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Mechanical Properties of Nanometer-sized Cu Contacts

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1. Introduction

Recent progress in nanotechnology has resulted from the development in the fabrication of nanometer-structured materials. The processes of the fabrication are designed based on the electrical and mechanical properties of individual nanometer-sized elements, such as wires, point contacts and quantum dots of nanometer or single atom width. The mechanical properties, e.g., strength, elasticity and plasticity, have not been unknown because of the difficulty with the strain-stress measurements of such fine elements, while the conductivity has been widely investigated. Recently, we have developed an experimental method for atomistic deformation mechanics of individual nanometer-sized structures based on high-resolution transmission electron microscopy (HRTEM)[1,2]. In this report, we demonstrated the experimental results of the mechanical properties of nanometer-sized Cu contacts, which have been expected as the elements of nanometer scale miniaturization of conductive networks for its higher conductivity and stability for electromigration compared with those of Al [3-6].

2. Method

The functions of atomic force microscopy (AFM) and scanning tunneling microscopy were combined with HRTEM. A tip of a silicon cantilever coated with a Cu film for AFM were manipulated using a tube type piezo electric device and contacted with another nanometer tip of a Cu plate at the applied voltage of 1 V; nanometer-sized Cu contacts were produced by this operation. Millisecond dynamics of atomic arrangements, sub-nano Newton scale force and conductance during the mechanical interaction processes between both tips, i.e., contact, successive compressive and tensile deformation and fracture, were simultaneously observed. High-resolution atomistic images were observed at a spatial resolution of 0.14 nm and a time resolution of 16 ms. The signals of force and conductance were recorded at intervals of 4 ms. Separation distance and width of minimal contact regions during the deformation were measured from each high-resolution image. The values of minimal cross section areas for the calculation of stress were estimated from the width. The separation distance and force were transformed to strain and stress, respectively, and strain-stress relation to analyze mechanical properties of individual nanometer-sized structures was obtained.

3. Results

Fig. 1 shows the time-sequence series of high-resolution images of a tensile deformation process of a Cu contact. The contact was supported with the dark regions in left and right sides. Both sides connected to the cantilever (A) and plate (B) in Fig. 1(a), respectively. The line fringes are {111} lattice fringes of 0.21 nm spacing. The bright regions in upper and lower sides are vacuum. There is no substrate on the back of the contact region; the deformation was controlled by the piezo manipulation. The cantilever tip was displaced to the left hand direction and the contact region was stretched. The contact region was thinned as shown in Fig. 1(a)-(c) and fractured as shown in Fig. 1(d).

Fig. 2 shows the variation in strain, tensile force, the minimal area of cross section and stress during the tensile deformation in Fig. 1 as a function of time. At the time indicated by a ~ d in Fig. 2, the high-resolution images in Fig. 1(a)~(d) were observed, respectively. The strain increases and the cross section area is reduced monotonically. On the other hand, a saw edge-like curve appears in the time-force and time-stress relations; the value of force or stress increases gradually and then descends vertically, and their coupled process repeats. In former moderate increasing stage in a coupled process, elastic deformation occurred. In later descending stage, plastic type deformation including slip and liquid like atomic flow arose. The Fig. 3 shows the strain-stress relation. The stress increases as the deformation proceeds, showing that the contact strengthens as the size of contact reduces to a few nanometers in width. The saw edge-like curve is also observed in Fig. 3. The period of strain and the slope of strain and stress in an elastic deformation process indicate the elastic limit ~ 0.1 and Young's modulus 0.2 ~ 1 GPa, respectively. The highest value of stress

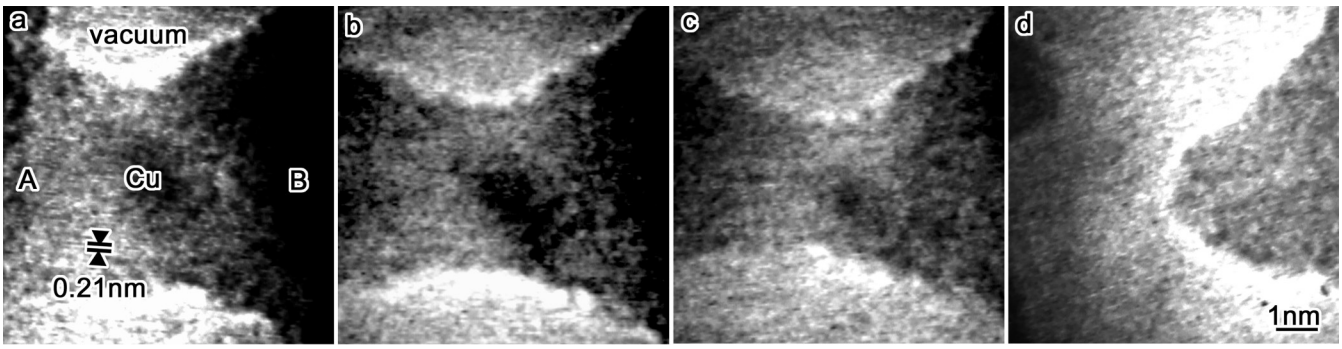

Fig. 1 Time-sequence series of high-resolution images of tensile deformation of a nanometer-sized Cu contact.

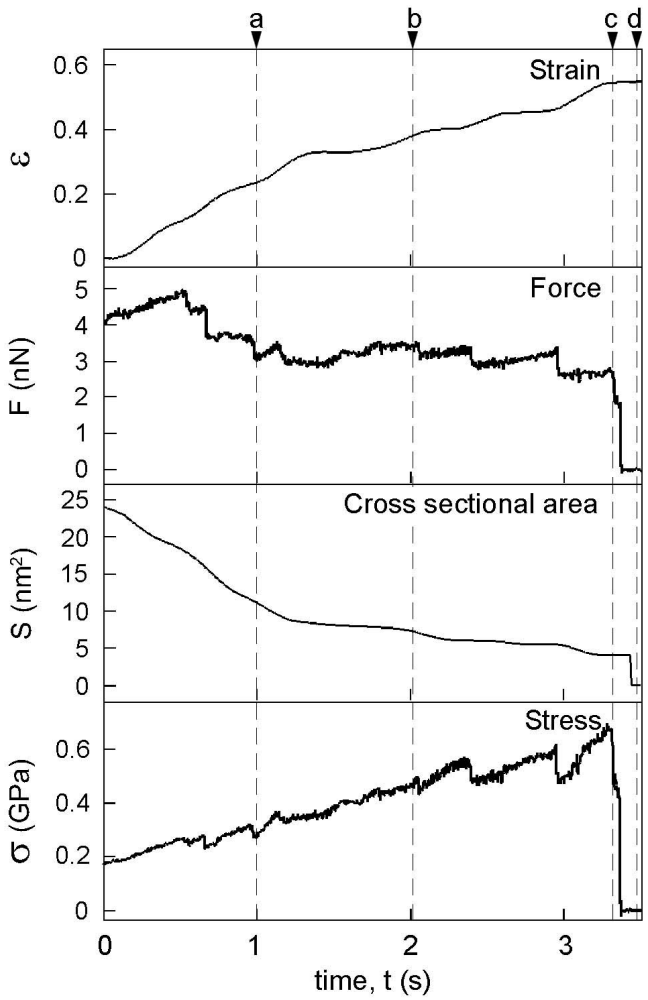

Fig. 2 Variations in parameters, i.e., strain, force, minimal area of cross section and stress as a function of time in the tensile deformation of Fig. 1.

implies the strength of the contact, i.e., 0.7 GPa. The values are similar to those of nanometer-sized Au contacts [7] and substantially different from those of coarse-grained Cu wires.

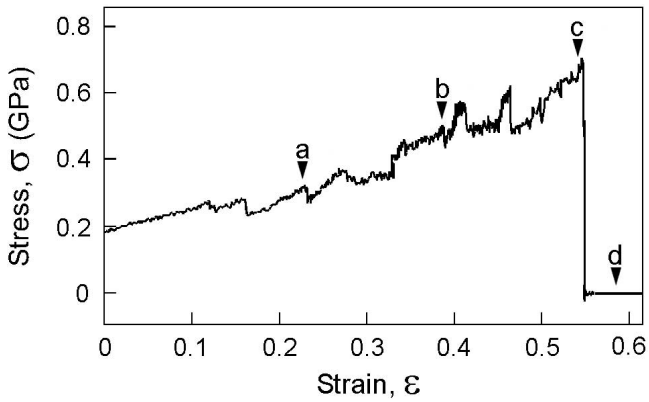

Fig. 3 Strain- stress relation in the tensile deformation of Fig. 1.

3. Conclusions

The present microscopy is the only quantitative experimental method that enables analysis of strain and stress, and their relation during mechanical interaction processes of nanomaterials. It was found that the mechanical properties of Cu contacts are significantly changed by the refinement to nanometer scale.

References

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