# STRETCHABLE ELECTRONIC DEVICE WITH REPEAT SELF-HEALING ABILITY OF METAL WIRE

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## ABSTRACT

This paper reports a stretchable electronic device with repeat self-healing ability of a wire crack caused by stretching deformation. The crack of metal wire is healed with assembled metal nanoparticles by dielectrophoresis, when a voltage is applied to the cracked wire covered with the nanoparticle solution. By designing a circuit, we controlled the applied voltage and current for the self-healing to be avoid excessive Joule heating in the assembled nanoparticles. This consideration enables us to heal a crack of tens of micrometers in width and to practically achieve a stretchable electronic device.

## INTRODUCTION

Various kind of stretchable electric devices such as stretchable displays [1] and health monitoring devices [2, 3] have been developed in recent years. Due to a stretching property of these devices, stretchable wires are one of key components; therefore, some research groups focused on self-healing wires which can get their conductivity again even if they are broken by stretching. Some research groups proposed wires using self-healing polymers [4, 5] and we proposed self-healing metal wires using dielectrophoresis of metal nanoparticles [6]. Both of these wires, however, have a limit of healable crack width. The wires using self-healing polymers can not heal without a contact of the broken wires, and the wires using dielectrophoresis of metal nanoparticles can heal only several-micrometers-cracks. In general, when a stretching deformation exceeds a breaking strain of a wire, a wide crack (around several tens of micrometers) is generated at the time. Metal wires originally have high conductivity; therefore, we focused on the self-healing metal wire using dielectrophoresis of metal nanoparticles. Here, we analyzed cause of limitation of healable crack width to realize a stretchable electronic device with the self-healing metal wire.

In a previous study, we reported that higher voltage applied to a cracked wire can heal a wider crack [6]. However, over several-micrometers-wide cracks were not healed even with high applied voltage. In this study, we focused on electric current flowing in assembled nanoparticle chain, because we considered that Joule heating due to high current might break the nanoparticle chain just when the nanoparticles are trapped with high applied voltage (figure 1). That is, assembled nanoparticle chain is broken if Joule heating is higher than certain threshold value, because heat generated in the nanoparticles and heat released into medium are not balanced. Therefore, by applying a certain voltage under changing applied current, we confirmed a wider crack can be healed with high applied voltage and low current. By designing a circuit based on result of above experiment, we also demonstrated self-healing of a cracked wire with a stretchable electronic device to show usefulness of our self-healing ability.

## MEASUREMENT OF HEALING CONDITIONS FOR WIDE CRACK HEALING

To confirm wires with a wide crack can be healed with high applied voltage and low current, pre-cracked gold wires on a glass substrate and gold nanoparticles aqueous dispersion were used. The gold wires on a glass substrate

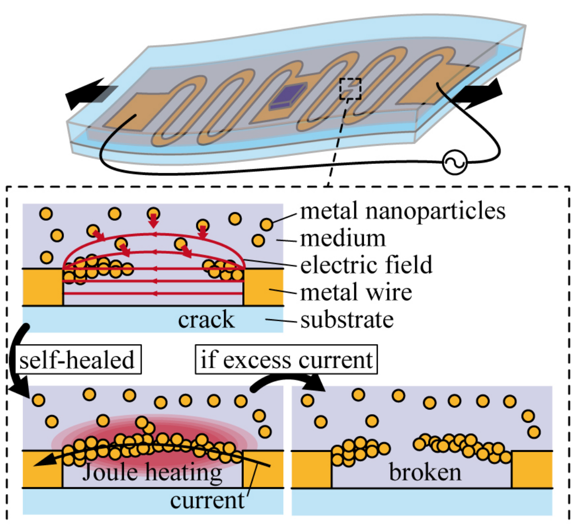


*Figure 1: Schematic illustrations of a stretchable electronic device with the self-healing metal wire.*

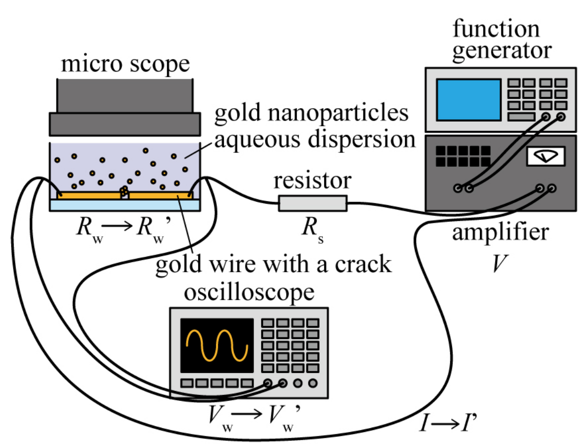


*Figure 2: Schematic illustrations of a Measurement Setup for self-healings of cracked wires.*

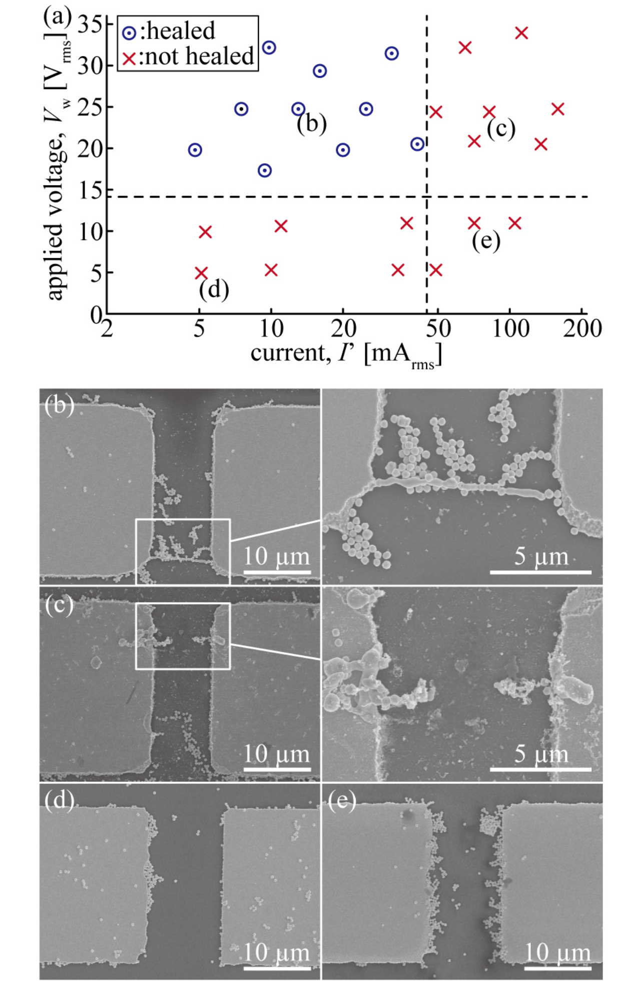


*Figure 3: Measurement of healing conditions with deferent values of voltage applied to a cracked wire, $V_w$, and electric current after healing, $I'$. (a) Healing condition plot between $V_w$ and $I'$ in the case of 10 µm in crack width. (b-e) SEM images of cracks after measurements.*

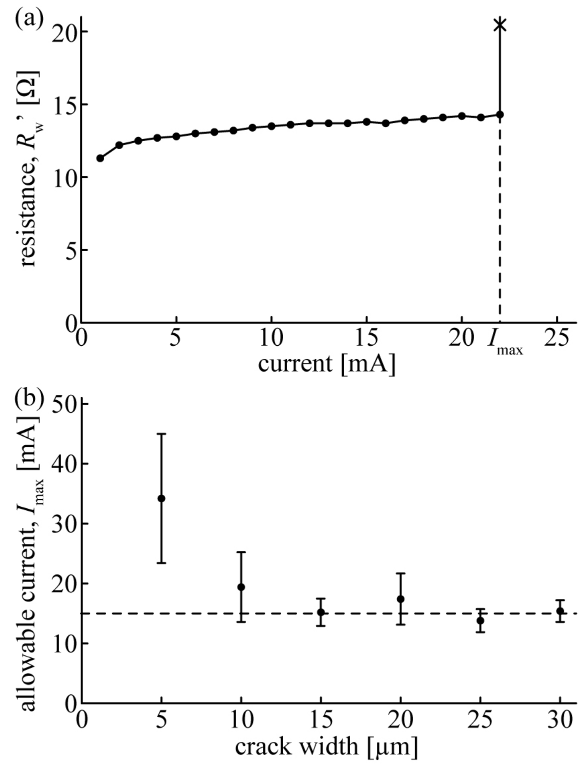


*Figure 4: Measurement of allowable current, $I_{max}$. (a) Resistance of wire after healing, $R_w$', change according to current in the case of 10 µm in crack width. (b) $I_{max}$ change according to crack width.*

were fabricated in a typical photolithography process. First, a 0.01-µm-thick chromium layer as adhesive layer and a 0.5-µm-thick gold layer were deposited on a glass substrate by an electron beam evaporation system. Then, the gold and chromium layers were patterned to a cracked wire shape (25 µm in wire width, 1 mm in wire length and 5 µm to 30 µm in crack width). The crack was located on the center of the wire, and the cracked wires were covered with 400-nm-diameter gold nanoparticles aqueous dispersion (742090, Sigma-Aldrich). Figure 2 shows a measurement setup of crack healing. $V$ is voltage applied to an entire circuit, $V_w$ and $R_w$ are applied voltage and resistance of cracked wire, $R_s$ is resistance of a resistor connected to the cracked wire in series, and $I$ is current flowing a circuit. $V_w$', $R_w$', and $I$' are the values of $V_w$, $R_w$, and $I$ after healing of the cracked wire, respectively. AC voltage (1 MHz in frequency) as $V$ was applied by a function generator (33500B, Keysight) and a bipolar amplifier (HAS4101, NF). Values of $V$ and $R_s$ were changed to change values of $V_w$ and $I$'. $V_w$ was applied for approximately 1 min, and $V_w$ was monitored by an oscilloscope (DSO-X 2024A, Agilent Technologies). If the cracked wire was healed, $V_w$ changed to $V_w$', approximately zero, because $R_w$' is much smaller than $R_s$. Therefore, $I$' was given by $V/R_s$. Value of $R_w$' was measured with a source meter (2614B, Keithley) by four probe method. After the measurement, the cracked wires were washed in pure water and dried for SEM observation of the crack.

Figure 3 shows results of healing condition measurement with a 10-µm-wide crack, deferent values of $V_w$ and $I$'. We considered that the applied voltage before healing, $V_w$, is important for crack healing and the electric current after healing, $I$', is important for breaking the nanoparticle chain by Joule heating. Figure 3(a) clearly indicates this consideration. In figure 3(a), cracked wires with high $V_w$ and low $I$' (17 $V_{rms}$ or more and 41 $mA_{rms}$ or less) were healed, on the other hand, cracks with low $V_w$ or high $I$' were not healed. Figure 3(b-e) shows SEM images of the crack after the measurement in figure 3(a). In the case of the healed wires, it was confirmed that the cracked wires were healed with a nanoparticle chain formation of gold nanoparticles as shown in Figure 3(b). A part of the assembled nanoparticles looks to melt into each other. The assembled nanoparticles would be heated and melted by Joule heating due to current, then

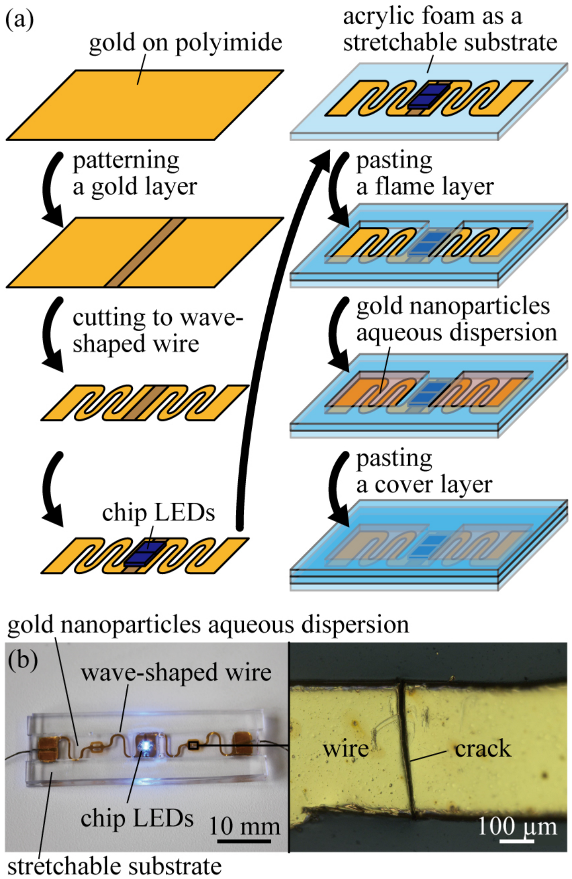


*Figure 5: Fabrication of a stretchable electronic device composed of self-healing metal wires and chip LEDs. (a) Schematic illustrations of a fabrication process of the device. (b) Optical images of the fabricated device.*

cooled by medium in a moment. In figure 3(c), in the case of high $V_w$ and high $I'$, a broken nanoparticle chain formation was observed. The assembled nanoparticles would be melted and broken by excess current. In figure 3(d, e), in the case of low $V_w$ and both low and high $I'$, a nanoparticle chain was not confirmed clearly, and some nanoparticles were trapped in the crack. In this condition, dielectrophoresis force acting on nanoparticles were weak due to the low $V_w$, and the nanoparticles would not be trapped.

To determine the critical current for breaking nanoparticle chain, applied current to healed wires was increased gradually. Figure 4(a) shows resistance after healing, $R_w$', change according to increased current with a 10-µm-wide crack. $R_w$' was suddenly risen at 23 mA, and that indicates that healed wire was broken again at the current. Therefore, we called a value just before breaking nanoparticle chain "maximum allowable current, $I_{max}$". Figure 4(b) shows $I_{max}$ change according to crack width. $I_{max}$ decreased as crack width got wider, and got closer to approximately 15 mA. We considered that because $R_w$' got higher as crack width got wider, Joule heating got higher even when value of current was low. That indicates that current flowing a circuit after healing should be smaller than 15 mA to heal several-tens-micrometers-wide cracks.

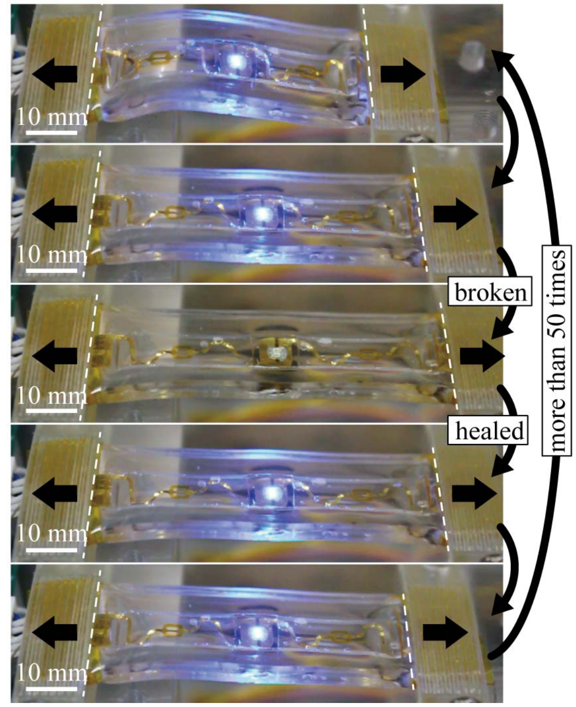


*Figure 6: A series of images of repeat self-healing demonstration with a cracked metal wire in a stretchable electronic device.*

## REPEAT SELF-HEALING OF STRETCHING DEFORMATION

Finally, we demonstrated self-healing of a crack with a stretchable electronic device. Based on results of measurement of healing conditions, we designed a circuit to control applied voltage and current. Figure 5(a) shows a fabrication process of a stretchable electronic device. First, a 0.01-µm-thick chromium layer and a 0.5-µm-thick gold layer were deposited on a 25-µm-thick polyimide film. A part of the gold and chromium layers were patterned to contact pads through a photolithography process, and the layers were patterned to wave-shaped wires by a cutting plotter (CE6000-40, Graphtech). Then, surface mount chip LEDs were mounted on the contact pads. The patterned layers were pasted on a 1-mm-thick acrylic form tape as a stretchable substrate, and another acrylic form tape as a flame layer was pasted on the stretchable substrate. 400-nm-diameter gold nanoparticle aqueous dispersion was dropped into the flame layer, and finally another acrylic form tape as a cover layer was pasted on the flame layer. Figure 5(b) shows a fabricated stretchable electronic device. A wave-shaped wire was pre-cut for a demonstration of self-healings. The crack width was approximately 11 µm. We connected a 10 kΩ resistor to the fabricated device in series, and an AC voltage (1 MHz, 28 $V_{rms}$) was applied to the fabricated device and the resister. Current of 2.8 $mA_{rms}$ flowed in the circuit when the wave-shaped wire was healed. The fabricated device was mounted to movable stages, and stretching deformation were applied to the fabricated device repeatedly with applied voltage.

Figure 6 shows a series of images of repeat self-healing demonstration. A crack in the wave-shaped wire was healed at the start of the demonstration; therefore, chip LEDs were emitting in upper image of figure 6. The fabricated device was stretched, and the healed wave-shaped wire was broken again at approximately 30% stretching (in middle images of figure 6). Then, the wave-shaped wire was healed and the chip LEDs emitted again in several seconds as shown in lower images of figure 6. This cycle of stretching deformation were repeated, and finally we confirmed more than 50 times self-healings.

## CONCLUSIONS

We developed a stretchable electronic device with repeat self-healing ability of a wire crack. First, we determined healing conditions of 10-µm-wide crack. As a result, in the case of 400-nm-diameter gold nanoparticles, we have shown that cracked wires were healed with high applied voltage (17 $V_{rms}$ or more) and low current (41 $mA_{rms}$ or less). Then, we have shown that the maximum allowable current as 15 mA to heal several-tens-micrometers-wide cracks. We also demonstrated self-healing of a cracked wire with a stretchable electronic device by designing an electric circuit based on results of above measurements. As a result, although the cracked wire was broken at approximately 30% stretching, the crack was healed again in several seconds. This cycle was repeated, and we confirmed more than 50 times self-healing.

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