MECHANICAL AND ELECTRICAL FAILURE OF TRANSPARENT NANOWIRE ELECTRODES

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Flexible transparent electrodes have to withstand large mechanical strains without sacrificing electrical performance. For such applications, silver nanowire (Ag NW) networks are highly promising as they combine mechanical flexibility with low sheet resistance and high optical transmittance. In order to improve the performance of such nanowire electrodes a microscopic understanding of the interplay between mechanical and electrical failure is required. This can be achieved by a combination of *in situ* (or interrupted) tensile tests in a scanning electron microscope (SEM) with 4-probe electrical measurements of the sheet resistence.

In the present work the effect of the coating direction on the mechanical and electrical failure of Ag NW electrodes have been studied. For this, the nanowires have been coated in a preferential direction on a thin flexible polymer using doctor-blading. Tensile straining up to 20% plastic strain has been carried out parallel and perpendicular to the preferential coating direction. As can be seen from Fig. 1 (left) the electrical performance shows a strong dependency on the relative orientation of loading and coating direction. Upon straining in preferential coating direction the sheet resistance increases significantly already after 5% plastic strain. In contrast, hardly any increase in sheet resistance is observed upon straining up to 20% perpendicular to the preferential coating direction. This behavior can be understood from SEM images of the Ag NW networks taken at different stages of tensile straining. To illustrate the difference, Fig. 1 shows SEM images of extreme cases where the Ag NW networks are strained to 50%. During straining in preferential coating direction (Fig. 1, middle) most Ag NWs are loaded in tension resulting in periodic (ductile) fracture, which is similar to the behavior of thin metallic films. The corresponding increase in sheet resistance indicates a severe reduction in percolation. In contrast, upon straining perpendicular to the preferential coating direction (Fig. 1, right) only few NWs aligned parallel to the tensile axis rupture whereas the majority of wires oriented perpendicular to the loading direction stay electrically intact. This explains the considerably smaller increase in sheet resistance in this case. Nevertheless, the nanowires aligned perpendicular to the loading direction are also severely plastically deformed. They show frequent kinking (encircled regions) which can be attributed to the lateral contraction of the polymer during tensile straining effectively putting the NWs under compression.

The microscopic structure of the kinks have been studied in detail using high-resolution transmission electron microscopy (HRTEM) which reveals perfect and partial dislocations, high-angle grain boundaries as well as chevron-type defects (not shown). Finally, the microscopic observations are compared with atomistic simulations in order to understand the effect of the five-fold twin structure of the Ag NWs on the bending and kinking behavior. Very good agreement between experiment and simulation is achieved.

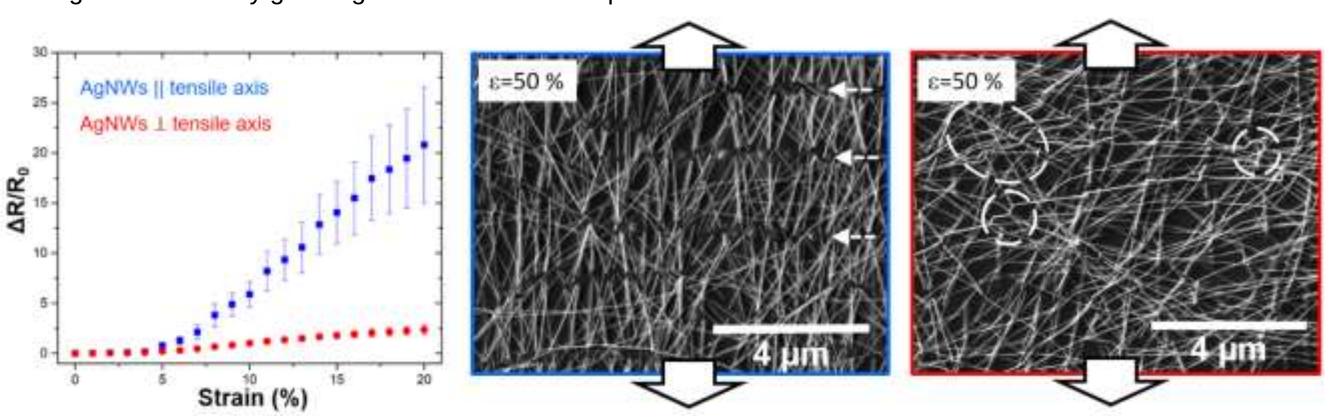

Figure 1 Influence of coating direction on the electrical and mechanical failure of Ag nanowire electrodes during uniaxial tensile testing.