Applied Physics Express **2** (2009) 081401

Electrode-Geometry Control of the Formation of a Conductive Bridge in Oxide Resistance Switching Devices

Kohei Fujiwara[1,2*], Takeshi Yajima[1], Yoshinobu Nakamura[1], Marcelo J. Rozenberg[3], and Hidenori Takagi[1,2]

[1] *Department of Advanced Materials, University of Tokyo, Kashiwa, Chiba 277-8561, Japan*
[2] *RIKEN, Advanced Science Institute, Wako, Saitama 351-0198, Japan*
[3] *Laboratoire de Physique des Solides, Université Paris-Sud, Orsay 91405, France*

Received June 8, 2009; accepted June 25, 2009; published online July 17, 2009

Control of the formation of conductive bridge between the metal electrodes in planar-type resistance switching device was attempted. We demonstrated in Pt/CuO/Pt devices that, using a triangular seed electrode for soft breakdown, the position and the size of the bridge can be controlled. The decrease in the size resulted in the drastic reduction of operation voltage and current to the same level as in capacitor-type stacked device. We argue that the planar-type device might have a certain advantage for future non-volatile memory application.

DOI: 10.1143/APEX.2.081401

Resistance switching (RS) effect induced by an electric-field stress in binary oxide insulators has attracted a great deal of attention due to the potential application in resistance random access memory called ReRAM.[1,2] Although the physical origin of the conductance change has not been fully understood yet, many key ingredients have been identified by a number of researches in the last five years.[3–13] In non-polar switching devices, where the switching operation does not depend on the polarity of applied voltage, an initial voltage application, called forming process, is commonly required to have the reversible RS.[1–11] The voltage required for the forming is normally larger than those for the subsequent switching called reset, from low-R state (LRS) to high-R state (HRS), and set, from HRS to LRS. The formation of metallic filament during the forming process has been widely believed.[3–10] By fabricating planar-type metal/CuO/metal RS devices, indeed, we recently succeeded in imaging directly such a conductive bridge structure within the oxide channel.[14] Forming is very likely a local reduction of oxide channel driven by electric field in a similar fashion to dielectric breakdown.

One of the important steps towards eventual application to memory device is the control of the location and the size of the bridge, since their variation from sample to sample affects the device reliability. If the forming process is a kind of dielectric breakdown,[14] it is not easy to predict its location (i.e., where the bridge forms). However, this could be in principle controlled by the fabrication of a "weak point". Indeed, in our previous study on planar-type devices, we observed that a conductive bridge, physically cut by focused ion beam (FIB), always showed a reconnection in the form of a new bridge that branches out from the broken point upon a second forming process.[14] This suggested that the location of the bridge can be pinned by fabricating a seed like a "lightning rod" within the electrode. The presence of well-defined apex point where a bridge is nucleated might constrain its width if the distance between the two facing apexes is close enough. In this report, we restrict ourselves to planar-type devices where the bridge can be directly observed, and we demonstrate the control of the location and size of the conductive bridge by means of the geometry of the electrodes. A triangularly shaped seed was created on top of the flat electrode of planar-type Pt/CuO/Pt RS devices. At the apex of the triangle the electric field generated at a given applied voltage should become strongest and lead to a soft breakdown. A reduced size, sub μm-scale, bridge was formed between two sharp and exactly opposite triangular electrodes. It showed a significantly reduced switching voltage and current, that is comparable to those reported in capacitor-type stacked devices.

Planar-type Pt/CuO/Pt devices were fabricated using FIB (JEOL JEM-9310FIB) technique as reported previously.[14] Polycrystalline CuO film was deposited on a thermally oxidized Si substrate by RF magnetron sputtering and, then, Pt film for electrodes was evaporated onto the CuO film by electron beam deposition. Two Pt electrodes with and without a seed for the formation of a conductive bridge structure were fabricated on the CuO film by FIB. Switching properties of the Pt/CuO/Pt planar-type devices were measured at room temperature in air with a source-measure unit (Agilent Technologies 4155C). The surface observation was conducted by a scanning electron microscope (SEM; Keyence VE-7800).

Planar-type Pt/CuO/Pt devices showed a non-polar RS operation typical of binary oxide RS devices. Figure 1(a) shows current–voltage (I–V) characteristics of a device without any seed electrodes having a channel length of 2.3 μm and a width of 95 μm. An insulating device turned into an LRS at a forming voltage of 35.8 V. In this process a current limit was set in a source-measure unit to protect the device from permanent breakdown. Subsequently by repeating set and reset transitions, at $V_{\mathrm{set}} \sim 11$ V and $V_{\mathrm{reset}} \sim 7$ V, respectively, we obtained a nonvolatile memory operation with an on/off resistance ratio over 10 as shown in Fig. 1(b). After the forming process a single bridge structure was clearly observed in the CuO channel between the two electrodes, as reported previously. The inset of Fig. 1(a) displays an SEM image of such a formed bridge pattern with ~1 μm width. Note that the whole electrode width (not shown) is 95 μm. The positions of the bridge varied from sample to sample, consistent with their unpredictable dielectric breakdown-like nature.

To test the naive idea that the bridge formation can be controlled by fabricating a soft breakdown seed on the electrodes, we fabricated different types of electrodes, such

---

[*] E-mail address: kfujiwara@riken.jp

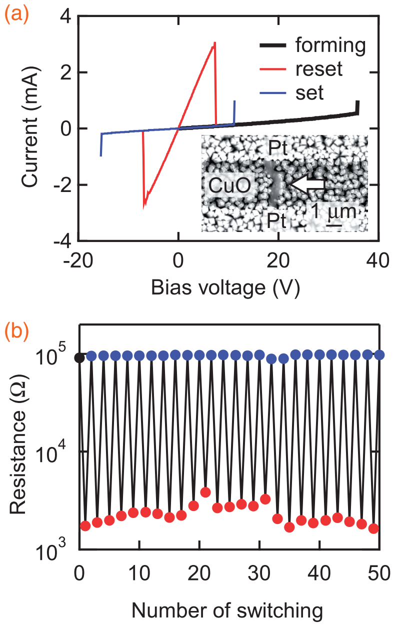

Fig. 1. Resistance switching and conductive bridge formation in planar-type Pt/CuO/Pt devices. (a) Typical *I–V* characteristics of a device having a channel length of 2.3 μm and a width of 95 μm. A current limit of 1 mA was set for forming (bold black line) and set (blue) operations. The inset shows an SEM image of a conductive bridge structure created by the forming process in a device with a channel length of 3.4 μm and a width of 95 μm. (b) Nonvolatile memory operation between HRS (black and blue symbols) and LRS (red) obtained by repeating the DC voltage application.

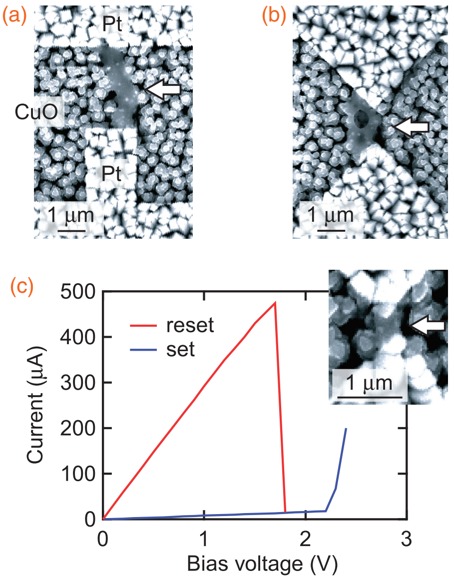

Fig. 2. Control of the position and the size of the conducting bridge in Pt/CuO/Pt planar-type device. (a) and (b) SEM images of a Pt/CuO/Pt device with seed electrodes patterned for the control of the formation of bridge structure. The images were taken after the forming process. The bridges were formed right at the seed electrodes, demonstrating that the nucleation of bridge can be controlled. (c) Triangular-shaped electrodes produced a sub-micrometer-scale bridge (inset). In the device, the resistance switching can be operated with ~2 V voltage and ~450 μA current.

as a rectangular shaped protuberance and a pair of opposite triangular shaped electrodes, as shown in Figs. 2(a) and 2(b), respectively. After the forming, we observed that the bridges were in fact nucleated between patterned seeds, which are indicated by the arrows in the figures. Clearly, it is to be expected that at the apex of seeds the electric field should be substantially enhanced compared with that near the electrodes. This naive technique worked not only for polycrystalline film but also for single crystal-based devices,[15] indicating feasibility of position control of the bridge structure.

When the gap between the electrodes was longer than 1 μm, the thickness of the bridge was of the order of 1 μm in the middle of channel as shown in Figs. 2(a) and 2(b). This is similar to the ones described previously for the devices without seed electrodes [Fig. 1(a) inset]. Consequently, no significant decrease in the voltage and current operation was observed with respect to the previous structure [Fig. 1(a)]. However, when the two sharp triangular electrodes were placed with a separation of ~300 nm, as shown in the inset of Fig. 2(c), the width of the bridge was significantly reduced to a few hundred nm and it became comparable to the size of grains of the polycrystalline film. This reduction in the dimensions of the bridge resulted in a significant decrease in the operation voltage and current. The *I–V* characteristics of this device, shown in Fig. 2(c), shows that the V_{set} and V_{reset} are now reduced to as small as 1–2 V, that is, one order of magnitude smaller than those of the devices with a bridge width of ~1 μm shown in Fig. 1(a). The reset current is reduced to just a few hundred μA, again almost one order of magnitude smaller compared with the devices with ~1 μm width bridge.

In fact, decreasing the distance between the two apexes of the electrodes significantly concentrates and enhances the electric field, therefore reducing the breakdown voltage. In addition, the current flow path is narrower, and hence there is a reduction in the bridge size. Moreover, the grains of the polycrystalline film might also promote the confinement in the formation of the bridge, since the highly insulative spatial gaps between grains prevent the electric conduction and current preferentially flows along grains.

On the basis of a previously advanced physical picture,[14] where we argued that the bridge contains thin Cu-rich conductive filaments with diameters of only a few tens nanometers, we may propose the following tentative explanation on the observed reduction in the voltage and current operation values. According to that model, the switching mechanism relies on a local reduction (set) and oxidation (reset) of the thin conducting filament within the bridge structure which are triggered by electric field and current density,[16] respectively. With reducing the length of the bridge structure the set voltage almost linearly decreased.[17] In contrast, the fact that a mere reduction of a factor of 2 in the width of the bridge produced a full order of magnitude of reduction in the reset current is rather surprising. The local oxidation responsible for the reset is likely to occur at the filament spot where its section is the tiniest. A physical size reduction may enhance fluctuations of the cross-section of those filaments, and hence produce the significant reduction in the reset process.

In the past, the planar device has been fabricated mainly with the goal of elucidating the physical mechanism of resistance switching from an academic point of view. However, having established that the operation voltage and current can be reduced to match those of capacitor-type stacked devices,[1–11] we believe that it is worth considering planar-type as an alternative structure for actual non-volatile memory design. Moreover, planar-type designs may eventually even have an advantage against stacked devices in that the processing can be simpler.

In summary, we have studied the conductive bridge formation process in planar-type Pt/CuO/Pt resistance switching devices. We demonstrated that the position of the bridge can be controlled by introducing a seed that pins the location of the soft breakdown of the dielectric oxide. By utilizing triangular shaped electrode seeds, we were able to reduce the size of the bridge to sub µm, similar to the polycrystalline grain size. This resulted in a drastic reduction of the power dissipation requirements for operation, demonstrating the potential of the planar-type resistance switching device for next generation nonvolatile memory applications.

Acknowledgment This work was supported by a Grant-in-Aid for Scientific Research S (19104008) from the Ministry of Education, Culture, Sports, Science and Technology, Japan.

---

1) S. Seo, M. J. Lee, D. H. Seo, E. J. Jeoung, D.-S. Suh, Y. S. Joung, I. K. Yoo, I. R. Hwang, S. H. Kim, I. S. Byun, J.-S. Kim, J. S. Choi, and B. H. Park: Appl. Phys. Lett. **85** (2004) 5655.
2) I. G. Baek, M. S. Lee, S. Seo, M. J. Lee, D. H. Seo, D.-S. Suh, J. C. Park, S. O. Park, H. S. Kim, I. K. Yoo, U.-I. Chung, and J. T. Moon: IEDM Tech. Dig., 2004, p. 587.
3) B. J. Choi, D. S. Jeong, S. K. Kim, C. Rohde, S. Choi, J. H. Oh, H. J. Kim, C. S. Hwang, K. Szot, R. Waser, B. Reichenberg, and S. Tiedke: J. Appl. Phys. **98** (2005) 033715.
4) K. Kinoshita, T. Tamura, M. Aoki, Y. Sugiyama, and H. Tanaka: Appl. Phys. Lett. **89** (2006) 103509.
5) S. H. Chang, J. S. Lee, S. C. Chae, S. B. Lee, C. Liu, B. Kahng, D.-W. Kim, and T. W. Noh: Phys. Rev. Lett. **102** (2009) 026801.
6) S. C. Chae, J. S. Lee, S. Kim, S. B. Lee, S. H. Chang, C. Liu, B. Kahng, H. Shin, D.-W. Kim, C. U. Jung, S. Seo, M.-J. Lee, and T. W. Noh: Adv. Mater. **20** (2008) 1154.
7) D. S. Jeong, H. Schroeder, and R. Waser: Appl. Phys. Lett. **89** (2006) 082909.
8) K. Jung, H. Seo, Y. Kim, H. Im, J. Hong, J.-W. Park, and J.-K. Lee: Appl. Phys. Lett. **90** (2007) 052104.
9) D. Ielmini, C. Cagli, and F. Nardi: Appl. Phys. Lett. **94** (2009) 063511.
10) K. M. Kim, B. J. Choi, B. W. Koo, S. Choi, D. S. Jeoung, and C. S. Hwang: Electrochem. Solid-State Lett. **9** (2006) G343.
11) I. H. Inoue, S. Yasuda, H. Akinaga, and H. Takagi: Phys. Rev. B **77** (2008) 035105.
12) M. J. Sánchez, M. J. Rozenberg, and I. H. Inoue: Appl. Phys. Lett. **91** (2007) 252101.
13) M. J. Rozenberg, I. H. Inoue, and M. J. Sánchez: Phys. Rev. Lett. **92** (2004) 178302.
14) K. Fujiwara, T. Nemoto, M. J. Rozenberg, Y. Nakamura, and H. Takagi: Jpn. J. Appl. Phys. **47** (2008) 6266.
15) T. Yajima, K. Fujiwara, Y. Nakamura, and H. Takagi: Ext. Abstr. (69th Autumn Meet., 2008); Japan Society of Applied Physics, 2a-J-1 [in Japanese].
16) T. Schmidt, R. Martel, R. L. Sandstrom, and Ph. Avouris: Appl. Phys. Lett. **73** (1998) 2173.
17) This result suggests that the switching region within the conducting filament, where the electric-field-driven set occurs, is downscaled similarly with the size reduction of the bridge structure. The direct detection of such a tiny segment is important not only for the elucidation of this scaling effect but also for the estimation of the threshold electric field of the local reduction.