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Citation: J. Appl. Phys. 112, 013104 (2012); doi: 10.1063/1.4731752
View online: http://dx.doi.org/10.1063/1.4731752
View Table of Contents: http://jap.aip.org/resource/1/JAPIAU/v112/i1
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Nanomodification of gold surface by picosecond soft x-ray laser pulse

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(Received 23 January 2012; accepted 30 May 2012; published online 3 July 2012)

We show experimentally the possibility of nanostructuring (about 20 nm) of gold surface by picosecond soft x-ray single pulse with low fluence of ~20 mJ/cm². The nanometer-scale changes of the surface structure are due to the splash of molten gold under fluence gradient of the laser beam. In addition, the ablation process occurs at slightly higher fluence of ~50 mJ/cm². The abatic model of ablation is developed which reveals that the low threshold fluence of this process is due to the build-up of the high electron pressure and the comparatively low electron-ion energy relaxation rate in gold. The calculated ablation depths as a function of the irradiation fluence are in good agreement with the experimental data measured for gold surface modification with ultra-short duration soft x-ray and visible lasers. © 2012 American Institute of Physics. [http://dx.doi.org/10.1063/1.4731752]

I. INTRODUCTION

The laser-induced ablation of materials is receiving growing attention because it opens new possibilities to provide precise microprocessing and fabrication of nanostructures on the surfaces of dielectrics, semiconductors, and metals. During past two decades, particular interest is on the use of ultra-short pulse lasers for modification of material surfaces due to the significance both in practical1,2 and theoretical aspects.3,4 Under intense pulse excitation, it is possible to create highly non-equilibrium state of matter,5,5 which can significantly reduce the laser fluence for beginning of surface modification process. Furthermore, new exciting possibilities have been opened with development of short pulse transient collisional soft x-ray lasers (SXRL),6 and the x-ray free electron lasers (XFEL)7 which are becoming available now for various applications.

The ablation thresholds of dielectrics (for example, LiF crystals)8,9 irradiated by nanosecond (ns) laser pulses are higher by an order of magnitude as compared with the threshold under pico- (ps) and femtosecond (fs) laser pulse irradiation. The observed dependences of the ablation threshold of the dielectrics on the duration of the laser pulses could be explained by existence of three various mechanisms of ablation. At subpicosecond laser pulse with rather high laser fluence, the ablation takes place like Coulomb explosion.10 At picosecond laser pulse, the spallative ablation mechanism occurs when the delivery of laser energy to the material is faster than the elastic reaction to the heating but is slower than the typical electron response times.9,11 As the acoustic relaxation time of the dielectrics is of the order of 10 ps, such ablation mechanism is valid for any laser wavelengths if the laser pulse duration is shorter than this value. At nanosecond laser pulses, the ablation takes place like thermal process when the absorbed energy density is comparable to the cohesive energy of the condensate state. The presence of various ablation mechanisms explains the experimentally observed difference of the ablation thresholds of dielectrics for ns and ultra-short laser pulses.

Already previous measurements have demonstrated that the ablation thresholds for SXRL irradiation of dielectrics are quite different compared with the ablation thresholds for the visible lasers. The decrease of the irradiation laser wavelength from infrared (IR) and visible to soft x-ray (SX) causes two orders of magnitude decrease of the ablation threshold and such result is not dependent on the laser pulse duration. The photon absorption and collisional relaxation processes are determined by the photon energy and the electron structure. The multiphoton ionization is necessary for the absorption and the creation of conduction-band electrons at IR and visible radiation.12,13 In this case, the attenuation length of the laser pulse is longer or comparable to the laser wavelength (i.e., ~micrometer). On the contrary, the soft x-ray pulses are absorbed in length of about 10 nm (Refs. 9 and 11) and the absorbed energy is accumulated in a very narrow surface layer. Therefore, the comparatively low fluences may produce the ablation. This is why the ablation threshold for dielectrics is so different for IR and visible radiation compared with that of x-rays despite the same duration of the laser pulses.

The laser ablation mechanism for the metals remains unresolved, because the existing experimental data are contradictory and inconsistent with theoretical predictions. This is especially true for ultra-short pulse laser interaction with...
metals. Among various metals, gold is known to have comparatively low rate of energy transfer from the electron subsystem (ES) to the ion subsystem (IS) after energy deposition.\textsuperscript{4,14} For this reason, experiments with gold will allow studying the two-temperature effects (electron temperature \(T_e\)) in the ablation of metals. The attenuation lengths of optical and SXR pulses in gold are comparable up to about 1 nm wavelength. This fact allows to perform the study of ablation with optical and SXRL pulses in scope of the common model.

The absorptance of metals for an optical pulse is much different from it for an x-ray pulse. The gold absorptances for optical pulses at ablation are equal to 13\% and 10\% in Refs. \textsuperscript{15} and \textsuperscript{16}, respectively. We take the gold absorptance to be 13\% for optical pulses. In this work, all experimental values of the absorbed fluences in gold for optical pulses are taken as the published fluences multiplied by 0.13. For x-ray pulses in the gold, an absorbed fluence is equal to incident irradiation fluence. The comparison of the ablation thresholds is performed for absorbed fluences as it has key significance.

There is considerable uncertainty in the experimental data of single-pulse laser ablation of gold. At the laser ablation with short (about 0.1 ps) optical pulse,\textsuperscript{15} the threshold absorbed fluence \(F_{abs}\) and the crater depth \(d\) have been measured to be about 9 mJ/cm\(^2\) and 10 nm, respectively. In another experiment\textsuperscript{17} also with short optical pulse, these values were 150 mJ/cm\(^2\) and 50 nm, respectively. With short duration soft x-ray pulse, the threshold value for the surface modification of gold was determined as \(F_{abs} \approx 20\) mJ/cm\(^2\).\textsuperscript{18}

The ablation thresholds in multi-pulse subpicosecond regime are also ambiguous. The threshold values of \(F_{abs}\) in the multi-pulse regime with 1 kHz repetition rate are about 6 and 20 mJ/cm\(^2\) in Refs. \textsuperscript{15} and \textsuperscript{19}, respectively. In an experiment in Ref. \textsuperscript{20} with 10 Hz repetition rate, the ablation threshold of \(F_{abs}\) was determined equal to about 70 mJ/cm\(^2\). The difference between single- and multi-pulse regimes was investigated in Refs. \textsuperscript{15} and \textsuperscript{21}. Many facts point that the ablation threshold \(F_{abs}\) at such repetition rates should be similar to values at single-pulse regime. However, the question about it remains open.

In this work, we experimentally study the nanometer scale modification of solid gold surfaces irradiated by single x-ray laser pulse. To describe the ablation process near the threshold fluence, we propose two-temperature atomistic model with electron-temperature-dependent (ETD) interionic potential. The use of this potential makes it possible to take into account the effect of the electron pressure on the behavior of ions and to clarify the experimental data on modifications of gold surface measured with the ultra-short duration SXRL and visible lasers.

II. EXPERIMENTAL SETUP AND RESULTS

The SXRL irradiation experiment was carried out by use of the SXRL facility at Japan Atomic Energy Agency (JAEA).\textsuperscript{22,23} The experimental setup was composed of three elements: the SXRL source, optics, and the sample. A schematic diagram of the experimental setup is shown in Fig. 1(a).

The soft x-ray seed pulse generated by the first Ag plasma was amplified with the second Ag plasma and finally had a wavelength of 13.9 nm, bandwidth of narrower than 10\(\times 10^{-4}\), the duration time of 7 ps, and the beam divergence of 0.35 mrad \(\times\) 0.3 mrad in the horizontal and vertical directions, respectively. The output energy of the SXRL pulse was varied in each shot, with the average of 200–300 nJ.\textsuperscript{23,24} The SXRL pulse was focused on the surface of an Au specimen by using a spherical Mo/Si multilayer coated mirror having a 1000-mm radius of curvature, which had been optimized for soft x-rays of 13.9 nm at an incidence angle of 2\(^\circ\).

FIG. 1. (a) Schematic diagram of experimental setup for irradiation of a sample by focusing a SXRL pulse. The sample stage with LiF crystal and Au targets moves in two directions: X-stage for delivering fresh targets, and Y-stage for changing focusing position of SXRL. (b) The luminescent image of a LiF crystal surface and visible (in DIC mode) images of LiF and Au surfaces damaged by irradiation of SXRL beam with energy of \(\sim 48\) nJ.
This mirror was placed at a distance of 2637 mm from the SXRL output. A Zr filter of 0.2 mm thickness was placed in front of the spherical mirror to reduce the scattered optical radiation from the laser produced Ag plasmas. The transmittance of the Zr filter and the reflectivity of the Mo/Si mirror at 13.9 nm were approximately 48% and 50%, respectively. Therefore, the total energy of the SXRL beam on the Au surface was 48–72 nJ.

The mechanically polished Au plate with a thickness of 0.5 mm was fixed on the surface of a LiF crystal. This Au–LiF side-by-side targets was mounted on the holder having two movable directions (see Fig. 1(a)). The target on the holder was moved in vacuum after each laser shot along the SXRL beam propagation direction and also perpendicular to it, in order to record the beam patterns at different focusing distances and to use the fresh LiF crystal or Au surfaces. All target surfaces were carefully aligned to assure equal focusing conditions on them. The Au and LiF targets were illuminated at various focusing positions of the SXRL beam. Usually for each focusing position at the beginning of experimental run we monitored some shots using LiF crystal. Then, we did shots on Au surface and after irradiation of Au we have once more checked the focused laser intensity using LiF detector. It allows determining the SXRL intensity distribution in each focusing position using the procedure described in Refs. 8 and 25 with the LiF crystal soft x-ray detector. Measured variation of the focal spot non-uniformity was ±40% along the focal spot for the lowest laser fluencies and ±15% for higher one.

After irradiation of the LiF crystal by the SXRL, the photoluminescence patterns of the color centers (CCs) in LiF were observed by using a confocal fluorescence laser microscope (OLYMPUS model FV300). A 488 nm Ar laser was used in the microscope to excite CCs, which then emitted luminescence in the spectral range of 500–800 nm with the peaks at 530 nm for F3 and 670 nm for F2, respectively. Typical luminescent image of the SXRL beam, recorded with the LiF crystal irradiated by the SXRL beam with energy of ~48 nJ is presented in Fig. 1(b). Due to the high sensitivity and the large dynamic range of the LiF crystal detector, high-quality images have been observed in a single SXRL shot with different pulse energies and not only at the best focal position, but also away from it. Thus, these provide the information on the best focusing position with high accuracy and controllably at varied SXRL fluences on the surfaces of the irradiated targets. High spatial resolution (about 700 nm) and high dynamic range of the LiF crystal detector8,25 allowed to record clearly resolved detailed structures in the intensity distribution of the SXRL beam (see Fig. 1(b)), together with the aberrations and broad scatterings of the XRL beam. With this diagnostic method, we found that the SXRL energy fraction in the best focusing spots, where the surface damage on LiF crystal was observed, reached 60% in this experimental series.

Different imaging techniques were used to investigate the damage structures on the surfaces of the Au plates and the LiF crystals and to measure the shapes and depths of the nanostructures on the surface. The sample surfaces were observed by a visible microscope (BX60, OLYMPUS Corporation) with the differential interference contrast (DIC) mode. The detailed structures of the modified surfaces, which could not be seen with a visible microscope, were observed by a scanning electron microscope (SEM, JSM-6380LVN, JEOL Ltd.) (Fig. 2). The cross sectional profiles of the induced patterns were measured by an atomic force microscope (AFM, Explorer, TopoMetrix Corporation) (Fig. 3). These images demonstrate that the surfaces of the Au samples were damaged in a single SXRL shot. The beam spot sizes at the threshold for nanostructure formation on the sample surfaces by the SXRL beam irradiation were found to be about 300 μm² for LiF crystal and about 50 μm² for Au targets. If we take into account the real intensity distribution of the SXRL beam in the focusing spot, which has been measured by the LiF crystal, the nanostructuring threshold for LiF crystal is ~9.6 mJ/cm²; and ~21 mJ/cm² for Au. It is necessary to mention that Au surface modification was not observed for the SXRL fluence of less than ~15 mJ/cm².

Figs. 2 and 3 show the SEM and AFM images of the irradiated Au surfaces by a single laser shot of the SXRL beam obtained near the threshold for nanostructure formation. Nanoscale surface modification is already clearly seen at the SXRL fluence of $F_{abs}=21 \pm 5\, \text{mJ/cm}^2$. According to the analysis of surface structures, the metal is redistributed on a surface but is not ablated. These changes are probably due to the splash of the molten gold under intensity gradient (i.e., pressure/temperature gradients) across the laser beam. In this case, the surface compression wave propagating in liquid layer plays the key role in modification of the sample. The typical obtained depth of the surface irregularities (nanoscale roughness) is of the order of 20 nm. Stronger change in the surface modification could be seen in Figs. 2(b) and 3(b). With increase of $F_{abs}$ to ~60 mJ/cm², the depth of the surface modification reaches to 50–80 nm. These changes most probably are determined by ablation process.

FIG. 2. SEM images of gold surfaces after irradiation by a single laser shot of the SXRL beam at different fluences of (a) $F_{abs}=21 \pm 5\, \text{mJ/cm}^2$ and (b) $F_{abs}=60 \pm 15\, \text{mJ/cm}^2$, respectively. Magnified yellow boxes show parts of the SEM images with higher spatial resolution.
Even larger depth modifications of \( \sim 100–150 \text{ nm} \) were observed in the hot spots of the SXRL beam when the fluence exceeds 100 mJ/cm\(^2\). It is necessary also to stress that in all experimental AFM images presented in Fig. 3 large amount of material deposition on the metal surface is clearly seen.

III. SIMULATION

A. Model

During ablation, the laser irradiation initially leads to the excitation of the ES. One of the main theoretical difficulties for construction of a model is the fact that the electron-ion relaxation time is comparable to the time-scale of the ablation itself and the accompanying processes (heat transfer, phase transitions, etc.) One way for modeling of this process is continuum approximation with two-temperature equation of state.\(^{26,27}\) This methodology, however, does not take into account of the phenomena at the atomic level (metastable phase decay, nucleation, etc.) that are essential for the description of ablation. Note that the similar situation takes place in various phenomena with high electron temperature: electrical explosion of conductors, formation of swift heavy ion tracks in a nuclear materials, etc.\(^{28–30}\)

Molecular dynamics (MD) models of the two-temperature (2T) system proposed in Refs. \(31–33\) consist in considering the ES as a continuum. The energy transfer from the ES to the IS is implemented using a Langevin thermostat. This approach can be used to describe many features of ablation but it gives significant overestimation of the crater depth as was shown for Cu (Ref. \(31\)) and Au. (Ref. \(34\)) This 2T model does not take into account the effects of electron pressure build-up\(^{35,36}\) and the changes of interionic forces as a result of the ES excitation.\(^{37–39}\)

Au is a noble metal with one s-electron and ten d-electrons per atom in the valence shell. A combined description of the localized d- and delocalized s-electrons is needed in order to address the actual electron pressure of this material. The total energy of ES also contains localized and delocalized parts.\(^{40,41}\) The delocalized energy of ES is determined only by the electron concentration and temperature like the energy of an ideal gas of free electrons. The pressure \( P_{\text{deloc}} \) of the delocalized electron energy may be taken into account in the ion dynamics by the blast force \( \sim \nabla (P_{\text{deloc}}) \sim \nabla (T_e^2). \)\(^{35,36}\) On the contrary, the localized energy of ES is determined by the positions of the ions \( \text{pari passu} \) with \( T_e. \)

In the present work, an atomistic 2T model with the interionic ETD potential is proposed for the description of the ablation process. The ETD-potential allows us to take into account an important part of the electron pressure of the localized electron energy in addition to the blast force of the delocalized electron energy.

Our model is implemented as a modification of the 2T model in the LAMMPS code.\(^{32,43}\) The evolution of the ES is described by the equation

\[
C_e \frac{dT_e}{dt} = \nabla (k_e \nabla T_e) - G(T_e - T_i) - \frac{I(t) e^{-s/l}}{l},
\]

where \( C_e \) is the electron heat capacity,\(^5 \) \( k_e \) is the electron thermal conductivity,\(^{32} \) \( G \) is the coupling constant for the electron-ion interaction,\(^{32} \) \( I \) is the absorbed laser intensity of the rectangular pulse of width \( \tau \), and \( l \) is the attenuation length. In our model, the SXR pulse is differed from the optical pulse only by \( l. \) The model does not take into account the absorption mechanism. The approximation is used that thermalization in ES instantly occurs. In Ref. \(44\), the time of the electron thermalization at laser excitation in gold is estimated to be equal to several hundred femtoseconds. It is faster than the considered processes in IS at the present model.

The creation of the ETD-potential of gold for the atomistic simulation is performed with force-matching method.\(^{45}\) This method is used for the development of the potential as implemented in the PotFit code.\(^{45}\) The method provides a way to construct physically justified interparticle potentials without referring to experimental data. The idea is to adjust the interparticle potential to optimally reproduce per-atom forces computed at the \( \textit{ab initio} \) level (e.g., density functional theory) for a fine-tuned set of small reference
structures. The reference data are calculated using the Vienna \textit{ab initio} simulation package (\textsc{vasp}) code\cite{vasp} (planewave basis cut-off energy is 500 \text{eV}, projector augmented-wave (PAW) pseudopotential, linear density approximation (LDA) xc-functional, $2 \times 2 \times 2$ Monkhorst-Pack k-mesh). We use 32 reference structures for the fitting database with 2929 atoms altogether. These structures represent 32 various states of gold (liquid and FCC-lattice at different densities). The calculations of the reference data are performed at three different $T_e$ of 0.1, 3, and 6 \text{eV} that is set as a parameter of the Fermi-Dirac distribution for partial occupancies of electron bands. The three interionic potentials (for each $T_e$) are created with the force-matching procedure. The potentials have the embedded atom method (EAM) form. The full EAM-potential is created using quadratic polynomial interpolation with respect to $T_e$ of the parameters of those three reference EAM potentials.

Fig. 4 shows the dependence of the total pressure (calculated by the \textsc{vasp} code) and the pressure of localized electron energy (calculated in the MD model with using of the ETD-potential and virial theorem) on $T_e$. The difference in pressures corresponds to the pressure $P_{\text{deloc}}$ of delocalized electron energy which cannot be described by ETD-potential.

The ion equations of motion are

$$m_i \frac{dv_i}{dt} = F_i(T_e) + F^{\text{lang}}(T_e, T_i) - \frac{\nabla(P_{\text{deloc}})}{n_i},$$

(2)

where $F_i(T_e)$ is the interionic force of the ETD-potential, $F^{\text{lang}}$ is the Langevin force that models the electron-ion energy transfer,\cite{Lang} the last term in Eq. (2) is the blast force,\cite{Lang,Te} and $n_i$ is the locally averaged ion concentration. Note that local variations of the ETD-potential with $T_e$ change the local properties of the IS (e.g., the melting temperature).\cite{Te} The values of $F_{\text{abs}}$ are determined by the change of the total energy of the ion subsystem during the two-temperature stage. The size of the simulation box is $2100 \times 28.6 \times 8.2$ \text{nm} in the $x$, $y$, and $z$ directions. The periodic boundary conditions in $y$ and $z$ directions are used. Au ions form a crystal in one half of the simulation box (at $1050 < x < 2100$ \text{nm}). During the simulation at $t < \tau$, the $T_e$ near surface layers may reach $3$ \text{eV} and the total pressure may reach 70 \text{GPa} (see Fig. 5). Fig. 6 shows the typical snapshots of the subsequent IS evolution. The crystal structure of ions melts and expands as the energy transfers from ES to IS. The liquid layer near surface forms during about 100 ps. Meanwhile, the zone of voids forms because the mechanical and thermal relaxations of the system lead to the creation of the region with negative pressure. The typical profiles of ion pressure along $x$-directions are shown in Fig. 7. The depth $d$ of ablation crater is calculated as: $d = N_e/n_{eq}S$, where $N_e$ is number of all removed ions during ablation, $n_{eq}$ is equilibrium ion concentration, and $S$ is surface area. The melt depth is calculated as depth of formed liquid layer: $N_i/n_{eq}S$, where $N_i$ is number of ions in liquid state (including the removed ions). Two variants of laser pulses are considered: $\tau = 7$ \text{ps} and $l = 18$ \text{nm} are chosen in order to model the x-ray pulses considered in this work, $\tau = 0.1$ \text{ps} and $l = 6$ \text{nm} are used for the modelling of experiments with optical lasers.\cite{J. Appl. Phys., 112, 013104 (2012)}

B. Results

Different mechanisms of ablation are found from the results of the simulation. At $\tau = 0.1$ \text{ps}, the two ablation regimes can be distinguished (see the curve 5 in Fig. 8). If $F_{\text{abs}} < 130$ \text{mJ/cm}^2, ablation is due to the electron pressure build-up (similar to the electron-driven ablation mechanism described in Ref. 26). Fig. 5 illustrates this ablation mechanism. At the initial moment of time, a high pressure is created in the near-surface layer due to the increase of a high electron

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig5.png}
\caption{The temporal change of the total pressure $P$ with the ion concentration $n_i$. The arrow schematically shows the evolution of state (taking into account $P_{\text{deloc}}$) near surface layer during the ablation at $\tau = 0.1$ \text{ps}, $l = 6$ \text{nm} (optical pulse) and $F_{\text{abs}} = 121$ \text{mJ/cm}^2: (a) initial normal conditions; (b) rapid heating of the electron subsystem ($T_e$ increases to 2.95 \text{eV}) by a laser pulse; (c) relaxation due to expansion and $T_e$ decreasing; (d) final state that corresponds to $P \approx -5.4$ \text{GPa} when void formation starts.}
\end{figure}
temperature (isochoric process). The formation of a layer with negative pressure takes place as a result of the joint action of the two pressure-reducing processes: the mechanical expansion in vacuum and the decrease of $T_e$ due to relaxation processes. At $F_{abs} > 125 \text{ mJ/cm}^2$, the fast electron-driven ablation with depth of tens of nm is present as well. However, in this case, such ablation cannot be distinguished from much deeper ablation with depth of hundreds of nm due to the rarefaction wave formation (like in Refs. 17 and 34) which starts to be realized. Therefore, the dependence $d(F_{abs})$ has the second ablation threshold. Such a peculiarity of the dependence $d(F_{abs})$ may be the reason of the overestimation of the ablation threshold and depth in the previous models of sub-picosecond pulses.\textsuperscript{17,34}

At the pulse duration of $\tau = 7$ ps, the ablation depth $d$ smoothly grows together with $F_{abs}$ (curve 7 in Fig. 8). In this case, the separation of two mechanisms is impossible (the time of electron-ion relaxation is comparable with $\tau$ and the electron-driven ablation does not occur explicitly). The effect of spallation takes place as a result of the joint action of mechanisms involved in both types of ablation. Note that the situation with two ablation threshold for sub-picosecond laser pulses and one ablation threshold for picosecond laser pulses was observed in multi-pulse regimes for copper in Ref. 46 and for gold in Ref. 19. The ablation mechanism associated with boiling is not investigated in this work. The fluence for realization of considerable boiling must be larger than examined fluences.

The direct atomistic simulation of the modification of surface by splash of the molten gold is difficult. Such a simulation demands the large computational resources. Several
billions of atoms are necessary for MD-simulation of similar process. However, the depth of surface modification \(d_m\) may be estimated by the melt depth. The melt depth slightly depends on \(\tau\). In Fig. 8, the melt depth for \(\tau = 7\) ps is shown. It is visible that the dependence of the melt depth on \(F_{\text{abs}}\) agrees with our experimental data on nanomodification of surface with SXR pulses. In addition, the ablation depth reaches the melt depth at \(F_{\text{abs}} \approx 80\) mJ/cm\(^2\). This fact confirms that the first changes of the surface structure probably are due to the splash of molten gold. However, at higher values of \(F_{\text{abs}}\), the ablation process determines nanomodification. Thus, the various mechanisms of the surface modification are disclosed. The \(d_m\) may be determined by one of such mechanisms (e.g., melting and splash at low fluences) or by several ablation mechanisms.

The most close agreement of the simulation results for optical pulses is observed with the experiment on ablation of gold in Ref. 20 where multi-pulse regime with very low (10 Hz) repetition rate was used. The second threshold of ablation conforms to data of Ref. 17. The discrepancy is observed between the simulation results and experiment in Ref. 15. One of possible reasons is that the modification of surface may be induced by the melting and splash of metal at laser irradiation.

IV. CONCLUSION

Our experiments and modeling demonstrate that material irradiated by short SXR pulses with \(F_{\text{abs}} \sim 20-50\) mJ/cm\(^2\) allows the nanostructuring of gold surfaces in depth of \(\sim 20\) nm. The experimental energy threshold of nanostructuring (20 mJ/cm\(^2\)) by SXRL pulse in this work is most probably related to the laser-induced melting and splash of gold. This threshold of nanostructuring is slightly smaller than the threshold of ablation (about 50 mJ/cm\(^2\)) at which a metal layer is removed. For optical pulses, the similar threshold of ablation is defined in the atomistic simulation in our investigation. This simulation results agree with other studies\(^{20}\) of gold ablation by sub-ps optical pulses. In addition, the ablation threshold in Refs. 17 and 34 may be the second threshold associated with rarefaction wave formation. The existence of the second threshold of ablation at sub-picosecond pulse also conforms to results of other studies.\(^{19,46}\)

Such result is rather different from the visible and SXRL ablation of dielectrics, where the distinction in the wavelength of lasers causes \(\sim 2\) orders of magnitude difference in the value of the ablation threshold. Such fact is ascribed to the different electron band structures of metals and dielectrics, their electron-ion relaxation stages, and different absorption mechanisms for visible and SXR photons. The main distinction between metal and dielectric is the presence of conduction-band electrons. For metals, the attenuation lengths are comparable for SXRL and optical pulses. In addition, the role of the electron pressure is very high in metals. We can conclude that for metals, and especially for gold, the relatively slow electron-ion relaxation time results in maintaining of the high electron pressure in the near surface region for several picoseconds, that is sufficiently long for the development of the hydrodynamic response that causes the formation of the negative pressure region and the ablation of a thin surface layer.

ACKNOWLEDGMENTS

The clusters of Moscow Institute of Physics and Technology (MIPT60), Moscow Joint Supercomputer Center (MVS-50K), and Moscow State University (“Lomonosov”) were used for calculations. The work was financially supported by the Programs for Basic Research of the Presidium of the RAS No. 2 (coordinator V. E. Fortov) and 23 (coordinator is N.F. Morozov), the RFBR Grants 12-02-00947 and 12-08-00666, the President RF Grants MK-7192.2012.8, SNL under the US DOE/NNSA ASC program and Japan basic research foundation (KIBAN B) No. 2136052 of JSPS.


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