Extended Abstracts of the 2014 International Conference on Solid State Devices and Materials, Tsukuba, 2014, pp428-429

Mechanism of OFF-State Lifetime Improvement in Complementary Atom Switch

Naoki Banno, Munehiro Tada, Toshitsugu Sakamoto, Makoto Miyamura, Koichiro Okamoto, Noriyuki Iguchi, Tatsuhiko Nohisa, and Hiromitsu Hada

Low-power Electronics Association & Project (LEAP), 16-1 Onogawa, Tsukuba, Ibaraki 305-8569, Japan
Phone: +81-29-879-8263 E-mail: banno@leap.or.jp

Abstract

We have investigated the mechanism of the improvement of the OFF-state lifetime in Complementary Atom Switch (CAS). The CAS consists of two two-terminal atom-switches connected in series with opposite direction. Each switch element can share the voltage stress, resulting in long OFF-state lifetime (>10years) and low programming voltage (<2V). We have demonstrated that the stress voltage in the forward-biased element is spontaneously mitigated and the reverse-biased one, which does not turn on due to its bipolar characteristics, shares a large part of stress voltage. The adjustment in the sharing ratio of stress voltage enhances the OFF-state lifetime.

1. Introduction

Nonvolatile programmable logic using atom switch (NPL) realizes low-power and low voltage operations [1]. The programming is realized by the resistance change due to the formation or annihilation of Cu bridge in the atom switch. In NPL, 6% of atom switch are programmed to be ON, whereas the remaining majority (94%) are in the OFF state. The OFF-state switches, should maintain its state for more than 10 years under bias condition at operation voltage of logic signal (V_{DD}) (Fig. 1). In previous works, Complementary Atom Switch (CAS) has been introduced to NPL to enhance OFF-state lifetime (Fig. 2) while keeping set voltage low. The CAS consists of two bipolar-resistive-change switch elements, namely atom switches, connected in series face to face [2].

In this work, we evaluate the transient voltages or resistances of two switch elements to investigate the mechanism of OFF-state lifetime improvement in CAS.

2. OFF-state reliability of CAS

The CAS is integrated in Cu BEOL on a 65nm-node CMOS (Fig. 3) [3]. The CAS is formed on the edge of two Cu lines which compose the each element of CAS. The AlTi buffer metal is deposited on Cu through contact hole, following by depositing a polymer solid electrolyte (PSE) and a Ru alloy/Ta top electrode. During the PSE deposition, the buffer-metal prevents the Cu electrode from oxidizing and changes to metal oxides of AlTiO [4].

When the stress voltage is applied to CAS, the forward-biased element (element 1) is subject to turn to ON-state due to the formation of Cu bridge. And the reverse-biased element (element 2) keeps its OFF-state until hard breakdown due to its bipolar characteristics. Figure 4 (b) shows the current-voltage characteristics of the element 1, the element 2, and the CAS. The element 1 turns to ON-state at around 1.8V, while the element 2 breaks down around 3.3V. The large breakdown voltage (>3.9V) contributes to the high OFF-state reliability of CAS. The load curve of the element 1 with element 2 as a load is shown in Fig. 5. Since two switch elements have similar resistance, the half of stress voltage to CAS is plausibly shared by each element.

3. Mechanism of improved OFF-state reliability

The stress voltage in the CAS is evaluated to clarify the mechanism of the improvement. In Fig. 6, the transient voltage of element 2 (V_{S2}) and the current through CAS (I_{CAS}) are measured under stress voltage (V_S) of 3V simultaneously. In the initial period (sharing period), half of the stress voltage is applied to each element as we expected.

After 10sec, V_{S2} starts to change from 1.5 to 1.75V. The voltage in element 1 (V_{S1}) also changes from 1.5 to 1.25V, where $V_{S1}=V_S-V_{S2}$. The reason for the change in V_{S1} may be originated from the fact that the Cu extracts from the electrode and drifts in PSE and reduces the resistance of the element 1. The resistance change in the element 1 mitigates V_{S1}, which prevents the Cu drift. Thus, the sharing ratio is spontaneously rectified to maintain OFF state in the CAS. In this period (namely, mitigating period), the lifetime of the CAS is enhanced by the combination of sharing V_S and mitigating V_{S1}.

Figure 7 shows that the lifetime (T_{50}) of CAS and switch element. T_{50} of forward-biased element is much shorter than that of reverse-biased element. Thus, the mitigation of the stress voltage in forward-biased element is essential to enhance the OFF state reliability. Figure 8 shows the distribution of failure elements under large stress voltage. Both breakdown of element 2 and turn-on of element 1 are observed, however, the most of the switch elements maintain its OFF states even for large V_S (=3.85V).

4. Conclusions

It is revealed that the OFF-state lifetime improvement of the CAS structure is originated from the effect of complementary sharing stress voltage and mitigating the stress voltage in forward-biased element. The bipolar nature of the atom switch is the key to improve the lifetime.

Acknowledgements

This work was performed as “Ultra-Low Voltage Device Project" funded and supported by METI and NEDO. A part of the device processing was operated by AIST, Japan.

References

[1] M. Miyamura, et al., isQED, p.3C-3 (2014).
[2] M. Tada et al., TED, 59, p.2357 (2012).
[3] N. Banno et al., VLSI, p. 39, (2012).
[4] M. Tada, et al., IEDM, p.693 (2012).

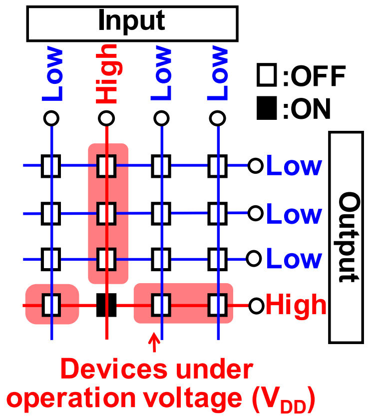

Fig. 1 Schematic of crossbar switch for nonvolatile programmable logic (NPL). Operation voltage of logic signal (V_{DD}) is applied to OFF-state switches aligned along signal lines.

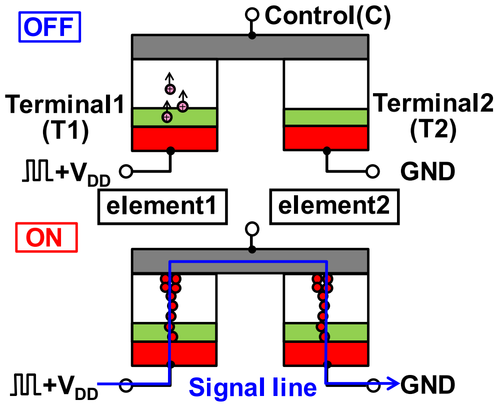

Fig. 2 Schematic views of Complementary Atom Switch (CAS) in OFF-state and ON-state. Stress voltage is shared by bipolar-resistive-change elements (atom switches).

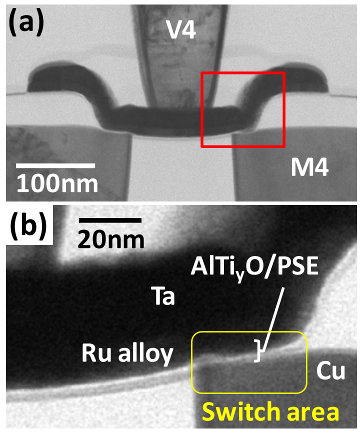

Fig. 3 Cross-sectional TEM images of CAS. (a) Low and (b) high magnification views. CAS is formed at edge of Cu interconnects.

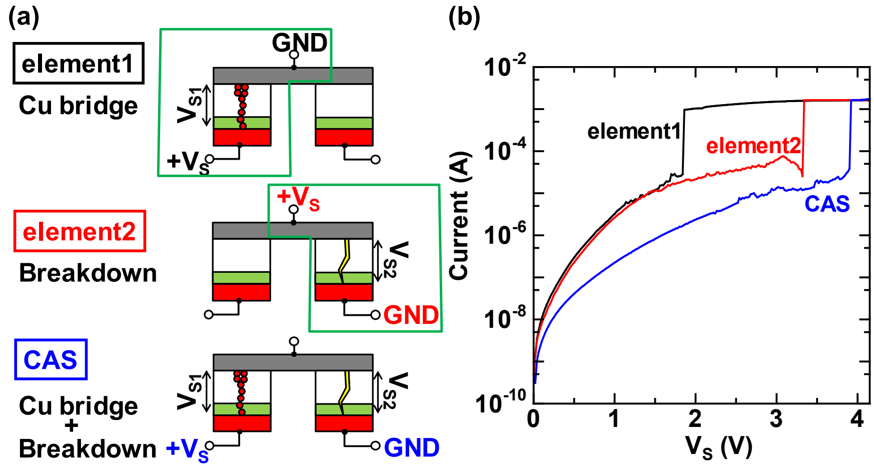

Fig. 4 (a) OFF-state failure modes of two switches (element 1 and 2) and CAS. Cu bridge is formed in element 1, element 2 brakes down when OFF-state lifetime of CAS terminates. (b) Current-voltage characteristics of element 1, element 2 and CAS.

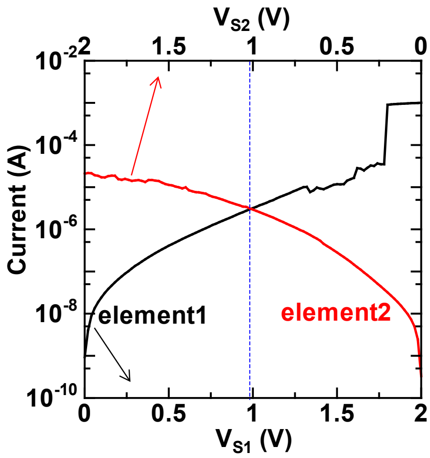

Fig. 5 I-V_{S1} curve of element 1 under stress voltage of 2V with load curve of element 2. Two curves cross at half of 2V.

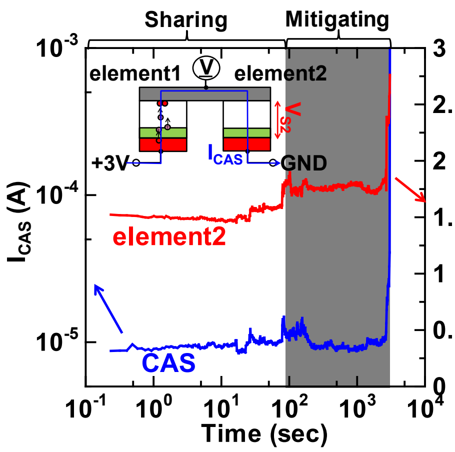

Fig. 6 Transient current of CAS (I_{CAS}) and transient voltage of element 2 (V_{S2}) under stress voltage of 3V.

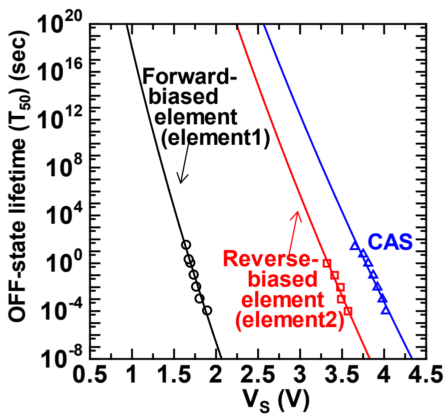

Fig. 7 Median of OFF-state lifetimes of forward-, reverse-biased element, and CAS.

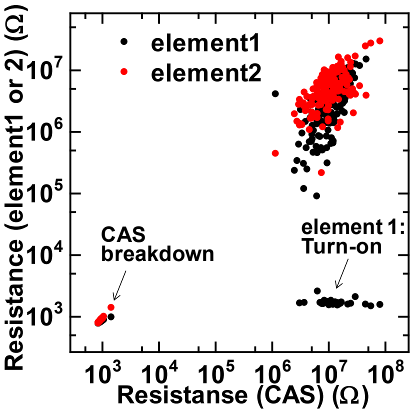

Fig. 8 Failure mode. Resistances of switch elements vs. those of CAS after applying pulse voltage. Pulse amplitude and width are 3.85V and 100ms.