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Mechanical Deformation Processing of Nanometer-Sized Silver Contacts

Hideki Masuda and Tokushi Kizuka

Institute of Materials Science, University of Tsukuba, Tsukuba 305-8573, Japan
E-mail: kizuka@ims.tsukuba.ac.jp

1. Introduction

Metallic nanometer-sized contacts (NCs) show intriguing electric properties for next-generation nanometer-sized devices, i.e., ballistic conduction and the quantized conductance defined by a quantum unit ($G_0=2e^2/h$; where e is the charge of electron and h is Planck's constant.) [1]. The production and electric properties of metallic NCs are investigated by mechanically controllable break junction and nanometer-tip manipulation techniques, both based on contact of nanometer tips and subsequent plastic deformation [2]. The structural dynamics of the NCs during the deformation was studied by simulation [3] and by *in situ* transmission electron microscopy (TEM)[4]. In this report, we investigated the tensile deformation of Ag NCs by *in situ* TEM.

2. Experimental method

The experimental method in this study was developed on the basis of *in situ* high-resolution TEM combined with subnanonewton force measurements used in atomic force microscopy (AFM) and electric conductance measurements used in scanning tunneling microscopy [4]. The nanometer-sized Ag tip of a Si cantilever for AFM was brought into contact with an opposing edge surface of a Ag plate of 5-20 nm in thickness by piezomanipulation while applying a bias voltage of 65 mV between the tip and the plate. The cantilever tip was then retracted to elongate the contact. A series of these manipulations was performed inside the transmission electron microscope at room temperature in a vacuum of 1×10^{-5} Pa. The structural dynamics of the procedure was observed *in situ* by the lattice imaging using a TV capture system. The force applied between the tip and the plate was simultaneously measured by optical detection of the cantilever deflection. The electrical conductance was measured using a two-terminal method. The high-resolution imaging and signal detection in this system were simultaneously recorded and analyzed for every image using our own software.

3. Results and Discussion

Figure 1 shows a time sequence series of high-resolution images of tensile deformation of a Ag NC. The cantilever tip and the plate are observed as dark contrast in the upper and lower regions of each frame of Figs. 1(a)-1(f), respectively. A contact between the two regions is observed in the middle of each frame. Lattice fringes of the (111) planes are imaged on the plate. As the cantilever tip was retracted from the plate along the direction indicated by the arrows in Figs. 1(b)-1(e), the NC is thinned to a few atoms or one atom width owing to slips on the (111) plane. Finally the contact breaks as shown in Fig. 1(f).

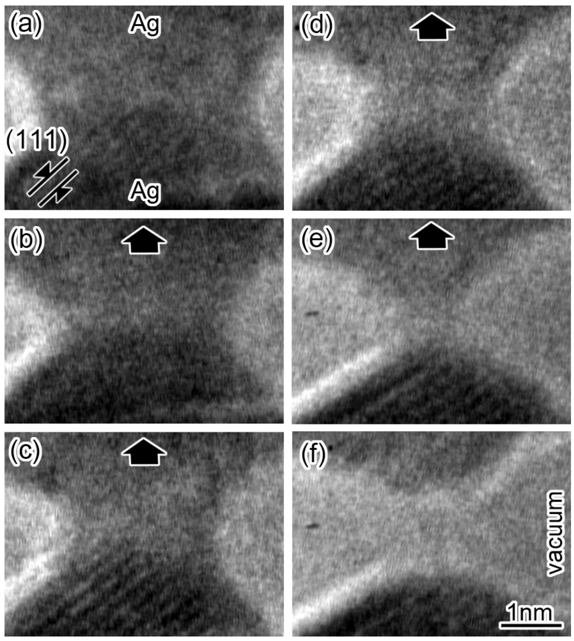

Fig. 1 Time-sequence series of high-resolution images of tensile deformation of Ag NC.

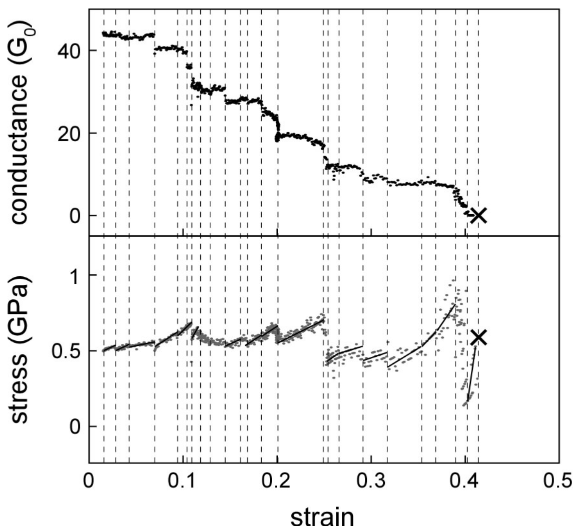

Fig. 2 Variations in conductance and stress as function of strain during tensile deformation seen in Fig. 1. The solid lines in the lower frame represent approximated curves. The crosses indicate fracture of NC. Cycles of elastic and plastic deformation are indicated by broken lines.

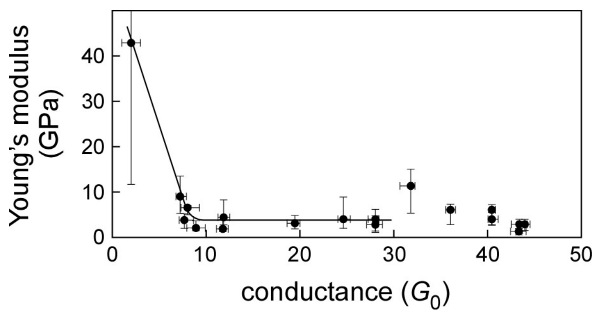

Fig. 3 Young's modulus for conductance value at each plateau in Fig. 2. The solid line is an approximated curve.

We measured the variations in the strain, the minimum cross-sectional area, the force, and the current, as a function of time. Then these variations were transformed into the relationships between the conductance and strain, and the stress and strain, as shown in Fig. 2. The conductance curve in the upper frame of Fig. 2 shows a stepwise variation. In the stress-strain relationship shown in the lower frame of Fig. 2, a saw-tooth curve is observed, showing the iteration of cycles of elastic and plastic deformation. The stress at each edge of the saw-tooth, which means yield stress for each structure having a plateau conductance, exceeds 0.5 GPa, involving sufficient strength for functional nanodevices assembled in LSI. It is found that a length of the conductance plateau corresponds to a cycle of elastic-plastic deformation, as shown by the broken lines in Fig. 2. Young's modulus for each cycle, i.e. each conductance value, was estimated, as shown in Fig. 3.

At the cycle at a strain of 0.12, a negative slope of the stress-strain relation is observed in Fig. 2. The negative slope reveals the relaxation of the NC. As a result, at the next period, the conductance recovers. It is found that such a relaxation occurs when Young's modulus exceeds 11.3 GPa, as indicated by the point at $32G_0$ in Fig.3. When Young's modulus exceeds this critical value for the relaxation, the NC reaches break, as shown in Fig.3.

When the conductance is larger than $10G_0$ except the relaxation event, Young's modulus is in the order of GPa, comparable to only 10 % of that of bulk Ag. For the conductance less than $10G_0$, Young's modulus increases up to 42.9 GPa. This increase reveals the reinforcement of atomic bonding owing to structural change from NCs to atomic sized contacts.

4. Conclusion

We investigated the variations in structure, conductance and Young's modulus of Ag NC during tensile deformation for processing and assembly. It was found from the stepwise conductance variation and the yield stress exceeding 0.5 GPa that Ag NCs are suitable for electronic nanodevices. Young's modulus increases to 11.3 GPa at the relaxation of strained structure, and 42.9 GPa at fracture.

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