A MULTI-AXIS PIEZORESISTIVE MEMS SENSOR FOR ACOUSTIC EMISSION

Nobuhiko Matsuda, Nguyen Minh Dung, Tomoyuki Takahata and Isao Shimoyama
The University of Tokyo, Tokyo, Japan

ABSTRACT

In this study, we present an approach for three-dimensional acoustic emission (AE) sensing based on the structure of a liquid-on-piezoresistive beam. The sensor has three piezoresistive beams, covered with silicone droplets, facing three orthogonal directions in order to produce directivity, and to measure three-dimensional AE. Since droplet surface tension is dominant over gravity at microscale, the liquid can keep its shape in any position. Different with conventional AE sensor, the proposed three-dimensional sensor can be downscaled since the beams were piezoresistor-based. Indeed, the assembled chips have the dimensions of 2.8mm×2.8mm×2.8mm. Experiment results demonstrate that the device has different frequency characteristics depending on vibrating direction, thus it can measure both in-plane and out-of-plane AE waves. Furthermore, the device has a clear bi-directional pattern, which is useful for AE source localization.

INTRODUCTION

Recently, as one of non-destructive testing methods for material degradation, acoustic emission (AE) sensors have attracted a significant amount of researches. Conventional AE sensors can be found in literature incorporating capacitive type [1] and piezoelectric type [2]. It is widely known that AE generated at crack in materials has three-dimensional component of vibration. Since the in-plane and out-of-plane AE waves have different propagation characteristics and different frequency characteristics [3], the measurement of three-dimensional AE is important in structural health monitoring. For the above conventional AE sensors, however, the signal to noise ratio is supposed to decrease in device miniaturization. Therefore, it is difficult to design a MEMS three-dimensional AE sensor with capacitive or piezoelectric types. This study will present a method to measure three-dimensional AE using ultra-thin piezoresistive beams combined with a non-vaporized liquid (HIVAC-F4). Since the device based on piezo-resistor, the high sensitivity can be maintained even when the device is downscaled. Furthermore, regarding the miniaturized simple structure and the low-cost fabrication process, our proposed AE sensor can provide solutions for structure monitoring system, which is rather difficult now due to the high-cost issue.

METHOD AND DESIGN

In our method, we used liquid-on-beam structure for measuring three-dimensional AE with high sensitivity [4-7]. As shown in Figure 2a, our 2.5 mm×2.5 mm×0.3 mm sensor chip consists of 300 μm piezoresistive beam covered by a 1 mm non-vaporized silicone oil droplet, which was doped on the top to measure vertical vibration of the droplet. We equipped a cube with 3 sensor chips on

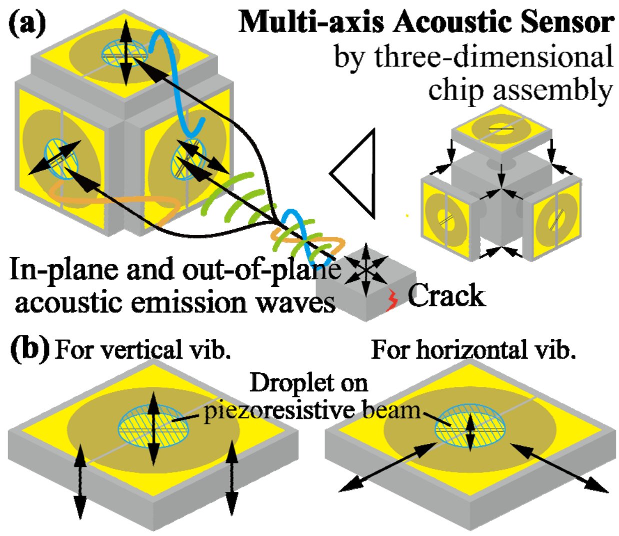

Figure 1: Schematic diagram for three-dimensional acoustic emission measurement. (a) Three liquid-on-piezoresistive beams on top and sides of a cube have orthogonal directivities. They sense each component of three-dimensional AE generated at a crack. (b) Each beam has vertical directivity because of the droplet.

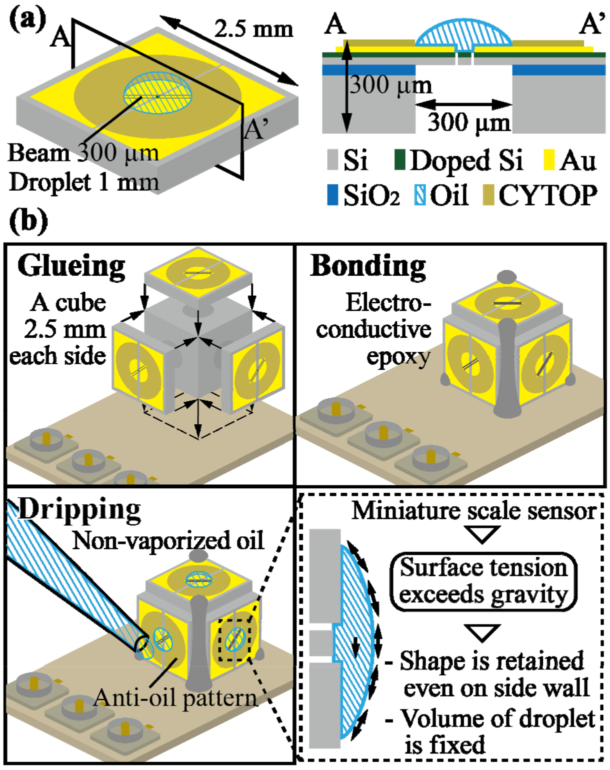

Figure 2: Design and fabrication. (a) Sensor chip design. (b) Fabrication processes. Surface tension retains the shape of the droplet according to the anti-oil pattern.

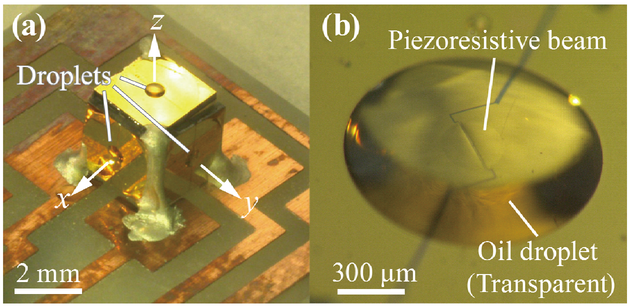

Figure 3: Device image. (a) Fabricated device. (b) Piezoresistive beam covered by an oil droplet.

its sides, bonded them with electro-conductive epoxy and dripped oil droplets on them (Figure 2b). According to the CYTOP anti-oil pattern, each droplet forms a dome of the same shape under the balance of surface tension. Owing that this effect far exceeds gravity at microscale, droplets could keep their shapes in any posture. The device image presents the shape of droplets sticking on top and side walls of a cube (Figure 3ab).

EXPERIMENTAL RESULTS

Frequency characteristics

Figure 4 describes the experiment conducted to measure the frequency characteristics of the device, by vibrating it in three orthogonal direction with a commercial exciter. Experimental set-up is shown in Figure 4a. The device was fixed onto the exciter with ultrasonic-conductive gel, and excited in vertical direction (z, by Olympus V101) or in horizontal direction (x and y, by Olympus V1548) (Figure 4b). The exciting voltage was 10 V. The calculated resistance change ratio of three piezoresistive beams in the range of AE frequency are plotted in Figure 4c. As the standard deviation of time-series resistance change ratio data without excitement was about 2×10^{-7}, the signal-to-noise ratio is up to 10^3. For x direction excitement, x-channel response is most significant especially in range of 20-40 kHz, and it is similar about y-channel response for y direction excitement and z-channel one for z direction excitement. These characteristics depict the selective vibration transmitting ability of droplet.

Directivity

Figure 5 illustrates the experiment for analyzing directivity of the device, where it was excited by sinusoidal shear waves generated with a commercial exciter (Olympus V1548). As shown in Figure 5a, the device was set onto the exciter with ultrasonic-conductive gel and horizontal shear waves were applied in the angle of every 22.5 degrees against the device. The exciting frequency was 20 kHz, which is in range of AE frequency. In Figure 5b the exciting voltage supplied to the exciter and the consequent resistance change ratios calculated from the device output are plotted. The amplitude of x-channel is significant in comparison with that of y- and z-channel in 180-degree condition, where the x-channel is directed toward the direction of excitement. Similarly, the y-channel amplitude is superior to the others in 270-degree condition, where y-beam is facing to the exciting direction. Figure 5c is a polar plot of peak-to-peak amplitude of x-, y-

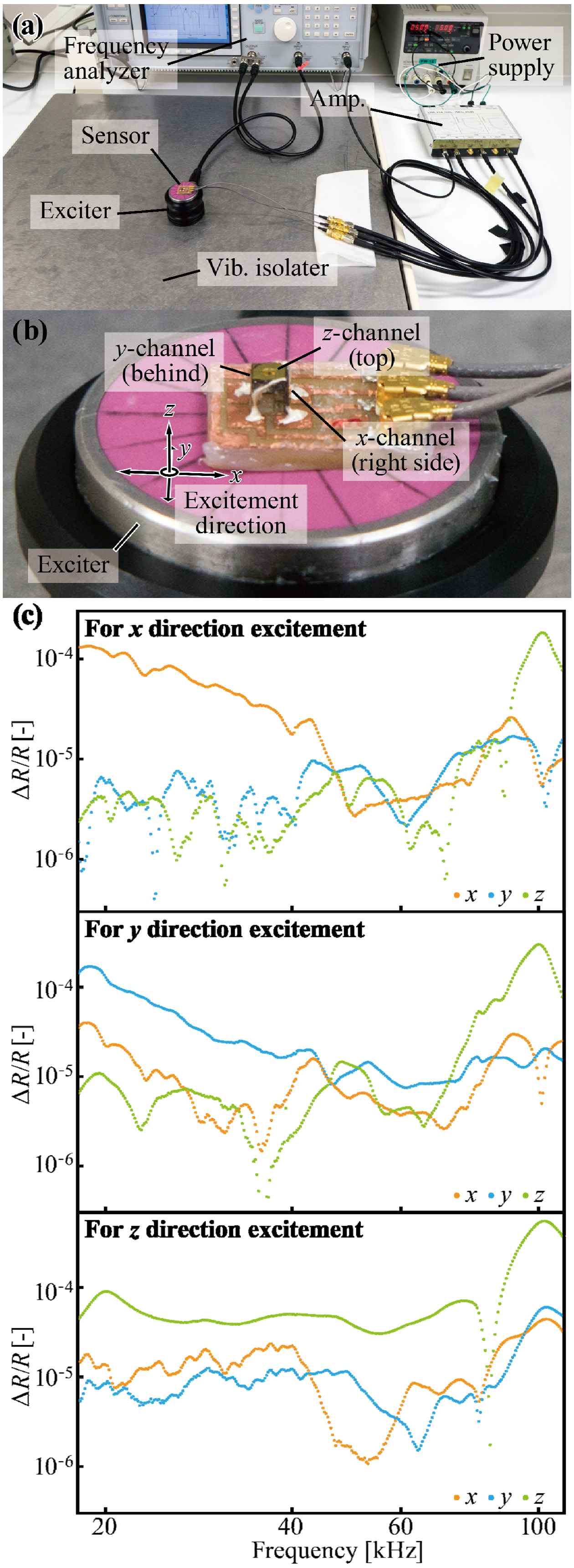

Figure 4: Frequency characteristics of each piezoresistive beams. (a) Set-up. (b) The directions of channels and excitement. (c) Frequency characteristics of x-, y- and z-channels. x-channel output is significant for x direction excitement, and the same about y-channel for y direction excitement and z-channel for z direction excitement.

and z-channels. The tendency of the amplitude fluctuation is a little outlying in some angle (e.g. 90-degree condition), which is thought to be on account of a conductivity aberrance because of gel repairing. Nevertheless, the ratio of two amplitudes keeps clear bi-directional pattern (Figure 5d). Thanks to its monotonicity, the incoming angle of the vibration could be calculated from this ratio. This directivity characteristic is of use for acoustic source localization and three-dimensional component analysis for AE.

CONCLUSION

In this study, we proposed a three-dimensional AE sensor based on liquid-on-piezoresistive structure. The sensor's size was 2.8mm×2.8mm×2.8mm. As the beams on orthogonal sides of a cube have vertical selective sensitivity, the device could sense the three-dimensional components of ultrasonic vibration. The experimental result demonstrates the device has clear directivity of bi-directional pattern. The tiny size and spatial characteristic of the sensor is of use for AE measurement.

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CONTACT

*Nobuhiko Matsuda, Tel: +81-3-5841-6318;
Email: n_matsuda@leopard.t.u-tokyo.ac.jp

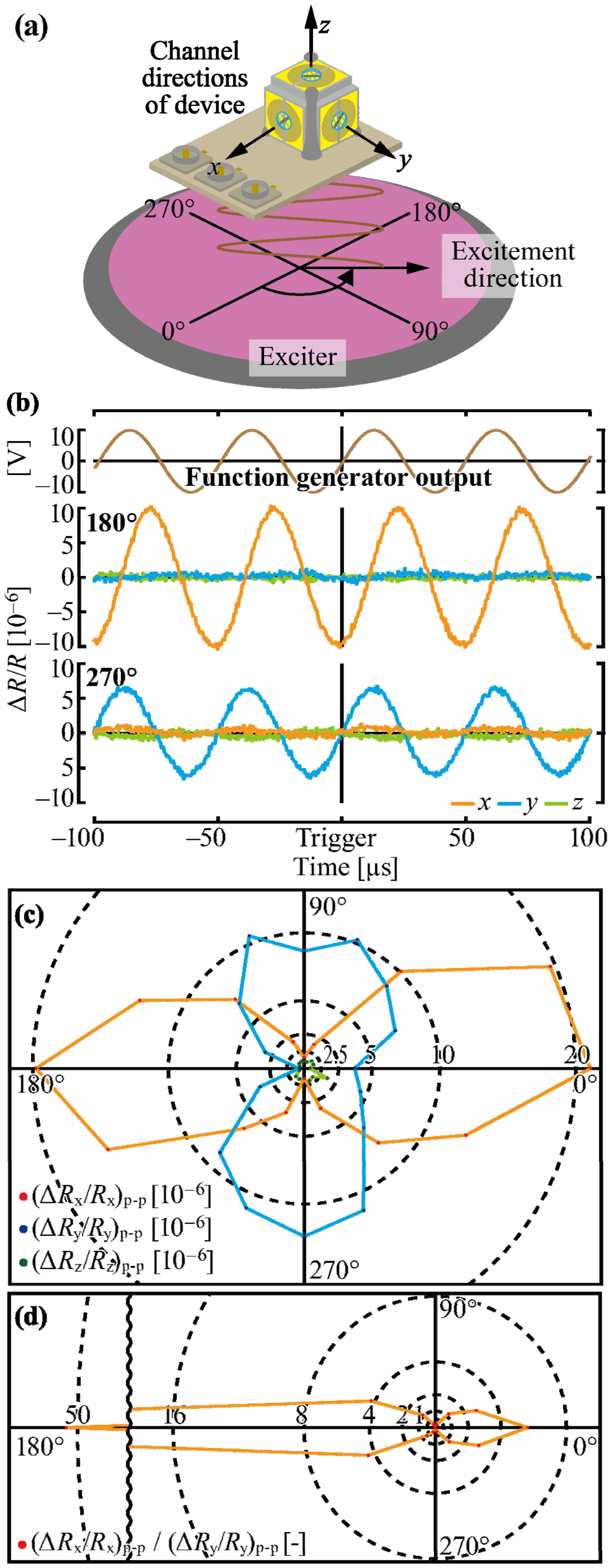

Figure 5: Directivity characteristics for sinusoidal excitement. (a) Schematic diagram for experimental set-up. (b) Responses for 20 kHz horizontal shear excitement. (c) Polar plot of the peak-to-peak amplitude of x-, y- and z-channel responses for each 22.5 degrees. (d) The ratios of the peak-to-peak amplitude of x-channel to that of y-channel in each angle. Clear bi-directional pattern was observed. Vibrating direction could be calculated from this ratio.