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The improved resistive switching properties of TaO_x-based RRAM devices by using WN_x as bottom electrode

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ABSTRACT

The WN_x films were successfully prepared on silicon-based substrates as bottom electrodes for the resistive random access memory (RRAM) cells in Pt (top)/TaO_x/WN_x (bottom) sandwich structure. The reproducible resistive switching (RS) characteristics of these cells were studied systematically for RRAM applications. The advantages of adopting WN_x instead of Pt as bottom electrode material were demonstrated, such as the improvement of the low resistive state value, the RS endurance and the uniformity of RS parameters. The X-ray photoelectron spectroscopy revealed that both the oxygen vacancies in the TaO_x film and the interfacial tungsten oxynitride (WON) layer formed between the dielectric TaO_x film and the WN_x bottom electrode play key roles in the RS performance improvement.

1. Introduction

Recently, resistive random access memory (RRAM) is considered as a promising candidate for NAND FLASH replacement due to its excellent scalability potential, ultra-faster operation, and low power consumption [1]. Typical RRAM cells often consist of at least one metal oxide layer such as transition metal oxide (TMO) or perovskite oxide, sandwiched between two metal electrodes as resistive switching (RS) functional layer. Generally, the cell requires an electroforming process to generate oxygen vacancy-conductive filaments through the oxide matrix, after which the cell may reversibly change its resistance between at least two stable states, enabling the data bits to be stored as resistance, in contrast to charges in flash memory devices. However, there are several problems to be solved before the commercialization of the RRAM devices. One of the representative obstacles is the electrical endurance characteristics which means how many times the RRAM cell can be switched [2]. The second problem includes the non-uniformity of RS parameters such as the on-/off-state resistance values and SET/RESET switching voltages [3]. The non-uniformity leads to false programming and gives rise to read-out hazards. Other obstacles include the relatively low resistance of the cell in low resistive state (LRS) and the large RESET (the process from LRS to HRS, high resistive state) current which becomes a barrier to the incorporation of RRAM in the highly integrated complementary metal-oxide semiconductor (CMOS) circuits. Furthermore, a higher RESET current generally leads to lower endurance [4].

The RS behaviors in oxide-based RRAM cell are often resulted from a migration of oxygen ions or oxygen vacancies in the functional oxide layer under an external electric voltage or pulse stress [5]. The RS process are generally accompanied with the (electric field driven) imbalanced migration of oxygen ions (or vacancies) in metal oxides, which often induces the loss of oxygen after repeated switching, caused a switching endurance problem. The non-uniformity in the RS parameters is often caused by ruptures of varying sizes at random locations along the conducting filaments [3]. Recent research results indicate that the aforementioned problems can be resolved effectively by adopting following two metal nitride: TiN or TaN as one of the two electrodes in RRAM cells because of the easy formation of a thin interfacial metal oxynitride (MON) layer: TiON [6] or TaON [7]. The formed MON can prevent the oxygen ions from running away as a diffusion barrier in the RS process, thus switching endurance improvement can be achieved. Meanwhile, the MON interface also improved the LRS value which may also benefit the improvement of endurance performance and help to decrease the RESET current. At last, by the insertion of the interfacial MON layer, the RS behaviors can be easily confined locally near this layer, thus the uniformity of RS parameters can be also improved. These good research results raise motivation to investigate other CMOS-process-friendly conductive metal nitrides, especially the refractory transition metal nitrides [8–10],

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such as WN_x [9,11], HfN_x [12], MoN [13], VN_x [8,14], ZrN_x [15], and CrN [16] as electrode materials or buffer layer for RRAM cells. The improvement of RS performance may be also achieved considering the easy formation of an ultrathin corresponding MON interface layer between these metal nitrides and the functional oxide layer due to the oxygen gettering nature of above nitrides due to their higher electronegativity of oxygen in comparison to that of nitrogen [17–20].

The WN_x are often used as high temperature conducting materials because of its thermal stability [8] and has been investigated for metal nitride gate electrode applications in CMOS systems [11]. Also, it has been demonstrated to be a good candidate for the diffusion barrier in the copper metallization [21]. Furthermore, the crystal structure, work function, resistivity etc. of WN_x can be tuned by changing the processing parameters for WN_x films fabrication [9,11] which will benefit the RS performance improvement of RRAM devices. In this study, the WN_x films have been successfully prepared on silicon-based substrates as bottom electrode for the RRAM cells in Pt (top)/TaO_x/WN_x (bottom) sandwich structure and the advantages of adopting the WN_x as bottom electrode have been evaluated.

2. Experiment

2.1. Device fabrication

First, 100-nm-thick WN_x bottom electrode was prepared on a commercial SiO_2 (300 nm)/Si substrate by DC reactive sputtering of W target in $Ar+N_2$ mixed gas ambient ($Ar:N_2$ flow rate ratio=97:3) at a sputtering power of 50 W. The base pressure of the sputtering chamber was below 1×10^{-4} Pa, which was evacuated by a turbo molecular pump. Then, 20-nm-TaO_x films were grown on as prepared $WN_x/SiO_2/Si$ substrates by a radio-frequency (RF) magnetron sputter using a TaO_2 (purity 99.9%) ceramic target in $Ar+O_2$ mixture ($Ar:O_2$ flow rate ratio=80:20). During sputtering, the substrate temperature was kept at 200 °C and the working pressure was maintained at 0.6 Pa. Finally, in order to achieve metal–insulator–metal structure, Pt top electrode with 150 nm in thickness with various areas was deposited by a DC sputter.

2.2. Physical characterization

The surface morphology was observed by FESEM. The surfaces of TaO_x and WN_x films are smooth, dense and without pores. The X-ray photoelectron spectroscopy (XPS) was employed to study the composition and chemical bonding states of the TaO_x/WN_x stacked films. The transmission electron microscopy (TEM) was used to investigate the microstructure of the prepared Pt/TaO_x/WN_x stacked films. Agilent 81150A was adopted to generate voltage pulses and Keithley 2400 sourcemeter was used to record the current–voltage (I–V) data. For transient measurement, after applying a voltage pulse on the sample, Keithley 2400 sourcemeter was switched by an Agilent 34970 switch mainframe to characterize the I–V properties. All the electrical pulse and the bias voltage were applied to the top electrode Pt while the bottom electrode WN_x was grounded.

3. Results and discussion

3.1. XPS characterization results of TaO_x/WN_x stack

For understanding the composition and chemical bonding states along the depth of the TaO_x/WN_x stacked film, which may be the critical factors for devices to show good RS behaviors and give clues to probe the underlying RS mechanisms, XPS analysis was performed and the results are presented in Fig.1(a)–(d). Fig.1(a) shows the XPS binding energy depth profile of Ta 4f and W 4f core level in the TaO_x/WN_x stacked films. We can observe that a very thin layer of nearly stoichiometric Ta_2O_5 formed at the

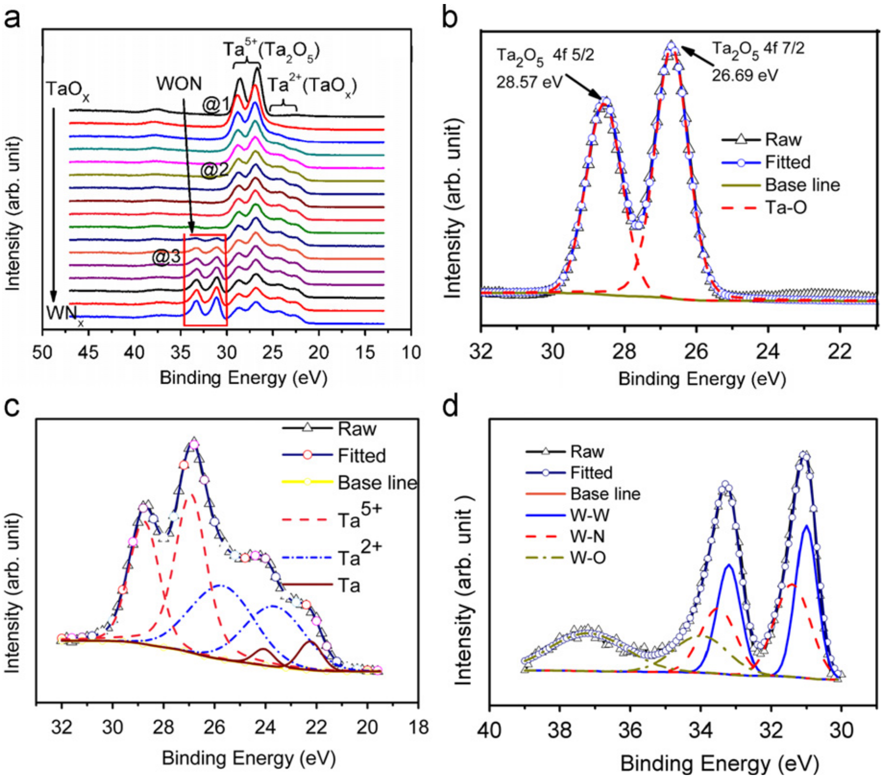

Fig. 1. (a) The XPS depth profile of Ta 4f and W 4f in the TaO_x/WN_x stacked film. [(b), (c) and (d)] The enlarged and deconvoluted core level spectra for the regions labeled @1, @2 and @n in (a), respectively.