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Review article

A review on laser drilling and cutting of silicon

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ABSTRACT

Silicon is the most widely used material in numerous fields. Traditional mechanical machining methods have been unable to meet the higher requirements of processing quality. Laser machining is especially suitable for processing hard and brittle materials due to the non-contact processing characteristics. This article summarizes the nanosecond, picosecond, femtosecond laser drilling and cutting technologies of silicon according to the classification of laser pulse widths. For the most typical field assisted machining technology, liquid-assisted laser drilling and cutting are also discussed. In consideration of the heat generated during laser processing is likely to cause stress in the material, resulting in micro-cracks and other processing defects. Laser induced thermal crack propagation cutting technology (LITP) successfully uses the cracks produced in laser machining to achieve the high cutting quality of silicon. As a new way of material internal processing, laser stealth dicing is the most promising method in the field of wafer cutting. The mechanism and processing characteristics of laser stealth dicing are described. At the end of paper, a summary and outlook are provided.

1. Introduction

Laser machining has shown great advantages in drilling [1], cutting [2], patterning [3] and functional surface preparation [4]. In general, the quality of laser processing is improved with the shortening of pulse width [5]. Millisecond laser is easy to introduce processing defects due to severe thermal damage and is mainly used for material removal at a relatively macro scale [6,7]. Nanosecond laser removes materials through thermal effect, the processing quality and accuracy are better than that of millisecond laser. Picosecond and femtosecond laser with shorter pulses are more conducive to process finer structures on the materials. The use of field-assisted laser processing provides a way to improve the processing quality further. As the most commonly used auxiliary processing method, liquid-assisted laser machining can effectively reduce the slag generated during material removal and obtain more ideal processing quality compared with the air environment [8,9]. Among many liquids, water-assisted laser processing is the most promising due to its advantages of convenience, and environmental protection [10,11].

Silicon plays an important role in the fields of electronics, biology and energy [12–14], the fine processing is very crucial to industry. Traditional machining methods using diamond tools have been unable to meet the high precision and machining quality of silicon [15,16]. In addition to drilling and cutting of silicon, laser stealth dicing has no debris which is almost impossible to achieve by blade dicing in the manufacturing of electronic components [17–19]. The emergence of laser machining technology not only solves the problems of tool wear, but also has high processing precision and low cost, especially in the preparation of functional surfaces. It is an ideal way to process hard and brittle materials in the micro-nano scales [20,21].

This paper systematically summarizes laser drilling and cutting of silicon with different pulse widths from nanosecond, picosecond to femtosecond. Liquid-assisted laser removal of silicon are also discussed. As a new processing method, laser induced thermal crack propagation cutting (LITP) of silicon is described. Researches on laser stealth dicing of silicon wafer are introduced to exhibit the advantages of laser machining inside material. The state of the art of laser machining of silicon is summarized, and the future perspectives are provided at the end of this review.

2. Laser drilling of silicon

2.1. Nanosecond laser drilling

Laser drilling is started from the formation of craters on the surface of materials. Silicon is removed by evaporating from the surface. This process is accompanied by liquid splashing and plasma plume formation [22,23]. The phase explosion is the key factor to change the dimensions

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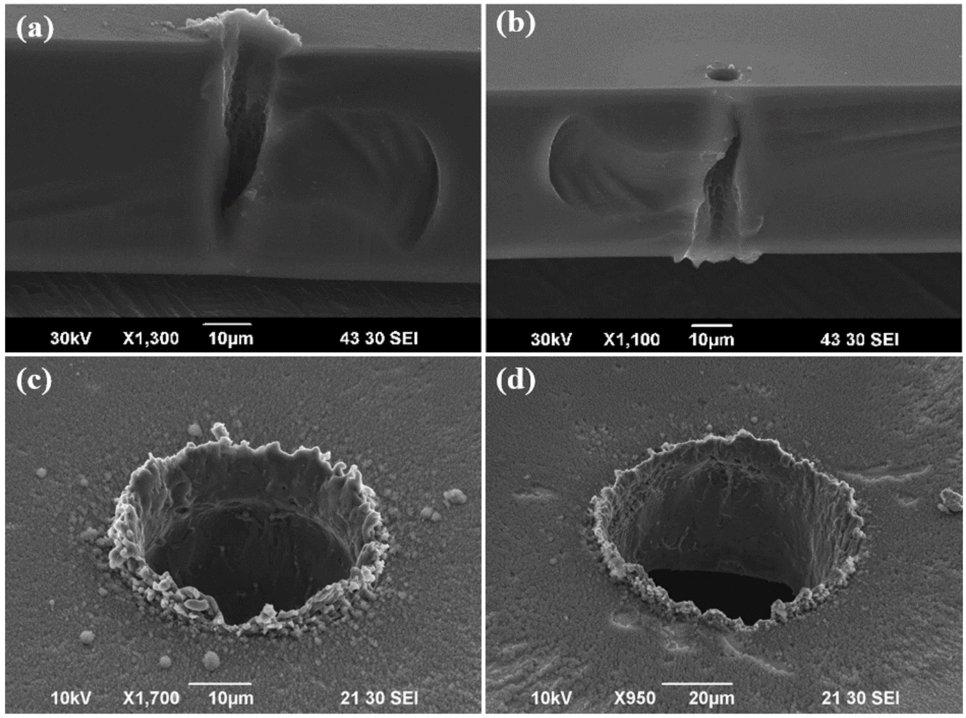

Fig. 1. SEM of holes at the different views and spot sizes with a fluence of 11 J/cm^2: (a) top, 20 μm; (b) bottom, 20 μm; (c) top, 40 μm; (d) top, 70 μm. [32].

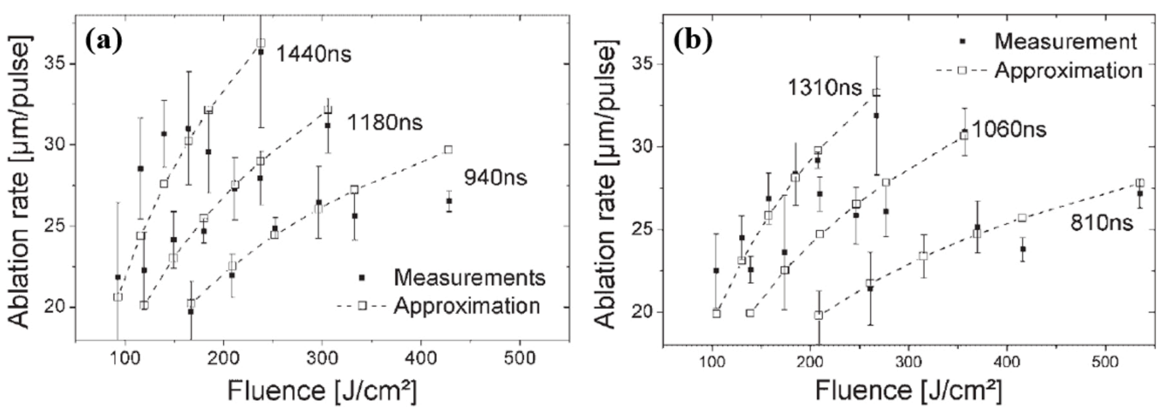

Fig. 2. The average ablation rate as a function of fluence at the laser wavelength of 1064 nm and different pulse durations [34].

of holes by influencing the thickness of liquid silicon at different laser influences [24–26].The percussion drilling with nanosecond UV laser was used to machine through holes in silicon by Lee et al. [27]. Effects of laser processing parameters on hole dimensions were investigated. Experimental results indicated that there was a logarithmic relationship between the depth of hole and laser fluence. With the increase in the number of laser pulses, the depth of hole increased linearly. This was usually expressed as the relationship between the ablation rate and the number of pulses [28,29]. Diameters at entrance and exits varied little in a certain energy range. It was also found that low fluence with multiple pulse numbers was more beneficial to obtain smaller diameter holes than high fluence with less pulse number. This might be related to the mechanism of thermal formation of high energy ions at different fluences [30,31]. This research has proved that laser drilling has more advantages than the chemical methods in processing speed, quality and environmental protection. Brandi et al. [32] used a nanosecond laser with different spot diameters to study the drilling efficiency of silicon. Fig. 1 shows the SEM of holes at the different views and spot sizes with a fluence of 11 J/cm^2. It was observed that the debris and recast existed at the entrance of hole. In contrast, the hole at the exit was much cleaner. The ablation efficiency improved with the decreasing spot size and this was mainly determined by the plume shielding effect. The interaction between laser and materials during drilling was complicated. Nanosecond lasers can also process sub-micron holes in micron-level holes through laser refocusing and waveguide effects [33]. Baier et al. [34] studied the ablation rate with nanosecond lasers drilling of silicon by theoretical calculations. Fig. 2 shows the average ablation rate as a function of fluence at the laser wavelength of 1064 nm and different pulse durations. In Fig. 2a, two pulses of equal fluence at 120 J/cm^2 can be obtained by splitting a pulse of 240 J/cm^2 at the pulse duration of 1440 ns. Although the ablation rate of a single pulse decreased by about 25 %, the overall ablation rate increased by about 45 %. Similarly, the

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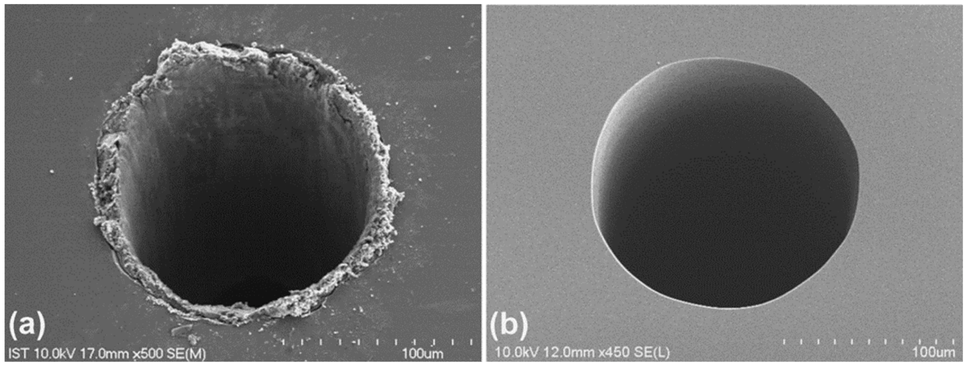

Fig. 3. SEM of laser drilling of silicon using conventional (a) and hybrid (b) laser drilling strategy [39].

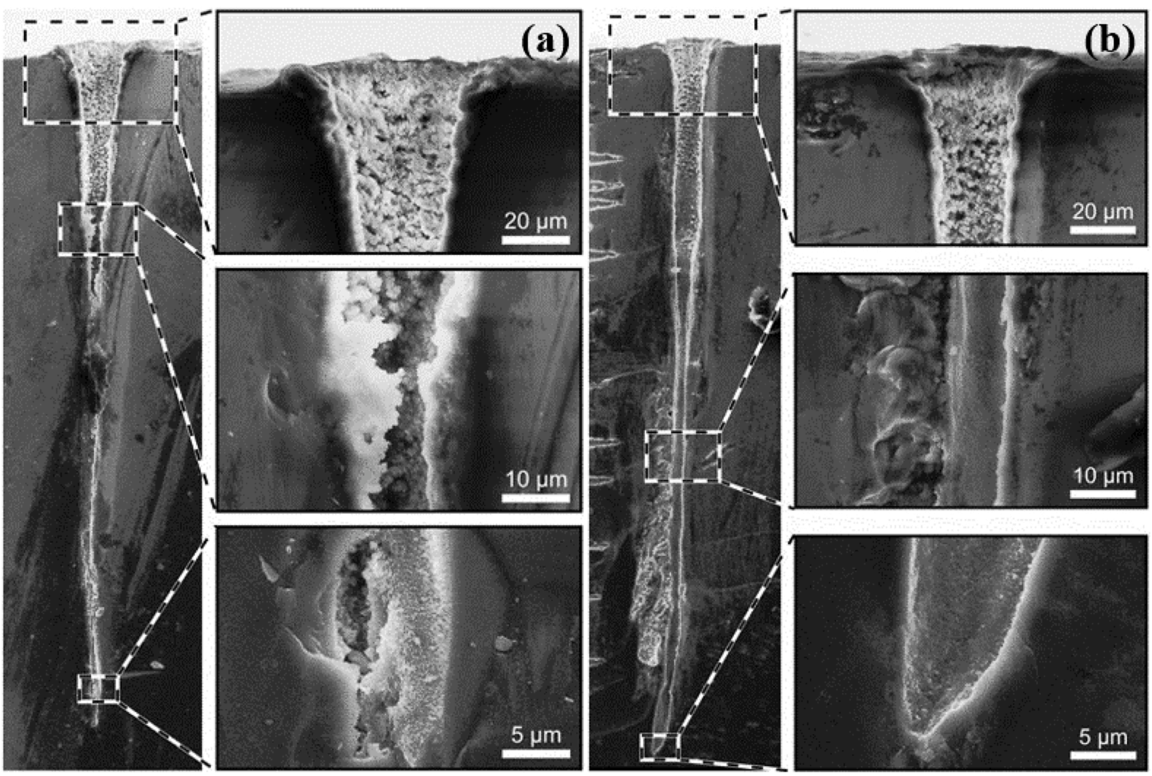

Fig. 4. SEM of the morphology of hole wall after laser percussion drilling with different pressure: (a) atmospheric, 1000 mbar; (b) vacuum, 10^{-2} mbar. (Number of pulses of 10000, pulse energy of 125 μJ) [45].

ablation rate can be increased by 50 % by dividing the pulse laser of 810 ns into two pulses in Fig. 2b. It was also found that longer pulse width had a higher ablation rate at the same fluence. This was mainly caused by the high temperature material slag formed in the process of nanosecond laser. The applications of combining laser splitter and Fourier transform lens were conductive to efficiently machine array holes and cavities on silicon for using in inkjet printer heads [35].

Silicon often requires coating other materials on the surface of hole wall in the electronic field. This is different from drilling the thin film directly on the silicon wafer [36–38]. Tang et al. [39] applied a nanosecond laser to improve the dielectric breakdown field of silicon by a hybrid drilling technology. Fig. 3 shows SEM of laser drilling of silicon using conventional and hybrid laser drilling strategy. As shown in Fig. 3a, a significant recast layer and debris existed at the entrance of hole as a result of nanosecond laser drilling. These substances contained compounds formed by the chemical reaction of silicon with air [40]. In order to meet the requirements of dielectric layer deposition, processing defects need to be removed. It is a very effective method to use organic solvents to etch holes processed by laser to remove processing defects. The high quality of hole can be obtained by wet chemical etching with a $HF:HNO_3:H_2O$ etchant in Fig. 3b. It is worth noting that since the dimension of hole is determined by the laser processing and chemical etching process, the processing parameters still need to be optimized for specific applications. The chemical etching method was also very effective to improve the quality of hole wall [41]. Micro-hole is an important structure connecting interlayers of devices, but it is very difficult to coat metal film inside the hole. Hidai et al. [42] performed an experimental study to investigate laser drilling of layered materials

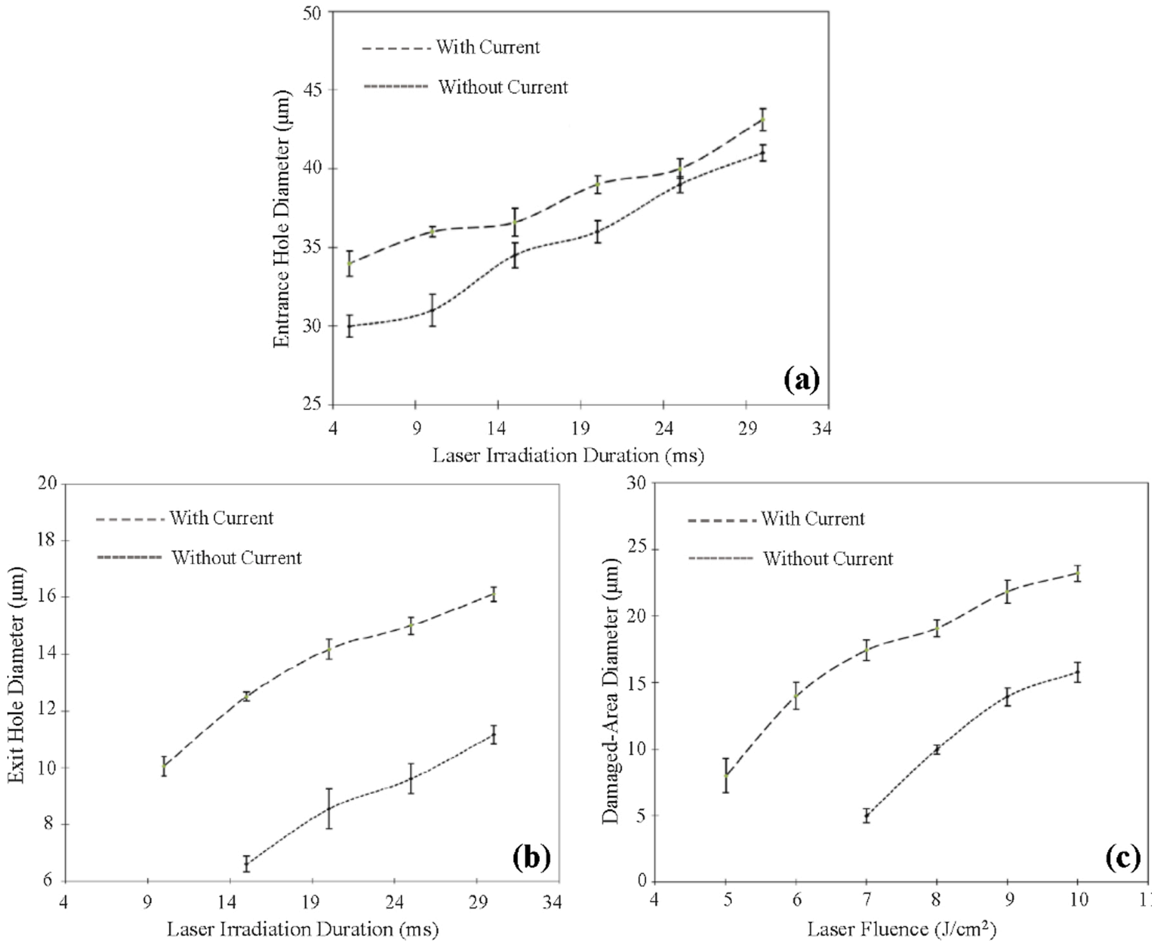

Fig. 5. Relationships between diameter, damaged-area diameter and laser processing parameters: (a) entrance hole diameter and laser irradiation duration; (b) exit hole diameter and laser irradiation duration; (c) damaged-area diameter and laser fluence for single pulse irradiation [47].

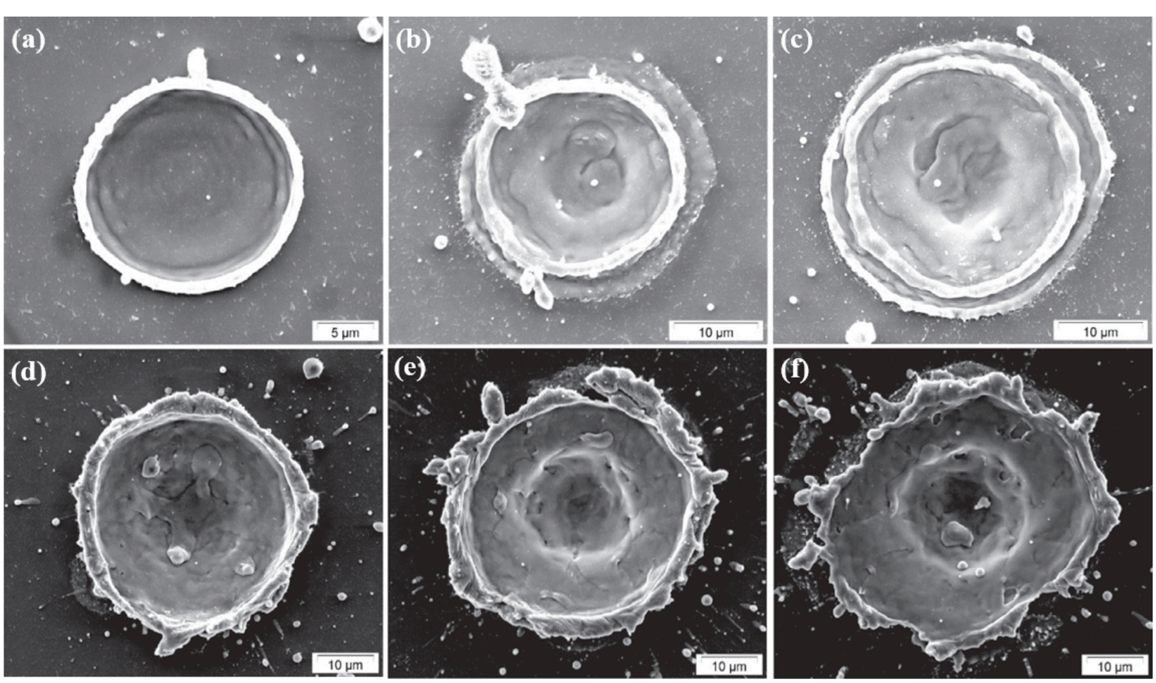

Fig. 6. SEM of craters at different fluence with 5 pulses and repetition rate of 50 Hz: (a) 3.1 J/cm^2; (b) 7 J/cm^2; (c) 10.3 J/cm^2; (d) 24.1 J/cm^2; (e) 32.7 J/cm^2; (f) 49.4 J/cm^2 [48].

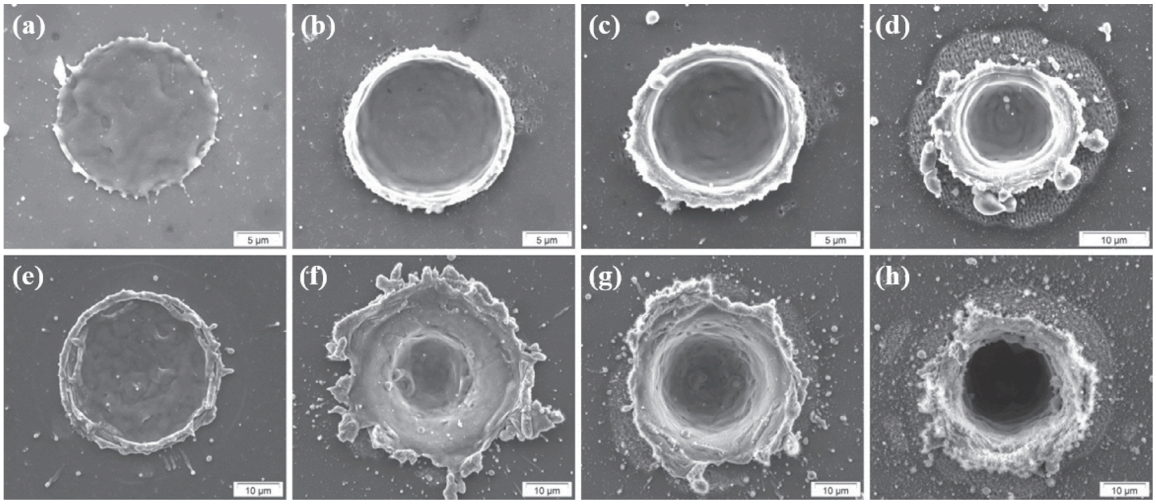

Fig. 7. SEM of craters at different pulses and fluence: (a) 1, 3.1 J/cm^2; (b) 10, 3.1 J/cm^2; (c) 20, 3.1 J/cm^2; (d) 50, 3.1 J/cm^2; (e) 1, 24.1 J/cm^2; (f) 10, 24.1 J/cm^2; (g) 20, 24.1 J/cm^2; (h) 50, 24.1 J/cm^2 [48].

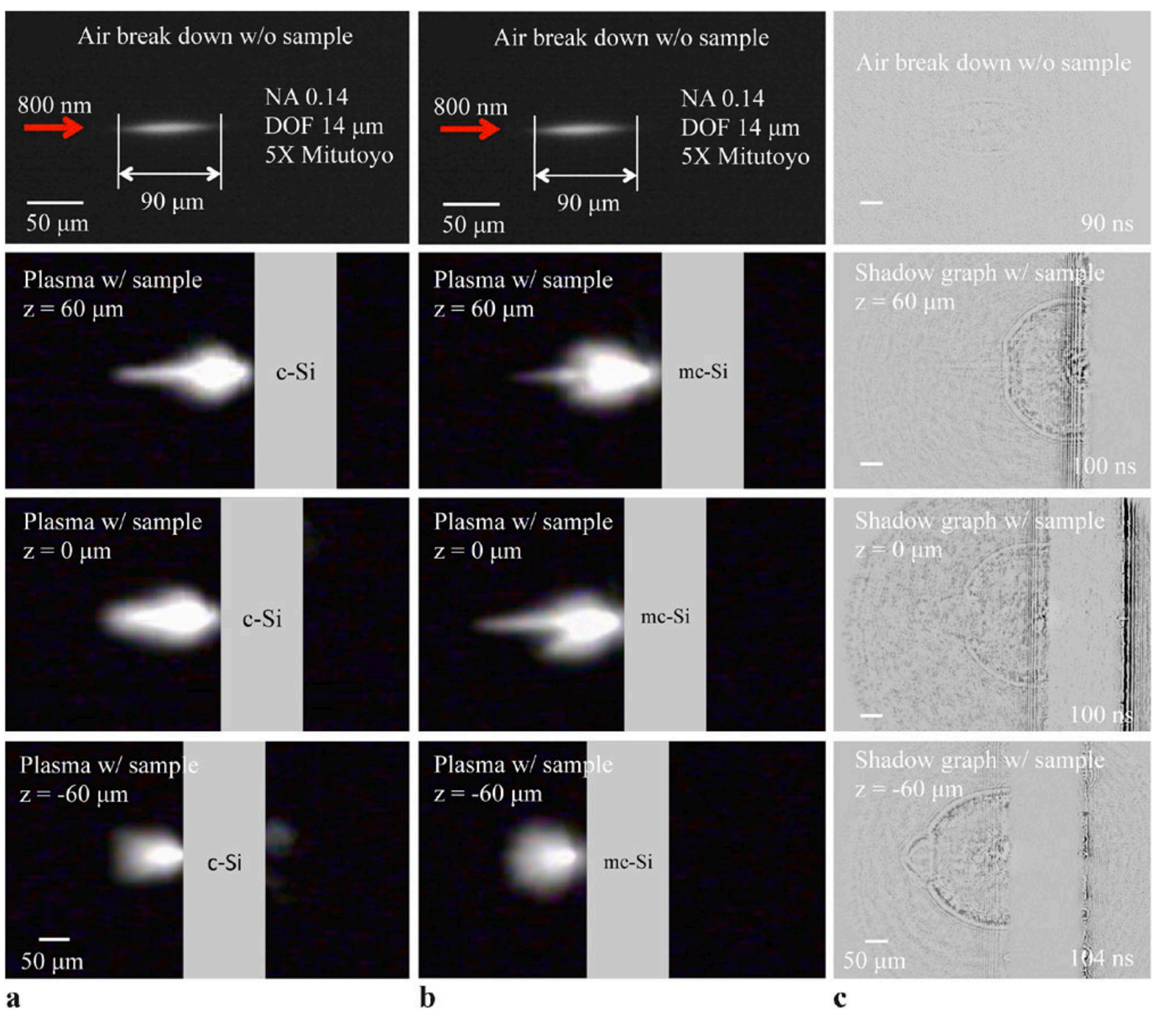

Fig. 8. Emission images of overlapping 1 to 3 pulses with pulse energy of 50 μJ, repetition rate of 100 Hz, exposed time of 33 ms at various positions of crystalline silicon (a) and multi-crystalline silicon (b). Shock images with pulse energy of 50 μJ at various positions of crystalline silicon and the pulse width of laser for illuminating is 40 ns (c) [53].

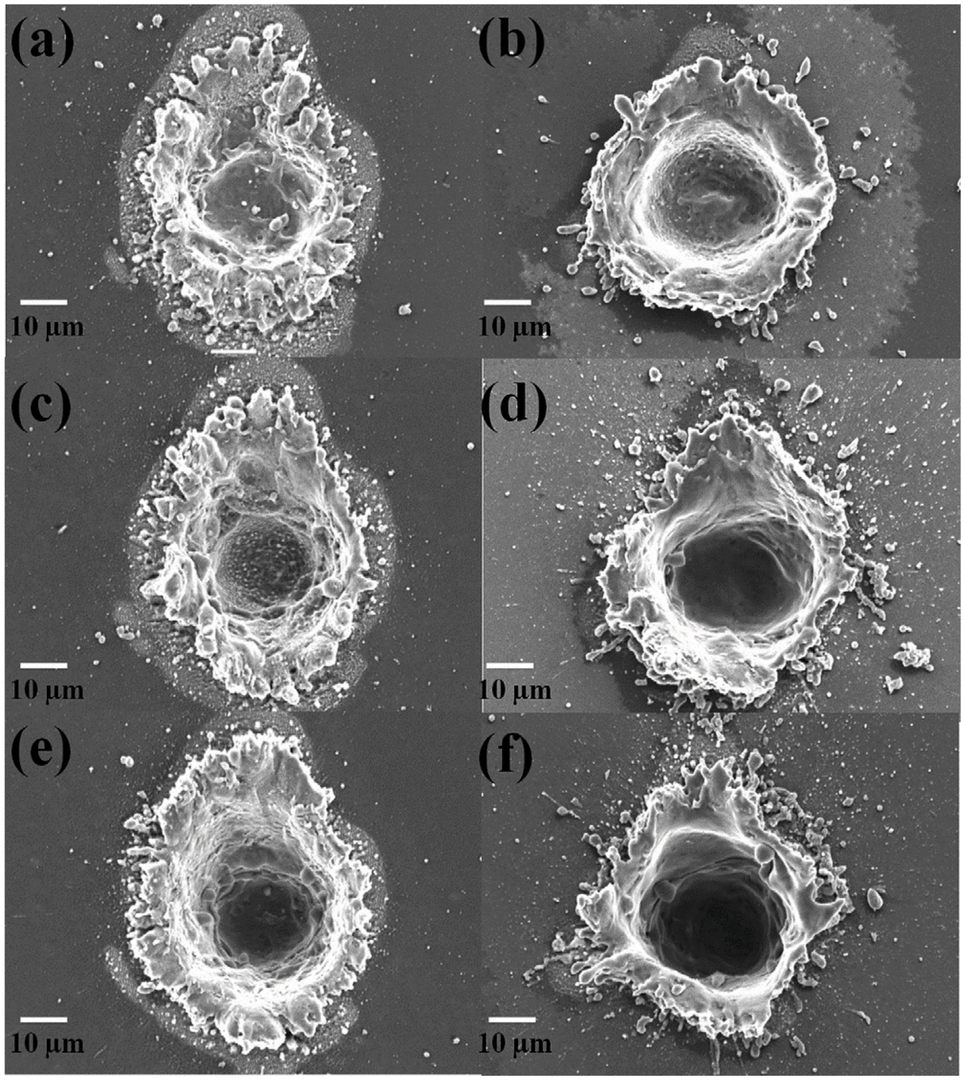

Fig. 9. SEM of femtosecond laser drilling of silicon at different temperature and number of pulses: (a) room, 10; (b) 873 K, 10; (c) room, 20; (d) 873 K, 20; (e) room, 30; (f) 873 K, 30 [59].

which consisted of metal substrate placed on silicon to solve this problem. According to the direction of material removal and evaporation, the required metal was plated on the inside of hole while laser machining the silicon hole. This method can also be used to deposit a gradient film inside a silicon hole by placing multi-layer metals above silicon. Compared with drilling first and then electroplating [43], it has more advantages to drill holes synchronously with plating metal.

2.2. *Picosecond laser drilling*

Although picosecond laser has more advantages than nanosecond laser in processing accuracy, the interaction between electron and lattice has to be considered. At this condition, the melting and evaporation process of materials is still in nanosecond order [44]. It is difficult to make up for the adverse thermal effects by changing processing variables. In addition to the laser processing parameters, the surrounding environment also has a significant impact on the quality of hole processing. Döring et al. [45] studied the influence of ambient pressure on the formation of hole in picosecond laser drilling of silicon. Fig. 4 shows SEM of the morphology of hole wall after laser percussion drilling with different pressure. A large number of material slags covered the inner wall of holes and penetrated the entire depth in Fig. 4a. In contrast, there is little difference between the entrance of hole in vacuum and that in air in Fig. 4b. However, as the processing depth increased, almost no slags adhered on the cross-section of hole. This was closely related to the laser transmission during the material removal process. The degree of laser scattering could be greatly reduced in vacuum since only debris clustered at the entrance of hole. Therefore, the vacuum environment is more advantageous in deep hole processing. By adjusting the laser induced plasma, it was possible to avoid the adverse effects of the melting materials at the hole wall [46]. This is also an effective way to obtain high-quality holes.

To obtain a higher removal rate of processed materials, Jiao et al. [47] proposed a method to improve the absorption coefficient of silicon by applying direct current to sample in picosecond laser drilling. Fig. 5 presents relationships between diameter, damaged-area diameter and laser processing parameters. As shown in Fig. 5a and b, diameters of hole at the entrance and exit sides increased with the increasing irradiation duration. In the state of current, diameters were larger than that in the case of without current. This was mainly achieved by increasing the free electrons in silicon to cause more collisions with photons. Thus, the removal rate was improved as a result of more photons were absorbed in silicon. In Fig. 5c, it can be observed that the damaged-area diameter increased with the increase of laser fluence. Although the current was

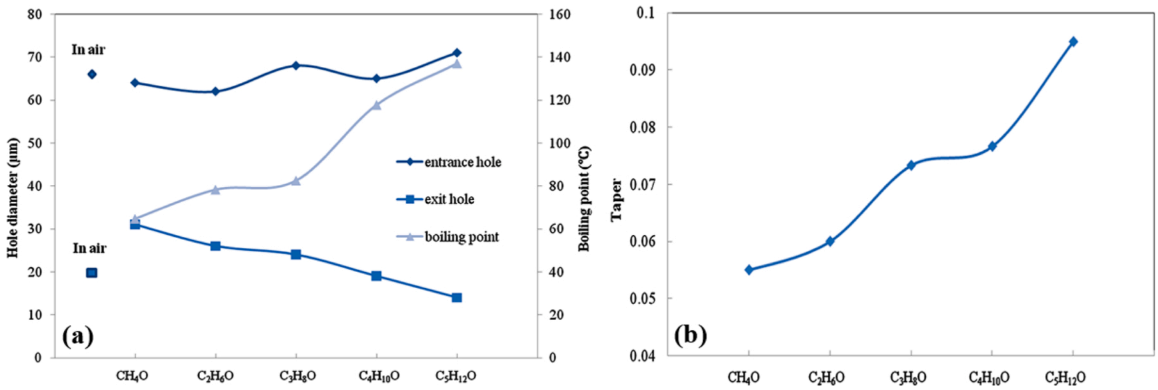

Fig. 10. Diameter (a) and taper (b) versus different types of assist liquid [63].

more conducive to material removal, it had a negative impact on the machining quality. However, this situation would be improved due to the cumulative effect when using multi-pulse processing. The ablation behavior of the material is also directly related to the removal rate. Shaheen et al. [48] studied picosecond laser with a Gaussian beam profile ablation of silicon. Fig. 6 shows SEM of craters at different fluence with 5 pulses and repetition rate of 50 Hz. The surface morphology of craters changed significantly with fluence under the fixed number of pulses and repetition rate. With the increase of fluence, the debris on the surface of craters increased and the recast layer thickened. However, there was a critical fluence to distinguish the surface morphology. When fluence was higher or lower than this value, the morphology of craters had a higher degree of similarity. Fig. 7 shows SEM of craters at different pulses and fluence. The effect of more pulse numbers on the depth of the crater was greater than that of the diameter. In contrast, higher energy density could not only process deeper crater, but also deposited more slags in the material processing area. It was found that the factors leading to the evolution of the surface morphology of craters may be the imperfect Gaussian distribution of the laser beam, the formation of molten materials and wave motion promoted by the successive pulses. The formation of diffraction patterns caused by pinholes placed in the optical path to filter low energy may also be another reason. In comparison to nanosecond laser with a flat-top beam profile, this study proves that there are significant differences in the ablation behavior of materials due to the diversity of laser beam characteristics.

2.3. *Femtosecond laser drilling*

The machining accuracy of femtosecond laser is higher than that of nanosecond and picosecond laser due to the thermal diffusion depth is less than the optical penetration depth at the short pulse width of 10^{-15} s [49]. However, the thermal load is still a key factor for femtosecond laser to obtain better processing quality [50]. From the material point of view, heat transfer characteristics and ablation threshold would affect the quality and ablation rate of femtosecond laser drilling [51,52]. Ahn et al. [53] observed the dynamic process of the interaction between the femtosecond laser and silicon. Fig. 8 shows emission and shock images of laser machining crystalline silicon and multi-crystalline silicon. As shown in Fig. 8(a) and (b), the intensity of plasma emission with silicon was stronger than that in air. The ablation was more obvious as the closer of silicon to the laser focus area. The plasma and focusing position are important factors in the process parameters [54,55]. These were the common characteristics of crystalline silicon and multi-crystalline silicon in laser processing, but the latter ejected more materials at a larger divergence angle. In Fig. 8(c), shock images at various positions of crystalline silicon were recorded to reflect the expansion of laser induced shock wave. Obviously, the shock wave expanded faster as the closer to the lens. The laser energy was also higher in the drilling area. For metal materials, the process of laser induced plasma is also an important research topic [56].

In actual processing, it is often necessary to comprehensively consider the processing accuracy and efficiency. However, these indicators are relatively contradictory. Since plasma has a greater impact on processing for femtosecond laser, the drilling accuracy of silicon can be improved with the aid of laser induced breakdown spectroscopy [57]. In research on silicon drilling using lasers with different pulse widths, Kaspar et al. [58] found that femtosecond laser processing exhibits a superheated solid state which was different from a superheated liquid state with nanosecond laser processing. Therefore, the molten materials were not existed in the machining areas, but it was easy to introduce

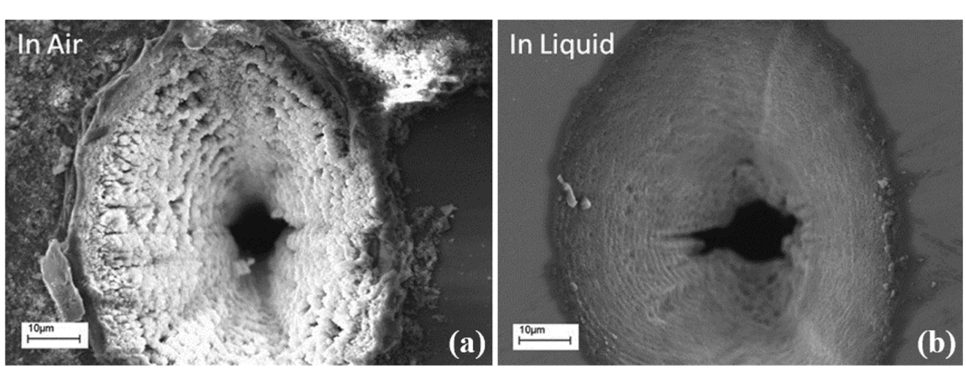

Fig. 11. SEM of hole by using femtosecond laser drilling of silicon in air (a) and liquid (b) [66].

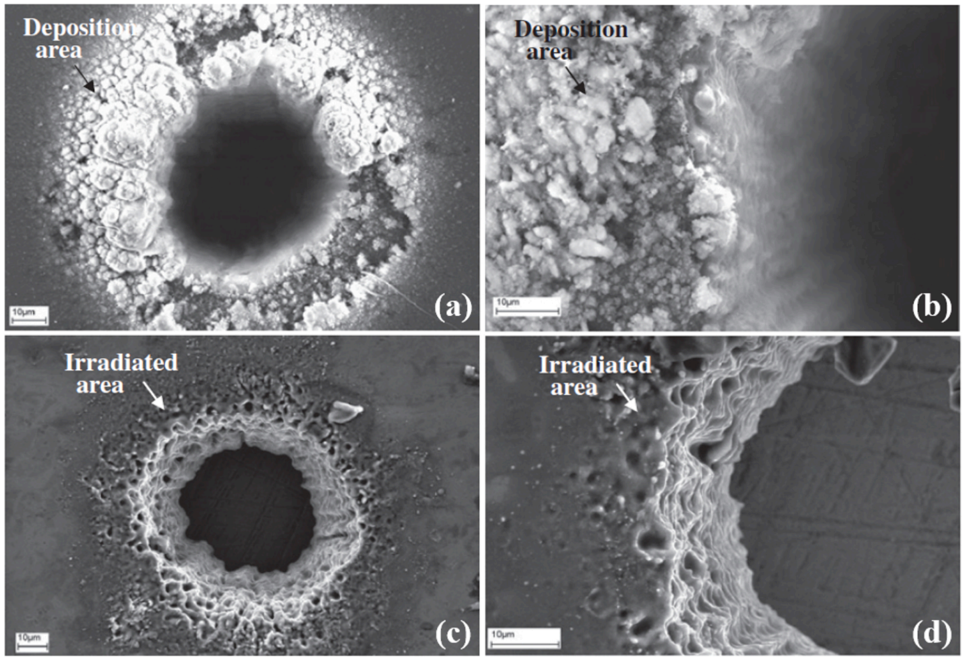

Fig. 12. SEM of laser drilling of silicon in air: (a) top surface; (b) crater edge; and in water: (c) top surface; (d) crater edge [67].

unfavorable mechanical damage by using a femtosecond laser. As mentioned before, the removal rate was improved by placing silicon in an electrified state while laser drilling [47]. The temperature of materials and laser induced plasma and the electron density near the machining zone would also affect the laser drilling effects [59,60]. Fig. 9 shows SEM of femtosecond laser drilling of silicon at different temperature and number of pulses. The diameter and depth of holes increased with the number of pulses from 10 to 30 at both room temperature and 873 K. The deeper holes and the smaller area of splashed slags were produced at the higher temperature with the same number of pulses. It can be found that increasing the temperature is conducive to material processing, but the expansion of the material may affect the machining accuracy [47].

2.4. Liquid-assisted laser drilling

Water jet guided laser processing is a very promising liquid-assisted laser drilling method due to the combining advantages of laser and

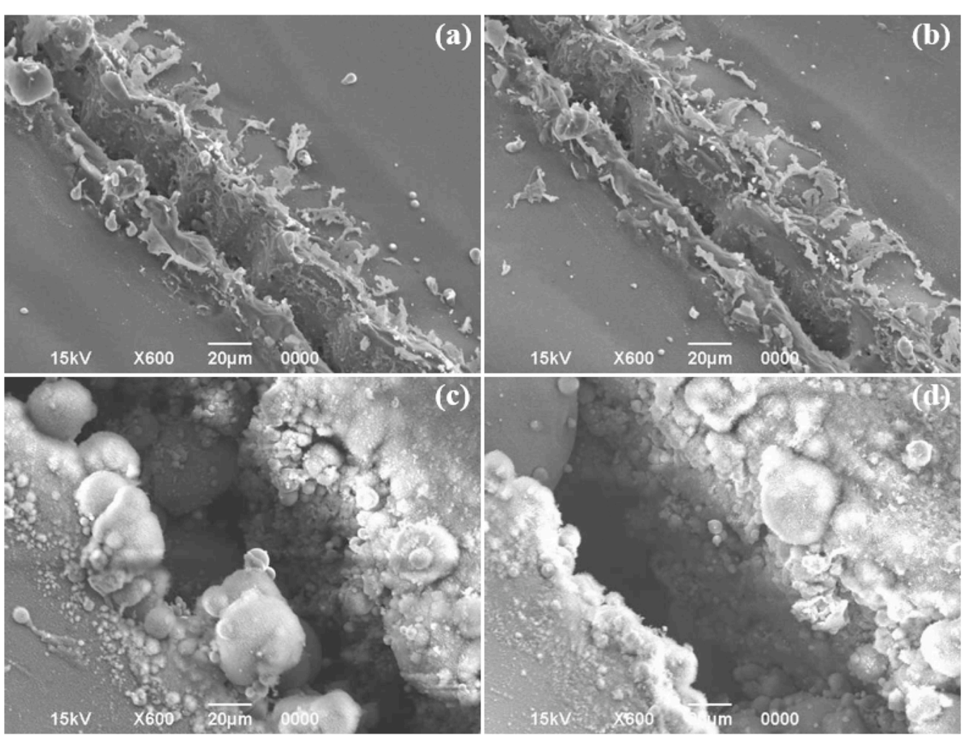

Fig. 13. SEM of laser cutting of silicon at different power: (a) 18 W; (b) 22 W; (c) 26 W; (d) 30 W [73].

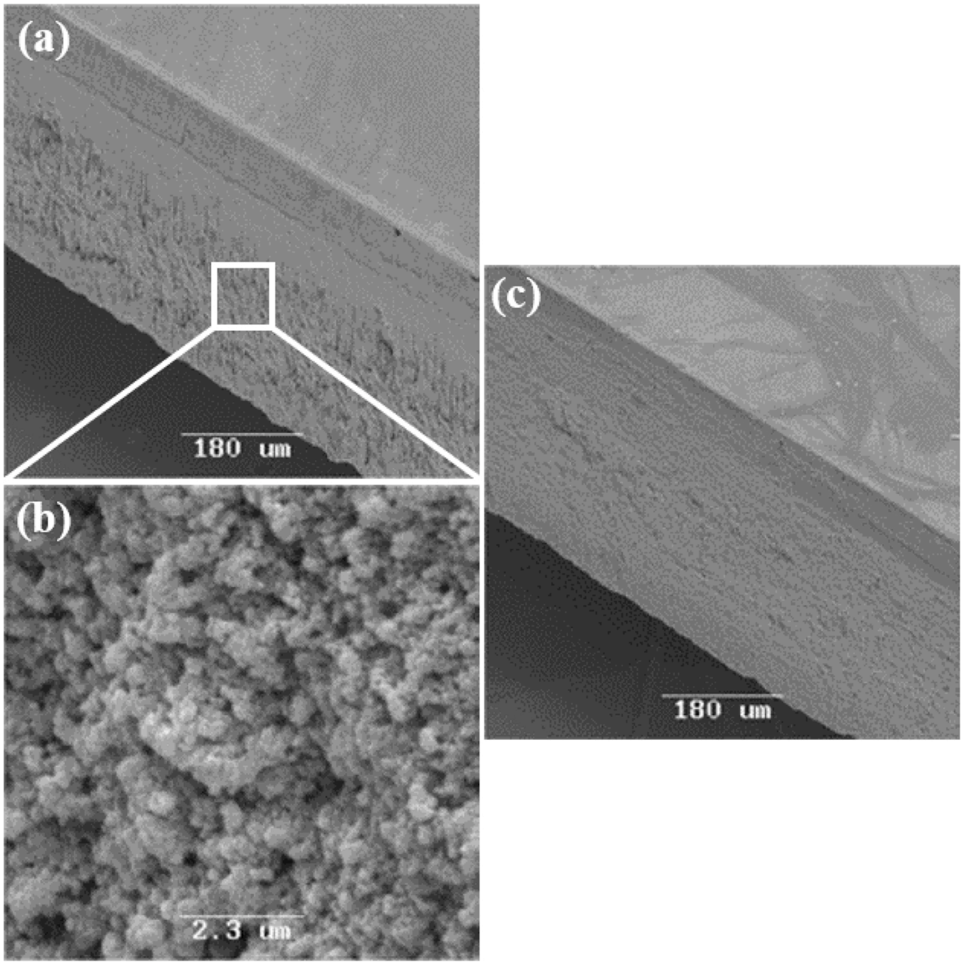

Fig. 14. SEM of laser cutting of silicon: (a) before cleaning; (b) magnified area in (a); (c) after cleaning [80].

liquid jet processing [61,62]. However, the laser is required to be totally reflected in the water column. This is not only a great technical difficulty, but also a high demand for processing equipment. In practical application, the material is usually placed in liquid which is more convenient for drilling. Jiao et al. [63] studied effects of liquids on the dimensions of hole in femtosecond laser drilling of silicon. Fig. 10 shows diameter and taper versus different types of assist liquid. In Fig. 10(a), the entrance diameter of hole was relatively stable in air and liquid. Exit diameter of hole changed from larger to smaller than air and decreased as the boiling point of liquids increased. The changing trend of the diameter of hole directly led to taper increased with the more carbon atoms of liquids in Fig. 10(b). Although the flow and evaporation of liquid are beneficial to the removal of slags, the efficiency of drilling decreased as a result of more heat absorbed with the higher boiling point of the liquid.

Samples usually have a higher ablation threshold and lower ablation depth in liquid than that in air. The thermal effect of laser is limited and the processed sample is cleaner by using liquid-assisted laser drilling. It is also applicable to the laser processing of silicon [64,65]. Fig. 11 shows SEM of Jiao et al. [66] using femtosecond laser drilling of silicon in air and liquid. It can be seen that the use of methanol as the auxiliary liquid greatly reduces the debris in material processing. In comparison to diameters of hole at exit side, it was found that the efficiency of drilling was higher in a liquid environment. This may be caused by the more drastic changes of plasma in liquid. The removal of debris was also affected by the bubbles generated in the liquid at a higher temperature. Although the liquid has a positive effect on the quality of laser drilling of silicon, the optimization of processing parameters is still very important. Wee et al. [67] systematically investigated effects of laser pulse frequency, fluence, scanning speed and focal plane position on machining of silicon hole in air and flowing water. Slag splashing was more severe at the higher laser pulse frequency, fluence and scanning speed in air. The laser radiation area expanded with the change of these processing parameters. The same effects on drilling of hole were observed by moving the focal plane position from negative defocus to zero. The influences of processing parameters on the taper of hole were different. Whether in air or water, taper decreased with increasing repetition frequency, but increased with increasing laser fluence. The effect of the change of the focus plane on the taper was consistent with the laser fluence. However, when processing in the air, the taper increased with the increase in scanning speed. The value of taper was almost unchanged in the water environment. Fig. 12 shows SEM of laser drilling of silicon in air and water. It was seen that compared to air, silicon holes processed in water had almost no material deposition, but the processed surface was rougher. This might be attributed to the cooling effect of medium, and the plasma generated during processing of the material. The

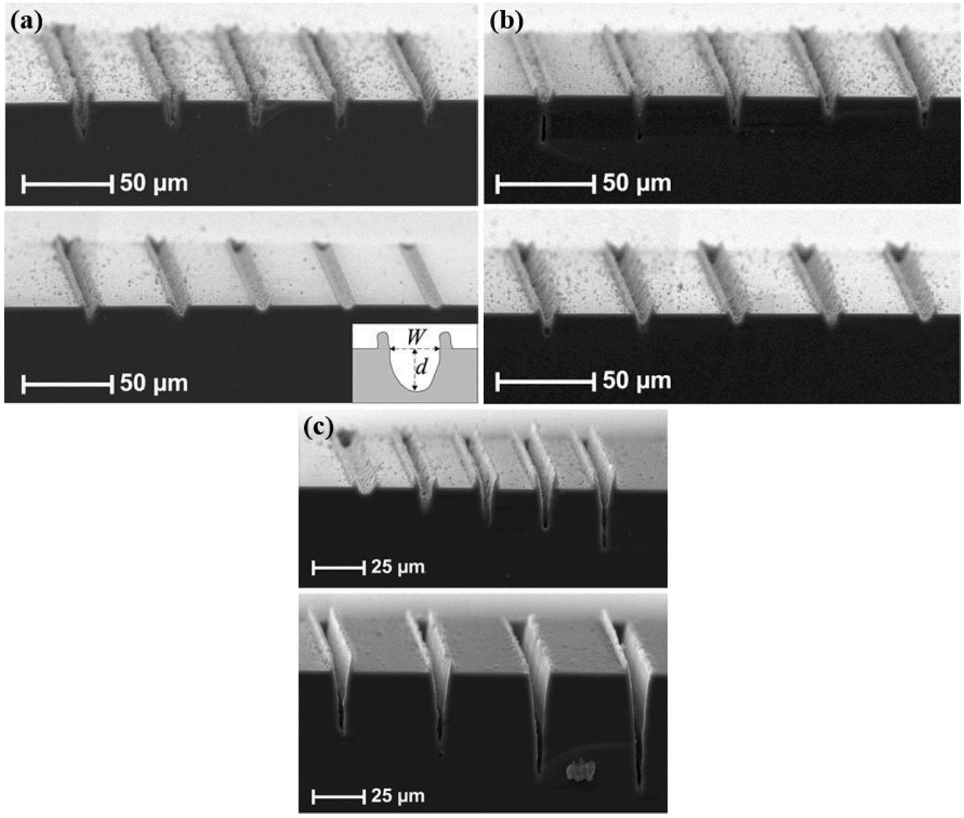

Fig. 15. SEM of groove cut with different processing parameters: (a) fluence at range from 11 J/cm^2 to 4.9 J/cm^2 (top) and from 3.9 J/cm^2 to 1.6 J/cm^2 (bottom) with single pass at 250 μm/s; (b) translation speed at range from 50 μm/s to 250 μm/s (top) and from 300 μm/s to 500 μm/s (bottom) with single pass at pulse energy of 4880 mJ/cm^2; (c) numbers of passes at range from 1 to 10 (top) and from 20 to 100 (bottom) with 500 μm/s at pulse energy of 4880 mJ/cm^2 [103].

reflectivity of laser in water was higher than that in air led to the entrance diameter of material increased. This has been confirmed by Chen et al. [68]. However, in terms of the depth of hole, the material removal rate may be reduced in water [69].

3. Laser cutting of silicon

3.1. Nanosecond laser cutting

In the drilling process, laser mainly removes along the depth direction of hole. While laser cutting is the processing of moving the laser beam laterally along the cutting surface to divide the material. In the study of Migliore [70], an elliptical beam has been proved to be more suitable for cutting silicon than circular beam. Sotnikov et al. [71] studied effects of different elliptical beam shapes on laser cutting of silicon further. In general, the cutting depth is inversely proportional to the cutting speed and directly proportional to the output power. By adjusting the spatial distribution of Gaussian elliptical beams, it was found that short elliptical beams could produce deeper grooves at higher cutting speed and lower output power. This was mainly related to the distribution of laser intensity and the overlapping degree of laser pulses. In high ellipticity, only one scanning time was needed to obtain ideal cutting quality with the elliptical beam. The elliptical distribution of laser beam was beneficial to improve the processing efficiency and save energy [72]. Mekloy et al. [73] studied the cut width, depth and morphology of laser cutting of silicon at different powers. Higher laser

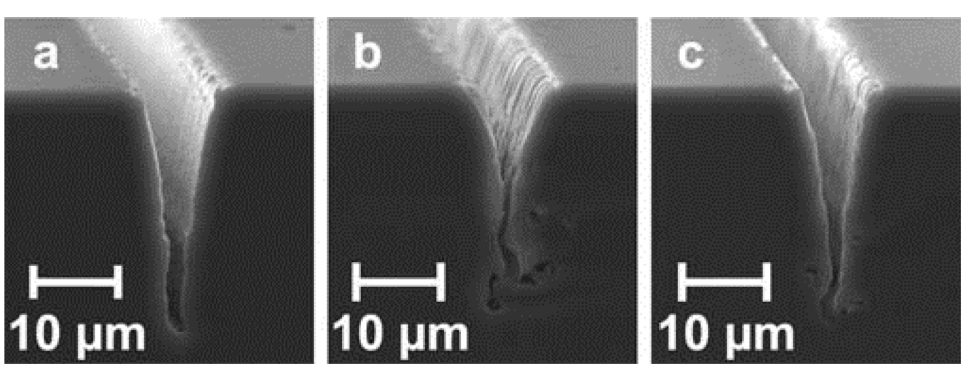

Fig. 16. SEM of the groove cut with different polarized laser: (a) linearly polarized laser, perpendicular to the translation direction; (b) linearly polarized laser, parallel to the translation direction; and (c) circularly polarized laser [103].

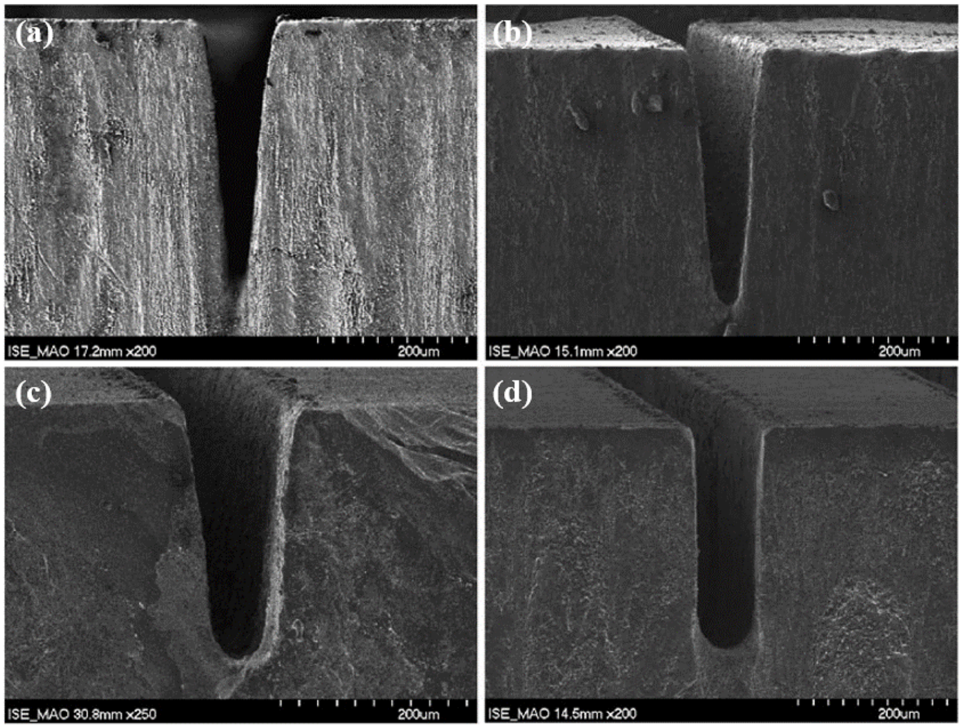

Fig. 17. SEM of groove produced with different solvents: (a) water; (b) FC-770; (c) FC-770 containing 0.02 mol Cl_2/L; (d) FC-770 containing 0.04 mol Cl_2/L [116].

power meant higher heat input in the irradiated area led to the wider and deeper kerf. Fig. 13 shows SEM of laser cutting of silicon at different power. It can be observed severer ablation and more debris of materials piled near the kerf. The surface roughness increased due to the surface damage accompanied by liquid and splash condensation after laser machining [74,75]. These are significant features of long pulse laser processing which is different from short pulse laser processing [76]. Cutting size and morphology are the key indexes to evaluate the cutting quality. This is closely related to the rational utilization of laser energy. The simulation method is used to simulate the absorption process of

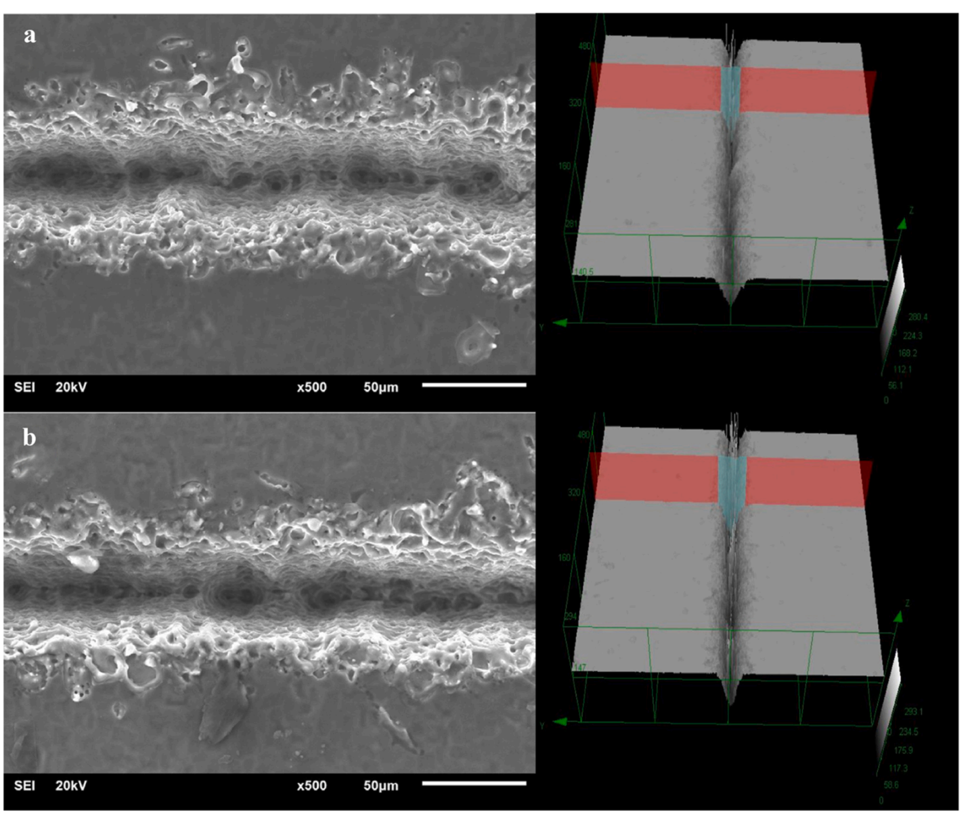

Fig. 18. Surface morphology of silicon under water flow rates of (a) 4 L/min and (b) 10 L/min [121].

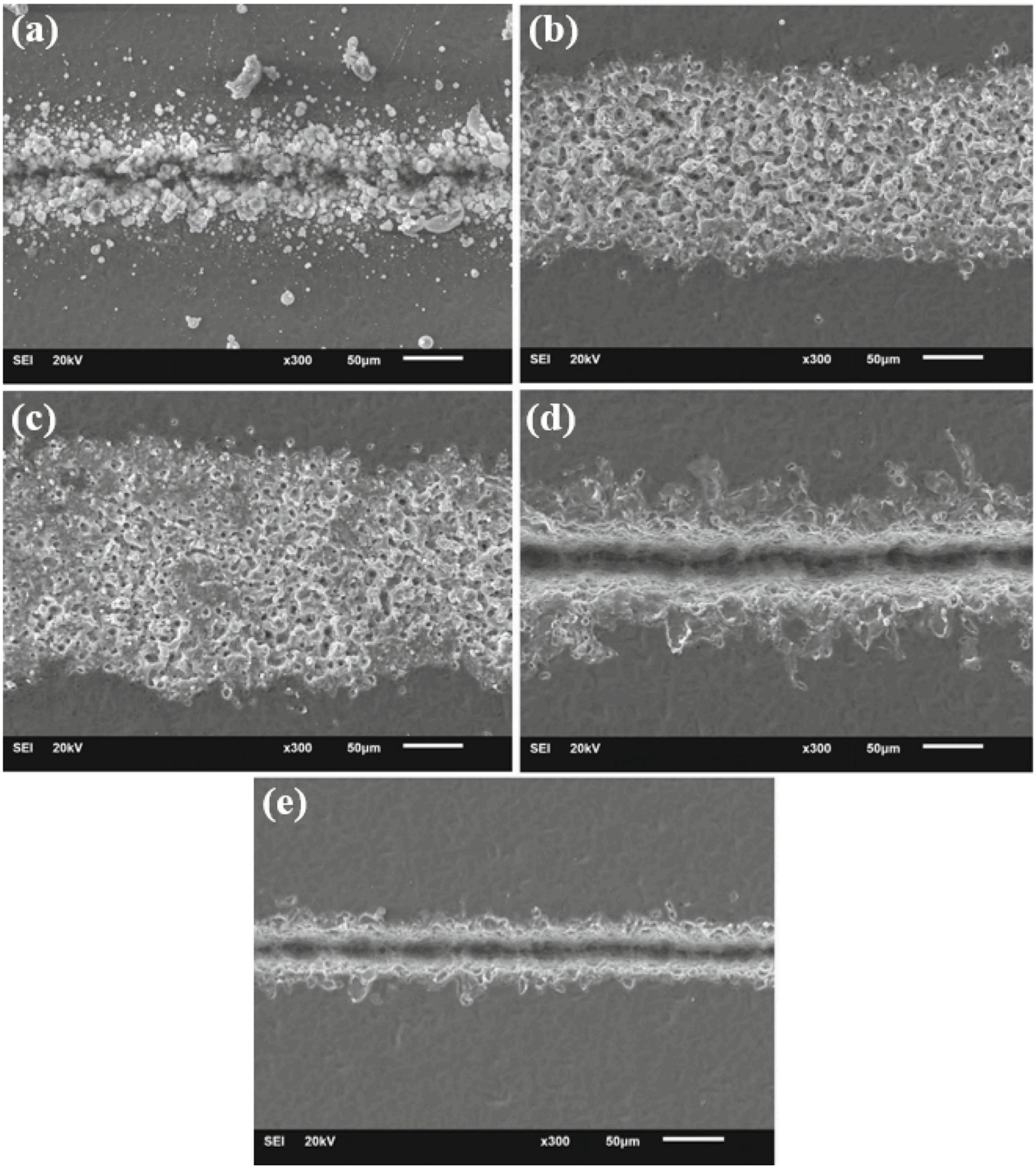

Fig. 19. SEM of silicon after laser ablation under different environment and laser pulse energy: (a) in air, 0.5 mJ; (b) in still water with an opened container, 0.5 mJ; (c) in still water with a closed container, 0.5 mJ; (d) in flowing water of 4 L/min with a closed container, 0.5 mJ; (e) in flowing water of 4 L/min with a closed container, 0.2 mJ [121].

laser induced plasma and energy, which provides a good reference for solving this problem [77].

3.2. Picosecond laser cutting

Although the pulse width of picosecond laser is much shorter than nanosecond laser, it still produces thermal effects during melting, boiling and evaporation of materials [78]. The lower peak power of picosecond laser leads to the machining quality is more sensitive to internal defects of material than femtosecond laser [79]. Ostendorf et al. [80] applied picosecond laser cutting of silicon. Fig. 14 shows SEM of silicon cut before and after cleaning. In Fig. 14(a) and (b), there was a significant ablation area on the cut surface and mainly composed of silicon dioxide. This phenomenon could also be observed in the cutting of silicon nitride [81]. Silicon can be protected to reduce or even avoid the chemical reaction by using inert gas in laser cutting [82]. These attached debris were cleaned away by using organic solvents. The quality of cutting surface was significantly better in Fig. 14(c). The ablation of material mainly occurred on the surface of the cutting channel and was easily removed by cleaning. The shape of groove was most closely related to laser fluence [83]. The adverse thermal effects of picosecond laser processing can be ignored by selecting the optimized processing parameters [84]. Haupt et al. [85] applied picosecond laser induced stress to dicing silicon. This was different from the compressive stress produced in the surface processing of silicon [86], but similar to the method of laser induced thermal crack propagation (LITP) for cutting materials. LITP would be discussed in the latter section. The material strength after picosecond laser cutting was comparable to that of

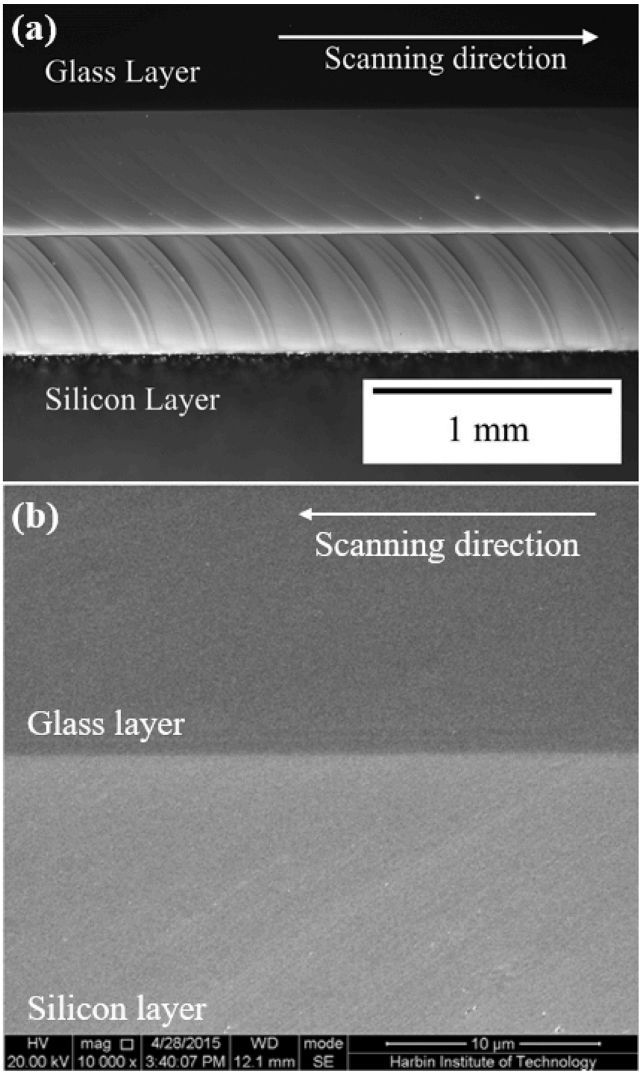

Fig. 20. Crack propagation profile (a) and SEM of the bonding condition (b) at the fracture surface [126].

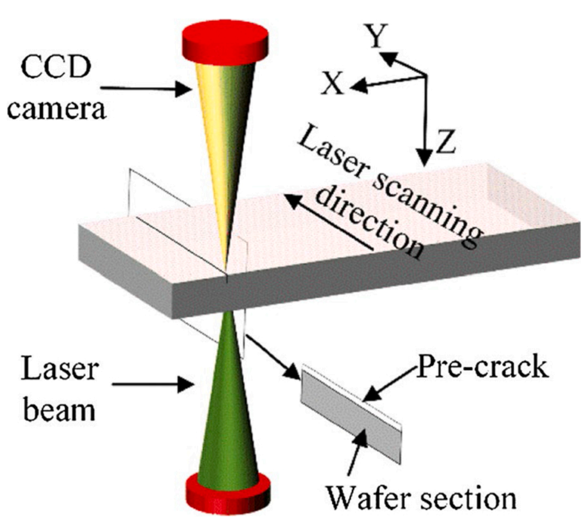

Fig. 21. The schematic diagram of LITP with pre-crack [128].

traditional blade cutting. The experimental results also indicated that picosecond laser had less damage to the processed material compared with longer pulse laser. Mur et al. [87] found that silicon changed from amorphous to crystalline state as the laser energy increased from below to above the ablation threshold. They proved that picosecond laser had the ability to control the crystallinity of silicon by tight focusing and precise control of spot position. Femtosecond laser could even form a nanocrystalline layer on the surface of silicon [88].This provides a new idea for fabricating functional structures. Although the processing morphology was significantly affected by the laser pulse width, for the spikes on silicon, the laser pulse duration was not crucial for the crystallinity of silicon [89]. In addition, picosecond laser is also suitable for glass and steel processing [90,91].

3.3. Femtosecond laser cutting

In femtosecond laser processing with higher peak power and shorter interaction time, the thermal damage is reduced greatly due to the materials are removed before the heat conduction occurs [92,93]. Femtosecond laser has the ability to process silicon parts with different shapes to meet the needs of industry. Especially in fields of semiconductor [36,94,95] and solar cell [96–98], femtosecond laser provides technical supports for manufacturing of highly integrated silicon devices. However, the high price of femtosecond laser hinders the applications. Although the processing accuracy of picosecond laser is lower than that of femtosecond laser, it has higher cost performance in the industry [99,100]. In aviation and aerospace fields, especially the thermal barrier coating parts for the turbine, femtosecond laser is still the first choice due to the advantages of the minimal thermal penetration area and higher removal accuracy [101,102]. As the basis of laser cutting, Crawford et al. [103] studied the femtosecond laser grooving of silicon. Fig. 15 shows SEM of grooved cut with different fluence (Fig. 15a), translation speed (Fig. 15b) and numbers of passes (Fig. 15c). It was found that the relationship between the groove depth and these processing parameters were different through data analysis. The groove depth was logarithmic to pulse energy and inversely proportional to translation speed. However, there was a linear growth relationship between the groove depth and the numbers of passes. The width of groove increased proportional with the increase of pulse energy, but was relatively independent of translation speed [104]. In addition to the dimensions, the groove morphology was significant affected by the polarization state of laser. Fig. 16 shows SEM of the groove cut with the different polarized laser. For linearly polarized laser parallel to the translation direction (Fig. 16b), the width of groove was narrower than that perpendicular to the translation direction (Fig. 16a). It was worth noting that there were a large number of branches at the bottom of groove. For circularly polarized laser (Fig. 16c), branches were less than that existed in Fig. 16b, but the width of groove was close to that in Fig. 16a. This meant that choosing the appropriate laser polarization state and combined with other processing parameters were essential to obtain the ideal processing quality of groove [36].

Strength of silicon affected by the periodic structures formed on the cutting surface in laser machining. Domke et al. [105] tested the backside breaking strength of silicon after laser cutting by the three-point bending method. It was found that more scanning times and lower cutting speed were conductive to obtain higher cutting quality and bending strength of silicon. This was mainly related to the type and scale of the periodic structure formed and whether the material was completely cut through. Further study demonstrated that not only the adverse thermal effects effectively reduced, but also the breaking strengths at both front and backside improved by changing the cutting paths [106]. The shorter pulse width of laser was conducive to obtain higher flexural strength of silicon due to the lower surface roughness and less ablated particles [107]. The induced stress and amorphization of silicon after ultrafast laser machining were lower than long pulse laser [108,109]. This also directly proved that laser with the shorter pulse width was more beneficial to ensure the nature of materials, even if nanoparticles were produced on the surface after ultrafast laser

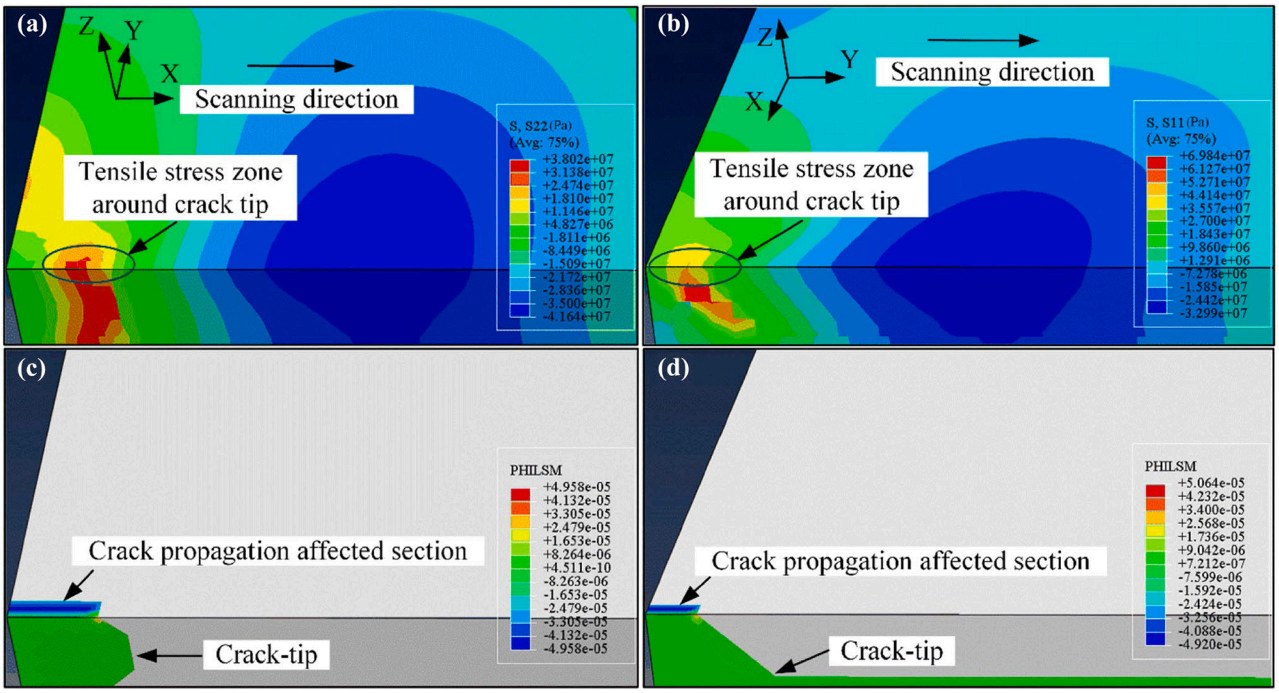

Fig. 22. Simulation of LITP (a: tensile stress distribution; c: crack propagation mode) and LITPC (b: tensile stress distribution; d: crack propagation mode) [128].

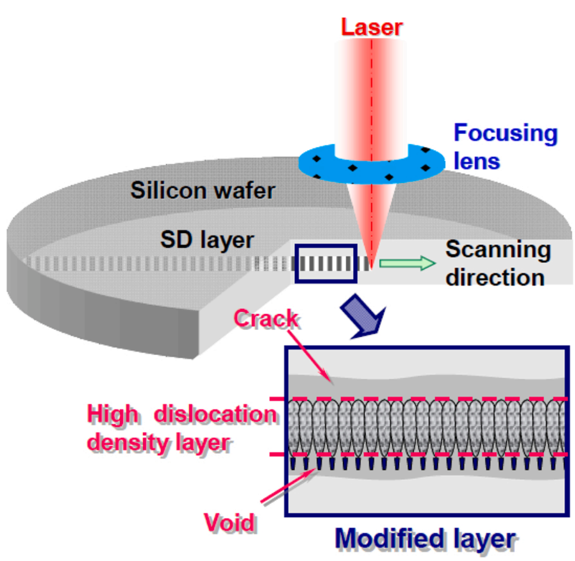

Fig. 23. The schematic diagram of laser stealth dicing (SD) [131].

machining [110]. Besides, the flexural strength of silicon after laser cutting with water drop was equivalent to blade dicing [111].

3.4. Liquid-assisted laser cutting

As mentioned earlier, liquid jet guided laser machining are rarely applied in drilling. However, it is widely used in cutting of silicon [112, 113]. This is different from the way of coaxial cutting silicon with laser and liquid jet [114]. Hopman et al. [115] found that the main process of laser cutting was the melting of silicon and then removal by liquid jet. If silicon was removed in the form of evaporation mainly, it was beneficial to cut thicker materials. Water and FC-770 were used as the liquid jet medium in the further study [116]. Fig. 17 shows SEM of groove produced with different solvents. Compared with the water medium, the groove bottom of the silicon processed in FC-770 solvent was more round. With the increase of Cl_2 content in FC-770 medium, the groove changed from V-shaped to U-shaped profile. The parallel groove walls were beneficial to reduce the loss of laser energy and material removal. Therefore, the notch of U-groove was convenient for cutting thicker materials more than silicon thin film [117]. In addition to liquid jet guided laser processing, hybrid machining with laser and water is also a good cutting technology. Tangwarodomnukun et al. [118] applied laser to soften silicon, and then the material was removed by water jet. Experimental results indicated that wider grooves were cut with higher pulse energy at closer distribution and higher pressure of water and impact angle. For the groove depth, the influences of laser pulse energy, distribution and water pressure were similar to that of groove width. However, the increase of jet impact angle would reduce the groove depth. The cutting quality was also affected by the distance between laser and water jet due to the interaction between heat and cooling sources.

Laser cutting under liquid is another typical liquid-assisted laser cutting method. Silicon can be cut seamlessly based on laser machining in liquid environment [119]. There is an optimal thickness of the liquid layer which can be obtained by detecting acoustic-wave emission [120]. The flow rate of liquid also affects the cutting quality by reducing the deposition of debris. Charee et al. [121] carried out experiments on laser cutting silicon at different liquid rates. As shown in Fig. 18, it can be observed that the higher water flow rater was more advantageous in machining the narrower groove and smaller damage zone. Fig. 19 shows SEM of silicon after laser ablation under different environments and laser pulse energy. There was a great amount of debris and obvious recast layers in air processing (Fig. 19a). The adverse effects of laser could be significantly reduced in water environment, but different processing settings still had differences. Many uncertain factors existed in laser cutting underwater, such as the reflection, refraction of light and water wave. Therefore, the ablated zone was wider in open and closed containers (Fig. 19a and b) than that in air. It was worth mentioning that the machining quality of groove was significantly improved in flowing water. The laser pulse energy was related to the groove depth and the size of damaged areas. Although the lower pulse energy had a better processing effect (Fig. 19d) than higher pulse energy (Fig. 19c). However, it was not conducive to deep groove processing. This could be

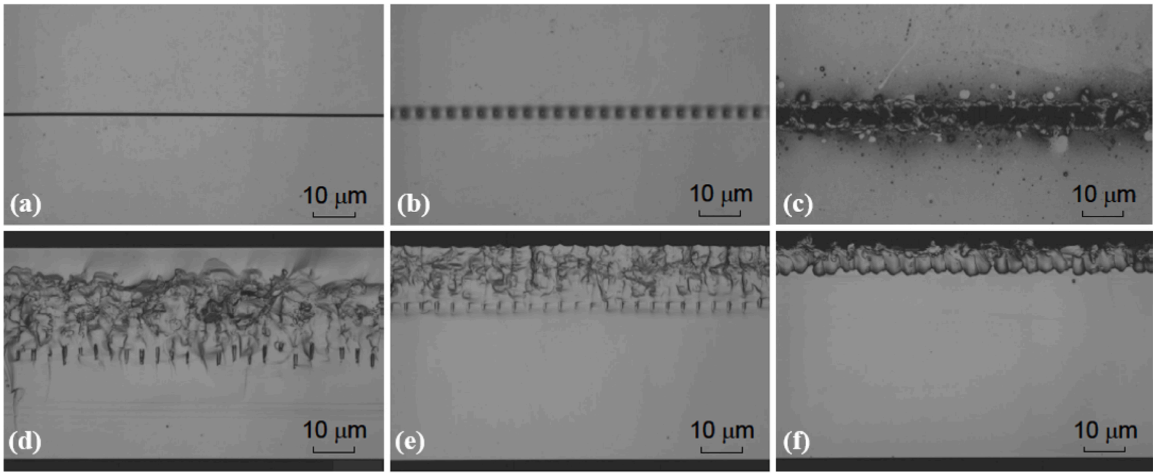

Fig. 24. Optical microscope graph of laser dicing of silicon at different focus position from the surface: (a, d) 30 μm; (d, e) 15 μm; (e, f) 0. (Top view: a, b, c; divided face: d, e, f) [140].

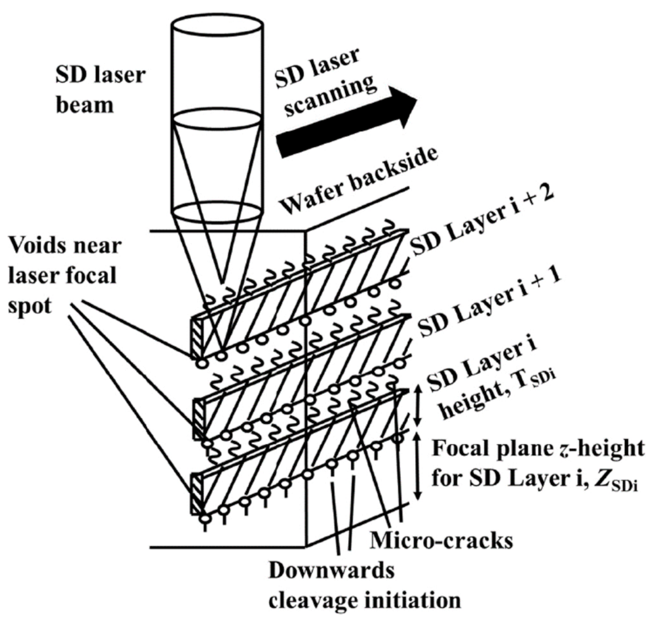

Fig. 25. Schematic of processing with multiple stealth dicing layers. (SD: Stealth dicing) [151].

effectively solved by increasing the number of cutting times. The deposition of debris and oxidation of silicon were aggravated as a result of increasing the water temperature [122]. In order to reduce the adverse thermal damage of laser, a good cooling effect can be achieved by placing silicon directly in ice layer. On the contrary, it was not conducive to cut silicon due to the removal of materials was prevented by the solids [123].

3.5. Laser induced thermal crack propagation cutting technology

Micro-cracks and other processing defects may be caused by the thermal effect in laser cutting of silicon [124]. As far as cracks are concerned, it is beneficial to cutting of materials by controlling the direction of propagation. This cutting technology is called laser induced thermal crack propagation (LITP). The mechanism of LITP is that the subsurface of silicon absorbs laser and produces stress which induces cracks to spread to the surface. Then the laser is scanned along a certain direction to complete the material cutting [125]. Cai et al. [126] applied LITP to cut silicon covered with glass. Fig. 20 shows the crack propagation profile (Fig. 20a) and SEM of the bonding condition (Fig. 20b) at the fracture surface. It can be seen that regular S-shaped ripples appear on the fracture surface and there is no debris, chipping or micro-cracks. The differences in physical properties of two-layer heterogeneous materials and the stress caused by heating were the main reasons for obtaining high cutting quality. LITP is also applicable to sandwich silicon covered with glass on both sides. Compared with the double-layer structure, an additional incident laser source is needed to machine on the top and bottom of materials [127]. During LITP, the cutting quality was affected adversely by the crack deviated from the cutting route. Cheng et al. [128] proposed a pre-crack method to ensure the unbiased propagation of cracks in laser cutting of silicon. Fig. 21 shows the schematic diagram of LITP with pre-crack (LITPC) produced by a diamond blade. Although the pre-crack was very shallow, it was sufficient to introduce material defects. Fig. 22 shows the simulation of tensile stress distribution and crack propagation mode in LITP and LITPC. In Fig. 22(a) and (b), the distribution of the maximum tensile stress near the crack tip was wider in LITP than that of in LITPC. It can be inferred that the crack growth under LITP has more uncertainty. The simulation results of crack propagation confirmed this condition. The crack tip was located in the middle of silicon and the influence area was larger in Fig. 22(c). In contrast, a corner was formed by the pre-crack and newly generated cracks, which had better propagation directivity. The cutting quality of silicon was good by using LITPC and the average surface roughness was about ten nanometers. Theoretical analysis indicated that crack propagation occurred when the stress intensity factor at the crack tip exceeded the fracture toughness of silicon. Based on this, the use of two laser beams parallel to the cutting line is expected to realize the non-thermally damaged cutting of silicon [129].

3.6. Laser stealth dicing

Stealth dicing uses a laser to pass through the surface to focus on the inside of the material and divides silicon by forming a modified layer [130]. The schematic diagram of laser stealth dicing is shown in Fig. 23 [131]. The key to realize stealth dicing is to select the laser wavelength that matches the optical properties of the material [132,133]. For surface processing, the machining quality is also affected by the laser wavelength [134]. But for stealth dicing, the appropriate wavelength directly determines whether the internal modification layer could be successfully machined. As far as silicon is concerned, the infrared wavelength of laser is preferred in stealth dicing due to the better permeability to the material.

In comparison to traditional blade dicing [135], laser singulation [136] and hybrid laser cutting technology [137–139], laser stealth

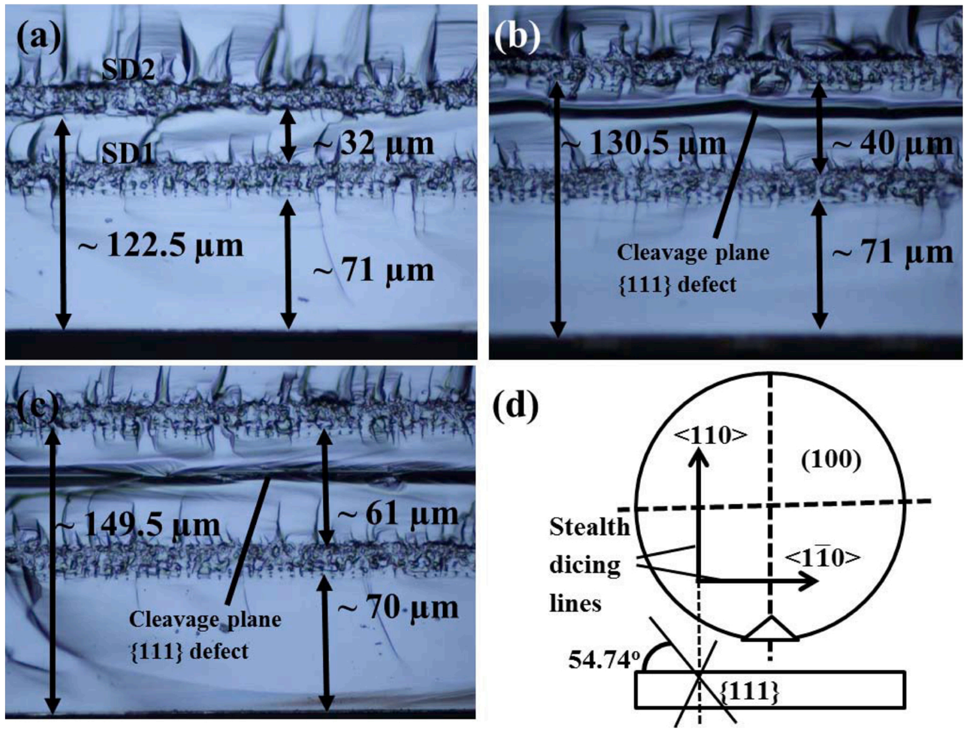

Fig. 26. Cross-section of two modified layer at different distances: (a) 32 μm; (b) 40 μm; (c) 61 μm; (d) distribution of cleavage plane [151].

dicing has great application prospects in the field of semiconductor industry. Ohmura et al. [140] processed silicon by changing the laser focus position. The experimental results are shown in Fig. 24. It was found that the focus position had a great influence on the surface and internal morphology of silicon. The requirement of stealth dicing is not only to form a modified layer inside the material, but also to reduce the surface damage as much as possible. Therefore, there was a suitable focus position (Fig. 24a and d). If the focus position was too shallow, the ablation of surface was aggravated while the modified layer was formed (Fig. 24b and e). More serious ablation of surface happened as a result of laser focused directly on the surface of silicon (Fig. 24c). In this condition, there was not exist a modified layer (Fig. 24f). The formation of the modified layer was accompanied by crack propagation, which was mainly related to the thermo-elastic-plastic behavior of silicon [141].

When laser stealth dicing of silicon, the formation of voids was found inside the material. Shimamura et al. [142] analyzed this process by molecular dynamics. Simulation results found that the temperature increased significantly in the areas of laser processing. At this time, crystalline silicon in solid state was melted to the liquid state. The volume of liquid silicon was smaller than that of crystal and proportional to the change of temperature. Therefore, voids were formed as a result of the contraction of materials at the cooling state. Tensile stress was induced by the voids in the melting region of silicon and then the voids connected to form a larger hole. After processing, the surface strength was improved by the residual compressive stress on the surface of stealth dicing [143].

It is difficult to achieve silicon dicing only by stress induced cracks for the thicker wafer. This problem can be effectively solved by multiple scanning, but it increases the processing time. Dual-focus dicing has been proved to have higher processing efficiency [144,145], but it is difficult to meet the strict dicing requirements. Spatial light modulation (SLM) technology realizes only one scanning accompany with multiple cutting paths inside silicon by distributing corresponding focus spots at different depths of material [146–148]. It is suitable for dicing thicker silicon. Moreover, the spherical aberration is compensated by SLM to obtain a better beam shape and focusing state [149,150]. Teh et al. [151] reported defect-free cutting of silicon by laser stealth dicing with multiple dicing layers (Fig. 25). In stealth dicing, not only the size of the modified layer, but also the crack propagation needed to consider. Fig. 26 shows the cross-section of two modified layers at different distances (Fig. 26a–c) and the distribution of cleavage plane (Fig. 26d). In Fig. 26a, only the modified layer can be observed. The cleavage plane appeared at the distance of over 40 μm between two modified layers in Fig. 26b and c. As shown in Fig. 26d, the V-shaped fracture was formed at the cleavage plane when the dicing tracks converged in silicon. It was important to select the appropriate cleavage plane to obtain high quality dicing. This technology has realized the near seamless dicing of silicon [152]. In addition to silicon, laser stealth dicing has been successfully applied in sapphire [153,154], quartz [155] and power device processing [156]. Laser stealth dicing combined with beam shaping technology are very promising to fabricate functional structure into materials [157,158]. For the slicing of ingot materials, laser stealth dicing technology is also expected to replace the diamond blade [159], wire saw [160] and electric discharge machining methods [161–163].

4. Summary and outlook

Laser machining technology has significant advantages in drilling and cutting of silicon. The processing quality is mainly characterized by the dimensions and surface morphology of material surface. Whether drilling or cutting of silicon, the processing quality improves from nanosecond, picosecond to femtosecond laser due to the differences in material removal mechanism. The optimization of processing parameters is very important to obtain the best processing technology. For laser drilling, the ideal hole is high circularity and low taper without heat affected zone and recast layer. For laser cutting, the angle between the two sides of groove needs to decrease to improve the cutting efficiency. It is also necessary to eliminate the adverse thermal effects of laser is similar to laser drilling, which is very difficult to realize only by optimizing processing parameters. Liquid-assisted laser machining provides an effective way to solve this problem. When processing in liquid environment, liquid can not only produce bubbles to remove debris, but also play a cooling role. Liquid-assisted machining has become a very promising way of manufacturing methods with hybrid fields. In addition to the field-assisted technology, a variety of new cutting methods emerge endlessly. Silicon can be cut by controlling the propagation path of laser induced crack. This technology is called LITP and realizes debris, chipping and cracks free cutting of silicon. Different from laser machining on the surface of materials, laser stealth dicing is to process the modified layer from the inside of silicon and then separate the wafer. Although laser stealth dicing has a good application prospect, the high requirements for optical systems limit its application to a certain extent. There are theoretical supports for a series of phenomena produced by laser processing inside silicon. The combination of simulation and processing experiments provide new ways to investigate new machining technology. At present, laser stealth dicing has only been applied to a few materials, especially silicon. The mechanism and application of laser stealth dicing of other materials still need to be further explored.

Declaration of Competing Interest

The authors report no declarations of interest.

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