Short communication

Picosecond laser drilling of silicon with applied voltage

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Abstract

The short pulse duration of a picosecond laser (ps) leads to high peak power and ablates materials with much reduced thermal effects. Commercial ps lasers generate high-repetition-rate pulses and become more accepted as a major tool for material removal applications. However, most of the commercial ps lasers emit pulses at infrared (IR) wavelengths with photon energy close to the Si band gap energy of 1.1 eV. The corresponding optical absorption coefficient is low. To improve the laser beam absorption in Si, several methods have been investigated. For instance, it is reported that the material removal efficiency has been improved by raising the substrate temperatures during laser drilling due to the enhancement of the Si absorption coefficient. However, such approach may result in reduction in machining accuracy due to thermal expansion of the substrate. In this paper, we propose a new method by applying a direct current (DC) across a silicon substrate during the ps laser drilling process. The externally applied voltage potential would lead to more aligned movement of free electrons and therefore increase electrical current flow in the silicon substrate. The hypothesis of this study is that more free electrons are made available in the Si substrate for collisions with the laser photons, which increases the Si absorption coefficient of the laser beam. It was found that the material removal is markedly improved with the assistance of the electrical current flow. The entrance hole diameter increased by 14% and the exit hole diameter increased by 90% when the current in the Si substrate was subjected to a fixed current of 0.5 A. However, a larger amount of material debris covering an enlarged surface area was observed under the applied DC voltage. The possible reasons for such observations are discussed based on the enhanced laser energy absorption as the result of the presence of electrical current in the Si substrate.

Keywords Picosecond laser · Energy absorption enhancement · Silicon

1 Introduction

Mechanical machining of hard and brittle materials such as ceramics and semiconductors tend to generate edge chipping and substrate breakage with high cutter tool wear. Ultra-short-pulse lasers with gigawatts peak power and high repetition rate have been proved to be efficient for high-precision processing of a wide range of materials including metals [1–3], polymers [4–6], ceramics [7–9], and silicon [8–13]. The distinctive advantages of ultra-short-pulse laser processing include minimal heat-affected zone and ability to process nearly all materials due to nonlinear absorption and with high precision and high repeatability [7–17]. Being the most important semiconductor material, silicon is widely used in the manufacture of integrated circuits for electronic products. Current methods of processing silicon include plasma etching for via holes, diamond sawing for wafer dicing, and photolithographic processes for surface micro-/nanostructuring. Alternative processes are always needed to improve efficiency, yield, dimensional accuracy and to be more environmental-friendly. Ultra-short-pulse laser processing is one such potential technique. The ultra-short-pulse duration and high peak power density enable precise material removal

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at the defined energy fluence, which can be controlled by adjusting the focal position relative to the substrate [18, 19]. In microelectronic and solar cell applications, drilling of consistent microholes in silicon is an important manufacturing process.

Picosecond pulse laser is generally a preferred tool for industrial applications due to its lower cost and easier to maintain as compared to femtosecond (fs) pulse lasers. However, most of the commercial ps lasers emit pulses at wavelengths in the infrared (IR) range (e.g., commonly at 1064 nm), which is close to the Si band gap energy of 1.1 eV. Therefore, the optical absorption coefficient at this wavelength at 300 Kelvin temperature is low. The Si absorption coefficient against photon energy of laser beams has been reported and is shown in Fig. 1 [20]. It is noticed that the absorption coefficient is temperature dependent. At higher temperature, the absorption coefficient is higher. Therefore, there is a need to enhance the silicon energy absorption of the ps laser beam for more efficient machining applications. It is reported [21, 22] that material removal rate has been increased by raising the substrate temperature during laser drilling due to the increase in the Si absorption coefficient. In the present study, we propose to apply a DC voltage potential across the silicon substrate during the laser drilling process and to evaluate its effect on laser ablation. When a short laser pulse interacts with Si, electrons absorb the photon energy and transit from the valence to the conduction band to become excited electrons (free electrons) via single- and/or multi-photon absorption. The carrier–carrier collisions (i.e., collisions among the electron–hole pairs) cause thermalization [23]. By applying a DC voltage across the Si substrate, more free electrons are made available for interactions with the laser photons. When the density of excited electrons (free electrons) reaches a threshold, the electrons behave as plasma leading to the absorption of the remaining pulse energy [24]. Based on the above phenomenon, our approach of applying a DC voltage across the Si substrate is assumed to play a role in influencing the laser beam absorption.

2 Experimental setup

The schematic experimental setup of the ps laser drilling process is shown in Fig. 2. The experiments were conducted using an infrared ps laser (Time-Bandwidth: Duetto). The ps laser emits ultra-short pulses of 12 ps at a central wavelength of 1064 nm (with a repetition rate ranging from 50 to 8200 kHz). A pair of galvanometer scanners with a telecentric F-theta lens of 100 mm in focal length is used to steer the beam movement. Compressed air at 3 bar was blown through an array of nozzles (diameter of 2 mm) parallel to the Si sample to take away laser-ablated materials.

The focal spot size determines the energy fluence for given pulse energy and is an important factor in laser materials processing. There are different ways of determining it with varying degrees of accuracy. One of the methods is the D^2—method (squared diameters) of the laser-ablated areas proposed by Liu [25]. The formula for calculating the focal spot size is given as:

$$D^2 = 2\omega_0^2 \ln\left(\frac{\phi_0}{\phi_{\mathrm{th}}}\right), \tag{1}$$

where ω_0 is the Gaussian spatial beam radius at $1/e^2$, ϕ_0 the maximum laser fluence, and ϕ_{th} the ablation threshold

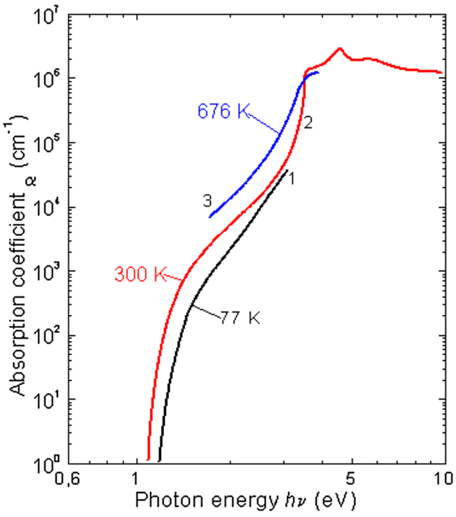


Fig. 1 Absorption coefficient vs. photon energy at different temperatures [20]. From Jellison Jr, Modine (1982). Copyright (1982) American Institute of Physics

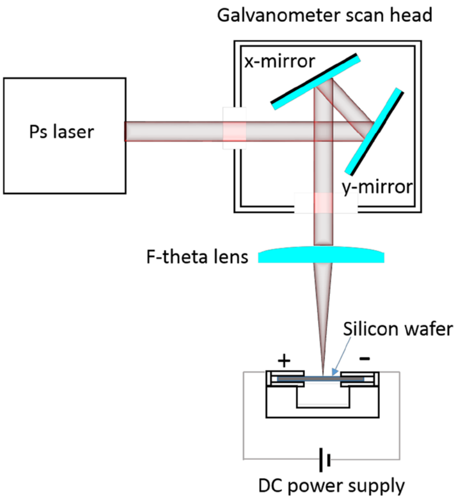


Fig. 2 Schematic laser processing setup with applied electrical voltage

fluence. It is possible to determine the Gaussian beam spot size by measuring the diameters of the ablated areas D versus the applied pulse energies. However, it is not always accurate in identifying the boundaries of the laser-ablated areas due to heat-affected zones. Gecys et al. [26] established the correlation between exposed area diameter and focus offset for laser ablation of a solar thin film. The laser fluence was varied by adjusting the focal position relative to the top surface. The offset distance from the top surface affected the actual "exposed area diameter" on the surface. This exposed area diameter is, however, different from the beam focal spot size. In our present study, we use a simple method [27] to calculate the focal spot size, which suits our need in evaluating how applying a DC voltage across the Si substrate would affect the laser beam absorption and the materials removal.

The radius of the focal spot, ω_0, is given by [27]

$$\omega_0 = \lambda f M^2 / \pi\omega \tag{2}$$

where ω is the radius of the beam at the lens and is about 3 mm after the beam expander, f the focal length of the lens, and M^2 the Gaussian beam's quality factor at about 1.3 for the ps laser. The focal spot diameter was calculated to be 29.4 µm. The substrate is commercially available semiconductor single crystalline silicon with thickness of 200 microns.

The average laser power was varied in the range of 0.245–4.9 W (3.61×10^4–7.22×10^5 W/cm^2) by adjusting the pulse repetition rate and pulse energy. Studies were carried out to determine the laser ablation threshold and to evaluate hole drilling performance. The average laser power was measured using a power meter after the scanning optics. A power supply that applied DC voltage (fixed at 32 V) to the silicon sample was used during the laser beam interaction with the Si substrate. The current in the silicon sample was measured as 0.5 ± 0.2 A. The laser-treated area on the silicon sample was characterized by a scanning electron microscopy (SEM). As the laser-drilled hole profile is not circular due to the non-uniform energy delivered by the laser beam, an image analysis software was used to capture the edge of the hole and to calculate the hole area by integrating the boundary line so as to evaluate the hole parameter objectively. The average diameter is deduced from the area of the laser-drilled hole.

3 Result and discussion

Figure 3 exhibits the entrance of the microholes drilled by the ps laser at the laser power of 4.41 W (or 6.5×10^5W/cm^2) under different irradiation duration. The left column (Fig. 3a, c) shows the hole entrance on the Si sample drilled under the applied electrical current of 0.5 A.

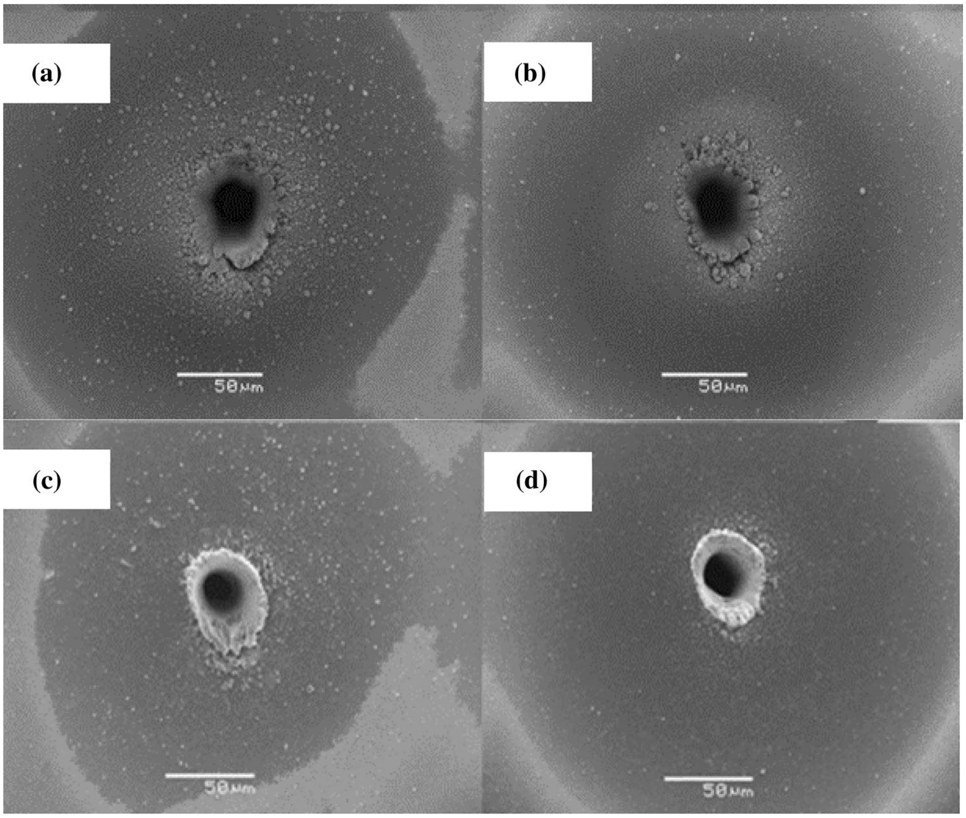


Fig. 3 SEM images of the microholes (entrance holes) drilled by the ps laser with varying irradiation duration. **a**, **b** 25 ms, **c**, **d** 15 ms. The left column show the Si sample drilled under an electrical current of 0.5 A, and the right column show the Si sample drilled without applying electrical current

For comparison, the right column (Fig. 3b, d) shows the entrance holes on the Si sample drilled without the applying electrical current. Each experiment was repeated for five times with same conditions, and the data with error bars for the entrance hole diameters that were extracted from the SEM pictures are plotted in Fig. 4. From the SEM pictures in Fig. 3, it is seen that the amount of ablated material deposited back onto the Si surface is markedly higher when the Si was subjected to 0.5 A electrical current, e.g., Fig. 3a, b with irradiation duration of 25 ms and Fig. 3c, d with irradiation duration of 15 ms. This would imply that the assistant gas flow was less effective in removing the debris generated during the ps laser drilling when an electrical current is applied. To explain the possible causes for the increased material redeposition onto the Si surface, it is useful to take a look at how laser-induced plasma forms and what the plasma constituents are. When the ps laser pulse interacts with the Si substrate, the high peak power density would take away loosely bound electrons to cause ionization of Si. A plasma plume is formed, which consists of neutral particles, free electrons, and ionic species in different excited states [28]. The particles in the plasma plume have different sizes ranging from nanometers to micrometers. The smaller particles (~ nm size) are probably formed in the expanding vapor plume, by condensation of vapor atoms. The larger particles (~ µm size) are generated by direct liquid ejection (large droplet liquid splashing) from the Si target. Moreover, when the peak laser power density reaches above 10^{10} W/cm^2, explosive boiling of the target material beneath the surface layer and mass ejection of large particulates would occur. These particles (charged or neutral) will fall back to the surface due to gravity. Those charged particles are also attracted to the Si surface due to the applied electrical field. The attraction force counters the gas blowing effect in removing the laser-ablated particles.

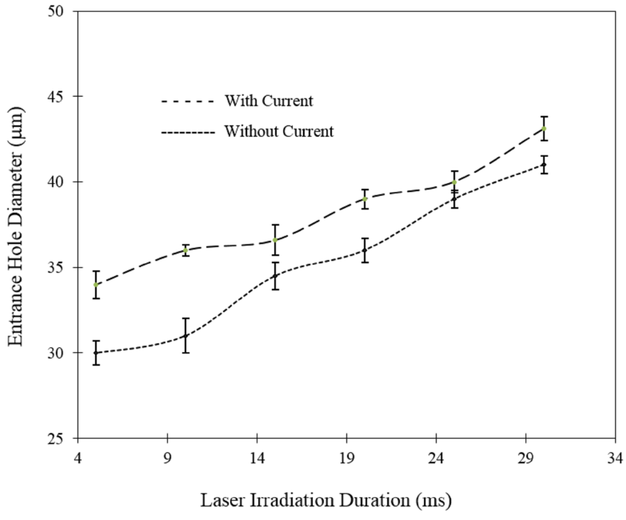


Fig. 4 Comparison of entrance diameters drilled with and without the applied current at different laser irradiation duration

It is clear from Fig. 4 that the entrance diameters drilled with the applying electrical current are larger than those without the current supply. It is further observed that the applied electrical current played a more noticeable role when laser irradiation duration is short. For instance, when the laser irradiation duration was about 4 ms (ms), the hole diameter increased by about 14%, whereas at longer irradiation duration, the hole diameter increased was about 5–7%. The observation may be explained based on the beam–material interaction mechanisms in the multi-pulse laser ablation of material. The ps laser has a wavelength of 1064 nm (photon energy of 1.16 eV), which is less than half of the direct band gap of silicon (3.4 eV) [20]. Under such conditions, the main mechanism of energy deposition is nonlinear absorption through two-photon absorption (TPA) and TPA-induced free carrier absorption (FCA). The TPA coefficient is reported as 1.5 cm/GW in Ref. [29]. In this process, the optical absorption property of silicon is strongly influenced by electron movement in the sample and highly dependent on the number of acoustic phonons (i.e., oscillating lattice atoms, which may form oscillating dipoles to interact with photons) [30]. Under laser irradiation, there is an increased possibility that an acoustic phonon in the lattice and a photon from the laser are simultaneously absorbed to create an indirect transition. As a result, a large number of electrons were photo-excited from valence band into conduction band. It is reported that applying a reverse voltage bias would sweep out the TPA-generated free carriers to reduce the nonlinear absorption [31]. In our study, where a DC voltage in forward direction is applied, more free electrons are made available. The possibility of collision between moving electrons and lattice atoms is thus significantly increased. This would result in a more violent lattice vibration, i.e., producing more acoustic phonons. A considerable amount of covalent bonds are destroyed [23] and multi-ionization occurs [24]. Hence, with the applied DC voltage in the Si substrate, the recoil pressure from the Coulomb explosion [32] ejects more ion and atom clusters from the laser-drilled crater that would lead to the erosion of the hole boundary in multi-pulses laser ablation. Correspondingly, a larger entrance diameter was obtained.

As discussed earlier, the effect of applying the DC voltage on the diameter became less significant when the laser irradiation duration was prolonged, i.e., when more laser pulses emitted. This observation may be explained by the multi-pulse accumulation effects (incubation) in high-repetition-rate laser ablation. It has been reported that the ablation threshold is lowered due to thermal accumulation effect [33–37]. The effective increase in the multi-photon absorption coefficients may be assumed due to the material modification caused by stress development, for example, due to defect formation and accumulation [32]. When the number of pulses is small, the impurities and defects occur in the crystalline lattice for laser ablation. As the number of laser pulses becomes larger, the defects and impurities become the seeds for avalanche ionization. While this multi-pulse accumulation process evolves, both the width (i.e., diameter) and depth of the crater increase. It was, however, reported that the diameter and depth change more significantly in the initial stages, and then, as the ionization reaches a limit, the diameter and depth vary less significantly [34, 35]. It is reasonable to conclude that both the applied electrical current and the multi-pulse accumulation effect influence the laser beam energy absorption. At a higher repetition rate and pulse numbers, the role of thermal incubation and accumulation becomes more apparent.

Figure 5 shows the SEM images of the exit holes under different laser irradiation durations. The left column shows the exit holes produced under the applied current, whereas the right column shows the exit holes produced without the applied current. It is clearly seen that the diameters of exit hole produced under the applied current are larger than those produced without the current supply. The data for the exit diameters were extracted from the SEM images and are plotted in Fig. 6 against the laser irradiation duration. When the irradiation duration was as 15 ms, the exit diameter drilled with the applied current is more than 90% larger than that drilled without the applied current. The enlarged exit hole under the applied current implies that the taper angle of the laser-drilled hole is reduced, which is important for many industrial applications. Similar to the entrance side, the amount of redeposited materials on the Si surface is much more under the applied current probably due to the attraction force of the electrical field.

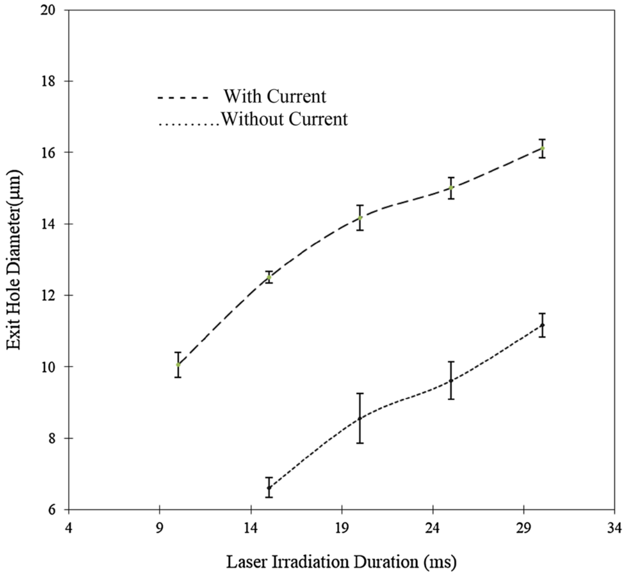
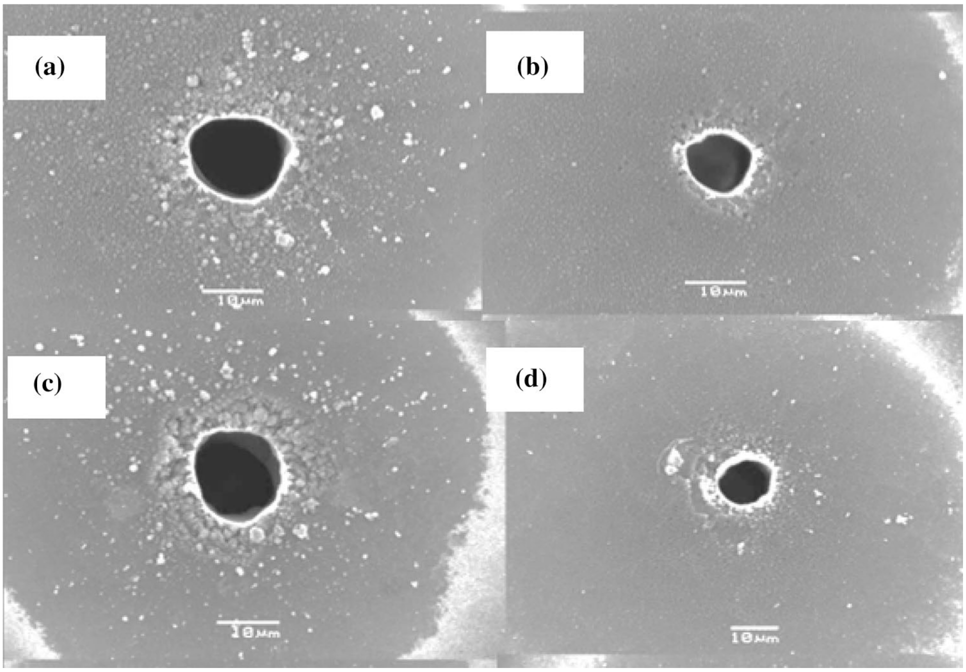


Fig. 6 Comparison of diameters of exit hole drilled with and without the applied current at different laser irradiation duration

To make quantitative assessment of the material redeposition, we use the term "damaged-area diameter" as a measure and plot it against laser fluence for single-pulse

Fig. 5 SEM images of the exit holes drilled by ps laser with irradiation duration of 25 ms (**a**, **b**), 15 ms (**c**, **d**). The left column shows the images drilled under current of 0.5 A; the right column shows the images drilled without current



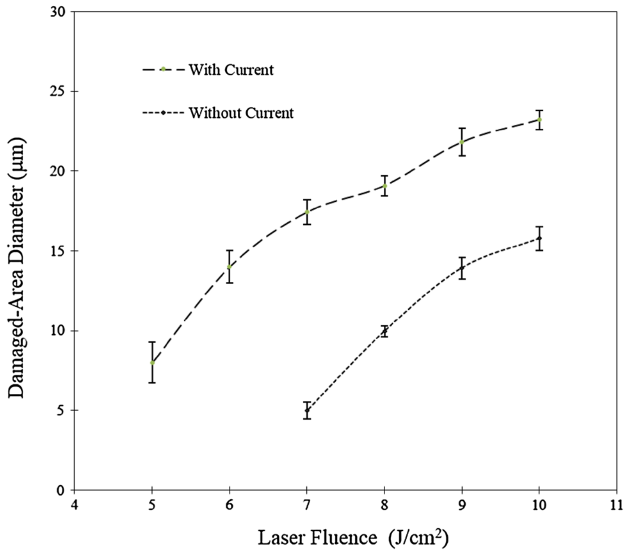


Fig. 7 Comparison of damaged-area diameter for one laser pulse with and without current at different laser fluence

ablation as shown in Fig. 7. In general, increasing the energy fluence resulted in larger amount of material removal, which splashed over a larger area on the Si surface. It is seen that with the applied current, the area covered by redeposited material was large even at a low level of laser fluence. On the other hand, under the same level of laser fluence, much reduced material redeposited back to the surface when there was no applied current. At the laser fluence of 7 J/cm^2, the debris-covered area is about 17 μm in diameter with the applied current and is more than three times (200%) of that (5 μm) produced without the applied current. When drilling through holes, the accumulative effect of multi-pulses irradiation further reduced the material ablation threshold leading to material removal in certain area that may not occur for single-pulse irradiation.

4 Conclusion

Picosecond laser drilling of silicon was investigated with an applied DC voltage across the Si substrate. The results showed that the entrance diameter was increased by up to 14% and the exit diameter was increased by up to 90% depending on the laser irradiation duration. The noticeable improvement in material removal may be attributed to the enhanced laser energy absorption of silicon with the applied electrical current. However, the laser-ablated surface was covered with more material debris probably due to the attraction force from the electric field.

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Compliance with ethical standards

Conflict of interest All author states that there is no conflict of interest.

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