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Article

A Study of Polycrystalline Silicon Damage Features Based on Nanosecond Pulse Laser Irradiation with Different Wavelength Effects

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Abstract:Based on PVDF (piezoelectric sensing techniques), this paper attempts to study the propagation law of shock waves in brittle materials during the process of three-wavelength laser irradiation of polysilicon, and discusses the formation mechanism of thermal shock failure. The experimental results show that the vapor pressure effect and the plasma pressure effect in the process of pulsed laser irradiation lead to the splashing of high temperature and high density melt. With the decrease of the laser wavelength, the laser breakdown threshold decreases and the shock wave is weakened. Because of pressure effect of the laser shock, the brittle fracture zone is at the edge of the irradiated area. The surface tension gradient and surface shear wave caused by the surface wave are the result of coherent coupling between optical and thermodynamics. The average propagation velocity of laser shock wave in polysilicon is 8.47×10^3m/s, andthe experiment hasreached the conclusion that the lasershock wave pressure peak exponentially distributes attenuation in the polysilicon.

Keywords: laser wavelength; polysilicon; laser damage; thermal shock

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1. Introduction

PVDF piezoelectric sensor, which has developed in recent years with its high response frequency (ns level) and above 20GPa pressure measurement range, is an ideal test component of laser shock wave [1]. Researchers have successively measured the attenuation law of laser shock wave in the solid target, shock wave velocity and stress wave waveform [2]. Silicon materials are excellent optical materials, usually used in the filter and substrate materials of optical systems, and they are widely applied in the microelectronics industry, optoelectronic industry and other fields. Because the band width of silicon materials is narrower than other materials (1.12eV at 300 K), they have a large intrinsic absorption of the infrared band laser. Meanwhile, they are brittle materials with a narrow plastic region, so they are prone to be damaged in the infrared wavelength of strong light irradiation [3]. Hsin-Chien Chen et al. [4] used laser to etch microchannels on the surface of polysilicon to increase photoelectric conversion efficiency of polysilicon solar cells. The results show that the efficiency of polysilicon solar cells and microchannels is increased by 0.23-1.50%. The fill factor of microchannelscan also improves Polycrystalline silicon solar cells. D.M. Karnakis et al [5] used nanosecond Nd: YAG at 355nm high-intensity laser etching of monocrystalline silicon. The results show that the abnormally high etching depth is observed on the silicon surface when the intensity of the incident laser exceeds a certain threshold. Mainly due to high-intensity laser explosive boiling mechanism with the secondary heating of the plasma, the laser energy change and come up with two different erosion mechanisms. L.A. Dobrza'nski et al [6] used the wavelength of 1064nm laser to treat the micro-texture of the solar polysilicon surface, which improved the solar cell trapping, effectively reduced the reflectivity and improved the efficiency of solar cells. R. Kumar et al [7] studied the microstructure evolution of silicon surface by laser etching. Therefore, it is of great practical significance to study the damage mechanism of silicon with different wavelengths.

2. Theoretical Analysis of Thermodynamic Effects of Polycrystalline Silicon Irradiated by Single Pulse Laser

2.1 Analysis of Vapor Pressure Effect

When the laser is irradiated to the surface of polysilicon, the laser is absorbed strongly. When the time waveform of output laser is Gaussian, the change of temperature rise with pulse time can be described as follows:

$$T(x,t)=\frac{2AI_0}{k}\sqrt{Dt}\,ierfc(\frac{x}{2\sqrt{Dt}}),t<t_p \tag{1}$$

When the pulse is completed, the temperature rise equation is:

$$T(x,t)=\frac{2AI_0}{k}\left\{\sqrt{Dt}\,ierfc(\frac{x}{2\sqrt{Dt}})-\sqrt{D(t-t_p)}\,ierfc[\frac{x}{2\sqrt{D(t-t_p)}}]\right\},t\geq t_p \tag{2}$$

When the laser is continuously irradiated to polycrystalline silicon, the surface temperature rises to the evaporation temperature of the target, which will build up pressure on the target as the target material evaporates. Assuming that the $p_v(T_s)$ temperature is the equilibrium vapor pressure, the expression is expressed as [9]:

$$p_v(T_s)=P_\infty\exp[\frac{L_v}{k_BT_s}(\frac{T_s}{T_b}-1)] \tag{3}$$

wherein T_s - target surface temperature, T_b -boiling point temperature, p_∞ -equilibrium vapor pressure at T_b temperature, L_v -latent heat of vaporization, k_B - Boltzmann constant. It is obviously that target surface vapor pressure is related to temperature, and it is a function of temperature.

2.2 Plasma Shock Wave Pressure Effect

Plasma generation occurs when a pulsed laser is irradiated on a target, which includes a plasma flash and a plasma blast process to produce a shock wave [10]. Plasma shock wave propagates against the incident direction in the form of ultrasound, which will have a certain pressure effect on irradiated area of the target. According to Phipps's pressure load analysis formula, we can get the pressure formula of the plasma shock wave on the surface of laser target area [11]:

$$P=bI(I\lambda\sqrt{\tau})^n \tag{4}$$

In the formula, $\lambda(nm)$ is the laser wavelength, $I_a(GW/cm^2)$ is the laser power density, $\tau(ns)$ is the laser pulse width, and b is the parameter determined for the material n=-0.3，b=5[12].

3. Experimental Equipment and Methods

The experiment uses the polysilicon sample of 30 mm×30 mm×0.25 mm, and removes oil on the sample surface with acetone, clean it with ethanol, and dry it with cold air. Taking the effect of laser thermal effects into account, according to the literature [13] on temperature and location relationship of laser ablation silicon material, when the temperature at a depth of 1.0×10^{-6}m is 300K, its thermal

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impact on PVDF can be ignored. The target surface has no absorbing and constrained layers, but PVDF piezoelectric sensors are attached to it and perpendicular to each other, the back surface of the target is closely fitted with PVDF through the clip. PVDF has a very thick base which can absorb the shock wave through PVDF. The Nd: YAG solid-state lasers (1064nm, 532nm, 355nm), pulse width of 10ns, laser spot diameter of 2mm, pulse laser energy range of 100-200mJ are used in the experiment. The acquisition device of shock wave pressure signal is shown in Fig.1.

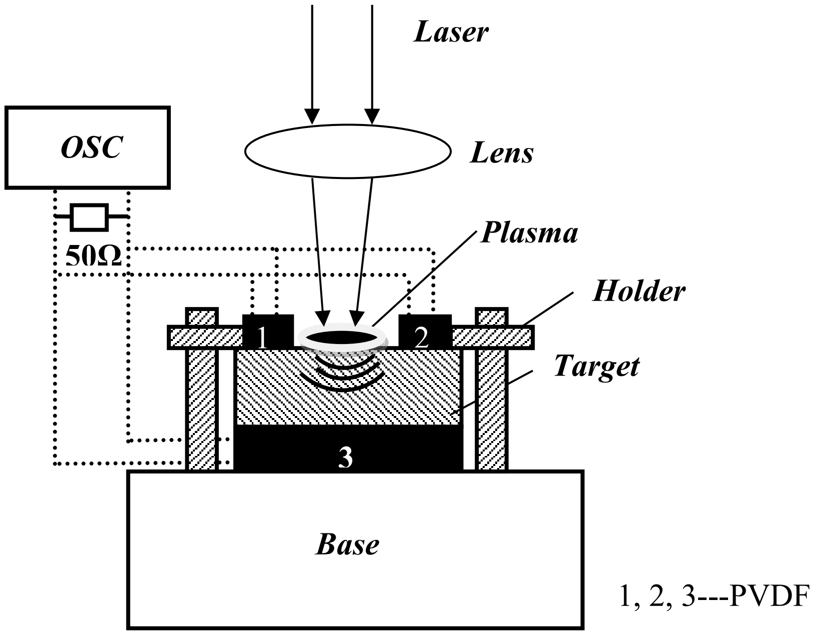

Fig. 1 Shock wave measurement experiment device schematic

4. Experimental Results and Analysis

4.1 Vapor Pressure Effect on the Target Surface

When using laser to irradiate the target, the energy absorbing particles collide with each other to transfer energy, the temperature of material surface will be significantly increased after being heated by laser energy[14]. As shown in Fig.2, sputtering and wave-like ripples appear outside the boundaries of the three-wavelength laser irradiated regions due to the high temperature of the material in the irradiated region and the propagation of waves to the surroundings. When the energy density of the laser exceeds the breakdown threshold of the polysilicon, a laser breakdown occurs. The vapor formed on the surface of the material forms a substance vapor with the outward splashing substance and continues to absorb the energy thus partially is ionized to form a high temperature and high pressure plasma. In the process of laser pulse, the splashing phenomenon of high temperature and high density molten material shows that the melted, gasified and ionized material is discharged acutely. Due to the further enhancement of the laser intensity, the surface of the irradiated polysilicon vaporize, the ionized breakdown of the ambient gas, or the gasified substance produces a high-speed laser detonation wave (LSD), at which time the expansion gas and the surface melted layer interact. First, high-speed air stamps molten liquid, and then couples to the solid part to form the pressure, causing liquid-solid interface deformation. At this point, the strain of the media is the result of thermal mechanical coupling. The laser shock wave causes the pressure wave in the melt layer to emit back when it encounters the solid-liquid interface. As the laser energy is large, the solution layer will peel off the solid surface and splash out, as shown in Fig.3. The melting and gasification of the polysilicon in the laser irradiation region provides the conditions for

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the removal of the material, but the vapor pressure contributes greatly to the migration of the material.

At 300K, the light penetration depth coefficients(α^{-1}) of polysilicon materials with different wavelengths (1064nm, 532nm, 355nm) were 0.01,1,1000 respectively. [15] The bandgap width Eg of the polysilicon is 1.12eV. Based on the Eq: $E(eV) = h\nu = 1.24 \cdot \lambda^{-1}$,the laser photon energy of the three wavelengths (1064nm, 532nm, 355nm) is 1.165eV, 2.33eV, 3.49eV. The absorption coefficients of the polycrystalline silicon material at 1064 nm, 532 nm and 355 nm were 10^3 cm^{-1}, 6.68×10^3 cm^{-1} and 10^6 cm^{-1}[16]. Under this energy, the wavelength of 1064 nm is mainly due to hot melting damage in the photothermal mode. During the irradiation process, the molten material is more, and the spray phenomenon occurs under the action of the vapor pressure and the more obvious ripples are formed; The wavelength of 532 nm is mainly due to hot melting damage and in the photothermal damage(The high photon energy opens the chemical bond of the material directly and causes a photochemical reaction to cause the debris of the material to be ejected in small or gaseous manner[17]). The main form of damage is hot melt damage and the melt is relatively less than 1064 nm, but also forms a clear ripple;The wavelength of 532 nm is mainly due to hot melting damage and in the photothermal damage, but the main damage is photothermal damage. The degree of ripple formation is relatively small.

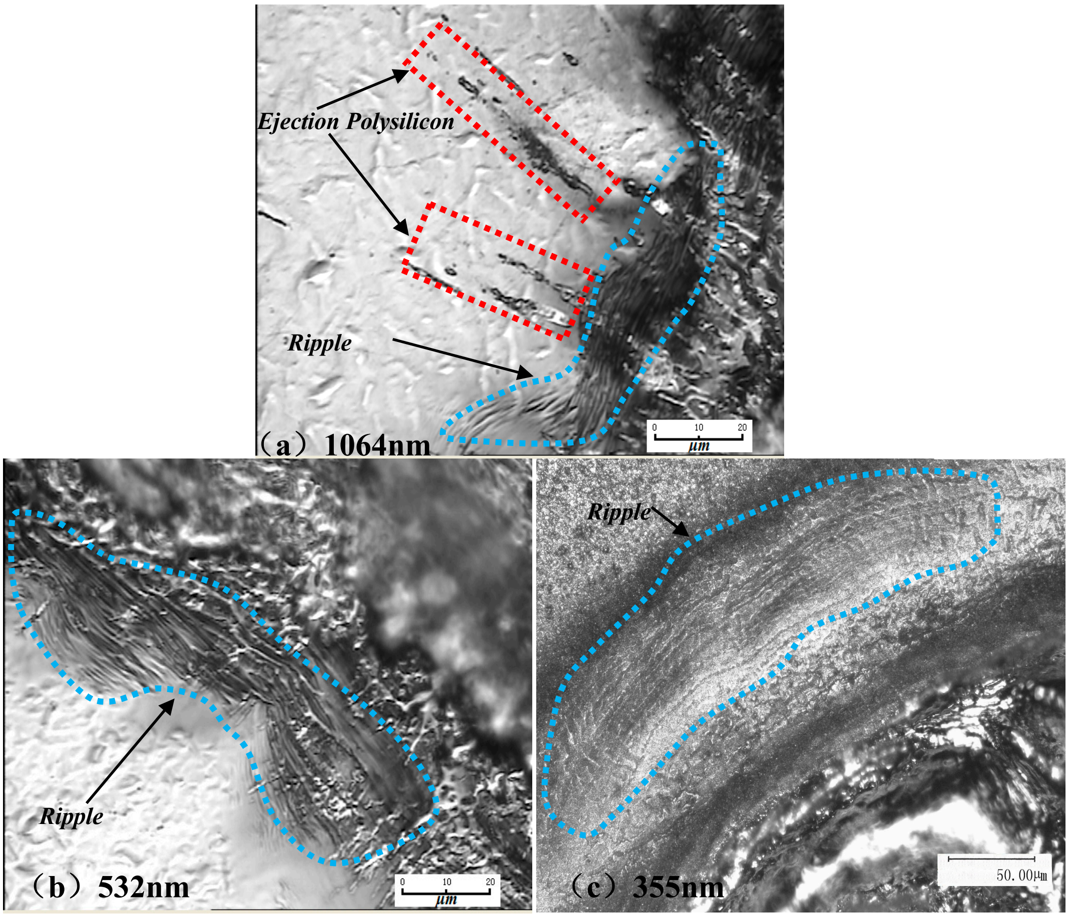

Fig.2 The ripple of three wavelengths after laser irradiation

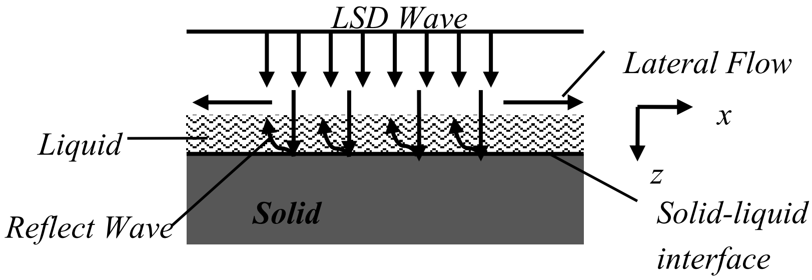

Fig. 3 Interactions of silicon melting layer and solid by LSD wave

When the laser irradiates the surface of the target, the laser will melt the surface layer of the target, and the pulse laser will generate the heat wave again, which causes the periodic change of the target surface [18]. Under the action of detonation wave impulse, a large radial vapor pressure will be generated, and the liquid will be pushed to the edge of the irradiated area to form a wave-like phenomenon. The high-pressure and high-speed expansion airflow stamps molten liquid and couples to the solid target part, producing the back pressure which is perpendicular to the surface to form the elastic wave source and produce the surface shear wave, then the propagation of the transverse wave causes the liquid-solid interface deformation. At the same time, the temperature gradient of the molten material forms a surface tension gradient, which aggravates the ripple phenomenon. In the modulated laser irradiation, the high temperature region of the liquid on the molten liquid surface is pulled to the low temperature region; it is the result of optical and mechanical coherent coupling. The thermal wave model theory can be used to analyze it, aiming at the phenomenon of corrugation on the silicon surface. Under the experimental conditions, the laser pulse width of wavelength 1064, 532and 355nm is 10ns, thus the thermal wave frequency can be obtained: $f \approx 1/2\tau = 50MHz$. Assuming that the stripe spacing d is wavelength λ of the thermal wave, the wave velocity can be obtained by the following Eq.(5) [18]:

$$v^2 = \frac{g}{m}\tanh mh + \frac{T_m}{\rho} \tag{5}$$

Wherein $m = 2\pi / d$, T is the surface tension, g is the gravitational acceleration, and ρ is density, the density of the silicon material is 2.3 g/cm^3 . Since $h \geq d/2$, d is small, so the above Eq.(6) is simplified as:

$$v^2 = 2\pi\frac{T}{\rho d} \tag{6}$$

Put $d = 2\mu m$, $\upsilon = 500m/s$ into Eq.(5), then the surface tension can be obtained: $T = 183N/m$.

According to the experiment phenomenon, we summarize the interaction process between high energy pulse laser and polysilicon material, as shown in Fig.4. When distributed laser of Gaussian irradiates polysilicon, the energy of the light spot center is the largest, so the center of irradiation area is the area of peak parameter. As shown in Fig. 4 laser irradiation area, due to the effect of high energy laser, the silicon material changes from solid to liquid on the surface of target, and moves toward light spot edge under the action of plasma pressure and steam pressure, then the melt recrystallizes again and becomes solid on the edge of the light spot. Upon Liquid state material is the steam, not fully ionization. On steam is the plasmas layer, because the area is completely ionized material, plasma layer will produce high pressure to compress steam layer, accelerate the ionization of molecular state material; Under the liquid state is the heat affected zone and beyond it is the solid area that not affected by the laser.

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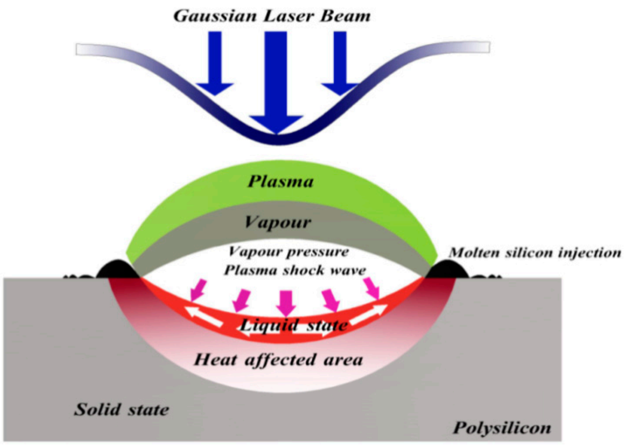

Fig. 4 Schematic diagram of irradiation upon polysilicon of pulse laser

4.2 Effect of Plasma Shock Wave Pressure upon the Surface of Target

4.2.1 Shock Damage Location of the Target Material Surface under the Laser Thermal

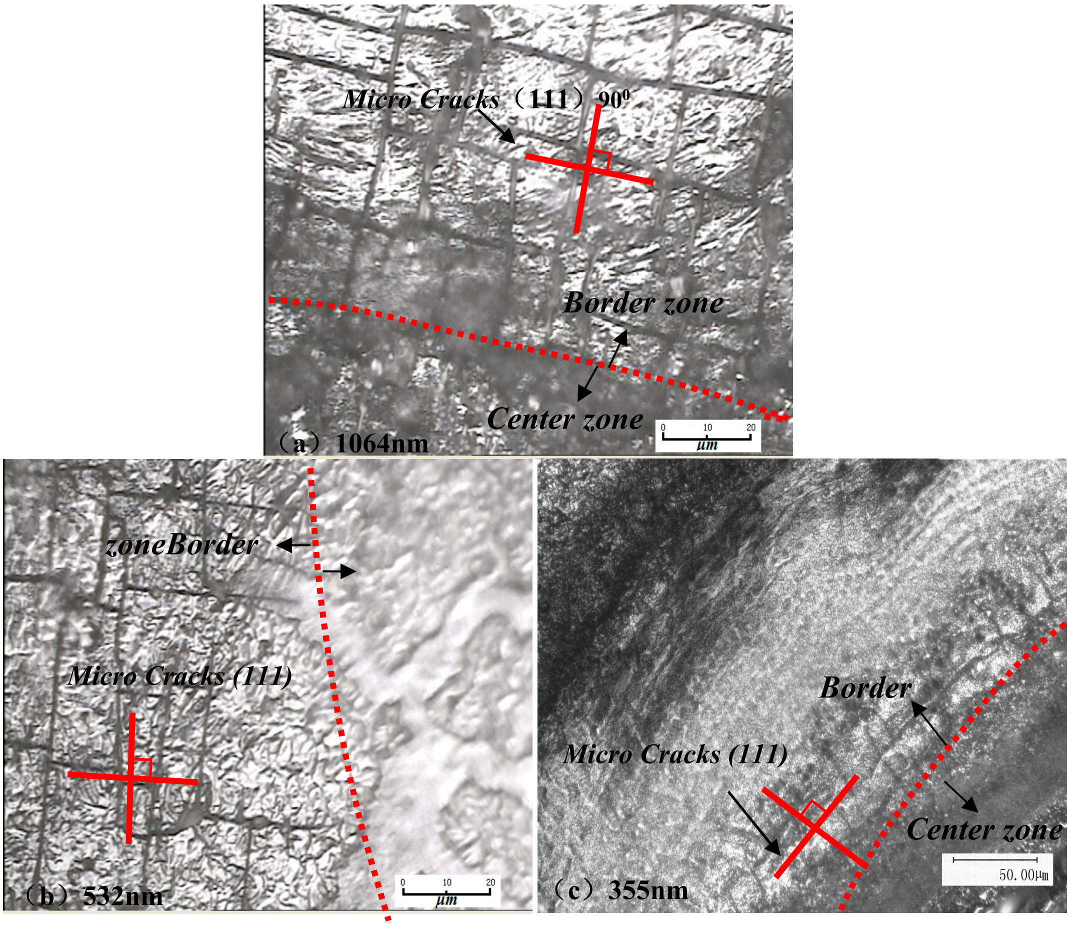

Fig. 5 Cleavage failure under laser shock waves

As in the above picture, the irradiation damage phenomenon under the power density 6.3 GW/cm^2 of three wavelength laser is shown. Because of the polysilicon materials on the (111) surface, bonding strength is the lowest between atomic bonds, and a cross type of crack damage area can be seen from Fig.5. Under the effect of laser shock wave, the priority, and destroyed front are

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mutual vertical, the angle is 900, this is due to (111) obeying the C2 symmetry, which is called brittle intergranular fracture. As shown in Fig.5, however, cleavage damaged area does not give priority to light spot center, and the maximum degree position is on the verge of irradiated area. The main reason is the effect of laser shock wave pressure, and we will analyze the longitudinal stress signals during the process of shock wave, and lateral strain in the following part.

4.2.2 The Dynamic Curve of Laser Shock Wave toward Target

PVDF piezoelectric film, with measuring range from 0 to 20 Gpa, nanosecond as its frequency response, and dynamic calibration being simple and fast, is an ideal sensor of super-high pressure measurement [20]. At t time, PVDF measured voltage signal V (t) and the shock pressure that on the surface of PVDF thin film P (t) within the scope of $P \in [0, 3\times10^{8} Pa]$ will meet the relation [21] :

$$P(t) = \frac{K}{A}\int_0^t \frac{V(t)}{R}dt \tag{7}$$

For dynamic calibration coefficient K, its value is 6.6×108Pa·cm²/μc , A is the effective area of PVDF, R is parallel resistance with PVDF, the resistance is 50. By Eq.(7), voltage signal detected by oscilloscope can be transformed to the laser- induced shock wave pressure signal, which, after transformation, turns out to be the actual shock wave relative pressure values.

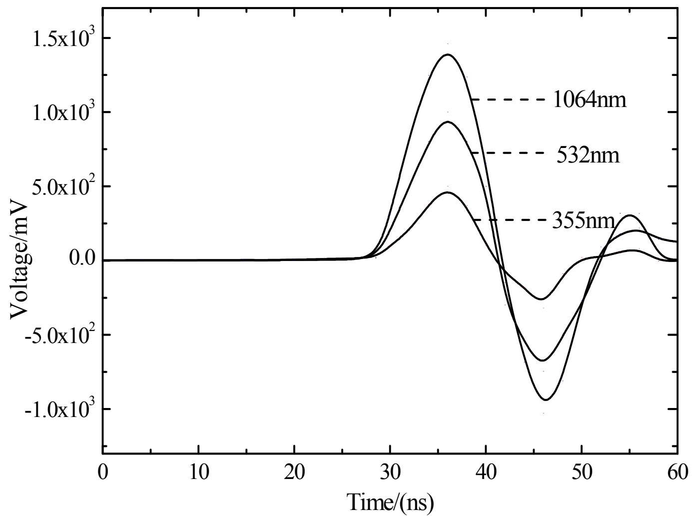

Fig. 6 The laser shock wave piezoelectric signal of three different wavelengths

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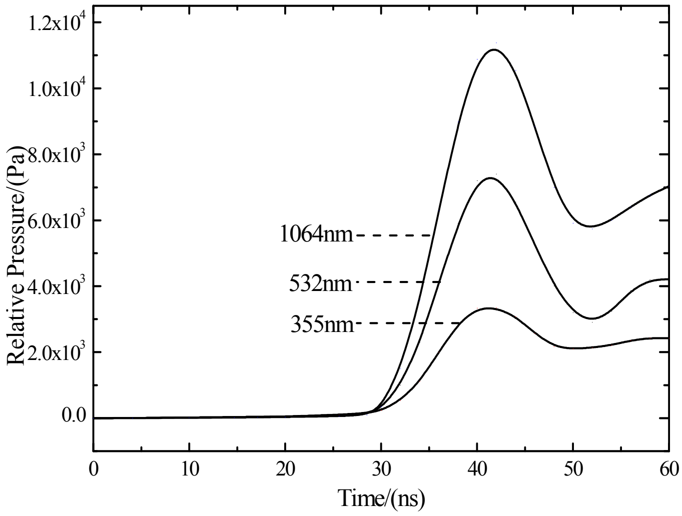

Fig. 7 Three wavelengths of relative pressure curve

When the pulse laser irradiates target material and produces shock waves on the workplace surface and produces reflection and transmission, the transmission wave becomes the form of stress wave in the target material. The stress wave transmits to internal of the target material and bounces back and forth. When laser shock wave transmits to the back of the target material, it will produce a voltage pulse on PVDF piezoelectric film, and the oscilloscope will record the voltage signal. When laser power density is 6.3 GW/cm^2, the first waveform cycle of the three wavelength laser shock is shown in Fig.6, with the decrease of wavelength, oscilloscope detected shock wave piezoelectric signal amplitude decreases.

The curve in Fig.6 and time integrates and becomes relative pressure curve Fig. 7. From Fig. 7 under the same power density, relative pressure of the wavelength of 1064 nm is the largest. With the decrease of the laser wavelength, shock wave pressure of laser ablation becomes smaller. The short wavelength laser has the characteristics as following: the greater photon energy, the greater the absorption coefficient, the shallower the penetration depth, as a result, the interaction mechanism of laser photons-silicon becomes stronger, makes short wavelength laser and polycrystalline silicon couple more fully. The wavelength of 1064 nm has high breakdown threshold. When the laser energy density is a constant value, as the wavelength from 1064nm decreases to 355nm, the photons and silicon coupling degree increases to strengthen the formation of shock waves.

However, the decrease of wavelength results in the decrease of critical breakdown power threshold and decreases laser-induced shock wave pressure which limit the formation of shock wave [22]. According to the empirical formula presented by Phipps: ($C_m = b(I\lambda\sqrt{\tau})^n$ b = 5, n = 0.3), the related parameters of silicon are put in and are shown in Fig. 8.

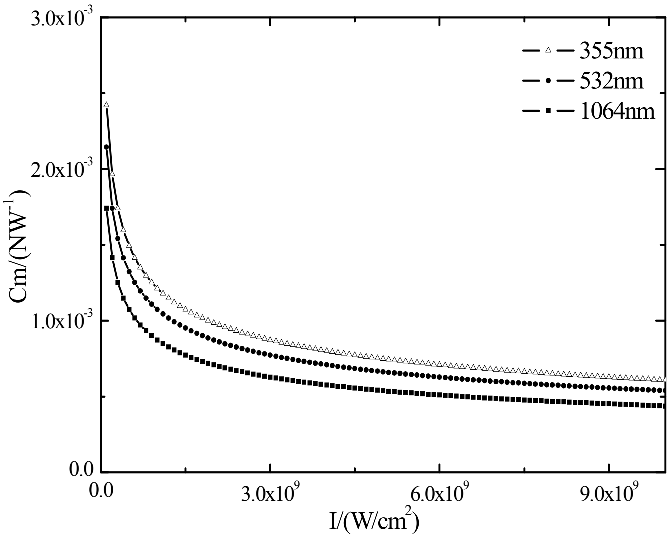

Fig.8 The relationship between laser parameters and coupling coefficient of the polysilicon

As can be seen from Fig.8, laser wavelength has a great influence on the impulse coupling coefficient. When the laser power density and laser pulse width is constant, with the increase of the laser wavelength the impulse coupling coefficient decreases. Wavelength of 355nm laser and polycrystalline silicon coupling degree is the largest and has highest efficiency. However, with the increase of laser power density, the impulse coupling coefficient is declining to equilibrium state. The main causes of this phenomenon is due to excessive steam layer and plasma spray produced by high-energy laser, subsequently, the laser cannot penetrate and produces plasma shielding. The explosion of steam and plasma produced by Laser irradiation on polysilicon make target material surface produce recoil pressure and impulse. High-energy nanosecond pulse laser works on the surface of target material and the pressure pulse duration is very short, and its mechanical effect can be characterized with impulse and impulse is one of the important parameters of shock wave mechanics effect, which can be expressed as [23]:

$$F = \int P(t)dt \tag{8}$$

Fig.9 shows the relations of ablation impulse of three wavelength single pulse lasers and time when the laser power density is 6.3 GW/cm^2. It is through integration of shock wave pressure of different wavelengths and time curve. As can be seen from Fig. 9, with the increase of pulse time, the impulse is to linear increase. With the increase of wavelength, ablation impulse strength increases. Due to the longer wavelengths, ablation impulse is greater than the short wavelength, leading to the most serious fracture degree of the surrounding of 1064 nm wavelength irradiation area.

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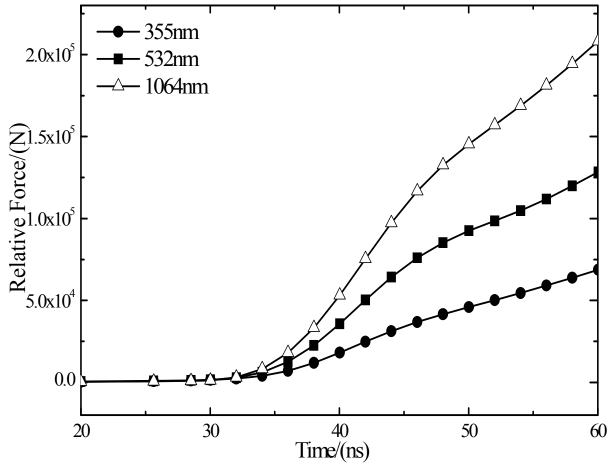

Fig.9 The relationship between impulse and time by different wavelengths

4.2.3 Dynamic Strain of Laser Irradiation Light Spot of Target Edges

Using PVDF piezoelectric film sensors to collect the dynamic wave signal of the laser irradiation polysilicon plane, the strain response of PVDF piezoelectric film is transverse strain, the longitudinal strain's effect and algebra and Eq. (8).

$$Q = (d_{31}\varepsilon_1 + d_{32}\varepsilon_2)E_{PVDF}S \tag{9}$$

Among them, ε_1 、 ε_2 are the two perpendicular directions, strain can be calculated through the detection of PVDF piezoelectric film on the charge transfer . At time transfer between charge and voltage signal V (t) on PVDF piezoelectric film satisfies:

$$Q(\mathrm{t}) = \int_0^{\mathrm{t}} \frac{V(\mathrm{t})}{R}\mathrm{dt} \tag{10}$$

The output voltage signal V (t) produced by oscilloscope into Eq. (8) and Eq. (9), $\varepsilon_1 - t$ curve and ε_2-t curve can be got.

Fig. 10 and 11, respectively, shows the oscilloscope outputs corresponding surface target material piezoelectric signal curve and strain curve when wavelength of 1064 nm, laser power density is 6.3 GW/cm². In Fig.10, through the calculation by Eq. (8) and Eq. (9) of the voltage signal, comes out the laser irradiation of polysilicon dynamic strain response curve. It can be found from Fig.10, under the action of pulse laser, material along the laser speckle phase radial strain (V1) and vertical direction strain (V2) change at the same trend. Laser waveform half- width is about 10 ns, consistent with the laser pulse width. In a single pulse laser action time, PVDF patch sensor detects firstly that surrounding material of irradiated area produces compressive strain because of compression, and then compressive strain decreases in tensile strain. With the passage of time, the state of dynamic strain curve around irradiation area is leveled off.

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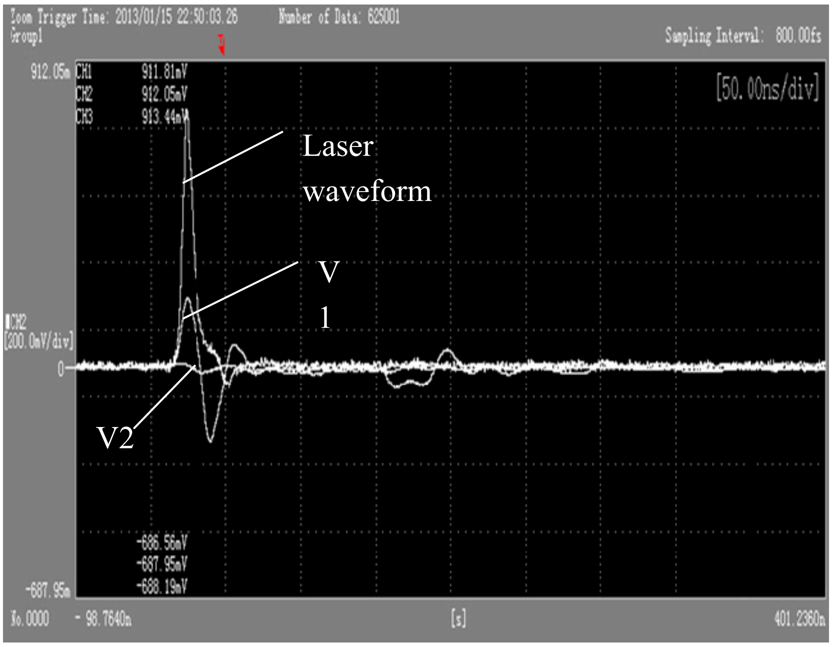

Fig.10 Piezoelectric signal curve when wavelength of 1064 nm, laser power density of 6.3 GW/cm^{2}on the target surface

In Fig.11, it takes the curve ε along the radial direction of laser speckle as an example to interpret the above phenomenon. Laser irradiation in unconstrained mode irradiates silicon and produces shock wave pressure, material surface of irradiation area produces thermal expansion due to the strong absorption of laser energy, causing surface thermal stress wave. Material particles in irradiation area under the action of the plane wave expand, making the material in the irradiation area in the compression state. Therefore, PVDF sensors detect that the compressive strain and compressive strain increase with the increase of laser shock wave pressure. When the laser shock wave is up to the peak pressure, compressive strain is corresponding to A point on the curveε .And then, within the time pulse width, as the time continues to the end, the laser temperature drops, and the laser shock wave pressure decreases, entering the stage of pressure unloading. Then, compressed material begins to rebound, leading to the compressive strain decrease. When the rarefaction wave spreads to the center of the impact zone, compressive strain decreases to point B. However, when the longitudinal stress wave returns to the surface of the target from the back of the target material, anti-media of high impedance (poly) spreads to anti-media of low impedance (air), which leads to the stress wave of laser transforming into elastic rarefaction wave and makes the material on the surface compress to point C under the action of tension. And the point D in figure is the result of impacts of following longitudinal wave. Finally, with the attenuation of shock wave, strain tends to achieve a balance.

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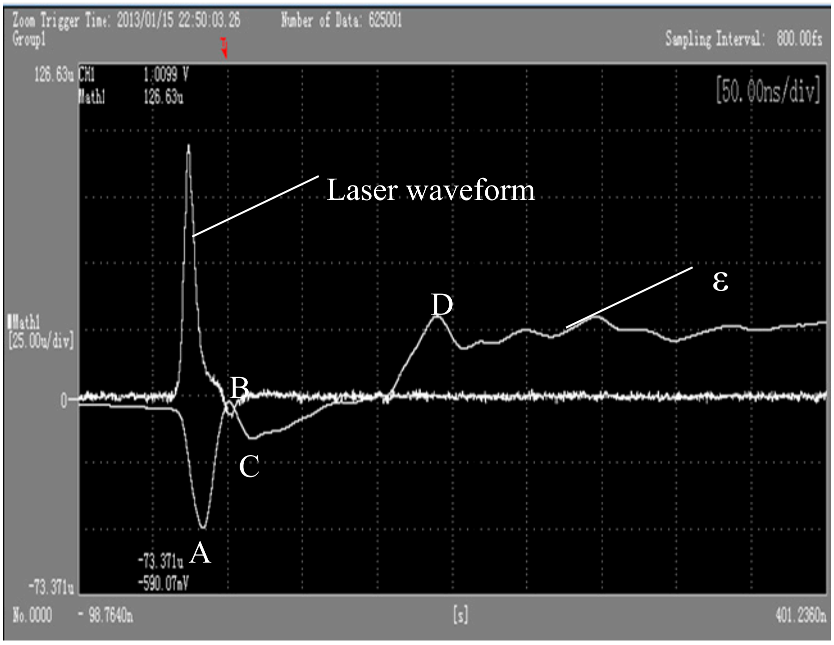

Fig.11 A Strain curve of target surface when wavelength is 1064 nm and laser power density is 6.3 GW/cm^2

It can be analyzed by combining with analyzing how PVDF detects the curve of stress wave on the surface as follows: under the irradiation of high energy laser,polysilicon is induced to produce plasma shock wave by laser ablation, and the shock wave produces a great pressure to the target. As a result, the material at the edge of radiating area transfers from compression to tension in a short time in that it is firstly influenced by compressive stress of thermal expansion wave. And under the irradiation of Gauss Beam of Light, the maximum tensile stress appears in the edge of the area, forming the effect of steam pressure and that of plasma shock wave, owing to the ablation under high energy laser. At the same time, the center of laser irradiation area forms softening effects after receiving the high-energy laser energy, and then it has the tendency to move forward under the action of shock wave, making the material around the spot center follow its displacement. But polysilicon belongs to brittle materials which have a narrow plastic zone, the transgranular cleavage is broken due to the sudden appearance of tensile stress. And a softening effect to a certain extent of the material in the center of laser irradiation area leads to a slight increase in the width of plastic zone, and makes the material which isat the edge of area appear to have a narrowest plastic zone. Therefore, when the material which is at the center of the area has a tendency of displacement, the degree of damage is higher. In Fig.5.a (1064 nm), there appear a large number of micro cracks at the edge of irradiation area, and the micro cracks in Fig.5.c(355nm) have less damage compared with the other two wavelengths. In conclusion, the reason why transgranular cleavage is broken is that shock wave effect which is induced by the laser, pressure effect and thermal coupling effect act jointly. Fig.12 shows the surface topography of cleavage damage fracture (111) and crystal structure. It can be seen from the diagram that the fracture, which has the weakest binding force of atomic link in the silicon material, appears to be smooth and flat and will be damaged firstly under the action of laser shock wave. And in the diagram, the face of [111] is perpendicular to (111) plane.

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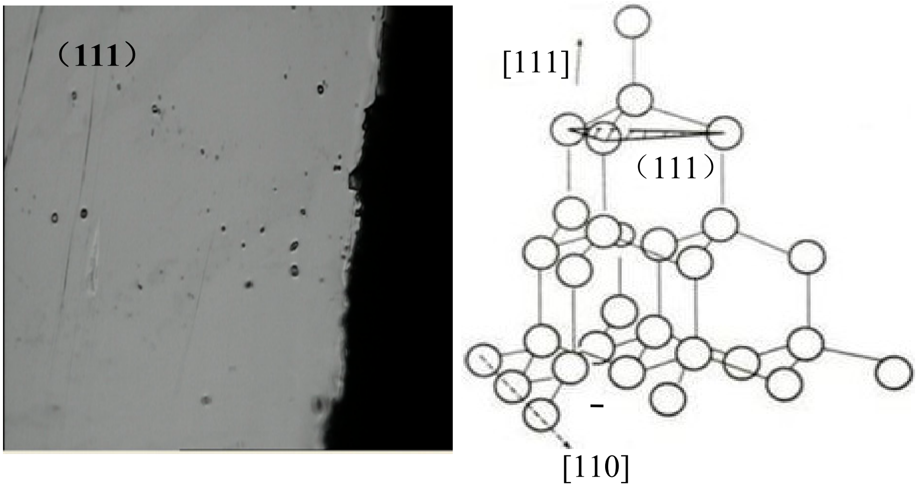

Fig. 12 Transgranular cleavage failure section and structure

According to the analysis formula of pressure overload which is put forward by Phipps, the semi-empirical formula of pressure can be concluded, which is about the pressure produced by the laser plasma shock wave to the target surface in the laser irradiation area.

$$P = bI(I\lambda\sqrt{\tau})^{n} \tag{11}$$

In Eq. (10): $\lambda(nm)$ is laser wavelength; $I_a(GW/cm^2)$ is the laser power density; $\tau(ns)$ is the laser pulse duration; b is the parameters of the silicon material determined by the material: $b=5$. And Fig. 13 can illustrate Eq. (10).

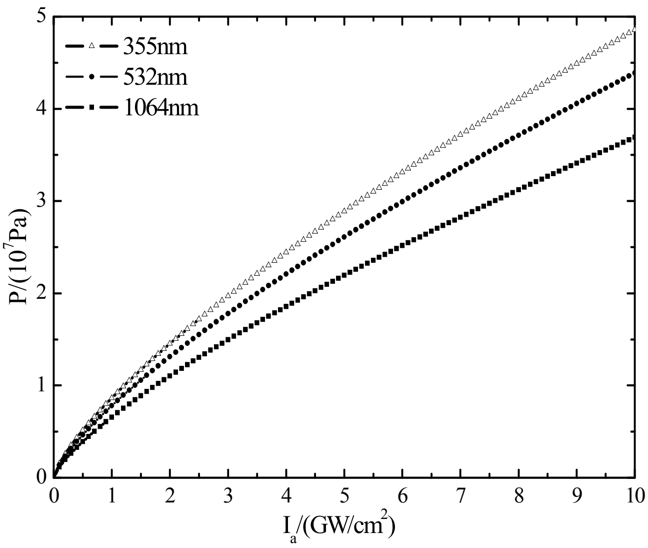

Fig. 13 A diagram which shows the relationship of pressure laser wavelength and power density

The relationship between laser wavelength and pressure of target surface in the laser irradiation area can be fully expressed in Fig. 13. In theory, with the increase of laser power density, the pressure is enhanced, and with the decrease of the wavelength, the pressure on the surface becomes greater. However, the energy of laser photon which belongs to short wavelength is great and a full consideration of the coupling between the short wavelength and material has been achieved. As a result, the breakdown threshold values of polysilicon is reduced, and when the laser energy is greater than the breakdown threshold, the excess energy will ionize the material in the irradiation area which is in the gaseous, atomic state quickly, so as to reduce the possibility of shock

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waves' formation. Meanwhile, the experimental phenomena is consistent with the research results about regularities of distribution of silicon's laser plasma pressure, which is carried out by Bao Lingdong and so on. [24]The experimental phenomena shows that Spot center has the biggest pressure, and it will have a tendency of displacement due to the pressure, driving the material which is at the edge of area. However, because of the brittle material's compressive strength being greater than tensile ability, the material at the edge of area will crack due to the great tensile stress.

4.3.The Attenuation Rule of Laser Shock Wave in Polysilicon

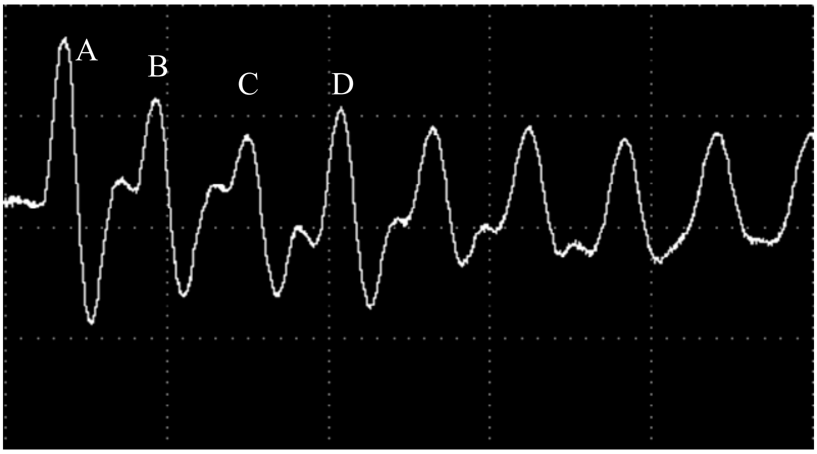

Fig. 14 The piezoelectric waveform of shock wave which is formed by the laser's 1064 nm wavelength inducing silicon's target surface

The piezoelectric waveform, whose laser power is 6.3 GW/cm² and the wavelength is 1064 nm, has the biggest amplitude, and is similar to the other waveforms. And then we take the 1064nm wavelength as an example to analyze its periodicity. It can be found that the biggest peak is formed by shock wave which is induced by laser and the reflection of following wave. Meanwhile, the average speed of shock wave' s spreading in polysilicon can be calculated according to its periodicity. As shown in Fig.11, the duration between the two neighboring pulses of voltage waveform is t, which means the time interval between the two adjacent laser shock waves' reaching target material on the surface. It can be red from the Fig.11 : t_{AB}=55ns，t_{BC}=60ns，t_{CD}=61ns. We can take the average: t_{ave}=59ns. And the thickness of the sample can be illustrated as follows: d = 0.25 mm. Therefore, according to the formula: $V = 2d/t$, the average speed of shock wave' s spreading in the sample of polysilicon can be concluded, that is, v = 8.47 x 103 m/s. Because shock waves induced by laser transmit back and forth in the polycrystalline silicon sheet, the unconstrained and absorbed layer of polysilicon target' s front surface is free surface. However, the acoustic impedance of polisilicon is six orders of magnitude larger than the acoustic impedance of air. Thus, the free surface can be regarded as the free end of reflection, and the size of wave pressure, which is formed after reflection, remains the same. Then, as the area of polysilicon sheet's rear surface where laser will function is pasted up with PVDF membrane, part of the shock wave will reach the base after a transmission through PVD membrane. And the base will absorb the shock wave which transmits through the PVDF. Compared with the thickness of polysilicon target material, the thickness of base can be ignored and the shock wave requires more time to reflect in the base than attenuate in target material. Therefore, the transmission wave will not affect the accuracy of experimental results. But, the loss part of shock wave which transmits into PVDF piezoelectric membrane needs a certain amount of compensation while measuring shock wave pressure. Dividing the actual peak pressure values of shock wave, which is formed by reflecting in polysilicon material surface for many times, by the formula: F^n , the peak voltage without transmission loss can be concluded.[25]：

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$$F^n = \left(\frac{Z_{si} - Z_{PVDF}}{Z_{si} + Z_{PVDF}}\right)^n \tag{12}$$

In the Eq. (12): $Z_{si} = 1.239\times10^6\, g\cdot cm^{-2}\cdot s^{-1}$, $Z_{PVDF} = 0.25\times10^6\, g\cdot cm^{-2}\cdot s^{-1}$, $F = 0.96$.

As mentioned above, the shock waves induced by the laser reflect continuously on the anterior and posterior surface of polycrystalline silicon sheet. Therefore, when the shock wave reflects on the anterior and posterior surface of polycrystalline silicon, the distance can be used to draw an attenuation rule of peak pressure of shock waves. And the peak pressure of shock waves is illustrated in Tab.1.

Tab.1. The peak voltage which is formed after laser shock waves' reflection in 0.25 mm wafers

Thickness/mm	0.25	0.75	1.25	1.75	2.25	2.75
Relative peak voltage/10^7Pa	4.2	3.5	2.7	2.2	1.7	1.4
Peak voltage withouttransmission loss/10^7Pa	4.2	3.6	2.8	2.3	1.8	1.5

The attenuation rule of laser shock wave's peak values in polysilicon is concluded by the method of exponential decay fitting (Fig.16):

$$P_{\max} = 5.37\exp(-\frac{x}{3}) - 0.7 \tag{13}$$

In the formula, $P_{\max}$ is shock wave's peak pressure and x is shock wave's spreading distance.

According to Eq. (12), we can conclude that the maximum of peak value is 4.67×10^7 Pa.

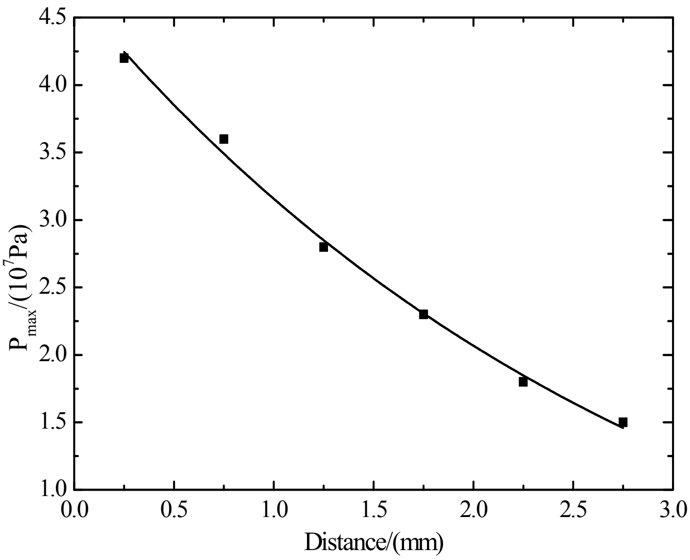

Fig.16 The attenuation rule of shock wave pressure in polysilicon.

5. Conclusion

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Based on the detecting techniques of PVDF piezoelectric membrane, this paper studies laser thermal shock's devastating phenomenon in the process of laser irradiating polysilicon material and analyzes the function of wavelength effect in the process of shock waves which is induced by laser on the polysilicon material damage. Meanwhile, this paper also uses the test results of PVDF piezoelectric films to analyze the failure mechanism during the process of laser irradiating polysilicon and Studies the propagation's law of laser shock wave rules which is in the brittle materials. Thus, the main results are as follows:

1. In the process of pulsed laser action, the combined action of steam pressure and plasma contributes to splash phenomenon of melt which has high temperature. And the melting and gasification of polysilicon in the area of laser irradiation provide conditions for the removal of material. Furthermore, the steam pressure and plasma pressure have made great contribution to the removal of material. And the decrease of the laser wavelength enables stronger coupling between laser and target, reducing the breakdown threshold value and weakening laser shock wave strength.
2. When the speedy expanding airflow of high pressure stamps molten and couples to the solid part of the target material, the recoil pressure will be produced which is perpendicular to the surface， and elastic waves will be composed to form transverse wave on the surface. Furthermore, the spread of transverse wave will cause the deformation of the liquid - solid interface, which is similar to the formation of water wave. At the same time, tension gradient that is on the surface of target material causes the phenomenon of moiré, and the higher the temperature of the molten material is, the smaller the surface tension will be; the lower the temperature is, the greater the surface tension will be. Under the modulated laser irradiation, the liquid on the high temperature zone is pulled to the low temperature zone, which is the result of the coherence and coupling between optics and mechanics.
3. Brittle material has a poorer ability to resist shear stress, so it is easy to find the phenomenon of cleavage destruction under the effect of laser shock wave, and the destroyed area is just the edge area of the laser irradiation.
4. The average spreading speed of shock wave in the sample of polysilicon is v = 8.47×10^3 m/s, and the attenuation tendency of the laser shock wave's pressure peak in polysilicon is in the form of exponential distribution.

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