DYNAMICS OF SILICON MELTING ON IRRADIATION BY INCOHERENT HIGH-POWER LIGHT PULSES

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For the first time the dynamics of anisotropic local melting of implanted silicon has been investigated for different regimes of light irradiation. The formation and growth of local melting zones (LMZs) on irradiation by light pulses have been recorded by a high-speed motion picture camera. For the first time the dependence of the number and size of the LMZs has been investigated in its dynamics. Additional data on the formation of defects in implanted semiconductors on irradiation by light pulses have been obtained.

An investigation of material melting and crystallization under nonstationary conditions on irradiation by high-power pulses of coherent and incoherent light has attracted great interest. On the one hand, this is caused by the necessity of studying physics of fast structural and phase transitions on irradiation by high-power light pulses with duration from several picoseconds to few seconds. On the other hand, this investigation is of undoubted practical importance, because it allows one to optimize the regimes of light pulse annealing of the ion-alloyed layers of semiconductors, pulsed solid-phase diffusion from surface sources, and oriented recrystallization of amorphous and polycrystalline silicon films on insulating substrates. Here, the problems of determining critical nucleus size, homogeneous and heterogeneous nucleation, and conditions and regimes of irradiation at which the effect of local melting is observed and (or) the pulse edge homogeneity and the required melting depth are provided, have assumed special importance.

One of the interesting physical effects observed during the interaction of the high-power optical radiation with the matter is the effect of anisotropic local melting of semiconductors. The effect involves the formation of the local melting zones (LMZs) on the semiconductor surface (Refs. 1–7) upon exposure to high-power pulses of coherent or incoherent light with pulse duration from ~0.2 ms to 10 s. These zones are separated by zones of nonmelted material. The experiments on the LMZ observation and the study of regularities of its formation were performed with the use of both coherent and incoherent light sources (cw CO_2, Nd:YAG, and Nd-glass lasers with pulse duration $\tau \sim 0.2$–6 ms, flash lamps with $\tau \sim 10$ ms, halogen incandescent lamps with $\tau \sim 10$ s, and others) (Refs. 1–3, 5, and 7).

For monocrystalline silicon, for which investigations are mainly performed, LMZs have the strictly bounded regular geometric shape, unambiguously related with the crystallographic orientation of semiconductor surface (Fig. 1).

In spite of the reasonably large number of works, there is no clarity and consensus in the explanation of the nature and mechanism of the effect of anisotropic local melting and its general regularities up to now. In order to establish the mechanism and the general regularities of anisotropic local melting as well as the nature of the liquid phase nucleation centers, it is necessity to pursue additional investigations including *in situ* experiments.

We have already established and studied the regularities of the LMZ formation in Ref. 8 for:

– monocrystalline silicon as functions of the conductance type, impurity concentrations, carriers, and crystallographic orientation of the surface;

– implanted silicon as functions of the energy, dose, implantation temperature, type of the implanted ion, and orientation of the substrate.

On the basis of the obtained results and analysis of the available literature data, a model was proposed, which, in our opinion, most completely and adequately describes the totality of experimental results. The mechanism includes the following basic principles:

– the existence of the barrier to the liquid-phase nucleation;

– the formation of the short-lived metastable state characterized by overheating in the solid phase relative to the equilibrium melting temperature;

– the increase of overheating as the light pulse duration shortens (with the corresponding increase of the radiation power density);

– the predominance of the heterogeneous mechanism of liquid phase nucleation on structure defects.

The first results obtained by us in the process of investigation of anisotropic local melting in its dynamics are given in this paper.

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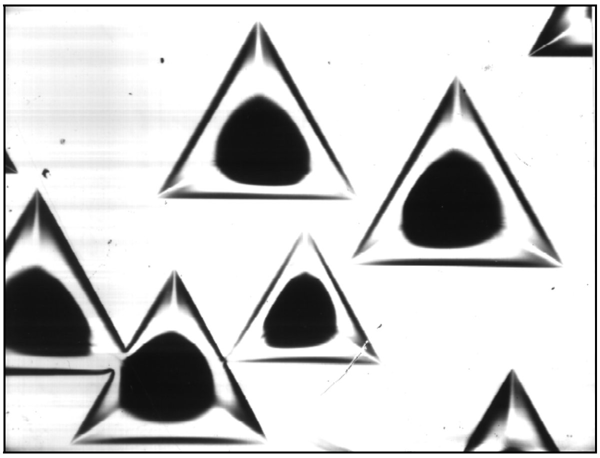

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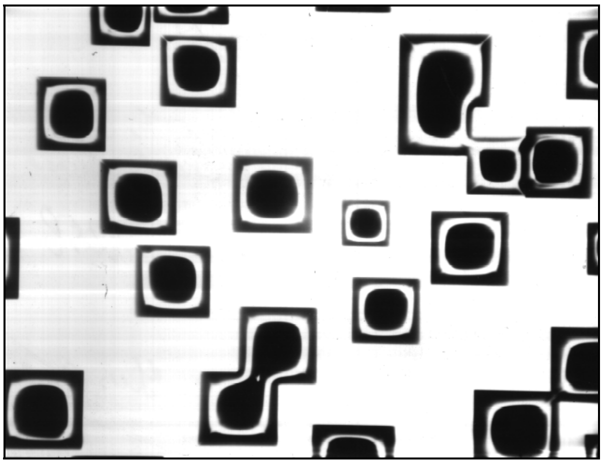

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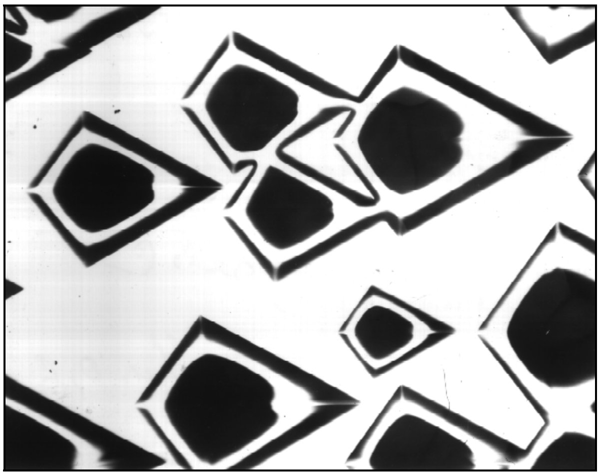

c

FIG. 1. Microphotographs of the surface of the monocrystalline silicon specimens with orientations: (111) *(a),* (100) *(b), and* (130) *(c) irradiated by light pulses in the regime of local melting.*

A special diffraction lattice (Ref. 9) was fabricated with the use of implantation to investigate the dynamics of the solid-phase epitaxy recrystallization of the amorphous ion-alloyed layer at temperatures of local melting, the lifetime of the local melt, and the salient features of liquid-phase recrystallization of LMZs (after termination of the light pulse). One of the variants of this lattice is shown in Fig. 2.

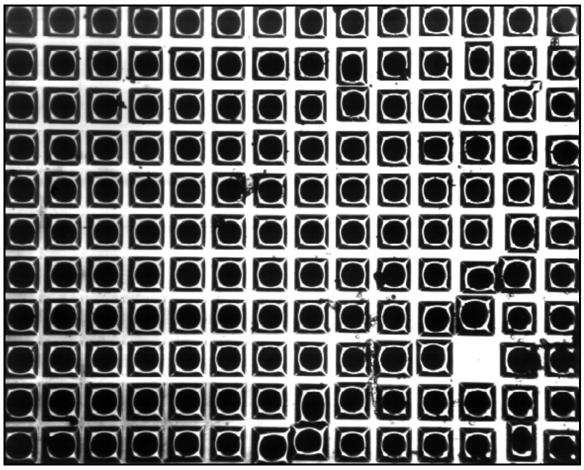

FIG. 2. Special diffraction lattice fabricated to investigate the dynamics of the effect of anisotropic local melting (view after the ion implantation and irradiation by a light pulse in the regime of local melting).

With this aim, the plates of monocrystalline silicon with the orientation (100) were preliminary implanted by the phosphorus ions through a thin metal grid using the ILU–3 ion-ray accelerator. The energy and the dose of implantation were chosen so that the amorphous layer started immediately from the specimen surface. As a result, amorphous cells bounded by the monocrystalline silicon lattice were formed on the surface. When this lattice was illuminated by the continuous radiation of a He–Ne laser, the diffraction pattern was observed whose intensity depended on the difference between the optical characteristics of the implanted and nonimplanted zones. Within the time over which the light pulse acted and as the implanted specimen was heated, the solid-phase epitaxy recrystallization of the amorphous layer occurred. Then local melting took place. The structure and phase transformations lead to the change of the silicon reflection coefficient and to the noticeable change of the diffraction efficiency.

Such changes of the diffraction efficiency of the implanted lattice were used to study the dynamics of the recrystallization and anisotropic local melting on irradiation by light pulses.

A qualitative waveform of the incoherent light pulse used for irradiation of silicon specimens in the regime of local melting is shown in Fig. 3. The UOL.P–1 setup was used to irradiate the specimens with three xenon lamps operating in the stroboscopic regime. The radiation power density I_0 was determined by the time during which the lamp was connected to a supply line for each half-period of supply voltage. The rate of increase of the specimen temperature in the leading edge of the heat pulse (Fig. 3*b*) depended on I_0 and the maximum temperature depended on I_0 and the light pulse duration τ.

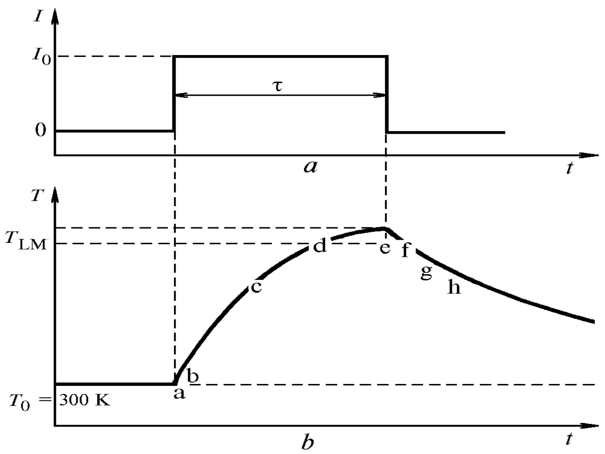

FIG. 3. Waveform of the incoherent light pulse (τ is the duration of the light pulse, I_0 is the radiation power density) (a); dependence of the temperature of the silicon specimen during the time over which the incoherent light pulse acts and after its termination (b) (calculation without regard for the formation of LMZs). Here, T_0 is the initial temperature of the specimen and T_{LM} is the temperature of local melting of the surface. The moments for which the diffraction patterns are shown in Fig. 4 are labeled by letters a, b, c, d, e, f, g, and h.

The photographs that illustrate the change of the diffraction pattern during the time over which the light pulse acted filmed with the SKS–1M–16 high-speed motion picture camera with a film speed of 1800 frames/s in case of illumination of the lattice by the continuous He–Ne-laser radiation are shown in Fig. 4. The diffraction pattern of the initial amplitude of the lattice is shown in Fig. 4*a*. It can be vividly seen that the diffraction efficiency (DE) of this lattice is relatively low at the expense of the low contrast between the reflection coefficients of monocrystalline and amorphous silicon on the laser radiation wavelength λ = 0.63 μm.

As the specimen with the regular diffraction lattice and epitaxy solid-phase recrystallization of the implanted layer is heated, the decrease of DE and its complete vanishing starting from the moment t = 70 ms (see Figs. 4*b* and *c*) occur. This means that the amorphous layer recrystallization has been completed or, at least, its thickness has become smaller than the skin depth of the sounding laser radiation. The diffraction pattern is seen again when the temperature of the specimen with the lattice achieves the local melting temperature. Therewith, local melting of the "amorphous" cells of the diffraction lattice (t = 119 ms, see Fig. 4*d*) is started.

As the melt area increases (up to complete filling of the amorphous cell), DE increases (Figs. 4*e* and *f*). The appearance of microrelief on the surface of melted zones makes essential contribution to the increase of DE, i.e., the refractive diffraction lattice transforms into the phase one (see Ref. 9). After termination of the light pulse, cooling of the specimen, and recrystallization of the local melting zones, the diffraction efficiency remained constant (see Figs. 4*g* and *h*).

Thus, on the basis of our analysis of the diffraction pattern during the time over which the light pulse acts one can clearly define the parameters necessary to establish the physical pattern of the effect:

– the duration of solid-phase recrystallization of the amorphous layer in the leading edge of the heat pulse;

– the moment of achievement of the melting temperature for monocrystalline and amorphous silicon;

– the lifetime of the melted state of surface zones during the time over which the light pulse acts and after its termination.

For the first time, the microphotographs of the formation and growth of the local melting zones on irradiation by light pulses have been obtained.

It has been shown that LMZs are initiated predominantly during the narrow time interval at the beginning of the light pulse. Then these LMZs grow and sometime merge into a single melted zone.

The nucleation of LMZs in a short time agrees well with the model previously suggested by us (see Ref. 8): the formation of LMZs takes place in the initial stage of the light pulse irradiation under conditions of overheating relative to the equilibrium semiconductor melting temperature in the solid phase. The LMZ density (their number per unit area) depends on overheating. The higher overheating, the greater number of defects becomes the nuclei of the local liquid phase.

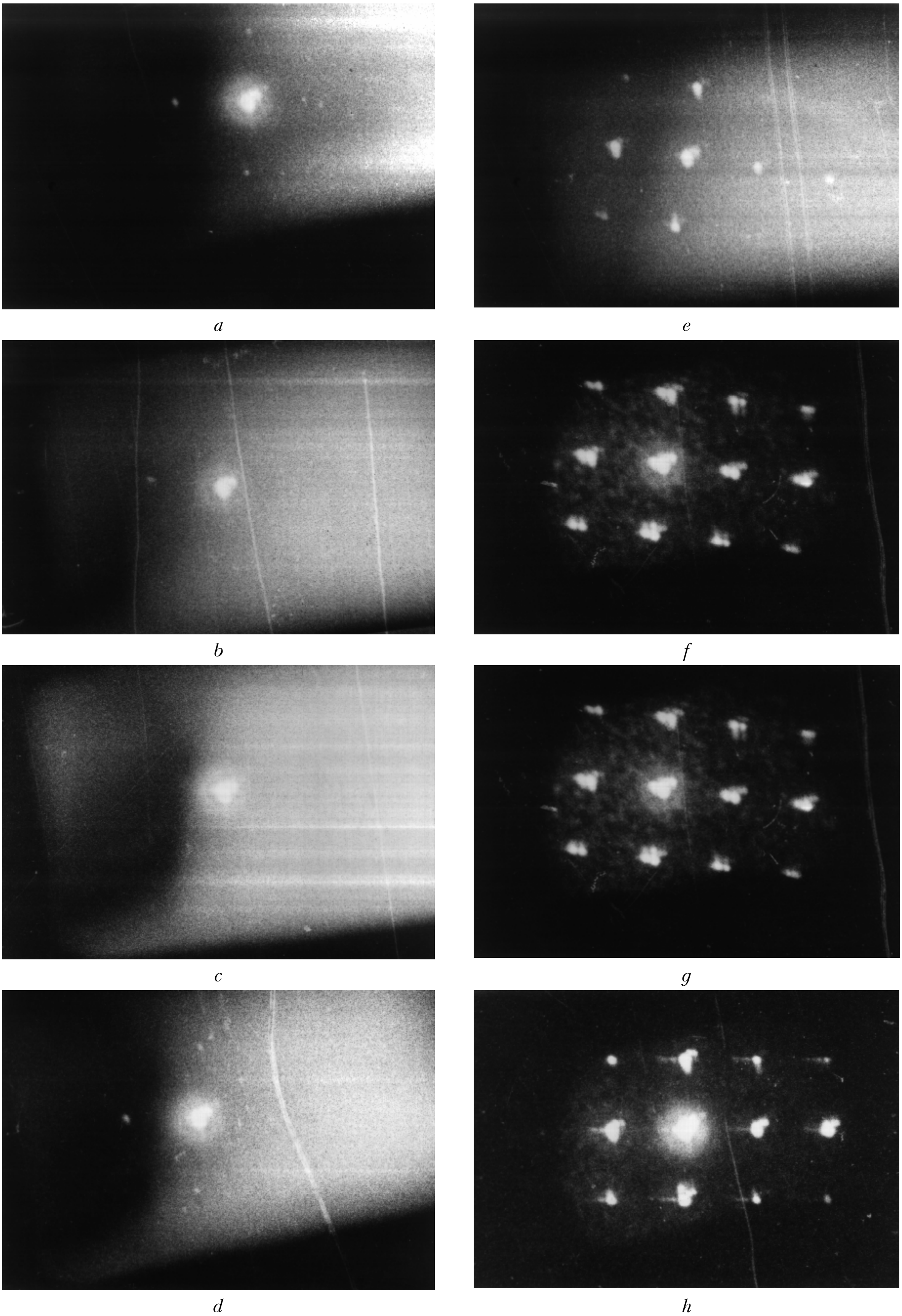

FIG. 4. Change of the diffraction pattern during the time over which the light pulse acts (τ = 129 ms).

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