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Structure and Conductance of Platinum Wires of Single-Atom Width Studied by *In Situ* Transmission Electron Microscopy

Kosuke Monna, Tomoko Matsuda and Tokushi Kizuka

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

1. Introduction

Nanometer-sized contacts (NCs) of metallic elements show intriguing electric properties as expected for next-generation nanodevices, 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]. For gold (Au) NCs, the conductance during thinning process decreases in a stepwise fashion and the conductance levels at the steps correspond to approximately integer multiples of G_0 [2]. For the last step of a height of approximately $1G_0$, a single-atom wire (ASW) has been predicted as the structure of the contact [3]. On the other hand, it has been reported that the conductances of ASWs composed of other kinds of metallic element, e.g. palladium (Pd), platinum (Pt), iridium (Ir), do not necessarily correspond to this unit conductance [4-7]. In particular, Ir ASWs show conductance ranging from 0.2 to $3G_0$, even though the width of the wires is the same [8]. According to similarity in surface reconstruction behavior, in addition to Au ASWs and Ir ASWs, it has been expected that Pt ASWs are stable [9]. In this report, we studied the relationship between the structure and the conductance of Pt ASWs by *in situ* high-resolution transmission electron microscopy (TEM) using a feedback control of current conduction.

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 used in atomic force microscopy (AFM) and electric conductance measurements used in scanning tunneling microscopy [10]. To produce Pt NCs, the nanometer-sized Pt tip on an AFM silicon cantilever was brought into contact with an opposing edge surface of a Pt plate of 5-20 nm in thickness by piezo manipulation while applying bias voltages of 13-52 mV between the tip and the plate. The cantilever tip was then retracted to transform the contacts to ASWs. 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 by high-resolution TEM using a television capture system. The images were captured with an interval of 17 ms. 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 with a sampling rate of 480 /s. The current through Pt ASWs was controlled using a feedback circuit. The high-resolution imaging and signal detection in this system were simultaneously recorded and analyzed for every image a period of 1/60 s using our own software.

3. Results and discussion

Figures 1(a)-1(c) show the histograms of observed conductance values for Pt ASWs. The distance between the tip and the plate was controlled by the current feedback system to observe Pt ASWs corresponding to conductances of 0.5, 1.0 and $2.2G_0$. The duration time for one count in Fig. 1 is 2 ms. Figures 2(a)-2(c) show high-

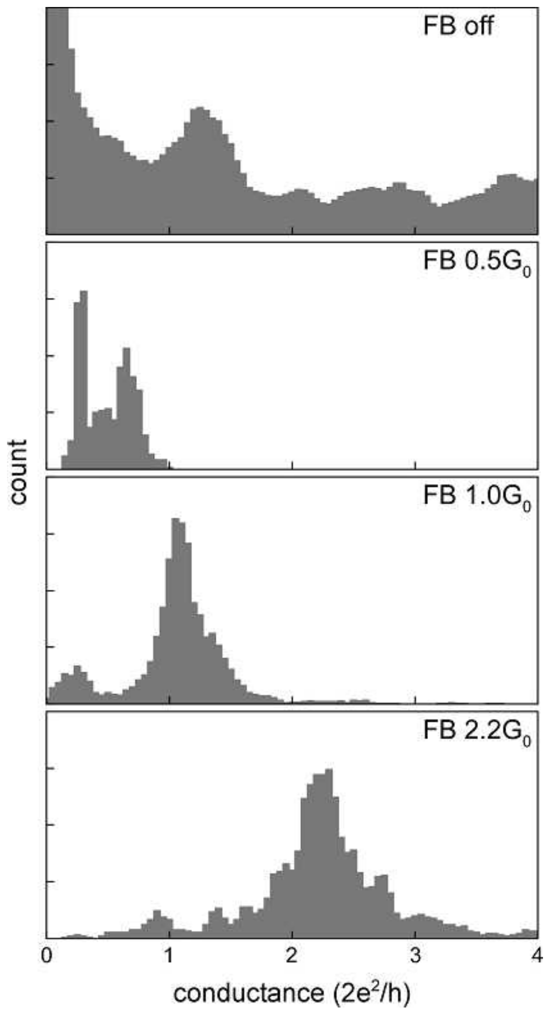

Fig. 1 Histograms of conductance values measured for Pt ASWs. The tip-plate distance was controlled by a feedback system to keep conductance at $0.5G_0$ (a), $1.0G_0$ (b) and $2.2G_0$ (c).

resolution TEM images of Pt ASWs at conductances of 0.5, 1.0 and $2.2G_0$, respectively, during the conductance measurements seen in Figs. 1(a)-1(c). The cantilever tip and the plate edge are observed in the upper and lower regions of each frame of Fig. 2, respectively. A contact boundary, i.e., the Pt ASW is observed between them in the middle of the frame. The measured forces for the Pt ASWs observed in Fig. 2(a)-2(c) were 1.0±0.3 nN. The forces were detected on the lowest step in the time-force curves. These results on the force measurements show that the cross-sectional areas in the three Pt ASWs observed in Figs. 2(a)-2(c) are the same, and are the areas of one single atom. In Fig. 1(c), the tip-plate distance was controlled to keep the conductance of $2.2G_0$, and the observed peak corresponds to the same conductance. In Fig. 1(b), the maximum peak corresponds to $1.0G_0$ as the same as the controlled value. In addition to this, other two peaks are observed at 0.3 and $1.3G_0$. Thus, the state at $1.0G_0$ is substantially stable to realize them, however, the states at 0.3 and $1.3G_0$ are rather stable than the $1.0G_0$, because no other state is observed if the $1.0G_0$ state is most stable. The conductance, $1.3G_0$, is similar to the value $1.5G_0$ reported by Smit *et al.* [5]. In Fig. 1(a), although the conductance was controlled to keep $0.5G_0$, two peaks are observed at the different conductance levels from the controlled value, i.e., 0.3 and $0.7G_0$. This shows Pt ASWs are unstable at $0.5G_0$. When conductance was controlled at larger than 3.0, the width of the contacts increases to two atoms length.

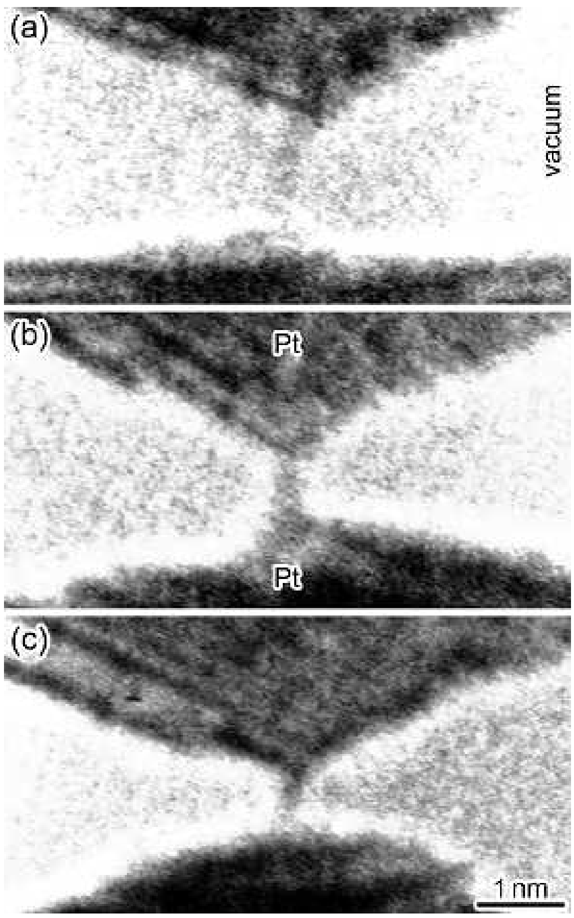

Fig. 2 High-resolution images of Pt ASWs showing conductance of $0.5G_0$ (a), $1.0G_0$ (b) and $2.2G_0$ (c). Images (a)-(c) were observed during the conductance measurements shown in the histogram in Figs. 1(a)-1(c), respectively.

4. Conclusion

The relationships between the structure and the conductance of Pt ASWs were investigated by *in situ* TEM with a feedback system. The results show distinctly that Pt ASWs are stable at four conductances, i.e., 0.3, 0.7, 1.3 and $2.2G_0$. The conductance ranges from 0.2 to $3G_0$, even though the cross-sectional area of the wires is the same as that of a single atom. This conclusion implies that the conductance of Pt ASWs can be controlled by the selection of their length.

The conductance of metallic ASWs at stable structures has been estimated during simple thinning processes at constant retraction speeds, and hence the observation time of the stable states has been restricted [2-3] less than several tens of milliseconds. The feedback method demonstrated in this study enables us to observe continuously the stable structures of metallic ASWs, which are expected as new nanodevices.

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