The Acoustic Characteristic Investigation of Micro Plasma Shock Wave Obtained by Femtosecond Laser Ablation of Silicon Wafer Surface

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Abstract. We experimentally investigate the acoustic characteristic of micro plasma shock wave obtained by femtosecond laser ablation of silicon wafer surface using F-P optical fiber acoustic sensor with anti electromagnetic interference. The experimental results show that each of the femtosecond laser pulse can only produce a plasma shock wave. Under the different femtosecond laser energy, the acoustic attenuation signal of single shock wave has been analyzed by using wavelet transform, the results indicated that the energy change of femtosecond laser has no effect on the frequency of the acoustic signal of the micro plasma shock wave and have only influence on the amplitude, meanwhile, the main frequency of the acoustic attenuation signal are distributed within range of 0-100KHz, According to these frequency components, we can conclude that the decay process of micro plasma shock wave is the fast transduction of the ultrasonic signal into the acoustic signal. This study can provide the experimental basis for femtosecond laser ablation mechanism and femtosecond laser plasma control application research.

1 Introduction

Research on femtosecond laser ablation phenomenon has a strong effect on comprehending mechanism of the interaction between femtosecond laser and materials, improving the efficiency of femtosecond laser micromachining, minimizing laser damage, and so on. When interacting with materials, non-linear phenomena will be induced, such as multi-photon effects, self focusing and avalanche ionization. Due to femtosecond laser has high peak power and intensity, the use of ultrashort lasers, i.e., fs lasers, has a reduced thermal effect on the ablated material compared to ns LA(laser ablation) and an ablation depth with improved precision can be obtained[1,2]. These special characteristics of fs LA have

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initiated new research paths for more detailed understanding of ultrafast laser-material interactions, plasma excited species expansion dynamics, and mechanisms of material removal[3]. Regardless of laser pulse duration (fs-ns), laser produced-plasmas (LPPs) are highly transient in both space and time, so studying plasma expansion dynamics and emitting species' kinetic properties is essential for most applications [4].

According to the existed experimental phenomena and results, people put forward different theories when dealing with different material, mainly including two-temperature model[5], micro explosion theory[6], theory of Coulomb explosion[7,8] and threshold theory[9]. Although the ablation process of different materials basically coincides with the threshold theory, still there is no clear understanding of the plasma dynamics characteristics and the interaction of femtosecond laser ablating different materials so far, and it is not even clear of the mechanism of its origin. This field needs more theoretical and experimental research [10].

Based on this, in recent years, people have carried out the research of dynamic characteristics and detection method of the femtosecond laser plasma. Some researchers developed an ultrafast time-resolved imaging technique for the plasma dynamics characteristics utilizing the optical polarigraphy technique and a chirped supercontinum[11]. Including laser induced breakdown spectroscopy [12],broadband ultrasonic technique[13], optimization of laser-induced breakdown spectroscopy [14], and so on, these methods also had been used widely. For diagnosis of the plasma wave, researchers employed a technique based on the modification of the spectrum of an intense femtosecond pulse generating the plasma wave, and an effective diagnostic method of laser-induced plasma based on measuring of the scattered microwave radiation has been proposed[]. The latest new method has been proposed to investigate the optical emission features of plasmas by using time of flight emission spectroscopy, but the decay processes occur on a nanosecond time scale and are functions of plasma parameters such as electron density and temperature. Measuring those parameters is difficult due to fast relaxation (1 ns), relatively low electron density.

The main difficulty lies in that femtosecond laser pulse time is so short that creating a pulse with high energy would produce plasma with small size. The existing technical means can only observe the early emerging, progress and ionization of plasma by over speed spectroscopy technique, and the emission wavelength shift and spectral intensity of spectral to analyze the expansion regularity of plasma, considering the atmospheric environmental impact around the aspects. The plasma energy status and decay process of target ablation stripping cannot be reflected. Considering the plasma is charged particles, the existing electrical probe in situ detection can be affected by the electromagnetic interference of plasma charged particles, thus affecting the accuracy of measurement. In this paper, the optical fiber F-P probe was used in situ measurement the acoustic signal process of micro plasma shock wave produced by femtosecond laser ablation of silicon wafer. We make a research on characteristics and the decay process of plasma obtained by femtosecond laser ablation target material, providing experimental basis for femtosecond laser ablation mechanism and plasma control.

2 Experimental setup

The schematic of experimental setup is shown in Fig.1. A commercial Ti: sapphire femtosecond laser with 180 fs laser pulses and 780 nm central wavelength, 500 Hz repetition rate was used in the system (Japanese Cyber Laser Company; LS-IF-FW-C-401). The pulse energy could be continuously varied by a variable neutral density filter and a mechanical shutter could turn the

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laser on and off. The laser beam is focused normally onto a sample mounted vertically on a translation stage. Before femtosecond laser irradiation, the silicon wafer is cleaned by ultrasonic bath for 15 min in acetone and rinsed in deionized water. For the F-P optical fiber sensing system, a tunable semiconductor laser with 1545 nm wavelength and 0.2 mw Power was used as the light source (Santec Company). The multi-channel data acquisition card of NI Company was used for data collection. The highly efficient signal processing circuit developed independently by our laboratory was used for photoelectric conversion. High speed CCD used in the experiment is a type of PCO.dimax HD high speed digital camera produced by PCO Company of Germany, the exposure time is 1.5us-40ms.

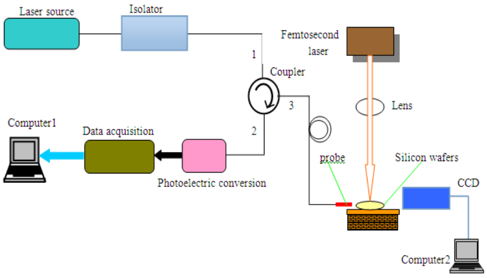

Fig.1 Schematic layout of the experimental setup

The ablation was carried out in air by irradiating the silicon wafer with different numbers of laser pulses and different laser energy. The numbers of the femtosecond laser pulses was set to 500Hz. The energy of the femtosecond laser was set to 110mw. The laser micro plasma shock wave could be formed when the laser beam irradiated on the silicon wafer. The acoustic signals of laser micro plasmas shock wave were detected by the optical fiber sensing probe and collected by data acquisition module. Then we can analyze the acoustic characteristic of laser micro plasmas shock wave by wavelet transform.

Meanwhile, CCD is connected with the computer by the 1394 interface and finished shooting photo storage through the MATLAB software programming to call CCD own function package, the high speed CCD camera had been applied to observe the expansion process of laser micro plasma. In comparison, the frequency and amplitude of the acoustic emission spectrum has been analyzed, the dynamic characteristic of the femtosecond laser micro plasma expansion has been researched.

3 Results and discussion

The acoustic signal of micro plasma shock wave with femtosecond laser pulse at 500Hz was studied. To determine the relation between the number of laser pulse and the number of micro plasma shock wave acoustic signal, we measured the acoustic signal of micro plasma shock wave with laser pulse at the number 500Hz. As showed in Fig.2, five acoustic signal of micro plasma shock wave can be obtained in 10 ms.

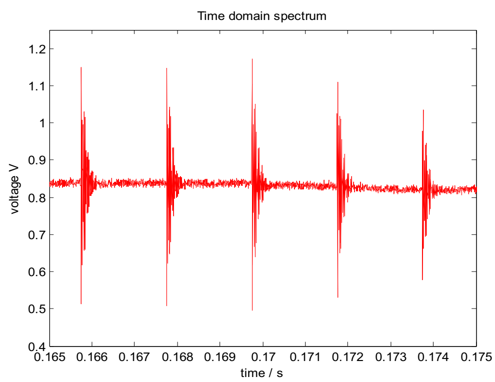

Fig.2 The acoustic signal of micro plasma shock wave by femtosecond laser ablation of silicon wafer surface under the condition of 500 Hz laser pulses

The micro plasma shock wave we have detected could be explained by the theory of micro-explosions. Multiphoton ionization and the ionization by electron impact (avalanche ionization) play the major role in femtosecond dielectric breakdown. The interplay of these two processs turns the material under irradiation into plasmoid. Because the pulse duration is much shorter than the electron-phonon energy transfer time, the electrons are heated while the ions stay cold. The micro plasma formed would produce a pressure which can be measured by the effective deposited energy inside the material.

When the pressure exceeds the Young modulus of the material, an explosion would appear thus triggers a shock wave. As for the energy deposition, the pressure outstripping the Young modulus of the material takes place with the subsequent shockwave at the end of the laser pulse. The shock wave decreases with the distance rapidly for the damping in the air.

Due to the wider signal bandwidth of femtosecond laser radiation, the composition of frequency is quite abundance and we can analyze the frequency spectrum of acoustic signal to investigate the acoustic characteristic of laser micro plasmas shock wave by wavelet transform. The acoustic signal is decomposed into different frequency channels, the characteristics of different frequency components can be obtained for the signal in different frequency bands.

In the study, the acoustic signals of single micro plasma shock wave were decomposed using db5 wavelet from which the spectrum features were extracted. The acoustic signal characteristic of single micro plasma shock wave was analyzed by db5 wavelet and the change of spectrum curve at different laser energy was obtained. The energy of the femtosecond laser was set to 110 mw. Figure 3 shows the acoustic signal spectrum of single micro plasma shock wave by db5 wavelet with femtosecond laser energy 110mw. In fig.3, a and d marking in the figure respectively stands for the low and the high frequency signals after wavelet transformation, the numbers after a and d indicate the progression of wavelet decomposition. As is shown from the Fig. 3, the acoustic emission signal frequency component of micro plasma shock wave is abundant, mainly focusing among the range of 0-100KHz. The amplitude of the signal is mainly affected by the change of laser energy which has little effect on the whole frequency range. The wavelet decomposition shows that level a_6 and d_1 is the low-frequency and high-frequency of acoustic emission signals derived from the micro plasma shock wave, mainly in 0~10KHz and 70~80KHz.

Through wavelet transform we can clearly determine the frequency component of the signal, it includes the frequencies of 0-100KHz. We can see that the energy mainly concentrate in the a6 which is the lowest frequency part of the signal. The proportion of other states' energy takes a decline trend from d6 to d1. The low frequency components (LF) take the major part of the signal. We can infer that the high frequency components (HF) attenuate quickly in the propagation of the micro plasma shock wave. In this way the dominant frequency of the signal shows a decreasing trend.

4 Conclusions

In this work, the direct femtosecond laser structuring technique developed previously by us for metals is extended to silicon that allows producing black silicon by structuring silicon surface with a grating of equally spaced parallel nanostructure-textured microgrooves.

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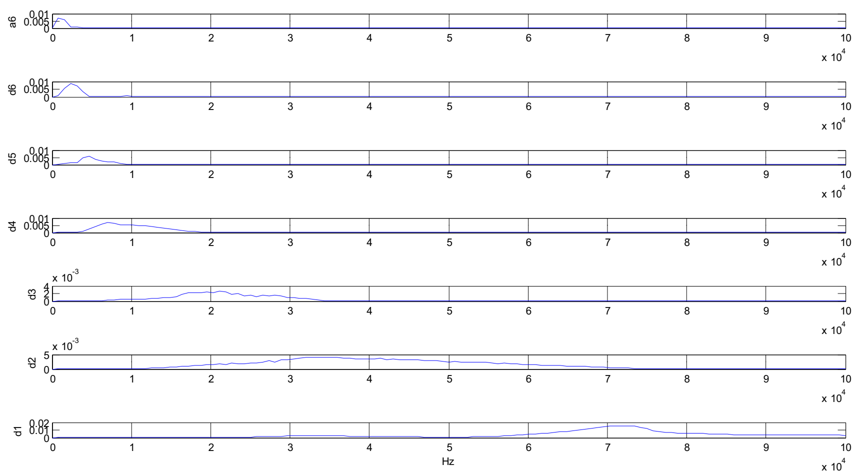

Fig.3 The acoustic signal spectrum of single micro plasma shock wave by db5 wavelet with femtosecond laser energy 110mw