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FLEXIBLE AND STRETCHABLE WIRING BY NDFEB MAGNETIC POWDER

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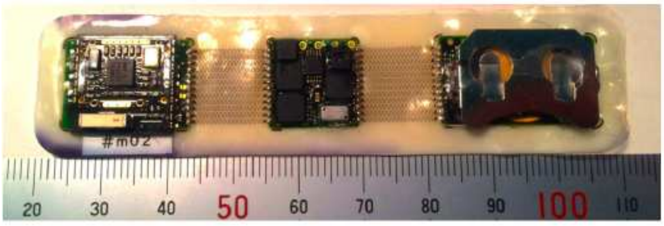
Abstract. *This paper describes flexible and stretchable wiring for wearable healthcare systems. The stretchable wiring was fabricated by filling magnetic and conductive powder in hollow silicone tubes. The powder consists of magnetic particles coated with conductive metal. The stretchability and stable conductivity are attributed to the magnetic force of the particles. To realize the wiring, the magnetic powder was coated with Au/Cu metal. The electrical and mechanical performance of the wiring was evaluated. The evaluation demonstrates that the wiring has conductivity of 4.92 S/cm and axial strain limit of 60%. The 1000 cycles of repetitive tensile tests revealed deterioration in the conductivity of the wiring. However, it is found that the deteriorated performance of the wiring can be retrieved by remagnetization.*

Keywords: Wearable healthcare monitoring system, Stretchable wiring, Magnetic powder, Flexible electronics

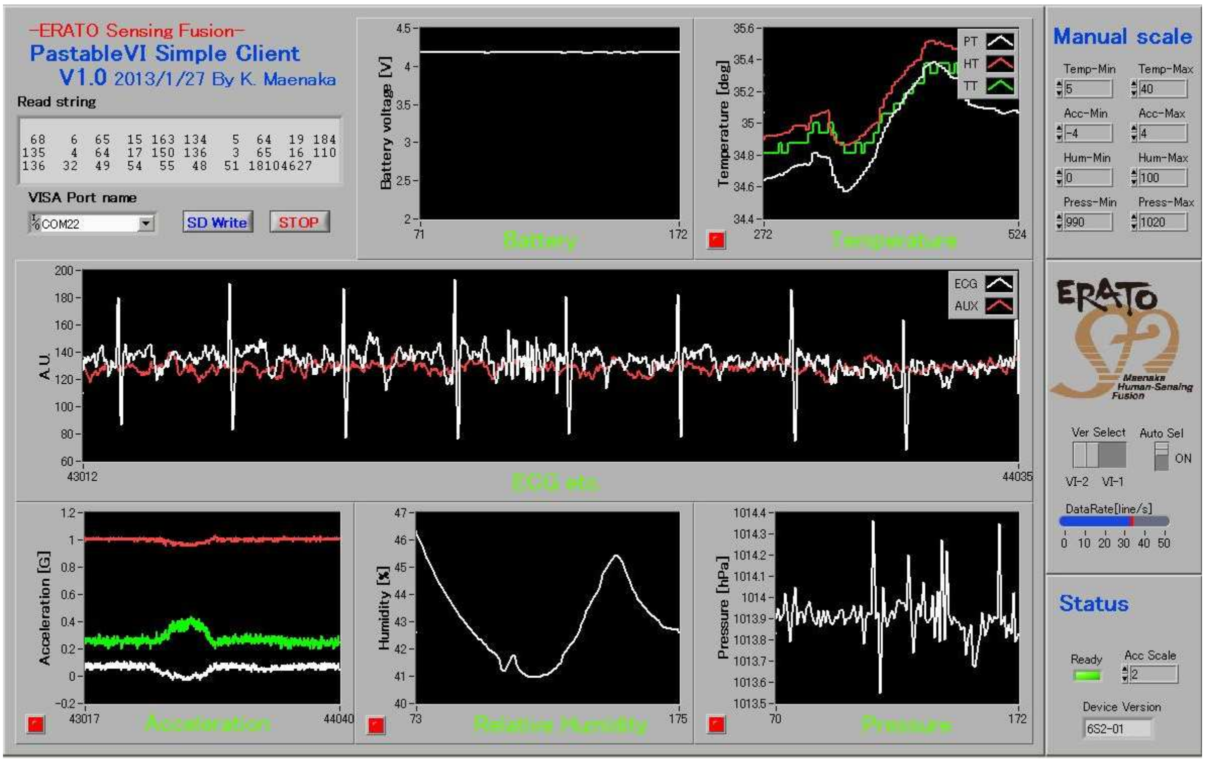
1. **Introduction.** Recently, a variety of wearable systems equipped with sensors were developed to provide biological information to wearers [1-4]. The devices help them to avoid lifestyle-related disease. In addition, the wearable devices have potential to be applied to various fields [5-7].

Our group have been developing the human monitoring system by using MEMS (Micro Electro Mechanical Systems) technologies [8]. The appearance of our monitoring system looks like an adhesive plaster (Figure 1(a)). This system is pasted directly onto the chest of human. This device has flexible substrate that was made of a poly dimethyl siloxane (PDMS) and three printed circuit boards (PCBs) including sensors for acceleration, pressure, humidity, temperature and ECG. Three PCBs are connected by the in-plane serpentine shaped wiring on the PDMS film. Wearers were able to manage their physical health condition as well as environmental condition by using this system (Figure 1(b)). To obtain biological data stably from the sensing wearable system, continuous adhesion to human body is essential. Therefore, the wearable devices should have flexibility and stretchability as human skin does. However, this device did not have enough stretchability for following the human skin movement. In order to improve stretchability of this device, stretchable wiring is demanded.

For the application to wearable devices, a variety of flexible and stretchable wirings have been researched, such as wavy-shaped metal wiring and conductive elastomer [9-14]. The structure of the wavy-shaped metal wiring is fabricated by depositing metal thin film onto the elastic substrate with wavy geometry, resulting in high conductivity and prevention from cracking due to the stress concentration. However, more robust wiring is still required for the wearable system. On the other hand, conductive elastomer does



(a)



(b)

FIGURE 1. Wearable human monitoring system, (a) overview of the device, (b) measured biological information for physical health condition and environmental condition

not have sufficient conductivity, because conductive elastomer is fabricated by dispersing conductive particles into elastic insulation media.

In this study, we propose stretchable wiring for wearable healthcare systems by using magnetic powder as a conductive material. To demonstrate the applicability to the wearable systems, the preliminary test wiring is fabricated and evaluated.

2. **Stretchable Wiring with Magnetic Conductor.** We proposed stretchable wiring by using magnetic powder conductor filled in the hollow silicone tube (Figure 2) [15]. The structure of this wiring aims to become self-healing wiring. The reason of self-healing is that particles attract others by magnetic force. The combination of the magnetic powder and silicone tube has some other advantages. The total resistance is low contact resistance being a dominant of total resistance because of aggregation of magnetic powder [16,17]. A silicone generally has biocompatibility and stretchability. In addition, the silicone tube filled with magnetic powder has stretchability in contrast to conductive elastomers because not dispersing powder into silicone.

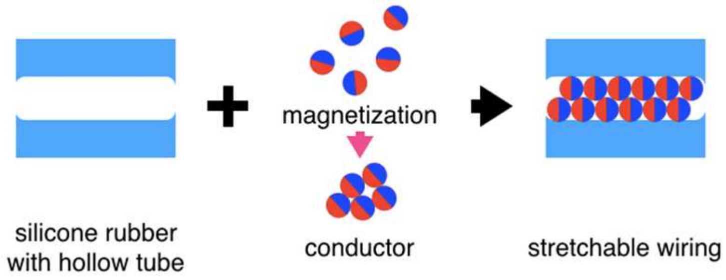
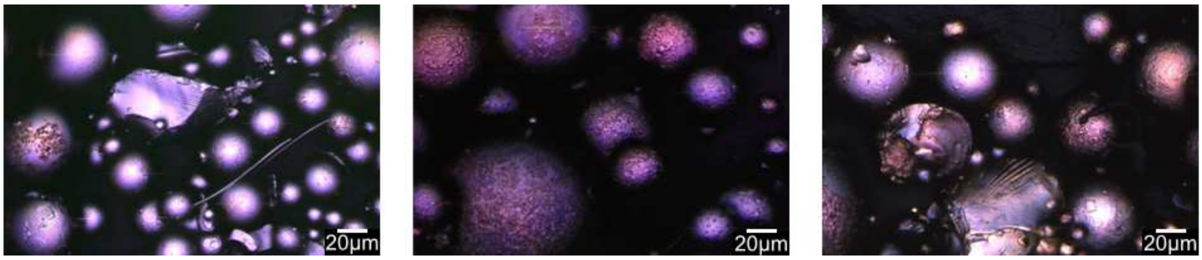


FIGURE 2. Concept of stretchable wiring by using magnetic powder



(a) (b) (c)

FIGURE 3. Conforcal laser scanning microscope pictures of NdFeB powder, (a) as fabricated, (b) after electroless capper plating, (c) subsequent gold sputtering

The NdFeB alloy powder (MQP S-11-9; Magnequench, Singapore) was used as magnetic conductor powder. The 50% particle size distribution ranges 40 to 60 μm in diameter. The powder keeps magnetic energy, BH_{max} of 80 to 92 kJ/m^3. The NdFeB has strong magnetic performance and a little conductivity [18,19]. However, NdFeB will be easy to oxidize. Oxidation causes degrading magnetic and electric performance. Furthermore, NdFeB powder does not show enough conductivity. Therefore, in order to prevent the oxidation and improve the conductivity, NdFeB powder was coated with metal film as shown in Figure 3.

Copper was firstly coated on the NdFeB powder as an adhesive layer by electroless plating (Figure 3(b)). In order to prevent condensation of powder, NdFeB powder was pretreated and plated in ultrasonic cleaner. In the next, the NdFeB powder was coated with gold film by a deposition-up type sputtering equipment (JFC-1100E; JEOL Ltd., Tokyo, Japan) (Figure 3(c)). Gold film improves conductivity of NdFeB powder. NdFeB powder was fixed on Teflon separator by magnetic plate (Figure 4(a)) and NdFeB was coated with gold film (Figure 4(b)). To coat gold film on the entire surface of the powder, the powder turns over by altering the pole of magnetic plate (Figure 4(c)). Then, the opposite side of powder was coated with Au film (Figure 4(d)). Magnetic powder coated with gold on one side is shown in Figure 5. The gold coated surface has high brightness (Figure 5(a)). After altering the pole of the magnet (Figure 4(c)), the surface without the gold was shown in Figure 5(b).

After the metal coating, the magnetic powder dispersed in acetone was filled in a hollow silicone tube. The slurry filling method increased filling ratio of the powder twice as much as dry powder filling because of liquid cross-linking adhesive force. Then electrode metal pins are inserted at the inlets. Subsequently, the tube was annealed at a temperature of 50°C in a dry air oven to drying out the acetone. The inlets were sealed with silicone-based adhesive. Finally the powder was magnetized by a shot pulse magnetization under magnetic flux density of 3 T, for longitudinal direction (M25HS-402; OP Electronics

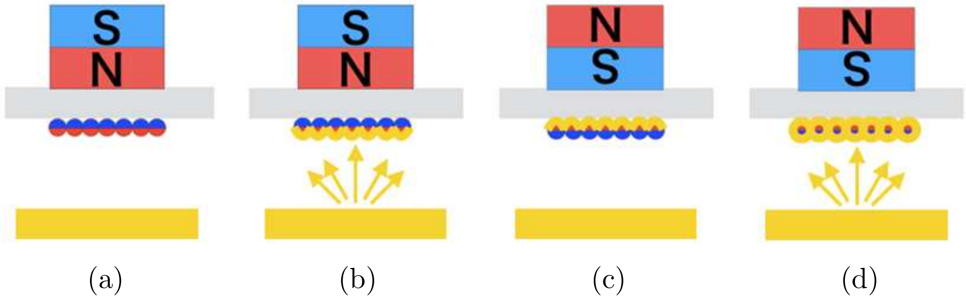


Figure 4. Process flow of gold sputtering, (a) putting magnetic powder on stage, (b) gold sputtering at first, (c) altering the pole of magnetic plate, (d) gold sputtering at second

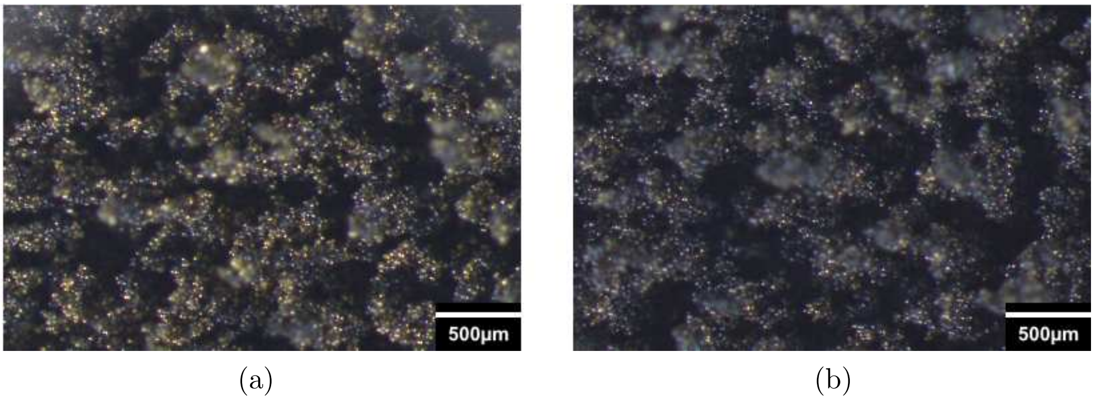


Figure 5. Magnetic powder coated with gold on one surface, (a) coated surface, (b) without coated surface

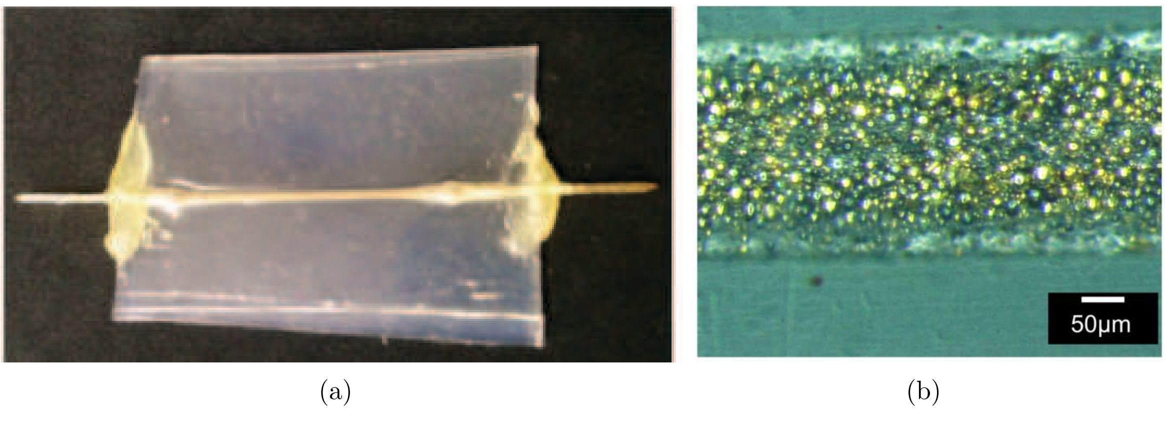
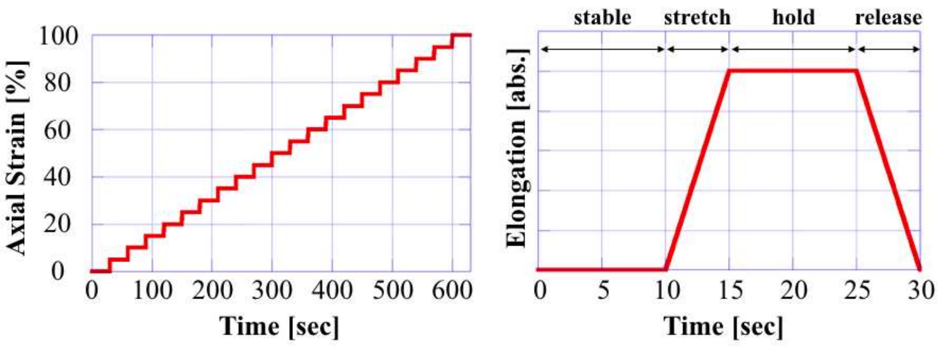


Figure 6. Fabricated wiring, (a) overview, (b) magnetic powder in silicone

Industory Co., Ltd., Tokyo). Figure 6 shows pictures of the fabricated wiring test samples. The magnetic powder filled in silicone tube was shown in Figure 6(b).

3. **Experiments.** Two types of evaluation with tensile tester were carried out. Figure 7 indicates the patterns of applied axial strains for each evaluation. In order to evaluate the relation between resistance and axial strain, the wiring was continuously stretched with the incremental strain of 5% every 30 seconds (Figure 7(a)). In addition, in order to evaluate the durability, wiring was repeatedly stretched and released. The stretching sequence was 10 seconds stable, 5 seconds stretch, 10 seconds hold and 5 seconds release



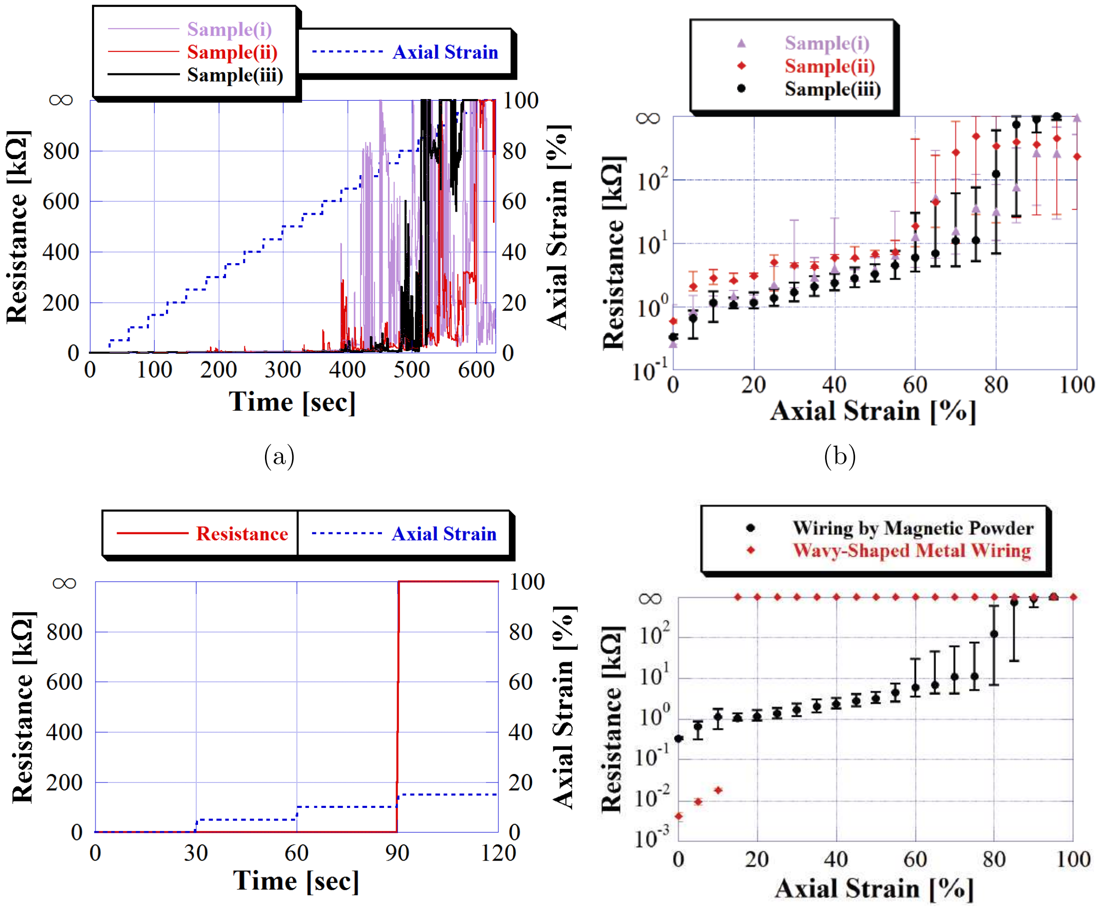
(a) (b)

Figure 7. Two kinds of tensile tests, (a) wiring was continuously stretched with 5% of incremental increase in strain every 30 seconds, (b) wiring was repetitively stretched and released

as shown in Figure 7(b). The voltage drop across the sample is measured during tensile test under a constant current condition of 1 μA.

4. **Results and Discussions.** Figure 8 shows resistance change during tensile test with continuously stretched with the incremental axial strain of 5%. For the experiments, three wirings of sample (i), sample (ii) and sample (iii), which were fabricated with the same process, were used in the evaluation. Sample (i), sample (ii) and sample (iii) have the diameter of 450 μm and the length of 20 mm, 24 mm and 26 mm, respectively. Figure 8(a) shows the time-series raw data, where the 1st vertical axis indicates resistance and the 2nd vertical axis axial strain. Since the limit of the resistance in measurements is 1 MΩ, the saturated values are defined as infinite resistance in the graphs. Figure 8(b) shows the average resistance versus axial strain, where the error bar shows the maximum and minimum resistances. All wirings were stable with the axial strain up to 60%. Under zero axial strain, the average resistances of the sample (i), sample (ii) and sample (iii) were 265 Ω, 586 Ω and 332 Ω, respectively. The corresponding conductivities are 4.75 S/cm, 2.78 S/cm and 4.92 S/cm. For the axial strain beyond 60%, the resistance increased and became unstable. The reason of unstable resistance can be explained that the contact points of powder are randomly and largely decreasing by strain. The resistances of three wirings are somewhat different because of the non-uniformity of the thickness of gold film on the magnetic powder. In the following experiments, sample (iii), which has the most stable resistance and the highest conductivity, is used.

For comparison with other types of stretchable wiring, a wavy-shaped metal wiring [20] was prepared and tested. The wavy-shaped metal wiring has sputtered gold/chrome with total thickness of 2.5 μm on roughened surface of silicone. The average roughness of silicone is 25 μm. The wavy metal film was covered with silicone again for protection. The fabricated wavy-shaped metal wiring has length of 40 mm and width of 15 mm. Figure 8(c) shows raw data of evaluation for wavy-shaped metal wiring. Figure 8(d) shows the resistance change vs. axial strain for magnetic powder wiring and wavy-shaped metal wiring. The error bars show the maximum and minimum resistance. The wavy-shaped metal wiring has much lower resistance and is more stable than the wiring by magnetic powder with axial strain below 10%. However wavy-shaped metal wiring suddenly lost the conductivity at axial strain beyond 15%, because of cracking of metal film. The wavy-shaped metal wiring has good performance for small strain; however, the magnetic



(a) (b) (c) (d)

Figure 8. Result of continuously stretching tensile test, (a) the raw data of three wirings by magnetic powder, (b) the relation of resistance and axial strain for wiring by magnetic powder, (c) the raw measurement data for wavy-shaped metal wiring, (d) comparison between the wiring by magnetic powder and wavy-shaped metal wiring

powder wiring has a continuous conductivity for large strain. The magnetic powder wiring is more robust than the wavy-shaped metal wiring for axial strain up to 60%.

Because the resistance of the magnetic powder wiring significantly changes by strain, the wiring is not suitable for the applications which require low resistance such as power supply line and antenna. However, it is useful for signal transmission line for CMOS systems, which have high impedance inputs.

Figure 9 shows the resistance change during long-term cyclic tensile test. The stretchable wiring was repetitively subjected to axial strain of 30%. The sudden increase of resistance just after applying axial strain and immediate decrease of resistance can be observed. It may be derived from the effect of tension and relaxation of the silicone. In Figure 9(b), two durations, first 10 cycles and last 10 cycles, are shown. For the last 10 cycles, the resistance increased compared with that for the first 10 cycles at the stretched and released state. This result implies the wiring is deteriorated by peeling away metal film at powder collision and collapsing the structure of close-packed powder during the cyclic stretching.

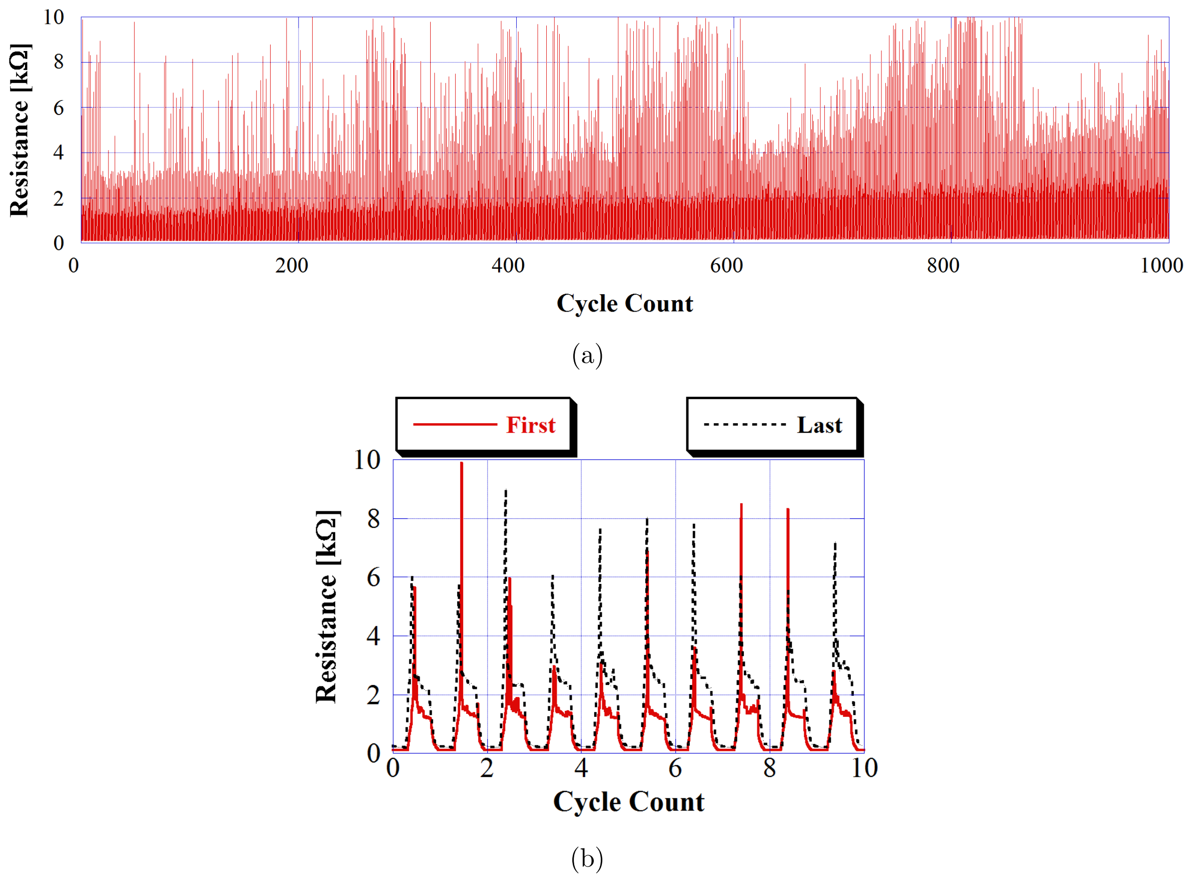


FIGURE 9. Resistance during cyclic tensile test (a) for 1000 cycles and (b) comparison between 10 cycles at the first and the last of the tensile tests

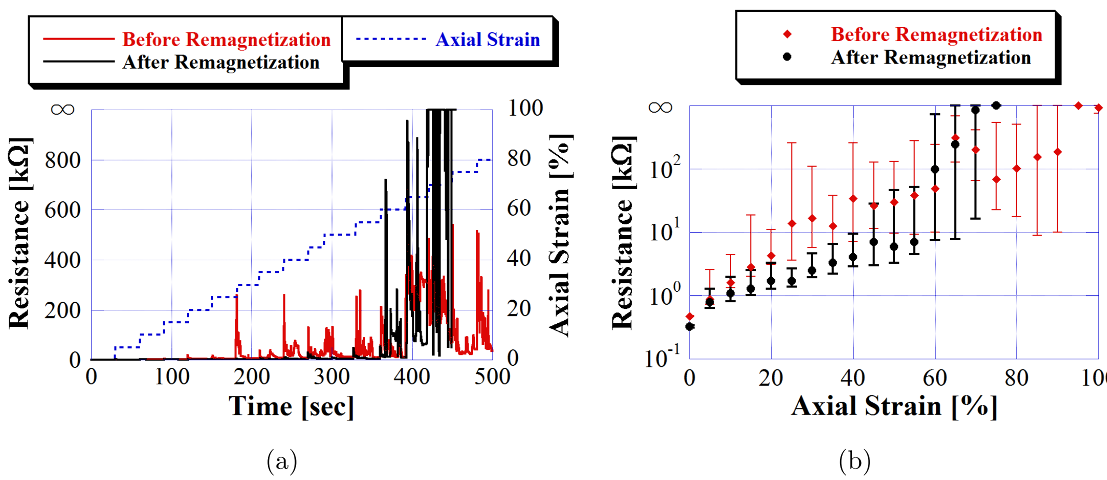


FIGURE 10. The effect of remagnetization, (a) the raw data of deteriorated wiring, (b) the relation of resistance and axial strain for deteriorated wiring

It can be presumed that performance of wiring deteriorated by cyclic tensile test is retrieved by aligning magnetic powder with remagnetization. Then, the deteriorated wiring was remagnetized by a shot pulse magnetization under magnetic flux density of 3 T, because of retrieving the conductivity.

To compare deteriorated wiring before and after remagnetization, continuously stretching tensile test was performed (Figure 10). Figure 10(a) shows the raw data of results for both before and after remagnetization. Figure 10(b) shows average resistance to axial strain for the deteriorated wiring. The wiring before remagnetization has unstable and lower conductivity. On the other hand, the wiring after remagnetization has more stable and higher conductivity. It is evident that wiring retrieves its performance by remagnetization. Remagnetization requires special apparatus, large and heavy magnetizer, and it is difficult to handle by end-user. However, in the case of application for wearable sensing system, the flexible substrate including this wiring is usually recycled part because it attaches directly to human skin, and in recycling processes the substrate can be remagnetized as well as a device cleaning.

In the evaluations, the stretchable wiring did not have a perfect self-healing property as shown in Figure 9(b). It is assumed that the imperfect self-healing property results from the insufficient adhesiveness and surface coverage of the gold film on the magnetic particles. By improving the film fabrication process, the imperfect self-healing property can be overcome. Nevertheless, the wiring with magnetic particles is more useful than conventional wavy-shape wiring when the wiring is subject to a large strain. The particle-based wiring without cracking will be very effective for wearable devices.

5. **Conclusions.** In this study, we demonstrate the fabrication and measurement of flexible and stretchable wiring by using magnetic powder as conductor in silicone rubber tube. NdFeB powder coated with Au/Cu metal film shows high conductivity. In addition, conductivity of wiring was stable with the axial strain up to 60%. It is also found that the deteriorated performance in the conductivity can be retrieved by remagnetization.

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