STRESS-FREE STRETCHABLE ELECTRONIC DEVICE USING FOLDING DEFORMATION

Yoshitaka Iwata[1], and Eiji Iwase[1*]*
[1]Dpartment of Applied Mechanics, Waseda University, Tokyo, Japan

ABSTRACT

We developed a two-dimensionally (2-D) stretchable electronic device with stress-free region by applying origami folding. The key idea is to achieve "a stretching deformation of whole device" by "a local bending deformation". Because our device has stress-free region, we can use a rigid chip (such as LED chips and MEMS sensors) and a metal wire without mechanical fracture or metal fatigue. In this paper, first, we proposed a 2-D stretchable structure by developing "miura-ori" folding. Next, we fabricated a 2-D stretchable electronic device, and confirmed that wire fatigue or cracks are not generated by repeated deformation. Finally, we demonstrated 2-D stretchability and bendability using the device with inorganic LED chips.

INTRODUCTION

Recently, many researchers have investigated bendable and/or stretchable thin film flexible devices [1-2]. Only bending deformation, there is a neutral plane (white region on Fig. 1) which does not cause compressive stress (blue hatched region of Fig. 1) or tensile stress (red region of Fig. 1) (Fig. 1(a)), and avoiding metal fatigue or cracks of wire is easy by placing electronic element in the neutral plane [3]. On the other hand, stretching deformation has no neutral plane (Fig. 1(b)), and stress generation is not able to be avoided in all regions of the device [4]. From these points of view, we noticed that stress-free stretching deformation can be produced by using local bending deformation which is generally known as a folding deformation (Fig. 1(c)). Therefore, we focused on folding deformation to achieve a stress-free stretchable electronic device.

The objective in this research is to provide stretching deformation using local bending deformation for stress-free stretchable electronic device. Fig. 1(c) shows our stretching deformation methods with stress-free region. As shown in Fig. 1(c), our stretchable device consists of hinge parts and plate parts. The hinge parts have a neutral plane and plate parts obviously do not cause stress. As a result, we can generate stretching deformation without mechanical fracture or metal fatigue by placing a wire on the neutral plane of the hinge parts, and also placing wire and rigid chips such as MEMS sensors on the plate parts. It can say our stretching deformation method effectively uses a local bending deformation for a stretching deformation of whole device. In addition to that, our stretching deformation method is useful for attaching to any curved surfaces. In general, for attaching a flat device to any curved surfaces such as spherical surface, stress generation in the device is not able to avoid due to the requirement of stretchability [5], and it is difficult to apply wire or electronic parts. However, folding deformation using local bending deformation is easy because it has a plane which does not cause stress in bending and stretching deformation. Therefore, our stretching deformation using local bending deformation is not only useful for stretchable electronic device but also for electronic device used on curved surface.

STRUCTURE DESIGN AND ANALYSIS

For the 2-D stretchable electronic device, we stared from "miura-ori" [6] as a stretchable structure. In this paper, 2-D stretchability means having both stretchability in two axes

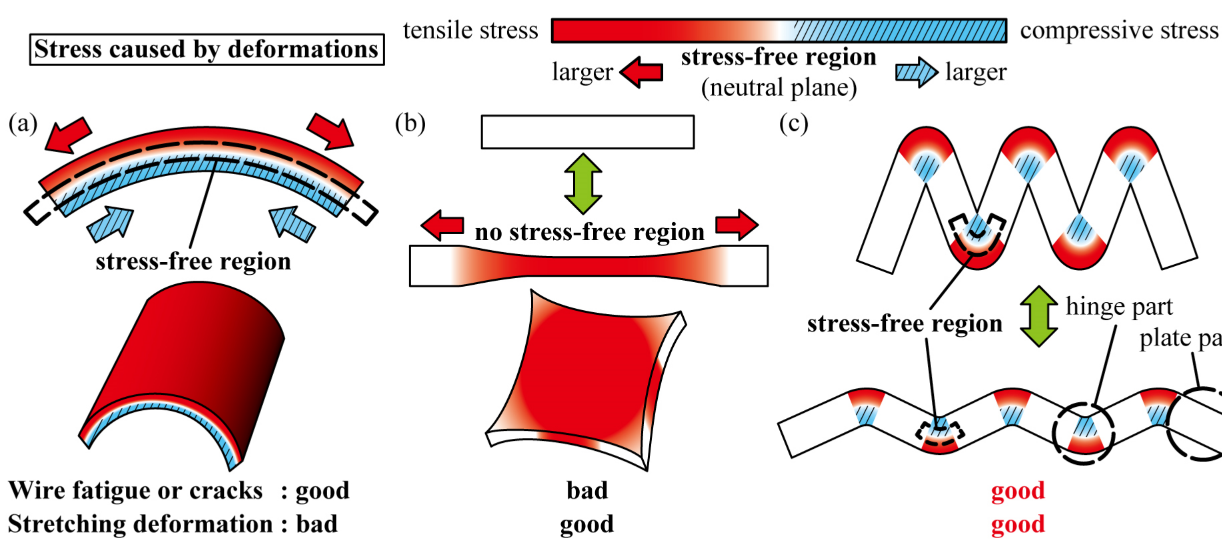

Figure 1: Schematic images of (a) bending deformation, (b) general stretching deformation and (c) proposed "stretching deformation of whole device" by "a local bending deformation". Tensile stress is caused at red region and compressive stress is caused at blue hatched region. There is no stress at neutral plane of white region.

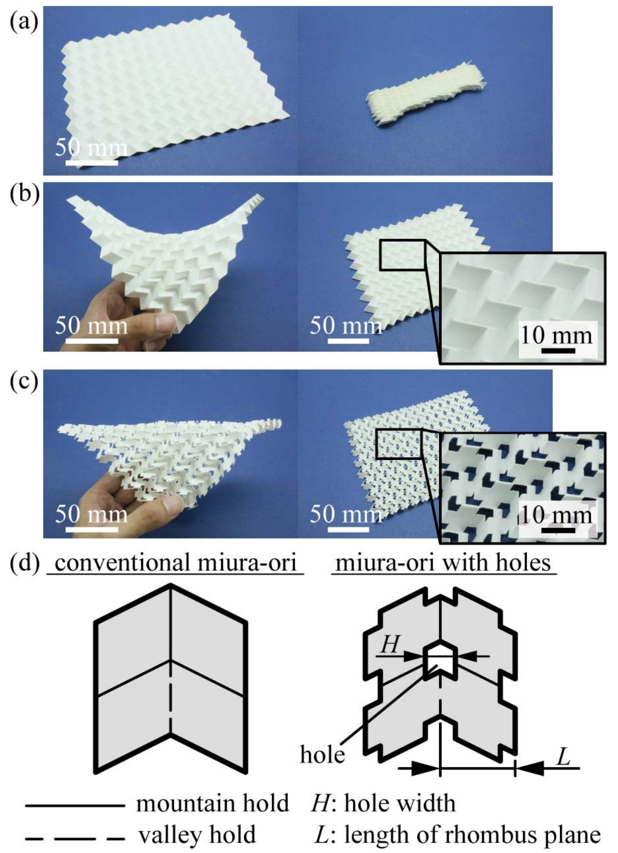

Figure 2: Deformation characteristic of miura-ori. (a) Stretching deformation. (b) Bending deformation of conventional miura-ori. (c) Bending deformation of miura-ori with holes. (d) Schematic a unit images of conventional miura-ori and miura-ori with holes.

and bendability in two axes. Miura-ori is one of folding method of 2-D flat sheet (Fig. 2(a)). Conventional miura-ori with only one degree of freedom is unable to bend freely and bends backward [7] (Fig. 2(b)). Therefore, we extended a conventional miura-ori by making holes at points of intersection of creases which enables to bend freely without being backward (Fig. 2(c) (d)). The extended miura-ori with holes can achieve 2-D stretchability and it can deform to any curved surfaces such as spherical surface. Larger holes of the miura-ori with holes leads to device more bendable, but larger holes make area for placing electronic parts smaller. We determined the hole width H to be 30% of rhombus plane length L in order to attach to a small spherical surface (Fig. 2(d)).

Next, we analyzed stress distribution in hinge part caused by bending deformation for preventing from wire fatigue or cracks. We considered a model of hinge part as shown Fig. 3(a). The hinge consists of Cu layer for wire and polyimide layer which supports the wire layer. By arranging a position of neutral plane near a surface of Cu layer, lower stress is produced on the surface of Cu layer, and wire problems can be prevented. In the case of considering about total stress on cross section of the hinge, it must be zero and given by

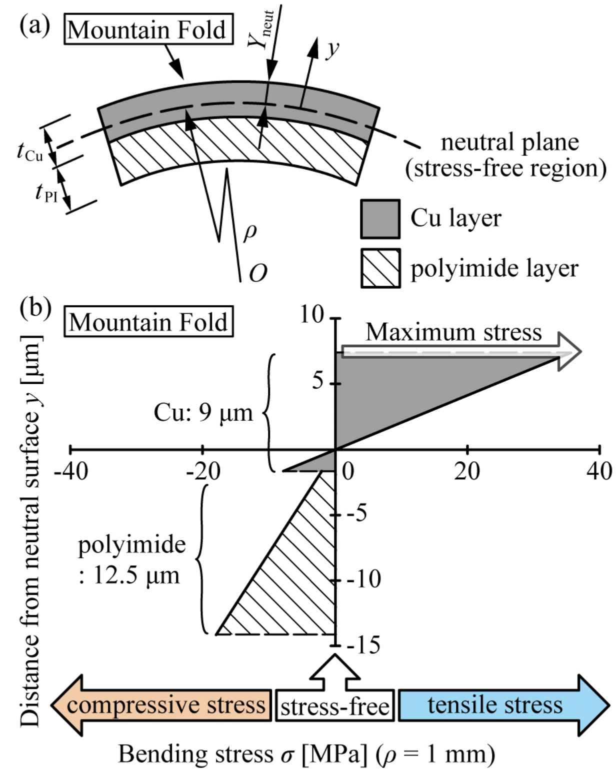

Figure 3: Analysis of neutral plane. (a) Modeling of hinge part for determining a position of neutral plane. (b) Bending stress on a cross section of polyimide-Cu substrate (Cu 9 μm, polyimide 12.5 μm).

$$\left(\frac{E_{\mathrm{Cu}}}{\rho}\cdot\frac{Y_{\mathrm{neut}}^{2}}{2}\right)+\left[-\frac{E_{\mathrm{Cu}}}{\rho}\cdot\frac{(Y_{\mathrm{neut}}-t_{\mathrm{Cu}})^{2}}{2}+\frac{E_{\mathrm{PI}}}{\rho}\cdot\frac{(Y_{\mathrm{neut}}-t_{\mathrm{Cu}})^{2}-\{Y_{\mathrm{neut}}-(t_{\mathrm{Cu}}+t_{\mathrm{PI}})\}^{2}}{2}\right]=0 \tag{1}$$

where Y_{neut} [m] is a distance from neutral plane to Cu layer surface, and ρ [m] is a radius of curvature of the hinge model. t_{Cu} [m] and t_{Pi} [m] are thickness of Cu and polyimide layer, and E_{Cu} [GPa] and E_{PI} [GPa] are young's modulus of Cu and polyimide. By calculating Eq. (1) about Y_{neut}, we can get the distance from the neutral plane to the surface of Cu layer. As a substrate for stretchable electronical device, we used a polyimide film with double sides coated by Cu (polyimide-Cu substrate) (Panasonic, R-F786W). To determine the thickness of Cu and polyimide which the neutral plane places near the surface of Cu layer by calculating Eq. (1), we measured young's modulus of Cu and polyimide by tensile test. The measurements using a force gauge (IMADA, ZTA-500N) and gripers for chucking tensile test pieces (IMADA, GP-15) were carried out based on ISO 527-3, and we got E_{Cu} = 4.84 GPa and E_{PI} = 1.27 GPa. We tested three times and these values are average of them. Based on the above analysis, we chose 9-μm-thick Cu film covered on both sides of 12.5-μm-thick polyimide film for the substrate. In condition of that, Y_{neut} is 7.37 μm, and maximum bending stress causes at 7.37 μm away from the

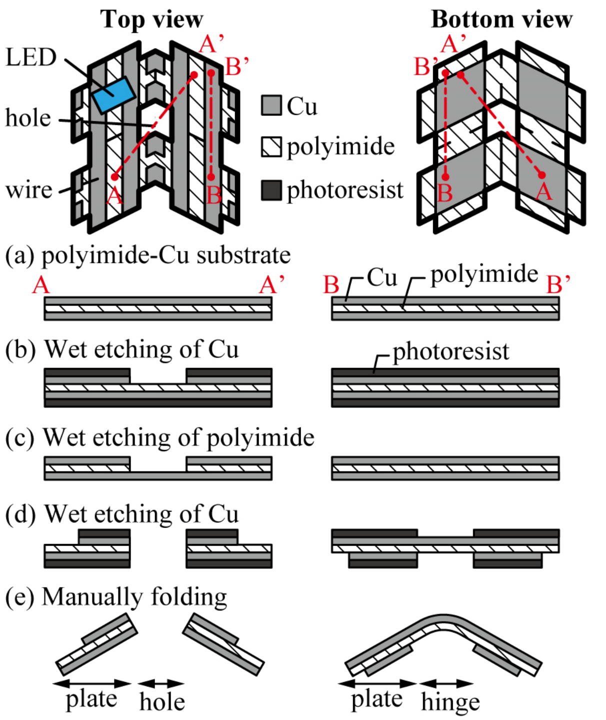

Figure 4: Fabrication process of 2-D stretchable electronic device at cross sections A-A' and B-B'.

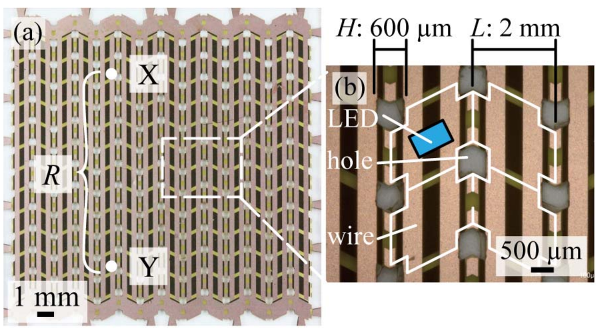

Figure 5: Fabricated 2-D stretchable electronic device in shape of miura-ori with holes.

neutral plane. Fig. 3(b) shows bending stress distribution at a cross section of polyimide-Cu substrate on mountain fold as shown Fig. 3(a). In case of valley fold which causes compressive stress at top Cu surface and tensile stress at bottom polyimide surface, compressive and tensile stresses switch value each other. The bending stress which causes on cross section of polyimide-Cu film is given by

$$\sigma = E\frac{y}{\rho} \tag{2}$$

where y is a distance from neutral plane (Fig. 3(a)). From Eqs. (1) and (2), in case of ρ to be 1 mm, the maximum stress which causes on the surface of Cu layer is 35.7 MPa (Fig. 3(b)). Therefore, the Cu layer should be deformed elastically, and it is able to avoid wire cracks or metal fatigue caused by repetition of deformation.

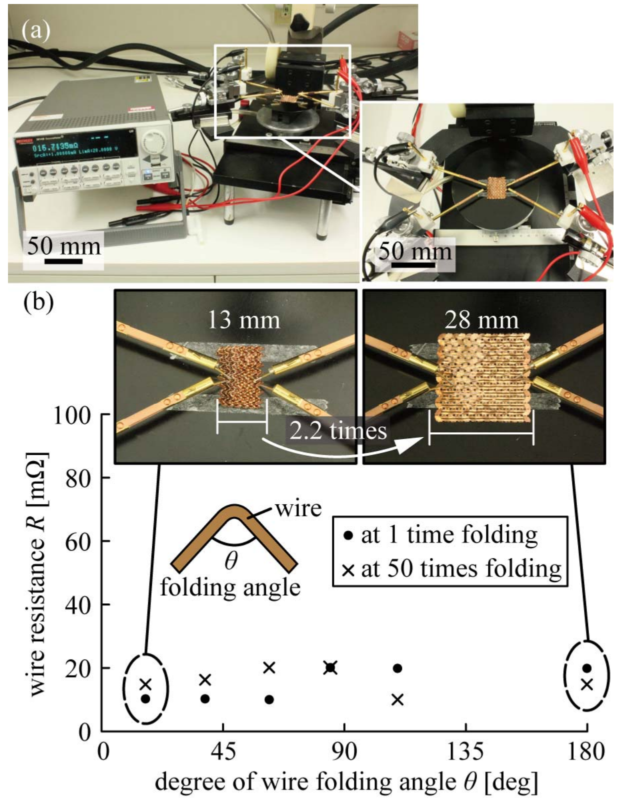

Figure 6: (a) Experimental setup with applying four probe method. (b) Wire resistance by applying repetition of deformation.

EXPERIMENTS

We verified that wire fatigue or cracks are not generated by repeated deformation by an experiment of measurement of wire resistance. And then, we demonstrated 2-D stretchability and bendability using a device which is attached inorganic LED chips.

We, first, fabricated a 2-D stretchable electronic substrate for measurement of resistance. The polyimide-Cu substrate which we mentioned before (polyimide: 12.5 µm, Cu: 9 µm) (Panasonic, R-F786W) was used for the device. Fig. 4 shows a fabrication process at cross sections A-A' and B-B'. Cu layer was patterned, and polyimide layer had holes by wet etching along the patterned Cu layer (Fig. 4(b)-(c)). The Cu layer was patterned again to wire shape (Fig. 4(d)), and the substrate was finally folded manually (Fig. 4(e)). To make plate parts more rigid, the back side of Cu layer was left except for hinge parts. Fig. 5 is photographs of fabricated electronic substrate. The wire width is 500 µm, length of rhombus plane L is 2 mm, and hole width is 600 µm which is 30% of rhombus plane length L for attaching to a smaller spherical surface. One unit is composed of four rhombus plane (Fig. 5(b)), and it consists of 7 vertical units and 7 horizontal units.

Next, we measured wire resistance with state of folded electronic substrate. We measured resistance R between a point X and a point Y in Fig. 5(a). Fig. 6(a) shows the experimental setup for measurement of wire resistance. The

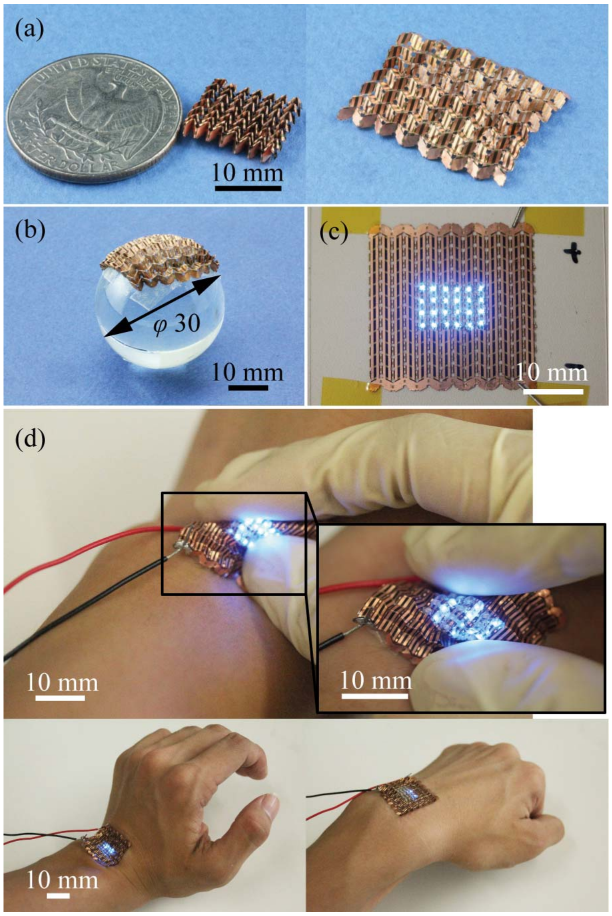

Figure 7: Demonstration of 2-D strethcability and deformability of 2-D stretchable electronic device. (a) Stretching and (b) spherical surface deformation. (c) The device with inorganic LED chips. (d) The device was attached to wrist and deformed by wrist motion.

measurement was carried out by using source meter (Keithley, 2614B) (Fig. 6(a)). By using four probe method, contact resistances between probes and wires can be removed. Fig. 6(b) shows the result of resistance measurement, and we measured at 6 kind of folding angles by repeating deformations of 1 time and 50 times. When the wire deformed 1 time and 50 times at any angles, the resistances were in between 10 mΩ to 20 mΩ and these would be negligible value as a resistance. This result indicates wire fatigue or cracks were not caused by repetition of folding deformation.

We finally demonstrated a 2-D stretchability and bendability using the stretchable electronic device. Stretching deformation (Fig. 7(a)) and 2-D bending deformation to spherical surface which diameter is 30 mm (Fig. 7(b)) were enable. In addition, we placed 24 inorganic LED chips (ROHM Co., Ltd., SMLP12BC7TT86) on the substrate and attached the electronic device to wrist. The device was applied 11.0 V and 0.02 A by power supply (Texio, PA18-3B) (Fig. 7(c)). The device deformed following to movement of a human wrist with turning on LED chips (Fig. 7(d)). In conclusion, our 2-D stretchable electronic device using folding deformation can deform without fatigue or cracks of wires.

CONCLUSIONS

We proposed a 2-D stretchable electronic device with stress-free region by applying miura-ori folding.

First, we applied miura-ori to the device structure. A conventional miura-ori is unable to bend freely and bends backward, so we extended miura-ori with holes which has holes at points of intersection of creases. And then, we analyzed the condition of thickness which does not cause mechanical fracture or metal fatigue. In the case of using 12.5-µm-thick polyimide film covered by 9-µm-thick Cu, the surface of Cu layer placed 7.37 µm from neutral plane. The maximum stress which causes on the surface of Cu layer was calculated to under 35.7 MPa, and it was considered wire fatigues or cracks would not be generated at this condition. To confirm this analysis, we fabricated an electronical substrate and folded. We measured wire resistance at 6 kind of folding angles by repeating deformations of 1 time and 50 times. The wire resistances were between 10 mΩ to 20 mΩ and they were negligible small value, so we concluded there were no wire fatigue or cracks by repeating folding deformations. Finally, we performed stretching and attaching to spherical surface of stretchable electronic device with inorganic LED chips. The device could be attached to wrist and followed to wrist motion without fatigue.

REFERENCES

[1] M. L. Hammock *et al.*, “25 th Anniversary Article: The Evolution of Electronic Skin (E-Skin): A Brief History, Design Considerations, and Recent Progress,” *Adv. Mater.*, vol. 25, pp. 5997-6038, 2013.

[2] M. Kaltenbrunner *et al.*, “An Ultra-Lightweight Design for Imperceptible Plastic Electronics,” *Nature*, vol. 499, pp. 458-463, 2013.

[3] J. Yoon *et al.*, “Ultrathin Silicon Solar Microcells for Semitransparent, Mechanically Flexible and Microconcentrator Module Designs,” *Nat. Mater.*, vol. 7, pp. 907-915, 2008.

[4] S. Xu *et al.*, “Stretchable Batteries with Self-Similar Serpentine Interconnects and Integrated Wireless Recharging Systems,” *Nat. Commun.*, vol. 4, 1543, 2013.

[5] H. C. Ko *et al.*, “A Hemispherical Electronic Eye Camera Based on Compressible Silicon Optoelectronics,” *Nature*, vol. 454, pp. 748-753, 2008.

[6] K. Miura, “Method of Packaging and Deployment of Large Membranes in Space,” *Institute of Space and Astronautical Science*, no. 618, pp. 1-9, 1985.

[7] M. Schenk *et al.*, “Geometry of Miura-Folded Metamaterials,” *Proc. Natl. Acad. Sci. USA*, vol. 110, pp. 3276-3281, 2013.

CONTACT

*Y. Iwata, +81-3-5286-2741, iwata5116@ruri.waseda.jp
E. Iwase, +81-3-5286-2741, iwase@waseda.jp