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Filament Analysis Utilizing Tiny Resistive Random Access Memory with Removable Bottom Electrode

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Abstract

Clarification of memory characteristics of tiny cell is important for practical use of resistive random access memory (ReRAM). However, the limitation of semiconductor micro-fabrication technology hinders to obtain memory characteristics in tiny cell with an area comparable to the size of filaments. In this paper, we established a method to prepare a very small memory cell by fabricating ReRAM structure on the tip of an atomic force microscope (AFM) cantilever. The effective cell size was estimated to be less than 10 nm in diameter due to electric field concentration at the tip of the cantilever, which was confirmed by an electric field simulator based on finite element method. The proposed structure, which has removable bottom electrode, enables not only preparation of tiny ReRAM structure but also execution of unique experiments by making the most of its high stability against the drift of a cantilever.

1. Introduction

NAND Flash memory will face a miniaturization limit after 20 nm generation. In this background, the development of a new memory that is suitable for miniaturization is required. One of the best candidates is resistive random access memory (ReRAM). ReRAM has an advantage in miniaturization, because of its very simple structure that is constructed simply by sandwiching a transition metal oxide film with top and bottom electrodes (BEs) [1]. In terms of practical use of ReRAM, clarification of memory characteristics of tiny memory cell is important. The limitation of semiconductor micro-fabrication technology, however, hinders to obtain memory characteristics in tiny cell with an area comparable to the size of filament.

In this paper, we propose a method to prepare a very small memory cell using an atomic force microscope (AFM) cantilever. By depositing a transition metal oxide film on the tip of a cantilever and contacting a bottom electrode with the cantilever, a tiny ReRAM structure is constructed at the contact area. This method does not need lithography and can provide ReRAM cell with small effective area by utilizing electric field concentration at the tip of a cantilever. Highly drift resistant structure with removable BE enabled performing a unique experiment to verify the presence of oxygen pool in an anode.

2. Experiment

A Pt film with the thickness of 20 nm was deposited on an AFM cantilever with the tip radius of 50 nm as a top electrode (TE), followed by the deposition of a NiO film with the thickness of 15 nm by using the DC magnetron sputtering method. A Pt/NiO/Pt structure was formed by contacting a Pt-BE, which was formed on a SiO_2/Si substrate, with the Pt/NiO structure formed on the tip of the cantilever, as shown in Fig. 1. Current-voltage (*I-V*) measurement was performed in contact mode of AFM.

3. Results and Discussion

Fig. 2 shows the advantage of our proposed structure compared with generally used conventional structure [2-4]. Fig. 2(a) shows conventional structure, in which NiO is sputtered on a Pt-BE and the cantilever that is used as a TE comes into contact with the NiO surface. A filament is formed in the NiO, meaning that a filament is present to the side of the Pt-BE in this structure. Therefore, a filament under measurement is easily missed due to the drift of the cantilever. On the other hand, Fig. 2(b) shows our proposed structure, in which a filament is present to the side of the Pt-TE. Since a filament under measurement moves with the drift, we can stably purchase one and the same filament. Figs. 2(c) and 2(d) show the time-dependence of resistance in low resistance state in conventional structure and our structure, respectively. The resistance became high within 2-3 min in Fig. 2(c). This increase in the resistance is due to the drift of the cantilever, since a conductive filament is still observed after the measurement shown in Fig. 2(c) as shown in the inset. On the other hand, the resistance was maintained at low resistance value more than 30 min in Fig. 2(d).This result indicates high stability of our structure against the drift compared with a conventional structure. This also indicates that we can even change position of the cantilever on BE in every measurement, without missing a filament under measurement.

For the estimation of the effective cell area of this structure, electric field distribution in the Pt/NiO/Pt structure that was formed between the cantilever and the Pt-BE was calculated based on finite element method. As shown in Fig. 3, effective area of the memory cell was estimated to be 10 nm in diameter when radius of Pt-coated cantilever and thickness of the NiO layer were set to the same values as used in this study, 70 nm and 15 nm, respectively.

In Fig. 4, we compare the *I-V* characteristics of the tiny ReRAM (Fig. 4(a)) with that of a normal sandwich structure (Fig. 4(b)). The area of the tiny ReRAM is ϕ10 nm, whereas the area of a normal sandwich structure is ϕ200 μm. Despite great difference of cell size, we cannot confirm a remarkable difference in *I*-*V* characteristics between Figs. 4(a) and 4(b). In both cases, both reset and set occurred independently of the polarity of applied voltage. This result shows very high applicability of ReRAM to miniaturization.

We performed a unique experiment to verify the presence of oxygen pool in an anode, by utilizing removable BE structure. This experiment was carried out in vacuum (1.5×10^{-3} Pa) to avoid the influence of oxygen and moisture contained in the air. First, a positive voltage was applied to the BE until the forming occurred as shown by blue squares in Fig. 5. Then, the cantilever was moved to a different point, and a positive voltage was applied to the BE. We observe *I*-*V* characteristics shown by red triangles in Fig. 5, showing that reset occurred successfully. Finally, after moving to a different point again, the occurrence of set was confirmed as shown by orange circles in Fig. 5. These results seem to be inconsistent with models that require an anode to play a role as an oxygen reservoir [5-7].

4. Conclusion

We proposed a fabrication method of tiny ReRAM structure using AFM cantilever. This method is highly resistant to drift and movement, and enables purchasing one and the filament. Effective cell area was estimated to be ϕ10 nm by electric field simulation. We confirmed no difference between Pt/NiO/Pt structures with areas of ϕ10 nm and ϕ200 μm, suggesting very high applicability to miniaturization. The removable BE structure enables acquisition of entirely new knowledge closely related to the resistive switching effect.

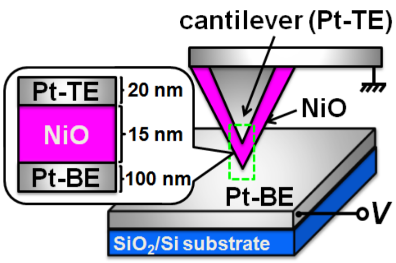

Fig. 1 A tiny ReRAM structure fabricated on the tip of a cantilever of AFM.

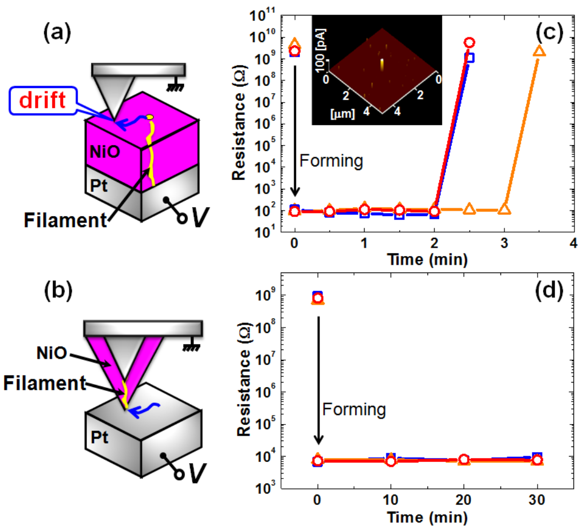

Fig. 2 (a) Conventional structure: NiO is sputtered on the Pt-BE. (b) Proposed structure: NiO is sputtered on the cantilever that is used as a TE. Time-dependence of resistance in low resistance state in (c) conventional structure and (d) proposed structure.

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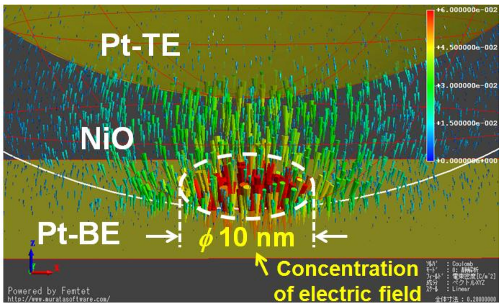

Fig. 3 Electric field distribution in the proposed ReRAM structure calculated by using an electric field simulator.

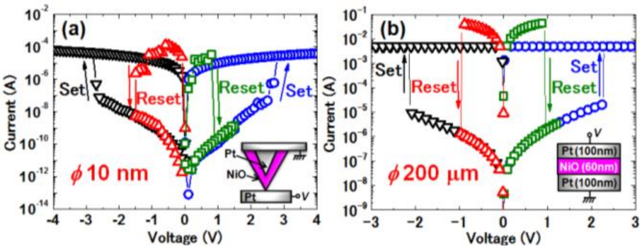

Fig. 4 *I*-*V* characteristics of Pt/NiO/Pt structures with areas of (a) ϕ10 nm and (b) ϕ200 μm.

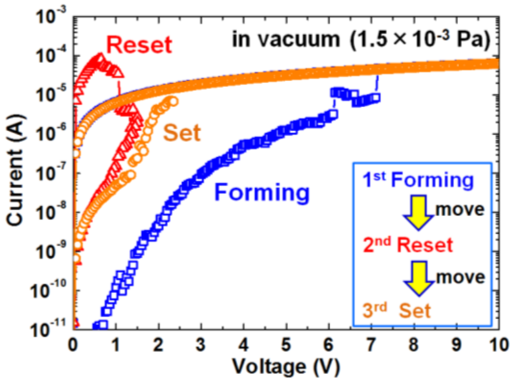

Fig. 5 *I*-*V* characteristics for successive forming, reset and set processes, which were measured at different points in every measurement, by applying positive voltage to the BE.