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In-situ TEM Observation for Formation of Au Nanowires and Nanogaps caused by Electromigration

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1. Introduction

The break junction process of metal wires caused by electromigration provides a spontaneous method to form nanogaps having a size of less than 10nm [1-3]. Many studies have been reported to make single electron devices [4-7], memory devices [8, 9], etc.

In this work, we tried to establish the method to form a nanogap by using a relatively wide metal wire formed by photo lithography as a starting material. It is well known that electromigration cuts the long metal wires at special position in the integrated circuits, on which thermal effects play an important role. For the purpose, we used *in-situ* transmission electron microscopy (TEM) observation [9, 10] to investigate the position-dependent structure change in Au wires caused by electromigration with the thermal effect produced by the current flow. Current measurements of the Au wire were simultaneously performed in a TEM instrument together with observing the structural change of the wire. The electromigration of Au was analyzed through these experiments.

2. Experimental procedure

Our device patterns were made on SiN/Si(100) substrates by using photolithography and the lift-off process after vacuum deposition. After the preparation of Au/Cr electrode pads (total 20-nm-thick), we made wires (bridges) composed of a 35-nm-thick Au layer. The width and the length of narrow wires to be studied were 5 and 10μm, respectively. For *in-situ* TEM observations, in order to obtain self-standing SiN membrane, the observation window was fabricated just under the Au wire by using a KOH aqueous solution. Experiments were performed using JEM2010 and 200CS microscopes attached by custom-made TEM holders with which the electric property can be measured [12]. The DC 2-terminal current measurements were performed by the use of a Yokogawa GS610 source-measure unit after adjusting the applied voltage manually. The typical resistance of the sample was about 80 Ω.

3. Results and discussion

At the initial state, the film contains many small mazy gaps which might be produced by the surface migration of Au during deposition. By starting the voltage application, the current increased to the maximum value (1st stage), gradually decreased (2nd stage), and finally dropped to zero indicating the wire destruction (3rd stage). All the samples followed this sequence though the time for destruction depended on the current density. Carefully checking the TEM as well as scanning electron microscopy (SEM) images of the sample at the 1st stage, Au grains became lager resulting in simplification of the current path. This fact must be a reason of the current increment at the 1st stage although the expansion of the mazy gaps was also recognized. Afterwards in the 2nd stage, the mazy gaps grew to voids while the grain growth continued. The growth of the void may cause the reduction of the current path resulting in the current decrease. This result implies that the voids and grains grew mainly by the thermal effect as a result of the current flow. However, the distribution of voids was inhomogeneous while it must be homogeneous in heat treated samples. In addition, it was also confirmed that the location of voids depended on the current flow direction (Fig. 1). When the current flew from the left-bottom edge to the right-up edge (thus the electrons flew oppositely), voids were initially formed in all area of the wire and its number increased. Continuing the current flow, the void formation became to concentrate near the end of negative voltage side (i.e. upper stream of the electron flow) so as to be aligned in an arc (Fig. 1a). By the alternation of the current flow, the position of void generation changed to another end of the wire (Fig.1b). By subsequent current alternation, void formation and growth occurred in the same way as recognized in Figs. 1c and 1d. This rapid change may be caused by the syner-

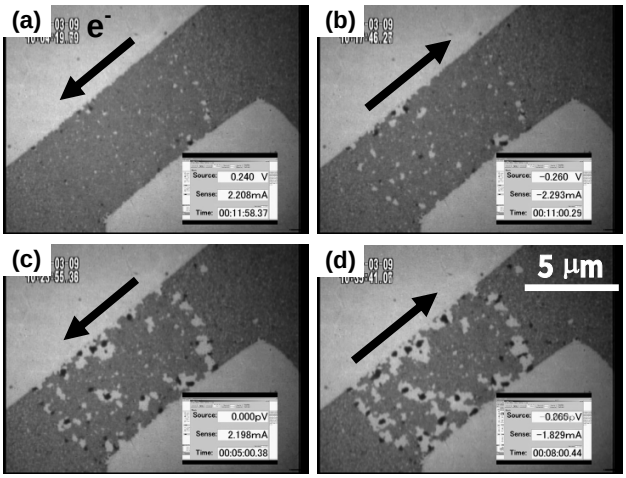

Fig. 1 A series of TEM images of Au narrow wire during alternation of the current flow. The arrows indicate the flow of electron which is opposite to the current flow. TEM images (a) after the current flow along one direction, and (b) to (d) after repeat of the current alternation.

gistic effect of increase in current density and rise in temperature. It should be noted that the wire was almost cut by the growth of the voids aligned in an arc, which suggest that we can control the position of the nanogap formed by the electromigration by the use of this phenomenon. The voids aligned in an arc indicated the fact that the thermal effects in the wire region also took an important role. In other words, increased temperature enhanced the electromigration of Au in the wire regions.

The final stage before nanogap formation is demonstrated in series as Fig. 2. Some black contrasts at the left side of Au nanowire in Fig. 2a disappeared in Fig. 2b by rearrangement of the grains, in which coalescence of grains occurred. At the same time, left of the narrowest part (black triangle) was reduced and the wire length increased. The reduction of the left part continued to Fig. 2c while the right part was almost unchanged. This indicates that the Au atoms at the left part might go further to the left. In Figs. 2c and 2d, the narrowest part of the wire became narrower and the reduction of the right part started. At this stage, shift of clear crystal plane was recognized during the narrowing process. The angle between the crystal facets was 120 degree, which suggests the Au {111} planes. This result corresponds well to the electromigration theory in which Au atoms move most easily along the <110> directions in the {111} planes according to the current flow. Further reduction of the right region was recognized in Figs. 2e to 2g. However, the width of the left part of the wire remained almost constant. In addition, the narrowest position of the wire indicated by the black triangle was confirmed to gradually move to the right (Figs. 2d to 2g). This phenomenon can be understood as follows. Au atoms from the right part flow to the nanowire region. Since the current density at the wire region is large and thus the transportation rate of Au atoms by electromigration must be the highest here, the Au atoms quickly move to the left. As a result, the amount of Au atoms at the upstream side of the wire decreases more quickly than those of downstream side.

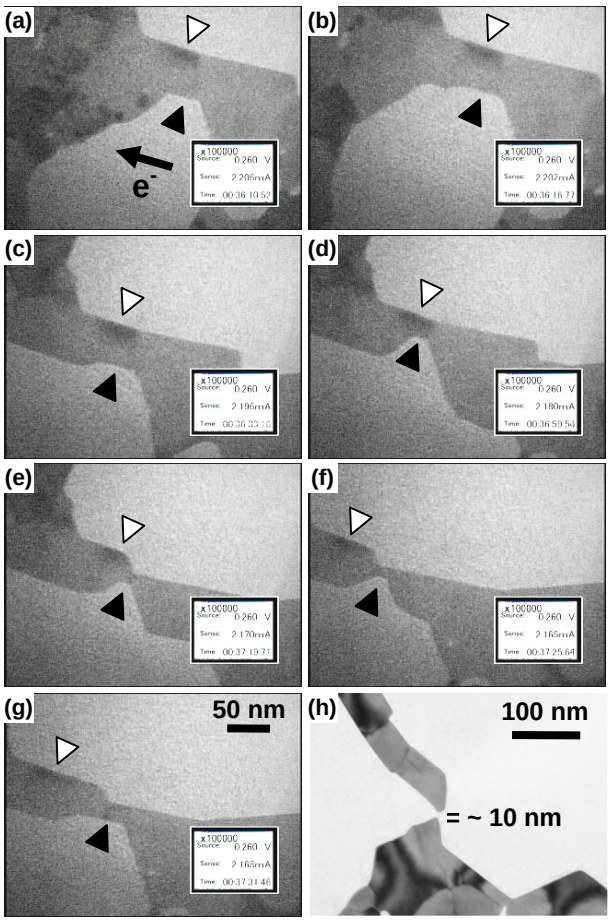

Fig. 2 A series of TEM images of Au nanowire (central part) after the continuous current flow (voltage: 260 mV). The interval between images are (a)-(b) 6 sec, (b)-(c) 17 sec, (c)-(d) 26 sec, (d)-(e) 20 sec, (e)-(f) 6 sec and (f)-(g) 6 sec. Dark contrast with white triangles correspond to each other. The images gradually shifted along the left direction due to the mechanical drift of the TEM holder. The narrowest positions are pointed by black triangles. (h) Area around the obtained nanogap consists of grown crystal with fine straight edges.

In Fig. 2g, an example of finally formed nanogap is shown. The narrowest part of the gap width was approximately 10 nm. Near the nanogap, large grains having the size of more than several tens of nm are recognized. The crystal facets are also clearly seen. The crystal growth during the current flow must be an important factor to obtain well qualified nanogaps.

4. Conclusion

We studied the electromigration occurred in relatively wide Au wires by the use of *in-situ* TEM. All of the results pointed out that heat generation caused by current is a key to form nanowire and nanogap. It was suggested that the position of the nanogap can roughly be arranged by setting the wire structure and current direction even though a relatively wide wire was used. *In-situ* TEM observation of electromigration in the wire suggests that the control of heat generation in the wire makes the nanogap sharp because of the well-controlled recrystallization of Au nanowires.

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