A TA_2O_5 SOLID-ELECTROLYTE SWITCH WITH IMPROVED RELIABILITY

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We present a novel solid-electrolyte switch for programmable LSI. We have used Ta_2O_5 solid electrolyte with very slow Cu^+ diffusion so that the turn-on voltage can be controlled to adapt to CMOS operation. Furthermore, we examined the ON-state reliability of the Ta_2O_5-switch and optimized the trade-off between turn-off current and ON-state reliability, both of which depend on the ON conductance. Ta_2O_5-switch achieves high durability against DC current (0.2mA, 105°C, 10years) and fair turn-off current (5mA). The novel switch can thus meet the requirements for programmable LSI.

The solid-electrolyte switch, composed of the solid electrolyte (CuS or AgS) sandwiched between oxidizable electrode (Ag or Cu) and indifferent electrode (Pt), has been reported by several groups [1]. When a positive or negative voltage is applied to the oxidizable electrode, the switch turns on or off. The switching presumably occurs when a nanometer-scale metallic bridge is created or annihilated inside the solid electrolyte. The switch has distinctive advantages of its small size ($4F^2$, F: minimum half line-pitch) and low ON-resistance (<100 Ω). When the novel switch is applied to a programmable LSI, the chip size can be reduced by 10 times and its performance (speed and power consumption) improves [2]. However, the switch with CuS or AgS has two difficulties on reliability. The turn-on voltage (V_{ON}) is too small (<0.2V) to maintain the OFF state during the normal logic operation [2]. And ON-state reliability should be improved for programmable switch. Here, we have demonstrated that the reliability is improved by reducing the diffusion rate of metal ions in the solid electrolyte.

An appropriate candidate for the solid electrolyte is a metal oxide, which has a smaller diffusion rate than CuS or AgS. We focus on Ta_2O_5 because of its process compatibility with Si-LSI [3]. Figure 1 shows current-voltage characteristics of the Ta_2O_5-switch composed of $Cu/Ta_2O_5/Pt$ stack. Even if a positive voltage was applied to the Cu electrode, the switch maintained in OFF state within an operation voltage of CMOS (≈1V). The switch turned on at 2.5V and the ON resistance (R_{ON}) was around 50Ω. Here, the current was controlled to be below 100μA by the voltage source. Inversely, applying a negative voltage turned the switch off. Figure 2 (a) and (b) show TEM image of switch. After turning on, the dark region with a diameter of 30nm was observed between the two electrodes (Fig. 2 (b)). By means of EDX analysis, the current path was found to be made of Cu bridge (Fig. 2 (c)). These results show that Cu+ ions are extracted from the Cu electrode and the Cu is precipitated between the two electrodes by the electrical field. Localized and metallic conducting path allows the switch to scale down to tens of nanometer while maintaining the ON resistance low [4]. The turn-on/off time ranged from 10 to 100μsec (Fig. 3) and cycling endurance was more than 1×10^4 cycles (Fig. 4). The switching time and cycling endurance meet the demand for switch elements in programmable LSI.

To achieve a highly reliable ON-state, a higher ON conductance (G_{ON}) can be used. However, the turn-off current (I_{OFF}) becomes higher in turn [5]. As shown in Fig. 5, I_{OFF} linearly increased in according to $I_{OFF} = 0.2 \times G_{ON}$. To evaluate the reliability of the Cu bridge, we measured the duration time in ON state while biasing DC current (I_{DC}) (Fig. 6) and estimated the maximum current for duration of 10years. As shown in Fig. 7, the median of duration (t_{50}) did not depend on G_{ON} but rather linearly depended on V_0^{-N} (where $V_{ON} = R_{ON} \times I_{DC}$, and N=12). And t_{50} was thermally activated with an activation energy (E_A) of 0.48eV. Thus, t_{50} is empirically given by $A\times V_0^{-N}\exp(E_A/k_BT)$, where A is constant. When we consider the ON state duration of 10years (=t_{50}) at 105°C (=T), the allowable voltage V_0 can be estimated by the equation. Thus, the allowable current I_{MAX} (= $V_0\times G_{ON}$) can also be derived. Considering the trade-off between I_{MAX} and I_{OFF}, the optimal G_{ON} is estimated to be around 0.02S (=50Ω) (Fig. 8).

References:

[1] Y. Hirose et al., J. Appl. Phys. 47 (1976) 2767; T. Sakamoto et al., Ext. Abs. SSDM (2002) 264; M.N. Kozicki et al., Proc. NVMTS (2004) 10; K. Terabe et al., Nature **433** (2005) 47.
[2] S. Kaeriyama et al., IEEE J. of Solid State Circuits, 40 (2005) 168.
[3] T. Sakamoto et al., Tech. Dig. VLSI Technology (2007) 38.
[4] T. Sakamoto et al., Appl. Phys. Lett. **91** (2007) 092110.
[5] N. Banno et al., Proc. IRPS (2008) 707.

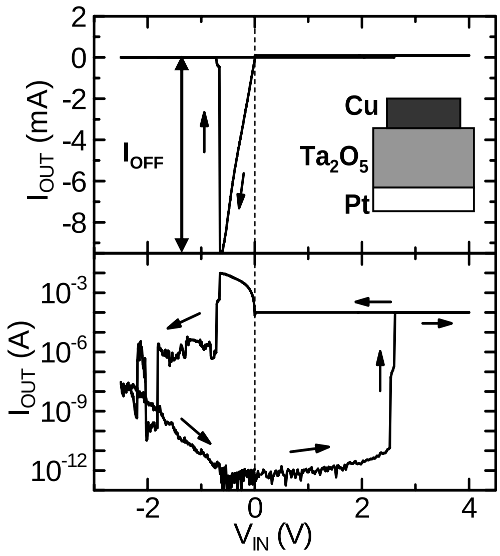

Fig. 1 Current-voltage (I_{OUT}-V_{IN}) characteristics of Cu/Ta2O5/Ta-solid electrolyte switch in linear and semi-log scales. Inset: Schematic of device structure.

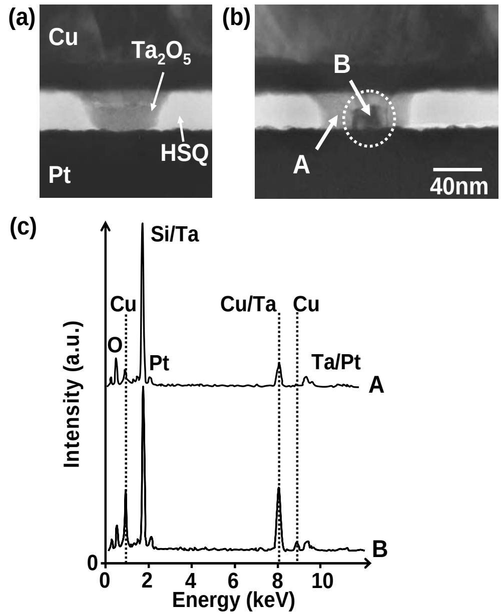

Fig. 2 TEM images of switch (a) before turning on and (b) after turning on. (c) Spectrum of energy dispersive X-ray spectrometer (EDX). EDX signals from points A and B in (b). Broken lines show Cu-related signals.

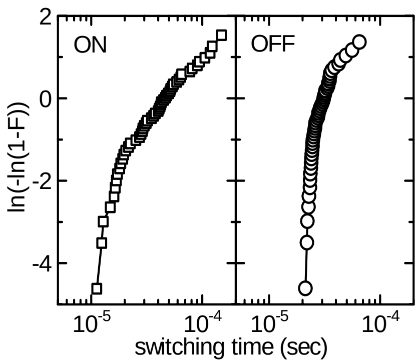

Fig. 3 Distribution of switching time for turn-on and turn-off.

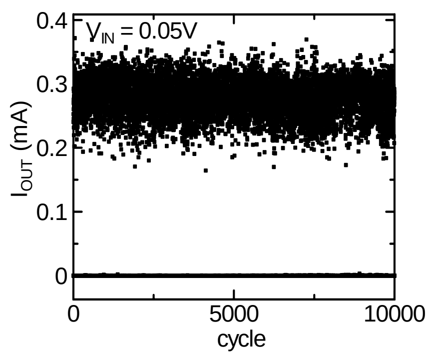

Fig. 4 Cycling endurance.

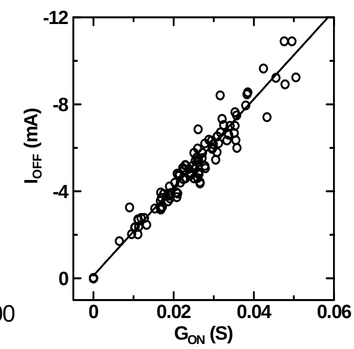

Fig. 5 Turn-off current (I_{OFF}) (shown in Fig. 1) versus ON conductance.

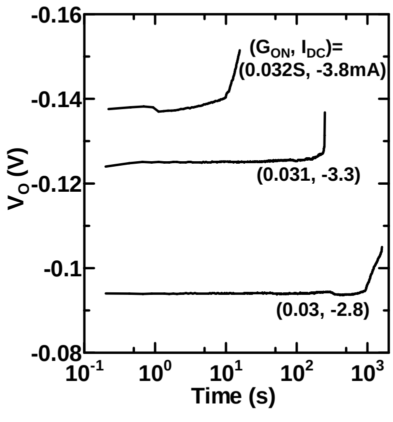

Fig. 6 Output voltage (V_O) versus time when negative DC current was applied to Cu electrode.

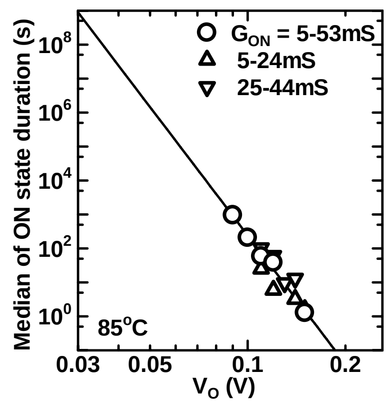

Fig. 7 Median of ON state duration (t_{50}) versus V_O for different ON conductance regimes in Fig. 6 at 85°C.

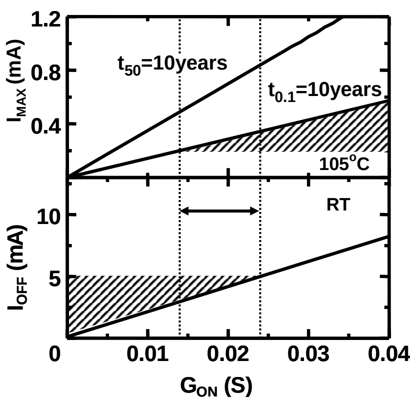

Fig. 8 Trade off between turn-off current (I_{OFF}) and allowable DC stress current (I_{MAX}) for 10 years and 105°C, which is compared with current in a single via in LSI interconncetion (~0.2mA).