Generation of surface acoustic waves in silicon with energetic femtosecond laser pulses

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The generation of surface acoustic wave (SAW) pulses in Si single crystal by femtosecond laser pulses with high energy of up to 30 mJ is studied. The generation is rather efficient even at a free silicon surface. In this case the shape of the observed SAW pulses corresponds to the thermoelastic mechanism despite the fact that a well developed ablation takes place. Excitation through a liquid layer is also studied and provides longer SAW pulses. SAW gratings are generated by focusing the laser beam through a mask and the changes in the spectrum of the pulse due to nonlinear interactions are observed. [DOI: 10.1063/1.1512985]

I. INTRODUCTION

The excitation of surface acoustic waves (SAWs) by a femtosecond laser pulse is of interest for several reasons. First, with energetic femtosecond laser pulses extremely high intensities and electric fields can be produced in a focused laser beam. At these extreme conditions new mechanisms of SAW generation may take place or well known mechanisms can manifest themselves differently.[1] Second, rather high frequencies can be reached since the upper limit is set in this case mainly by the size of the focal spot of the laser beam. Third, the fast creation of excitations with femtosecond laser pulses makes them a powerful tool in studies of relaxation processes,[2] in particular by generating thermoelastic gratings.

II. EXPERIMENTAL SETUP

Our experimental setup included a mode-locked Ti:sapphire laser seed generator pumped by a Millenia diode-pumped solid state laser. The amplifier consisted of three subsystems: a dispersive pulse stretcher, a regenerative amplifier, and a compressor. The regenerative amplifier had two stages of amplification: one is a Spectra-Physics Spitfire pumped by the frequency doubled output of a Merlin laser and the other was a TSA-25 amplifier pumped by the frequency doubled output of a Quanta-Ray Nd:yttrium–aluminum–garnet laser. The output of the Spitfire operated at 1 kHz with the energy per pulse about 0.7 μJ and the output of the TSA-25 was at 10 Hz with the energy per pulse up to 30 mJ. The duration of pulses was about 60 fs and the wavelength about 800 nm.

For the generation of SAWs with a plane front, the TSA laser pulse was sharply focused with a cylindrical lens to a strip with a length ~5 mm and a width ~10 μm. For generation of a SAW grating, a mask with a periodic structure of transparent and opaque stripes was positioned in front of the lens. In some experiments a layer of absorbing or transparent liquid was imposed onto the surface in the excitation region.

The excited SAWs were registered with a probe-beam-deflection technique that could measure propagating pulses at two distances from the source in a single laser shot.[3] The upper limit for the power of the probe beam was set to avoid the melting of the sample surface and saturation of the photodiodes. The calibration coefficient for the measurements presented below was about 10 m/(s V). The SAW pulse signal was registered in a wide frequency range with a digital oscilloscope (Tektronix TDS 680 C, 1 GHz real-time bandwidth).

III. RESULTS

In Fig. 1 the SAW pulse registered at a distance $x = 3.6$ mm along the ⟨001⟩ axis in the (110) plane of silicon is shown. This pulse with a duration less than 10 ns and the amplitude of the normal velocity of 4 m/s was produced at a free surface of silicon in a single laser shot. In the (110)

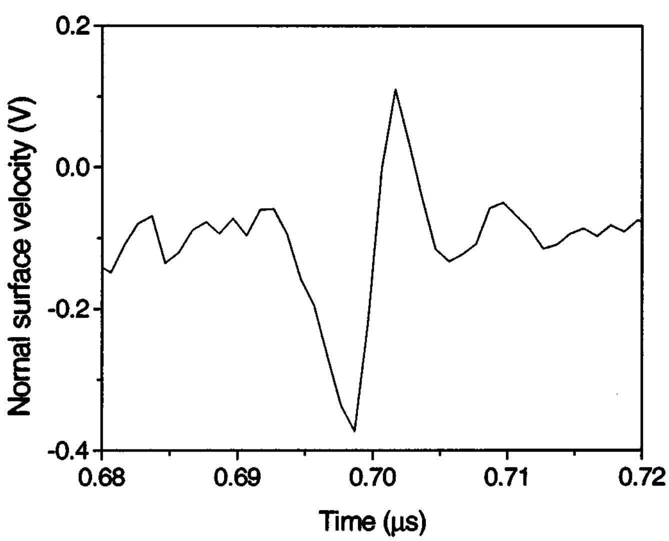

FIG. 1. SAW pulse registered at a free surface of silicon in (001) plane at distance $x = 3.6$ mm from the source.

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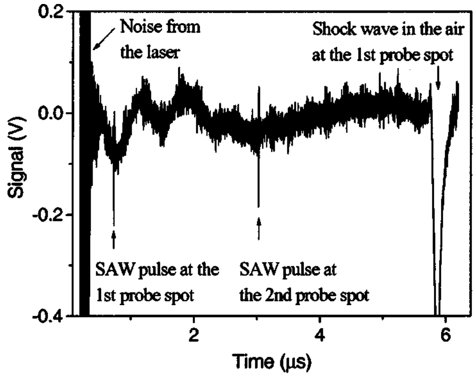

FIG. 2. Signal sequence registered with dual-probe-beam deflection setup.

plane the manifestation of the acoustic nonlinearity is relatively weak[4] and only a slight steepening of the slope in the center of the pulse was observed during its propagation. The laser fluence in this case was about 60 J/cm^2 and well above the ablation threshold, since even at 7 J/cm^2 the ablation was noticeable. The optical breakdown at the surface took place and was accompanied by the generation of a strong shock wave in the air that was detected at the first probe spot as a large and relatively wide (negative) peak. The signals corresponding to arrivals of different waves to the first and second probe spots are shown in Fig. 2 on a larger time scale. The delay of the shock wave in the air at the second probe spot was too large for this signal to be captured on the oscillogram.

SAW pulses were also generated through a liquid layer. We used suspension of fine carbon particles in water or glycerol, which produced similar results. With this method the achieved amplitudes were on the order of magnitude the same as with the ablation at the free surface, however, no strong shock wave in the air was registered. The pulse observed is shown in Fig. 3. When a liquid film is not strongly absorbing (as for water and glycerol) the laser radiation is absorbed in silicon and leads to an explosive evaporation of the liquid in the layer adjacent to the solid surface. As a result, a strong pressure pulse is produced that exerts a force normal to the surface of the solid. The pulse depicted in Fig. 3 has a typical shape for this case,[5] with two broad wings and a narrow peak of opposite polarity inbetween.

A SAW grating was generated at the (111) surface of silicon with propagation in the ⟨110⟩ direction (Fig. 4). The comparison of frequency spectra at two propagation distances $x=1.9$ mm and $x=12.3$ mm (Fig. 5) reveals spectral changes with the propagation distance, namely a relatively higher amplitude of the second harmonic and development of additional peaks in the spectrum at intermediate frequencies.

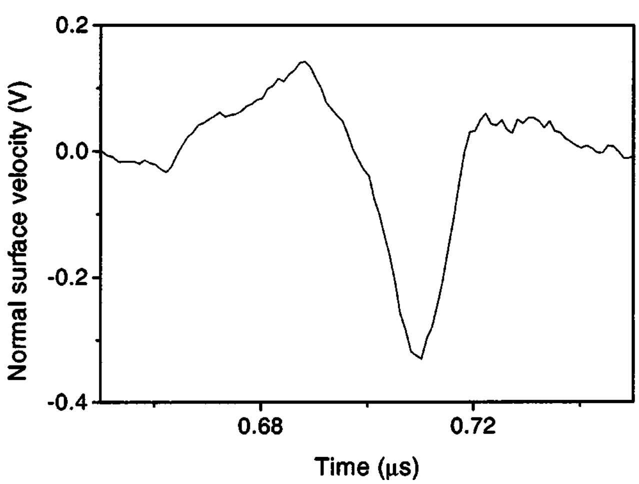

FIG. 3. SAW pulse generated through a liquid layer.

IV. DISCUSSION AND CONCLUSION

The shape of the SAW pulse generated by a femtosecond laser pulse at a free silicon surface (Fig. 1) corresponds to the thermoelastic mechanism of excitation despite the fact that well developed optical breakdown and ablation take place at the surface. This is quite different from the dependences observed with nanosecond laser pulses,[6] where the occurrence of ablation with the increase of the laser fluence marks the predominance of the ablative mechanism, which manifests itself also in the change of the pulse shape. Another remarkable feature observed with femtosecond laser pulses at 800 nm is the high effectiveness of SAW generation at the free surface, compared to the generation with a liquid layer. With nanosecond laser pulses the latter approach could produce SAW pulses with about 50 times higher amplitude than those generated at a free surface.[7] With femtosecond laser pulses the amplitudes in these two cases are close (compare Figs. 1

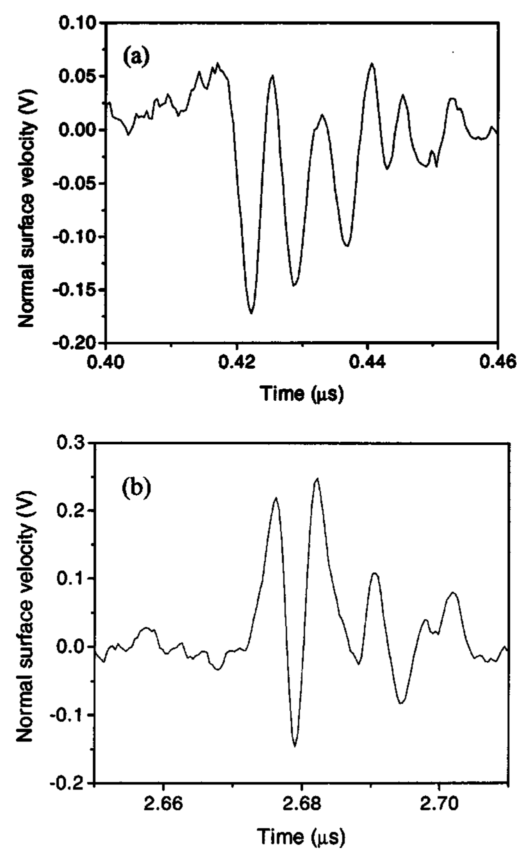

FIG. 4. SAW grating detected at two propagation distances $x_1=1.9$ mm (a) and $x_2=12.3$ mm (b).

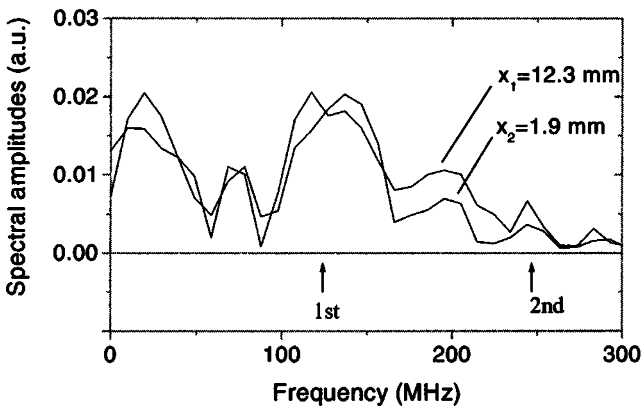

FIG. 5. Spectra of the pulses presented in Fig. 4; first and second harmonics are indicated by arrows.

and 3). One reason for this can be that the absorption at 800 nm in silicon is close to optimal (the penetration depth is about the lateral dimension of the focal region). Another possible reason is that the screening of the surface due to the formation of plasma does not have time to develop during the action of the laser pulse itself, as it takes place for nanosecond laser pulses. Consequently, the energy of the fs laser pulse is used more efficiently in the generation process.

In summary, the generation of SAW pulses with femtosecond laser pulses was rather efficient at a free surface of Si. The shape of the observed SAW pulses corresponded to the thermoelastic mechanism, although a well developed ablation took place. The amplitudes of the pulses in this case were close to those with the excitation through a liquid layer, where the duration of the pulses was longer. In the experiments with SAW gratings that were generated by focusing the laser beam onto the surface through a mask and propagated in the (111) plane of Si, the nonlinear interactions were displayed in the spectrum of the pulse due to the increase of the amplitude of the second harmonic and development of additional peaks in the spectrum.

ACKNOWLEDGMENT

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