Giant Electroresistance Switching of Two-dimensional Ferroelectric α-In_2Se_3 on p^+-Si

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ABSTRACT

Recently, the demonstration of the ferroelectricity of α phase In_2Se_3 (α-In_2Se_3) has opened new opportunities to develop two-dimensional small bandgap ferroelectric memories. Conventional ferroelectric hetero-junction memories have been widely studied but the performance is still limited by the large bandgap of oxide-based ferroelectric materials and limits the diode ON current and results in low ON/OFF ratio. Accordingly, we propose a novel resistive switching memory device based on the unique ferroelectric and semiconductor properties of α-In_2Se_3. By forming the hetero-junction of α-$In_2Se_3$with the highly degenerated p^+-Si substrate, we achieve a giant ferroelectric resistive ON/OFF ratio of 2.3×10^6.

INTRODUCTION

Among various types of non-volatile memories (NVM), ferroelectric memory is one of the most promising candidates for the next-generation memory technology due to its ultra-high density up to 0.5 Tbit/cm^2 [1] and ultra-low energy consumption below 400 fJ/bit [2]. α phase In_2Se_3 (α-In_2Se_3) is a two-dimensional (2D) low bandgap ferroelectric materials with small dielectric constant that have great potential on ferroelectric memory devices. This two-dimensional (2D) material was found to have ferroelectric properties at room temperature even at the monolayer limit and a small coercive field on nano-scale thickness [3, 4], which benefits further miniaturization and design of nano-scale electronic devices. The dangling bond-free surface of 2D materials offers attractive merits like defect-free atomically flat surface towards uniform polarization that enables unperturbed switching behavior [5]. Here, we propose a new 2D ferroresistive system of α-In_2Se_3/p^+-Si heterojunction that can achieve a giant ferroelectric resistive switching by modulating tunneling barrier. The p^+-Si substrate provides a chance for better integration with CMOS.

MATERIAL CHARACTERIZATION

The Raman spectrum of exfoliated α-In_2Se_3 is consistent with the previous Raman scattering characterization of α-In_2Se_3 [8] and a cross-sectional transmission electron microscopy (TEM) image of our exfoliated α-In_2Se_3 confirms the two-layer hexagonal (2H) structure (Fig. 2). To elucidate the ferroelectric properties of α-In_2Se_3, we analyze the hysteresis behaviors via piezo-response force microscopy (PFM). The phase hysteresis loop and magnitude butterfly curve observed in Fig. 3 clearly shows the ferroelectric switching behavior of the α-In_2Se_3 with coercive pole up and pole down voltages of approximately +4.7 and −6.3 V, respectively. To get further insight on the ferroelectricity-induced hysteresis loops and explore its associated ferroelectric switching memory effect, we measure the α-In_2Se_3 surface potential change at the virgin state (Fig. 4) and polarized states (Fig. 5) via scanning Kelvin probe microscopy (SKPM). Accordingly, we obtain a α-In_2Se_3 work function (WF) 0.1 eV lower than Au (5.1 eV), which means it is 5 eV at virgin state, and a ~70 meV WF difference between two polarized states is observed.

FERRORESISTIVE SWITCHING

The device structure is shown as Fig. 6. First, Au electrodes are sputtered on commercial highly degenerated p^+-Si substrate with a 50-nm SiO_2 passivation layer. Next, the SiO_2 is patterned by standard lithography process and then dry etched by RIE. As the last step, we dry transfer α-In_2Se_3 via PDMS film mechanical exfoliation to prevent degradation by heat and chemicals during fabrication. Fig. 7 shows the OM picture of our fabricated sample.

The Au/α-In_2Se_3/Au structure exhibits ohmic I-V behavior as shown in Fig. 8. Due to the ferroelectric behavior of α-In_2Se_3, an ON/OFF ratio of 40 is observed in the I-V hysteretic loops of Au/α-In_2Se_3/Au (Fig. 9). A much larger ON/OFF ratio of 10^6 is observed in the I-V hysteresis loops of Au/α-In_2Se_3/p+-Si (Fig. 10), which indicates obviously that the larger hysteresis comes from the α-In_2Se_3/p+-Si hetero-junction. The large ON current difference partly come from different flack size and contact area. Moreover, different ferroresistance behaviors of these two samples indicate different transport mechanisms. A 2000 second-retention test reveals a steady giant low resistance state (LRS) to high resistance state (HRS) resistance ratio of 10^5-10^6 measured at the reading voltage (V_{read}) of 0.1 V (Fig. 11). To further corroborate the I-V hysteresis characteristics and assess the device stability, we perform an endurance test of 150 sequential set and reset cycles (Fig. 12); each set (reset) cycle consists of sweeping the voltage from 0 V to +8 V (0 V to −8 V) and subsequently reads the current at V_{read} of 0.1 V. We observe that both HRS and LRS remain fairly stable during the whole endurance test with a memory window of 10^5.

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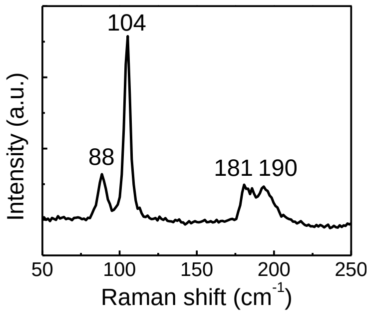

Fig. 1. Raman spectrum of exfoliated α-In_2Se_3 flake.

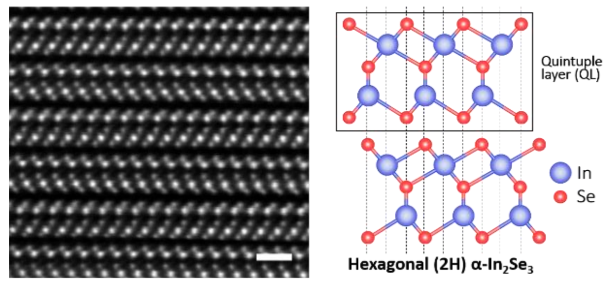

Fig. 2. Cross-sectional high resolution TEM image of the 2H α-In_2Se_3 layered atomic structure and the corresponding ball-stick models of two quintuple layers. Scale bar: 1 nm.

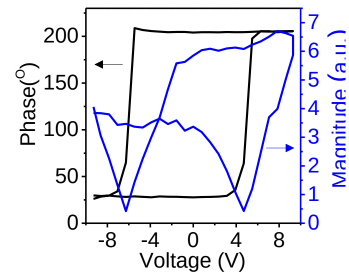

Fig. 3. PFM phase hysteretic loop and magnitude butterfly curve of the bare α-In_2Se_3 surface as a function of the applied bias.

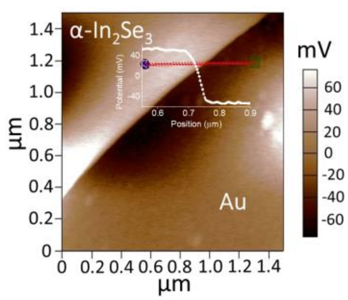

Fig. 4. SPKM surface potential profile at the α-In_2Se_3/Au interface. The inset indicates the potential profile along the red line, revealing a potential difference between the α-In_2Se_3 and Au of ~0.1 eV.

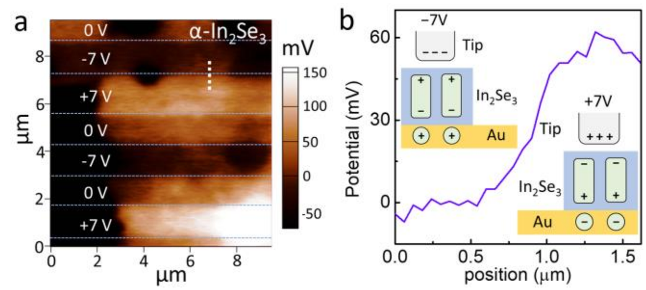

Fig. 5. (a) SPKM potential of unpolarized α-In_2Se_3 (0 V) and after polarization voltages of ±7 V. (b) The corresponding Potential-Position relation and illustration of the potential curve. A potential difference of ~70mV is observed between two polarized states.

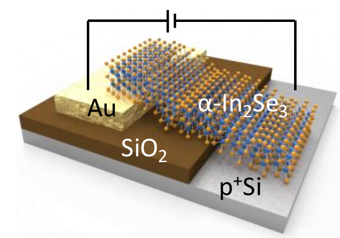

Fig. 6. Schematic of the α-In_2Se_3 /p^+-Si heterojunction.

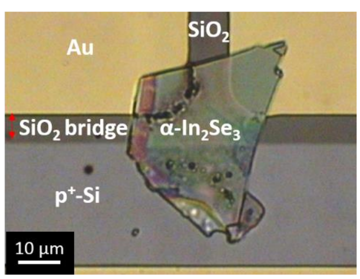

Fig. 7. Optical image of the α-In_2Se_3 /p^+Si heterojunction.

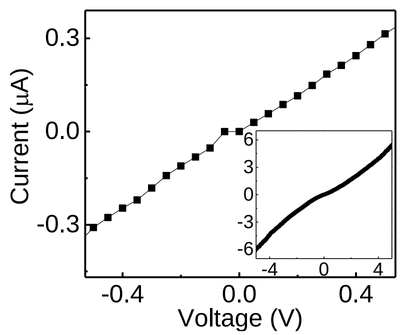

Fig. 8. I-V curve of the Au/α-In_2Se_3/Au structure. It shows a linear behavior in the range of ±0.5 V. The inset shows the I-V relation in the range of ±5 V.

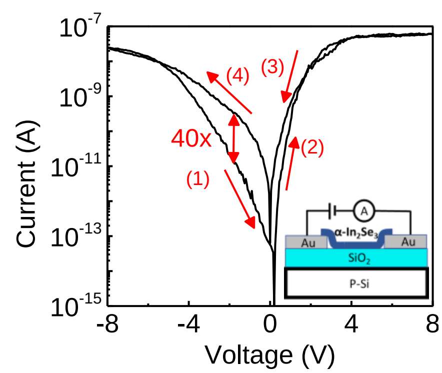

Fig. 9. The hysteresis behavior of the Au/α-In_2Se_3/Au shows an ON/OFF ratio of 40. The arrows indicate the sweeping direction as well as the pole up (set) and pole down (reset) bias voltage.

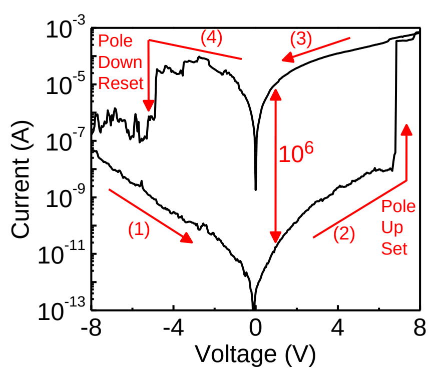

Fig. 10. The hysteresis behavior of the Au/α-In_2Se_3/p^+-Si shows a 10^6 ON/OFF ratio which is significantly larger than that of Au/α-In_2Se_3/Au.

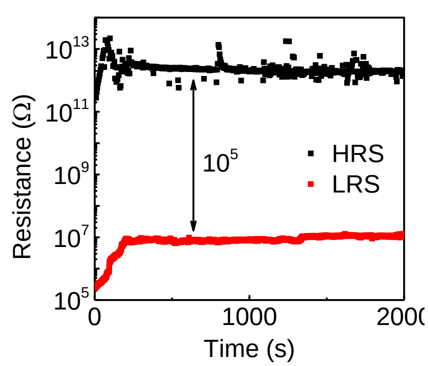

Fig. 11. Retention test of Au/α-In_2Se_3/p^+-Si shows a stable LRS to HRS resistance ratio of five orders magnitude at V_{read} = 0.1 V.

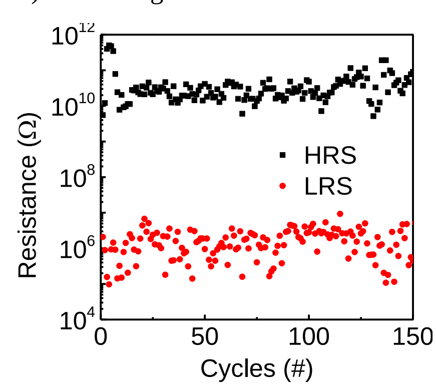

Fig. 12. Endurance test of Au/α-In_2Se_3/p^+-Si. Two memory states maintain a ~10^4 resistance ratio during 150 cycles.