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Laser surface micro-/nano-structuring by a simple transportable micro-sphere lens array

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A micro-sphere array optic was employed for laser surface micro-structuring. This array optic consists of a hexagonally close-packed monolayer of silica micro-spheres. It was organized through a self-assembly process and held together on a glass support, without using any adhesives. The array assembly was then reversed, placed in direct contact with the substrate and exposed to 515 nm, 6.7 ps laser pulses. During the exposure, the silica spheres act as micro-lenses, which enhance the near-field light intensity underneath them. As the spheres are confined in the space between the substrate and glass support, they are not ejected during laser machining. Using this type of direct write laser machining, a large number of identical features (nano-holes) can be produced in parallel simultaneously. The holes drilled are a few hundred nanometres in diameter and the depth depends on the number of laser pulses applied. The impact of laser machining on the micro-spheres was also studied. The micro-spheres were contaminated or partially damaged after micro-structuring. Combination of a moderate laser pulse energy and multiple shots was found to ensure a good surface structuring quality and minimum damage to the spherical particles. © 2012 American Institute of Physics. [http://dx.doi.org/10.1063/1.4767471]

I. INTRODUCTION

Ordered monolayers, made of micro-spheres, have interesting scientific and technological applications, mainly in the fields of photonics1 and micro-/nano-fabrication.2 Laser patterning using a contact particle lens array (CPLA) is a near field technique, which has been extensively investigated.3 In this method of laser surface patterning, spherical particles are spread in the form of a monolayer over the substrate surface to be machined. Subsequently, the layer is irradiated by laser (termed “direct CPLA” hereinafter for clarity). By laser interaction with the spherical particles, intensified optical fields are generated at the contact point of the sphere with the surface and cause substrate material ablation and removal. Although this method has been used to fabricate sub-micrometre or nano-holes on polymer,4,5 metal6–8 semiconductor,9,10 and dielectric substrates,11–13 there are some significant limitations to this kind of laser processing. A prerequisite is that the substrate has to be hydrophilic to allow a monolayer to be formed by the self-assembly process.14 Therefore, hydrophobic surfaces or water soluble material cannot be patterned in this way. Moreover, the spherical particles detach, i.e., eject from the substrate after a single laser shot.15 Thus, laser multi-shot processing is not feasible. Additionally, the re-deposition of the detached particles will contaminate the monolayer assembly in the vicinity of the laser spot. Hence large area structuring is difficult to achieve.

Transportable contact particle lens array (termed here as transportable CPLA) was devised by Khan and O’Connell independently.5,16,17 In their studies, the experiments can be generalized into a four-step procedure: (1) close-packed monolayer of silica spherical particles were assembled on a hydrophilic surface first, and (2) then held together by an adhesive and supported by an intermediate medium such as a fused silica glass or a polymer tape (termed CPLA-support for clarity); (3) these spherical particles along with the CPLA-support were then transported onto the substrate (the free surface of the sphere is now in direct contact with the substrate to be laser machined) and subsequently in step (4) the system was irradiated by a laser in a conventional manner, except that the laser beam passed through the CPLA-support. This concept addresses the limitations of conventional laser micro-structuring by means of direct CPLAs. Especially when a flexible tape was used as the CPLA-support, the spherical particle array can be applied onto non-flat surface for laser texturing.16 One the other hand, when using transportable CPLA, the adhesive and CPLA-support have to be chosen with great care. For instance, both the adhesive and the CPLA-support have to be transparent to the laser light. This becomes a problem when short laser wavelength is used (i.e., 248 nm or 266 nm) since the adhesives are commonly made of polymer materials which have a limited transparency in the UV. Even where a highly transparent adhesive is used, partial absorption of the laser energy by the CPLA-support or by the adhesive may still cause their temperature rising and consequently may result in damage of the CPLA-support and the adhesive. CPLA-support melting and re-deposition of the molten CPLA-support on substrates have been observed.16
In this study, we propose an alternative for transportable CPLA for laser-based micro-/nano-structuring, which will be discussed in Secs. II C and II D. This transportable CPLA is easy to prepare and it does not require any adhesives or an intermediate supporting medium. Thus, this transportable CPLA can be used with lasers of all wavelengths. This transportable CPLA can also be used for multi-shot laser processing, which makes it possible to realize in the future large area laser processing using this transportable CPLA by overlap scanning. In this work, we studied laser multi-shot irradiation and the evolution of surface morphology with increasing number of laser shots.

Because the spheres are in direct contact at places where laser ablation takes place, the spheres are exposed to extreme conditions brought by laser ablation, i.e., very high temperatures and shock pressures, etc. Depending on the machining conditions, sometimes an enhanced optical field occurs even at the surface of the spheres. Although attention should be paid to the impact of the laser structuring process on the spheres, to the best of authors’ knowledge, such investigation has not been published. The results of this work reveal that the spheres are indeed susceptible to damage. Both redeposition and damage are observed on the surface of the micro-spheres, at the vicinity of the contact points. Therefore, despite the fact that the micro-sphere array is re-usable, the life-time is limited. The damage can be minimized by reducing laser pulse energy. Nonetheless, as they are easy to assemble, new transportable CPLAs can always be prepared prior to laser texturing process.

II. EXPERIMENTAL SETUP AND MATERIALS

A. Materials

The substrate used in this study was a single side polished (100) silicon wafer lightly doped with phosphorus. The wafer thickness was 0.55 mm and the average surface roughness $R_a$ was less than 1 nm. The surface of the as-received silicon substrate was slightly hydrophobic. No pre-treatment to the surface was done prior to the laser structuring experiment.

The monolayer of the spherical particle lens array was formed from silica micro-spheres obtained from microParticles GmbH, Germany (diameter 1.3 μm with a standard deviation of 40 nm, refractive index $n = 1.4$). The silica spheres were supplied as a 5 wt. % suspension of particles in water.

A 1 mm thick glass slide (soda lime microscope glass slide) was used as the smooth surface and sphere support for the monolayer assembly. In order to clean the surface, the glass was first ultrasonically cleaned in ethanol and then in isopropyl alcohol (IPA), for about 5 min each. The glass was then rinsed in deionised water and dried in a flow of pressurized air. The glass slides transmit 93% of the total incident laser energy at 515 nm.

B. Equipment

A frequency-doubled Trumpf TruMicro 5050 Yb:YAG laser, wavelength 515 nm obtained using a Second Harmonic Generation unit, 6.7 ps pulse duration, with an average maximum power of 25 W at 400 kHz repetition rate was used for these experiments. In actual experiments, a lower repetition rate was chosen and the pulse energy was optically attenuated. The linearly polarised laser beam was guided over the samples by a two-mirror galvo scanner system (IntelliScan 14 from Scanlab GmbH, Germany) and focused by a telecentric f-theta lens (Ronar of Linos, Germany), of 100 mm focal length.

The sample surface was characterized by SEM (JEOL Neoscope JCM-5000) and a confocal laser scanning microscope (CLSM, VK9710 of Keyence, Japan), for morphological study and for measuring the depth of the patterns, respectively. The micro-spheres are made of dielectric material. Therefore, for SEM evaluation of the spheres, a thin gold coating of some 10 nm was sputtered on the surface of the micro-spheres before SEM analysis.

C. Micro-sphere array preparation and transportation

The deposition of the spherical particles was carried out in a way as described by Micheletto et al.18 Drops of the suspension containing the micro-spheres were applied on the cleaned surface of the glass slide. The glass slide was then tilted by 9° with respect to the horizontal direction and stored inside a glass beaker to slow down water evaporation. The evaporation step took a few hours. During drying, the micro-spheres arranged themselves in a hexagonal close-packed array under capillary forces.14,19

Next, the monolayer formed on the surface of the glass was then reversed and laid onto the substrate for laser micro-/nano-structuring (see Figures 1(a) and 1(b)). The micro-spheres stay in place in this step—they are held on the glass slide by Van der Waals force, which is much larger than gravity force and the system is rigid to external agitation.20 As the intensified light field exists in a space, only a few hundred nanometre directly underneath the sphere, for laser structuring it is important to ensure a seamless contact between the spheres and substrate. As reported elsewhere,14 there is always a region with a multi-layer of micro-spheres on the glass slide and this multi-layer region should be carefully kept out of the contact zone.

The laser power was measured after the laser beam passed through the glass slide and the monolayer of micro-spheres. The transmission is 54%. The loss is due to a combination of reflection and scattering.

D. Laser processing

The laser beam had a Gaussian power density profile with a focal spot size of about 15 μm. The substrate surface was positioned in the laser focal plane. Laser structuring was performed in a clean room under atmospheric conditions. The laser pulse energy given in the paper is the total pulse energy released onto the sample. The loss of the laser pulse energy in the optical path will be taken into account while calculating the laser fluence underneath the micro-sphere. During irradiation, the laser beam passed through the glass slide support (see Figure 1(c)) and by interaction with the spheres intensified spots were generated in the near field.
(details are discussed in Sec. III A). Each of the high intensity spots generated a feature on the substrate surface. At each location, single laser shot as well as multiple shots were used to structure the substrate.

A schematic representation of the experimental procedures is drawn in Figure 1. The procedure introduced in this paper has following features: (1) it is easy to assemble; (2) both spherical particles and the CPLA-support are made of silica, therefore, they transmit UV light, which makes this transportable CPLA suitable for surface patterning using short laser wavelength (Excimer lasers for instance); (3) it withstands high laser fluence. Compared to the other transportable CPLAs reported in literature,5,17 the one applied in this paper is simpler and quicker to assemble since it does not require any additional adhesion or an intermediate substance as CPLA-support.

It is noted that the focal distance is longer with the presence of the glass slide in the optical path. The actual focal plane for the experiments reported in this paper was identified experimentally: trial ablation on silicon was carried out, with a glass slide laid on the top of the silicon substrate (without micro-spheres). A series of ablation was made at gradually lengthened distance between the laser scanner and the sample surface. The distance at which ablation craters with minimum diameter were produced was defined as the focal length. In our experiments, this actual focal distance is 0.3 mm longer than the free space focal distance. The micro-spheres may also influence the position of the focal plane. However, the influence of the micro-spheres was neglected since the dimension of the micro-spheres is much smaller than that of the glass slide.

III. RESULTS AND DISCUSSION

A. Near field modelling

It is not obvious that a thick glass slide carrier with micro-spheres underneath can be used to focus the laser light. Therefore, first of all, we wanted to verify whether this setup could be used to focus the laser light efficiently. Second, the spot size of the laser underneath a micro-sphere is of interest, which is desirable when laser fluence underneath a sphere is to be estimated. Geometrical ray tracing is not applicable here since the size of the optics (the micro-sphere) is comparable to the wavelength of the light. Furthermore, it has been well documented that near-field effects can be predominant when a dielectric sphere is used as a micro-lens, even when the size of the sphere is a few times larger than the laser wavelength.21 In order to study the distribution of the electromagnetic field in and underneath the dielectric particle, the optical near-fields around a silica particle and on silicon substrate were simulated using commercially available software Lumerical-FDTD. This software is a 3D Maxwell solver employing the finite-difference time-domain (FDTD) method.22 At 515 nm wavelength, silicon presents a strong absorption by linear inter-band processes.23 This has been taken into account in the simulation. Figure 2 illustrates the initial condition of the simulation. In the calculation, an isolated silica sphere is considered. It is sandwiched between a glass slide and a surface polished silicon substrate. The slab shown in white is the silica glass. The optical index of the glass is 1.4615 at 515 nm wavelength. The sphere has the same index as the glass slab and is 1.3 μm in diameter. The silicon substrate (pink in colour) is considered to have infinite thickness. The complex index of refraction of silicon was set to 4.224 + 0.06i. The blue arrow indicates the direction of laser polarization (denoted by \( E_0 \)) and the purple arrow indicates the laser propagation direction (denoted by vector \( k \)). Because the laser focus spot size is large compared to the size of the micro-sphere, a plane wave is taken to represent the laser light for the sake of simplicity. As an initial condition, the maximum laser pulse energy used in the experiments is taken for calculating the strength of electric field \( E_0 \). The region encircled in the brown rectangle is the FDTD simulation domain.

The calculated electromagnetic field around the silica sphere and the energy absorption inside the silicon substrate are shown in Figure 3. The laser polarization is along the x-axis and the propagation is along the z-axis. Figure 3(a) and 3(b) present the optical field in the system, in x-z and y-z planes.
One can see that there is an intensified electric field inside the silica sphere. The free-electron density in such an electric field can reach $10^{22}$ m$^{-3}$. Based on a Drude approximation of the dielectric function, this density is not sufficient to induce a strong change of the refractive index of the silica sphere.\(^\dagger\) From these graphs, an intensified electric field inside the silica sphere within the laser spot is given by $Q_s = Q_p (r/\omega_0)^2$, where $Q_s$ is the energy deposited on a micro-sphere, $r$ and $\omega_0$ are the radii of the micro-sphere and laser focus spot, and $Q_p$ is the laser pulse energy, from 0.2 $\mu$J to 1.6 $\mu$J in the experiments. The local laser fluence under the micro-sphere $F_s$ is given by $F_s = Q_s/(\pi a^2)$, where $a$ is the radius of the absorption area underneath a micro-sphere. The local laser fluence underneath the micro-spheres $F_s$ is 0.6 J/cm$^2$, 1.2 J/cm$^2$, and 4.8 J/cm$^2$, for laser pulse energy $Q_p$ of 0.2 $\mu$J, 0.4 $\mu$J, 0.8 $\mu$J, and 1.6 $\mu$J, respectively. The loss of the laser energy in the optical path has been taken into consideration in the calculation. The laser fluence $F_s$ is higher than the ablation threshold of 0.1 J/cm$^2$. Therefore, ablative material removal is expected in the experiments.

The morphology of the silicon surface will change after laser irradiation and this change will modify the electric field distribution.\(^\dagger\) The initial simulation conditions used in the FDTD simulation will be violated when the silicon surface is no longer flat. Therefore, the simulation results will concern only a single/first laser pulse irradiation at the virgin silicon surface.

### B. Laser structured silicon substrate

The SEM images in Figure 4 show some typical laser micro-structured surfaces created by means of a transportable CPLA. The centre of the image is roughly corresponding to the centre of the laser spot. Pulse energies of 0.2 $\mu$J, 0.4 $\mu$J, 0.8 $\mu$J, and 1.6 $\mu$J were applied to produce these samples, by single shots. With laser pulse energy in the range of 0.2 $\mu$J to 1.6 $\mu$J, similar circular-shaped features with pitch corresponding to the spacing of the spherical particle array are generated on the substrate. At the lowest pulse energy applied (0.2 $\mu$J, see Figure 4(a)), only subtle imprints are observed in SEM images, without any pronounced material removal. The appearance of the circular marks is thought to result from silicon amorphization.\(^\dagger\) The circular features made with laser pulse energy of 0.4 $\mu$J are better visible, see Figure 4(b). Features are clearly seen on the substrate when the laser pulse energy was raised to 0.8 $\mu$J, see Figure 4(c). The diameters of the circular-shaped features at the centre of the image were measured to be equal to 390 nm. This is in reasonable agreement with the diameter of the beam below a sphere in the simulation, as given in Figure 3(c). Measured from the irradiation centre outwards radially, the size of the features decreases slightly. Also the features in the centre of the irradiated zone have sharp edges compared to those in the peripheral area. This is probably due to a stronger interaction occurring at the centre of the irradiated area because of the higher laser fluence at the centre of the Gaussian spot. When the laser pulse energy exceeded 1.6 $\mu$J, onset of silicon melting was observed from the centre of the irradiated area, i.e., small droplets appear in the centre of the circular features, see Figure 4(d).

In the case of laser surface structuring by means of direct CPLA, the spheres are normally ejected after a single laser shot. This detachment may be due to the thermal expansion of the substrate surface caused by the absorption of the laser energy, which is proposed as the mechanism for removal of similar-sized particles on a silicon surface under...
laser irradiation. At higher laser pulse energy, laser ablation will occur and the detachment of the spheres may be caused by ejection of the ablated material. Throughout this study, we found that at low laser pulse energy, the spheres are not removed from the glass support after repeated laser shots. Hence, the transportable CPLA held on a glass support can be used for laser structuring with multiple laser shots. The SEM images presented in Figure 5 show the transportable CPLA itself after a laser structuring process. In Figure 5(a), three rectangular areas can be seen (indexed i, ii, and iii). The samples in each rectangular marked area were made with identical laser pulse energy, from top to bottom (areas indexed by i, ii, and iii), 1.6 µJ, 0.8 µJ, and 0.4 µJ, respectively. In each rectangle, four tracks were made with 1, 2, 4, and 8 shots (from top row to bottom row), respectively. An area in Figure 5(a) is marked and indexed with letter b, which is magnified and shown in Figure 5(b). Partial detachment of the spherical particles from the glass support has been observed right after the first laser pulse, at a laser pulse energy of 1.6 µJ (Figure 5(b)). At 0.8 µJ, only some of the particles were ejected after 4 laser pulses and the number of removed spherical particles is much smaller than at a laser pulse energy of 1.6 µJ. It is believed that the spheres disappeared from the glass support were left on the surface of the substrate during the laser process or during the separation of the support and the substrate. The transfer of the sphere from the glass support to the substrate may be caused by adhesion. That is, the attractive force between the substrate and the spheres is strong compared to the attractive force between the spheres and the glass support. When the laser pulse energy was 0.4 µJ and lower, the spheres were not removed during laser irradiation, even after multiple shots. Therefore, laser pulse energy 0.4 µJ is an upper limit to the process window for multiple-shot large area structuring.

The laser pulse energy which allows multiple-shot processing was further investigated. The SEM images in Figure 6 illustrate the evolution of the features with increased number of laser shots. The samples were made with laser pulse energy of 0.4 µJ and 0.2 µJ. As discussed above, at 0.4 µJ, circular features are observed on the substrate after a single laser shot,
FIG. 5. Spherical particle array on glass support, after laser processing. In each rectangle in (a), the laser pulse energy applied was, from top to bottom, 1.6 $\mu$J, 0.8 $\mu$J, and 0.4 $\mu$J, respectively; the area indexed with letter b is further magnified and displayed in (b) particle detachment at 1.6 $\mu$J.

FIG. 6. Features made with (a) 2 laser pulses and (b) 4 pulses, laser pulse energy 0.4 $\mu$J. (c) 4 pulses and (d) 8 pulses, laser pulse energy 0.2 $\mu$J.
but no significant material removal is visible (Figure 4(b)). As shown in Figure 6(a) after 2 laser pulses, a regular array of circular features with geometrical characteristic spacing corresponding to that of the monolayer is obtained. There is no evidence of displacement of the spheres after the first laser pulse. Any displacement caused by the first laser pulse would have caused formation of additional features at irregular locations by the second laser pulse. Further increasing of the total number of laser shots at this pulse energy level led to silicon melting. Melting was clearly observed on the sample that received 4 laser pulses (Figure 6(b)). The melting took place at the centre of the irradiation area, where the Gaussian intensity profile displays its peak fluence. At even lower laser pulse energy 0.2 µJ, pronounced material removal is observed after 8 laser pulses (Figure 6(d)). No evidence of significant silicon melting has been identified at these conditions. These results imply that this optic array can be used for large area machining, by laser scanning and overlapping laser pulses. Furthermore, it appears that there is a rather broad process window in terms of the total number of laser shots per location, especially at low laser pulse energy, for application of this technique to large area machining.

The surface morphology of the features was studied using CLSM. The 3D surface topology is presented in Figure 7(a). Figure 7(b) shows an extracted 2D profile along a section of features. It is evident that bowl-shaped holes have been produced. The uneven profile at surface level is due to re-depositions of ablated material and localized recast at the hole edge. Such a bowl-shaped profile has been identified for all the features generated in the laser irradiated area, irrespective of the laser pulse energy evaluated, and irrespective of the number of laser pulses applied. Unlike laser structuring with direct CPLA reported in literature, “sombrero-type” bumps or hillock-type features, which protrude from the substrate surface level are absent in our experimental results. As stated in Sec. III A, the laser fluence underneath the micro-spheres $F_s$ is beyond the ablation threshold and material removal from the silicon substrate is expected. It is believed that the spheres which are in direct contact with the substrate, during and after the material phase transition provided spatial confinement. This suppresses the outflow of the ablated silicon from the centre of the feature. The material re-deposition at the edges of the holes (see Figure 7(b)) is indicating a radial flow of the ablated material from the centre of the irradiated zone to the peripheral areas. These factors together give rise to the formation of bowl-shaped holes. The fact that bowl-shaped features without protrusion are produced by this process may be desirable in certain applications, such as friction reduction at silicon surfaces, where bowl-shaped holes can serve as lubricant reservoirs and as traps to capture wear debris.

The depths of the bowl-shaped holes were measured and plotted against the number of applied laser shots and are presented in Figure 8. Each data point represents an average value of measurements made at ten different holes selected from the centre of a structured area. In the case melting took place at the centre of the laser structured area (see Figure 6(b), for an example), the measurements were made on the holes situated in areas adjacent to the central melting zone. Comparison of the depth of the holes made by single shot at different laser pulse energy shows a noticeable difference between low pulse energies (0.2 µJ and 0.4 µJ) and high pulse energies (0.8 µJ and 1.6 µJ). The reason accounting for the difference is that the thermal affect is no longer negligible at high laser pulse energies, which correspond to high local laser fluences $F_l$. The ablation behaviour of ultra-short laser pulses is laser fluence dependent. Thermal transition happens at high laser fluence, which leads to a significant heat diffusion and increased material removal. A thermal transition fluence of 1.1 J/cm² has been reported for picosecond laser (7.3 ps and 515 nm) ablation of crystalline silicon. In our study, at pulse energy of 0.2 µJ and 0.4 µJ, the local laser fluence underneath the micro-sphere, $F_s$ of 0.6 and 1.2 J/cm², is smaller than or close to the transition fluence. Therefore, the thermal effect was insignificant. On the other hand, at pulse energy of 0.8 µJ and 1.6 µJ, the local laser fluence of 2.4 and 4.8 J/cm² is higher than the transition fluence, leading to an increased material removal rate. The correlation between hole depth and laser pulse energy (or corresponding fluence $F_l$) is in accordance with the literature. From Figure 8, it can also be observed that the maximum hole depth is about 140 nm. With high laser pulse
energy of $1.6 \mu J$ and $0.8 \mu J$, this is achieved by a single laser
shot or after 2 shots. At lower laser pulse energy of $0.4 \mu J$
and $0.2 \mu J$, the hole depth increases with the number of laser
shots. A careful comparison of the amount of material
removed by individual laser pulses reveals that the material
removal by the first laser pulse is less efficient than by the
successive laser pulses. At low laser pulse energies, the first
laser pulses may initiate damage which acts as absorption
centre for the successive laser pulses. As a result, the laser
pulses following the precedent pulses are absorbed more effi-
ciently by the silicon lattice. Consequently, more efficient
absorption leads to more efficient material removal. The
increased drilling efficiency achieved after the first of a few
laser pulses may also be explained from the diameter of the
laser beams below the spheres, as a function of the distance
to the spheres. That is, the highest laser intensity below the
silica sphere is located approximately a wavelength away
from the surface of the micro-sphere (see the inset in Figure
1(c)). After the first laser pulse, laser focus position does not
change, since the spheres stay in their position. However, the
substrate surface has receded downward after the first pulse
due to material removal. Then the receding surface comes
closer to the laser focus. Therefore, stronger ablation can
take place for the successive laser pulses and hence leading
to more material removal.

C. Sphere array damage

The glass transition temperature for the silica spheres is
below 1200°C. The melting temperature of silicon is
1412°C. If such high temperatures are reached at the con-
tact points between the spheres and substrate, the spheres
will soften, deform, or even damage. Since the micro-
spheres resided on the glass support even after the laser pro-
cess in this research, it was possible to analyze the effect of
laser patterning on the spheres. The SEM images in Figure
9 show the micro-spheres before (Figure 9(a)) and after they
were used for laser processing. The spheres used for a single
shot and 8 shots, at a laser pulse energy of $0.2 \mu J$, are shown
in Figures 9(b) and 9(c). Compared to “un-used” spheres,

![Figure 9](image_url)

FIG. 9. SEM images showing (a) as-prepared spherical particle array; (b) the particle array after a single laser shot; (c) after 8 laser shots. The arrows in (c) point at the damages on the micro-spheres. The laser pulse energy is $0.2 \mu J$ in (b) and (c). In (d), more remarkable damage is shown on the spheres at a laser pulse energy of $0.6 \mu J$, in a single shot.
debris deposition was observed on the spherical particles after a single laser shot. The debris should originate from the substrate after laser ablation. More deposition is noticeable after 8 shots. Circular-shaped spots are visible on the spheres after 8 laser pulses. These spots are smaller (diameter less than 290 nm) than the circular features created on the silicon substrate. The size of the circular spots on the spheres increased at higher laser pulse energy. Figure 9(d) shows the spheres used at a laser pulse energy of $0.6 \mu J$, after a single shot. The size of the spots on these spheres is apparently larger. The formation of these spots appears to be due to local softening or melting of the silica spheres themselves. It is also possible that the round spots are re-solidified silicon melt, which was ejected from the substrate during laser irradiation. Additional surface topology information of the spheres would help a better understanding of the formation mechanism of these spots. This information has however not been successfully obtained yet. Nevertheless, with such damage and contamination present, the light focusing quality that the sphere can provide for the successive laser pulses would deteriorate. Hence the damage effect has to be given due considerations in multi-shot laser processing. In order to reuse this kind of transportable CPLA, the laser pulse energy applied should be kept low.

IV. CONCLUSIONS

A simple, adhesive-free transportable micro-sphere optic array was proposed for laser surface structuring. The focusing optic consisted primarily of an array of silica spheres assembled and mounted on a glass plate support. This assembly is put in direct contact with the substrate that is to be laser structured. The substrate to be machined does not need to be pre-treated prior to laser structuring. Since this transportable CPLA does not require any adhesives or an intermediate support, there is no limitation to the laser wavelength to be selected for surface structuring.

When illuminated, these spheres focus the incoming laser beam and enhance the optical field at the contact points of the spheres with the substrates surface. The results from single shot experiments were shown to be in good agreement with electromagnetic simulations of the radiation. At an appropriate low laser pulse energy, the assembly is robust. Arrays of nanometre-sized holes were drilled in the substrate by multiple laser shots. Re-deposition of the substrate material and damage of the spheres themselves have been observed on the surface of the spheres after the laser structuring process. Low laser pulse energy is found to be appropriate for avoiding undesirable surface melting on the substrate and to minimize damage to the spheres.


