Pressure amplification of laser induced plasma shockwaves with shock tubes for nanoparticle removal

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Abstract—A method using shock tubes for amplifying the dynamic pressure of Laser Induced Plasma (LIP) shockwaves for removing sub-100-nm nanoparticles is introduced and demonstrated. The higher the amplitude of the pressure generated, the smaller the particles that can be removed and, thus the more useful for a variety of applications. Constraining the expansion of the LIP core with a shock tube is a non-contact approach to increase pressure amplitude by an order of magnitude for removal of particles without damaging the substrate through shockwave and LIP radiation heating effects. Heat transfer to the substrate increases as the distance from the LIP core to the substrate (gap distance \(d\)) decreases. LIP shockwaves in air, however, demonstrate a pressure decrease on an order of magnitude per every 5 mm in the reported experimental set-up. The shock tube technique allows for higher pressures at distances significantly further from the core of LIP. In the current investigation, the effect of a set of shock tubes to amplify the transient pressure of the LIP-generated shockwave fronts has been studied to evaluate their pressure amplification performances. The effectiveness of a shock tube is quantified in terms of its pressure amplification factor. Through experimental data from several shock tube geometries examined, pressure amplification factors of 11.00 have been experimentally verified which is a ratio of shock-tube-generated transient pressure of 523 kPa to in-air LIP transient pressure of 47.5 kPa at the same gap distance \(d = 10\) mm. The potential advantages of shock tubes as an amplification approach are discussed.

Keywords: Laser-induced plasma cleaning; pressure amplification factor; sub-100-nm particle removal; nano-particle removal; shock tube.

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1. INTRODUCTION

Laser-induced plasma (LIP) as a means of generating strong pressure fields in a non-contact manner (i.e., without contact to a solid) with a substrate can be used for practical applications, such as precision removal of nanoparticles from substrates including patterned wafers and extreme ultraviolet lithography (EUVL) photomasks. In the semiconductor industry, feature sizes are shrinking to a nanometer scale because of the demand for faster and more efficient integrated circuits; as a result, the tolerable particle size on the substrates is currently being reduced to sub-100-nm levels. According to the International Technology Roadmap for Semiconductors (ITRS) of 2005 [1] for front end processes the projected future requirements are as follows: the removal of 90-nm particles by 2008, 65-nm particles by 2010 and 45-nm particles by 2013. The ITRS of 2005 also predicts that EUVL mask techniques will necessitate that 46-nm-sized defects be removed by 2008, 36-nm-sized defects by 2010 and 26-nm-sized defects by 2013. According to the ITRS, the requirement for removal of sub-100-nm particles without substrate damage is a major issue in semiconductor manufacturing and will continue to guide the industry in coming years. However, keeping feature structures intact and adhering to an increasingly more stringent defect-density requirement will ultimately decide the effectiveness of a particular removal process.

2. EMERGING PARTICLE CLEANING TECHNIQUES

The techniques being investigated for sub-100-nm nanoparticle removal along with the LIP removal technique include processes involving brush scrubbing, megasonic cleaning, CO₂ snow cleaning and laser steam cleaning. In the brush-cleaning technique, full contact of the brush with the nanoparticle is necessary for efficient particle detachment [2]. This technique relies on the drag force (which decreases as \( O(L^2) \) where \( L \) represents the characteristic length scale) exerted by the fluid on the particle for particle removal as the particle adhesion force is \( O(L) \) [3]. Thus, for removing smaller particles, substantially higher pressure or higher brush velocity are required. Particle redeposition after cleaning, and damage are reported as major problems with brush cleaning [4]. Megasonic cleaning employs ultrasonic waves above 1 MHz. The pressure gradients acting on the particle, induced by acoustic streaming, are responsible for particle removal in this technique [5]. The forces acting on the particle decrease as \( O(L^3) \) and may not be effective for sub-100-nm particle removal, in particular when strict low-damage risk tolerances are specified [5]. The gas cavitation generated by the acoustic waves due to increased radiation power for nanoparticle detachment is also reported as a potential concern for localized damage and an effective drying technique has to follow megasonic cleaning to avoid postcleaning complications [6]. Another emerging nanoparticle removal technique is the CO₂ snow cleaning. With this technique, small dry ice particles are formed by the rapid expansion of liquid CO₂ triggered with the
aid of nozzles. These ice particles impinge onto the contaminant particles on the substrate. The momentum and the drag force of the CO₂ particles then contribute to the particle detachment [7]. Structural damage and particle redeposition as well as the requirement for a very high purity gas supply are the major concerns in this technique [8], especially for nanoparticle removal applications. The laser steam cleaning process is an attempt to increase the efficacy of the direct laser-irradiation method; however, laser-irradiation methods can cause extreme thermo-mechanical stresses in a localized area on a substrate surface and have led to observations of substrate damage [9].

3. LASER-INDUCED PLASMA TECHNIQUE

LIP-generated shockwaves and their effectiveness in generating removal forces sufficient to detach sub-100-nm PSL particles from silicon substrates have been recently demonstrated [10] and have directed further study with this technique and the utilization of shock tubes. In the LIP technique, a pulsed laser beam is focused and due to the dielectric breakdown of air, the formation of a plasma is initiated at the focal point of the lens as depicted in Fig. 1a. The plasma generated in air takes the form of a three-dimensional near-ellipsoid and from its boundary a shockwave is created that departs outward normal to the boundary [11]. In the current LIP procedure, this shockwave front is directed onto the particle to break the nanoparticle–substrate adhesion bond. The gap distance \(d\) is the main process parameter in the LIP approach and it is defined as the distance between the center of the plasma core to the surface of the transducer (or substrate) (Fig. 1b). Contact of the plasma core to the substrate may lead to damage and must be avoided. In the LIP nanoparticle removal, the two major thermo-mechanical effects to which the substrate is subjected are shockwave–gas interactions and the radiation heating generated by the LIP core. In general, the magnitude of the pressure of the shockwave front is too low to cause surface damage. The damage threshold for patterned wafers and thin films is known to be substantially lower than for blank silicon substrates, especially at pressure levels required for the removal of sub-100-nm particles. More recently, it has been determined that the major source of damage from LIP at small gap distances (less than 1 mm) is due to the thermo-mechanical effects, i.e., stress fields created by the thermal expansion of the substrate, rather than due to purely mechanical effects (e.g., the pressure of the shockwave front) [12, 13]. Based on this observation, it is concluded that minimizing the effect of the thermal field is a critical step in damage mitigation for sub-100-nm particle removal. The strength of the thermal field generated by the LIP core is proportional to the pulse energy of the laser and the gap distance \(d\); therefore, a method that decreases the laser pulse energy and/or increases the gap distance while keeping the shockwave front pressure constant is of practical interest, and finding the optimal gap distance at which there is maximum particle removal without damage is of precedence. Since the magnitude of the shockwave pressure
Figure 1. Instrumentation diagram of the experimental setup for in-air LIP shockwave transient pressure measurement (a) and a schematic diagram of the shock tube pressure amplification setup (b). The gap distance \( d \) represents the distance from the LIP core to the substrate transducer. The exit gap distance \( d_g \) represents the distance from the exit of the shock tube to the substrate transducer.
is inversely proportional to the distance from the origin of the shockwave, as the LIP core is focused closer to the substrate, it is possible for smaller nanoparticles to be removed. However, as the gap distance \(d\) (from the LIP core to the substrate) decreases to the threshold distance, this can damage the substrate due to heat transfer from the plasma core and the shockwave which can induce thermo-elastic stresses in the substrate [14]. This implies that the gap should be near the critical gap distance at which the thermal field is unlikely to damage the substrate to allow for maximum removal of the smallest size particles.

4. PRESSURE AMPLIFICATION

In the current study, the effect of a set of shock tubes to amplify the transient pressure of the LIP-generated shockwave fronts has been investigated to evaluate their pressure amplification performance. A shock tube is essentially a pipe with one end blocked and a narrow aperture on the side in which a focused laser beam enters, in order to form LIP on the inside of the shock tube cavity (Fig. 1b). The principle behind the use of a shock tube for pressure amplification is that the tube creates a geometric constraint on the expansion of the LIP core and its increased pressure shockwave front, consequently causing several reflections to undergo positive interference and result in a stronger pressure field produced at the exit of the shock tube (Fig. 2). Shock tubes deliver higher pressures at distances significantly further from the point of LIP when compared to in-air LIP measurements. These higher pressures from shock tubes are quantified in terms of the pressure amplification factor \((\Phi)\), defined as the ratio of the peak transient

![Figure 2. Schematics of the boundaries of shockwave front for in-air LIP (a) and LIP formation within a shock tube (b).](image-url)
pressure generated with the shock tube to the peak transient pressure generated in air, while evaluating at an equivalent gap distance.

As the requirement for particle removal drops below the sub-100-nm size, higher removal pressures will be required and this can be achieved through the use of higher-powered lasers or, by moving the LIP core closer to the substrate. Commercially available higher powered lasers could generate a higher pressure magnitude and, as a result, create additional thermal radiation, inadvertently increasing the risk of radiation and shockwave heating damage to the surface of a given substrate. Also note that high-powered lasers are substantially more expensive which can become a roadblock for the LIP method, so with the aid of shock tubes, low-powered lasers can be used to obtain the required transient pressure amplitudes for sub-100-nm particle removal, while keeping the damage risk from radiation and shockwave propagation constant or possibly lower.

The objective of the current study was to characterize and evaluate the various shock tube designs based on their effectiveness in maximizing the pressure amplification factor \(\Phi\) obtained from transient pressure measurements for a given pulsed laser. Six different shock tubes were evaluated based on the premise that restricting the volume required for expansion of both plasma and shockwave will increase the pressure.

5. EXPERIMENTAL PROCEDURE

The shock tubes used in this experimental investigation were cylindrical tubes made of brass with an aperture of 1 mm in diameter along the length of the tube with one end of the tube sealed. The major design parameters considered for designing shock tubes are length, cavity depth, inner wall diameter and the number of apertures. The six shock tubes (named as ST1–ST6) were designed and dimensions were determined from consecutive iterations of each previous design [15] (Fig. 3).

A single laser pulse is focused through a lens on a point inside the cavity of a shock tube (Fig. 1b) to generate LIP. Due to the geometric constraint of the tube, the consequent pressure front is directed out at the exit of the shock tube towards the pressure transducer positioned at a distance \(d_g\), termed as exit gap distance (Fig. 1b). The experimental setup (Fig. 1a) consists of a pulsed laser with a wavelength of 1064 nm, a pulse energy of 370 mJ, a pulse width of 5 ns, a repetition frequency of 10 Hz and a 5-mm beam diameter. A 100-mm convex lens with a 1064-nm specific anti-reflective coating was utilized to converge the beam in air, both with (Fig. 1b) and without (Fig. 1a) the shock tube. A dynamic pressure transducer (Kistler, 603B1) with a central resonance frequency of 500 kHz was employed for pressure measurements. The charge output of the transducer was converted into the voltage output using a charge amplifier (Kistler 5010). The output from this charge amplifier was connected to a digitizing oscilloscope (Tektronix TDS 3052) generating digital waveforms which were acquired and saved in a computer for signal processing and further analysis.
In order to focus the laser beam into the aperture of the shock tube, the shock tube was mounted on a precision $xyz$ linear translation stage (Newport, MFA-CC) for accurate position control. The pressure transducer was mounted onto two 25-mm additional manual micrometer stages which allowed for varying the exit gap distance $d_g$ in the experiments. Exit gap distance $d_g$ is of particular interest, because it represents the distance between the end of the shock tube to the face of the pressure transducer. This exit gap distance simulates the distance from the end of the shock tube to the substrate surface. When $d_g \approx 0\,\text{mm}$, the cavity of the shock tube is nearly closed by the transducer and the pressures measured at these minimal gap distances are unusable due to the possibility that mechanical vibrations through
the shock tube might result in damage to the substrate from contact with the shock tube, as well as contamination from the material of the shock tube on the substrate.

The major design parameters considered for designing shock tubes are cavity depth, inner wall diameter, and the number of apertures (Fig. 3). Shock tubes ST1 and ST2 are used to study the effect of cavity diameter and axial position of LIP relative to the exit of the shock tube. ST1 and ST2 have four different aperture holes (marked H1–H4) for examining the effect of LIP. When a particular hole was being tested, the other three holes were plugged before the pressure measurements were made. ST3 has the same inner diameter as ST2 and has only one aperture hole, and the cavity is 4 mm deep, which is used to study the effect of pressure and cavity depth. ST4 incorporates a diverging nozzle design with a slight increase in the depth of the cavity to 8 mm, which is used for investigating the pressure amplification due to the cross-section of the tube. ST5 was an attempt to simulate a resonator shock tube to match the resonance frequency of the shock tube structure, resulting in maximum pressure amplitude. ST6 possesses the combined positive qualities of the previous designs (ST1–ST5), including a deep 11-mm cavity and a narrower 3-mm inner diameter allowing for a longer column for shockwave expansion, before emerging out of the shock tube.

The transient pressure measurement experiments were carried out without a shock tube with a gap distance of \( d = 2–14 \) mm to obtain baseline data for comparisons. All the experiments were then repeated with the shock tubes (ST1–ST6) and pressure waveforms were acquired. In shock tube experiments, mainly two design parameters for performance enhancement are of interest: gap distance \( (d) \) and exit gap distance \( (d_g) \). The shock tubes have different gap distances \( (d) \) from the LIP, varying according to the dimensions of the shock tube and differences in cavity depths (Fig. 3). However, all the experiments (except for ST6) were carried out starting from a minimum exit gap distance \( d_g = 1 \) mm to \( d_g = 7 \) mm. For all shock tube designs the shockwave exits through the open end of the shock tube nearly as a plane wave.

**6. RESULTS AND DISCUSSION**

In the experiments conducted, transient pressure waveforms were obtained for \( d = 2 \) mm to \( d = 14 \) mm for LIP without a shock tube to obtain a baseline for comparison of the pressure amplification factor (\( \Phi \)). Waveforms were then acquired for each ST1–ST6 (Fig. 3) ranging from \( d_g = 1 \) mm to \( d_g = 7 \) mm. From all the waveforms acquired the maximum pressure and position of the shockwave front were determined for each tube from the LIP core. It is not practical to perform nanoparticle removal at \( d_g \approx 0 \) mm due to complications arising from LIP inside a shock tube as potential mechanical vibrations through the shock tube might result in damage to the substrate from contact, as well as potential contact contamination. See Table 1 for the transient pressures for each shock tube at \( d_g = 1 \) mm.
Table 1.
Transient pressure $P$ and pressure amplification factor ($\Phi$) measurements for each shock tube, and respective hole identification and gap distance ($d$)

<table>
<thead>
<tr>
<th>Shock tube</th>
<th>Hole ID</th>
<th>$d$ (mm)</th>
<th>$P$ (kPa)</th>
<th>$\Phi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ST1</td>
<td>H1</td>
<td>2</td>
<td>175</td>
<td>1.29</td>
</tr>
<tr>
<td></td>
<td>H2</td>
<td>4</td>
<td>291</td>
<td>3.32</td>
</tr>
<tr>
<td></td>
<td>H3</td>
<td>6</td>
<td>235</td>
<td>3.80</td>
</tr>
<tr>
<td></td>
<td>H4</td>
<td>8</td>
<td>423</td>
<td>7.40</td>
</tr>
<tr>
<td>ST2</td>
<td>H1</td>
<td>2</td>
<td>407</td>
<td>3.00</td>
</tr>
<tr>
<td></td>
<td>H2</td>
<td>4</td>
<td>343</td>
<td>3.92</td>
</tr>
<tr>
<td></td>
<td>H3</td>
<td>6</td>
<td>427</td>
<td>6.89</td>
</tr>
<tr>
<td></td>
<td>H4</td>
<td>8</td>
<td>543</td>
<td>9.50</td>
</tr>
<tr>
<td>ST3</td>
<td></td>
<td>3</td>
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<td>4.14</td>
</tr>
<tr>
<td>ST4</td>
<td></td>
<td>7</td>
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<td>7.74</td>
</tr>
<tr>
<td>ST5</td>
<td></td>
<td>10</td>
<td>22</td>
<td>0.48</td>
</tr>
<tr>
<td>ST6</td>
<td></td>
<td>10</td>
<td>523</td>
<td>11.00</td>
</tr>
</tbody>
</table>

All measurements are for an exit gap distance of $d_e = 1$ mm.

Figure 4. Peak transient pressure readings $P$ for in-air LIP shockwave generation for varying gap distances $d$.

Transient pressure measurements without a shock tube were carried out in air from a gap distance of $d = 2$ mm to $d = 14$ mm. The peak transient pressure amplitude was measured as 135 kPa at $d = 2$ mm with maximum pressure decreasing exponentially with the increase in gap distance ($d$) (Fig. 4). Transient pressure measurements for the six shock tubes were then characterized for their peak values to be compared against the value without a shock tube. For the shock tube designs ST1 and ST2 all four holes were tested revealing changes in pressure as the focal point of the LIP was shifted towards the base of the cavity (i.e., further away from the opening), with the transient pressure amplitude ranging from 175 kPa to
423 kPa as the focal point was shifted from H1 to H4 at constant exit gap distance $d_g = 1$ mm. Exit gap distance $d_g = 1$ mm consistently gave the highest pressure and was used almost exclusively for peak pressure measurements. The peak pressure obtained with ST2 for each aperture at constant exit gap distance $d_g = 1$ mm ranged from 405 kPa for the topmost hole (H1) to 343 kPa (H2), 427 kPa (H3) and finally 543 kPa (H4). Incidentally ST2–H4 was the deepest in the cavity (furthest from the exit), but generated the highest pressure while blocking the remaining three apertures (Table 1 and Fig. 5). The peak pressure amplitudes measured for the shock tubes ST3, ST4 and ST5 were 435 kPa, 467 kPa and 22 kPa at $d_g = 1$ mm, respectively. The peak pressure attained with ST6 reached 523 kPa at $d_g = 1$ mm (Fig. 6a). However, when ST6 was moved such that there was a small air gap ($d_g \approx 0$ mm), a transient pressure waveform of approx. 750 kPa was recorded (Fig. 6b), showing a pressure extreme possible by a further optimized shock tube. The peak pressure amplitudes and the pressure amplification factors obtained with each of the six shock tubes and also without the shock tube, while evaluating the transient pressure waveforms for pressure versus gap distance ($d$) are reported in Table 1 and Fig. 7a. Finally, the pressure amplification factors ($\Phi$) versus gap distance ($d$) for all shock tube designs are presented in (Fig. 7b).

7. CONCLUSIONS AND REMARKS

The thermo-mechanical damage risk generated by LIP shockwaves and heat radiation level can be substantially reduced by amplifying the transient pressure utilizing shock tubes thereby moving the LIP core away from the substrate while generating the same pressure. The objective of the current investigation was to maximize the
Figure 6. (a) Transient peak pressure readings $P$ for shock tube design 6 (ST6) across a range of gap distances ($d$) from 10 mm to 14 mm with initial exit gap distance ($d_g$) of 1 mm and (b) the transient pressure waveforms for ST6 for exit gap distance $d_g$ of 0 mm to 5 mm. The dashed line is for the pressure waveform for $d_g \approx 0$ mm.

Pressure amplification of LIP shockwaves with shock tubes

pressure amplitude created from the LIP shockwave front for a given pulsed laser using shock tubes in order to increase gap distance, thereby decreasing the damage risk. The main aspects of this investigation were modifications of shock tube parameters and to test the effects of cavity diameter, length, hole position and shape on the transient pressure generated. The effects of these shock tube design parameters in amplifying the transient pressure amplitude were successfully evaluated with respect to their differing geometric constraints associated with the LIP propagation
and expansion. The resulting pressure amplification factors are compared to understand the effect of geometry of the shock tube on the shockwave pressure generated at the end of the shock tube. It is determined that shock tubes substantially intensify the shockwave pressure.

The shock tube ST6 recorded a peak transient pressure of 523 kPa measured at a gap distance of 10 mm, which results in a peak pressure amplification factor of 11.00. ST2 with hole (H4) recorded a peak transient pressure of 543 kPa measured

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**Figure 7.** Transient pressure readings $P$ versus gap distance $d$ for each shock tube design including the un-constrained LIP in air (a). The pressure amplifications factor $\Phi$ versus gap distance $d$ for each shock tube designs (b). The initial points (leftmost) are for exit gap distance of $d_g = 1$ mm.
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at a gap distance of 8 mm, resulting in \( \Phi = 9.50 \). A maximum pressure of \( \approx 750 \text{ kPa} \) was generated using ST6, but at an exit gap distance \( d_g \approx 0 \text{ mm} \), and this is not desirable due to the possibility of mechanical damage to the substrate and contamination issues associated with contact in nanoparticle removal applications. The effective area of the LIP shockwave can be possibly increased by using a set-up with an inclined shock tube (mounting the shock tube at an angle) to the substrate. Another possible pressure amplification technique could include moving the shock tube into a denser fluid medium such as water.

The shock tube amplification method could be beneficial for various applications such as damage-free sub-100-nm sized particle removal from substrates which may include patterned silicon wafers, extreme ultraviolet lithography photomasks, as well as the development of photo-acoustic medical procedures due to reduced pulse-energy requirements, allowing the possible use of lower powered lasers to deliver laser pulses through fiber optics. The peak pressures and pressure amplification factors together demonstrate that a trend toward optimization for even greater transient pressures is possible, proving shockwave amplification of LIP by shock tubes to be useful.

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