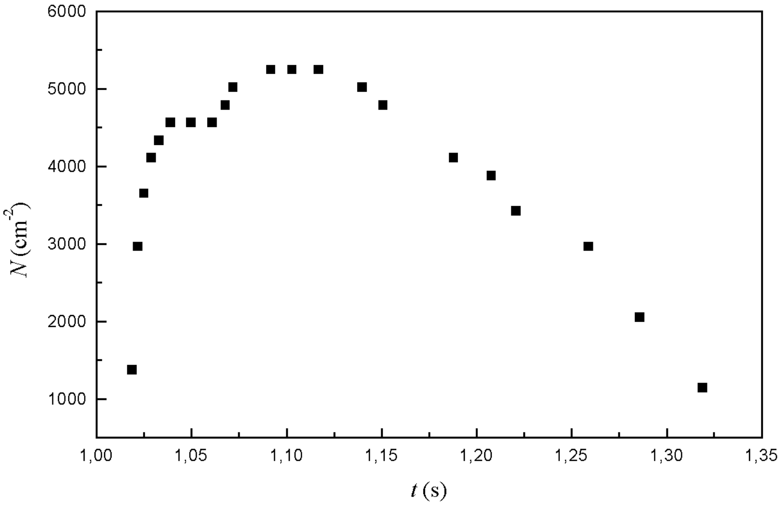

Figure 4. The *in situ* time dependence of the density of local molten regions during a light pulse lasting $\tau_p = 1.74$ s.

sizes of the LMRs mainly increase during the same time interval. These results are in good agreement with a model of anisotropic local melting which was suggested earlier [1, 3]: the existence of a short-lived metastable state, characterized by superheating in the solid phase. Moreover, the LMR density depends on the superheating value [3]. The higher the irradiation power density used for the heating of the semiconductor, the larger the superheating value, and the faster the formation of the first nuclei of the LMRs. Also, the larger the value of the superheating, the greater the number of surface defects which become centres of liquid-phase nuclei formation.

The following experimental fact supports the superheating model. If the thermal 'radii of influence' of the neighbouring LMRs overlap, the growth of the LMRs slows down.

The energy of superheating is needed to overcome the barrier to the formation of the liquid-phase nuclei—that is, for creation of nuclei with a size larger than the critical one. This barrier may exist for either or both of the following reasons. Firstly, there may be strains on the boundary between the monocrystalline silicon and the native oxide of silicon [1]. Secondly, this barrier may be caused by incomplete wetting of silicon by its own melt [4, 5].

The superheating value ΔT depends on the pulse duration ranges. According to literature data, it can be up to 10^3 K for the picosecond and nanosecond ranges of pulses [5].

According to these results, the following model may be advanced. A great amount of heat is transferred to the semiconductor surface during the light pulse irradiation. This process is nonstationary and the heat is not distributed homogeneously over the thickness of the sample. As a result, a specific short-lived state is formed, in which the semiconductor surface is superheated in the solid-state phase with respect to the equilibrium melting temperature. Some surface areas, which contain defects, begin to melt. The temperatures of these local molten regions immediately decrease down to the equilibrium melting temperature. The LMRs created begin to absorb heat from neighbouring superheated solid regions. As a result, the temperature of the superheated regions decreases down to the equilibrium melting point. No new LMRs are formed and the sizes of the existing LMRs increase due to absorption of the energy of the light pulse.

To achieve an unambiguous understanding of the anisotropic local melting mechanism, calculations according to different effect models are necessary, as well as additional *in situ* experiments for various light pulse durations and irradiation power densities. Such experiments would allow the determination of the nucleation behaviour for different rates of semiconductor heating.

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