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Time-Resolved Two-Dimensional Imaging of sub-GHz Surface Acoustic Waves Induced by Ring-Shaped Optical Excitation

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1. Introduction

Surface acoustic waves (SAWs) in megahertz-gigahertz frequency region have been widely exploited in micro- or nano-scale materials characterization, filter devices in telecommunication, and sensors. For developing such applications, the spatiotemporal monitoring of the transduction of the acoustic waves is a powerful tool.

For evaluating structural, elastic, and thermal properties of materials, in micro- or nano-scale, a technique called picosecond laser ultrasonics has been widely used.[1)] This is based on an optical pump-probe method, where laser pulses with picosecond temporal width are used to generate acoustic waves in the medium, and the propagation of these generated acoustic waves is monitored with delayed light pulses. By adding a facility for scanning the probing spatial position to a standard picosecond ultrasonics measurement setup, one may achieve the spatiotemporal monitoring of the propagation of the acoustic waves in megahertz-gigahertz frequency region.[2)]

In such a measurement, typically the excitation light is tightly focused on the sample to generate acoustic waves efficiently. This result in a relatively high energy density at the excitation point and may cause a damage on the sample. This would be a potential problem for thin, small, and delicate samples. In this study, we aim to develop a measurement technique that mitigates the sample damage by shaping the excitation light into a ring form instead of a circle with small radius. This would allow one to measure the samples that are difficult to assess using conventional methods.

2. Experiment

To image the SAWs, a typical picosecond ultrasonics measurement setup is used. This employs two groups of laser pulses: pump light pulses and probe light pulses both from a single mode-locked Ti-sapphire laser.[2,3)] The temporal width of the laser pulses is about 0.2 ps, and the repetition frequency is 80 MHz. The central wavelength of the pump and probe light is 415 nm and 830 nm, respectively. By

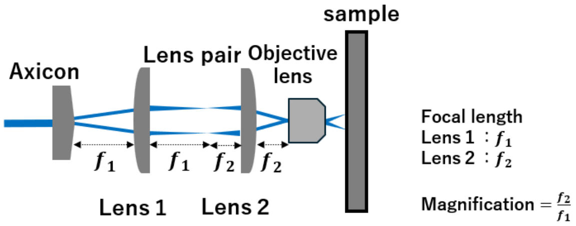

Fig. 1 The pump light is shaped into a ring by passing through the axicon lens. A pair of lenses with different focal lengths ($f_1 > f_2$) is used to make the pump light fits into the entrance aperture of the objective lens. By choosing the different focal lengths ($f_1 > f_2$), the size of the final ring shape on the sample can be adjusted.

irradiating the sample with the pump light pulses, the SAWs are excited. The delayed probe light pulses are focused on the sample to detect the surface displacement caused by the SAWs using an interferometer. By scanning the position of the focused probe light pulses two-dimensionally over the sample surface, the spatial image of the SAWs at a single moment, which is defined by the delay time between the arrival of the pump light pulses and that of the probe light pulses onto the sample, is obtained. Additionally, by varying the delay time, the time resolved SAW images are obtained.

To shape the pump light irradiation pattern into a ring, an axicon lens and a relay optical system are used as shown in **Fig. 1**. The axicon lens has a conical shape and converts a collimated beam to a (broad) diverging ring. By introducing this diverging beam to a convex lens (in our case, a microscopy objective of x50), the beam is focused to a thin ring shape. The diameter of the formed ring depends on the apex angle of the cone and the distance from the lens. In other words, the ring-shaped pump light formed through the axicon lens expands as it propagates away from the lens. To capture this expanding pump light into the entrance aperture of the objective lens efficiently, the relay optical system composed of two lenses is used. By passing through a pair of lenses with different focal lengths, the diameter of the final focused ring can be adjusted.

The sample is a Si (111) substrate. A chromium and a gold thin film (thickness 5 nm and

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100 nm, respectively) are deposited in this order on the mirror polished surface of the substrate. The SAW imaging measurement is done from the gold coated surface with the described optical setup. The pump beam intensity is 22 mW which is much higher than usual power up to 10 mW for the conventional point focused excitation.

3. Results

Figure 2 shows the SAW images at several different delay times. The delay time zero corresponds to the arrival of the pump light pulse to the sample surface. The propagation of ring-shaped SAW wavefront from the excitation ring both inward and outward is observed. Especially, at the delay time 9.12 ns, the focusing of the inward propagating wave is observed. Thanks to the newly designed pump light shaping optics, the SAWs are efficiently generated with the ring-shaped acoustic source.

The dispersion relation shown in **Fig. 3** is calculated using a spatiotemporal Fourier transform on the experimental results. The small anisotropy related to the Si crystalline structure is ignored here. Because of the limited number of obtained frames (30 in this case), the curve is reflected at 1.2 GHz due to the aliasing. Two different modes are observed

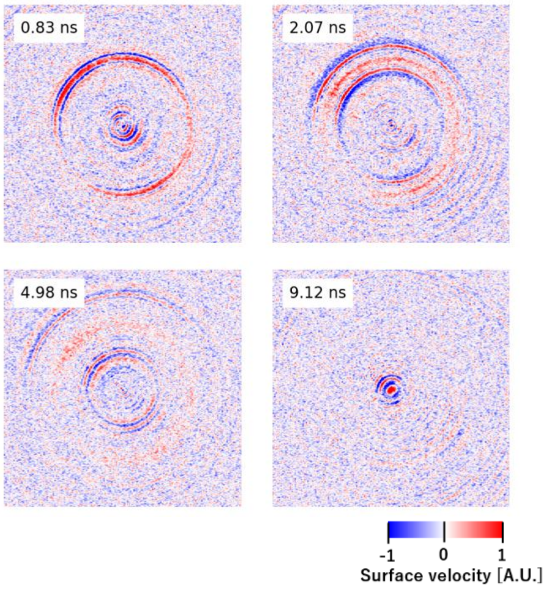

Fig. 2 The SAW images measured over about 100 μm × 100 μm area at several different pump-probe delay times. The image at 0.83 ns shows the moment immediately after the SAWs are excited, whereas the images at 2.07 ns, 4.98 ns, and 9.12 ns show the propagation of the SAWs after the excitation. At 9.12 ns, the SAWs excited from the entire ring overlap at the center of the image, resulting in a significant increase in the amplitude.

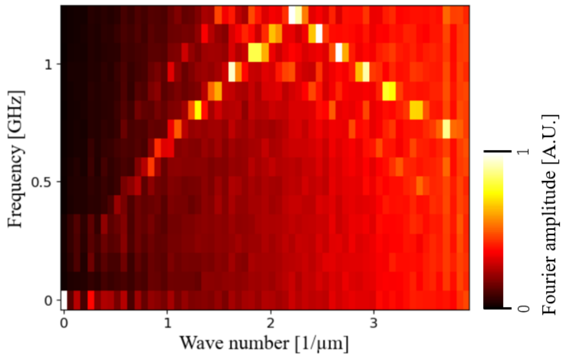

Fig. 3 The dispersion relation calculated from the spatiotemporal Fourier transform of the measured SAW data.

with the sound velocity 7500 m/s and 5000 m/s at the limit of k=0. The latter is interpreted as the Rayleigh-like mode and the former is interpreted as the surface skimming longitudinal wave (Sezawa mode). Both modes show significant dispersion caused by the Au film loading on the Si substrate. Considering the aliasing effect, the measurement setup is capable to excite the acoustic waves with the frequency up to 1.7 GHz or with the wavelength down to around 1.7 μm. (spatial resolution ~ 0.9 μm)

4. Conclusion

The conventional pump-probe system for SAW imaging is improved using an axicon lens and a relay optical system. With this setup, we successfully image the propagation of waves propagating both inward and outward directions from the ring-shaped excitation source by using ring-shaped pump light. Using spatiotemporal Fourier transform, the dispersion relation for the propagating SAWs is obtained. The results confirm that the SAWs with the wavelengths down to 1.7 μm is excited. This would extend the applicability of the imaging method to various fragile samples which are not endurable for the intense point-focused excitation light.

References

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