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Ultra-Low Power Devices by Taking Advantages of Atom Switches with Polymer Solid-electrolyte

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1. Introduction

Silicon large-scale integrated (LSI) circuits are intelligent systems and key devices that facilitate the transmission, processing, and storage of information in an advanced, information-age society. LSI has penetrated into every aspect of human life and is used daily as tools for handling of information. Miniaturization of semiconductor devices has so far been realizing both LSIs' performance improvement and power reduction. However, it has been becoming very difficult to keep this scenario with decreasing device size down to a few ten nanometer scale. In contrast, internet traffic volumes have been exponentially increasing with the spread of video contents having high definition data, requiring LSIs with higher performance and causing much more power consumption.

A flexible and energy-efficient hardware is desired to address future computing systems. A solution to overcome these issues is a replacement of the conventional SRAM-based switch element to the nonvolatile-resistive-change device, namely switch, which has high OFF/ON resistance ratio. A nonvolatile programmable logic as an accelerator for CPU can drastically improve the performance/power efficiency (Fig. 1).

In this paper, a three terminal complementary atom switch (CAS) for low power systems and some key features of process technologies are discussed.

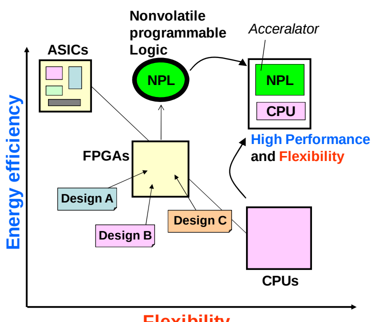

Fig. 1 Tradeoff relationship between energy efficiency and flexibility in ULSIs.

2. Complementary Atom Switch

Atom switch consisted of a solid-electrolyte sandwiched between an active electrode (Cu) and an inert electrode (Ru) [1] is promising as a switch in programmable logic device (PLD) in place of SRAM switch. Nanometer size metal bridge formed in a solid electrolyte makes current pass for logic in LSIs, and the pass is maintained after the external power supply is cut.

A two-terminal atom switch integrated in Cu BEOL had realized the nonvolatile programmable logic (NPL) [2]. The 70% dynamic power and 72% area reductions had been demonstrated in the NPL fabricated in 90nm-node, test-vehicle featuring the two-terminal atom switches [3, 4]. For the further scaling, lowering the programming voltage is a key to reduce the area of the programming transistors since the HV transistors occupy the large area. However, the reduction in the programming voltage is still challenging in the conventional two-terminal switches since the reduction of programming voltage Vp degrades the OFF-state reliability at operation voltage Vop (Fig. 2(a)).

Fig. 2(b) shows the concept of the complementary atom switch [5]. Two of bipolar, resistive change elements are connected in series with opposite direction. The "control" terminal is placed between the two bipolar elements to program the elements. A logic signal is bi-directionally transferred between "Terminal-1(T1)" and "Terminal-2(T2)" when the both elements are programmed to be ON-state. In the OFF-state, namely the both elements are programmed to be OFF-state, two elements are complementary to each other for the voltage stress owing to the "bipolar" resistive-change characteristic.

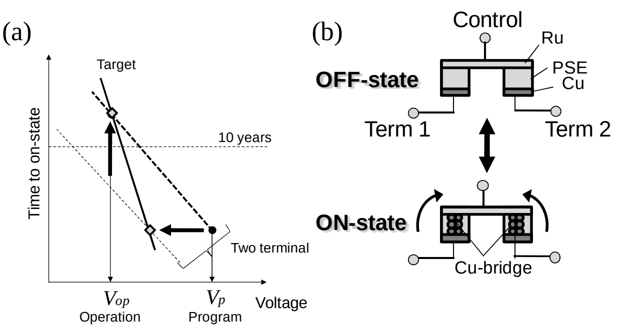

Fig. 2 (a)Tradeoff relationship between time-to-ON state and applied voltage in the atom switches. (b)Concept of the complementary atom switch.

First, when logic operation voltage of Vop is applied between T1 and T2, the elements divide Vop, hence ~Vop/2 is applied to each element. The decreased stress voltage results in higher reliability than that of a single atom switch. Second, when the OFF-resistance of the element biased to “turn-on” starts to degrade with high leakage current, the other element biased to “turn-off” balances the voltage owning to its high resistance. The element biased to “turn-off” maintains the off-state until breakdown.

3. Switching properties

The CAS featuring Cu/TiO/PSE(polymer solid electrolyte)/Ru stacks is integrated in Cu BEOL [6]. Fig. 3 shows I-V characteristics of (a) I_{T1C} and I_{T2C} during set and reset operations, and (c) I_{T2T1}-V_{T2T1} read operation characteristics in both of the on- and off- states.

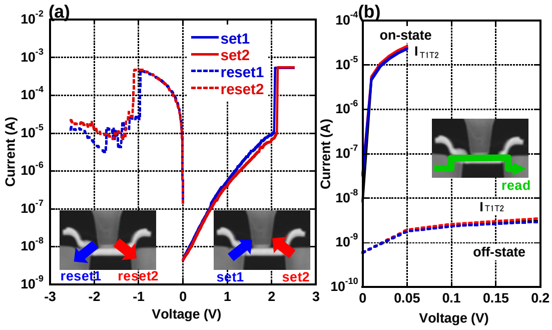

Fig. 3 I-V characteristics of CAS. (a) I_{CT1} and I_{CT2} during set and reset operations. (b) I_{T1T2} in on- and off-states.

4. Variability in programming voltage

The narrow distribution in Vp is essential to applying the CAS to the programmable logic which is composed of large-scale crossbar switch blocks. The CAS has the electrode corner at the Cu metal line-edge, which contributes to reduce the Vp and its variation [6]. The electric field concentration enhances Cu injection at the edge of the Cu line, resulting in the accurate positioning of the metal conduction path. The surface roughness of the Cu electrode strongly depends on the hole-cleaning processes [6]. After the dry-etching of the contact-hole on the Cu metal, a wet- or dry-cleaning process is applied. The Cu surface morphology of rms=3.3nm after the wet-cleaning is larger than that of 1.9nm after the dry-cleaning, which may originate from the Cu dissolving and/or the deposition of organic chemicals in the wet-cleaning. The combination of the smooth Cu surface from dry-cleaning and lightning effect on CAS drastically reduces the variation of Vp (Fig. 4).

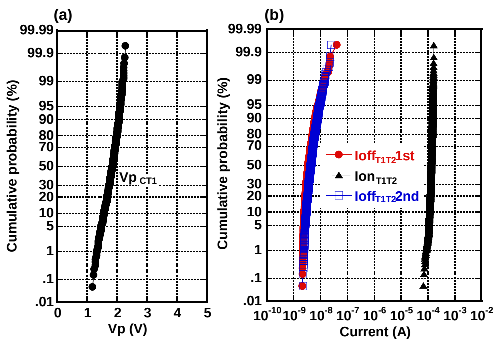

Fig. 4 Distributions of (a) Vp_{CT1} and (b) first Ioff ($Ioff_{T1T2}$1st), second Ioff ($Ioff_{T1T2}$2nd) and Ion_{T1T2} in 1k-b array.

5. Crossbar switch operation

A 32×32 crossbar switch composed of a CAS, which is located at each cross-point of the vertical and horizontal lines, is demonstrated. The CASs in diagonal elements are successfully programmed to be on-state and the others to be off-state (Fig. 5(a)). The improved variability in Vp results in a wide write margin. We also demonstrate that the signal is transferred via the programmed path without crosstalk (Fig. 5(b)).

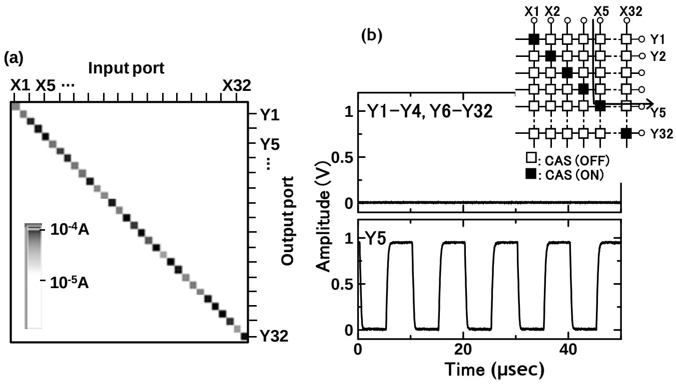

Fig. 5 (a) Current map of 32x32 crossbar switch after programming diagonal elements. (b) Outputs of Y1 - Y32 when signal applies to X5.

6. Conclusions

A new concept of three terminal complementary atom switch (CAS) to resolve the tradeoff relationship between low programming voltage and high disturbance reliability has been proposed. The CAS is integrated on 300-mm Si wafers with a 65-nm-node process. By improving the device process, a 32×32 crossbar switch block can be programmed with 1.8V-transistors. The crossbar switch is a promising switch block for ultra-low power NPLs.

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