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PAPER

Flexible substrate with floating island structure for mounting ultra-thin silicon chips

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Abstract

A flexible substrate with a novel floating island structure design was developed for mounting ultra-thin silicon chips. The structure reduced the strain propagated from the stretching base to the ultra-thin silicon chips. While conventional structures reduce strain by 64.2%, the floating island structure reduced strain by 90.2%. Furthermore, tests for operational stability and durability were conducted using an ultra-thin operational amplifier (OPAMP) mounted on the flexible substrate with a floating island structure, where the OPAMP was thinned to 30 μm by chemical mechanical polishing. The ultra-thin OPAMP operated with no strain effects even when repeatedly stretched to 30% elongation. Also, the ultra-thin silicon chip mounted on the floating island structure demonstrated durability against >25 000 stretching cycles. This research is applicable for functional wearable devices using ultra-thin silicon chips and featuring high flexibility and stretchability.

1. Introduction

Flexible hybrid electronic (FHE) technology which combines flexible electronic technology with conventional silicon electronic technology is promising for the development of wearable devices owing to its advantages including flexibility, light weight and low height. Many wearable sensor devices using FHE technology have been reported, including electrocardiogram, pulse wave sensors and mental stress [1–6]. To fabricate the FHE device, a common strategy to make the silicon chip flexible is thinning by chemical mechanical polishing, reactive ion etching and microelectromechanical processes [7–11]. Ultra-thin silicon chips can endure the bending of the flexible substrate. Vanfleteren *et al* reported an ultra-thin microcontroller (thickness: 20 μm) that performed on a flexible substrate at a curvature radius of 3.3 mm [12, 13]. Also, K. Bock group reported roll-to-roll process and chip-foil packaging using ultra-thin silicon chips [14, 15].

However, ultra-thin silicon chips are very weak against tensile strain, which means that the silicon chips have flexibility but do not have stretchability. When tensile stress is applied on the silicon chips such as operational amplifier (OPAMP) and MCU, carrier mobility and the threshold voltage of the electrical charge is changed. As a result, the performance of the electronic devices are changed [16–18]. Moreover, when the tensile stress is further increased, the chips are broken, easiliy.

Generally, a meander structure is formed on the flexible substrate to impart stretchability to the FHE device as shown in figure 1 [19, 20]. In this design, an island structure is incorporated in the meander structure, upon which the ultra-thin silicon chip is mounted. When tensile stress is applied to the substrate, the meander structure absorbs the tensile stress and, as shown in figure 2(a). Usually, the back or both sides of the island structure are attached to the stretchable substrate, such as textile in a conventional structure. For this structure, the strain propagated from the edges of the flexible substrate is reduced by the meander structure. However, the strain propagated from the attached points of the island structure cannot be reduced. To solve this problem, we propose a floating island structure to reduce the strain propagated, as shown in figure 2(b). This structure can reduce the strain on the ultra-thin silicon chips because the island structure is not attached on stretchable base.

In this paper, the advantages of the floating island structure are described. First, a fundamental experiment was conducted to demonstrate the reduced strain in the floating island structure compared with that in conventional structures. Next, stretching test

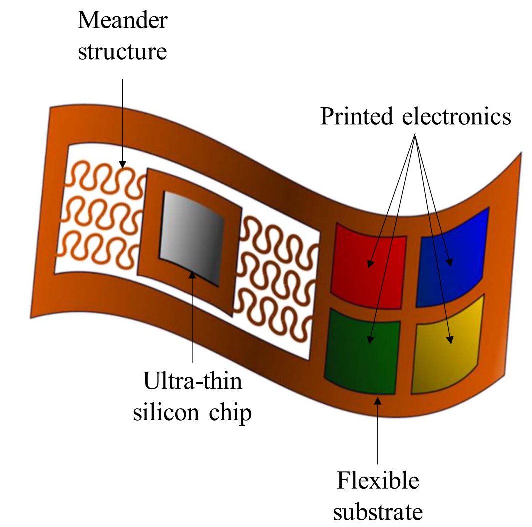

Figure 1. Image of flexible hybrid electronics (FHE) device using ultra-thin silicon chip.

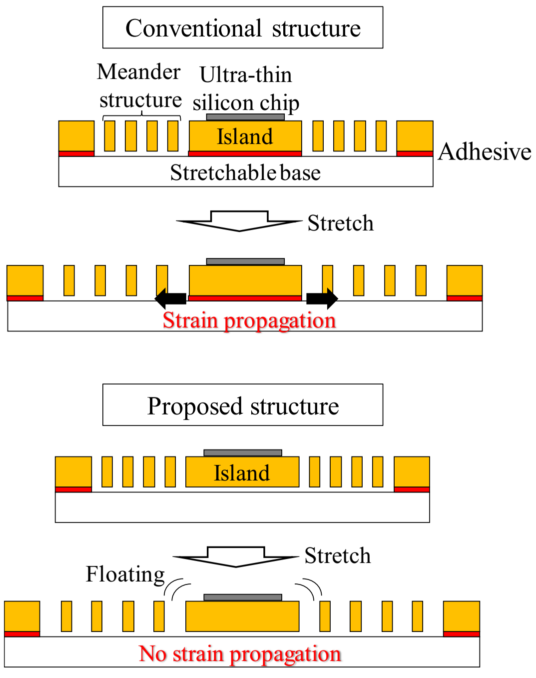

Figure 2. Cross-section view of flexible substrate with conventional structure (a) and proposed structure (b).

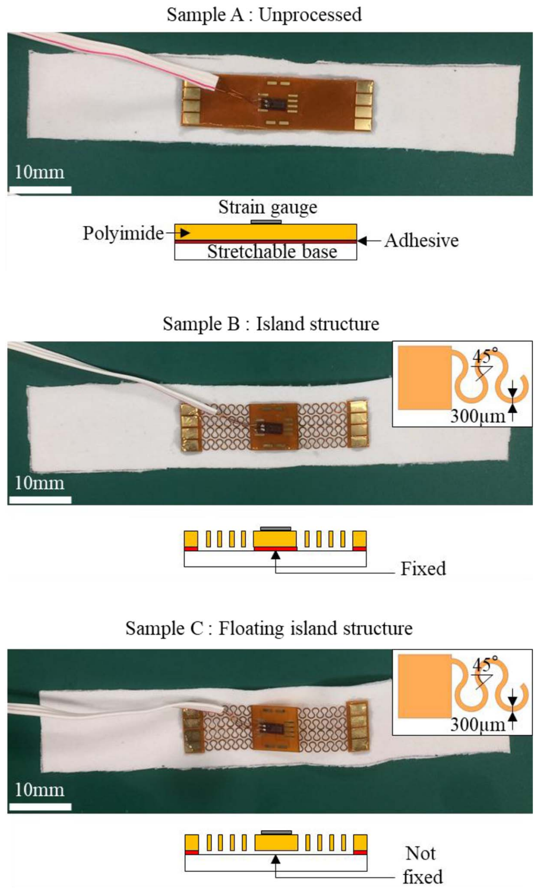

Figure 3. Photograph and image of test sample. Unprocessed flexible substrate (a), flexible substrate with island structure (b) and flexible substrate with floating island structure.

of an ultra-thin OPAMP chip mounted on the floating island structure was conducted to demonstrate its effectiveness.

2. Methods

2.1. Structure

Figure 3 shows three flexible substrate samples (Samples A, B, and C) on which strain gauges were mounted. The flexible substrate material was polyimide (MB18-25-18CEG, NIPPON STEEL Chemical & Material Co., Ltd., Japan) and was 125 μm thick and 60 mm $\times$ 20 mm in area. Eight meander structures were formed on Samples B and C by laser cutting machine (3500 U, EO Technics Co., Ltd., Japan), where each meander structure was 300 μm wide and was fan-shaped with a 1 mm radius and a 45° connection angle. The power, frequency and speed of laser cutting were 4 W, 350 mm s^{-1} and 80 kHz, respectively. The island was 10 mm $\times$ 10 mm in area for Samples B and C. A strain gauge (KFGS-2-120-C1-11L5M3R, Kyowa Electronic Instruments Co., Ltd., Japan) was attached at the center of the flexible substrate. The flexible substrate was affixed with adhesive paste (CA-193, CEMEDINE Co., Ltd, Japan) to a stretchable base (MCM3749, Under Armour, Inc., U.S.A). The adhesive pasete was cured at room tempreture in 30 min. Sample A did not have a meander structure and the entire surface of the back side of was affixed to the stretchable base. Sample B had meander structures and the island structure and edge portions of the flexible substrate were affixed to the stretchable base. Finally, Sample C had meander structures and only the edge portions of the flexible substrate were affixed to the stretchable base.

2.2. Experimental setup

Figure 4 shows the experimental system. The samples were attached to a tensile test machine

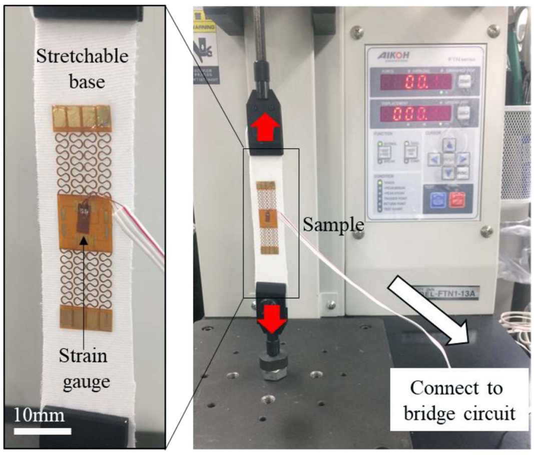

Figure 4. Photograph of experimental setup of stretching test.

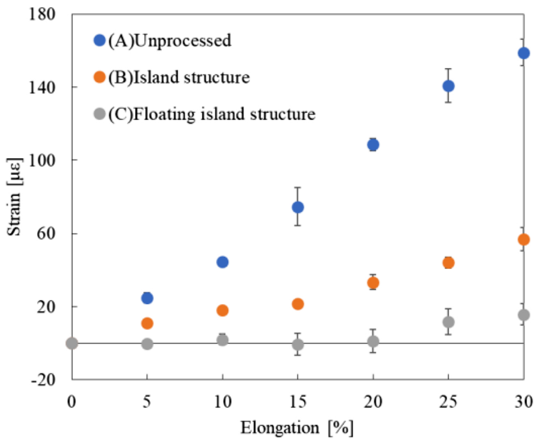

Figure 5. Strain value on flexible substrate when the elongation was changed from 0% to 30%.

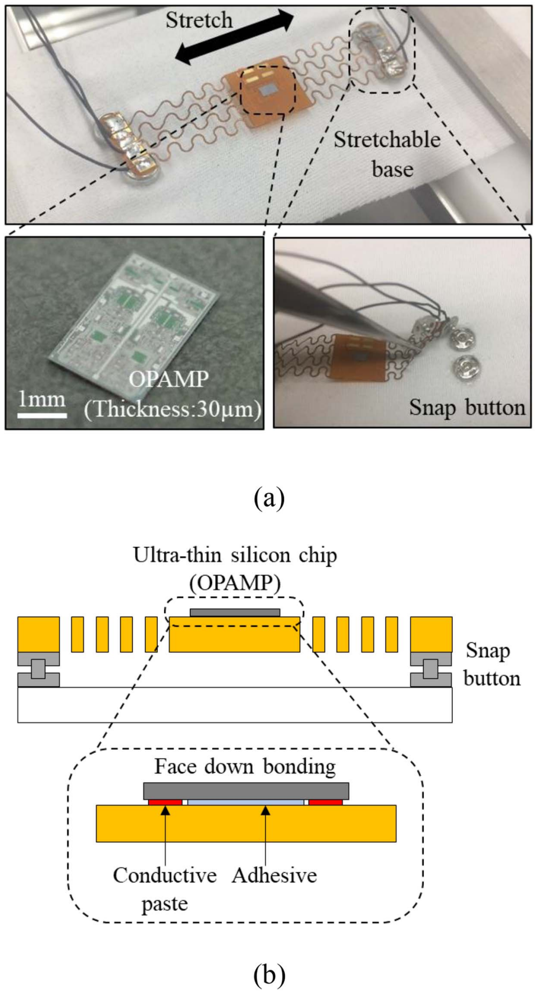

Figure 6. Photograph of test sample which ultra-thin OPAM was mounted on flexible substrate with floating island structure (a) and image of cross-section view of the test sample (b).

(Model-FTN1-13A, Aikoh Engineering Co., Ltd., Japan), where both sides of the textile were clamped and a tensile stress was applied. The strain gauge was connected to a bridge circuit (Model PCD-400A, Kyowa Electronic Instruments Co., Ltd., Japan) to obtain the strain value. During testing, the elongation of the sample was from 0% to 30% (i.e. from 80 to 104 mm). First, the sample was initialized by being stretched several times to stabilize the stretchable base, until the sample exhibited no hysteresis in the strain value. After initialization, the strain was measured after each 5% elongation. This experiment was conducted three times for Samples A, B and C, respectively.

3. Results

3.1. Evaluation of floating island structure

The experimental results are shown in figure 5. The strain value was average of three times experimental. From the results, the strain values of Samples A, B and C were 59.0, 57.0 and 15.7 $\mu\varepsilon$, respectively. In Sample A, the strain value increased in proportion to the elongation of the stretchable base. In Sample B, the strain value also increased in proportion to the elongation, but with a smaller strain than that of Sample A. In Sample B, the strain propagated from the back side of the flexible substrate and, at 30% elongation, was 35.8% the strain of Sample A. This indicates that the meander structures reduced the strain propagation by only 64.2%. In Sample C, however, the strain value was almost zero until 20% elongation, whereupon the strain value reached 0.97 $\mu\varepsilon$. As the elongation was further increased, the strain value of Sample C increased in proportion to the elongation with a value that was 9.8% that of Sample A. Therefore, the floating island structure reduced the strain propagation by 90.2%.

3.2. Operation of ultra-thin silicon chip

Next, an ultra-thin silicon chip was mounted on the floating island structure to test for operational stability and durability during 30% elongation. Figure 6 shows the test sample comprising an operational

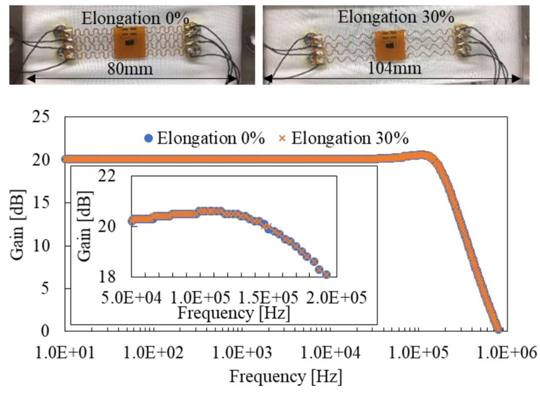

Figure 7. Frequency characteristics when elongation of test sample was 0% and 30%.

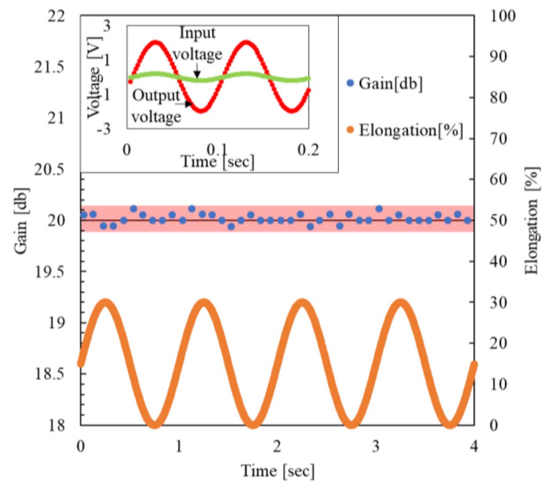

Figure 8. Gain value when the elongation of test sample was changed from 0% to 30%, repeatably.

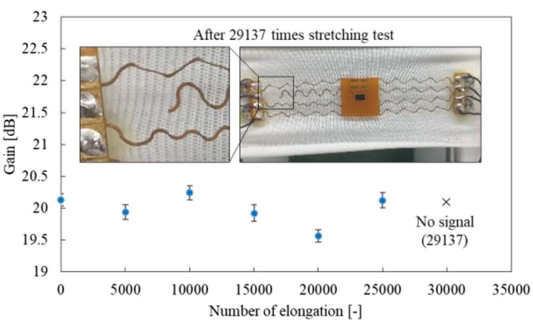

Figure 9. Gain value which were measured after every 5000 times stretching test.

amplifier (OPAMP; OPA2277-DIE, TEXAS INSTRUMENTS Inc., U.S.A) thinned to 30 μm in thickness by chemical mechanical polishing (LP50, LOGITEC Ltd, England). The OPAMP was mounted face-down to the electrode pad of the floating island structure with a conductive adhesive paste (RA FS 074, TOYO INK Co., Ltd, Japan) by a mounting machine (Model 7372E, WEST BOND Inc., U.S.A). The propagation of strain is expected to be reduced by using face-down becasuse the surface of OPAMP become close to a neutral axis [21]. The flexible substrate with the OPAMP mounted on the floating island was then affixed to the stretchable base with snap buttons, where two snap buttons were used on each edge of the stretchable base. The flexible substrate possessed eight meander structures, through which the electrode pad of the ultra-thin OPAMP was connected to the outside. External resistors (3 and 27 kΩ) were used to create a noninverting amplifier circuit with a 20 dB amplitude. The test sample was attached to the tensile test machine (DMX-FS-A06i, YUASA SYSTEM Co., Ltd, Japan) by cramping both edge and stretched from 80 mm to 104 mm (elongation: from 0% to 30%). Firstly, frequency characteristics of ultra-thin OPAMP was measured when static stretching was applied on test sample. The swept frequency was from 10 Hz to 1 MHz. Figure 7 shows result of the experiments. In both characteristics before and after stretching, the gain was stable at 20 dB at frequencies below 100 kHz, and decreased at frequencies above 100 kHz. Since the GB product of the OPAMP based on date sheet was 1 MHz, it was confirmed that the OPAMP operated correctly. From these results, it was confirmed that the characteristics of the operational amplifier did not change due to the CMP process and mounting process. In addition, there was no significant difference in frequency characteristics before and after stretching. From the above result, it was confirmed that the ultra-thin OPAMP mounted on the floating island structure was not affected by static stretching. Next,the characteristics of ultra-thin OPAMP was checked in dynamic stretching test.

The test sample was stretched by 30% elongation at 1 Hz by the tensile test machine. The input voltage of 0.4 V p–p at 10 Hz from the power supply was amplified by the ultra-thin OPAMP. The output voltage was measured by an oscilloscope. The results are shown in figure 8, where plots give the amplitude value calculated input voltage and output voltage and elongation value of stretchable base. The results show that the amplitude value was stable at 20 dB even while the base was repeatedly stretched by 30%. The red band in the plot indicates the range of the fluctuation of gain measured during the stable condition without stretching. The fluctuation of gain during the stretching test was equivalent to that of the red band, and thus it is considered that the ultra-thin silicon chip mounted on the floating island structure functioned properly, unaffected by stretching.

Furthermore, figure 9 shows the results of the stretching durability test, wherein the signal amplitude was measured after every 5000 stretching cycles. The OPAMP signal was obtained until after 25 000 stretching cycles. However, the signal was stoped because a portion of the meander structure was broken owing to fatigue when streching cycles reached 29 137. It means the ultra-thin chip was not broken. The above result shows that the floating island structure mounted with the ultra-thin OPAMP has an expansion durability of >25 000 stretching cycles at a 30% elongation.

4. Discussion and conclusion

The purpose of this study was to develop a mounting structure that endowed stretchability and high durability to an FHE device containing an ultra-thin silicon chip. The floating island structure was proposed and experiments were conducted to demonstrate its effectiveness.

The porpose of first experiment was fundamental evaluation of the floating island structure. The conventional flexible structure (Sample B) only reduced the strain to 64.2% that of the unprocessed flexible substrate (Sample A). While the floating island structure (Sample C) reduced the strain value by 90.2%. In the floating island structure, the 15.7 $\mu\varepsilon$ (Sample C, 30% elongation) strain was considered to have propagated from the meander structure. The meander structure dictates the stretching limit where, in this experiment, the strain value of Sample C was almost zero until the elongation reached 20%. This limit depends upon the design and material of the meander structure. Therefore, optimizing these factors can reduce the strain even further. Furthermore, under tensile stress, the stresses applied to the ultra-thin silicon chip of Samples A, B and C were 26.8, 10.1 and 2.63 MPa, respectively, assuming that the Young's modulus of silicon is 169 GPa [22] and that all of the strain is transmitted to the chip. These values are less than the tensile breaking strength of silicon (1.89 GPa). However, because the strength of thin materials largely depends on the its surface roughness [23], it is necessary to reduce the stress. As a result, the following conclusions were drawn.

(a) Transmission of the tensile strain cannot be reduced perfectly using only the meander structure.
(b) The floating island structure reduced the strain transmission by 99.8% at a 20% elongation and by 90.2% at a 30% elongation.
(c) Optimizing the meander structure can be expected to increase the strain transfer reduction even further.

Next, the performance stability and durability were tested using an ultra-thin OPAMP chip mounted on the flexible substrate with the floating island structure. As a results, it was confirmed that the output signal was not affected by both of static and dynamic stretching test. This result shows that the thinned OPAMP operates stably even with 30% elongation. In addition, a stretch durability test was conducted. Although the signal was interrupted after 29 137 stretching cycles, the cause of failure was fatigue fracture of the meander structure and not breakage of the ultra-thin OPAMP chip. The durability of this design can be further increased by optimizing the design and material of the meander structure. Generally, stretching of apparel textile on the upper body is less than 30%, excepting the areas near the elbows and shoulders [24]. Therefore, the floating island structure can be used to operate an FHE device on clothing, except the high-stretch areas near elbows and shoulders. As a result, the following conclusions were drawn.

(d) The ultra-thin OPAMP chip mounted on the flexible substrate with a floating island structure performed even during tensile tests (both of static and dynamic) with 30% elongation.
(e) The test sample was broken after 29 137 stretching cycles owing to fracture of the meander structure.

We note that a limitation exists regarding sealing that was not addressed in this study. Typically, FHE devices and electronic devices are sealed to increase the mechanical strength of the electronic components and to improve resistance to humidity and temperature. In wearable devices in particular, it is a very important barrier against body sweat and static electricity. For example, polydimethylsiloxane (PDMS) was used to seal a flexible substrate comprising a meander structure and an ultra-thin silicon chip by filling the structure. Widely used as a sealing material for FHE devices, PDMS is a material with excellent flexibility, elasticity, and durability. Furthermore, to increase the durability of the ultra-thin chip portion of the structure, a soft core/shell structure [25] and graduated structure [26] have been proposed as a sealing method. However, in these structures where the entire flexible substrate is embedded in a sealant, the strain is transmitted from the sealing material to the island structure. Therefore, we intend to develop a new structure that features both a floating island structure and sealing.

In conclusion, we reported a novel mounting method using the floating island structure that reduced the propagation of tensile strain. Also, this paper focused on the FHE application of this method. However, the application of this method is not limited to ultra-thin silicon chips, but is also appropriate for packaged chips. In future work, we will mount devices such as vital sign sensors on the floating island structure substrate and deploy them as wearable devices.

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