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In Situ High-Resolution Transmission Electron Microscopy of Electromigration in Silver Nanocontacts

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1. Introduction

As the relentless miniaturization of LSI is progressing to nanometer scales, the fracture mechanism of each reduced device structure has to be studied in complying with variation in the structural stability of nanomaterials during current impression. In nanocontacts (NCs) of noble metals (gold, silver (Ag), and copper (Cu)), current density exceeds ~TA/m^2 when the contact size is smaller than the electron mean free path [1, 2]. As a result, electromigration (EM) occurs, leading to their fracture. On the other hand, in NCs, it is found that EM induces self-organized structural recovery of wire shapes. Thus, EM brings about new production methods of nanostructures [3].

In this study, we investigated structures, conductance and stress of Ag NCs under higher voltages to cause EM, observed its process directly by *in situ* transmission electron microscopy (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, as used in atomic force microscopy (AFM) and electronic conductance measurements, as used in scanning tunneling microscopy [4]. A Ag nanotip on a silicon microcantilever for AFM was brought into contact with an opposing edge surface of a Ag plate of 5–20 nm in thickness by piezomanipulation. Then, bias voltages of 20–200 mV were applied between the tip and the plate. A series of these manipulations was performed inside the TEM at room temperature in a vacuum of 1×10^{-5} Pa. The structural dynamics of the process was observed *in situ* by the lattice imaging of high-resolution TEM 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 EM in a Ag NC. The cantilever tip and the plate are observed as dark contrast in the upper and the lower regions of each frame of Figs. 1(a)–1(f), respectively. A NC is observed in the middle of each frame. The lattice fringes of the $(111)_{Ag}$ with a spacing of 0.24 nm are imaged on both the tip and the plate. Fig. 1(a) shows an image of the Ag NC before voltage application. In Fig. 1(b), EM occurred and the NC thinned when bias voltages of ~100 mV are applied. At this time, no change is observed in the bases of the electrodes. In Figs. 1(c)–1(e), the NC width decreases to a several atoms. During this thinning, the tip side becomes thicker whereas the plate side becomes thinner. Thus, this implies that atoms migrate from the plate side to the tip side; EM direction was clearly observed by the present method. Finally, the NC breaks, as shown in Fig. 1(f).

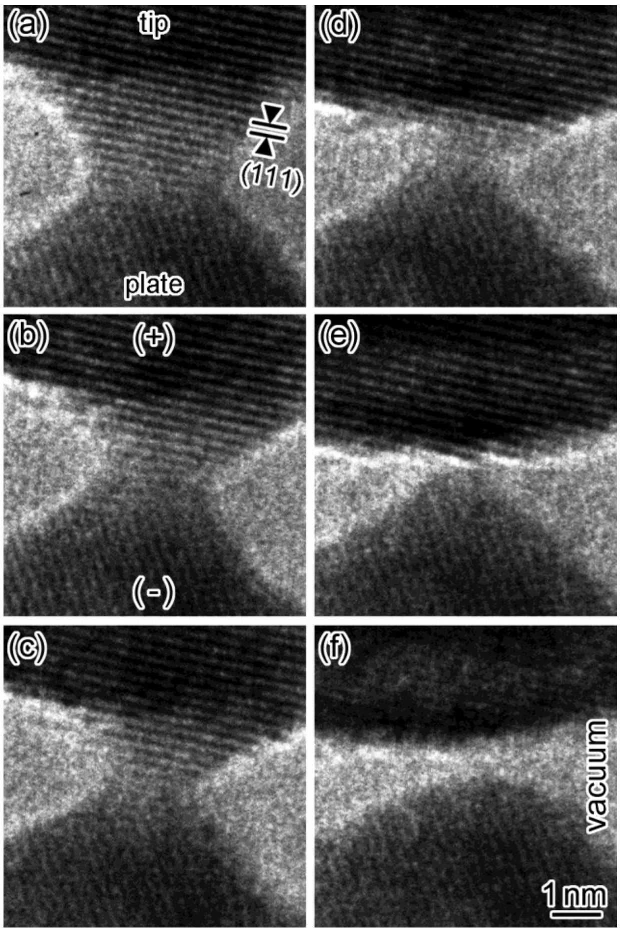

Fig. 1 Time-sequence series of high-resolution images of EM in Ag NC. The upper and the lower dark regions are biased positively and negatively, respectivel

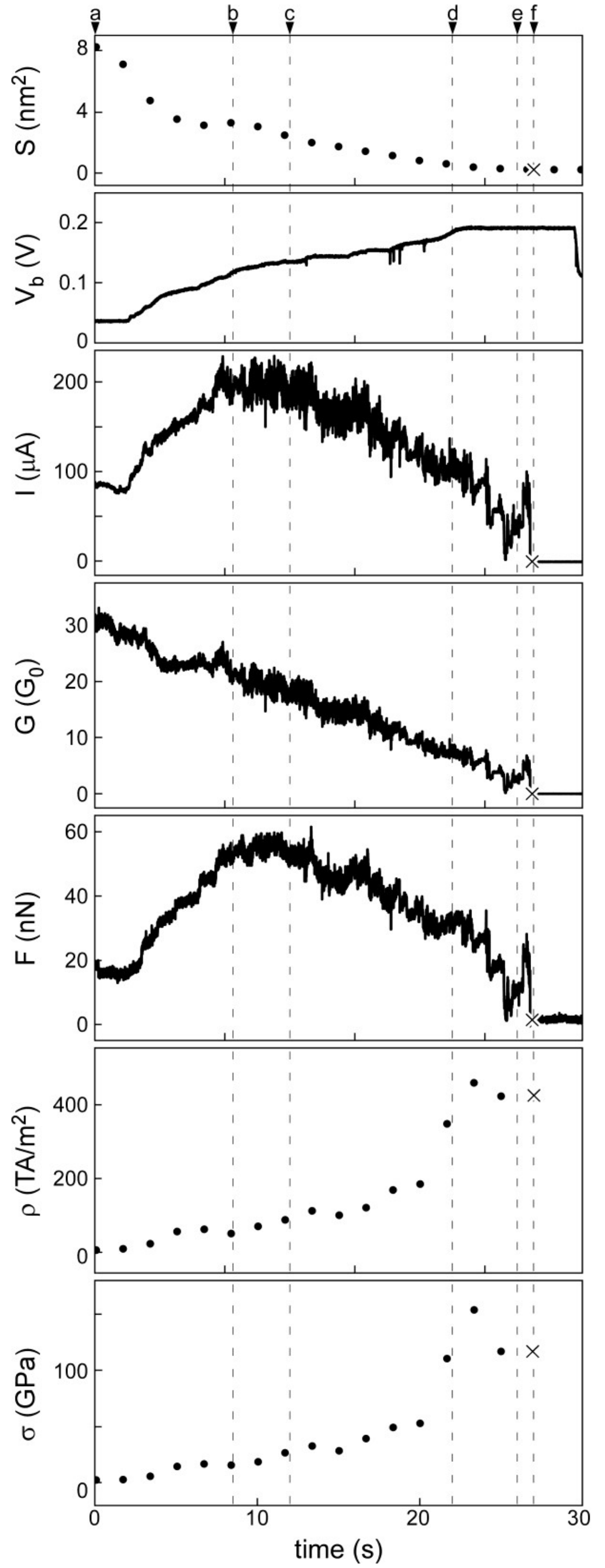

Fig. 2 Variations in minimum cross-sectional area (S), biased voltage (V_b), current (I), conductance (G), force (F), current density (ρ), and stress (σ) as function of time. The times with a–f correspond to the time at recording of the images of Fig. 1(a)–1(f), respectively. The crosses (×) indicate fracture.

Figure 2 shows variations in the minimum cross-sectional area of, the bias voltage applied in, the current through, the conductance of, the force acting on, current density of, and stress applied to the Ag NC during the procedure presented in Fig. 1 as a function of time. The time associated with a–f (hereafter time a–f) corresponds to the time of the image in Figs. 1(a)–1(f). We assumed that the shape of the cross section of the NC at a minimum width was circular. We calculated the current density and the stress by dividing the current and the force by the area. As bias voltage increased, the area of the NC decreased. At time b, current oscillation becomes largeer. This oscillation also implies the start of EM. The average current density is approximately 100 TA/m^2. This value is about 10^6 times larger than that of bulk Ag wires of 10 mm diameter. A significant increase in current density is observed before the fracture (~450 TA/m^2). At this time, the maximum stress is observed (~150 GPa). These values are 10^2 times and 10^3 times larger than the previous result for the Cu NCs, respectively [1]. The present EM causes at a current density of ~100 TA/m^2. It is reported that for Ag nanowires with a length of 10 μm and a width of 390 nm, EM occurs at ~3.5 kA/m^2 [5]. The present current density is 10^8 times larger than this value.

The electron temperature of the NC during EM was estimated to be 400–500 K [6]. It is also suggested that electrons do not interact with each other and with atoms when a contact is smaller than the electron-phonon interaction length [7]. Therefore, it is deduced that the present Ag NC is not melted.

4. Conclusion

EM in Ag NCs was directly observed by *in situ* TEM. The relationships between the structural modification, current density and stress were simultaneously analyzed. The threshold bias voltage was ~100 mV. In this experiment, we *in situ* observed the thinning process of the NCs. Therefore, we can control the contact size using EM.

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