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Voltage Contrast in SEM for revealing charge transport through silver nanowire transparent electrodes

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The next generation of optoelectronic devices requires transparent conductive electrodes to be lightweight, flexible, cheap, and compatible with large-scale manufacturing methods [1]. Two dimensional networks of silver nanowires (Ag NWs) synthesized by reduction of $AgNO_3$ with ethylene glycol and poly(vinylpyrrolidone) (PVP) as a surfactant [2, 3] are considered a highly promising candidate as a replacement for sputtered indium tin oxide (ITO) in organic thin-film solar cells [4]. Such Ag NW transparent electrodes have a high transparency and conductivity at low material consumption. In contrast to ITO transparent electrodes Ag NW electrodes can be processed also on flexible substrates and show good performance even after strong bending of the substrate [5]. Moreover, the fabrication by printing processes allows for up-scaling. Because of these advantages there is great interest in understanding charge transport through such NW networks [6]. However, the microscopic mechanism and the role of NW junctions are not yet well understood. In the present study we performed voltage contrast dependent scanning electron microscopy (VC-SEM) to investigate ultrasparse Ag NW networks near the electrical percolation threshold.

The Ag NWs are dispersed on Si covered with 200 nm SiO_2. Figure 1shows secondary electron (SE) SEM images of an ultrasparse Ag NW network at different values of the electrical potential (Figure 1a-c). The contrast profile of one Ag NW is shown in Figure 1d. At U = 0 V the contrast is mainly determined by material and orientation contrast, and the NWs appear bright. With increased positive potential the darker contrast points to a reduced SE yield on the Ag NW and in the vicinity of the Ag NW which can be explained with the help of the schematic shown in Figure 1e. If the Ag NWs are positively charged the SEs coming from the Ag NWs and also the SEs coming from the nearby substrate are attracted by the Ag NWs due to the attractive potential of the Ag NWs' surfaces. Therefore the low energetic SEs cannot reach the detector, so that a dark corona is formed. The extension of this corona depends on the applied potential. The higher the potential, the higher the threshold energy below which SEs are captured by the positively charged Ag NW and cannot reach the detector.

Because of this strong contrast formation VC-SEM can be used to investigate conduction channels within an ultrasparse Ag NW network. Figure 2 shows a Ag NW network electrically isolated by a LASER-cut. Four different positive potentials were applied. At U = 10 V only the upper area of the network appears dark indicating that the upper and the lower area are not electrically connected. At U = 11 V also the lower area shows dark contrast implying charge transport to this area. Interestingly, the newly connected area shows less contrast indicating a lower potential. Contrast profile analysis can lead to a quantitative statement concerning the potential difference of the two areas. Moreover, a detailed analysis shows that the charge transport is reversible pointing to a resistive-switching phenomenon.

Further investigations are underway to evaluate the microscopic processes that initiate charge transport across nanowire junctions and control the resistive-switching behavior [7].

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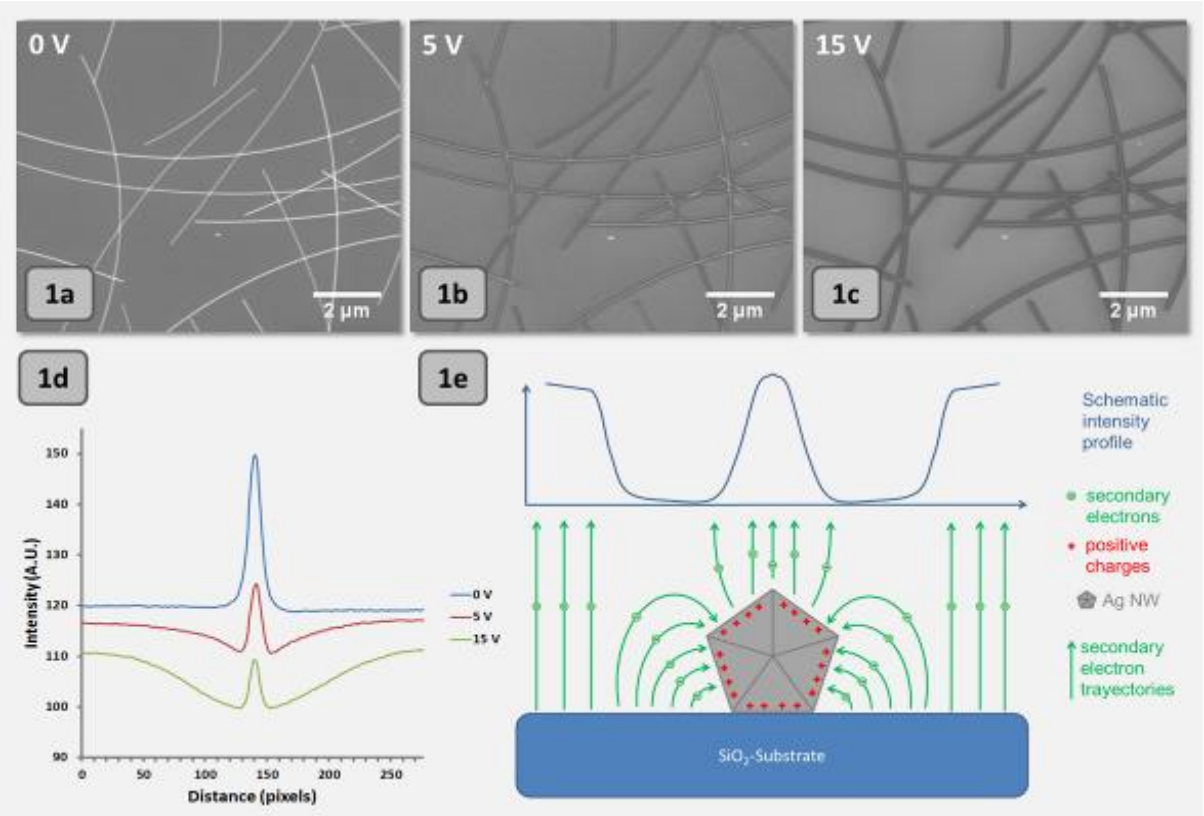

Figure 1.a-c. Voltage contrast series of an ultrasparse Ag NW network on Si with 200 nm SiO_2. **1d.** Contrast profiles of an exemplary Ag NW for each image of 1a-c**. 1e.** Model on the formation of the contrast profile in the positive-potential state.

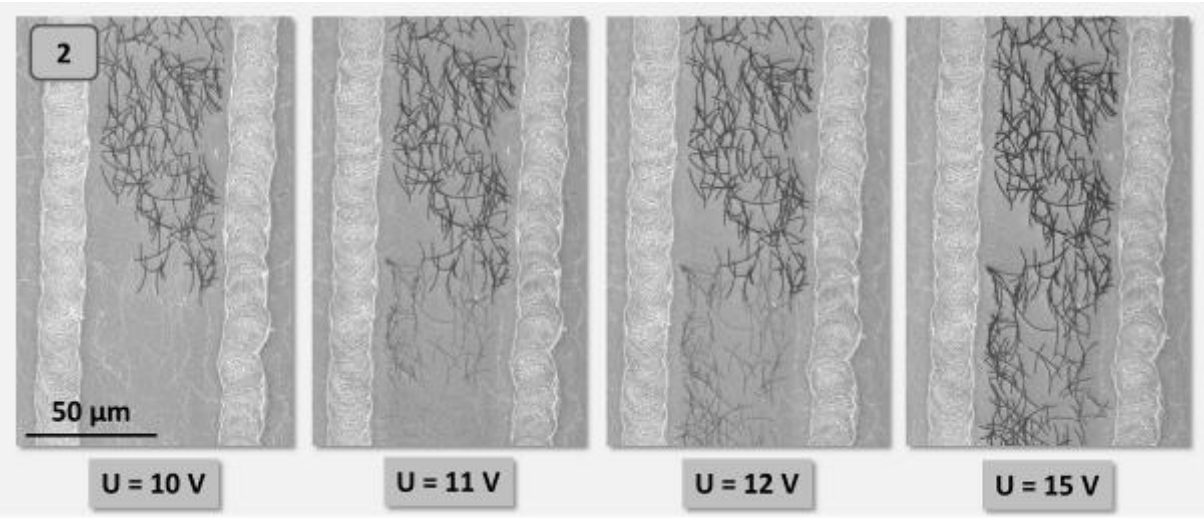

Figure 2. Voltage contrast series of an ultrasparse Ag NW network electrically isolated by a LASER-cut, showing different conductive cells which connect through at U = 11 V. The cells show different contrast profiles, because they are not at the same potential.