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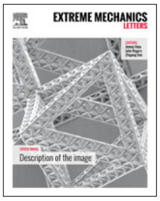

Compression and tension bending fatigue behavior of Ag nanowire network

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ABSTRACT

Fatigue behavior of Ag nanowire network subjected to different degrees of compressive bending strain was investigated and compared against the results from tensile bending strain. Ag nanowire network under compression showed excellent reliability showing only a 6.0% increase in fractional resistance at 400,000 cycles, which is superior in comparison to that under tensile strain. The Ag nanowire network under compression was shown to cause buckling of the Ag nanowires, which then relaxed the elastic strain imposed on the Ag nanowire that led to enhanced reliability. The buckled nanowire, however, can cause strain localization especially with small radius of bending, thus causing the failure to occur within the length of individual nanowires unlike in the case of nanowire network under tensile strain that was shown to fail at the junctions with high stress concentrations.

1. Introduction

Ag nanowires have drawn much interest due to their versatility to be applicable to various futuristic devices such as flexible electronics, [1,2] thin film heaters, [3,4] and novel sensors [5,6]. Among these wide variety of applications, the Ag nanowire network is regarded as a promising candidate for flexible transparent electrode to be used in a flexible display due to its higher conductivity and transmittance [7–9] compared to those of major competitors such as graphene [10,11] and carbon nanotube [12,13]. Numerous studies have been performed to enhance the electrical and optical characteristics of the Ag nanowire transparent electrode by focusing on the optimization of the synthesis and deposition methods [7–9,14,15]. However, systematic studies of reliability or fatigue behavior under various bending conditions are yet to be explored fully even though the bending fatigue behavior is vital for the design of stable flexible transparent electrodes. Here, we report bending fatigue tests on the Ag nanowire network under different bending conditions, i.e. compressive and tensile bending strain, and successfully elucidated a detailed fatigue behavior of the Ag nanowire network depending on bending strains.

In our previous work, it was suggested that Ag nanowire network has enhanced fatigue resistance under bending fatigue in comparison to that of thin films due to two major reasons [16]. First, while fatigue failure of metal thin films is known to be caused by the formation of voids and protrusions as a result of dislocation interaction at the film/substrate interface, [17,18] metal nanowires are expected to have enhanced fatigue resistance due to the lack of dislocation activity within a nanowire [16,19,20]. Dislocation nucleation is known to be limited in metal nanowires, [21,22] and any nucleated dislocations can easily escape to the nanowire surface due to the dislocation starvation effects [23–26]. Therefore, the limited ability to nucleate and accrue dislocations within a nanowire result in not only the high strength, but also excellent fatigue resistance since the dislocations are not retained within the nanowire that in turn suppresses fatigue failure. Next, the geometrical advantage of the network that is able to

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simply stretch the network rather than imposing heavy strain on the nanowires is expected to be of major reason for the excellent fatigue resistance of the Ag nanowire network. While thin films are confined to the substrate, the nanowire network are anchored at junctions, thereby simply re-orienting the network to accommodate bending before straining individual nanowires [27]. The network geometry would result in the better stretchability than that of the thin films; therefore, the Ag nanowire network show significant enhancement in fatigue resistance.

While the deformation mechanism of the Ag nanowire network under tensile cyclic straining was reported in our previous work, further study on the fatigue behavior under different loading condition such as compressive bending strain was not yet been reported. Both tensile and compression loading conditions are important for industrial applications such as flexible displays and hence different loading conditions were explored in the present study. Bending fatigue tests of the Ag nanowire network were performed under different bending strain conditions of both compressive and tensile bending while imposing a bending strain of 2.5%, which corresponds to bending radius of 5 mm for substrate thickness of 125 μm. The evolution of fatigue failure was traced by the resistance change that is monitored *in situ* during the cyclic bending. SEM analysis was used to examine the morphology at different loading conditions to determine the deformation mechanism under compressive bending fatigue and how it differs from that of tensile bending fatigue.

2. Material and methods

2.1. Fabrication of Ag nanowire network

Modified polyol process was used to synthesize the thinner and longer Ag nanowire solution, and a detailed description of the process is available in Ref. [3]. A commercially available electrostatic spray system from NanoNc, Inc. was used to deposit the synthesized Ag nanowire solution onto flexible polyimide substrates (Dupont, Kepton E, 0.125 mm $4(W) \times 70(L) \times 0.125(T)$ mm). A thin polyvinylpyrrolidone (PVP) layer that induces anisotropic growth [28] are encapsulating the as-synthesized Ag nanowires, thereby causing high junction resistance since PVP acts as an insulating layer. Therefore, post-annealing process is typically required to reduce the resistance of Ag nanowire network, [7] and a box furnace annealing was conducted at 180 °C for 25 min. A four point resistance measurement system (FPP-2400) from Dasol Eng Co., Ltd. was used to measure the sheet resistance of the fabricated Ag nanowire electrode. In order to study the effect of bending fatigue on the resistance and deformation of the Ag nanowire network, the sheet resistance was fixed to 5.6–6.4 ohm/sq in the as-deposited state that was reduced to 3.2–3.6 ohm/sq after annealing at 180 °C for 25 min. The total transmittance is 73% for the Ag nanowire network with initial sheet resistance of ∼6 ohm/sq, and the more detailed optical and electrical properties of the Ag nanowire network can be found in the work by Kim et al. [9].

2.2. Bending fatigue test

Bending fatigue tests were performed by using a cyclic bending fatigue tester, which can perform more than 400,000 bending cycles while monitoring resistance *in situ* with excellent resistance resolution of ∼0.003 ohm [29,30]. The Ag nanowire network on the polyimide substrate is mounted in between the two parallel plates using screw bolts, and a uniform strain is imposed by choosing the appropriately calculated spacing between the two plates. The nominal strain imposed on the nanowires for a given plate spacing is then calculated according to $\varepsilon = y/R$, where y is the neutral plane which can be determined by the substrate thickness and R, the radius, means a half value of the distance between the plates. To apply repeatable bending strain, the lower plate moves horizontally with a fixed plate motion distance that determines the strain induced area. During cyclic bending, the middle section is subjected to uniform bending then released as the lower plate moves horizontally. More detailed description on the bending fatigue test system can be found in the Ref. [16]. The number of bending cycles was chosen to be 400,000 cycles, and the tests were performed at a plate movement distances of 10 mm. The same bending fatigue tests were performed more than 5 times for each bending condition to ensure the reproducibility of the fatigue behavior. The tensile bending strain is applied when the nanowire network is placed on convex surface while the compressive bending strain is possible by mounting a specimen in an inverted way, in which the nanowire network is placed on concave surface. The neutral plane is located in the same distance from the convex and concave surface; therefore, the same amount of strain is applied to the each specimen under both tensile and compressive bending strain conditions.

3. Results and discussion

3.1. Fatigue behavior of Ag nanowire network under compressive and tensile bending strains

Fractional resistance change ($(R - R_0)/R_0$) over cycles under different bending conditions of compressive and tensile bending strain is shown in Fig. 1(a). Both the compressive and tensile cyclic bendings showed similar behavior in resistance change where the increase in fractional resistance is more pronounced in the initial stage followed by the transient then steady-state. The difference, however, is the amount of fractional resistance increase, and compressive bending strain showed significantly lower fractional resistance increase than tensile bending strain over all range of cycles. In the initial stage of bending up to 20,000 cycles, the specimen under tensile bending strain exhibited a 4.1% increase in the fractional resistance while the specimen under compressive bending strain showed a 2.6% increase. The gap of the fractional resistance increase between the results under tensile and compressive strains then became narrower from 1.5% at 20,000 cycles to 0.4% at 400,000 cycles.

The difference in the fatigue behavior between the specimens under tensile and compressive bending strain

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