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Electrical Properties of Metal Film with Micro-Holes on a Polymer Substrate: Applications for Flexible Electronic Devices

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A new type of metal film on a polyethylene terephthalate (PET) substrate was fabricated with a pattern of holes using a photolithography-based wet process, and its application to the interconnection design of flexible electronic devices was demonstrated. The intended diameters for the holes in the patterns of the metal films were 10 μm, 30 μm and 50 μm. The hole-patterned samples showed much better electrical properties in the high-strain region. Furthermore, the absolute value of the electrical resistance for the hole-patterned sample was low, even by comparison with a no-pattern sample, for some of the critical values of tensile strain. The results of this study show potential application to the interconnection design of flexible electronic devices.

Keywords: interconnection, flexible electrode, electronic devices, solar cell, OLED

1. INTRODUCTION

To meet the demand for renewable energy, the photovoltaic solar cell has experienced exponential growth over the past several years. Flexible solar cells and electronic displays are major two examples of new types of integrated electronic devices that have large area and are foldable.[1-4] In the near future, many flexible devices consisting of metal films on polymer substrates will be available on the market.[5-6] When the electronic devices are stretched, the polymer can deform, but the metal films may fracture to failure. The physical properties of metal films on a polymer substrate can be modulated through interfacial adhesion and process parameters.[7] Though the reliability of the flexible electronic devices is mainly determined by the electrical properties of the metal films on polymer substrates, only a few research results in this field have been reported.[8]

In the present study, we designed and fabricated a new type of metal electrode on a polymer substrate that can be used as an interconnection in flexible electronic devices. Unlike a conventional metal electrode, an array of hole-patterns was fabricated on the metal films in this study. The effect of the hole-patterns on electrical properties was investigated using *in-situ* methods during a tension test. Also, the change in electrical resistance for different types of electrodes was characterized for its application to flexible electronic devices.

2. EXPERIMENTAL PROCEDURE

The deposition of chromium (Cr) and aluminum (Al) films on PET substrates was carried out using an electron-beam evaporation system. The samples were layered composite structures composed of a metal coating on a PET substrate. The thickness of the PET substrates in the composite structures was 125 μm. As shown in Fig. 1(a), three types of samples were fabricated using different combinations of metal films on the PET: Al film on the PET (Al/PET sample), Cr film on the PET (Cr/PET sample), and Al film on the PET substrate with a Cr interlayer (Al/Cr/PET sample). The thickness of the Al and Cr films on the PET substrate was fixed at 100 nm. The thickness of the Cr interlayer for the Al/Cr/PET sample was controlled at 20 nm.

For each sample, we fabricated an array of etching patterns on the metal film coated on the PET substrate using a photolithography-based wet process. The diameter of the designed patterns on the mask was fixed at 10 μm, 30 μm and 50 μm, respectively. The pitch for the holes on the mask was fixed at 5 times the diameter of each hole. Fig. 1(b) shows the schematic design of the specimen having etched patterns in the gauge length region. To obtain the applicability of metal film for the polymer substrate, the change in electrical resistance for each sample was characterized using a tension test [model: INSTRON-5582], as shown in Fig. 1(c). Optical microscopy (OM) and scanning electron microscopy (SEM) were utilized to observe any macro- and micro-cracks that occurred during the tension test.

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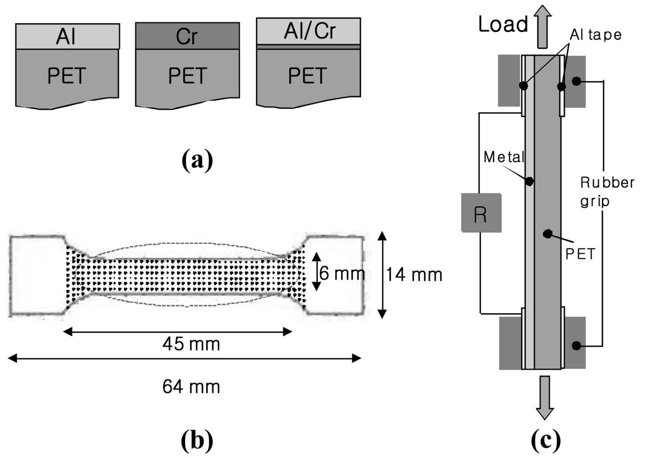


(a)

(b)

(c)

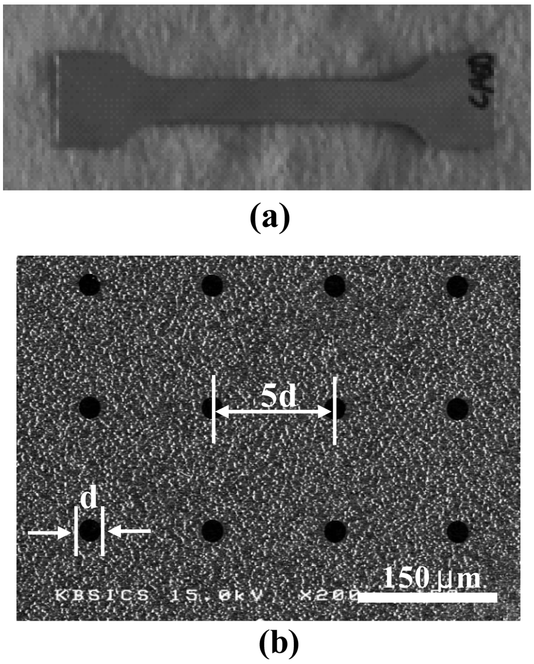
Fig. 1. Schematic diagrams of the sample for tension test and experimental units: (a) cross-sectional view of samples, (b) Specimen shape for tension test, (c) *in-situ* electrical resistance measurement set-up for the tension test.

3. RESULTS AND DISCUSSION

Figure 2(a) shows the OM image of the Al/PET sample before the tension test. The width and gauge length for the sample were 6 mm and 45 mm, respectively. In the region of gauge length, an array of holes was uniformly formed on the Al film, as shown in Fig. 2(b). The size and pitch of the holes, as measured from the SEM image, were 27 μm and 150 μm, respectively. These results showed that the size of the hole diameters on the Al film were about 90 % of those on the mask.

Fabricated metal film on a PET substrate must have the capacity to endure bending or stretching with no failure of its electrical properties. Therefore, it is important to understand the electrical behavior of the sample under an externally applied strain.[9] Figure 3 shows the *in-situ* electrical resistance for the samples, metal films coated on PET substrates, and their dependence on tensile strain during the tension test. For the no-pattern samples, the electrical resistance of the Cr/PET sample was much higher than that of either the Al/PET or the Al/Cr/PET samples at 0% strain. The average values of measured resistance for the Cr/PET, Al/PET and Al/Cr/PET samples were 382 Ω, 8.7 Ω, and 6.1 Ω, respectively.

When we compared the change in electrical resistance of the sample dependence on tensile strain, it was clear that the electrical resistance for the no-pattern samples increased sharply at a low-strain level compared with the patterned samples. Additionally, the absolute value of the electrical resistance for the no-pattern samples was high, even in comparison with patterned samples, in the range of some critical values of tensile strain, as shown in Fig. 3. The critical strain for Cr/PET, Al/PET and Al/Cr/PET samples were around 2.5%, 20%, and 45%, respectively.



(a)

(b)

Fig. 2. (a) Optical micrograph of the Al/PET specimen for the tension test and (b) SEM micrograph with an array of holes on the metal film in the gauge length of the specimen.

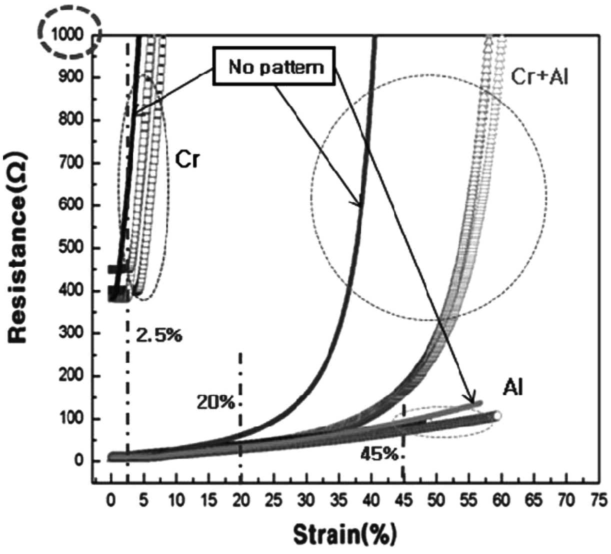


Fig. 3. Change of electrical resistance for sample dependence on tensile strain.

During large-tensile strain, electrical properties of the patterned samples were better in comparison with the no-pattern samples, which is very important for application to flexible electronic devices. The etched-hole array of the metal films coated on the PET substrates seemed to provide stress relief when macro-cracks were generated near the holes.[10] When a macro-crack would form, it would decrease the formation of micro-cracks in the middle region of two neighboring holes. Therefore, the number of micro-cracks

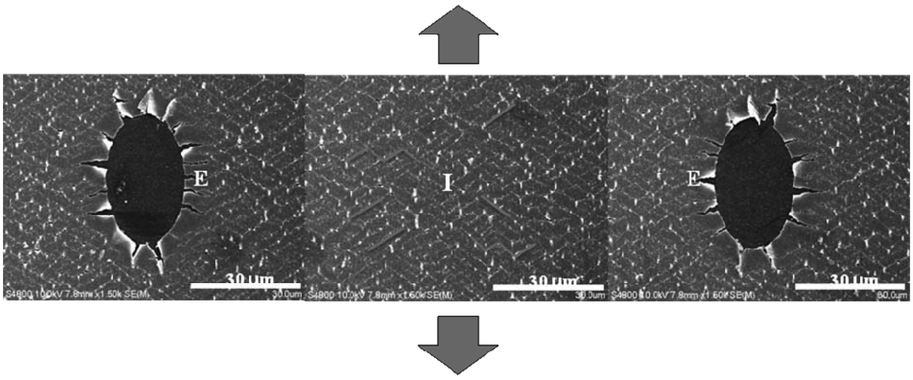


Fig. 4. SEM micrograph of Al/PET samples with 30 µm-sized hole after the tension test. Arrow shows the direction of tensile stress during the tension test. The mark E near the hole and the mark I in the middle of the sample represent macro-cracks and micro-cracks, respectively.

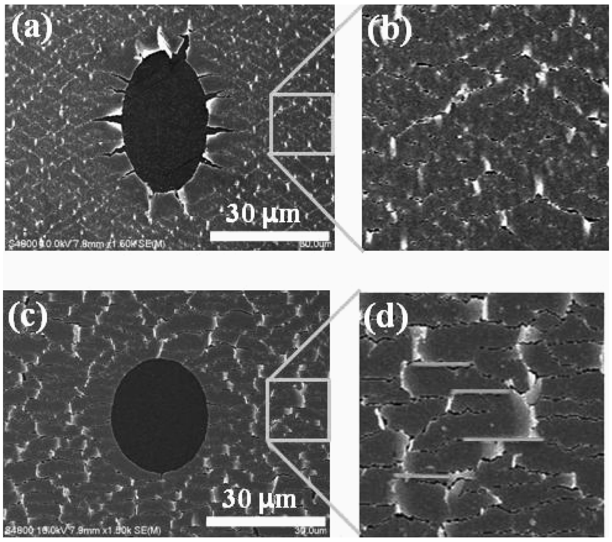


Fig. 5. SEM micrographs of the sample after the tension test. (a) and (c) are from Al/PET and Cr/PET samples with 30 µm-sized hole, respectively. (b) and (d) are the enlarged images of a square in (a) and (c), respectively.

was low with a patterned sample compared with a no-pattern sample. This result is useful for application to interconnection design in flexible electronic devices.[11]

Figure 4 is an SEM image of the Al/PET sample after the tension test. As we expected, the shape of the holes changed from circles to ovals during the tension test. Several macro-cracks (mark E) were observed around the etched holes. Though the direction of macro-crack propagation near the etched holes was perpendicular to the hole, surfaces, the direction of the micro-cracks (mark I) created in the region of two neighboring holes was not. Rather, the micro-cracks showed a wavy or zigzag shape. In addition, the angle between the tensile load and the direction of the micro-crack for an Al/PET sample was about 45 degrees. These phenomena could be the reason for no severe change in electrical resistance of the Al/PET sample in the large-tensile strain.

Figure 5 shows the SEM image of each sample after the tension test: Figs. 5(a) and (b) are from the Al/PET sample; And, Figs. 5(c) and (d) are from the Cr/PET sample. When the Al/PET sample was compared with the Cr/PET sample, the size of the macro-crack at the hole edge was much different. The macro-crack could be observed in the Al/PET sample but not in the Cr/PET sample. Also, the mode of the micro-cracks was fairly different. Micro-cracks in the Al/PET sample were small and assumed a zigzag appearance. However, the micro-cracks in the Cr/PET sample had a rectangular shape. In particular, the micro-cracks in the Cr/PET sample were perpendicular to the tensile stress. Under large tensile strain, the change in electrical resistance for the Cr/PET sample was much different when compared with the Al/PET sample. The changes in electrical resistance for the Cr/PET sample had an increased sensitivity due to the inherent brittle behavior of metal Cr with a body-centered structure. Adhesion strength between a metal film and a polymer substrate and its effect on electrical properties under a tensile strain should be studied in the future.

4. CONCLUSIONS

We designed and fabricated a new type of metal film on a PET substrate with the aim of applying it to the interconnection design of flexible electronic devices. Compared with no-pattern samples, the hole-patterned samples showed much better properties of electrical interconnection in regions under large-tensile strain. The improved electrical properties of the hole-patterned samples will be very useful for application to flexible electronic devices. It was concluded that the effect of the hole array on the metal films coated on the PET substrates was a matter of stress relief by generating macro-cracks near the hole. The creation of macro-cracks prevents the generation of micro-cracks, which increases the electrical resistance of metal films on a polymer substrate. This result has potential for application to the interconnection design of flexible electronic devices.

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