1. Introduction

Wearable devices are attracting a lot of attention for The IoT (Internet of Things), in which everything has an internet address. Wearable devices are expected to be applied to various fields such as healthcare, fitness, entertainment, and manufacturing, since they can be routinely used to sense biometric information or to deliver information. Various forms of devices have already been proposed that feature wearability. “Hard” devices such as wristwatches or glasses-type have been manufactured; and “soft” devices such as clothes-integrated or patch-type devices have also been proposed. In the latter case, a close fit to the human body is needed to achieve a natural-feeling and comfortable-to-use device that does not cause discomfort. High conformability will be required in any such device to follow the curved surfaces and movements of the human body.

It is difficult to achieve a next-generation wearable device by using conventional PWBs or FPCs, since they cannot bend or stretch to conform to changing shapes. Therefore, there is a need for the development of materials and structures for a new device that allow a high degree of flexibility by featuring stretchable properties. Special wiring is needed to the flexibility of the entire device to tolerate strain and minimize any stress on active components whose characteristics would risk being degraded even by slight physical distortion. This has led to the promotion of development of materials and structures such as “stretchable wiring”: Metal wiring patterned to follow a meandering shape, conductive fibers knitted or woven as wiring, and conductive paste printed on stretchable substrate are reported as example of stretchable wiring.[1–3]

Meander metal wiring shows low electrical resistivity and high thermostability. Conductive fibers have high resistivity but can be used in fabrics. Those technologies are useful in the field of flexible device applications. In order to realize the stretchability, extensibility of material itself is required. The conventional technologies such as meander metal wiring and conductive fibers are limited in stretchability. It was reported that conductive printed paste showed 100% elongation,[4] however, it shows high resistivity and resistance variation which depends on the shape of itself.
This structure is composed of a spiral shape wirings placed around lands arranged in a grid, in which the wiring is both separated and supported by a polymeric layer. The spiral shape provides a high wiring capacity in the limited space between the lands. In this structure, furthermore, the wires are isolated from each other by the support layer, resulting in good deformability and robustness. This makes it possible to achieve both high density and conformability.

This spiral-shaped wiring is made of metallic foil, allowing the electrical resistance low and stable whether the wiring is stretched. A conventional solder mounting process is applicable to this metal wiring.

The wiring and insulating layer are formed using a photo process as used in the conventional PWB process. Consequently, productivity is high.

2.2 Process

Our method of forming a stretchable wiring is shown in Fig. 2. There are three processes: (a) a photosensitive polyimide (PI) sheet is laminated on copper foil; (b) the PI sheet is patterned in a spiral-shape by exposure and development using copper foil as the carrier sheet, and (c) the spiral-shaped wiring is formed by wet-etching a copper foil using patterned dry film resist.

By means of these processes, a stretchable wiring based on a PI layer is prepared. Since the PI substrate isolates the wires from each other, it is possible to deform and extend, the PI layer also plays the role of a reinforcing layer.

3. The Characteristics of Stretchable Wiring

3.1 Comparison of the repulsion force due to the shape

We first examined the change in behavior of the electrical resistance and the repulsion force in response to the tension caused by displacement when the wiring is extended. We compared spiral-shaped wiring to meander wiring with the same line width and land pitch.

The measurement settings and wiring shape are shown in Fig. 3. We measured the electrical resistance and the repulsion force of both wiring shapes by extending it by 10% at a rate of 0.4 mm/s, holding it for 30 s, and returning it to its initial length at the same speed. In this case, the number of turns in a spiral shape indicates the rotation number of the wiring from the center land to the inflection point.

The measurement results are shown in Fig. 4. Conformability can be qualified by the repulsion force in the state of percentage of extension. The repulsion forces in the state of 10% extension are measured in three cases - meander wiring, spiral-shaped 1/2 rotated, and spiral-shaped 3/4 rotated. Meander wiring shows 1.9 N, followed by spiral-shaped 1/2 rotated 0.9 N, and spiral-shaped 3/4 rotated 0.5 N. They show different repulsion forces in relation to the wiring shape and the number of turns in the spiral structure, despite having the same line width and land pitch.

Further, it was found that the wiring resistances of both
shapes change little, even when extended up to 10%; the resistance value at that time is low, at about 0.01 Ω, because they consist of metallic foil.

Additionally, it was investigated whether the metal wiring returns to the initial state after 10% expand. As a result, it was found that there are hysteresis characteristics in the repulsion forces against expansion and contraction, and it was confirmed that the wirings remained in the extended state when the repulsion forces become substantially zero while reducing the tensile length after 10% expand. It is considered to be due to the permanent strain occurs in the wiring. The elongation ratios in the state of no repulsion forces are measured in three cases; meander wiring shows about 8.9%, followed by spiral-shaped 1/2 rotated about 7.3%, and spiral-shaped 3/4 rotated about 5.6%. It was found that the wiring shape also affects the recovery force to the initial state after elongation, and it needs to suppress the overstretching and/or reinforce the shrinking force as example of countermeasures.

3.2 Breakdown elongation

Secondly, we evaluated the breakdown elongation, which means how far the wiring can be extended until it breaks. It was stretched at a constant speed of 0.4 mm/s under the same conditions as shown in Fig. 3(a). The results are shown in Fig. 5. The breakdown elongation rates differed according to the wiring shapes. The greater the numbers of spiral turns, the greater were the breakdown elongation rates. The elongation range is wide, since the wiring resistance increases gradually until just before breakage.

In this study, the spiral wiring was designed such that the lands are at the same intervals position and the line width is constant. We calculated the ratio of the actual spiral wiring length to the distance between the two adjacent centers of the spiral structure (land pitch). The results of comparing the calculated value with the limit elongation rates shown in Fig. 4 are shown in Table 1.

The breakdown elongation rates roughly match the calculated values. It can be seen that the surplus length of the wiring between lands has potential for elongation. Since the ratio of wiring is determined by the land pitch, line width, and line interval, etc., the breakdown elongation rate increases with greater land pitch or decreasing the line width and interval. The spiral shape can efficiently pack long wiring within a limited volume. This is one of the reasons for this configuration showing a high elongation property.

4. Durability When Repeatedly Stretched

It is important for stretchable wiring not only to extend
but also to fit the human body as it shrinks. Since wiring that made of only metal and a PI layer shows insufficient shrinkage, this wiring was sandwiched in a 30 \( \mu \)m-thick thermoplastic polyurethane (TPU) sheet. We then evaluated the initial reliability of this wiring when subjected to repeated 10% stretching. The results are shown in Fig. 6 and 7.

The meandering-pattern wiring showed slightly increased resistance in the early stages of the stretching test: the wire broke after 82 cycles. No breakage was observed in the spiral-shaped wiring, and its resistance changed little, even after 200 cycles.

Observation of the fracture point in the meandering-pattern wiring revealed that breakage takes place at a location with the tightest curvature. We conclude that the breakage was caused by metal fatigue brought on by repeated deformation during stretching.

The above results show that spiral-shaped stretchable wiring has higher reliability. Further, this wiring can be applied not only to two-dimensional stretching, but also to three-dimensional deformation, giving it potential to fit to curved surfaces with low rebound. This characteristic gives it excellent adaptability to wearable devices.

5. Demonstration
5.1 Flexible RGB-LED display

We demonstrated a 45 × 80 matrix LED display at 3-mm pitch using spiral-shaped wiring. LED chips were mounted on the center land of each spiral structure. Both sides of the substrate were then laminated with TPU sheet. The substrate was made of a four-layer FPC, since it is necessary for each chip to produce all three RGB colors. Unnecessary parts on the substrate were cut off using a laser. The substrate is illustrated in Fig. 8 (a). This is a passive-matrix drive display with a drive voltage of 5 V. Its appearance at the time of lighting is also shown in Fig. 8 (b). The spiral-shaped wiring was found to be superior in flexibility and stretchability to a display with meander wiring at the same pitch.
5.2 Stretchable LED display

We also demonstrated a stretchable LED display of 3-mm pitch with spiral-shaped wiring made of using a photo process. The spiral structure was formed using the process shown in Fig. 2. Next, a solder resist layer was formed and LED chips were mounted on it. The chip size is 1005. Photographs of the wiring and the chip-mounting structure are shown in Fig. 9 (a) and (b).

Figure 9 (c) shows a sealed stretchable display using a soft polyurethane gel. Since this seal gel is even softer than the TPU sheet, it has no adverse effect on the stretchability or deformability of the display. Short-circuiting between the wires and disconnections is also prevented by its sealing effect. This demonstration confirms that a stretchable display can be driven without disconnections occurring, even while stretched or bent.

5.3 Conformable wiring for biosensors

We have processed a spiral wiring structure in patch-like form designed for use by attachment to a curved surface or a stretching and bending structure, such as part of the human body. The stretchable wiring was bonded to the stretchable fabric and coated with an adhesive gel on the side that comes into contact with the human body. One manner of adhering to the body is shown in Fig. 10 (a). Thus it can be attached by fitting to the location of the curved shape, and it can also be greatly deformed, as shown Fig. 10 (b). However, we have still not yet evaluated the setup with respect to biocompatibility.

6. Conclusion

We have designed a stretchable type of wiring with a novel structure, composed of spiral-shaped metal wiring and a PI layer that anchors the wires. We have confirmed that it has 3D-conformability, low-resistance stability, and process applicability that allows conventional processes to be used for its manufacture, and demonstrated stretchable LED displays.

Since the resistance of this wiring is very low, it is possible to apply it to the devices such as an LED displays that require the flow of relatively high currents. Moreover, the wiring is not only highly stretchable: it also provides an excellent fit owing to its softness and ease of deformation, which allow it to be used in applications that require direct contact with the human body.

In the future, this wiring technology is anticipated to be used for purposes that include flexible displays or in digital signage, as well as in fields such as bio-sensing or wearable devices.

References


Susumu Sawada
He joined Panasonic Corporation in 2005 and since then he has been engaged in the research and development of substrates and electronic packaging technology. He is now engaged in research of wearable sensor devices.

Yoshihiro Tomita
He received the M.S. degrees in Physical Chemistry, from Osaka University, Japan, in 1984. In 1984, he joined Matsushita Electric Industrial Co., Ltd. (current Panasonic Corporation). He currently researches packaging technology for wearable and stretchable devices.

Koichi Hirano
He received his B.S. and M.S. degrees in chemistry from Kyoto University, Japan, in 1993 and 1995 respectively. He joined Matsushita Electric Industrial Co., Ltd. (now Panasonic Corporation) in 1995. He has been engaged in the development of substrates, electronic packaging and modules. He has concurrently served as a researcher of Japan Advanced Printed Electronics Technology Research Association (JAPERA) from 2011 to 2016. He is now engaged in research of sensor devices. He is a member of JIEP.

Hiromi Morita
He received the M.E. degrees in Metallurgical Engineering from Tohoku University, Japan, in 1990. He joined Matsushita Electric Industrial Co., Ltd. in the same year and has been developing the analytical technique for the semiconductor and display devices. In 2015, he was the Manager of Wearable Devices Research Team, Platform Technologies Research Department, Device Research Laboratory, Advanced Research Division, Panasonic Corporation. Since 2016, he is the Chief Researcher of sensing technology Research Group.

Hideki Ohmae
He joined Panasonic Corporation in 1990. He has developed LCD panel for projector, projection television system using DMD and image processing circuit for PDP television in AVC Company, and OLED display and wearable LED display in R&D division of Panasonic. He has joined a member of Society for Information Display since 2015. He is a chief researcher in Advanced Research Division of Panasonic, and currently developing a wearable sensor device.

Takashi Ichiryu
He joined Matsushita Electric Industrial Co., Ltd. (now Panasonic Corporation) in 2002. He has been engaged in the development of substrates (Multilayer PCB and FPC), electronic packaging and modules. He is now engaged in the development of packing technology for power semiconductor devices and modules.

Takashi Nomura
He joined Sanyo Electric Co., Ltd. (now Panasonic Corporation) in 1985. He has been engaged in the development of substrates and electronic packaging. He is now engaged in the development of packing technology for power semiconductor devices and modules.

Koji Kawakita
He joined Matsushita Electric Industrial Co., Ltd. (now Panasonic Corporation) in 1987. He has been engaged in the development of ceramic material, Multilayer PCB, electronic packaging and modules. He is now engaged in the development of packing technology for power semiconductor devices and modules.