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TEM In situ Plastic Deformation of Silver Nanowires

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Silver nanowires present a series of positive characteristics that give them versatility and a wide range of applications. In this investigation we report the plastic deformation and failure of silver nanowires, produced using the polyol method [1], using a specialized AFM holder (Nanofactory Inst.) to perform a mechanical three point bending test in situ TEM (JEOL 2010F). This holder has a silicon tip and a reference cantilever to measure the applied load. With this arrangement it is possible to observe the AFM tip, the contact radius with the region of interest, changes on the shape of the nanostructure as well as measure the applied force in the range of nanonewtons. The mechanical test of the nanowires was recorded on video by a CCD camera coupled to the microscope at 15 frames per second (fps). The samples rested on the gold bondwire, (Figure 1) and were finely approached towards the AFM tip at a 0.5 nm step by means of a piezoelectric material. From the video it was possible to analyze the mechanical response of the nanowire, in both regimens elastic and plastic, to an applied load making it possible to estimate variables such as the nanowire's suspension length, deflection angle, rupture point and the displacement of the AFM tip, needed to estimate the Young's Modulus (E).

AFM imaging and indentation experiments were performed using a Multimode NanoScope V using silicon nitride triangular cantilevers. The normal force was calibrated by recording the deflection of the cantilever as a function of the scanner displacement while in contact with a sapphire substrate. AFM nanoindentation measurements are based on the force plots acquired (on seven nanowires) at five different points of the nanostructure; the tensile modulus in each plot was obtained using a modified Hertz model that correlate the data of the applied force and the indentation depth of the tip. [2] Figure 2 shows the height profile of a silver nanowire and the elasticity distribution values obtained for the experimental indentations.

As measured from the recorded experiment and the acquired TEM images, the beam length between supported ends was 475 nm. The average diameter of the nanowire was observed to be 60 nm with an average side of 29 nm. The load of the tip on the nanostructure can be calculated using Hooke's law with the value 155 N/m for the spring constant (k) and the deflection (x) of the tip. To obtain the Young modulus (E) of the Ag NWs during in situ three point bend testing the equation for the maximum deflection of the midpoint of the nanowire $\delta=(FL^3)/(48EI)$ where 'I' is the moment of inertia of a pentagonal beam as observed from HRTEM images acquired. The calculated Young's modulus of the beam during one of this experiments was calculated to be 109.5 GPa. As the applied load increase the nanowire deflects until it reaches fracture and completely separates.

During the deformation event it was possible to detect contrast lines related to surface stresses moving briskly along the beam, reminiscent of a thin membrane on the surface of the structure. An observation of the area of the nanowire at the vicinity with the load, reveled a region without contrast lines which can be associated to the compressive stress, and underneath that region, another with the associated to tensile stress. Nevertheless, failure of the pentagonal nanostructure started on the side where the load was applied. Finally, as the yield stress is reached the beam diameter decreases, leading to a plastic regime which continues until a maximum deflection of 65 nm where and ends with a fracture by necking. Experiments realized with the Multimode's silicon nitride tip attained a Young's modulus of 97.2 ± 10.9 GPa which is in agreement with reported data of 94 GPa for this diameter scale [3]. This increase on resistance, with respect of the bulk material, is attributed to a surface effect and the unique five-fold twin microstructure of the silver nanowire [4].

References:

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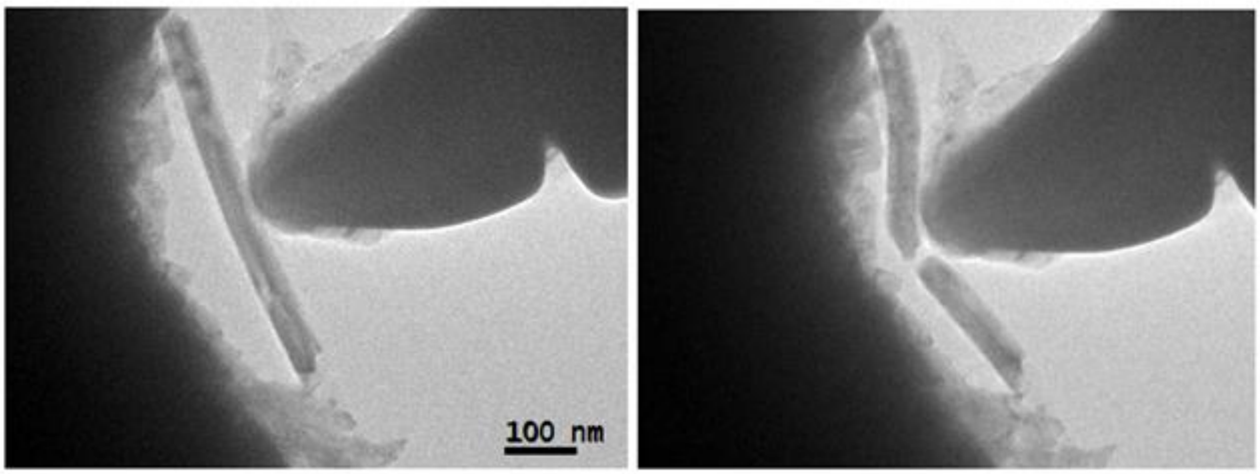

Figure 1. Three point bending configuration of the Ag NW with a length of 576nm. The AFM tip has an approximated length of contact on the Ag NW of 60nm.

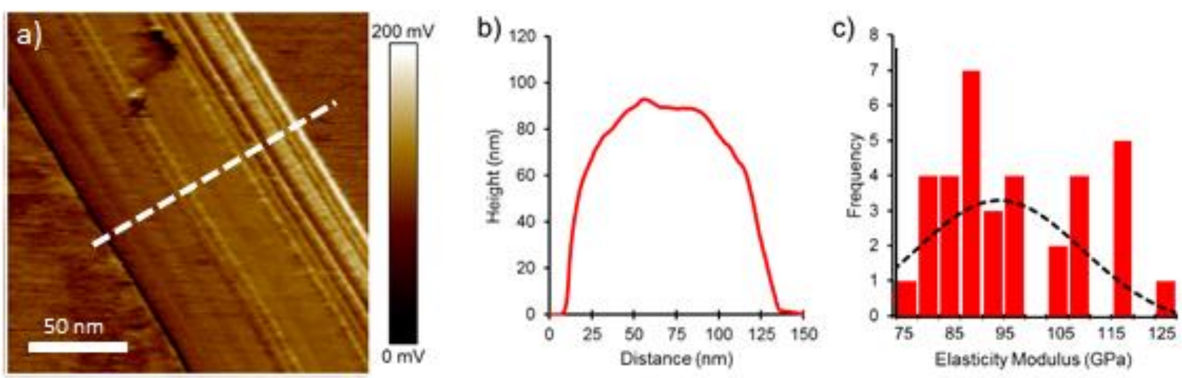

Figure 2. Figure 4 – a) Contact-Friction image of a silver nanowire used for the nanoindentation experiments. b) Height profile of the nanowire highlighted in a). c) Histogram of the effective elastic modulus computed for the approach force plots obtained in contact mode.

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