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Directional detection of acoustically induced electric polarization with a differential antenna

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1. Introduction

Bone is principally composed of hydroxyapatite, which is responsible for its strength, and collagen fiber, which is responsible for its toughness. It is known that collagen fibers are remodeled to optimize the orientation to mechanical loading (Wolff's law).[1,2] This concept implies that collagen orientation can be a new indicator for assessing bone quality. For example, in healthy cortical bone, collagen is aligned along the bone axis, but this orientation is reported to be disorganized in chronic kidney disease causing osteoporosis.[3] Furthermore, collagen orientation will also be important in assessing the integrity of collagen fibers during the healing process of fractures. Despite the recognized importance of bone quality, collagen diagnostic techniques have not yet been established.

This study focused on the piezoelectricity of bone, which is reported to be mainly derived from collagen. Piezoelectricity of bone was first discovered in dehydrated femoral cortex suggesting a link between bone collagen orientation and piezoelectricity.[4] The obtained piezoelectric tensor shows the uniaxial symmetry with the direction of collagen fiber orientation as the principal axis. This implies that the anisotropic feature of piezoelectric polarization is an index for evaluating the quality of bone. However, most studies have been based on experiments on dehydrated bone fragment samples using tensile-compression testing machines[4] or piezoelectric force microscopes.[5] Therefore, there is a need to develop piezoelectric measurement methods that can assess wet or living tissues.

Recently, we have demonstrated a unique ultrasonic method to measure the acoustically induced electric polarization originated from piezoelectricity.[6-8] The principle of this technique is based on the generation and detection of acoustically stimulated electromagnetic (ASEM) response through electro- or magneto-mechanical coupling of materials. The ASEM method has the advantage of measuring the piezoelectricity even in living wet tissues owing to high-frequency ultrasound modulation. The polarization was detected by a capacitive antenna (a metal plate) with a resonance circuit tuned to the ultrasound frequency. However, there are still challenges to be addressed in its application to clinical practice. First, it is necessary to devise an ASEM detection scheme that avoids the noise from human body because the human body acts as an antenna to receive ambient external radio waves. Second, it is needed to improve the signal-to-noise ratio (SNR) because the ASEM signal is extremely small. Third, the quantitative evaluation of collagen orientation requires the directional detection of acoustically induced polarization. To solve the above challenges, we attempted to detect the polarization using a differential antenna (two parallel metal plates) that probes the difference of the induced charges on two plates. In this paper, we report that the differential antenna is a promising detection scheme to address the above challenges.

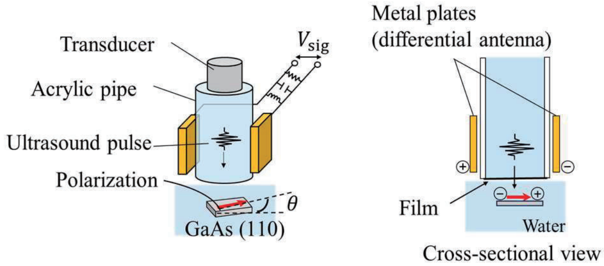

Fig. 1 Schematics of the measurement set up. The left figure shows the cross-sectional view of the ASEM probe.

2. Experimental Setup

We have measured the characteristics of the differential antenna using a typical piezoelectric GaAs(110) wafer with piezoelectric component d_{14}. Acoustically induced polarization is expected to occur in the ⟨001⟩ direction when ultrasound waves are applied to the piezoelectric axis of ⟨110⟩.[6] In the directivity of a capacitive differential antenna, the sensitive direction is parallel to the normal vector of the two metal plates. The GaAs sample is submerged in a glass dish and ultrasound pulses (center frequency: 3.8 MHz) are applied to the surface of the sample through an acoustic delay media (water in an acrylic pipe) as shown in **Fig. 1**. The bottom of the acrylic pipe was sealed with polyvinylidene chloride (PVC) film with approximately 110-μm thickness. The ASEM signal is detected by a differential antenna with an LCR resonator tuned to the frequency of the ultrasound waves. The signal picked up by the antenna is amplified with a gain of 32 dB and averaged at a repetition frequency of 1 kHz.

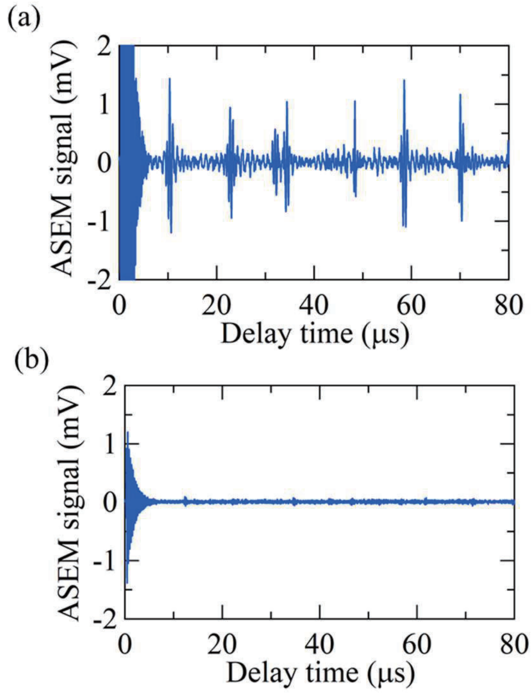

Fig. 2 Time traces of ASEM signals detected by (a) a single metal plate and (b) a differential antenna (two metal plates) under the condition that the human hand is close to the antenna without the sample.

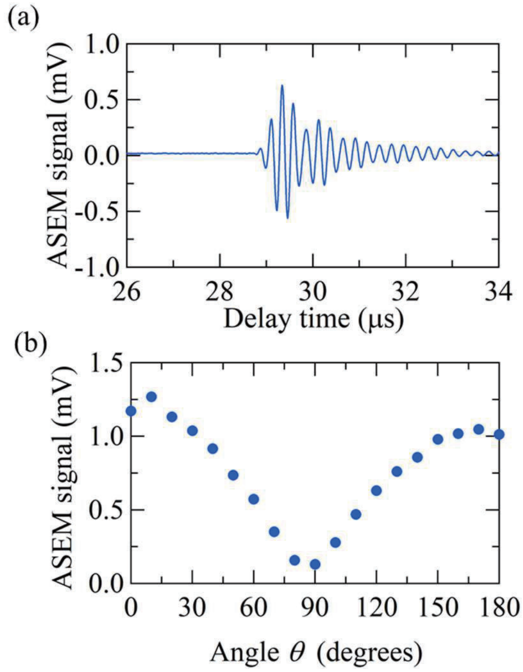

Fig. 3 (a) Time trace of ASEM signal from GaAs at $\theta = 0$. (b) Angle θ-dependence of the ASEM signal from GaAs received by a differential antenna.

3. Results and discussion

Figure 2 shows the time traces of ASEM signals obtained with a single metal plate antenna[7,8] and a differential antenna introduced under the condition that the human hand is close to the antenna. Here, one of the metal plates is grounded for the single antenna. With a single metal plate antenna, spike signals caused by external noise from human body are detected, but with the differential antenna, they are hardly observed.

In the case of a differential antenna, the signal voltage is expected to increase by a factor of two due to the opposite charges on each metal plate caused by the electric dipole. Furthermore, due to the reduction of external noise mentioned above, the SNR is predicted to increase by a factor of about 30 times, which has been roughly confirmed in experiments.

In order to confirm the directivity of the differential antenna, the angle θ dependence of ASEM signal from GaAs is measured in the fixed antenna, where θ is the angle between the normal vector of the metal plates and the piezoelectric [001] axis of GaAs in the surface of the GaAs(110) wafer. A typical time trace of the ASEM signal at $\theta = 0$ is shown in **Fig. 3**(a). In the θ-dependence of the ASEM signal $V_{\mathrm{sig}}(\theta)$ (Fig. 3(b)), the signal exhibits the maximum around $\theta = 0$ and the minimum around $\theta = \pi/2$ with a directivity of $V_{\mathrm{sig}}(0)/V_{\mathrm{sig}}(\pi/2) = 10$.

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4. Conclusion

It was shown that the introduction of the differential antenna not only made the ASEM signal less susceptible to external noise, but also improved the SNR and provided directivity.

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