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Морфология монокристаллического кремния, облученного комбинацией миллисекундных и наносекундных лазерных импульсов при изменении времени задержки между ними

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Экспериментально исследована морфология монокристаллического кремния при облучении в комбинированном режиме миллисекунд–наносекунд. Во время эксперимента были использованы прецизионный точечный термометр для мониторинга, теневой метод измерения эволюции плазмы и металлографическая микроскопия для анализа состояния объекта после эксперимента. Изучены спайность и механизмы абляции монокристаллического кремния при различных плотностях лазерной энергии и изменения временно́го взаиморасположения импульсов. Анализ показывает, что морфология лазерных повреждений при воздействии наносекундных импульсов представлена в виде небольших ямок с аккуратными краями, в то время как под действием комбинированных лазерных импульсов возникают множественные повреждения в виде трещин, включая как регулярные сколы, так и области неправильных трещин. При комбинированном воздействии миллисекундный импульс осуществляет предварительный нагрев, в результате чего изменяются теплофизические свойства монокристаллического кремния, в частности, коэффициент поглощения.

При изменении времени задержки между миллисекундным и наносекундным импульсами можно варьировать энергетическое взаимодействие между кремнием и наносекундным импульсом, влияя тем самым на эффект повреждения. Полученные данные могут служить справочным материалом по устойчивости кремниевых материалов и устройств на основе кремния к лазерным повреждениям.

Ключевые слова: *комбинированный лазер, монокристаллический кремний, температура, морфология*

Morphology of monocrystalline silicon irradiated by combination of millisecond-nanosecond lasers with different delays

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Based on the millisecond-nanosecond combined laser mode, the irradiated morphology of monocrystalline silicon was studied experimentally. During the experiment, a high-precision point thermometer was used for monitoring, a shadow method to measure plasma evolution, and a metallographic microscope to analyze after experiment were used, the cleavage and ablation law and mechanism of monocrystalline silicon were studied under different laser energy densities and delay time conditions. The analysis shows that when the combined laser acts on silicon, the millisecond laser has the effect of preheating. The preheating effect will change the thermal physical properties of monocrystalline silicon, such as the absorption coefficient. Controlling the delay time can improve the energy coupling between silicon and nanosecond laser. Changing the delay time also changes the effect of the damage.

Keywords: *combined laser, monocrystalline silicon, temperature, morphology.*

OCIS code: *140.3330*

INTRODUCTION

Monocrystalline silicon is the main material of optoelectronic devices [1], and it is also an excellent infrared window. It is often used as a substrate and filter, and plays an important role in highly integrated circuits and laser system design. The damage of monocrystalline silicon after being irradiated by laser will cause damage to the function of the device and the degradation of beam transmission quality, and even cause the failure of the entire photoelectric system. Therefore, the research on the characteristics, laws and mechanism of laser irradiated crystalline silicon is very meaningful.

At present, the research of laser-acting monocrystalline silicon is mainly focused on a single pulse width [2–3]. With the urgent needs of ablation efficiency, the mode of combined laser has been paid more and more attention by researchers [4–8]. Lehane C. *et al.* combined lasers with pulse widths of 0.15 and 3.5 ms to study the efficiency of laser drilling on stainless steel materials under different time intervals. Studies have shown that subsequent pulses will accelerate the evaporation of molten stainless steel and have a powerful effect on the solid position. Double pulses are an effective means to improve the efficiency of laser drilling [9]. Jafarabadi M.A. *et al.* used double-pulse lasers to act on metallic aluminum to study the phase explosion threshold and damage morphology. Studies have found that the phase explosion threshold is lower under the action of dual-pulse lasers, and when the laser energy density is low, the shielding effect of the plasma will affect the depth of the molten crater [10]. Lv X. *et al.* analyzed the damage threshold of monocrystalline silicon by the combined millisecond-nanosecond laser, established a two-dimensional axisymmetric thermophysical model, and studied the temperature distribution in all directions after laser irradiation [11–12].

This work adopts the laser mode of millisecond-nanosecond double pulse combination. The millisecond pulse laser has a high output energy but low power density and has a strong thermal effect on monocrystalline silicon. The nanosecond pulse laser has low energy but high peak power density. The migration of molten silicon has the effect of impact pressure. The combination can take advantages to increase the coupling efficiency of laser energy, accelerate the damage speed, improve the morphology and structure, and improve the damage efficiency.

EXPERIMENT SYSTEM

The experimental device of combined pulsed laser damage to monocrystalline silicon is shown in Fig. 1. The laser in the experiment is a product of Lei Bao. The millisecond laser is a Melar-100 Nd:YAG pulsed laser with a wavelength of 1064 nm and a pulse width of 1.0–3.0 ms adjustable. The nanosecond laser is a Vlite-300 double-pulse laser. The wavelength is 1064 nm, the pulse width is 12 ns, and the millisecond laser output is split by a spectroscope, and a part of it enters the energy meter of VEGA FL500A for energy measurement, the other part is perpendicularly incident on the surface of the silicon sample through a focal length of 500 mm focusing lens. Nanosecond pulsed laser energy is determined by taking the average of multiple offline measurements.

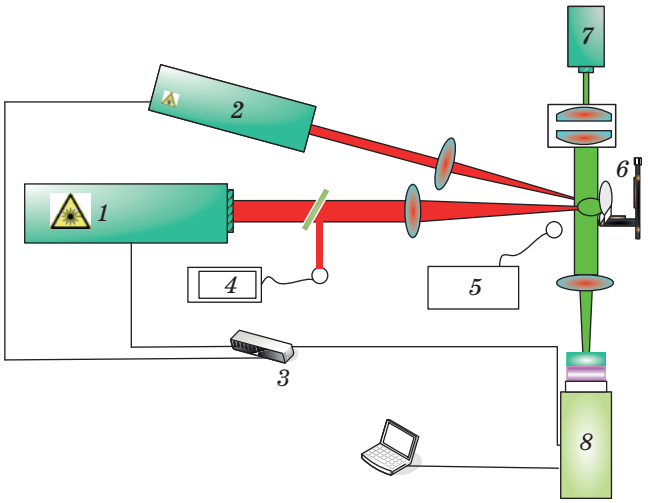


Fig. 1. Experimental system of combined pulse laser damage to monocrystalline silicon. *1* — millisecond laser, *2* — nanosecond laser, *3* — digital delay controller, *4* — energy meter, *5* — pyrometer, *6* — sillicon, *7* — semiconductor laser, *8* — high speed camera.

High-precision point thermometer KMGA 740 is used to directly measure the surface temperature of monocrystalline silicon. The semiconductor probe laser source has a wavelength of 532 nm and a line width of less than 0.7 nm. After passing through the beam expansion system, it is vertically shot into the plasma expansion zone. The high-speed camera is used to observe the combustion wave expansion changes. The high-speed camera has a frame rate of 200,000 fps and uses digital pulses. The delay generator (model DG645) is triggered synchronously with the laser. The silicon target material is clamped on a two-dimensional translation table. In the experiment, the crystal plane orientation of the monocrystalline silicon target material is (100) type, one is single-sided polishing, the radius is 12.7 mm, the thickness is 4.0 mm, and the other is for double-sided polishing, the side length square is 2.0 cm and the thickness is 0.5 mm. The experiment was carried out in an air environment, with an ambient temperature of 19 °C, a relative humidity of 30%, and an air pressure of 10^5 Pa.

RESULT ANALYSIS

The so-called combined laser uses millisecond pulse laser and nanosecond pulse laser to act on monocrystalline silicon. When the millisecond laser acts before the nanosecond laser, the delay time Δt is positive, and when it acts later than the nanosecond laser, the delay time is negative. The delay is zero when simultaneously acting. Let us study the effect of the nanosecond laser during and after the action of the millisecond pulsed laser, and analyze the temperature evolution of the center point of the laser irradiation.

Figure 2 shows the temperature evolution at the center point of monocrystalline silicon irradiated by the combined pulse laser. The nanosecond laser power density is 5.7×10^8 W/cm^2, and the millisecond laser energy density is 817.4 J/cm^2. It can be seen from Fig. 2 that

(1) With the increase of the millisecond laser action time, the temperature of the center point gradually increases, and there is no obvious deflection when the solid-liquid phase transition occurs at the melting point of about 1687 K, because the higher millisecond laser energy makes the temperature rise faster than the temperature falls, and the deflection will be submerged. When the temperature reaches the vicinity of the vaporization point, a vaporization plateau occurs. At this time, the thermal conductivity of monocrystalline silicon decreases, the heat transfer rate is slower, and the duration becomes longer.

(2) At the moment of nanosecond laser input, there will be a sharp peak on the temperature

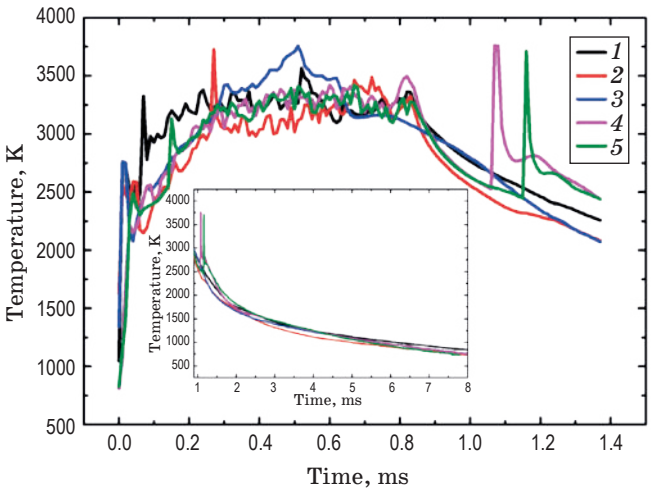


Fig. 2. Temperature evolution of silicon center point irradiated by combined pulse laser. The nanosecond laser power density is 5.7×10^8 W/cm^2, the millisecond laser energy density is 817.4 J/cm^2. *1* — $\Delta t = 0.1$ ms, *2* — $\Delta t = 0.3$ ms, *3* — $\Delta t = 0.7$ ms, *4* — $\Delta t = 1.1$ ms, *5* — $\Delta t = 1.2$ ms.

evolution curve. The power density of nanosecond laser is relatively high, and the temperature of the target material increases rapidly after absorbing energy. The peak temperature will increase with the increase of nanosecond laser energy. Delay time is also a factor affecting the peak temperature. The delay time determines the initial temperature and performance of the target when the nanosecond laser is input. The peak temperature will increase with the increase of the initial temperature. When the nanosecond laser stops working, the temperature drops rapidly. Although the millisecond laser continues to work, the working conditions of the nanosecond laser cannot be maintained. Energy is transferred from the center to the outside, and a new thermal balance is gradually established.

(3) When the delay time is greater than the millisecond pulse width, it is equivalent to the single millisecond action before the nanosecond action. The nanosecond injection time is within the millisecond pulse width time, which belongs to the double pulse combined action. Although the temperature will drop after the nanosecond laser is applied, it will also increase the temperature curve. Therefore, when the pulse delay is greater than the millisecond pulse width, the overall temperature curve of the vaporization platform will decrease. If the millisecond laser is used alone, this phenomena is more pronounced when the generated temperature is between the melting point and the vaporization point.

(4) After the action of the combined pulsed laser is finished, because there is no energy injection, it is in the thermal diffusion stage, and the temperature drops rapidly. It is found that when the delay time is greater than the millisecond pulse width of 1.0 ms, the faster the temperature drops. At this time, the millisecond laser has stopped, and the nanosecond laser has broken the original temperature balance. The molten silicon surface is subjected to impact force, which accelerates the heat dissipation and heat dissipation. The effect of heat convection makes the speed drop faster.

Figure 3 shows the changes in the ablation morphology of monocrystalline silicon under different delay conditions, including three cases where the delay of the two beams is 0.0 ms, the delay is within the millisecond pulse width, and the delay is after the millisecond pulse width. The millisecond laser energy density is 227.0 J/cm^2, and the nanosecond laser power density is 2.0×10^9 W/cm^2. Under different delay conditions, the damage morphology of monocrystalline silicon irradiated by the combined laser is significantly different.

(1) When the millisecond and nanosecond lasers act at the same time, they only appear as the superposition of the energy of the two beams, which act together on the silicon wafer at room temperature. After the silicon wafer absorbs energy, the temperature rises, and the heat transfers out of the spot to generate a temperature gradient, causing brittleness crack growth and local peeling of the surface. The millisecond laser action time is much longer than the nanosecond laser, so the damage is mainly thermal ablation.

(2) As the delay increases, and within the millisecond pulse width, the millisecond laser acts before the nanosecond laser and has a preheating effect on the target. With different delays, the injection time of the nanosecond laser is different, the reached temperature of the preheated and material properties are different. When the delay is 0.2 ms, the monocrystalline silicon does not reach the melting point and no molten liquid is produced on the silicon surface. Nanosecond laser injection is equivalent to irradiating a silicon wafer with a certain temperature distribution. The preheating of the laser increases the absorption coefficient of the silicon material, which enhances the absorption of nanosecond laser energy and improves the coupling rate of the laser energy and the material.

(3) When the delay time is 0.4–1.0 ms, and the preheating of the millisecond laser has made the silicon target material reach the melting point, the phase transition area becomes larger, and the damage area increases. With the increase of delay time, the increase of the melting depth causes the increase of the liquid silicon in the molten pool. When the nanosecond laser is injected, the impact force of the nanosecond laser causes the liquid silicon to spray and flow, and there will be splashes on the edge of the damaged area. Under the action of gravity and surface tension, the liquid silicon flows back into the molten pool, and there will be partially solidified silicon at the edge. The surface splash is the most serious when the pulse delay is 0.8 ms. Considering that this is related to the millisecond pulse width, after 0.8 ms, it is almost the end of the millisecond pulse width. The laser energy in the subsequent milli-

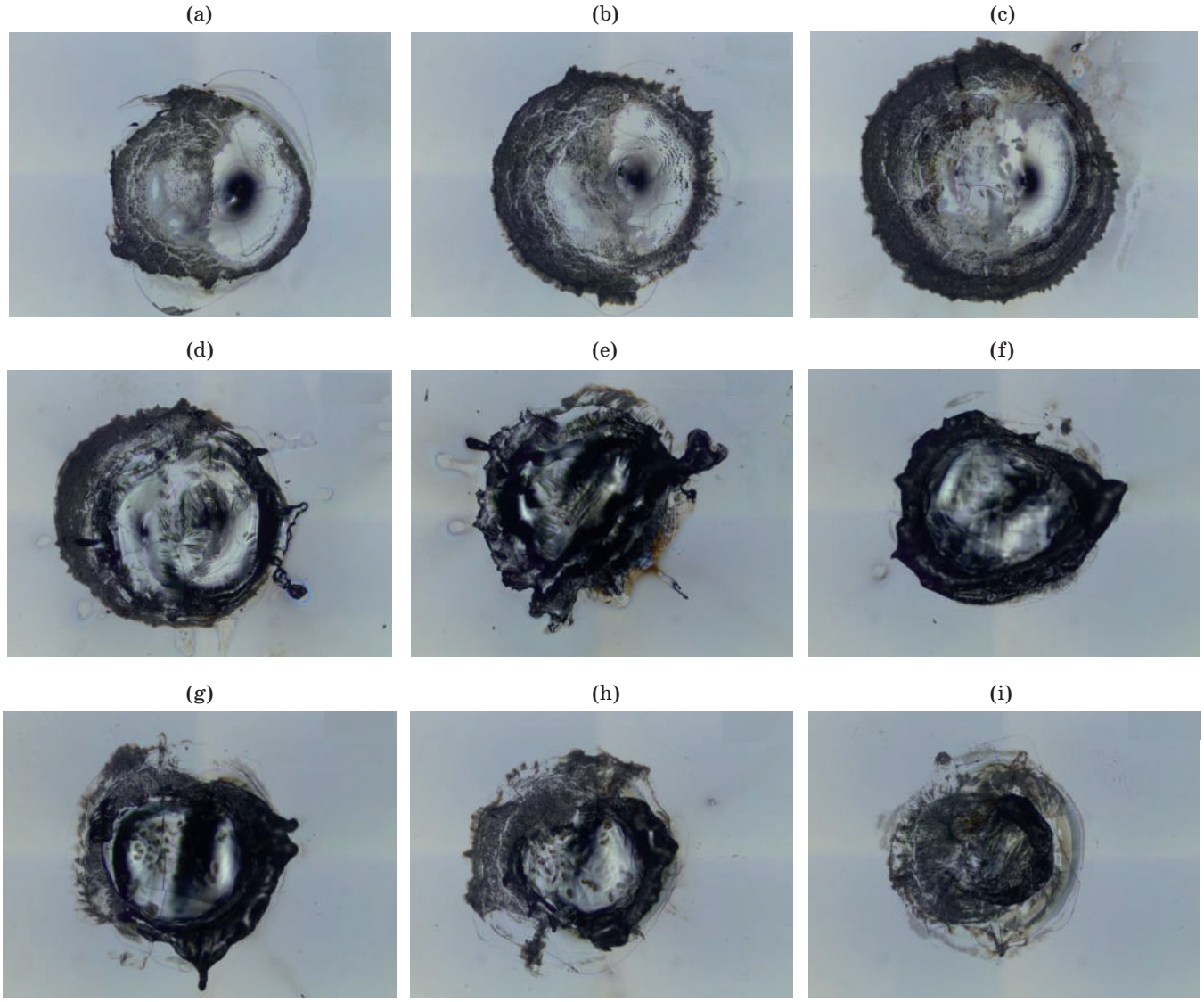


Fig. 3. Damage morphology under different delay time conditions. The millisecond laser energy density is 227.0 J/cm^2, the nanosecond laser power density is 2.0×10^9 W/cm^2. (a) 0.0 ms, (b) 0.2 ms, (c) 0.4 ms, (d) 0.6 ms, (e) 0.8 ms, (f) 1.0 ms, (g) 1.4 ms, (h) 1.8 ms, (i) 2.4 ms.

seconds has been significantly reduced, and the ablation slows down.

(4) When the delay is greater than the millisecond pulse width, the millisecond laser stops working at this time, and the damage area is smaller than when the nanosecond laser is input within the millisecond pulse width. Nanosecond laser has very short action time, low energy and higher power density. It mainly plays a role in ablation and impact. When the delay is 1.8 and 2.4 ms, the silicon target has been cured and has a certain temperature. The surface morphology is irregular, and the ablation is further aggravated on this basis.

Figure 4 shows the evolution of combustion waves induced by combined lasers with different delays in monocrystalline silicon. The laser parameters are the same as in Fig. 3. When the delay time is 0.0 ms, the millisecond and nanosecond lasers act at the same time, and plasma is generated instantaneously. At 0.5 μs, the plasma expands to form a combustion wave. The combustion wave front moves against the direction of laser transmission. The millisecond laser works continuously within 35 μs, but the laser energy density is low, only maintaining plasma near the silicon surface, and the expansion distance is short. The nanosecond laser has

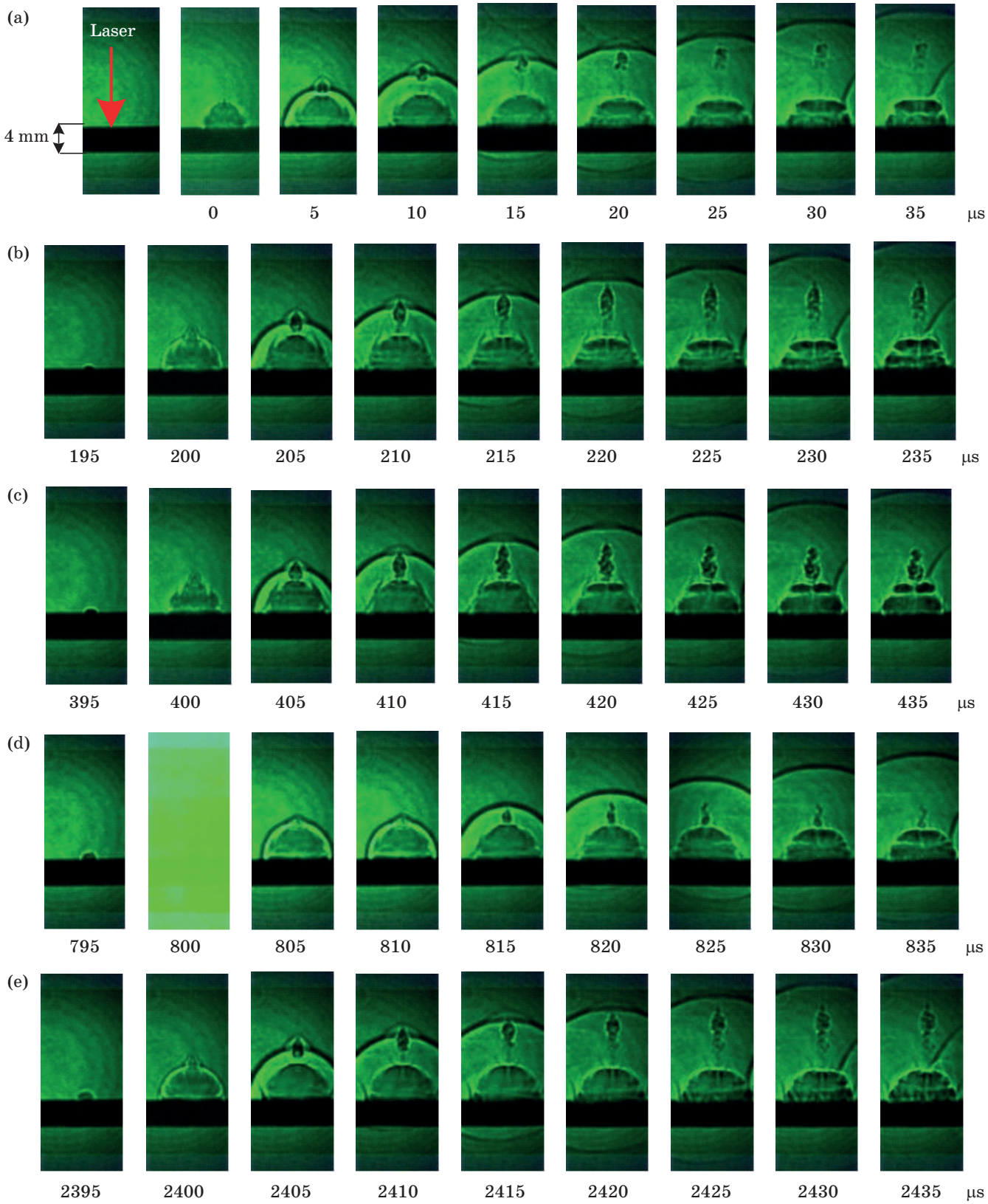


Fig. 4. Expansion and evolution of combustion waves induced by combination laser. The millisecond laser energy density is 227.0 J/cm^2, the nanosecond laser power density is 2.0×10^9 W/cm^2. (a) $\Delta t = 0.0$ ms, (b) $\Delta t = 0.2$ ms, (c) $\Delta t = 0.4$ ms, (d) $\Delta t = 0.8$ ms, (e) $\Delta t = 2.4$ ms.

a higher power density, and after the plasma is generated, it expands rapidly, forming a combustion wave that moves forward. When the delay time is 0.2 and 0.4 ms, due to the preheating effect of the millisecond laser, the amount of plasma induced by the silicon target increases, and the expansion speed and expansion distance become larger. When the delay is 0.8 ms, the nanosecond laser induces a small amount of plasma, and the expansion speed is the smallest. Because at the moment of nanosecond laser injection, the silicon target has melted and there is a large amount of liquid silicon on the surface. Part of the energy of the nanosecond laser will be lost through convection diffusion, and part of the energy will be converted into the kinetic energy of liquid silicon splashing, which induces the silicon to generate plasma. Energy becomes smaller. When the delay time is 2.4 ms, the plasma expansion state is similar to that when the delay time is 0.2 ms, indicating that the solidification of the molten silicon is basically completed.

The nanosecond laser power density is 2.0×10^9 W/cm^2, and the millisecond laser energy is 227.0 and 390.2 J/cm^2. It can be seen from Fig. 5 that as delay time increases, the monocrystalline silicon damage area first increases and then decreases, and the amount of change is small after about 2.0 ms. Under the combination, the damage area reaches the peak value when the delay is 0.4 ms. After measurement, at 0.4 ms, the temperature at the center point of laser irradiation is about to reach the melting point of monocrystalline silicon. Although no melting occurs, the thermal physical properties of the silicon target have been changed. The internal thermal movement of monocrystalline silicon is intense, the energy of the millisecond laser is mainly used for surface heating, and the thermal diffusion depth is not large. At this moment, nanosecond laser is injected, and the silicon target material instantaneously melts and vaporizes, and the surface layer damage range is large. After a delay of 2.0 ms, the monocrystalline silicon has basically been cured, and when the nanosecond laser is applied again, there is little difference in damage morphology.

The nanosecond laser power density is 1.2×10^9 W/cm^2, and the millisecond laser energy density is 342.0 J/cm^2. It can be seen from Fig. 6 that the morphological damage from exposure to the combined laser radiation is more severe

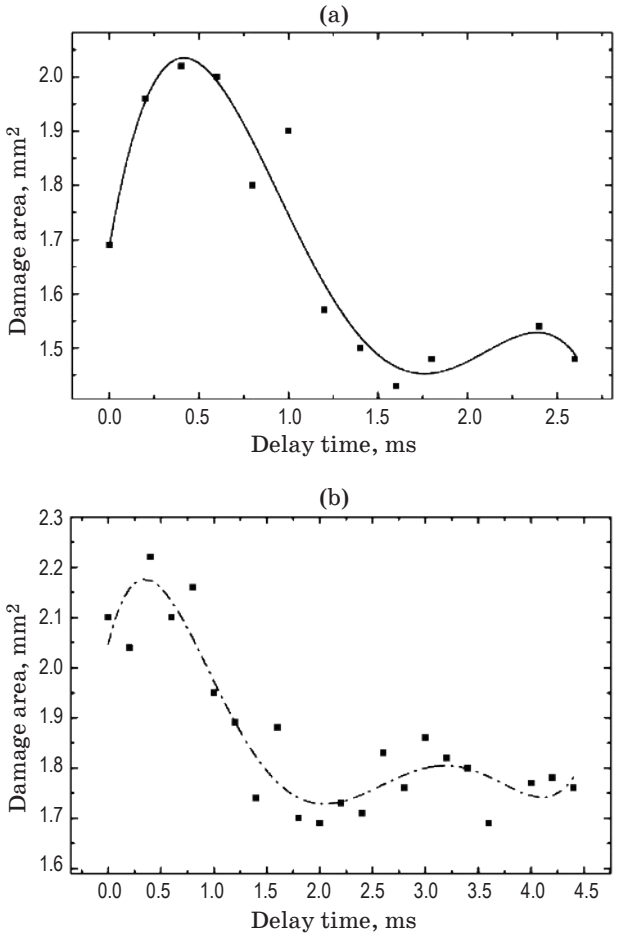


Fig. 5. Damage area of monocrystalline silicon changes with delay time. The nanosecond laser power density is 2.0×10^9 W/cm^2. (a) $I_{ms} = 227.0$ J/cm^2, (b) $I_{ms} = 390.2$ J/cm^2.

than from the effect of only single nanosecond laser alone, and the morphological characteristics are also different. The nanosecond laser has a higher power density, and the energy is quickly deposited on the surface of the target to cause ablation. The appearance is small ablation pits and the edges are clean. Because the nanosecond laser is incident at an oblique angle, the spot is not regular circular. When combined laser action, for the same total energy, the delay has a significant effect on the damage morphology. Obvious 90° cleavage cracks appear when the delay time is 0.1 ms, mainly because the crystal orientation of the silicon surface is (100). As the time delay increases, the erosion and splash damage increases, and when the time delay is less than 0.4 ms or greater than 1.0 ms, in addition to ablation damage, there are more fracture damage areas.

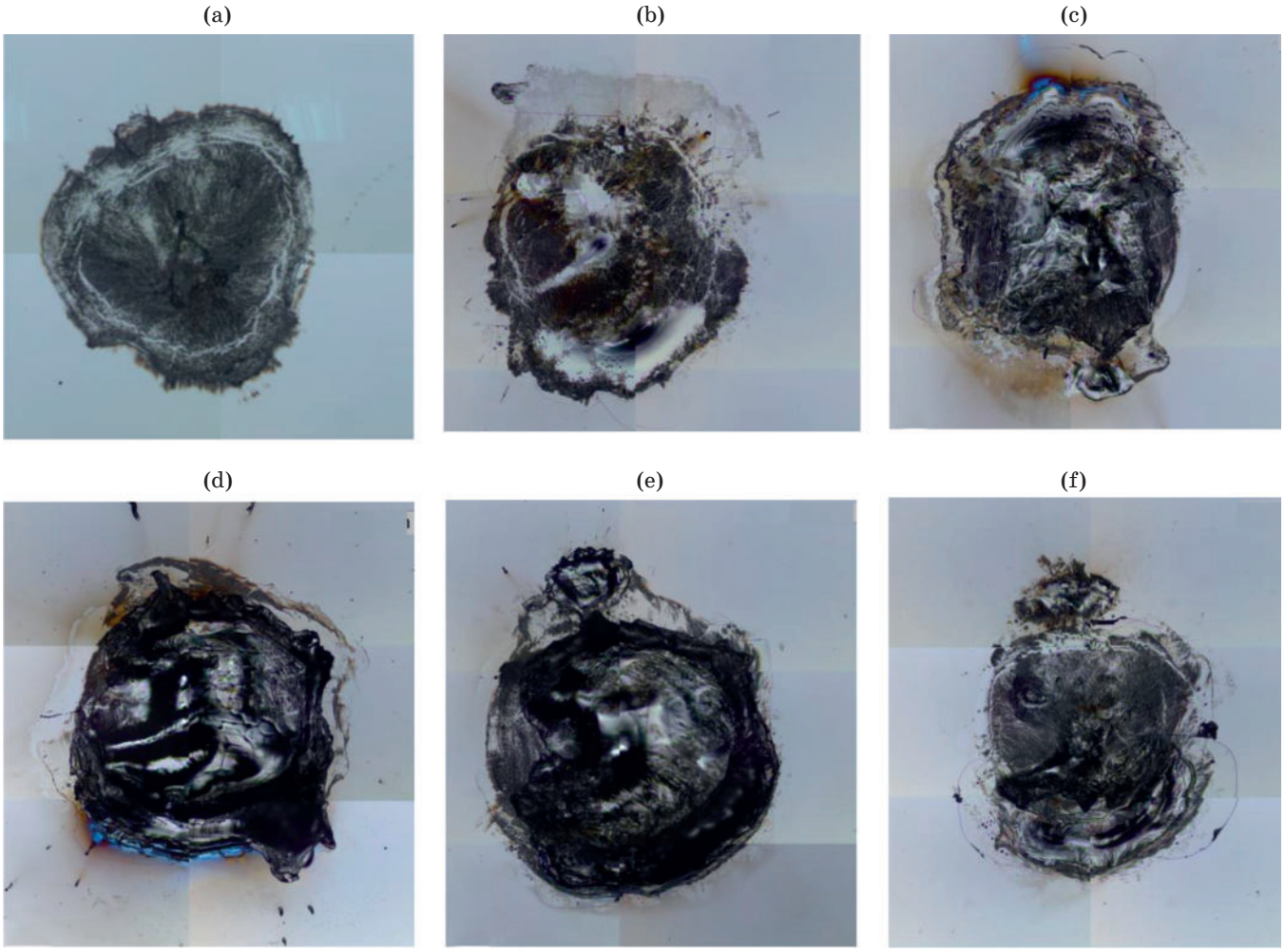


Fig. 6. Comparison of damage morphology between nanosecond laser and combined laser. The nanosecond laser power density is 1.2×10^9 W/cm^2, the millisecond laser energy density is 342.0 J/cm^2. (a) single nanosecond, (b) $\Delta t = 0.1$ ms, (c) $\Delta t = 0.4$ ms, (d) $\Delta t = 0.8$ ms, (e) $\Delta t = 1.0$ ms, (f) $\Delta t = 1.3$ ms.

The millisecond laser energy density is 342.0 J/cm^2. Figure 7 shows the effect of nanosecond laser energy density on the combined laser damage morphology. The nanosecond power density of Figs. 7(a–c) is 1.0×10^9 W/cm^2 and Figs. 7(d–f) is 1.2×10^9 W/cm^2. As the energy density of the nanosecond laser increases, the ablation damage increases. The statistics of 99 damaged silicon wafers with time delays of −0.1, 0.0, and 0.1 ms, 55 wafers showed peeling morphology, and the peeling morphology acquisition rate reached 55.6%. Counting 275 silicon wafers with a delay of 0.2–1.3 ms (interval 0.1 ms), 69 damaged silicon wafers have peeled off, and the peeling morphology acquisition rate is 25.0%. When the pulse delay is extremely short or acts simultaneously, the silicon at room temperature is momentarily subjected to a large impact force to cause brittle fracture, and the crack extension causes local peeling. As the pulse delay increases, when the preheated silicon is irradiated by the nanosecond laser, the laser energy is more likely to aggravate thermal ablation and splashing through the convection of the molten silicon.

Figure 8 shows the relationship between the single crystal damage area and the nanosecond laser energy density when the millisecond laser energy density is 734.3 J/cm^2. With a fixed millisecond laser energy, the damage area of monocrystalline silicon increases with the increase of nanosecond laser energy density. When the nanosecond laser power density is below 8.3×10^8 W/cm^2, the damage area increases gently, and when the energy density is greater than the energy density, the damage area increases rapidly. As the nanosecond energy in-

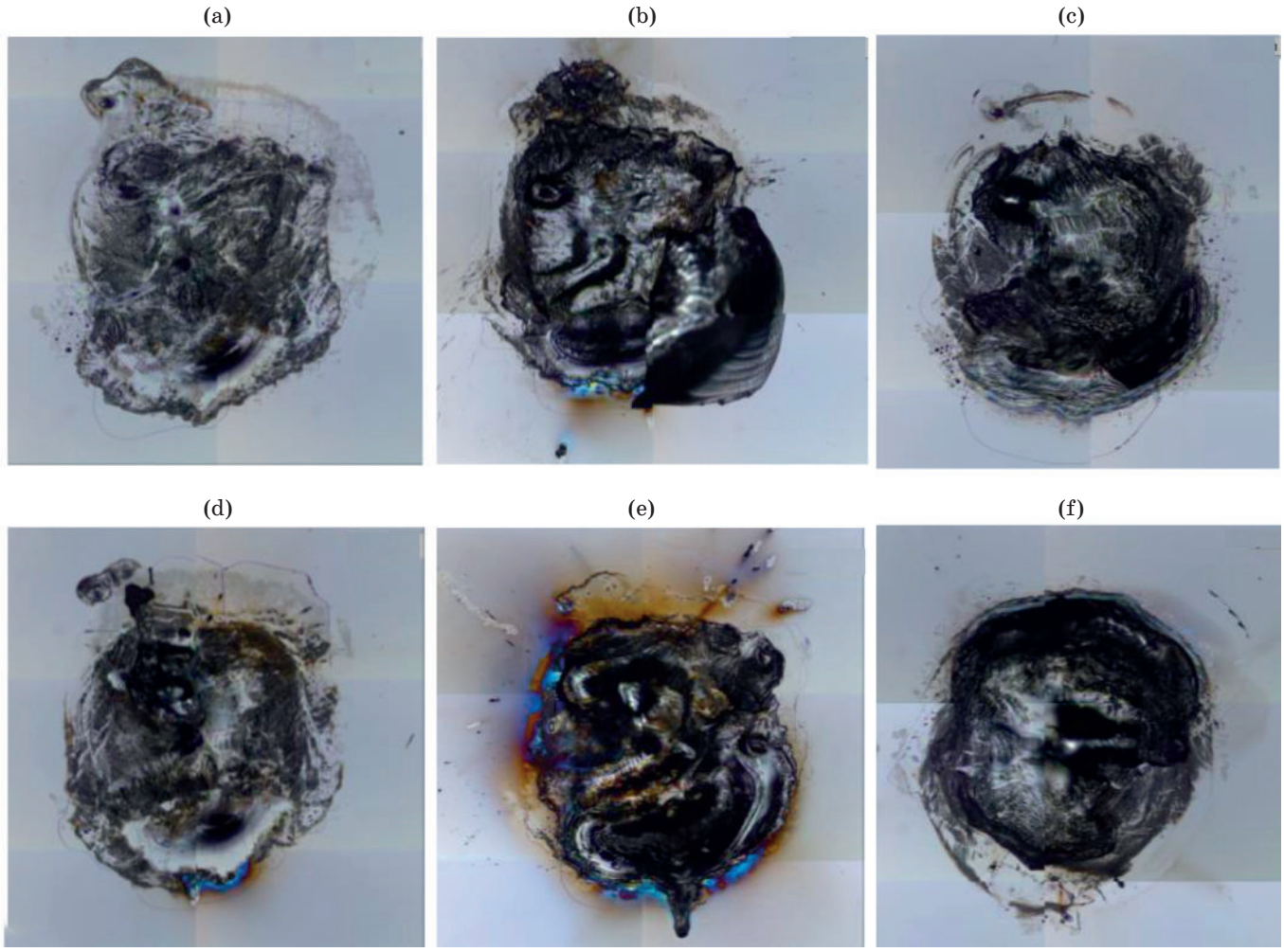


Fig. 7. Combined laser damage morphology of nanosecond lasers with different energy densities. The millisecond laser energy density is 342.0 J/cm^2. (a) $\Delta t = 0.2$ ms, (b) $\Delta t = 0.7$ ms, (c) $\Delta t = 1.2$ ms, (d) $\Delta t = 0.2$ ms, (e) $\Delta t = 0.7$ ms, (f) $\Delta t = 1.2$ ms. The nanosecond power density of (a–c) is 1.0×10^9 W/cm^2 and (d–f) is 1.2×10^9 W/cm^2.

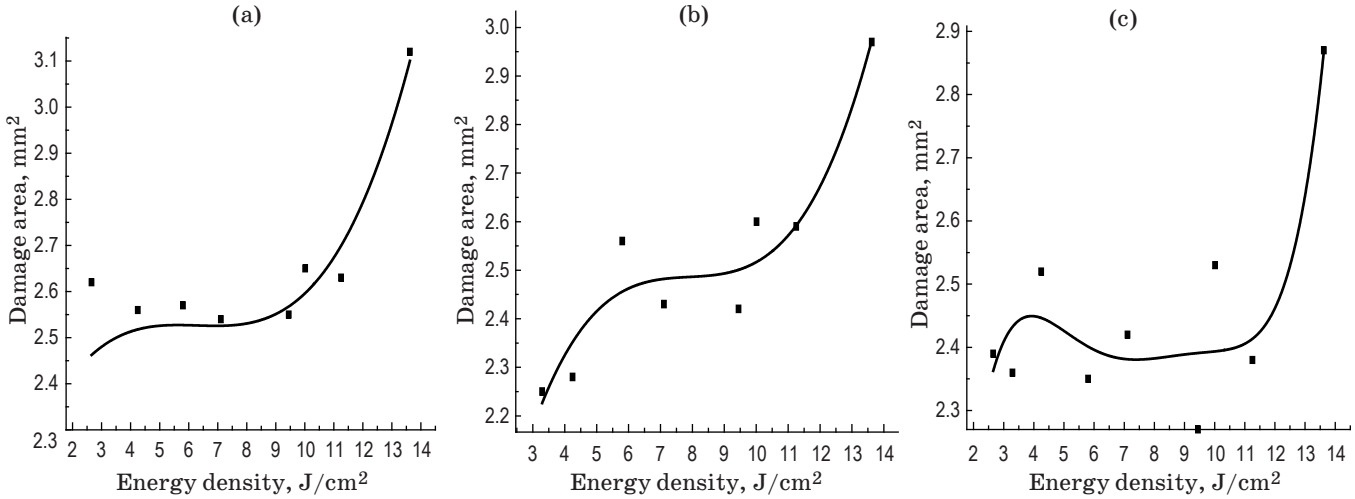


Fig. 8. The damage area varies with the energy density of nanosecond laser. The millisecond laser energy density is 734.3 J/cm^2. (a) $\Delta t = 0.4$ ms, (b) $\Delta t = 0.7$ ms, (c) $\Delta t = 1.0$ ms.

creases, the thermal diffusion radius increases, thereby increasing the damage area. With the energy density of the millisecond laser and nanosecond laser fixed, the damage area decreases with the increase of delay time.

CONCLUSIONS

In this article, the morphology of monocrystalline silicon was experimentally studied using a millisecond-nanosecond combined laser, the mechanism of damage of various morphologies was analyzed, and the influence of damage morphology, laser energy density, power density and delay time on the damage effect were investigated. When combined with the laser function, the millisecond laser has the effect of preheating, and the preheating effect will change the physical characteristic parameters such as the absorption coefficient of monocrystalline silicon, and improve the energy coupling rate of the nanosecond laser. When the time delay is greater than zero, the millisecond laser preheats the monocrystalline silicon. When the millisecond laser preheating temperature reaches near the melting point, the damage area is the largest when the nanosecond pulse laser is injected. When the nanosecond laser is injected in the millisecond pulse width, the peak temperature of the monocrystalline silicon increases with the increase of the delay time. When the delay time is 1.4 ms, the thermal diffusion and convection increase the temperature drop rate of the monocrystalline silicon. When the delay time is around 0.8 ms, there is a large amount of liquid silicon in the molten pool, the surface splashing is the most serious, the induced plasma volume is small, and the expansion speed of the combustion wave is reduced. The exfoliation morphology acquisition rate of the combined laser in the delay time from −0.1 to 0.1 ms (interval 0.1 ms) is about 2.2 times that of the delay time 0.2–1.3 ms (interval 0.1 ms). The combined laser energy density is fixed, and the damage area is the peak value when the delay is 0.4 ms. When the energy density of the nanosecond laser is increased, the thermal diffusion radius becomes larger and the damage area increases.

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