Switching Properties of Electromechanically Bistable and Multistable Bridges for Nonvolatile Memory Applications

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Introduction

The nonvolatile NEMS memory concept we reported in Refs. [1,2] is based on the electro-mechanical bistability of the sub-μm-long NEMS structure (Fig. 1). It features a buckled SiO_2 bridge which is suspended in the cavity and incorporates the Si nanodots (SiNDs) as single-electron storage. The bridge flips by applying the gate electric field, and its flip-flop motion may be sensed electrically by MOSFET underneath. In this paper, we first experimentally investigated the electromechanical switching properties of the buckled SiO_2 bridges as there has virtually been no systematic study on such electromechanically bistable and multistable switches[3].

Electromechanical Switching of Single Bridge

In the present work we adopted test structures with a few to ten μm long bridges for simplicity. Fabrication processes of the test structures are shown in Fig. 2. To measure the switching voltage V_s of the bridge structure, we applied V_g with appropriate steps followed by structural observations by scanning electron microscope (SEM), repeatedly. Fabricated bridges showed clear upward-bending with an initial displacement of 800 nm as shown in Fig. 3 (a). The bridges held the upward-bent state for V_g up to 36 V and then switched to the downward-bent state at 37 V (Fig. 3(b)). We calculated the bridge displacement as a function of V_g numerically by using the 2D finite element method simulation and estimated V_s to be 28 V by assuming Young's modulus for a Cr thin film (140 GPa) and 32 V for bulk Cr (280 GPa) (Fig. 4(a)) for the structure depicted in the inset. These values are comparable to the experimental results, and this fact indicates that V_s can be reduced by scaling down the bridge dimensions such as the thickness and initial displacement as we demonstrated theoretically [2]. Actually a 10-μm-long bridge was switched at V_g of 20 V if we use a thinner SiO_2 for the bridge as shown in Figs. 5(a) and 5(b).

We also attempted to observe the electromechanical switching by injecting charge directly into the SiO_2 bridges. We fabricated an upward-bent SiO_2 bridge without metal coating (Fig. 6(a)) and kept applying an electron beam onto it in the blow-up mode of the SEM. The SiO_2 bridge was naturally charged with the electron beam and finally flipped to the downward-bent state shown in Fig. 6(b) once the sufficiently high density of electrons were stored on the bridge.

Observation of mechanically-excited states

We also observed in some cases the bridges exhibit their higher-order excited states, depending on their structural dimensions. For example, Fig. 7 shows the first mechanically-excited state of the bridge observed for a 20-μm-long and 100-nm-thick SiO_2 bridge. Figures 8(a) and 8(b) show the electromechanical switching observed for a 25-μm-long and 100-nm-thick SiO_2 bridge coated with a 15-nm-thick Cr metal layer when a voltage of 38 V was applied. The results clearly show that the bridge switches from its ground state to the first excited state. For the bridges with SiO_2 thickness of 100 nm, we found that such mechanically-excited states occur for the bridge length over 15 μm. Such excited states were also confirmed in simulation when an uneven force was applied to bridges (Figs. 9(a) and 9(b)). In practice, any structural or elastic inhomogeneities of the bridges may trigger the switching to such excited states, which may cause serious errors in our NEMS memory operations. On the other hand, we found with simulation that the electromechanical switching between two ground states (i.e., the upward- and downward-bent states) can be achieved at lower switching voltages if the switching process goes through such excited states rather than going over the maximum point in the mechanical potential which represents the bridges being squashed into flat. Such switching processes may be used to reduce the programming/erase voltages of our NEMS memory.

Conclusion

We report on the first experimental demonstration of electromechanical switching for bistable and multistable bridges as a key building block for fast and nonvolatile NEMS memory. Switching voltages observed for fabricated bridges were found consistent with numerical simulation results, proving a good scalability of the bridges. We also demonstrated the mechanically-excited states of the bridges, which may be utilized for reducing the switching voltages.

References

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[2] T. Nagami *et al.*, IEEE Trans. Electron Devices **54**(5), 1132 (2007).

[3] B. Hälg, IEEE Trans. Electron Devices **37**(10), 2230 (1990).

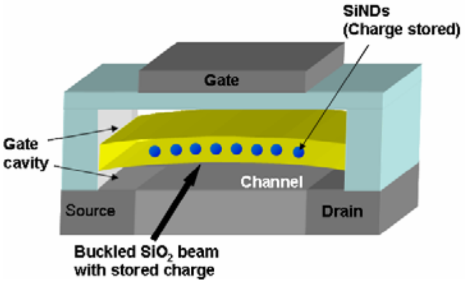

Fig. 1: A schematic illustration of NEMS memory structure.

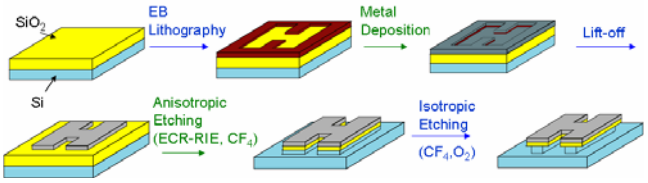

Fig. 2: A flow chart of fabrication process for buckled SiO_2 test structure.

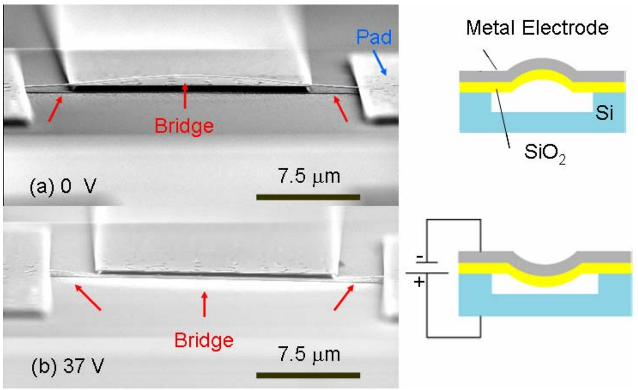

Fig. 3: SEM images of a buckled SiO_2 bridge covered with a thin Cr layer (a) before and (b) after applying V_g of 37 V together with schematics.

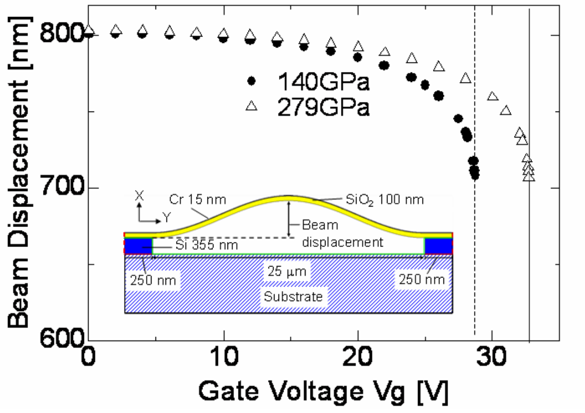

Fig. 4: Beam displacement as a function of V_g for two different Young's modulus. Inset: a schematic of the bridge used in the estimation of V_s by using 2D FEM calculation.

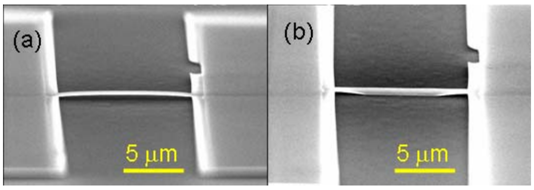

Fig. 5: SEM images of a buckled SiO_2 bridge covered with a thin Cr layer (a) before and (b) after applying 20 V.

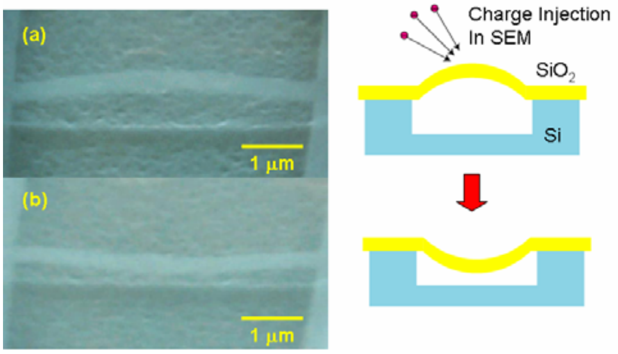

Fig. 6: SEM images of a buckled SiO_2 bridge (a) before and (b) after changing to the high-magnitude observation.

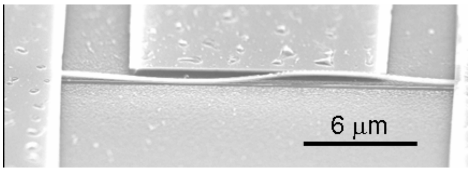

Fig. 7: A buckled SiO_2 bridge of higher order bending

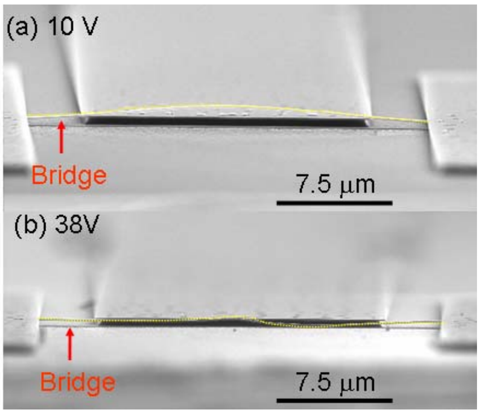

Fig. 8: A buckled SiO_2 bridge (a) after applying V_g of 10 V and (b) after applying V_g of 38 V.

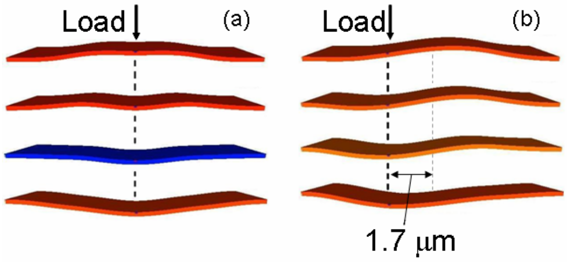

Fig. 9: Calculated higher-mode bending structure after loading to bent bridges. Force was loaded at (a) the centre and (b) the position of 1.7 µm far from the centre.