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Observation of induced shear acoustic phonons by Brillouin scattering

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In order to overcome the low accuracy of velocity measurements by Brillouin scattering, we have tried to make use of the induced coherent phonons, which brings intense Brillouin scattering peaks. To induce phonons, we used a tilted ZnO film transducer developed in our laboratory. As a result, we obtained the intense Stokes peak in the silica glass sample which was much larger than that obtained from the thermal phonons. Because Brillouin scattering enables the simultaneous measurement of longitudinal and shear phonons velocities, this technique opens the new feature for the non-destructive elasticity measurement.

1 Introduction

Recently, thin film becomes a key technology in the area of semiconductor devices. Brillouin scattering measurement is an efficient nondestructive method of observing the wave properties in a minute part of such kind of thin material, using a focused laser beam at hypersonic frequencies [1, 2]. This technique enables the simultaneous measurement of longitudinal and shear wave velocities. However, the measurement accuracy of the observed wave velocities is lower than those of other methods, such as ultrasonic pulse techniques. It strongly depends on the measurement condition and transparency of the sample. Usually, the expected error of wave velocity sometimes becomes several percent or more, because of the weak Brillouin light scattering from the thermal phonons [3].

In this study, we have tried to overcome the above problem, making use of the induced longitudinal and shear waves radiated from the ZnO film transducer. Several shear wave measurement techniques using induced waves have already reported [4-5]. However, these techniques are not completely adequate for actualizing convenient and simple non-destructive measurement of wave velocity with an appropriate accuracy. In particular, it seems difficult to measure the anisotropic velocity in a minute area. Therefore, we here propose a combination of Brillouin scattering and a tilted ZnO transducer, which is applicable to various samples. Making use of the tilted ZnO film transducer, we have succeeded in the measurement of intense longitudinal and shear Brillouin peaks.

2 Methods

2.1 Measurement system

Brillouin scattering measurement system is shown in Fig. 1. It is performed using a six-pass tandem Fabry-Perot interferometer (JRS scientific instruments) with an Argon ion laser at a wavelength of 514.5 [nm]. The actual diameter of the focused laser beam in the sample was approximately 50 [μm]. The laser power near the sample was 60 [mW]. The scattered light was received by a photomultiplier (Hamamatsu, 464s) and averaged by the photon counter after the analog to digital conversion. It was then recorded as a frequency spectrum in the computer.

In this measurement, the wavelength and the direction of the observed phonons are determined by the scattering geometry, which specifies the directions of the incident and scattered light. In this study, the Reflection Induced ΘA (RIΘA) scattering geometry in Fig. 2 was used. This geometry is attained by attaching a flat metal to the reverse side of the samples as a reflector, and enables the simultaneous measurement of phonons that propagate in both wave-vector directions of $q^{\Theta A}$ and q^{180}. The wave vectors can be selected easily by changing the incident angle.

In the spectrum, three pairs of peaks are seen symmetrically. The two inside pairs of peaks are ΘA scattering Brillouin peaks (shear and longitudinal acoustic phonons) and the other pair is the 180º scattering Brillouin peaks. From the spectrum, we can obtain the frequency shifts of both $f^{\Theta A}$ and f^{180}, which give us the wave velocities from the following equations.

$$v^{\Theta A} = \frac{f^{\Theta A}\lambda_0}{2\sin(\Theta/2)} \tag{1}$$

$$v^{180} = \frac{f^{180}\lambda_0}{2n} \tag{2}$$

Here, λ_0 is the wavelength of the incident light, n the refractive index.

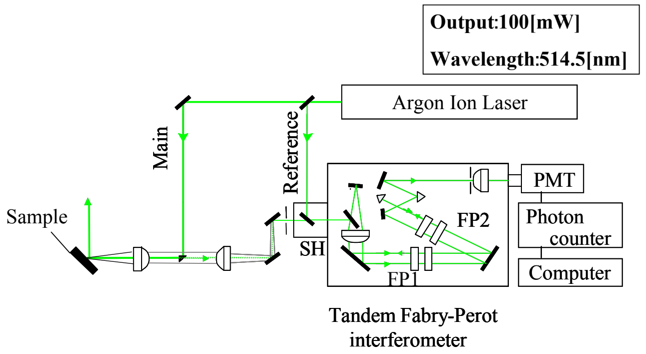
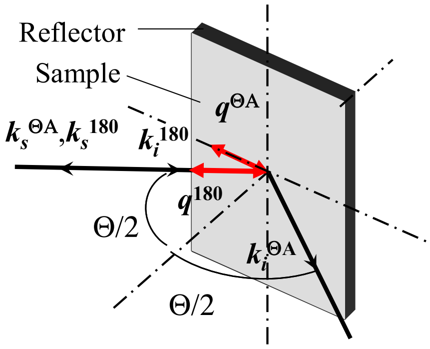


Fig. 1 Block diagram of the measurement system.



k_i: The wave vector of the incident light.

k_s: The wave vector of the scattered light.

q: The wave vector of the sound wave.

Θ/2: The angle between incident laser beam and normal line of sample surface.

Fig. 2 RIΘA scattering geometry.

2.2 Sample

In this study, we have attempted to observe induced shear and longitudinal acoustic phonons in a silica glass sample, using the ZnO film transducer developed in our laboratory [6, 7]. The crystallite c-axis of this film tilted to the substrate, which enables effective radiation of shear and longitudinal waves in the GHz range. In addition, this film can be fabricated on any material without the need for the epitaxy technique. Here, the transducer (film thickness: 2.4 [μm], resonance frequency of fundamental shear mode: 600 [MHz], longitudinal mode: 1.20 [GHz]) was deposited on one side of the silica glass sample (Tosoh, ED-B) with the size of $3 \times 10 \times 35$ [mm^3]. On the reverse side of the sample, a copper film was deposited as a light reflector. The sample configuration is shown in Fig. 3. We have induced continuous longitudinal or shear wave propagation in the silica glass sample using a signal generator (E8257D, Agilent technologies) and a pico probe (LCP18, NPS). We tried to induce and observe shear and longitudinal waves.

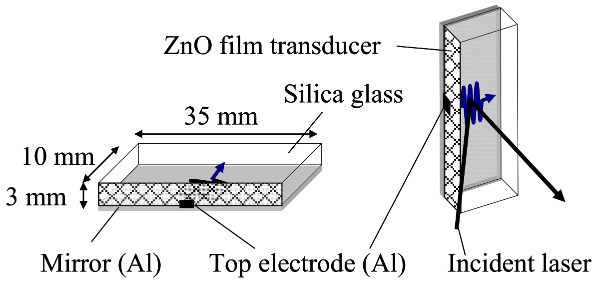
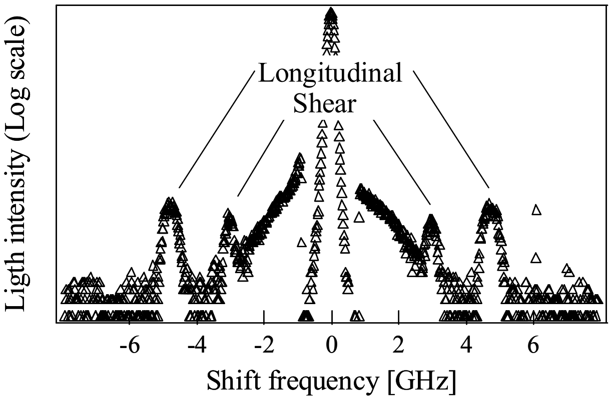


Fig. 3 The sample configuration.

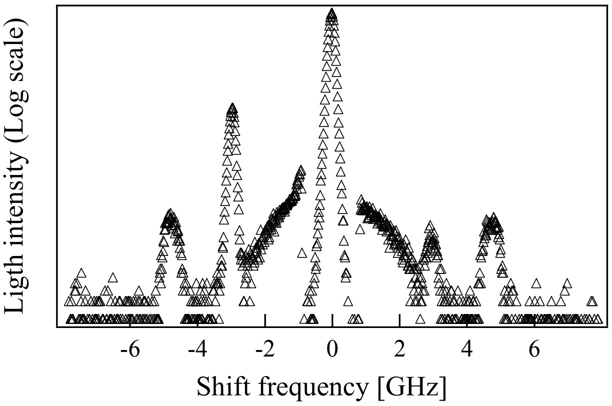
3 Results and Discussion

3.1 Observation of induced shear wave

Figure 4(a) shows the Brillouin spectrum from the silica glass sample without the induced wave. A pair of small ΘA scattering peaks due to the shear acoustic phonons is observed at 3.00 [GHz]. 180° scattering peaks are outside of this spectrum, Here, we chose $\Theta/2=12.0°$. At this angle, the shift frequency $f^{\Theta A}$ (shear acoustic phonons) is near the fifth resonance frequency of the ZnO film transducer. Figure 4(b) shows the Brillouin spectrum from the sample with induced shear waves, obtained using the fifth resonance (3.00 [GHz]). We have induced shear acoustic waves with the same polarization direction as that of the incident laser. The Stokes peak is strongly amplified. This result corresponds with the propagation direction of the induced wave. The Stokes peak intensity is approximately 3500 counts (power P_{sw} applied to ZnO film transducer is 15 [dBm]). In contrast, the anti-Stokes peak due to thermal phonons is approximately 30 counts. Moreover, the FWHM (full width at half maximum) of the Stokes peaks is around 150 [MHz], which is as narrow as the central elastic peak.

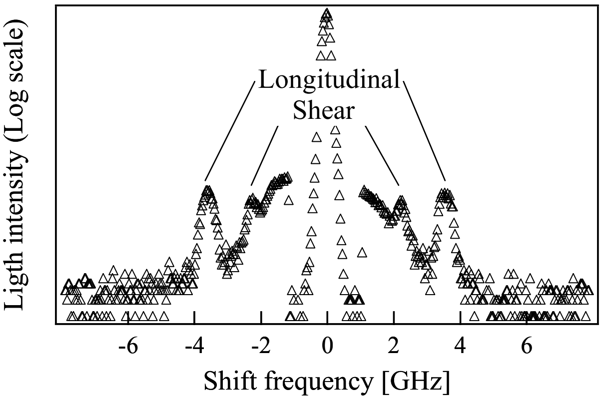


(a) Without shear wave excitation ($\Theta/2=12°$).

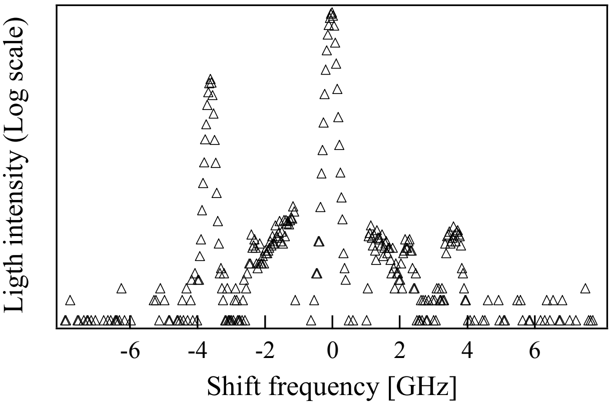


(b) With shear wave excitation ($\Theta/2=12°, f_{sw}=3.00$ GHz).

Fig. 4 Brillouin spectra from a silica glass sample.



(a) Without longitudinal wave excitation($\Theta/2=9°$).



(b) With longitudinal wave excitation

($\Theta/2=9°, f_{lw}=3.65$ GHz).

Fig. 5 Brillouin spectra from a silica glass sample.

3.2 Observation of induced longitudinal wave

A similar experiment was done using the longitudinal wave. Figure 5(a) shows the Brillouin spectrum from the sample without the induced longitudinal wave. We chose Θ/2=9.0º, because Brillouin peaks of longitudinal acoustic phonons are observed at 3.65 [GHz]. Figure 5(b) shows the Brillouin spectrum from the sample with induced longitudinal waves, obtained using the third longitudinal resonance (3.65 [GHz]). The Stokes peak is strongly amplified. The Stokes peak intensity is approximately 2000 counts (power P_{lw} applied to ZnO film transducer is 15 [dBm]). In contrast, the anti-Stokes peak due to thermal phonons is approximately 10 counts.

3.3 Identification of induced phonons

In the measurement of the foregoing paragraph, scattered light was amplified by the waves radiated from the ZnO film. In order to confirm this amplification, scattered light intensity was measured as a function of input power to ZnO and the measurement position in the sample as follows.

Figure 6 shows the relationship between the microwave power input to the ZnO film transducer and the observed light intensity. The light intensity increases with the input microwave power. This increase is almost linear in the range from -5 to 15 [dBm]. In a lower region, the slope of the light intensity shows slightly non-linear behavior because of the effect of thermal acoustic phonons.

Figure 7 shows the light intensity distribution in a silica glass sample. The light intensity becomes lower as a function of distance from the ZnO film transducer. The two curved lines represent estimated values of attenuation in the silica glass sample. Curved lines for 127 and 179 [dB/cm] were obtained from the estimated values of propagation loss at 3.65 [GHz] (longitudinal wave) and 3.00 [GHz] (shear wave), respectively [8, 9]. The distribution of the light intensity is in good agreement with the estimated value.

These two results tell the amplification of the Stokes peak was performed by the induced phonons.

4 Conclusion

We have succeeded in the Brillouin scattering measurement of longitudinal and shear acoustic waves induced by the tilted ZnO film transducer. This ZnO film transducer can be fabricated on various solid materials, and enables easy measurement of longitudinal and shear wave velocities in plane. Moreover, using a microscope system, we will be able to observe much smaller regions (approximate minimum size is 10 [μm]) [10]. We can also expect longitudinal and shear wave measurements in much thinner film layers to be possible, making use of the advantage of this scattering geometry [11]. This technique might lead to the expansion of the measuring object.

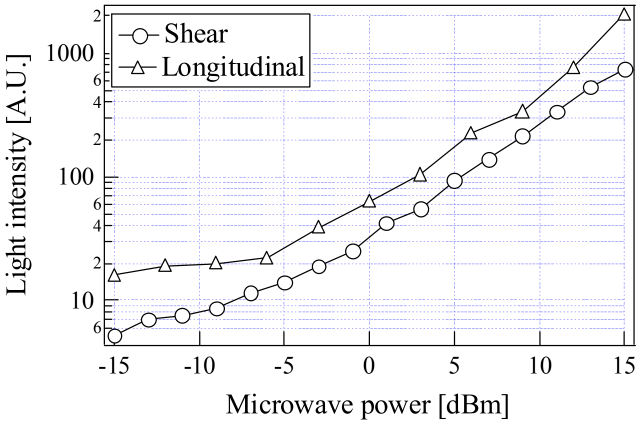


Fig. 6 Relationship between applied microwave power and light intensity.

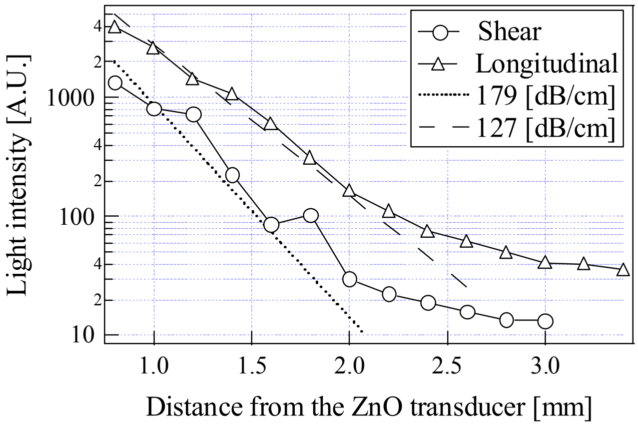


Fig. 7 Light intensity distribution in a silica glass sample.

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