Scripta Materialia 114 (2016) 112–116

Contents lists available at ScienceDirect

Scripta Materialia

journal homepage: www.elsevier.com/locate/scriptamat

Regular Article

Cold welding of Ag nanowires by large plastic deformation

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ARTICLE INFO

Article history:
Received 23 December 2014
Received in revised form 6 December 2015
Accepted 6 December 2015
Available online 21 December 2015

Keywords:
Nanojoining
Nanomechanics
Cold welding
Nanowire
Plastic deformation

ABSTRACT

The conventional cold welding concept was extended to nanoscale, in which silver nanowires were welded together by large plastic deformation. A nanoindenter was employed as a cold welding tool to visualize and conduct welding. The MD simulation shows that unlike single crystal nanowire, sufficient plastic deformation is key to realize successful welding when the two nanoobjects have large orientation mismatching. The lattice orientation of joint interface is complex but no defects were found in both experimental and simulation.

Since interconnect formation is critical for the assembly and integration of nanocomponents to enable nanoelectronics- and nanosystems-related applications [1], nanojoining is currently under intensive development. The nanojoining methods include laser beam [2,3], electron beam [4], soldering [5], sintering [6], resistance welding [7], and ultrasonic welding [8,9]. Most of these processes are designed to make thousands of joints simultaneously. However, few methods can join two targeted nanowires while leaving the surrounding nanoobjects intact, because nanoscale-sized heat sources are hard to obtain. Cold welding does not require any heat source and as such becomes an attractive solution for bottom-up assembly at nanoscale [9,10].

In terms of the conventional cold welding method, pressure is used to produce a weld at room temperature with substantial deformation at the weld [11,12]. Obviously, macroscopic deformation is the key process factor because during deformation surface oxides are broken and more contact area is created between clean metallic surfaces inducing diffusion and recrystallization at the interface, and hence bonding. Therefore, whether this process concept could be extended to nanoscale is determined by the plastic deformability of the nanoobjects. In this paper, the conventional cold welding concept was extended to nanoscale, in which two targeted silver nanowires were welded together at room temperature and atmosphere environment by large plastic deformation, not by the agglomerative behavior of nanoobjects.

The silver nanowires were prepared in water in a seeded polyol solution with PVP as a structure directing reagent as previously described [13]. Electron diffraction patterns confirmed that the nanowires were fivefold twinned with pentagonal cross section, and the axis was oriented along the <100> direction. TEM images showed that organic shells covering the surface of as-synthesized Ag nanowires had a 2.5–5 nm thickness. The Ag nanowires (NWs) solution was drop-cast onto polished single crystal silicon sheet. A microhardness indenter was used to mark the location of the nanowires by conducting micro-indentations. The morphology of the nanowires used in these experiments was examined by Scanning Electron Microscopy (SEM), before and after cold welding. A Hysitron TriboIndenter nanoindenter in conjunction with an AFM was used to perform imaging and cold welding tests. A three-sided pyramidal diamond (Berkovich) indenter was selected to image and locate the nanowires and then in situ indent the wires with the same tip. The force–displacement curves were recorded with a resolution of 1 nN and 0.04 nm, respectively. The nanojoints were cross-sectioned using the Focused Ion Beam (FIB) (Zeiss NVision 40). A tungsten coating was deposited prior to FIB milling to protect the nanowire surfaces upon exposure to the Ga + beam.

Before cold welding tests, nanoindentation was performed on single nanowires in order to confirm if sufficient plastic deformation of the fivefold twinned pentagonal silver nanowires could occur before fracture. An array of indents with different loads was successfully conducted on one single silver nanowire (~400 nm in diameter and

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http://dx.doi.org/10.1016/j.scriptamat.2015.12.010
1359-6462/

larger than 20 μm in length) for the purpose of comparison. Figs. 1a and 1c show the indents on one single nanowire under the loads of 50 μN and 400 μN, respectively. Figs. 1b and 1d are the high magnification images of Figs. 1a and 1c, respectively. Fig. 1e shows the load-depth curve under different indentation loads. The nanowire remained straight after the indentation tests and did not move, suggesting that the adhesion forces between the nanowire and the substrate were strong enough to prevent it from rolling or being dragged during the nanoindentation test and the scan after the test [14,15]. The shapes of the nanowire after indentation tests in Fig. 1b (50 μN) and Fig. 1d (400 μN) indicated that a considerable amount of plastic deformation occurred. The 400 μN indented Ag nanowire was very flat and the maximum width was about twice the original diameter, whereas the 50 μN indented nanowire was considerably thicker and narrower than that indented at 400 μN. Some grain boundaries are shown in Fig. 1d and the grain size was in the range of tens to few hundreds of nanometers. It suggests that new grains formed after large scale (more than 50%) plastic deformation.

When the maximum load was close to 50 μN (the inserted picture in Fig. 1e), the indentation depth was 24 nm which was 6% of the nanowire height. The hardness and elastic modulus values of the silver nanowire were measured to be about 0.63 and 45 GPa, respectively. The measured hardness of nanowire was higher than that of the bulk silver (about 0.4 GPa when indentation depth was larger than 1 μm), but smaller than nanowires with about 45 nm diameter (about 0.87 GPa when indentation depth was less than 15 nm) [14, 16]. An obvious pop-in mark was found in the curve of the 50 μN indentation load, which indicates plastic deformation associated with dislocation nucleation and motion [17–19]. A similar phenomenon was also observed in nanoindentation of silver nanowires (less than 100 nm in diameter) by both AFM and Berkovich nanoindenter tip [14,15].

The AFM mode of the nanoindenter can visualize the nanowires and locate a specific indent zone, making the selective cold welding process possible, in which two crossed nanowires can be visualized and cold welded without affecting the surrounding nanowires. Fig. 2 shows the crossed silver nanowires after cold welding by nanoindenter. When the load was 50 μN (Fig. 2a), no significant plastic deformation was found in the wires and a barely observed indent appeared on the top wire (inserted picture in Fig. 2a). When the load was larger than

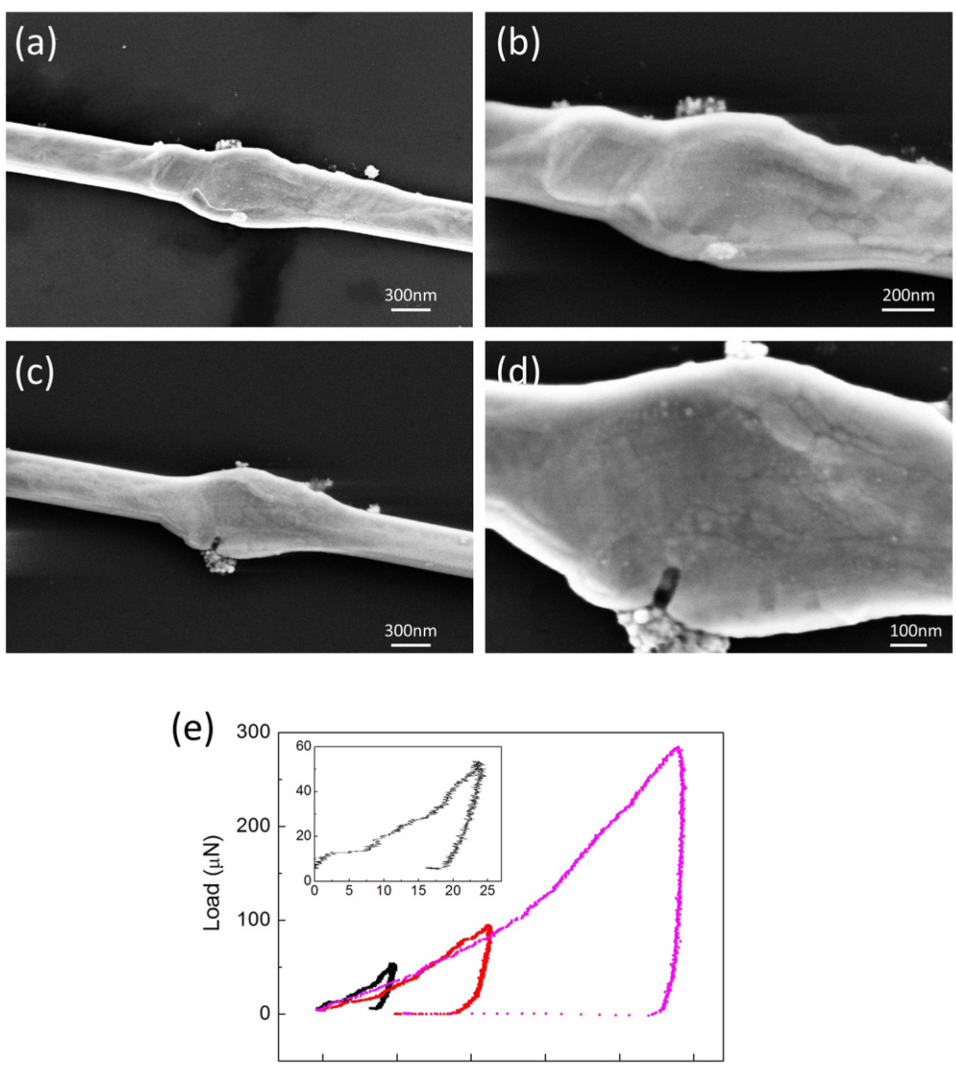

Fig. 1. Nanoindentations on single nanowire: (a) and (b) morphology of nanowire after 50 μN indentation load; (c) and (d) morphology of nanowire after 400 μN indentation load; (e) load-depth curve of different loads on the same nanowire, the insert is 50 μN.