Extended Abstracts of the 2008 International Conference on Solid State Devices and Materials, Tsukuba, 2008, pp. 56-57

C-1-5

In Situ High-resolution Transmission Electron Microscopy of Electromigration in Nanometer-sized Copper Contacts

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1. Introduction

As the relentless miniaturization of LSI is progressing to nanometer scales, the fracture mechanism of each reduced electronic device may have to be revolutionized in complying with variation in the structural stability of nanomaterials during current impression. Electromigration (EM) causes racture of wires and their connecting interfaces, whereas it is found that EM induces self-organized structural recovery of breaking copper (Cu) wires when the diameter is reduced to a few nanometers [1-6]. In this study, we observed EM in nanometer-sized Cu contacts directly by *in situ* transmission electron microscopy (TEM), and analyzed the current and force during EM.

2. Method

The experimental method used 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 electric conductance measurements, as used in scanning tunneling microscopy [7]. To produce nanometer-sized contacts (NCs), the nanometer-sized Cu tip on an AFM silicon cantilever was brought into contact with an opposing edge surface of a Cu plate of 10-20 nm in thickness by piezomanipulation while applying bias voltages of 120-240 mV between the tip and the plate. The cantilever tip was then retracted to thin the contacts to a nanometer scale. A series of these manipulations was performed inside the 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 by high-resolution TEM using a television capture system. The force applied between the tip and the plate was simultaneously measured by optical detection of cantilever deflection. The electrical conductance was measured using a two-terminal method with a sampling rate of 480 /s. 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

Figures 1(a)-1(d) show a time-sequence series of high-resolution images of EM in a Cu 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(d), respectively. A contact between the tip and the plate is observed in the middle of each frame. Lattice fringes of the {111} planes with a spacing of 0.21nm are imaged on both the tip and the plate. Fig. 1(a) shows an image of the Cu NC before EM. In Fig. 1(b), EM occurred, and in Fig. 1(c), EM finished. Fig. 1(d) shows an image of subsequent fracture. Although the piezoelement for the manipulation was not moved between the states seen in Figs. 1(b) and 1(c), we could confirm that the tip approached the plate as time passed. This spontaneous approach implies that the atoms moved from the tip side to the plate side during EM.

Figure 2 shows variations in the strain and minimum cross-sectional area of the Cu NC, force applied to the NC, and current through the NC during the procedure shown in Fig. 1 as a function of time. The time associated with triangles a-d (hereafter time a, b, c and d) corresponds to the time in which each image in Figs. 1(a)-1(d) was observed. The strain was estimated from the variation in the distance between the cantilever tip and the plate. We assumed that the shape of the cross section of the NC at a minimal width was circular, and measured the width from the images. We calculated the stress by dividing the force by the minimum cross-sectional area. A significant increase in current density is observed between times b and c, and average current density during the period is approximately 120 TA/m^2. This value is about 10^5 times larger than that of

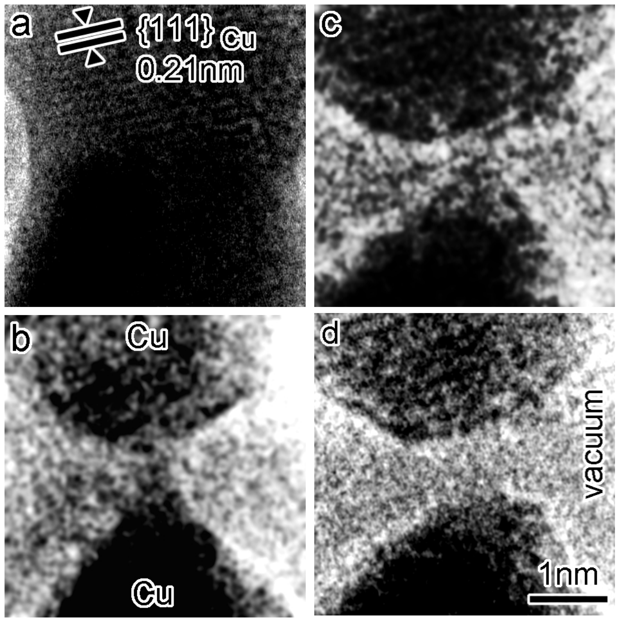

Fig. 1 Time-sequence series of high-resolution images of EM in Cu NC.

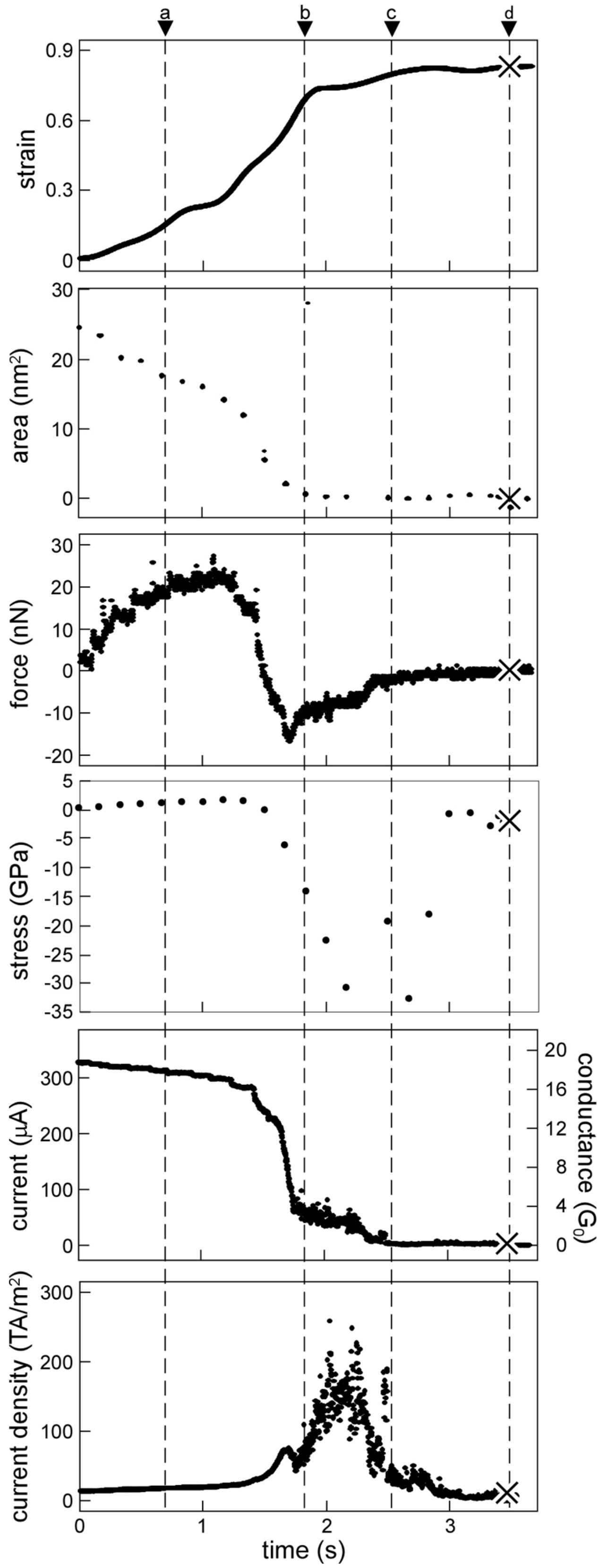

Fig. 2 Variations in strain, minimum cross-sectional area, force, current (with conductance) as function of time. The time with triangles a-d corresponds to the time at the recording of the images of Fig. 1(a)-1(d). The crosses (x) indicate fracture.

a bulk copper wire of 10 mm diameter. EM is caused at a current density of 63 TA/m^2. It is reported for Cu nanowires with a length of 10 nm and a width of 6 nm that EM occurs at a current density of 90 TA/m^2 [7]. The present current density is in good agreement with the previous result for the Cu nanowires. Before EM, tensile strength for the NC, i.e., the maximum stress observed, is 1.6 GPa at a strain of 0.26. Then the stress influenced during EM; the value is estimated to be from -31 to -14 GPa and this absolute value is considerably larger than the tensile strength. This directly shows that the tip is compressed owing to EM since positive forces acted on the NC before the increase in the current density.

4. Conclusion

EM in Cu NCs was studied by *in situ* TEM. The relationships between the structural modification, strain, cross-sectional area, force, stress, total current, and current density during EM were directly analyzed. Among these parameters, the strain, stress, and current density are obtained on the basis of the structural observation.

In this experiment, EM can be confirmed by both high-resolution observation of the structure and the force measurement. From the relationship between the force and current density, we can define a critical current density at which EM starts. Therefore, the present method enables us to analyze EM precisely.

Acknowledgment

This work was partly supported by funds for the Special Research Project on Nanoscience and the University Research Projects of the University of Tsukuba, and Grants-in-Aid from the Ministry of Education, Culture, Sport Science and Technology, Japan (Nos. 18310075 and 19651047).

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