Ultra-Low Power Nano-electromechanical Switch Realized by Controlled and Reversible Crack

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***Abstract*- A novel nanoscale device realized by the electrically controlled reversible single nanocrack in an alloy film/ferroelectric oxide heterostructure has been demonstrated. The crack state (open/closed) can be programmed under a cyclic electric field and is nonvolatile. In addition, due to its mechanical switching behavior, a high on/off current ratio (>10^5) and near-zero static power consumption can be achieved. Our proposed nanoscale device concept offers a new implementation of nanoelectromechanical (NEM) switch, which can be used for a nonvolatile random-access memory and configurable logic tables.**

***Keywords*- nanoelectromechanical switch, controlled nanocrack, ferroelectric domain switching, nonvolatile memory.**

I. INTRODUCTION

The NEM switch has attracted widespread attention due to its outstanding characteristics including ultralow power consumption and ultrahigh on/off current ratio [1-3]. However, until now, practical implementations of NEM systems have been hindered by complicated process for device fabrication. Recently, the crack-based devices, which could function as a mechanical switch, have also been widely researched despite the fact the cracks are usually regarded as defects [4-5]. In this work, based on the reversible crack driven by the ferroelectric domain switching, we proposed a new concept of NEM switch with a simple fabrication process.

In section II, we describe the concept of the crack-based NEM switch. In section III, we present the experimental results and section IV shows the simulation results. Section V concludes the paper.

II. THE CONCEPT OF CRACK-BASED NEM SWITCH

The schematic of the crack-based NEM switch is shown in Figure 1a. A 'bridge-like' structure is patterned in the alloy thin-film on the ferroelectric oxide layer. Such a structure can concentrate the applied electric field, which can induce the crack formation at the desired position. Once the crack is generated in the device, the negative and positive electric fields can be applied to control crack opening and closing, respectively, functioning as a mechanical switch. Accordingly, the high resistance state (HRS, or OFF state, as shown in Figure 1b) and low resistance state (LRS, or ON state, as represented in Figure 1c) are obtained under cyclic electric fields. The opening and closing of the crack is driven by the deformation at the interface, which is produced by the domain switching in the ferroelectric layer [6]. In contrast to the conventional methods for NEM switch, for example, electrostatic, thermal, piezoelectric and resonant switching, the proposed method exploiting the reversible crack offers a very simple approach for the implementation of NEM switch.

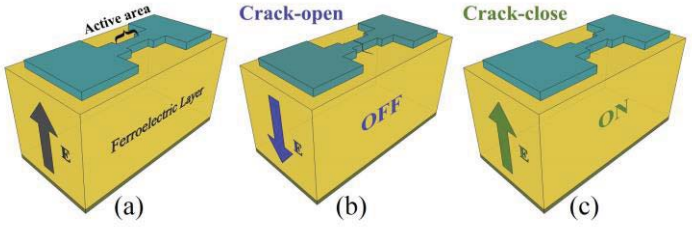

Figure 1. (a) Schematic of an electromechanical device based on a controlled reversible nano-crack. (b) The open state of the crack under a negative electric field, which is opposite to the direction of the poling electric field on the ferroelectric oxide. (c) The closed state of the crack under a positive electric field.

III. EXPERIMENTAL RESULTS

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A 40 nm $Mn_{50}Pt_{50}$ film was deposited on a (001)-oriented $0.7PbMg_{1/3}Nb_{2/3}O_3$-$0.3PbTiO_3$ (PMN-PT) substrate (5 × 5 × 0.5 mm^3) at room temperature by magnetron sputtering. The MnPt alloy thin film was chosen due to its moderate ductility. Silver paste was coated on the back of the PMN-PT substrate as the bottom electrode (Figure 2a). The bridge-like structure is patterned using the photolithograph followed by the etching process. Figure 2a also shows the schematic of the measurement setup. Keithley 2400 source meter was used to apply the constant 0.1 V voltage and measured current I_a. Keithley 2410 was used to apply the high control voltage V_c between the top and bottom electrodes.

Firstly, for generating the crack in the device, the triangular voltage waveform V_c (the interval is 10 V) with a gradually increasing $V_{c(max)}$ was applied, as shown in Figure 2b. In our device, when $V_{c(max)}$ reached 130 V, one crack was generated at the edge of the active area. Then the negative and positive voltages were applied to manipulate the crack opening and closing. It can be clearly seen from Figure 2c, when V_c varied from -100 to 0 V, the crack was open with a width of ~50 nm. While the crack was well closed after V_c sweeping from +100 to 0 V. Thereby, the voltage manipulation of crack state demonstrates a good nonvolatile control.

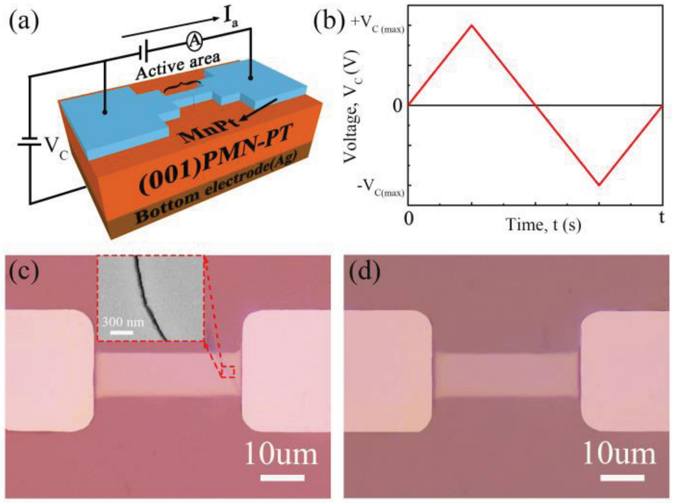

Figure 2. (a) Schematic of the bridge-like structure device and the measurement setup. (b) Electrical waveform for both generating and manipulating the cracks. The positive direction is defined from the bottom to the top electrode. Optical images of the active area with the crack (c) opening and (d) closing. The inset in (c) shows the local SEM images.

The electrical measurement results are shown in Figure 3a. I_a sharply decreased from ~ 3×10^4 to 1 nA upon applying the negative V_c with a magnitude of -50 V and I_a remained unchanged when V_c recovered back to 0 V (indicated by arrow 1 and 2 in Figure 3a). Symmetrically, the positive V_c with a magnitude of +70 V switched I_a from 1 nA to the saturated value rapidly and I_a also kept unchanged with U sweeping from +100 to 0V (represented by arrow 3 and 4 in Figure 3a).

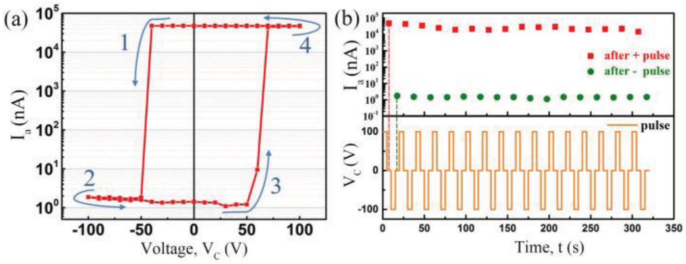

Figure 3. (a) The current I_a as a function of U, measured by applying a constant voltage of 0.1 V at room temperature. The voltage step and time interval of U were fixed at 10 V and 5 s, respectively. (b) Repeatability test for crack opening and closing via voltage pulses. The amplitude and duration of the pulse were 100 V and 5 s, respectively.

Moreover, the repeatability test has also been performed, as shown in Figure 3b. The alternating +100 V, 0 V and -100 V with a time interval of 5 s were applied and I_a was measured after the voltage was retreated. The positive voltage results in the high values of I_a (represented by red square) while the negative one induces the low values of I_a (indicated by green circle). Both the high and low values of I_a change little after a dozen times tests, illustrating a good repeatability of the non-volatile control.

In this crack-based device, the writing energy comprises two parts: one is for switching the polarization and the other one is for the additional surface energy. For such a ferroelectric-oxides-based device the polarization switching voltage can be estimated using $P_rSV/2$ [8] (P_r is the remnant polarization, S is the cell area and V is the switching voltage). For the PMN-PT film with a thickness of 2 μm, the switching voltage can be dramatically reduced to 1 kV/cm × 2 μm = 0.2 V. Considering a further scaled down crack-based cell with a size of 200 nm (length) × 100 nm (width) × 50 nm (thickness of the MnPt film plus crack depth in the PMN-PT film) and P_r = 30 μC/cm^2, the polarization switching energy per bit can be obtained as 15 μC/cm^2 ×200 nm × 100 nm × 0.2 V = 0.6 fJ. In addition, the surface energy can be calculated by γA [5] (γ is the surface energy density and A is the surface area) and is acquired as 2 × 1 J/m^2 (a typical approximation value [5]) × 100 nm ×50 nm =10 fJ. Then the total writing energy per bit is 10.6 fJ, which is much lower than the conventional MRAM and PCM.

IV. SIMULATION RESULTS

In addition, in our device, the crack position can also be precisely controlled, which is a key point for practical application. As demonstrated in the experimental results, in the bridge-like structure, the crack was generated at the edge of the active area. Considering that the crack formation was originated from the ferroelectric domain switching, which is determined by the applied electric field, we performed the simulation of the electric field distribution using COMSOL Multiphysics. As shown in Figure 4a, the E_Z (z component of the applied electric filed) distribution is not uniform in the whole structure. The highest values of E_Z (red zones in Figure

4a) are mainly distributed at the corners. Particularly, the distribution in the active area is enlarged in Figure 4b, in which the highest values of E_Z are distributed at the edges (dashed circle). Interestingly, the crack demonstrated in the experimental results shown in Figure 3c and 3d is located exactly in this zone.

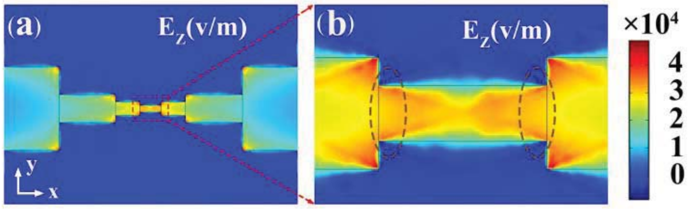

Figure 4. (a) The top-view E_Z distribution in the patterned device using COMSOL Multiphysics simulation. (b) The enlarged view for the active area.

V. CONCLUSION

In summary, a novel nanoelectromechanical device based on the controllable and reversible single nano-crack has been demonstrated. The control of the opening and closing of the crack in the device has been realized with good repeatability. As this kind of device exhibits nonvolatile ON and OFF states and the high (> 10^5) on/off current ratio with ultra-low power, it offers the possibility to develop new non-volatile memory or other functional electromechanical devices.

VI. ACKNOWLEDGMENT

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