Laser Cleaning of Particles with the aid of Freezer/Chilling Plate

B.C. Lim*, M.H. Hong*,**, A. Kaur**, L.P. Shi* and T.C. Chong*,**

*Data Storage Institute, DSI Building, 5 Engineering Drive 1, (Off Kent Ridge Crescent, NUS), Singapore 117608
E-mail: LIM_Boon_Chong@dsi.a-star.edu.sg
**Department of Electrical and Computer Engineering, National University of Singapore, 4 Engineering Drive 3, Singapore 117576

In steam laser cleaning, a thin water film layer, formed by the condensation of steam, on the substrate surface is used as an energy transfer medium to effectively remove particulate contaminants from the substrate surface. In this work, a new method is adopted for water film formation. Instead of steam condensation, the water film is now formed by condensation of ambient water vapour, a more uniform water film results and this new method would simplify the experimental setup of steam laser cleaning. Using this new method of water film formation and a pulsed 532 nm Nd:YAG laser (pulse width of ~70 ns at a pulse repetition rate of 5 kHz), the dependence of cleaning efficiency on processing parameters, such as laser fluence, pulse number/unit area, and temperature, are investigated and cleaning efficiency will be compared to that of dry and steam laser cleaning.

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1. Introduction

Particle removal from substrate surfaces is an issue that is addressed in several industries, such as semiconductors, optics, photonics, and micro-electromechanical systems (MEMS) [1]. According to the review [2], for a particle less than 20 μm, the ratio between adhesion force and gravitational force is greater than 10^5. This ratio gets even higher as particle size decreases and this explains why the cleaning force required for particle removal increases for smaller particles.

Laser cleaning techniques have been demonstrated to provide the cleaning force required to remove various particulate contaminants from several substrate surfaces [3-6] effectively. Examples include removal of aluminium and tin particles from magnetic head sliders [4], cleaning of metallic particles from silicon surfaces [5-6], and cleaning of aluminium and silicon particles from quartz [7].

An effective laser cleaning technique is steam laser cleaning. During steam laser cleaning, a thin layer of liquid, such as water or isopropanol (IPA), is used as an energy transfer medium to assist in the removal of particles [5, 8]. Under laser irradiation, this liquid film layer undergoes rapid heating and is explosively vaporized, generating a cleaning force high enough for particle removal. To create a thin liquid layer on the substrate surface, the liquid is usually heated up to generate steam vapour and then a carrier gas is used to transfer the steam to the substrate surface which results in condensation and subsequently the formation of a thin liquid film on the substrate surface.

In this work, instead of steam condensation, the water film is now formed by ambient water vapour condensation. This is achieved by firstly cooling down the substrate below the dew point using a chilling plate. Fig. 1 shows the water film formed by ambient water vapour condensation and that formed by steam condensation. A more uniform water film results for the case of ambient water vapour condensation.

(a)

(b)

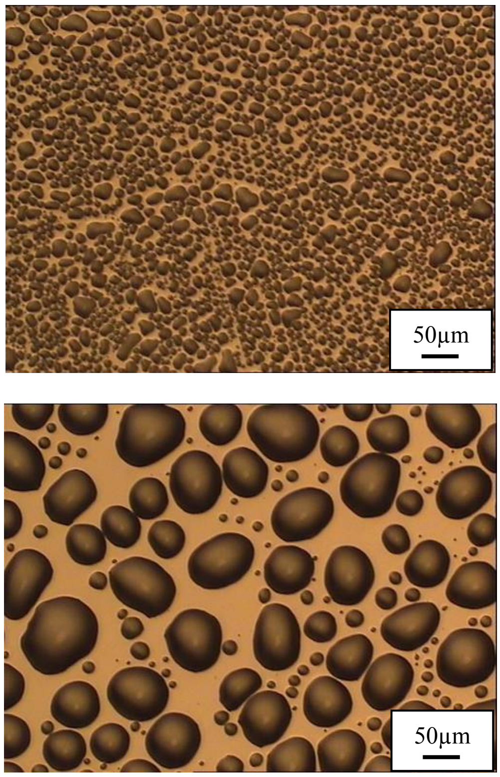

Fig. 1 Optical microscope images of water film layer formed by (a) ambient water vapour condensation and (b) steam condensation.

By adopting this new method (which will be referred as chilled laser cleaning hereafter), the experimental setup is simplified as compared to steam laser cleaning and its cleaning efficiency under different processing conditions will be investigated. Results obtained demonstrated that the cleaning efficiency of chilled laser cleaning is comparable to that of steam laser cleaning under the same processing parameters.

2. Methodology

Fig. 2 shows the experimental setup used in this work. The laser source used is Lightwave Series 210G DPSS Nd:YAG 532 nm (pulse width: ~70 ns at a pulse repetition rate of 5kHz) and it has a TEM_{00} Gaussian output profile. The beam spot size is estimated to be approximately 100 µm by deliberate ablation of a silicon sample and then measuring the diameter of the ablated hole using an optical microscope. To control laser fluence, a polarizing beam splitter and a half waveplate are used. Silicon wafers with thickness of 200 µm and polished mirror-like surface are used as substrates.

The contaminants used are 1 µm polystyrene (Duke Scientific 5100A) in colloidal form and they are deposited onto the substrate surface as follows: A droplet of colloidal solution is deposited on the substrate surface using a syringe, then a compressed air gun is used to blow and move the droplet on the whole substrate surface, drying the droplet and spreading the contaminants on the substrate surface in the process.

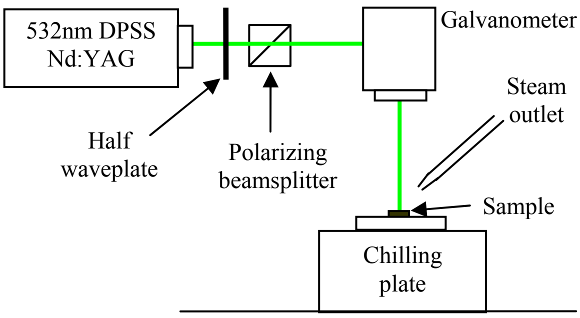

Fig. 2 Experimental setup for laser cleaning

Experiments are carried out under normal room conditions. During the cleaning process, the silicon substrate will be placed onto a chilling plate. After which the galvanometer scans the laser on the substrate surface within a 3 × 3 mm square as shown in Fig. 3. Due to scanning, overlapping between laser beam spots can occur along the laser scan path (in the horizontal direction) depending on the pulse repetition rate and scanning speed used. The line spacing between scan lines is a parameter set during the software design of the laser scan path and it will affect the overlap between laser beam spots (in the vertical direction) along adjacent laser scan lines. The degree of overlap in the horizontal and vertical directions will determine the number of laser pulses applied on each point on the substrate surface.

In order to cool down the substrate temperature to the desired value during chilled laser cleaning, a chilling plate is used. It allows one to control substrate temperatures within the range from -10 °C to 100 °C. After cooling for some time, a thin water film is formed and then laser is irradiated on the substrate. For steam laser cleaning, de-ionized water is boiled to generate steam and a steam outlet is used to direct the steam onto the substrate surface using compressed air as the carrier gas. The steam outlet is only directed at the substrate surface just before laser irradiation to form the water film layer. During dry laser cleaning, the chilling plate is switched off and the steam outlet is removed from the setup.

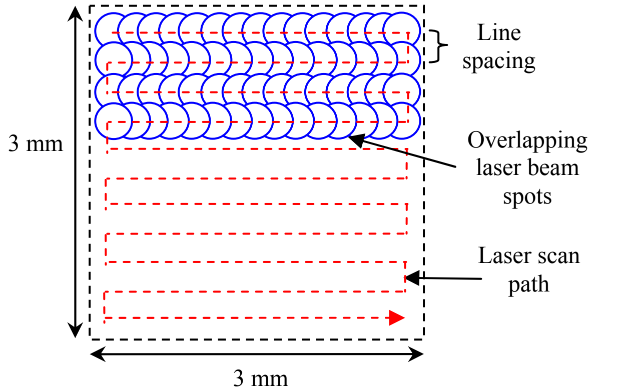

Fig. 3 Scan path taken by the laser during scanning on a 3 × 3 mm square area on the substrate surface.

Images before and after cleaning are captured using an optical microscope, this allows us to count the particles in each picture and then to quantify cleaning efficiency using the following equation.

$$\text{Cleaning efficiency} = \frac{\text{Number of particles removed}}{\text{Number of particles before cleaning}} \times 100\% \qquad (1)$$

To ensure that the same area on the sample is observed, samples are laser marked before the cleaning process, as shown in Fig. 4.

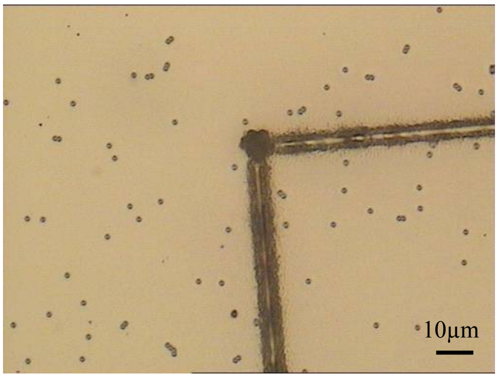

Fig. 4 Sample is marked by laser before laser cleaning to allow easy location of the same area for calculation of cleaning efficiency.

3. Results and Discussion

3.1 Comparing cleaning efficiencies of dry (DLC), chilled (CLC) and steam (SLC) laser cleaning

In reference [9], it was mentioned that as aging time (time between sample preparation and laser cleaning) increases, adhesion force between particles and substrate surface increases. Thus, to ensure a fair comparison among the various cleaning techniques, preparation of each set of samples (e.g. Sample 1 for DLC, SLC and CLC) is done on one single day and experimentation for this same set is done on another. In this way, the aging time is the same for each set of samples.

During CLC, the water film layer is formed just before laser irradiation and vaporizes during laser irradiation. To create a similar cleaning process during SLC, the steam outlet is directed on the substrate surface only just before laser irradiation to form the water film layer and subsequently removed during laser irradiation. This will allow more accurate comparison between SLC and CLC.

Table 1 shows the cleaning efficiencies obtained for the various laser cleaning techniques.

Table 1 Comparing cleaning efficiencies of dry, chilled and steam laser cleaning techniques. Standardized process parameters: laser fluence: 1.0 J/cm^2, pulse repetition rate: 5 kHz, pulse number/unit area: 133 pulses/mm^2, scan count: 1, particles: 1 µm polystyrene (Duke Scientific 5100A).

Method	Sample	Cleaning efficiency (%)	Average cleaning efficiency (%)
DLC	1	12.1	**13.4**
	2	14.9	
	3	13.3	
SLC	1	48.1	**52.9**
	2	75.6	
	3	35.1	
CLC (-2 °C)	1	67.6	**60.3**
	2	33.3	
	3	80.0	

Results shown in Table 1 illustrate that the cleaning efficiency of chilled laser cleaning (60.3 %) is comparable to that of steam laser cleaning (52.9 %) and is around 40-50 % more efficient than dry laser cleaning (13.4 %).

It is clear that the cleaning efficiency of DLC is not as good as SLC and CLC. This observation is also reported elsewhere [5]. This is due to the absence of an energy transfer medium. When the substrate is irradiated with laser, the silicon surface heats up at an extremely fast rate leading to superheating of the energy transfer medium, which in this case is water. It undergoes explosive vaporization, generating a large cleaning force to remove particles from the substrate surface. Also, the laser fluence required for explosive vaporization is usually lower than the cleaning threshold required in DLC, thus DLC is not as effective as SLC or CLC.

The results also show that the cleaning efficiencies for SLC and CLC exhibit a wide range. This large deviation in cleaning efficiency might be due to the differences in thickness of the water film layer which is not monitored during experimentation. A difference in water film thickness was shown in reference [8] to affect cleaning efficiency. It was mentioned that cleaning is effective only for a narrow range of water film thickness. Below or above this range, the cleaning becomes less effective.

3.2 Dependence of chilled laser cleaning efficiency on laser fluence, pulse number, and temperature

In this section, chilled laser cleaning will be examined more closely on how different processing parameters will affect its cleaning efficiency.

Fig. 5 shows the cleaning efficiencies of CLC and SLC under varying laser fluences, the graphs obtained further support the observation that both laser cleaning techniques have comparable cleaning efficiencies. In general, cleaning efficiency increases with laser fluence and it begins to saturate after 2 J/cm^2. Because the substrate is heated up to higher temperatures at higher laser fluences in the same time frame for each single pulse, the water film is vaporized more explosively giving rise to larger cleaning force. At laser fluences below 1 J/cm^2, it is observed that the water film did not vaporize totally which might explain for the lower cleaning efficiencies.

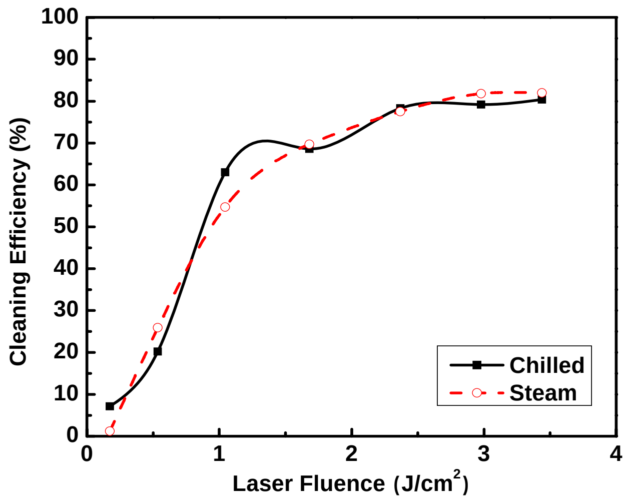

Fig. 5 Cleaning efficiency of chilled and steam laser cleaning under varying laser fluence. Both techniques show comparable cleaning efficiencies at the same fluence and there is a general increasing trend of cleaning efficiency with laser fluence. Standardized process parameters: pulse repetition rate: 5 kHz, pulse number/unit area: 133 pulses/mm^2, scan count: 1, particles: 1 µm polystyrene (Duke Scientific 5100A), temperature: -2 °C (for CLC).

Melting of the silicon substrate was observed sparingly for fluences above 1 J/cm^2. Fig. 6 illustrates this and it shows a silicon substrate cleaned at a fluence of 3.4 J/cm^2 which is the highest laser fluence used in this work. The highest cleaning efficiency obtained in this work for CLC is around 80%. To further improve cleaning efficiency without damaging the substrate, one can use a fluence lower than 1 J/cm^2 coupled with an increase in scan count, i.e. the substrate is cooled and irradiated in this sequence repeatedly for a few times.

Since a pulsed laser was scanned on the substrate surface, pulse number/unit area is used as a process parameter for investigation. It is varied by changing either the scanning speed or the line spacing as illustrated in Fig. 3 earlier. Changing the laser pulse repetition rate will vary the laser pulse energy and subsequently the laser fluence, thus the laser pulse repetition rate is kept constant at 5 kHz.

To increase pulse number/unit area, one can do so by either decreasing the scanning speed or the line spacing and vice versa.

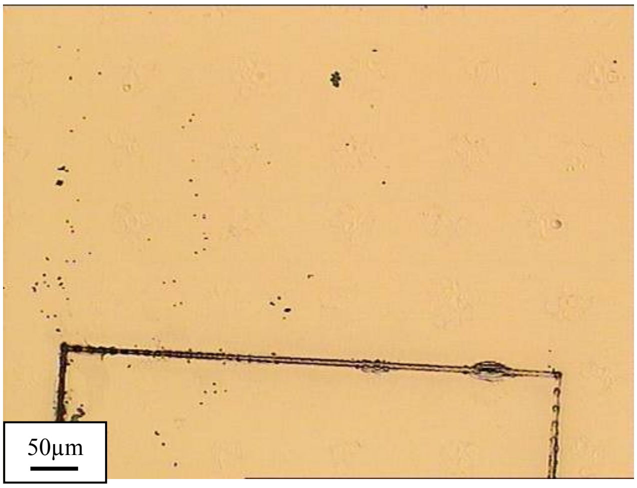

Fig. 6 Optical microscope image of Si surface after the cleaning process shows melting at some areas. Process parameters: Laser fluence: 3.4 J/cm^2 pulse repetition rate: 5 kHz, pulse number/unit area: 133 pulses/mm^2, scan count: 1, temperature: -2 °C (for CLC).

The total number of laser pulses irradiated on the substrate is estimated using the following equation:

$$\text{Total pulse number} = \left(\frac{\text{scan length}}{\text{scan speed/pulse repetition rate}}\right) \times \text{Number of scan lines} \quad (2)$$

The unit used for scan length is mm, scan speed mm/s, and pulse repetition rate Hz. Dividing scan speed by pulse repetition rate gives the distance between adjacent laser pulses along scan lines. Next, the whole expression given in the bracket gives the laser pulse number along a scan line. Thus, multiplying this with the number of scan lines in the scan area gives the total pulse number, so from equation (2), one can then calculate the pulse number/unit area. Note that since the beam spot size is around 100 µm and the pulse repetition rate used is 5 kHz, the maximum scan speed is 500 mm/s and the maximum line spacing is 100 µm such that the laser pulses lie side by side in the whole 3 × 3 mm square area during laser scanning. This corresponds to a pulse number/unit area of 100 pulses/mm^2. Lower values will result in the separation of laser pulses.

Since pulse repetition rate used is 5 kHz, there should not be enough time for ambient air to condensate between successive pulses. This will mean that during CLC, there are some elements of DLC and when pulse number/unit area increases, the ratio of DLC versus CLC increases.

Fig. 7 shows the cleaning efficiency of CLC under varying pulse number/unit area. Generally, the cleaning efficiency increases with pulse number/unit area linearly. This is logical as with an increase in pulse number/unit area, a particle or contaminant is irradiated by more laser pulses, thus the chances to be removed increases.

Fig. 8 shows the effect of temperature on cleaning efficiency. At temperatures -2 °C to 5 °C, condensation of ambient water vapour occurs and the cleaning process is CLC. Upon laser irradiation, this water layer is explosively vaporized and creates a large cleaning force. At temperatures -4 °C, the water film freezes. Upon laser irradiation, this ice layer melts and doesn't fully vaporize. Thus, most of the laser energy went into melting the ice layer instead of vaporizing the water film leading to a smaller cleaning force when compared to the cases between -2 °C to 5 °C. From 20 °C to 100 °C, no condensation of ambient water vapour occurs and the cleaning process is DLC. As expected, the cleaning efficiency at this temperature range lowers even further.

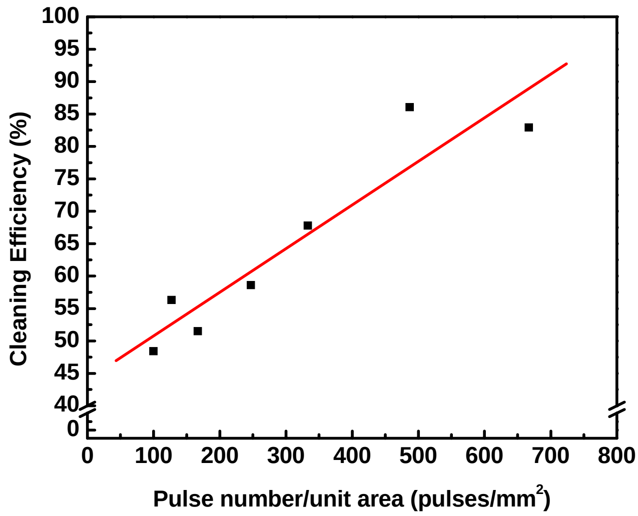

Fig. 7 Cleaning efficiency of chilled laser cleaning under varying pulse number/unit area. Cleaning efficiency increases with pulse number/unit area. Standardized process parameters: laser fluence: 1.0 J/cm^2, pulse repetition rate: 5 kHz, scan count: 1, scan count: 1, particles: 1 µm polystyrene (Duke Scientific 5100A), temperature: -2 °C.

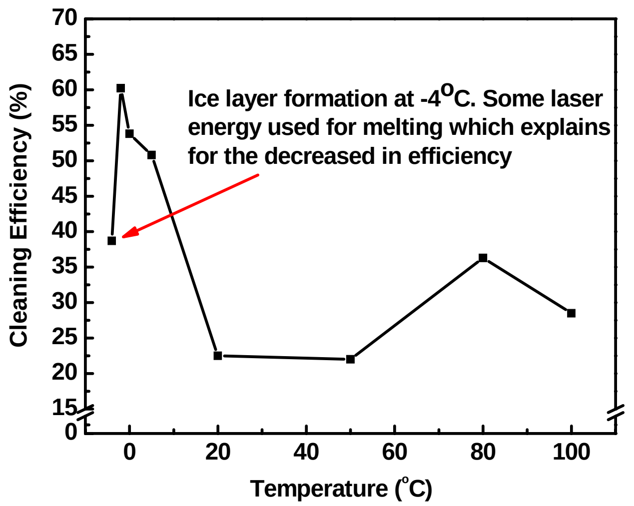

Fig. 8 Cleaning efficiency of chilled laser cleaning under varying temperatures. Standardized process parameters: laser fluence: 1.0 J/cm^2, pulse repetition rate: 5 kHz, pulse number/unit area: 133 pulses/mm^2, scan count: 1, particles: 1 µm polystyrene (Duke Scientific 5100A).

3.3 Cleaning efficiency of chilled laser cleaning for 300 nm silica particles

Fig. 9 shows optical microscope images captured before and after cleaning of 300 nm silica particles. From the images, it is obvious that CLC is capable of removing 300 nm silica particles from a Si surface.

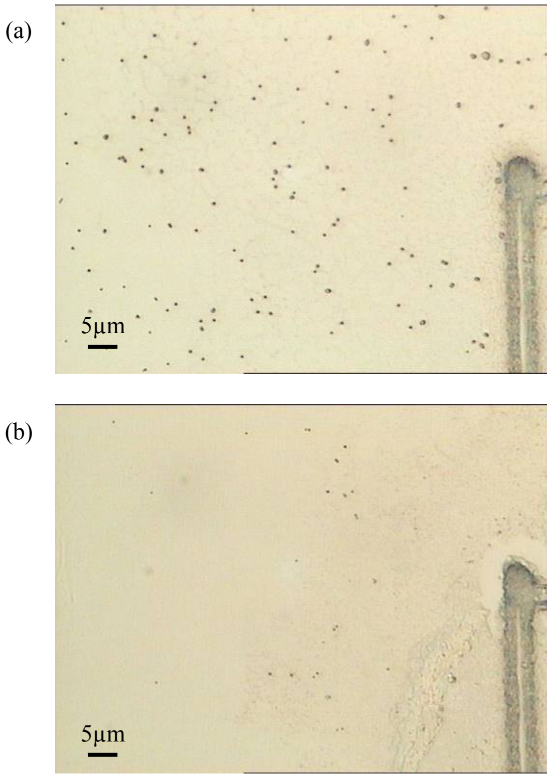

Fig. 9 Optical microscope images before (a) and after (b) cleaning using CLC for 300 nm silica particles. Most of the silica particles are removed after the cleaning process. Process parameters: laser fluence: 1.0 J/cm^2, pulse repetition rate: 5 kHz, pulse number/unit area: 208 pulses/mm^2, scan count: 1, particles: 300 nm silica, temperature: -2 °C.

Despite being efficient at particle removal, CLC does have its shortcomings. Firstly, thick substrates or non heat conductive substrates will result in a long cooling time. Secondly, water film layer thickness is dependent on the relative humidity of the surroundings, which is not constant under normal room conditions, and also cooling duration. Thus, there is a need to control these two parameters. Then the use of a chilling plate poses the problem of water marks as after the cleaning process, ambient water vapour will continue to condense on the substrate surface which is still being cooled by the chilling plate. This means that a post-cleaning drying process is needed if a chilling plate is used. Also, this condensed water film might trap particles in the air and result in recontamination.

A probable solution will be to use a freezer instead of a chilling plate to cool the substrate surface. It is sprayed directly onto the substrate surface and has the advantage of rapid cooling. Moreover, after laser irradiation, the temperature of the substrate surface will rise above the dew point and thus no condensation of ambient water vapour occurs. This will prevent water marks.

4. Conclusions

In summary, the cleaning efficiency of CLC in removing particles from a silicon substrate under varying process parameters was studied and results obtained illustrate that in general, cleaning efficiency of CLC increases with laser fluence and pulse number/unit area. CLC is also demonstrated to be as efficient as SLC in removing particles from a silicon surface and it is able to remove 300 nm silica particles from a silicon surface.

With CLC, a new method of forming a thin water film layer on the substrate surface was introduced. Ambient water vapour was condensed on the cooled substrate surface to create a thin water film. Since ambient water vapour is used, the experimental setup of CLC is simpler compared to that of SLC. There is no longer the need for tubes or pipes to direct steam to the substrate surface. Moreover, it is easier to form a uniform water film layer for a large substrate with this setup. Finally, due to the lower initial temperature of the substrate, the heat dose on the substrate is lower.

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