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Training effect in the hysteretic I–V curve

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ABSTRACT

We observe the training effect in the hysteresis of current–voltage (I–V) curve for an Au/NiO/Au nanostructure. Training effect is described as a systematic change in current at a particular voltage when the applied voltage is successively cycled. We clearly demonstrate that training effect could be analyzed by a phenomenological relaxation model, suggesting that relaxation of the trapped charge carriers coupled to Au/NiO interface gives rise to the training effect where relaxation process is strongly influenced by the excitation of applied voltage.

1. Introduction

The reproducibility of the hysteresis in current–voltage (I–V) characteristics typically gives rise to the memory effect which is fascinating for the technological applications. One of the best promising applications of memory effect is the resistive random access memory (RRAM) in the two terminal device [1–3]. The origin of hysteresis in the I–V curves have been investigated in varieties of materials such as semiconducting oxides [4–9], superconducting oxides [10], phosphides [11], organics [12–14]. Different models such as filamentary effect [6–9], charge-trap model [1,2,15], insulator-metal transition [5,16], diffusion of oxygen vacancies [4,17], Schottky effect [18,19], multiparticle tunneling in the superconductors [10], have been proposed for interpreting the origin of the hysteresis in I–V curves.

In this Letter, we report an interesting scenario of training effect in the hysteresis of the I–V characteristics in an Au/NiO/Au nanostructure. Training effect is described here as a systematic change of current at a fixed voltage in the highly reproducible I–V characteristics when applied voltage is successively cycled. Training effect has been observed in magnetic hysteresis loops [20,21] which is not realized before in the hysteresis of I–V curves. We clearly demonstrate that training effect in different sorts of measurements of I–V curves could be analyzed satisfactorily by a phenomenological relaxation model [22] which has been developed with the help of discretized Landau–Khalatnikov equation for interpreting training effect. The results suggest that the trapped charge carriers coupled to Au/NiO interface lead to the observed effect where relaxation of the trapped charge carriers is strongly influenced by the excitation of applied voltage.

2. Experimental

NiO film was deposited on a cleaned Si (100) single crystal by the sol–gel dip-coating technique [23] where substrate was dipped several times in a solution composed of Ni^{2+} source. Nickel nitrate was added and homogenized with dehydrated alcohol. Polyethylene glycol (molecular weight, 20 000) was then added to the solution in the ratio of 70 mg polyethylene glycol with 1 ml 0.06 M active solution. Homogeneous solution was filtered and finally it was used for the chemical deposition. After each layer deposition the prepared substrate was dried at 100 °C for 20 min followed by a 20 min annealing at 500 °C in air. The layer deposition and subsequent heat treatments were done for the successive 25 times.

Powder x-ray diffraction pattern of the film was recorded in a Seifert XRD 3000P diffractometer using CuK_α radiation. The surface topology of NiO film was probed by the atomic force microscopy (AFM) using a microscope, Veeco-diCP II. Nearly ∼100 nm thick Au electrodes was deposited on the NiO surface using an ion coater (Eiko Engineering, Japan) where electrical contacts were further viewed by field-emission SEM microscopy (JEOL, JSM-6700F). All the electrical measurements were carried out in ambient air without any device encapsulation using a source meter (Keithley, 2400) coupled with a computer by the GPIB network.

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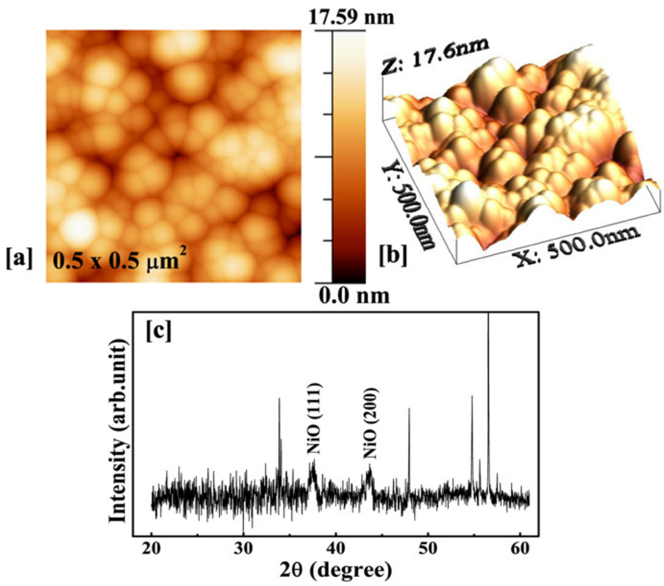

Fig. 1. (a) Two and (b) three dimensional AFM images of NiO film. (c) Powder x-ray diffraction pattern of NiO film on Si (100) substrate at room temperature.

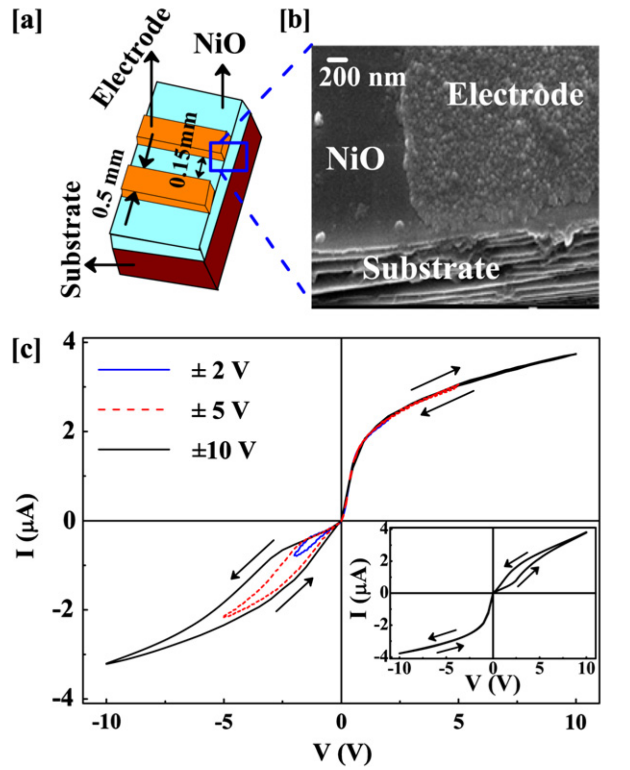

Fig. 2. (a) A schematic configuration of the two-terminal device. (b) SEM image of the NiO film highlighting NiO, Au electrode, and Si (100) substrate. (c) I–V curves measured in between ±10.0 V, ±5.0 V, and ±2.0 V. Inset exhibits I–V curve in between ±10.0 V when measurement was performed by interchanging the electrical terminals at the Au contacts.

3. Results and discussions

Powder x-ray diffraction pattern of the film at room temperature is shown in Fig. 1(c). Broadened peaks corresponding to polycrystalline NiO are observed along with the sharp peaks of Si substrate. Two and three dimensional images are shown in Figs. 1(a) and 1(b), respectively. Fig. 1(a) exhibits compactness and grain size of the NiO particles having ∼20 nm average diameter whereas Fig. 1(b) reveals the surface roughness (root mean square roughness ∼2.0 nm) and thickness (∼170 nm) of the film. We note that average size of Au particle is ∼40 nm which is almost doubled of the average size of NiO particles. The convincingly larger size of the Au particle confirms that Au particles do not enter into the NiO film. The details of the geometry of deposited Au electrode and electrical connection are demonstrated in Figs. 2(a) and 2(b) where the image in Fig. 2(b) was taken by Scanning Electron Microscopy (SEM). Note that the distance between two Au electrodes is 0.15 mm which is considerably large for observing typical resistive switching mechanism.

The I–V curves measured within ±2.0 V, ±5.0 V, and ±10.0 V at room temperature are shown in Fig. 2(c). The curves are highly reproducible having contrast features depending on the polarity of the applied voltage. For positive voltage the curves coincide exactly in the increasing and decreasing cycles while minor hysteresis loops are observed in the negative polarity. As seen in the inset of figure the feature in I–V curve is altered having hysteresis in the positive polarity when measurement was performed by interchanging the electrical terminals at the Au contacts. We further note that the behavior was reproducible when measurements were repeated by interchanging the terminals several times. The results in Fig. 2(c) clearly demonstrate that transport mechanism at one of the Au/NiO interfaces leads to the hysteresis in the I–V curve. It is important to point out that the ratio between high and low conducting states in the observed I–V curve is very low compared to the typical manifestation of resistive switching having ratio >10 for NiO film [6–9,24]. The resistive switching mechanism in NiO is usually explained by formation and rapture of nanoscale filamentary path due to the local Joule heating. Thus hysteresis in the present observation is not a typical manifestation of resistive switching. Nevertheless, the reproducibility of hysteresis in the I–V curve is significant which typically causes the memory effect in two-terminal devices. In order to investigate the memory effect a particular sequence of voltage pulses such as write–read–erase–read (W–R–E–R) having 10 s pulse duration was applied which is shown in Fig. 3(a). The corresponding measured current pulses are shown in Fig. 3(b). Here, +2.5 V was applied to write '1' or high conducting state where '1' state was read by a low voltage at −1.0 V. The high conducting state was then erased by a −2.5 V to achieve the '0' or low conducting state which was detected or read by an another −1.0 V pulse to complete a pulse sequence. The observed current pulses for the applied R voltage pulses are further highlighted in Fig. 3(c). We note that the values of current after each W and E voltage pulses are distinctly different, although the same read voltage pulse (−1.0 V) was applied. The results demonstrate the memory effect. The excellent memory effect was further checked with the similar pulse sequence having different pulse duration such as 1 s. We further note that measured current in the positive voltage (during W pulse) almost follows the voltage pulse whereas a signature of relaxing entities is noticed [indicated by the broken curves in Fig. 3(c)] in the measured current pulses with time at the applied negative R voltage pulses. The systematic increase in the absolute value of current ($|I|$) is carefully noticed where changes of current with time at the end of each R voltage pulses are indicated by the broken curves in Fig. 3(c). The absolute values of the current measured at the end of first R pulse indicated by the upper broken curve are plotted with number of cycles (λ) in Fig. 3(d) represented by the open symbols which exhibit the sharp increase of $|I|$ between first and second cycles (each cycle consists of W–R–E–R pulse sequence) followed by the monotonous increase of $|I|$ with the increase of λ. The increase of $|I|$ with increasing λ is described here as a training effect.

In order to interpret training effect Binek [22] recently proposed a phenomenological model with the help of a discretized Landau–