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Development of beyond-10 GHz ultrasonic microscopy by asynchronous picosecond ultrasonics

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1. Introduction

In spite of development of various imaging techniques, it is important not only to observe the structure but also to evaluate the physical properties. Among them, the ultrasonic microscopy can evaluate the mechanical properties and nondestructively investigate inside opaque structures, resulting in wide use in industry and the medical field. However, its spatial resolution has not been superior to that of optical microscope[1-4]. To improve resolution, it is necessary to decrease the wavelength of ultrasound. It is difficult for conventional techniques using piezoelectric transducers to generate ultrasonic pulses whose widths are shorter than a few nanoseconds, and further resolution improvement cannot be expected[5].

In this study, we design nm-order acoustic lens to focus beyond-10 GHz ultrasound and make it by using the focused ion beam (FIB) method. GHz-sub THz ultrasound is excited by asynchronous optical sampling (ASOPS) picosecond ultrasonics[6–10]. We also estimate the acoustic propagation and reflection process using finite element calculations.

2. Acoustic lens

We design an acoustic lens made on SiO_2. The space between a lens and a sample is filled with water for acoustic coupling. Therefore, considering the sound velocity difference between SiO_2 and water, we calculate the ideal lens shape, where all of the incident ultrasound focuses at one point. Then, we determine the lens profile to be aspheric with a diameter of 1 μm and a depth of 520 nm. The focal length from deepest point is 650 nm.

To make acoustic lens, we the FIB method. We fabricate lenses on thermal dioxide films on Si substrates with various conditions using Ga ion FIB, where the voltage and current are 30 kV and 1–10 pA, respectively.

We calculate time-dependent wave propagation using the finite element method using COMSOL 5.4. A 10 GHz ultrasound pulse is generated by heating the Al layer equivalent to a laser pulse with a Gaussian profile. The echo reflected from the sample surface and pressure distribution at the focus plain are analyzed.

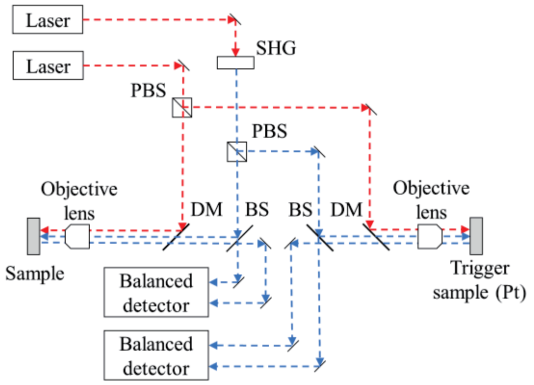

Fig. 1 Schematic of the optical systems. Red and blue dot lines denote pump and probe light, respectively.

3. Asynchronous Picosecond ultrasonics

We use originally developed ASOPS measurement system. We show the schematic of the optics in **Fig. 1**. We use two titanium/sapphire femto-second pulse lasers as pump and probe light pulses. We convert the wavelength of the probe light pulses into 400 nm by a second harmonic generator (SHG). Pump and probe light pulses are split into trigger and measurement specimen paths by polarization beam splitters (PBSs). To overlap pump and probe lights, we use dichroioc mirrors (DMs), which reflect and transmit 800 and 400 nm lights respectively. Both pump and probe light pulses enter the specimens through objective lenses. We use balanced detectors (BDs) to extract the reflectivity changes caused by the pump light. In our ASOPS system, we use a trigger sample of ~100 nm Pt film on Si substrate to measure Δf each time to convert and average measurement data.

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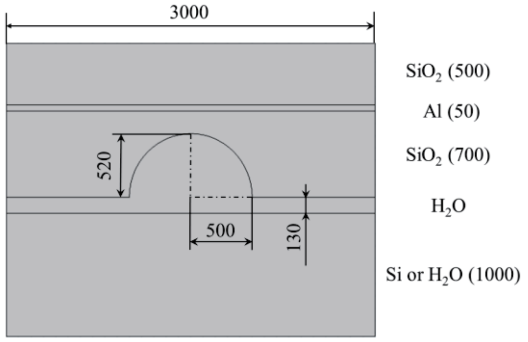

Fig. 2 The model of finite element simulation. The unit is nm.

4. Result and Discussion

We show the simulation model in **Fig. 2**. We apply a 10-GHz heat pulse in the Al film and simulate the corresponding stress and strain propagation. **Figure 3** shows the calculated strain changes on the Al top surface. We apply a thermal Gaussian pulse at 0 ps, whose pulse width is 100 ps, leading to thermal expansion and acoustic pulse propagation. We can observe several signals around 320 and 900 ps. The former is a reflection signal from the interface between SiO_2 and water, and the latter is a reflection signal from the bottom Si surface. We estimate the resolution of 10 GHz ultrasonic focused at the focal point without a sample. We show the profile of pressure in **Fig. 4**. The waveform exhibits a Gaussian shape, with a full width at half maximum (FWHM) of 168 nm. Therefore, the ideal resolution for the current measurement system is ~170 nm. Resolution can be improved by using higher frequency ultrasound; picosecond ultrasonics can excite 1–1000 GHz ultrasound. We try to fabricate small and smooth acoustic lens to prevent acoustic attenuation and scattering because higher frequency ultrasound has higher space resolution and higher attenuation.

4. Conclusion

We design and make an acoustic lens and simulate. We simulate echoes in the nm-order acoustic lens system beyond 10 GHz. The use of high frequency ultrasound could lead to even higher resolution, and the ASOPS system measurements will enable imaging in shorter periods of time.

Acknowledgment

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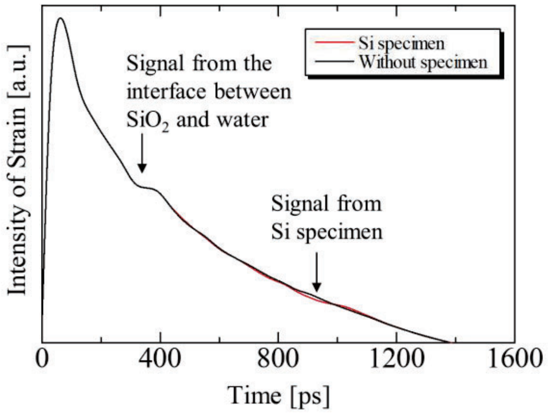

Fig. 3 Strain changes on the top surface of Al film calculated by time-dependent calculation.

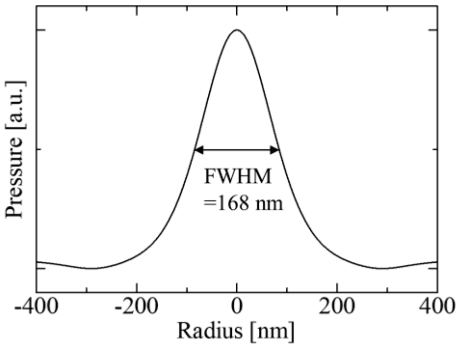

Fig. 4 Calculate sound pressure profile of a 10 GHz ultrasonic pulse at the focal plane of the lens. The horizontal axis is the distance from the center axis of the sample and the vertical axis is normalized pressure.

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