Nanosecond laser ablation of silver nanoparticle film

Jaewon Chung
Sewoon Han
Daeho Lee
Sanghoon Ahn
Costas P. Grigoropoulos
Jooho Moon
Seung H. Ko
Nanosecond laser ablation of silver nanoparticle film

Jaewon Chung
Korea University
Department of Mechanical Engineering
Seoul 136-713, Republic of Korea
E-mail: jmoon@yonsei.ac.kr

Daeho Lee
Sanghoon Ahn
Costas P. Grigoropoulos
Univ. of California
Department of Mechanical Engineering
Berkeley, California 94720-1740

Jooho Moon
Yonsei University
Department of Materials Science and Engineering
Seoul 120-749, Republic of Korea
E-mail: jmoon@yonsei.ac.kr

Seung H. Ko
KAIST
Department of Mechanical Engineering
291 Daehak-ro, Yuseong-gu
305-701, Republic of Korea

Abstract. Nanosecond laser ablation of polyvinylpyrrolidone (PVP) protected silver nanoparticle (20 nm diameter) film is studied using a frequency doubled Nd:YAG nanosecond laser (532 nm wavelength, 6 ns full width half maximum pulse width). In the sintered silver nanoparticle film, absorbed light energy conducts well through the sintered porous structure, resulting in ablation craters of a porous dome shape or crown shape depending on the irradiation fluence due to the sudden vaporization of the PVP. In the unsintered silver nanoparticle film, the ablation crater with a clean edge profile is formed and many coalesced nanoparticles of 50 to 100 nm in size are observed inside the ablation crater. These results and an order of magnitude analysis indicate that the absorbed thermal energy is confined within the nanoparticles, causing melting of nanoparticles and their coalescence to larger agglomerates, which are removed following melting and subsequent partial vaporization.

Subject terms: nanosecond laser; ablation; nanoparticle; gold; silver; sintering.

Paper 121491P received Oct. 15, 2012; revised manuscript received Jan. 11, 2013; accepted for publication Jan. 11, 2013; published online Feb. 7, 2013.

1 Introduction

Pulsed laser ablation (PLA) has been extensively studied in the past as an effective technique for the direct patterning of thin metal films. In an ultra-short (femto or pico-second) PLA process, precise crater profiles with a clean and abrupt boundary have been successfully demonstrated due to the very short time scales involved in the ablation process that tend to suppress, although not completely eliminate thermal transfer. However, nanosecond laser ablation involves the melting and vaporization of thin metal films, and the vaporized plume can create a recoil pressure that expels the molten pool resulting in the elevated rim structure at the periphery of the crater as shown in Fig. 1. For high-resolution patterning, these effects should be minimized.

Nanoparticles show a significant depression of melting temperature compared to bulk materials due to the thermodynamic size effect. In addition, nanoparticles capped by a surface monolayer or an organic additive can be suspended in various solvents without agglomeration. Consequently, electrical micro-conductors can be fabricated on flexible polymer films by using the cost effective drop-on-demand (DOD) inkjet printing and the subsequent sintering process at a reduced temperature suitable to polymers. However, the typical resolution of the DOD inkjet printing process is on the order of 20 to 100 μm, so laser hybrid schemes are being developed. Here, fabricating high resolution patterns with a clean edge profile has the practical importance in many applications. For example, an organic field effect transistor (OFET) requires small channel length to reduce the effective resistance and therefore increase drain current and speed. In addition, a uniform film topography is desirable, since charge-carrier transport in an OFET is strongly related to the morphology.

Previously, with this goal in mind, the nanosecond laser ablation of an hexanethiol self-assembled monolayer (SAM) protected gold nanoparticles was explored. In brief, an unsintered gold nanoparticle film showed submicrometer sized patterning with an abrupt crater profile [Fig. 2(a)], while a sintered gold nanoparticle film exhibited the characteristics of a metal film, one of which is an elevated rim structure [Fig. 2(b)]. In addition, the ablation threshold fluence of unsintered gold nanoparticle film was at least ten times lower than the reported threshold fluence for the sputtered gold film. These results were explained by considering the unusual properties of the hexanethiol SAM protected gold nanoparticles such as melting temperature depression of the gold nanoparticles of a few nanometers in size, desorption of SAM, weak bonding between nanoparticles, and the efficient laser energy absorption due to surface plasmon. However, the dominant effect is still unknown, and thus it is uncertain whether similar results can be obtained for other nanoparticles of different sizes, capping layers and optical and thermal properties. To answer this question, polyvinylpyrrolidone (PVP) protected silver nanoparticles are employed in the current study. In addition, the results of scanning electron microscopy (SEM) as well as atomic force microscopy (AFM) images are shown for better understanding of nanosecond laser ablation of nanoparticle films.
The silver nanoparticles are synthesized by the polyol method. Silver nitrate used as a precursor of silver nanoparticles is dissolved in ethylene glycol and PVP is added to prevent the synthesized silver nanoparticles from agglomeration. This solution is stirred vigorously in a reactor fitted with a reflux condenser, and heated to 120°C. The reaction is maintained for 30 min and the solution is cooled to room temperature. The silver particles are separated from the liquid by centrifugation and repeatedly washed with ethanol. The resulting particles are dried at room temperature. The average diameter of the prepared silver nanoparticles is 20 nm. These nanoparticles are dispersed in a mixed solvent of ethylene glycol and ethanol at a volume ratio of 5:1 with respect to the dried Ag. The solid loading of the ink is 20% in weight. The formulated ink is ball-milled for 24 h, and then filtered through a 5 μm nylon mesh.

This nanoparticle solution is inkjet printed or spin-coated on a silicon substrate and nanoparticle films of several hundred nanometers in thickness are obtained by evaporating the solvent at a moderate temperature lower than the sintering temperature.

Figure 3 shows the relative resistance change of the silver nanoparticle film depending on curing temperature. Relative resistance decreases sharply at about 100°C, at which the silver nanoparticle film is deduced to sinter. Note that, in the case of hexanethiol self-assembled monolayer protected gold nanoparticles, the surface monolayer is desorbed and removed from the gold nanoparticles, which initiates sintering of the gold nanoparticles according to the result of thermogravimetry analysis. However, the silver nanoparticle film sinters while PVP is still present, which is known to decompose and vaporize above 400°C. After curing at 200°C for 1 h using a hotplate, the room temperature resistance becomes two to three times higher than that of bulk silver. Figure 4 shows SEM images of the silver nanoparticle film cured below the sintering temperature (hereafter referred to as “unsintered nanoparticle film”) and that cured above the sintering temperature (hereafter referred to as “sintered nanoparticle film”). In the unsintered silver nanoparticle film, particles of several tens nanometers in size can be still observed. After sintering, however, a strong inter-particle necking occurs, which forms a porous structure with the average grain size of 50 to 100 nm. This signifies that the sintering process is dominated by the PVP layer melting and the subsequent diffusion between the nanoparticles rather than the full melting of the nanoparticles, since the full melting of 5 nm sized silver nanoparticles occurs above 500°C. It is noted that the...
thicknesss of the alkanethiol protected gold nanoparticle film decreased more than 50% during sintering process due to both sintering compaction and removal of the surface monolayer, whose size is comparable to that of gold nanoparticle. However, the thickness of the silver nanoparticle film decreases about 20% due to only sintering compaction.

The prepared silver nanoparticle films are ablated by using a frequency doubled Nd:YAG nanosecond laser [532 nm wavelength, 6 ns full width half maximum (FWHM) pulse width] (Fig. 5). The prepared nanoparticle films are attached vertically on the xyz translating and tilting micromachining workstation. An infinity-corrected long working distance objective lens focuses the laser beam, which is expanded to cover the entrance pupil, and also takes images the ablated sample surface in combination with a zoom lens, a charge couple device (CCD) camera. A dichroic mirror (DM) prevents the reflected laser beam from irradiating on the CCD, but transmits the white light illumination. The incident energy after the objective lens is varied from 0.001 ~ 6 μJ using neutral density (ND) filters to ablate prepared nanoparticle films. In addition, the incident energy is finely adjusted by using a half waveplate (λ/2) and a polarizing beamsplitter (PBS). Ablation experiments are carried out varying the incident energy, the number of irradiating laser pulses and the focused beam waist. The ablated morphology of the nanoparticle film is characterized by optical microscopy, AFM and SEM.

3 Results

Figure 6(a) through 6(d) shows the AFM height images and the corresponding cross-sectional profiles of the ablation crater in the unsintered silver nanoparticle film. Both the ablation radius and the ablated depth increase with incident energy (E), and the silicon substrate is exposed at the incident energy of 0.37 μJ [Fig. 6(d)]. In the sintered silver nanoparticle film [Fig. 6(e) through 6(h)], two different morphologies are observed in the AFM images. At low energy, the sintered nanoparticle film appears to be inflated [Fig. 6(e) and 6(f)]; at a high energy [Fig. 6(g) and 6(h)], the silicon substrate is exposed due to strong ablation and the elevated rim is formed at the periphery of the ablation crater. Here, the center peak fluence (Fpeak) is calculated from incident energy (E) and the measured beam waist (ω0, 1/e2) using Eq. (1).

SEM images in Fig. 7 provide better clues of the ablation process in the silver nanoparticle film. In the sintered silver nanoparticle film [Fig. 7(a) and 7(b)], the absorbed thermal energy conducts well through sintered porous structure, which results in a molten pool. This molten pool is expelled by the recoil pressure of ablated vapor plume, which resolidifies at the periphery of the ablated crater. At a low fluence [Fig. 7(a)], the recoil pressure is not strong enough to expel the molten pool, and the resolidified splash forms a porous dome structure. The porous structure is possibly caused by the sudden vaporization of the PVP capping layer. At a high fluence [Fig. 7(b)], this recoil pressure exerted on the molten pool is strong, so that the silicon substrate is exposed at the center region of the ablation crater, while the most of expelled molten pool is resolidified at the periphery of the ablated crater forming crown-shaped ablation crater. Note that some of the resolidified splashes that appear to be broken in Fig. 7(a) and 7(b) were due to AFM scanning, which was carried out before these SEM images were taken.

In the unsintered nanoparticle film [Fig. 7(c)], many coalesced nanoparticles of diameters varying from 50 to 100 nm are observed inside the ablation crater formed by AFM images [Fig. 6(a) through 6(d)]. In addition, large particles are observed more often in the center of the ablation crater, while small particles at the periphery of the ablation crater. Figure 8 shows the SEM images of the ablation craters in the unsintered nanoparticle film for different irradiated laser
pulses. Here, the number of coalesced nanoparticles of diameters from 50 to 100 nm increases with the number of irradiated laser pulses and the substrate is exposed when laser pulses are irradiated three times.

Since unsintered nanoparticles are disconnected, thermal energy does not conduct well to form a continuous molten pool. Instead, the absorbed thermal energy is presumed to be confined inside the nanoparticles to melt the nanoparticles and subsequently coalesce to larger agglomerates. During this process, the coalesced nanoparticles are expelled from the nanoparticle film by the build-up pressure possibly generated by the vaporized silver on the nanoparticle surface. Note that laser heating lasts only a few nanoseconds, so the inter-particle necking structure such as Fig. 4(b) is not observed in Fig. 8.

The ablation threshold peak fluence ($F_{\text{th}}$) of the unsintered nanoparticle film is obtained from the ablation volume using AFM topography for $a_{\text{th}}$ of 13 nm (Fig. 9). The threshold fluence ($F_{\text{th}}^\ast$), which is calculated from x-axis intercepts, is 0.051 J/cm$^2$.

In an order of magnitude analysis, the unsintered silver nanoparticle film is assumed to absorb light energy according to Beer’s law.$^1$ In addition, assuming that the conductive heat transfer through the unsintered silver nanoparticle film is negligible during the laser pulse duration ($t_{\text{pulse}} = 6$ ns), (i.e., thermal diffusion length [$l_T = (Dt_{\text{pulse}})^{0.5}$] is much smaller than both the beam waist ($a_{\text{th}}$) and the optical absorption depth [$l_A$, inverse of absorption coefficient, $a$]), the temperature field $T(r, z)$ of the unsintered silver nanoparticle film can be approximated as$^1$

$$T(r, z) = T_\infty + \frac{(1 - R)F_{\text{th}}}{\rho c_p l_A} \exp\left(-\frac{2r^2}{w_0^2}\right) \exp\left(-\frac{z}{l_A}\right), \quad \text{(2)}$$

where $T_\infty$, $R$, $\rho$, and $c_p$ represent the ambient temperature, reflectance, density, and heat capacity of the unsintered silver nanoparticle film, respectively. Using Maxwell-Garnett effective medium theory,$^{17,21}$ the effective dielectric functions and the corresponding refractive indices of particles in a matrix medium can be obtained and $R$ and absorption depth ($l_A$) are calculated (Fig. 10). Table 1 summarizes the important properties of bulk silver and the resulting properties of the unsintered silver nanoparticle film using effective medium theory. Here, the volume fraction of particles in the nanoparticle film is assumed to be 0.609, which is the sphere random packing density.$^{22}$ Using the values in Table 1 and the ablation threshold fluence ($F_{\text{th}} = 0.051$ J/cm$^2$), the center temperature on the surface [$T(r = 0, z = 0)$] is calculated as 1480 K, which is comparable to the melting temperature of bulk silver (1235 K).

When the conductive heat transfer is considered, the center temperature on the surface after the duration of a laser pulse ($t_{\text{pulse}}$) can be calculated using the following equation.$^1$

$$T(r = 0, z = 0) = T_\infty + \frac{(1 - R)F_{\text{th}}}{\rho c_p l_A} \int_0^{t_{\text{pulse}}} \frac{1}{1 + \frac{\partial T}{\partial z}} \exp\left(-\frac{\sqrt{D\tau}}{l_A}\right) \exp\left(-\frac{4\sqrt{D\tau}}{l_A}\right) \text{erf}\left(\frac{\sqrt{D\tau}}{l_A}\right) \text{d}\tau. \quad \text{(3)}$$

Note that the term inside the integral approaches the value of 1 when thermal diffusivity becomes very small, and then Eq. (3) becomes identical to $T(r = 0, z = 0)$ of Eq. (2). Here, to calculate Eq. (3), the thermal diffusivity ($D = k/\rho c_p$) for the unsintered silver nanoparticle film should be known. Assuming that the void in the unsintered nanoparticle film is filled with PVP, the thermal conductivity of unsintered nanoparticle film, $k$, can be obtained using the Maxwell Garnett type effective medium approximation [Eq. (4)].$^{24}$

$$k = \frac{k_p(1 + 2R_k k_m/r_p) + 2k_m + 2f[k_p(1 - R_k k_m/r_p)] - k_m}{k_p(1 + 2R_k k_m/r_p) + 2k_m + 2f[k_p(1 - R_k k_m/r_p)] - k_m}. \quad \text{(4)}$$

Here, $k_p$, $k_m$, $r_p$, and $R_k$ represent the thermal conductivities of the particle and medium, the radius of the particle, and Kapitza resistance, respectively. Using typical values of $10^{-8}$ to $10^{-7}$ m$^2$K/W for the $R_k$ of metal nanoparticles$^{25,26}$ and 0.1 to 0.3 W/mK for the $k_m$ of polymer vinyl,$^{27}$ the thermal conductivity of the unsintered nanoparticle film, $k$, can be found to lie in the range from 0.1 to 0.6 W/mK. In Fig. 11, the corresponding center temperature...
on the surface ranges from 1280 to 1390 K, which is comparable to the melting temperature of bulk silver (1235 K), again.

Therefore, \( F_{th} \) is presumed to be the energy required for small nanoparticles to melt and coalesce to larger nanoparticles whose melting temperature is comparable to that of the bulk material.\(^\text{19,20}\) It is also noted that the calculated absorption depth \( (l_A = 169 \text{ nm}) \) is smaller than the thickness of the unsintered silver nanoparticle film (500 nm), so there is a strong temperature gradient in the \( z \)-direction and only the surface layers can be heated and ablated without exposing the substrate.

Figure 12 shows the ablation radius \( (r_A) \) depending on peak fluence. The ablation radius increases sharply at the low fluence near the ablation threshold value and the increasing rate of the ablation radius decreases at a high fluence. From the Gaussian beam profile, the ablation radius \( (r_A) \) can be approximated as the position where the fluence is the same as the ablation threshold fluence. The resulting equation is:\(^\text{16}\)

\[
r_A = \frac{a_0}{\sqrt{2}} \sqrt{\ln \left( \frac{F_{\text{peak}}}{F_{\text{th}}} \right)},
\]

and the curves by Eq. (5) agree relatively well with the measured ablation radius in Fig. 12.

Figure 13 shows the effect of multishot ablation. The square and diamond symbols correspond to the incident energies of 0.018 and 0.007 \( \mu \)J, respectively. Here, the
solid symbol indicates the ablated volume data, which are obtained from an unexposed substrate and an empty symbol indicates the exposed case. In Fig. 13, the linearity of the ablated volume is very good until the substrate is exposed, which indicates that digital control of the nanoparticle film ablation volume is possible. In addition, the slopes of the linear fitting (i.e., the ablated volume per pulse) are 1.39

Table 1 Important properties of bulk silver and the resulting nanoparticle film properties based on effective medium theory.\textsuperscript{21}

<table>
<thead>
<tr>
<th>Properties</th>
<th>Bulk silver</th>
<th>Silver nanoparticle film</th>
</tr>
</thead>
<tbody>
<tr>
<td>( f ), volume fraction of particle</td>
<td>0.609</td>
<td></td>
</tr>
<tr>
<td>( n ), real part of refractive index at 532 nm</td>
<td>0.129\textsuperscript{23}</td>
<td>3.818</td>
</tr>
<tr>
<td>( \kappa ), real part of refractive index at 532 nm</td>
<td>3.25\textsuperscript{23}</td>
<td>0.251</td>
</tr>
<tr>
<td>( \rho ), density (kg/m(^3))</td>
<td>10460</td>
<td>6388</td>
</tr>
<tr>
<td>( c_p ), heat capacity (J/kg/K)</td>
<td>262 at 800 K</td>
<td></td>
</tr>
<tr>
<td>( k ), thermal conductivity (W/mK)</td>
<td>429</td>
<td>0.1 to 0.6</td>
</tr>
<tr>
<td>( D ), thermal diffusivity (m(^2)/s)</td>
<td>( 1.57 \times 10^{-4} ) (6 ( \sim ) 21) \times 10^{-8}</td>
<td></td>
</tr>
<tr>
<td>( R ), reflectance</td>
<td>0.96</td>
<td>0.34</td>
</tr>
<tr>
<td>( l_a ), optical absorption depth at 532 nm (nm)</td>
<td>13</td>
<td>169</td>
</tr>
<tr>
<td>( l_T ), thermal diffusion length (nm)</td>
<td>960</td>
<td>19 ( \sim ) 35</td>
</tr>
<tr>
<td>( T_m ), melting temperature (K)</td>
<td>1235</td>
<td></td>
</tr>
<tr>
<td>( T_v ), boiling temperature (K)</td>
<td>2435</td>
<td></td>
</tr>
<tr>
<td>( \Delta h_m ), heat of melting (J/kg)</td>
<td>( 1.04 \times 10^5 )</td>
<td></td>
</tr>
<tr>
<td>( \Delta h_v ), heat of vaporization (J/kg)</td>
<td>( 2.32 \times 10^6 )</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 11 The center temperature on the surface calculated using Eq. (3) depending on thermal conductivity of silver nanoparticle film.

Fig. 12 Ablation radius of the unsintered silver nanoparticle film changing the peak fluence (incident energy) for different focused beam waists (a) \( w_0 = 13 \) \( \mu \)m, (b) \( w_0 = 2.9 \) \( \mu \)m. The ablated data where the silicon substrate is exposed are also included. The curves are drawn from Eq. (5) using the ablation threshold fluence of 0.051 J/cm\(^2\).

Fig. 13 Ablated volume of the unsintered silver nanoparticle film depending on the number of irradiated pulses. The focused beam waist (\( w_0 \)) is 2.9 \( \mu \)m. The rectangle and diamond symbols correspond to the cases of the incident energies (peak fluence) of 0.018 \( \mu \)J (0.139 J/cm\(^2\)) and 0.007 \( \mu \)J (0.055 J/cm\(^2\)), respectively. The solid symbol indicates the case when the bottom substrate is unexposed, and the empty symbol indicates the exposed case.
and 0.56 \mu m^3/pulse for the incident energies of 0.018 and 0.007 \mu J, respectively. For both cases, the incident energy per ablated volume (E/V_{ablation}) can be calculated to be about 0.013 \mu J/\mu m^3, while the light energy absorbed per ablated volume to be 0.0085 \mu J/\mu m^3 considering reflectance (Table 1). The light energy absorbed can be divided into heating, melting, and vaporization energies of nanoparticles and is expressed as follows:

\begin{equation}
\frac{(1-R)E}{V_{ablation}} \approx \rho c_p(T_v - T_{\infty}) + \Delta h_m + \Delta h_v.
\end{equation}

Here, \(T_v\), \(\Delta h_m\), and \(\Delta h_v\) represent the boiling temperature, latent heat of melting and vaporization, respectively. The energy absorbed per ablated volume [(1-R)E/V_{ablation}] is calculated as 0.028 \mu J/\mu m^3 considering all three terms, while it can be calculated as 0.007 \mu J/\mu m^3 including only the heating and melting energies of nanoparticles in Eq. (6), which is comparable to the experimentally identified light energy absorbed per ablated volume of 0.0085 \mu J/\mu m^3. These results indicate that the nanoparticle film may not be ablated by full vaporization of nanoparticles. Instead, the nanoparticles melt and coalesce to larger nanoparticles upon heating, and these nanoparticles are removed by surface melting and subsequent partial vaporization. In an earlier work, coalesced gold nanoparticles of 5 to 50 nm in size were observed in the ejecta of the unsintered gold nanoparticle film, which also support the above explanation.

4 Summary

The nanosecond laser ablation process of nanoparticle films is studied using PVP protected silver nanoparticles (20 nm diameter).

In the sintered silver nanoparticle film, absorbed light energy conducts well through the sintered porous structure, resulting in the formation of a molten pool. This molten pool is expelled by the recoil pressure of the ablated vapor plume, and resolidifies at the periphery of the ablated crater. Here, the SEM images show ablation craters of porous dome shape or crown shape depending on the irradiation fluence due to the PVP capping layer.

The SEM images of the unsintered silver nanoparticle film ablated at the wavelength of 532 nm show many coalesced nanoparticles of 50 to 100 nm in size inside the ablation crater. Large particles can be observed more often in the center of the ablation crater. According to an order of magnitude analysis, the measured ablation threshold peak fluence of 0.051 J/cm^2 is comparable to the fluence required to heat the silver nanoparticle film to the melting temperature of bulk silver. In addition, the absorbed light energy per ablated volume is also comparable to the energy required to heat and melt the ablated volume, but not to vaporize the entire ablated volume. In an earlier work, the coalesced nanoparticles of 5 to 50 nm in size were observed from the ejecta of the unsintered gold nanoparticle film. These results indicate that the unsintered nanoparticle film may not be ablated by full vaporization of nanoparticles as synthesized. Instead, in the unsintered silver nanoparticle film, the absorbed thermal energy is presumably confined within the nanoparticles, causing melting of nanoparticles and their coalescence to larger agglomerates, that are removed following melting and subsequent partial vaporization. Nonetheless, the ablated volume of unsintered nanoparticle film increases linearly with both the incident energy and the number of irradiated laser pulses, which indicates that digital control of the nanoparticle film ablation volume is possible.

The ablation threshold peak fluence (F_{th}) of all unsintered nanoparticle films (alkanethiol self assembled monolayer protected gold nanoparticles (0.03 J/cm^2) and PVP protected silver nanoparticles (0.05 J/cm^2) are in the same range. These results suggest that the melting and coalescence of the nanoparticles and its partial vaporization rather than the vaporization of the capping agents is dominant in the ablation of an unsintered nanoparticle film.

Acknowledgments

Financial support to Korea University by the Korea Research Foundation Grant funded by the Korean Government (MOEHRD, Basic Research Promotion Fund, KRF-2007-331-D00053) and to the University of California, Berkeley by the U.S. National Science Foundation under a grant from King Abdullah University of Science and Technology is gratefully acknowledged.

References


Jaewon Chung is an associate professor at Korea University, Seoul, Korea, in the Department of Mechanical Engineering. He received his BS and MS degrees in mechani-
cal engineering from Yonsei University, Seoul, Korea, in 1995 and 1997, respectively and the PhD degree in mechanical engineer-
ing from the University of California, Berkeley, in 2002. He was postdoctoral asso-
ciate in Engineering System Research Center at University of California, Berkeley, from 2002 to 2004 and has worked in the Center of Micro and Nano Technology at Lawrence Livermore National Laboratory as a visiting collaborator. He joined the faculty at Yonsei University as an assistant professor in 2004. His research interests are in direct writing methods, including DOD inkjet printing, electrohydrodynamic jetting and laser material processing.

Sewoon Han is a PhD candidate of mechani-
cal engineering at Korea University, Seoul, Korea. He obtained his BS (2004) in mechanical engineering from Myongji University, Yongin, Korea, and MS (2008) in mechanical engineering from Korea University. His current research interests are in lab-on-a-chip techniques including development of a new assay for transendo-
thelial migration of immune cells, cancer metastasis, and in vivo-like differentiation of neural stem cells.

Doeho Lee is a PhD candidate of mechanical engineering at UC Berkeley. He obtained his BS (2002) in mechanical and aerospace engineering from the Seoul National University, Seoul, Korea, and his MS (2007) in the same university with a specialty in FLUENT modeling and analysis of fuel cell sys-
tems. From 2002 to 2005, he worked at an industrial pump manufacturing company. He joined the laser thermal lab at UC Berkeley in 2006. His current research interests include the development and application of laser processing for transparent conductive oxide films, laser assisted printing techniques for the fabrication of functional nanostructures, and photovoltaics and optoelectronics.

Sanghoon Ahn is a PhD candidate of mechanical engineering at UC Berkeley. He obtained his BS (2006) in mechanical and aerospace engineering from the Seoul National University, Seoul, Korea, and his MS (2008) in the same university with a specialty in micro/bio fluidics. He joined the laser thermal lab at UC Berkeley in 2008. His current research interests include laser processing for advanced solar cell (thin film solar cell and rear contact solar cell) fabrication and time resolved study of ultrafast time scale thermal conductance of nanostructure.

Costas P. Grigoropoulos is a professor in the Department of Mechanical Engineering at the University of California at Berkeley and Materials Science/Engineering Faculty at the Environmental Energy Technologies Division of Lawrence Berkeley National Laboratory. He received his diploma degrees in naval architecture and marine engineering (1978), and in mechanical engineering (1980) from the National Technical University of Athens, Greece. He holds an MSc degree (1983), and a PhD (1986), both in mechanical engineering from Columbia University. He is a fellow of the American Society of Mechanical Engineers and an associate editor for the Journal of Heat Transfer and the International Journal of Heat and Mass Transfer. His research interests are in laser materials micro/nanoprocessing, nanoe-
engineering, laser-induced thin film crystal growth for large area electronics, fabrication of flexible electronics, hydrogen storage, advanced energy applications, ultrafast laser interactions with mate-
rials, microscale and nanoscale transport.

Jooho Moon is a professor in the Department of Materials Science and Engineering at Yonsei University, Seoul, Korea. He holds an MS and PhD in materials science and engineering from the University of Florida. He did his postdoctoral research in the materials processing center at MIT from 1996 to 1998. He was awarded a Japan Society of the Promotion of Science fellow-
ship in 1998. He joined the faculty at Yonsei University as an assistant professor in 2000 and was promoted to professor in 2009. His research interests include ink-jet printing of self-assembling colloids and functional nanopar-
icles, printed electronics and displays, micro solid oxide fuel cells, solar cells, and organic-inorganic hybrid materials. He has co-authored more than 120 publications in peer-reviewed journals.

Seung H. Ko is currently an associate pro-
fessor at Korea Advanced Institute of Science and Technology. He got the PhD degree from University of California, Berkeley under Professor Costas Grigopoulous in 2006. Later that year, he started a postdoctoral fellow position at UC Berkeley and a project researcher at Lawrence Berkeley National Lab till 2009. His main research interests are next genera-
tion, unconventional micro/nano fabrication approach development as an alternative to the conventional photolithography and vacuum deposition based processes. The novel micro/ nano fabrication process development includes new material develop-
ment, high resolution direct patternning process development, and specific application development.