Development of confocal picosecond ultrasonics
共焦点ピコ秒超音波の開発

Nobutomo Nakmaura[1†], Atsushi Maehara[1], and Hirotsugu Ogi[2]
([1]Grad. School Eng. Sci., Osaka Univ.; [2]Grad. School Eng., Osaka Univ.)
中村暢伴 [1†]，前原敦 [1]，荻博次 [2] ([1] 阪大院 基礎工, [2] 阪大院 工)

1. Introduction

Picosecond ultrasonics [1] is a powerful method for characterizing nanometer- and micrometer-scale structures. It has been applied for several structures such as thin films [2], multilayers [3], nano wires [4], and nano dots [5], and acoustic and elastic properties have been evaluated successfully.

In picosecond ultrasonics, acoustic pulses are excited and detected using ultrashort pulse lights, pump and probe lights. When the picosecond ultrasonics is applied to transparent materials, an oscillational signal, so-called Brillouin oscillation, is observed in the probe light reflected from a specimen. The oscillation is caused by interference between light reflected at a specimen surface and that scattered by an acoustic wave propagating in a specimen. Because frequency of the oscillational signal depends on the sound velocity of the acoustic pulse, sound velocity is measurable from the frequency. The frequency is calculated from the signal using Fourier transformation, and the sound velocity averaged over the path where the acoustic pulse propagates is determined as the resultant sound velocity.

In nanometer- and micrometer-scale structures, it is exposed that acoustic and elastic properties are not necessarily uniform due to nonuniform distributions of residual stress, defects, and texture. Therefore, measurement of local properties is required for comprehensive understanding of the properties. In picosecond ultrasonics, by narrowing the time scale of the signal used for Fourier transformation, local sound velocity can be determined. However, measurement accuracy of sound velocity is lowered as the time scale becomes narrower.

In this study, we propose another method for evaluating local sound velocity, in which picosecond ultrasonics is combined with confocal microscopy. In conventional microscopy, light reflected at the focal point is predominantly detected, but that reflected around the focal point is detected as well. Therefore, resolution in the depth direction is not high. In contrast, in confocal microscopy, light reflected around the focal point cannot pass through a pinhole, and the resolution in the depth direction is improved. Using the microscopy, three-dimensional analysis is possible by moving the focal point, and the confocal microscopy is used widely nowadays. In addition, the confocal optics has an affinity to other optical measurements, and it has been applied for Raman microscopy [6] and Brillouin scattering [7]. Under the circumstances, in this study, we combine picosecond ultrasonics with confocal microscopy for evaluating local sound velocity in nanometer-scale structures.

nobutomo@me.es.osaka-u.ac.jp

2. Optics of confocal picosecond ultrasonics

In picosecond ultrasonics, acoustic waves are excited by irradiating a specimen surface with pulse light generated by a femtosecond pulse laser. The pulse light is called pump light. The specimen is then irradiated with another pulse light, probe light, and reflected probe light from the specimen is detected by a balanced detector. The reflected probe light contains light reflected at the specimen surface and that backscattered by the acoustic pulse propagating in the specimen, and interfered light is detected. Because length of optical path of the scattered probe light changes as the acoustic pulse propagates in the specimen, an oscillation pattern appears in detected signal. This signal is called Brillouin oscillation. Using the Brillouin oscillation, an acoustic pulse that propagates for more than 10 μm is detectable [8]. However, the depth resolution of the conventional picosecond ultrasonics is not high, and acoustic waves that propagates at different depths are detected simultaneously, which makes evaluation of local sound velocity difficult. This difficulty should be solved by using the confocal optics.

Figure 1 shows the confocal optics embedded in picosecond ultrasonics. Pinhole and lens are embedded in the optical path of the probe light. When an acoustic pulse is located at the focal point, scattered probe light is focused again at a pinhole, and it passes through the pinhole. However, when an acoustic pulse is not at a focal point, scattered light cannot pass through a pinhole, and intensity of detected signal becomes significantly small, which makes it possible to detect propagation of acoustic pulses only at the focal point.

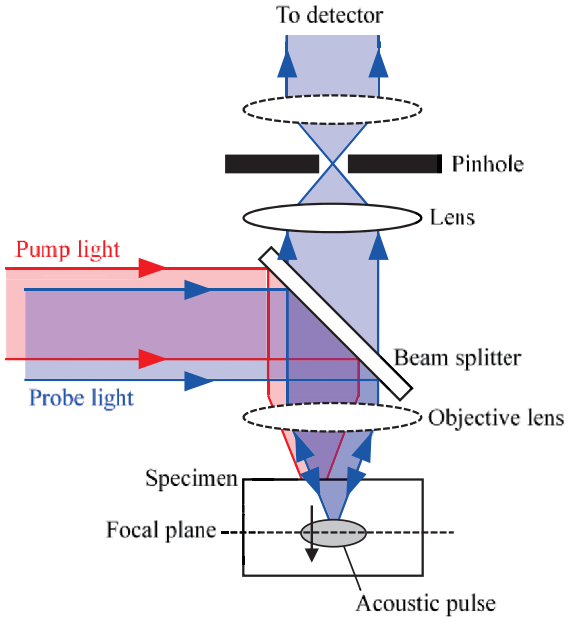

Fig. 1 Confocal optics added into picosecond ultrasonics.

3. Results and discussion

We used two Ti-Sapphire pulse lasers with repetition rate of 10 MHz and wavelength of 800 nm as light sources. The lasers were synchronized. Pump light was modulated at 1 MHz for lock-in detection by passing through the acousto-optic modulator. Wavelength of the probe light was changes to 400 nm by passing through a second harmonic generation crystal. The pump and probe lights were introduced into a confocal laser scanning microscope. In the microscope, the lights were reflected at a beam splitter, and pass through an objective lens. Specimen surface was then irradiated with the lights. Probe light reflected from the specimen was then passes through the pinhole, and it was detected by the balanced detector as shown in Fig. 1. Objective lens with magnification of 40 and numerical aperture of 0.95 was used. Diameter of a pinhole is controllable using the software equipped with the microscope. Silica film deposited on quartz substrate was used as a specimen. Al film was deposited on the silica film as a sound source.

Figure 2 shows the experimental results. First, the objective lens was moved so that the focal point is located at the specimen surface, and measurement was performed with the pinhole full open. The result is shown in Fig. 2(a). An abrupt increment of the signal around 17 ps indicates that an acoustic pulse is excited at this moment. Then, oscillation of the signal appeared. The signal attenuated monotonically with time. This is the typical behavior observed in picosecond ultrasonics. Then, the focal point was moved into the specimen, and the pinhole size was changed so that the focal depth becomes about 1 μm. The result is shown in Fig. 2(b). The waveform is different from that observed in Fig. 2(a), and a wave packet is observed. When the focal point was moved, the wave packet shifted, and it was confirmed that the picosecond ultrasonics can be combined with the confocal microscopy.

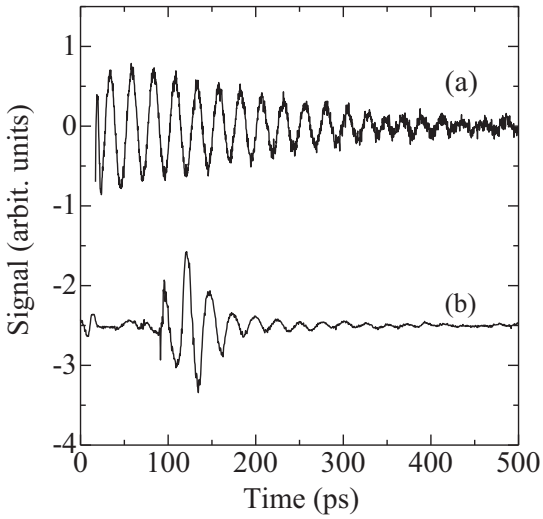

Fig. 2 Signal obtained using confocal picosecond ultrasonics when the pinhole is (a) full open and (b) focal depth is 1 μm.

4. Conclusion

We developed picosecond ultrasonics combined with confocal microscopy. A wave packet was observed in the signal, and it was confirmed that the confocal picosecond ultrasonics has a potential to measure local sound velocity.

References

1. C. Thomsen, H. T. Grahn, H. J. Maris, and J. Tauc, Phys. Rev. B **34** (1986) 4129.
2. H. Ogi, M. Fujii, N. Nakamura, T. Yasui, and M. Hirao, Phys. Rev. Lett. **98** (2007) 195503.
3. B. M. Clemens and G. L. Eesley, Phys. Rev. Lett. **61** (1988) 2356.
4. G. A. Antonelli, H. J. Maris, S. G. Malhotra, and J. M. E. Harper, J. Appl. Phys. **91** (2002) 3261.
5. J.-F. Robillard, A. Devos, and I. Roch-Jeune, Phys. Rev. B **76** (2007) 092301
6. G. J. Puppels, F. F. M. de Mul, C. Otto, J. Greve, M. Robert-Nicoud, D. J. Arndt-Jovin, and T. M. Jovin: Nature **347** (1990) 301.
7. G. Scarcelli and S. H. Yun: Nat. Photonics **2** (2008) 39.
8. A. Nagakubo, M. Arita, H. Ogi, H. Sumiya, N. Nakmaura, and M. Hirao, Appl. Phys. Lett. **108** (2016) 221902.