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Mechanical property of metallic nanowires: the shorter is stronger and ductile

Chaolun Ni[1], Qi Zhu[1], Jiangwei Wang*

Center of Electron Microscopy and State Key Laboratory of Silicon Materials, Department of Materials Science & Engineering, Zhejiang University, Hangzhou 310027, China

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ABSTRACT

Optimal design of microelectromechanical devices requires tuning both the size and length scales of their nanocomponents, however the length effect on mechanical behavior of small crystals remains poorly understood. Here, in situ nanomechanical testing reveals a remarkable length-dependent mechanical property in silver nanowires, where both the strength and ductility display a net increase with the length reduction. Quantitative analysis shows that reduction of crystal size and crystal length could induce a completely-opposite strengthening in metallic nanowires due to the distinct operating mechanisms. These findings provide new insights into the size-dependent deformation in metallic nanowires, holding important implications for designing durable nanostructures/nanodevices.

1. Introduction

Mechanical properties of small crystals have attracted considerable attentions due to their potential applications in microelectromechanical systems and nanodevices [1–5]. During the past two decades, numerous studies have been conducted to reveal the size-dependent deformation of nanostructured materials [6,7], and it is well-established that the smaller crystals tend to be stronger due to the source-controlled deformation [6,8–15]. Specifically, the operating dislocation sources changed from the traditional ones (e.g. Frank-Read sources) in bulk to the truncated sources (e.g. single-arm dislocation sources and surface sources) in micron/sub-micron crystals [12–15] and the dislocations nucleated from these sources can be easily exhausted from the crystals due to the confined volume [8,9], resulting in a higher deformation stress.

Although the size-dependent strengthening has been well-documented [6,7,16], previous studies mainly focused on the size effect by tuning the diameter or cross section of nanowires/nanopillars, while the influence of crystal length (another important geometrical parameter) was usually ignored. Given the requirement for miniaturizing microelectromechanical systems and nanodevices, both the diameter and length of nanostructures should be considered for the optimal design. Therefore, a systematic understanding of the sample length effect on mechanical behavior is of critical importance for developing damage-tolerant devices. Recent simulation studies showed that a ductile-to-brittle transition occurred in the metallic nanowires with the increase of nanowire length, which originated from the transition of length-dependent dislocation activities from multiple slips to single slip [17,18]. However, experimental study on the length effect in metallic nanowires remains lacking due to the technological challenge to fabricate samples with same diameter but different lengths. Besides, an aspect-ratio dependent hardening was observed in micron-sized copper single crystals, in which the strength increased dramatically with the reduction of crystals' aspect ratio, accompanied by a switch of deformation mechanism from single slip to dislocation pile-up [19]. Given that the aspect ratio of crystal can be tuned by changing either the crystal length or diameter, the origin of this aspect-ratio effect and the contributions of crystal length and diameter to such length effect remain largely unclear. Acquiring a fundamental understanding on these questions will not only provide new insights into the size-dependent mechanical behavior in small crystals but also hold important implications for the rational design of small devices with high damage tolerances.

Here, the effect of nanowire length on the mechanical behavior of silver (Ag) nanowires was studied using in situ nanomechanical testing inside transmission electron microscope (TEM). A remarkable length-dependent mechanical behavior was revealed in Ag nanowires with same diameter, where both the strength and ductility of Ag nanowires showed a net increase with the reduction of nanowire length. Such unique length effect on deformation can be attributed to the activation

* Corresponding author.
E-mail addresses: jiangwei_wang@zju.edu.cn, wangjw1984@gmail.com (J. Wang).
[1] These authors contributed equally to this work.

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of statistical flaws in nanowires with different lengths. Quantitative analysis shows that the reduction of crystal size and crystal length could induce a completely-opposite strengthening in metallic nanowires due to the distinct operating mechanisms.

2. Materials and methods

The Ag nanowires were ordered from Plasmachem Gmbh (Berlin, Germany). In situ TEM-AFM tensile tests were conducted inside a FEI Tecnai F20 field emission gun TEM equipped with a TEM-scanning tunneling microscope (STM) platform from Beijing PicoFemto Co. The AFM cantilever (bought from Nanosensor Inc.) was installed as the force sensor and Ag nanowires on an Al rod served as the other end of the platform. Before tension, the AFM cantilever and Ag nanowire were welded together via the deposition of amorphous carbon at the contact area inside TEM. Tensile testing was carried out subsequently by pulling back the nanowire side. The spring constant of the cantilever was calibrated to be 28 N/m. The tension was displacement controlled with the deformation speed of about 0.8 nm/s. By directly measuring the deflection (Δd) of the cantilever and the length of nanowires, the stress-strain curves can be obtained. The engineering stress was calculated by $\sigma = 4F/\pi d^2$, where d is the diameter of nanowires, assuming that nanowires have a circular cross section.

3. Results

Fig. 1a–b shows the structure of as-synthesized Ag nanowires, which have a face-centered cubic (FCC) structure with the growth direction of [110]. Statistical measurements indicate that the nanowire diameters are ranging in 60–220 nm, with an average value of 158 ± 2 nm. Dark-field TEM image and electron diffraction pattern of the Ag nanowire suggest the existence of a twin lamella, parallel to its growth direction of [110] (Fig. 1a–b). Close observation in Fig. 1c demonstrates the localized surface variations (± 1 nm, marked out by the red arrows) in the Ag nanowire. Fig. 1d–h shows the deformation morphologies of an Ag nanowire with the diameter of 156 ± 1 nm. Before deformation, the nanowire was tilted into the [1$\bar{1}$0] zone axis. Initially, the Ag nanowire had a gauge length of ~ 1420 nm. Upon tension, the Ag nanowire was stretched to elongate slightly and reach ~ 1570 nm after fracture, corresponding to a total elongation of ~ 10.6% (Fig. 1d). During this process, numerous stacking faults (SFs) were emitted from free surface [20], which then propagate into the nanowire and further interact with each other, resulting in the fracture of the nanowire (as evidenced by the numerous slip traces on the fracture surface in Fig. 1e). It needs to point out that although the pre-existed interfaces (grain boundary or TB) may also act as the nucleation sites for dislocations and SFs under certain conditions [21], surface nucleation of defects dominate the deformation of Ag nanowires tested here, probably due to the existence of surface variations that induce the stress concentrations [22–24]. Post-fracture characterization in Fig. 1e indicates that the deformation of this Ag nanowire mainly occurred in a localized region (with a length of ~ 405 nm) near fracture surface, which was denoted as the “deformation zone”. Fig. 1f–h shows the microstructures at different regions of the fractured nanowire. Obviously, high density of nanoscale twins and stacking fault (SFs) formed on the fracture surface of the nanowire (Fig. 1f), suggesting the

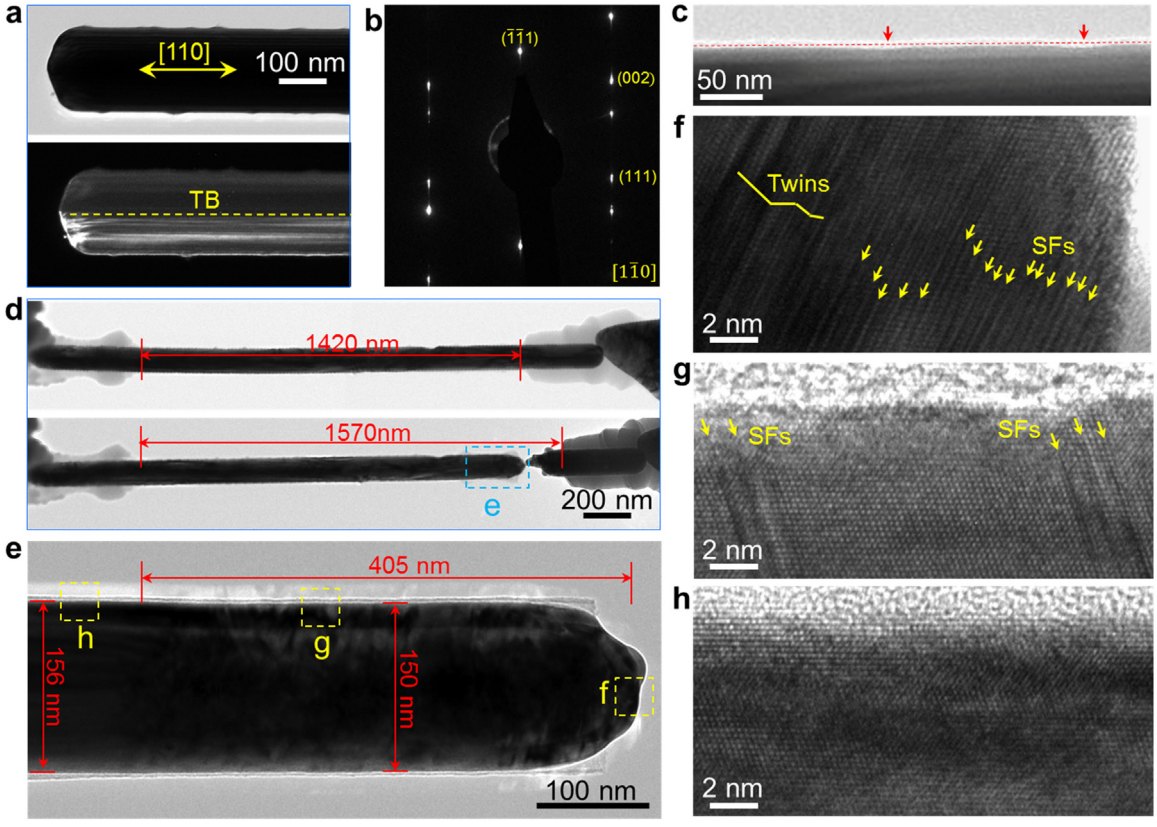

Fig. 1. Structure and tensile fracture morphologies of Ag nanowire. (a) Structure of the as-synthesized Ag nanowire with the growth direction of [110]. Dark-field TEM image reveals the existence of a twin lamella along the nanowire axis. (b) Electron diffraction pattern showing an FCC structure of the Ag nanowire. (c) Localized surface variations (± 1 nm) in the nanowire, as marked out by the red arrows. (d) Deformation morphology of an Ag nanowire with the diameter of 156 ± 1 nm. (e) Fracture morphology of the nanowire, showing a ~ 405 nm deformation zone with numerous dislocations and slight diameter decrease. (f) High density of nanotwins and stacking faults (SFs) on the fracture surface; (g) low density of surface-nucleated SFs in the region away from the fracture surface; (h) no deformation induced defect in the region out of the deformation zone (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).