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Citation: Applied Physics Letters **104**, 181902 (2014); doi: 10.1063/1.4875928
View online: http://dx.doi.org/10.1063/1.4875928
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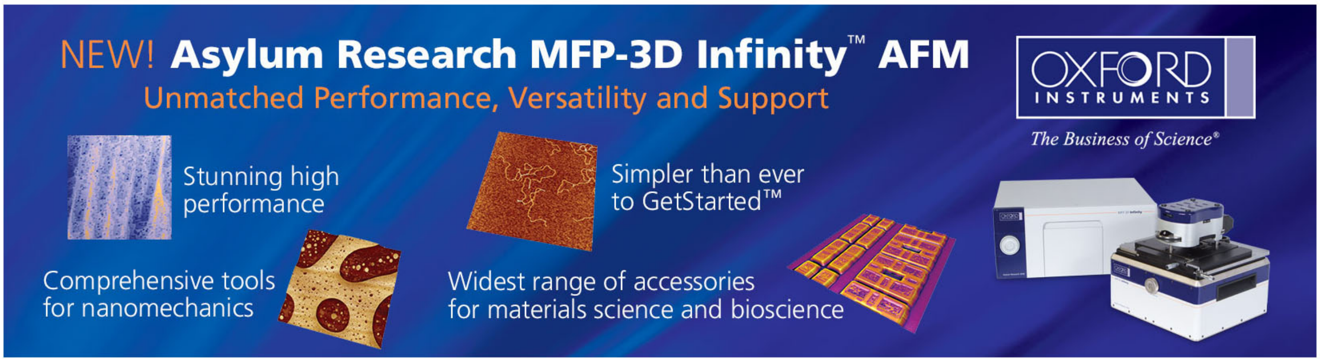

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APPLIED PHYSICS LETTERS **104**, 181902 (2014)

Influence of substrate heating on hole geometry and spatter area in femtosecond laser drilling of silicon

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(Received 19 February 2014; accepted 29 April 2014; published online 7 May 2014)

The objective of this research is to evaluate the effects of the hole geometry and the spatter area around the drilled hole by femtosecond laser deep drilling on silicon with various temperatures. Deep through holes were produced on single crystal silicon wafer femtosecond laser at elevated temperatures ranging from 300 K to 873 K in a step of 100 K. The laser drilling efficiency is increased by 56% when the temperature is elevated from 300 K to 873 K. The spatter area is found to continuously decrease with increasing substrate temperature. The reason for such changes is discussed based on the enhanced laser energy absorption at the elevated temperature. © *2014 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4875928]

Femtosecond laser with peak power in the range of gigawatts has been proved to be an efficient tool in precision machining of a wide range of materials including metals,[1] polymers,[2] ceramics,[3] and silicon.[4,5] When interacting with a substrate material, the ultrashort pulses cause minimal thermal diffusion and therefore produce more precise machined features with minimal heat-affected-zones.[6] The nonlinear absorption of the ultrashort pulse laser energy enables precise drilling of hard and brittle materials, such as silicon, which is a challenging task by conventional mechanical drilling methods. In microelectronic and solar cell applications,[7] drilling of consistent micro-holes in silicon is an important manufacturing step. Femtosecond pulse laser has been demonstrated as a potential tool for such effective drilling applications. However, issues in redeposition (spatter)[4] of the laser-ablated materials around the drilled hole and the hole taper angle remain largely unresolved. In laser-material interactions, the optical absorption coefficient is an important factor that determines how much laser energy is coupled into the substrate for the material ablation process. The silicon band-gap energy, as a function of temperature, decreases with increasing temperature. In other words, the optical absorption coefficient of silicon increases with temperature.[8] It is primarily for this reason, we proposed to apply a heating device to pre-heat the silicon substrate during the laser drilling process. There are some studies which have considered the environmental temperature's influence on surface roughness of laser grooving on various materials,[9,10] laser ablation threshold of silicon for one pulse.[11] However, we have not found any research working on the interaction of workpiece temperature and laser ablation for the case of deep through hole. In this study, the objective is to evaluate how the enhanced optical absorption of the laser energy at the elevated substrate temperature would affect the hole geometry and the spatter area around the drilled hole.

The experiments were conducted on silicon with laser power varied from 200 mW to 400 mW. The laser emitted pulse of 200 fs with linearly polarized lights at a central wavelength of approximately 775 nm (nominal repetition rate of 1 kHz). The total pulse energy was attenuated by a rotating half wave. The mechanical shutter was controlled to release the desired laser on the substrate. The laser beam was focused with a focusing lens of 75 mm focal length. The average laser power after the lens was measured using a power meter. A three-dimensional computer numerically controlled (CNC) stage was implemented to position the specimens. In the current study, through holes were produced on polished single crystal silicon wafer with thickness of 300 μm which was fixed on the stainless steel block with two heaters inside. The temperature of silicon wafer ranging from 300 K to 873 K in a step of 100 K was monitored by two calibrated thermocouples. The number of pulses was varied from 10 to 5000 for each temperature step. In the experiment, the drilled sample underwent acid etching by hydrofluoric acid (HF) to remove the spatter around the hole and make the boundary distinguishable. It is true that the hole profile is not regular due to the nonuniform energy delivered by the laser beam. In order to evaluate the hole parameter objectively, the image analysis software was applied to capture the edge of the hole and calculated the area of the hole by integrating the boundary line. Average diameter can be obtained from the area of the hole assuming that the hole has perfect circularity.

Fig. 1 exhibits the front side of the micro-holes drilled by fs laser with laser power of 200 mW at various temperatures. The diameter of the entrance hole increases by 25% at the 873 K comparing that at 300 K. In this study, the photon energy of 775 nm laser is below the direct band gap of silicon (3.4 eV).[12] Therefore, the main mechanism of electron excitation in the silicon is through the indirect band gap transition. In this process, the optical absorption property of silicon highly depends on the number of acoustic phonons, which is a function of temperature.[13] At elevated temperature, there are more acoustic phonons, thus there is more possibility that an acoustic phonon in the lattice and a photon

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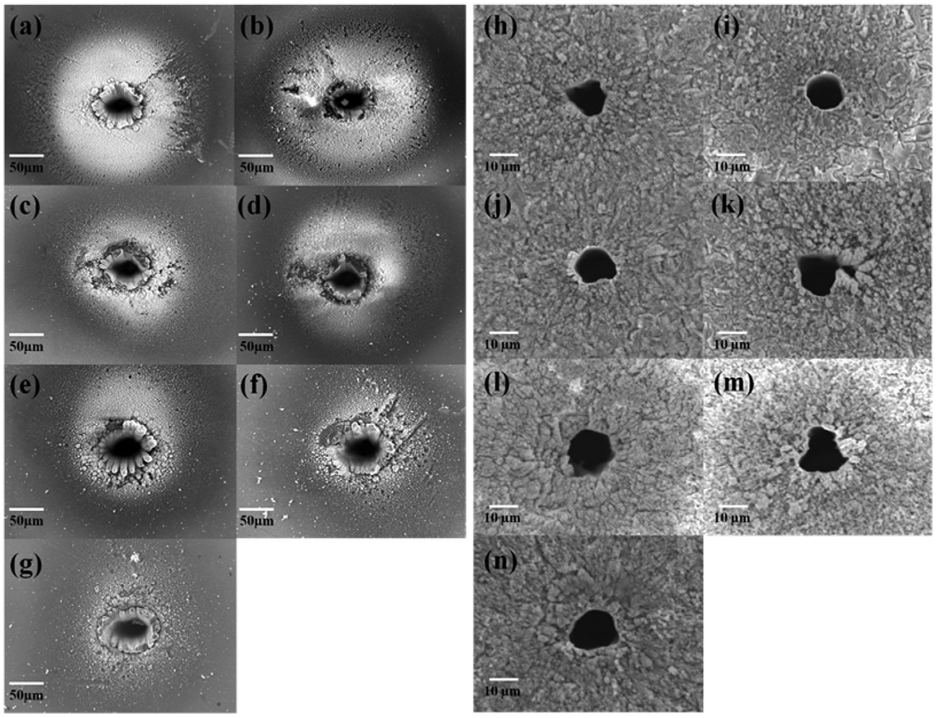

FIG. 1. SEM images of the front side (left two columns) and back side (right two columns) micro-hole drilled by fs laser at temperature 300 K ((a) and (h)), 373 K ((b) and (i)), 473 K ((c) and (j)), 573 K ((d) and (k)), 673 K ((e) and (l)), 773 K ((f) and (m)), 873 K ((g) and (n)).

from the laser irradiating can be simultaneously absorbed to create an indirect transition. As a result of a large number of electrons photoexcited from valence band into conduction band, a considerable amount of covalent bonds are destroyed[14] and multi-ionization occurs.[15] Hence, at elevated temperature, the pressure from the coulomb explosion[16] ejects more ion and atom clusters that account for the more material damage in the early stage of multi-pulse laser ablation. It is reasonable to conclude that the higher substrate temperature causes a larger entrance hole diameter. Fig. 2(a) represents the values of the entrance hole diameter at various laser power levels as a function of the substrate temperature form 300 K to 873 K. The variation of temperature below 500 K has no significant effect on the entrance hole diameter. However, when the temperature is raised to 600 K the entrance hole diameter sharply increases. Jellison, Jr. and Modine[12] reported that the optical absorption coefficient silicon at 694 nm has a precipitous increase around 573 K when temperature increases. This is the possible reason for sharp increase of the entrance hole diameter at 600 K.

On the other hand, we understand that under the high temperature, due to comparatively higher optical absorption coefficient of silicon as well as the decrease of the optical penetration depth, more energy from the laser will focus in a thinner layer at the top silicon surface. This results in larger material removal rate in the vertical direction which causes a larger ablation depth. Fig. 3 compares the geometry of laser drilling hole at room temperature and at 873 K. In order to investigate the temperature's influence on hole geometry at very early stage of the hole formation, low number of pulse in terms of 10, 20, and 30 was chosen. Fig. 3 shows that at 873 K the depth of hole is larger than that at 300 K at each step of number of pulse. The wall taper of drilled hole is smaller at elevated temperature which means that the hole is shallower at 300 K.

Meanwhile, it is observed that the exit hole diameter produced at the elevated temperature is larger than that under the room temperature as shown in Fig. 1. At the laser power of 200 mW, the exit hole diameter drilled under the elevated temperature of 873 K is more than 30% larger than that drilled under the 300 K as shown in Fig. 1. The laser drilling efficiency in terms of material removal volume is increased by 56% at 873 K. We also observe that less number of pulses is needed to penetrate the silicon thickness at higher temperature. It is known that during the percussion laser drilling, the material is removed layer by layer for each laser pulse.

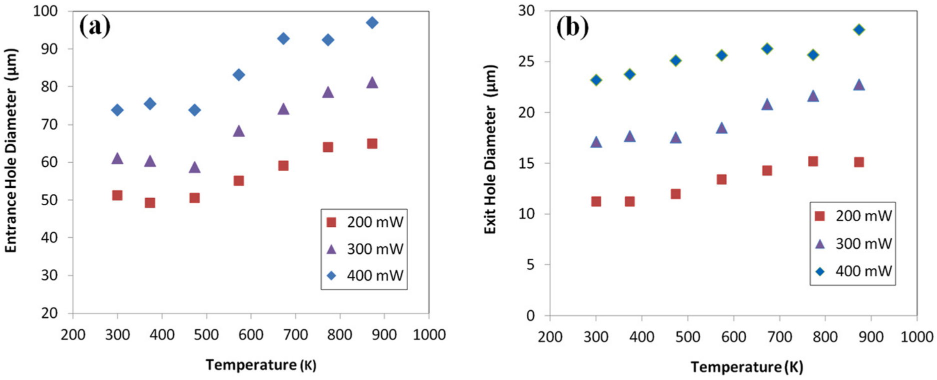

FIG. 2. The entrance hole diameter (a) and exit hole diameter (b) as a function of substrate temperature at average laser power of 200 mW, 300 mW, and 400 mW, respectively.

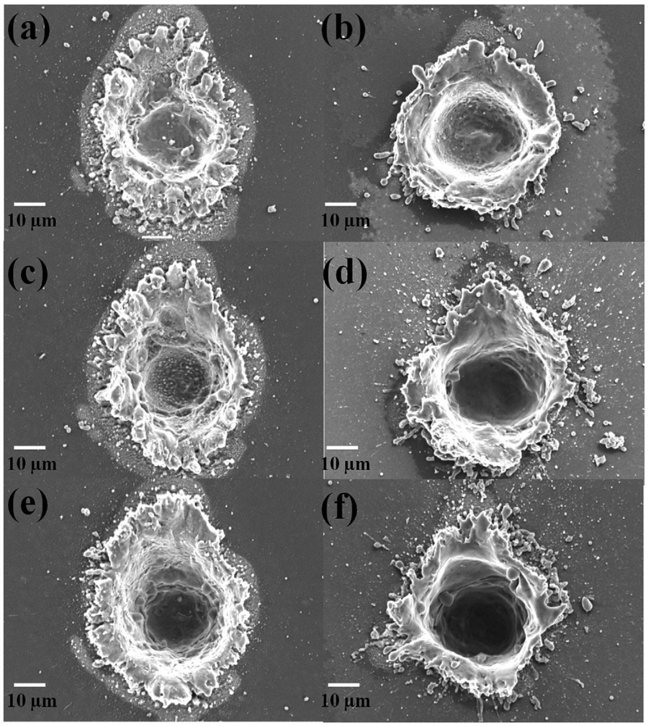

FIG. 3. Comparison of laser drilling hole at room temperature (left column) and at 873 K (right column) with number of pulse of 10 ((a) and (b)), 20 ((c) and (d)), 30 ((e) and (f)).

As mentioned above, under the elevated temperature, a less tapered hole is obtained after the irradiating of first several pulses. As reported by Ruberto *et al.*,[17] the laser drilling hole at initial stage acts as a waveguiding for the successive laser pulses. In the waveguiding process, less tapered angle wall is helpful in delivering the laser beam to the deeper position. In addition, it is reported[18] that multiple reflection of following laser beam in the shallow hole causes more serious energy loss due to the absorption of the laser power by hole wall. That means at the elevated temperature, the relatively straight wall of drilled hole delivers more laser energy to the bottom of hole, resulting in the larger exit hole. Fig. 2(b) exhibits the value of exit hole diameter at various laser power levels as a function of the substrate temperature form 300 K to 873 K. Generally, the exit hole diameter gradually increases with increasing substrate temperature. The influence of temperature increase can be reduced due to considerable laser energy loss which comes from the multi-reflection of laser beam on the hole wall. Therefore, no sharp increase of exit hole diameter is observed.

As the ablation products, the debris is hardly avoided when silicon is machined by femtosecond laser in air environment. In the initial stage of the laser ablation, the formation of debris originates from the atoms and clusters due to the coulomb explosion.[19] Thereafter, the recoil pressure from the fast evaporating molten layer provides the energy to eject the hot atom cluster and liquid droplet. The recoil pressure[20] can be expressed as follows:

$$P_r = 0.56 P_s(T_s)\,, \tag{1}$$

where P_s is the saturated vapor pressure at T_s. In the case of elevated temperature, the P_r is expected to be higher due to larger T_s. The increase of P_r should have resulted in a stronger force to push away the debris and produce a larger spatter area. However, the observation from Fig. 4 shows a contrary result when elevating the temperature. Fig. 4 indicates that the spatter area is dramatically reduced by half with increasing of the substrate temperature from 300 K to 773 K at various number of pulse and power density. It is reasonable to explain the mechanism for the spatter area

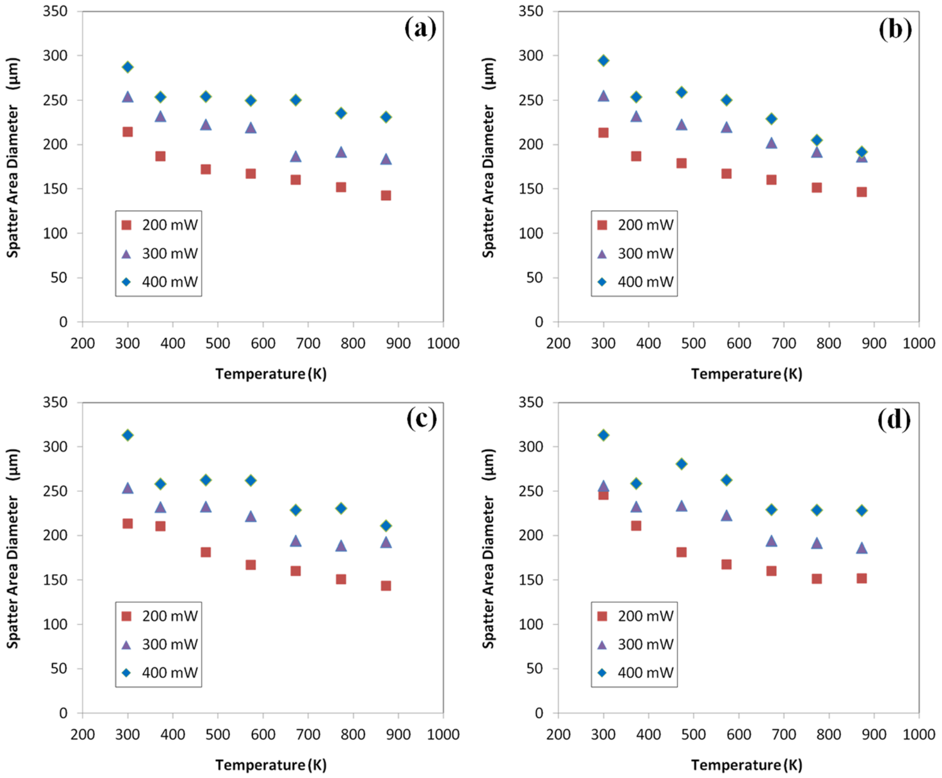

FIG. 4. The spatter area as a function of substrate temperature at number of pulse of 2000 (a), 3000 (b), 4000 (c), 5000 (d) with various power densities.

reduction at the elevated temperature in terms of the enhanced energy absorption. For the multi-pulses laser ablation, the laser radiation is strongly absorbed by the laser induced plasma.[21] As the drilling depth grows, part of the plasma plume is trapped in the laser drilling hole[22] and become a semi-medium between the laser beam and silicon surface. In this situation, the material removal mechanism consists of laser ablation, plasma etching, and joule heating from the heat conduction of the hot plasma. During this process, coupled with the thermal energy supplied due to the substrate heating, the energy from plasma joule heating may be sufficient to melt a larger amount of the material. This would produce larger liquid droplets with increased gravity that cannot be pushed so far as the small particles do, even if the recoil pressure is growing. The amorphization and redeposition of these liquid droplets accumulate at the periphery of the hole and forms the spatter. As seen from Figs. 1 and 3, the particle size in the spatter formed at 873 K is significantly larger than that formed at 300 K. The granular structure around the hole may indicate the presence of liquid material during the laser process. In case of laser drilling under the elevated temperature, coarser pillars can be found in the granular structure. This may indicate the forming of melting droplets before their resolidification.

In conclusion, the femtosecond laser deep drilling on silicon was systematically investigated at various elevated substrate temperatures. The result indicates that the entrance hole diameter is increased by 25% and the exit hole is increased by 30% when the substrate temperature is elevated to 873 K. The laser drilling efficiency is greatly increased by elevating the temperature. The high drilling efficiency is attributed to enhanced laser energy absorption of silicon wafer and subsequent waveguiding effect. The spatter area is found to continuously decrease with increasing substrate temperature. A large size ejection material is found around the ablation area, which suggests that liquid phase is increased by the joule heating from the heat conduction of the hot plasma.

This work was supported by a start-up grant from Nanyang Technological University and an AcRF Tier 1 grant from Ministry of Education, Singapore.

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