Single-pulse excimer laser nanostructuring of silicon: A heat transfer problem and surface morphology

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We present computer modeling along with experimental data on the formation of sharp conical tips on silicon-based three-layer structures that consist of a single-crystal Si layer on a 1 μm layer of silica on a bulk Si substrate. The upper Si layers with thicknesses in the range of 0.8–4.1 μm were irradiated by single pulses from a KrF excimer laser focused onto a spot several micrometers in diameter. The computer simulation includes two-dimensional time-dependent heat transfer and phase transformations in Si films that result from the laser irradiation (the Stefan problem). After the laser pulse, the molten material self-cools and resolidifies, forming a sharp conical structure, the height of which can exceed 1 μm depending on the irradiation conditions. We also performed computer simulations for experiments involving single-pulse irradiation of bulk silicon, reported by other groups. We discuss conditions under which different types of structures (cones versus hollows) emerge. We confirm a correlation between the presence of the lateral resolidification condition after the laser pulse and the presence of conical structures on a solidified surface. © 2008 American Institute of Physics. [DOI: 10.1063/1.2910196]

I. INTRODUCTION

In the past decade a large number of publications on laser nanotexturing of silicon and other materials have emerged. Unlike laser ablation, laser texturing does not rely on material removal but relies on mass redistribution in the molten region produced by inhomogeneous heating. While there are numerous publications on laser micro- and nanotexturing of silicon, most of them are based on multipulse laser irradiation conditions. Along with many reports about multipulse laser nanotexturing, there are interesting publications about single-pulse laser silicon nanotexturing as well.

Our technique is based on a single-pulse excimer-laser irradiation that allows one to controllably fabricate Si cones (and dense arrays of such cones) with heights in the range of 0.2–2 μm and with an apical radius of curvature of several tens of nanometers. The KrF excimer laser radiation is absorbed entirely in a thin surface layer (the absorption coefficient of Si at λ = 248 nm is about 1.8 × 106 cm⁻¹). This surface layer becomes a source of heat that causes melting of a significant portion of the film. In a recent publication we offered a model of cone formation in thin silicon films with a thickness equal to or less than 200 nm deposited on a silica substrate.12 Below, we consider larger silicon layer thicknesses in the range of 0.8–4.1 μm and we also discuss the case of bulk silicon. Because the underlying silica has a much lower thermal conductivity than silicon, for silicon layers with a thickness of 0.8–1.1 μm heat is still dissipated predominantly in a lateral direction through the surrounding silicon film. For thicker silicon layers of 2.3 and 4.1 μm the process of heat dissipation becomes similar to that in the standard silicon wafer, namely from the surface toward the bulk.

II. EXPERIMENTAL

Spatially homogenized, single pulses of radiation from a KrF excimer laser (λ = 248 nm, Lambda Physik, model LPX 205) were used to image pinholes or slits onto uniformly illuminated circular spots or lines on the sample surface by means of a projection system with a demagnification factor of 8.9 and a resolution limit of 2 μm. Pinhole masks with a diameter of 50 μm producing laser spots with diameters of 5.6 μm were used. The laser pulse energy was measured to be stable within 5%. We used silicon-on-insulator (SOI) wafers that consisted of a single-crystal Si layer on a 1 μm layer of silica on a bulk Si substrate (SOIS). They were plasma-etch-thinned to different thicknesses of the Si layer in the range of 0.8–4.1 μm. The laser processing was performed in ambient, clean-room conditions, and the sample surface topography was then examined by contact-mode atomic force microscopy on a Park Autoprobe LS AFM system using Contact Ultradev® tips. The atomic force microscopy (AFM) images of tips fabricated by a single pulse of fluence 2.0 J/cm² are shown in Fig. 1. We measured cone formation thresholds of 1.5 and 1.75 J/cm² in the 0.8 and 1.1 μm film thickness cases, respectively. No cones were formed on the surfaces of the films with thicknesses of 2.3 and 4.1 μm after single-pulse irradiation with fluences up to 3.0 J/cm².

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III. COMPUTER SIMULATION

To demonstrate the role of lateral heat dissipation in the final surface morphology, we provide numerical modeling of the heat transfer in silicon structures subjected to a single-pulse laser irradiation.

Our computer simulation of the melting process does not include a possible height change; it includes only heat transfer and serves to determine “preconditions” for formation of conical structures during resolidification. The analytical model of mass transfer for the case of a crystalline Si film was offered in Ref. 12, where we also introduced the predominantly lateral heat flow criteria,

\[ H_{\text{film}} < \sqrt{\frac{\sigma T}{L_m}} \]

Here, \( \frac{\partial T}{\partial z} \) is a vertical temperature gradient averaged over the radius at the Si/SiO\(_2\) interface, and \( \frac{\partial T}{\partial r} \) is a radial gradient averaged over the \( z \) values at a radial coordinate \( r \) equal to the laser spot radius \( R_0 \).

Since the computer simulation process was already described in Ref. 12, here we state briefly what is different in the current work. In Ref. 12, our main equation for silicon was

\[ \frac{\partial T}{\partial t} = \frac{Q(r,z,t)}{\rho c T} + \frac{\sigma T}{L_m} \delta (T-T_m) / c. \]

where \( Q(r,z,t) \) is the laser heat source, \( \sigma = K / \rho c T \) is the thermal diffusivity, \( K \) is the thermal conductivity, \( c \) is the specific heat, \( L_m \) is the latent heat of melting, \( r \) and \( z \) are cylindrical coordinates, and \( \rho \) is density. The delta function term in Eq. (2) reflects the latent heat absorbed or released at the phase transition temperature, \( T = T_m \).

Here, we perform a two-dimensional heat transfer and melting computer simulation for SOI structures. These structures were irradiated with single 25 ns pulses of a fluence in the range of 1.5–2.75 J/cm\(^2\). In our computer simulation we used fluences in the range of 1.5–2.0 J/cm\(^2\). Under these conditions melting starts during the first half of the pulse and the evaporation process should be taken into account.

Although for these fluences the amount of evaporated material is still insignificant, the latent heat of evaporation, \( L_v \), is significant (13 700 J/g) and needs to be included in the energy balance to obtain physically reasonable temperature values on the silicon surface. \( L_v \) was included by introducing a second delta function, so our heat transfer equation could be written as

\[ \frac{\partial T}{\partial t} = \frac{Q(r,z,t)}{\rho c T} + \frac{\partial}{\partial z} \left( K(T) \frac{\partial T}{\partial z} \right). \]

Here, \( \mathcal{R} \) is a radius vector, and \( K(T) \) is temperature-dependent thermal conductivity, (W cm\(^{-1}\) K\(^{-1}\)).

For solid silicon, \( K(T) \) was approximated as follows:

\[ K(T) = 1.521/T^{1.226} \quad \text{when} \quad T \leq 1200 \text{ K} \]

\[ K(T) = 8.97/T^{0.5} \quad \text{when} \quad T > 1200 \text{ K}. \]

The function \( K(T) \) was smoothed in the phase transition interval (1635 K, 1735 K) from the value of 0.218 W cm\(^{-1}\) K\(^{-1}\) at 1635 K (solid Si) to 0.57 W cm\(^{-1}\) K\(^{-1}\) (melted Si). \( c(T) \) is a temperature-dependent specific heat, \( c(T) = 1.978 + 0.000354(T - 1200) \text{ J/cm}^3 \). \( T_e \) is the average value for the evaporation temperature, \( T_e = 2900 \text{ K}. \)

Despite its deficiencies in the description of evaporation process, Eq. (3) gives a reasonable estimation of the temperature distribution, and we are interested in finding only temperature distributions at this point. After introducing dimensionless variables \( T \rightarrow T/T_m, r \rightarrow r/R_0, z \rightarrow z/R_0 \), and \( t \rightarrow t/t_0 \), the delta functions in Eq. (3) were approximated by the finite functions \( \exp[-(T-1)^2/2\delta^2]/\sqrt{2\pi\delta} \) (Refs. 15 and 16) and \( \exp[-(T - T_e)^2/2\delta_t^2]/\sqrt{2\pi\delta_t} \), where \( \delta = 0.0297 \) for melting (which corresponds to a 50 K temperature interval of phase transition around \( T_m \)) and \( \delta_t = 0.178 \) for the melting/vapor transition (which corresponds to a 300 K temperature interval around \( T_e \)).

In general, the value of \( \delta \) could vary and is determined by the radial step of numerical simulation, since the half-width radius of the delta-like function should be bigger than the radial step. The much larger value of \( \delta_t \) corresponds to the fact that, unlike melting, evaporation occurs in a much broader range of temperatures.

For silica layer we used the equation

\[ \frac{\partial T}{\partial t} = \Delta T \times 0.04, \]

since the thermal conductivity of silica is 2.2 \( 10^{-2} \) W cm\(^{-1}\) K\(^{-1}\) at 1000 K.\(^{17} \) Here, \( \Delta T = \partial^2 T/\partial r^2 + 1/r \partial T/\partial r + \partial^2 T/\partial z^2 \).
Experiments on bulk silicon irradiation, we used results from distribution in bulk silicon. To make a comparison with experiment, the case of 2.3 mm is closer to the case of bulk silicon than to the case of thin film.

Considering heat transfer conditions, the case of 2.3 mm laser spot radius strongly violated, since \( \sqrt{\sigma T} \approx 0.7 \) mm and we attribute the absence of cones to smooth resolidification predominantly from the bottom.

Next, we will compare the results of Figs. 2–4. Figure 2 for 800 nm film and 1.5 J/cm\(^2\) fluence is the case where the cone was actually formed. While at the top of the film the solidification front moves in a lateral direction toward the center, melting still continues at the bottom of the film at the

IV. DISCUSSION

When the thickness of the film was increased while the 50 \( \mu \)m pinhole mask diameter (\( R_{\text{spot}} \approx 2.8 \) mm) was kept unchanged, there were no observable changes on the surfaces of the films with thicknesses of 2.3 and 4.1 mm after single-pulse irradiation with fluences up to 3.0 J/cm\(^2\). In this case the condition for film thickness \( H_{\text{film}} \leq \sqrt{\sigma T} \leq R_{\text{spot}} \) was strongly violated, since \( \sqrt{\sigma T} \approx 0.7 \) mm and we attribute the absence of cones to smooth resolidification predominantly from the bottom.

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time moment equal to 50 ns from the beginning of the pulse. We see that between times 25 and 75 ns the solidification front at the surface advanced laterally more than 600 nm toward the center.9

This is the case of the pure lateral resolidification (PLR) condition, which leads to cone formation. Figure 3 corresponds to a case with an increased thickness of 1100 nm and the same 1.5 J/cm² fluence. Though the PLR length on the surface is about 500 nm, with a much smaller melt depth it leads to a weaker lateral/vertical resolidification ratio. According to our experiment this is the case of fluence being below the threshold value for the thickness of 1100 nm and the cone was not formed.

Figure 4, for 1100 nm film and 1.75 J/cm² fluence, looks very similar to Fig. 2 (for 800 nm and 1.5 J/cm²)—in both cases cones were formed. Again, one may notice that there is a strong lateral solidification at the surface of the film while there is still a melting process at the bottom at the time up to 62 ns. The depth of melt is 1.5 times larger compared to that in Fig. 3 and more material can be involved in mass transfer in this case.

In the case of 2.3 μm thick Si film (Figs. 5 and 6), the condition for film thickness $H_{\text{film}} \leq \sqrt{\sigma \tau R_{\text{spot}}}$ was strongly violated, and the cone was not formed. Indeed, we can see from the simulation result (Fig. 5) that the PLR condition appears for a shorter time with the PLR length being about 200 nm, and lateral solidification does not dominate. After increasing the fluence to 2 J/cm² we still get a similar picture of resolidification (Fig. 6).

The PLR condition tends to disappear while we are moving from 0.8 μm films to thicker films, and eventually becomes negligible for the case of bulk silicon. Nevertheless, even for bulk silicon certain conditions in undersurface layers can lead to cone structure formation. Coming back to condition Eq. (1), for bulk material it can be rewritten as

FIG. 5. Isotherms $T = T_m$ calculated at different time moments for the laser spot radius 2.8 μm in 2.3 μm Si film on SiO₂ substrate with fluence 1.5 J/cm².

FIG. 6. Isotherms $T = T_m$ calculated at different time moments for the laser spot radius 2.8 μm in 2.3 μm Si film on SiO₂ substrate with fluence 2.0 J/cm².

FIG. 7. Isotherms $T = T_m$ in bulk Si calculated at different time moments for the Gaussian 1 ns pulse with a laser spot radius 1.3 μm and fluence 0.82 J/cm².

FIG. 8. Isotherms $T = T_m$ in bulk Si calculated at different time moments for the 90 ns pulse with a laser spot radius 1.8 μm. This setting led to formation of cones with a height of about 0.3 μm (Ref. 11).
where $z_g$ is the melt/solid border coordinate at the bottom of the melt pool.

In Ref. 7 a 1 ns Gaussian pulse of fluence close to 1 J/cm$^2$ was applied on a silicon wafer and was concentrated on the spot with a radius of 1.3 $\mu$m. In this case melting occurs in the beginning of the pulse. The thermal diffusivity $\sigma$ of liquid silicon could be estimated as 0.2 cm$^2$/s (Ref. 18) and, in the estimation of the authors of Ref. 7, the average melt depth $H_{\text{melt}}$ is 150 nm. The value of $(\sigma \tau)^{1/2}$ for a 1 ns pulse is about 140 nm, so the criterion $(\sigma \tau)^{1/2} > H_{\text{melt}}$ does not hold, and the effect of lateral resolidification is not expected to be significant in the experimental setup of Ref. 7. Indeed, looking at the solid/melt interface simulation results for this particular experimental setting (Fig. 7), one can see that, though resolidification starts laterally, it reveals itself in the layer of the order of 20–30 nm and the entire effect of lateral resolidification is insignificant.

At the same time, the Gaussian radial energy distribution in the beam and the shorter pulse duration (compared with our experimental setup) lead to higher thermal gradients and stronger surface tension differences inside the irradiated spot. Hence, temperature-dependent surface tension effects dominate in the experimental setting of Ref. 7.

The results of a two-dimensional computer simulation for the experimental settings of Ref. 11 are displayed in Fig. 8. The fluence $F_0$ was 5 J/cm$^2$ and the pulse length was 90 ns; the laser spot radius on the silicon surface was 1.8 $\mu$m. In this case the criterion $(\sigma \tau)^{1/2} > H_{\text{melt}}$ is satisfied, since $(\sigma \tau)^{1/2} \approx 1340$ nm.

While comparing Figs. 7 and 8 one can see that in the case of a pulse of 90 ns the depth of the melt is much larger. In Fig. 8, there is an undersurface layer of about 100 nm where phase transition isotherms are quite close to a vertical line (lateral resolidification), while a similar layer in Fig. 7 is about 25 nm. At the same time, the resolidification process of Fig. 8 is much slower, and it corresponds to smaller temperature gradients in the experiment of Ref. 11 (hence, to smaller surface tension effects). Only the central part of the beam cross section, in which the uniformity was better than $\pm 5\%$, was illuminated onto the area of the LSD mask in the experiment in Ref. 11, which also significantly reduces temperature gradients in the central part of the melt and hence surface tension effects. Overall, lateral resolidification plays a more significant role in the experiments of Ref. 11 and can lead to cone formation.

According to Ref. 11, only vertical profiles with a central depression were formed when 10 ns laser pulses were applied instead of 90 ns pulses. This could be explained by the shorter thermal diffusion length and hence bigger vertical gradient in near-surface silicon layers, so the vertical heat transfer is increased (and hence the ratio of lateral to vertical heat transfer is reduced) in comparison with the case of 90 ns pulses. At the same time 10 ns pulses produce bigger average thermal gradients and hence, a bigger surface tension effect.

Another “extreme” example of conical structures formation was reported in Ref. 6, where bulk silicon was irradiated by very long YAG:Nd$^{3+}$ laser pulse. The laser wavelength was 1.06 $\mu$m and the pulse length was 0.2 ms; hence, the thermal diffusion length after the pulse was about 600 $\mu$m. Cones with a height of 50–100 $\mu$m and the radius of curvature of about 1 $\mu$m at the tip were created by a single-pulse irradiation.

For the case of irradiation of bulk Si with excimer KrF laser (average pulse length of 25 ns), it was shown that the melt depth is not more than 400 nm for moderate fluences, while the value $(\sigma \tau)^{1/2}$ is about 700 nm (see Fig. 3). In our experiments we could not attain spot radii less than 1.7 $\mu$m. One can notice that the right part of the inequality Eq. (5) could be better satisfied for the case of bulk silicon by slightly decreasing the laser effective spot radius to a value of the order of 1 $\mu$m or less (hence, simultaneously increasing the average radial gradient). That can be achieved by applying a special microlens system, such as a monolayer of silica microspheres.

We should note that our estimate Eq. (5) may not be a necessary condition for the formation of cones. Our model of conical microstructure formation was based on the difference in liquid/solid densities under the condition of lateral resolidification. The “density difference” mechanism requires a predominantly radial (lateral) heat transfer and hence, the nanopulse should be long enough to provide for that condition (the thermal diffusion length right after the pulse should be of the order of or bigger than the melt depth). Another possible known mechanism of Si micro/nanostructuring involves the temperature dependence of Si surface tension; it leads predominantly to the formation of a depletion region on the surface of silicon (although we do not exclude a possible existence of additional mechanisms that can contribute to the formation of structures). The interplay of the pulse length time, laser fluence, and the beam focusing in each particular experiment determines which mechanism might prevail on the bulk silicon.

V. CONCLUSIONS

In the case of single-pulse irradiation of silicon films with different thickness in the range of 0.8–4.1 $\mu$m on insulating substrates, computer simulations revealed a strong correlation between the formation of conical microstructures and the condition of pure lateral resolidification. This condition exists when resolidification near the surface starts predominantly laterally, with a phase border moving toward the center of the laser spot, while at the bottom the melting process still continues.

The experimental results are consistent with the introduced lateral heat flow criterion Eq. (1).

In the case of silicon wafer, it is more difficult to satisfy the lateral heat flow criterion Eq. (5), since the heat energy dissipates into the bulk of silicon. Still, the condition Eq. (5) is achievable either by using longer pulses or by providing a stronger (within 1 $\mu$m radius) beam concentration.
Some of the possible applications of silicon sharp cone arrays include laser marking of silicon wafers,\textsuperscript{11} emitters for field-emission devices,\textsuperscript{19} scanning probe microscopy, and solar cell devices.

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\textsuperscript{13}A. E. Bell, RCA Rev. \textbf{40}, 295 (1979).
\textsuperscript{18}R. Hull, Properties of Crystalline Silicon, EMIS Datareviews Series (EMIS, Stevenage, UK, 1999), Chap. 4.1.