1. Introduction

Ag nanowires (NWs) have applications in flexible electronics because of their excellent electrical and optical properties. The polyol process used to fabricate Ag NWs leads to a distinctive penta-twinned structure containing five {111} twin planes sharing a common axis along [110]. In order to predict and increase the reliability of these electrodes made by Ag NWs, understanding their failure mechanism under cyclic loading is necessary. Here we study the mechanical performances of these wires through TEM analysis of individual NWs after cyclic deformation. This is achieved by spraying Ag NWs onto porous polycarbonate disks covered by an electron transparent collodion thin film, selected filters suspended over pores in the disks can be identified for repeated TEM study after deformation. An increase in density of bamboo defects in the Ag NW networks is observed after increasing numbers of fatigue cycles. Further characterization using precession assisted scanning nanobeam electron diffraction (NBED) suggests that the bamboo structure is caused by crystal rotation in the penta-twinned NWs around the [110] growth direction. We propose that the torque that generates rotation is induced by the presence of NW/NW joints within the network allowing circumferential loading of individual NWs when the network is in global tension.

2. Background

Ag NWs make electronics Flexible

Mechanical performances of Ag NWs

The reliability of flexible devices

Fig. 1 Penta-twinned Ag NWs and their applications

3. Sample and experiments

Structure Characterization and ex-situ fatigue Experiments

Fig. 2 Characterization of Penta-twinned Ag NWs

Fig. 3 Schematic of ex-situ fatigue experiments. The two-layer composite film with Ag NW networks is observed under TEM before fatigue tests, then it is fixed on the PET substrate for cyclic bending. After fatigue tests, the sample is characterized again in the same position.

4. Experiment Results: bamboo faults

Bamboo faults characterization

Fig. 4 TEM images of Ag NWs before and after 50 k fatigue times under 5% strain. (a) and (b) shows that the wires are bent after fatigue. (c) and (d) indicates that one bent wire fractured after fatigue. NWs failure under tension is presented in (e) with welded junctions and (f) without welded junctions. (g) is the histogram of end point density and bent wires density as a function of different fatigue times

NWs Networks Characterization

In our previous studies, the network resistance Rn is expressed as $R_n \approx K(\tau_0 + \tau_1)/R_0^2$ where K is a constant; $\tau_0$ and $\tau_1$ are the wire resistance and junction resistance respectively; R0 is the average length of the wire and u is the diameter.

Table 1 Resistance of Ag NW electrode from both experiment and model predictions

<table>
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<tr>
<th>Sample</th>
<th>Current density</th>
<th>Current flow</th>
<th>Rn in model</th>
<th>Rn in experiment</th>
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<tr>
<td>NW1</td>
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<td>1.00</td>
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<tr>
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Fig. 5 Imaging of bamboo faults after fatigue tests (a) Ag NWs in networks before fatigue tests and (b) after fatigue tests. (c) The appeared bamboo faults characterized by scanning nano-beam diffraction methods.

Fig. 6 bamboo faults formed after fatigue tests. Data decomposition and crystal orientation indexation results: (c) < -8 -1 -8 > and < 8 1 9 >

Lattice model and torsion force analysis

Figure 2 shows [0x10] (a) Ag NWs in networks before fatigue tests and (b) after fatigue tests. (c) The appeared bamboo faults characterized by scanning nano-beam diffraction methods.

Fig. 7 bamboo faults formed before fatigue tests data decomposition and crystal orientation indexation results: (c) < 9 1 9 > (d) < 8 1 9 >

Fig. 8 Structure analysis of the bamboo faults. (b) and (c) show the Ag electrode resistance of the Ag NWs with and without twists, respectively. Continuing this approach produces a complete stacking fault across the NW as shown in (d).

Fig. 9. Formation of the torsion force in Ag NWs. (b) bamboo faults density changes as a function of the Ag NWs coverage rate on polymer film

5. Conclusions

The failure behaviours and microstructure defects of Ag NW networks are studied under TEM systematically. Based on the new sample preparation methods, the NWs deformation process and the microstructure changes of penta-twinned Ag NWs in network under high cyclic loading are discussed in this study. Further characterize into the inner structure of penta-twinned Ag NWs shows that bamboo faults appear after fatigue tests, the crystal structure of which is characterized using SPED follows by signal decompositions. Lattice coherent rotation model is proposed here, and the torsional forces is thought to be from the NW junction when tensile stress applied in the network. Bamboo faults density vanished in some wires indicates that they maybe reversible. This also supported by the higher energy of bamboo faults. The study here reveals failure modes of Ag NWs in networks and give a useful guidance to microstructure changes of NWs applied in flexible electrodes. The exploration on the fatigue performances of penta-twinned Ag NWs, like the bamboo defaults, may stimulate further interest to explore the unique fatigue performances metal NWs in networks.

5. Acknowledgements and References