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Refining femtosecond laser induced periodical surface structures with liquid assist

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ABSTRACT

Laser induced periodic surface structures were generated on silicon wafer using femtosecond laser. The medium used in this study is both air and ethanol. The laser process parameters such as wavelength, number of pulse, laser fluence were kept constant for both the mediums. The focus of the study is to analyze spatial wavelength. When generating surface structures with air as a medium and same process parameter of the laser, spatial wavelength results showed a 30% increase compared to ethanol. The cleanliness of the surface generated using ethanol showed considerably less debris than in air. The results observed from the above investigation showed that the medium plays a predominant role in the generation of surface structures.

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1. Introduction

Laser induced periodic surface structure (LIPSS) can potentially be used for engineering surface properties such as thermionic emission which is used in variety of industrial applications [1]. Generation of periodic surface structure on different materials using different lasers has attracted lot of attention since it was first reported by Birnbaum [2]. Various research reported in the literatures are using ultra-short pulse lasers to generate finer and cleaner periodic structures on a variety of materials such as semiconductors [3], metals [4] and dielectrics [5]. The processing parameters of ultra-short laser include wavelength, number of pulses, laser fluence, pulse duration, incident angles and polarization. These have been investigated for their effects on the spatial wavelength and depth of periodic surface structure. The periodic structures were observed oriented perpendicularly to polarization of incident laser radiation. The LIPSS period induced by ultra-short pulses at normal incidence is slightly less than the laser wavelength. Pulse duration has a significant impact on the features of LIPSS. Compared to femtosecond pulse laser, the ns laser or other long pulse produces ripples with coarser and deeper structures [6] due to its relative larger thermal effect. In addition, the wavelength of LIPSS is considerably large [7–9] when apply the longer pulse. Thus, the femtosecond laser with minimal thermal effect is preferred in order to obtain a fine and ordered periodical surface structure.

It is reported that the period ripples are resulted from the optical interference of the incident laser irradiation with surface scattered waves [10]. The nonuniform surface energy distribution leads to periodic material melting and resolidification. Recent literature reports the experiment results of laser material interaction and thereby periodic surface structures generation in a medium which is air. Very few studies [1] have focused on the laser induced periodic surface generation using ethanol as replacement to air, which is the subject of this paper.

In this study, experiments on silicon wafer were conducted using femtosecond laser to generate periodic surface structures. The experiments were conducted using both air and ethanol as a medium. The spatial wavelength and cleanliness is studied. The effect of each medium on the surface structure generated is investigated and analyzed.

2. Materials and methods

The laser emitted pulse of 200 fs with linearly polarized light at a central wavelength of approximately 775 nm (nominal repetition rate of 1 kHz). The total pulse energy was attenuated by a rotating half wave. The mechanical shutter was controlled to release the desired laser on the substrate. The laser beam was focused with a focusing lens of 75 mm focal length. The average laser power after

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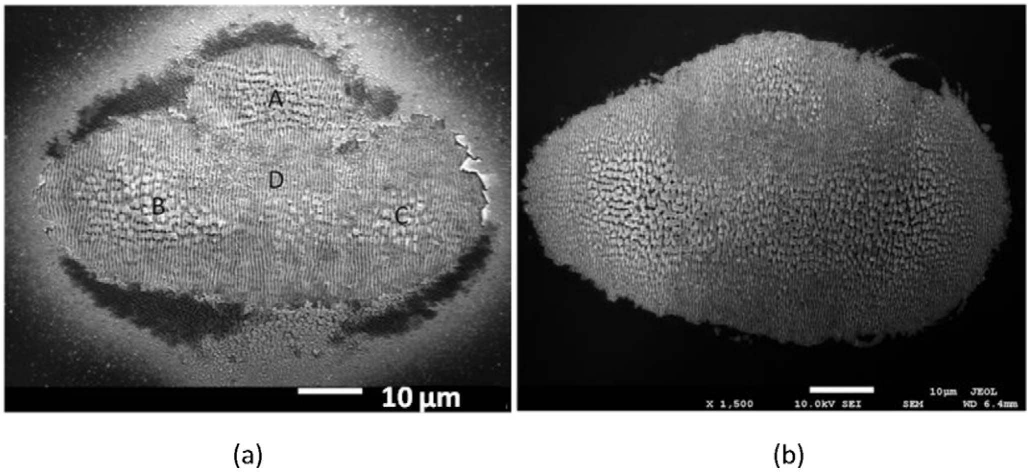

Fig. 1. SEM image of LIPSS formed in air (a) and in ethanol (b) by the p-polarized laser beam with 100 pulses at pulse energy of 7 µJ.

the lens was measured using a power meter. A three-dimensional CNC stage was applied to position the specimens. In our study, LIPSS was produced on polished single crystal silicon wafer. The pulse energy applied at the Si surface was 7 µJ. The number of pulses was varied from 1 to 500. Deposition of thin liquid films on the Si surface was achieved with the aid of a buret before the firing of the laser pulses. The thickness (assumed uniformly distributed here with relatively low surface tension) of liquid film is estimated to be 0.1–0.2 mm by dividing the volume with the area.

3. Results and discussion

Fig. 1(a) shows the SEM image of a silicon surface area irradiated in air by 100 laser pulses at a fluence of 0.2 J/cm^2 which is lower than the single pulse damage threshold of 0.4 J/cm^2 [11]. As shown from Fig. 2(c), a magnified image of the ripple area is acquired in the center of machining spot (zone D). The observation reveals that, with spatial periods of 630 nm (less than laser wavelength of 775 nm) ripples are formed perpendicular to the direction of the polarization of the laser irradiation. These ripples are characterized by nearly parallel lines extending over the entire area despite some melting zones *i.e.* A, B, C as shown in Fig. 1(a), which are due to the accumulation of thermal effect from the intensive energy of hot spot in the laser beam. This hot spot is caused by the non uniform energy delivered by the Laser beam. A more uniform energy distribution can be achieved either by tuning the optics or by using improved apertures. The ripple area is covered by a large amount of debris coming from the redeposition of ejection materials. Figs. 1(b) and 2(d) show the LIPSS on silicon irradiated in ethanol environment and when applied the exact same laser parameters as in the air. There are two distinct differences in the features of LIPSS between air and ethanol environment.

Firstly, the ripple area in liquid is much cleaner than that in air. The amount of debris is significantly reduced when ethanol is used as the assist liquid. The vapor bubbles were produced as a result of the temperature rise in the liquid induced by absorbed laser energy [12]. The bubble generation would be accompanied with shock waves, which will provide an additional force or source to clean off the debris induced by laser ablation [13]. The enhanced mechanical wave emission helps the removal of laser ablated materials. The amount of debris on the Si surface is therefore reduced. According to the literature [14], the dimension of bubbles generated by fs laser is estimated below 1 µm. These micro-size bubbles were observed around the peripheral of the laser irradiated area (not in the laser beam path). Thus, the bubble's scatter effect of laser beam was not observed.

Secondly, as observed from Fig. 2, when the number of pulse is fixed at 10, the ripple period LIPSS in ethanol is 455 nm that is about 40% less than that in air (772 nm) and the laser wavelength (775 nm). This result shows that the change of environment medium plays an important role in the formation of LIPSS. For normally incident p-polarized laser beam, the period of surface ripples resulting from the interference between incident laser light and the excited surface plasmon wave is given by:

$$\Lambda = \frac{\lambda}{\eta} \quad (1)$$

where λ is the incident light wavelength, $\eta = Re[\varepsilon_1\varepsilon_2/(\varepsilon_1+\varepsilon_2)]$ [10] is the real part of the effective refractive index of interface for surface plasma, ε_1 is the complex dielectric constant of material, ε_2 is the complex dielectric constant of medium. The complex dielectric function is given as follow $\varepsilon = (n+ik)^2$. When ethanol is applied as medium instead of air, η is calculated to be 1.75 for $\varepsilon_1 = 13.8 + 0.059i$, $\varepsilon_2 = 3.5 + 2.1i$ [15]. The ripples period Λ is found to be 442 nm which is rather close to the experiment result of 455 nm. When we apply this model to calculate the period of ripples formed in air, the value of spatial wavelength is 780 nm which approximates the experiment result of 772 nm with the number of pulse 10. However, the spatial wavelength is decrease sharply with increasing the number of pulse to 100 as shown from Fig. 3. This discrepancy is likely because this model neglects the effect of transient increment of laser induced electron density in conduction bond which will lead to an increase of real part of refractive index [16]. The LIPSS spatial period decrease when increasing η. According to Eq. (1). Nevertheless, in the case of ethanol environment, there is no apparent change in the spatial wavelength when number of pulse increase from 10 to 400. One possible reason for this phenomenon is that the effect of plasma confinement [17] is enhanced due to the presence of liquid thin film. The previous study [18] reported that compared with drilling in air the plasma size and duration are much reduced when laser irradiating in water. Thus, in the case of liquid environment the temperature rise in the ablation area due to the heat conduction from the plasma is much reduced. This process can prevent the sharp increase of electron density in conduction bond when the applying more laser pulse. Thus, the spatial wavelength can remain almost unchanged with the assistance of ethanol.

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