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Resistive switching characteristics of sputtered AlN thin films

Zong-Liang Tseng [b,*], Lung-Chien Chen [b], Wan-Ying Li [a], Sheng-Yuan Chu [a,c,**]

[a] Department of Electrical Engineering, National Cheng Kung University, Tainan 70101, Taiwan, ROC
[b] Department of Electro-Optical Engineering, National Taipei University of Technology, Taipei 106, Taiwan, ROC
[c] Center for Micro/NanoScience and Technology, National Cheng Kung University, Tainan 70101, Taiwan, ROC

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ABSTRACT

AlN thin films were deposited on Pt/Ti/SiO_2/Si substrates using a radio-frequency magnetron sputtering technique. The effect on the switch current–voltage characteristics of four different materials in the electrode fabricated on top of the AlN film was investigated. The deposition time and nitrogen content in the sputtering atmosphere were changed to adjust the thickness and composition of the AlN thin films, respectively. The influence of film thickness and content on the resistive switching behavior was discussed. The possible mechanism of resistive switching was examined via analyses of the electrical resistive switching characteristics, forming voltage, and on/off current ratio.

1. Introduction

A material that exhibits resistive bistable behavior can be in one of two stable states and switched controllably from one state to the other, i.e., so-called resistive switching. Memory based on resistive switching, called resistive random access memory (RRAM), can be used for non-volatile storage at low operation voltages, with high endurance and speed and a simple structure. Resistive bistable materials can be classified into three types, namely, perovskite-type oxides (e.g., $PrCaMnO_3$) [1,2], binary metal oxides (e.g., MO) [3], and organic materials [4,5].

Recently, resistive bistable metal nitride thin films, such as aluminum nitride (AlN) [6–10] and Si_3N_4 [11–13], have been reported. Metal nitride thin films have many advantages, such as high hardness, thermal conductance, erosion and wear resistance, and dielectric constants (under appropriate fabrication conditions). In addition, according to several previous works, AlN thin films have a large energy gap (approximately 6.2 eV), a high refractive index (1.9–2.1 for polycrystalline films), high chemical and thermal stability, and high electrical resistivity ($\sim 10^{14}\ \Omega$ cm) [14]. The capacitance–voltage (*C*–*V*) characteristics of AlN are similar to those of pure SiO_2. The dielectric constant of AlN is 12.4 [15]. As a result, AlN films have good functional performance and industrial potential for RRAM. Alternatively, highly crystalline sputtered AlN films are obtained by heating the substrate (250–500 °C) [16]. When no substrate heating is used during the sputtering process, the AlN films exhibit an amorphous state. Most reports of AlN-based RRAMs use crystalline AlN film as the resistive bistable layer. However, to the best of our knowledge, few reports have discussed the resistive switching behaviors of low-crystalline or amorphous AlN films deposited at low temperatures.

In this paper, AlN thin films were deposited on Pt/Ti/SiO_2/Si substrates using radio-frequency (RF) magnetron sputtering. In particular, substrate heating was not used during the low-temperature process. The top electrode type, film thickness, and composition of AlN were varied to evaluate their effect on resistive switching characteristics. The filament hypothesis was used to explain the possible conduction mechanism of this AlN-based memory device.

2. Experimental procedure

AlN thin films were grown on Pt/Ti/SiO_2/Si substrates using an RF magnetron sputtering system (Kao Duen tech., Taiwan) from a 2-in. (5.08 cm) Al metal target at room temperature. The sputtering conditions of the AlN films were as follows: a constant argon flow rate of 9 sccm, RF power of 80 W, and a working pressure of 5 mTorr. Detailed conditions of the sputtering process are listed in Table S1. The deposition rates of the AlN films under different working gases were determined using scanning electron microscopy (SEM, Hitachi S4800), and the thicknesses of the AlN films were determined according to the deposition time (Fig. S1). Current–voltage (*I*–*V*) measurements were conducted using a parameter analyzer (Agilent 4155C) to confirm resistive switching. The

* Corresponding author.
** Corresponding author.
E-mail addresses: tw78787788@yahoo.com.tw (Z.-L. Tseng), chusy@mail.ncku.edu.tw (S.-Y. Chu).

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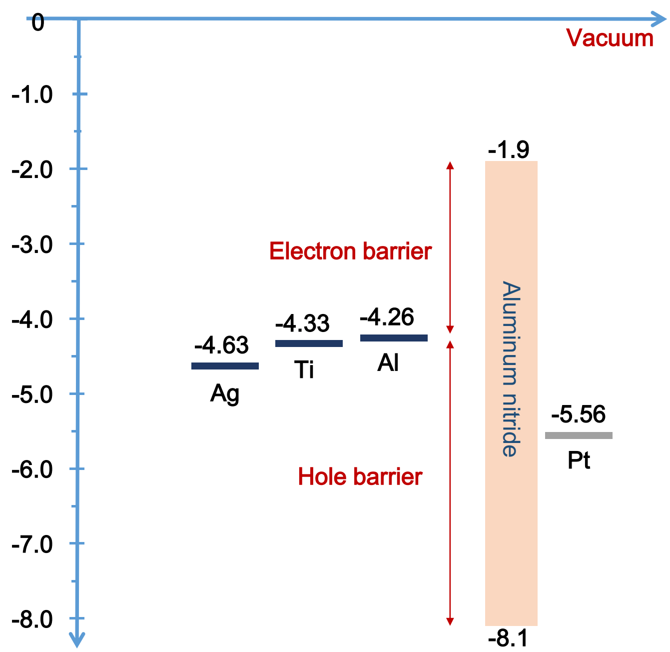

Fig. 1. Energy band diagram of metal/AlN/Pt memory cells.

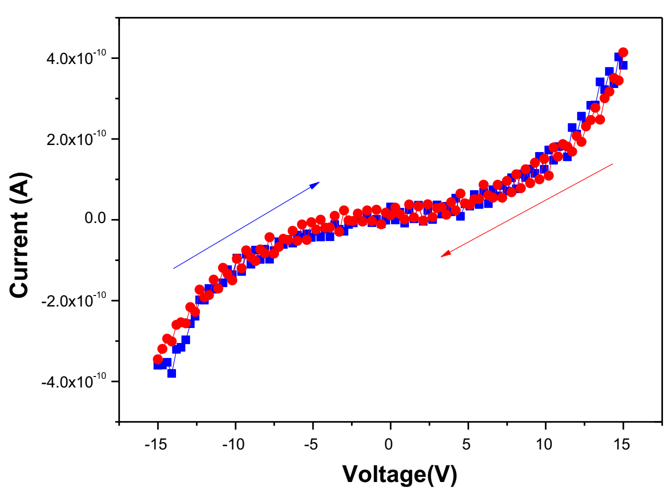

Fig. 2. *I–V* curve of Pt/AlN/Pt memory cells.

scan area of the atomic force microscope (AFM, NTMDT P47H) images was 1.5×1.5 µm. An X-ray photoelectron spectroscope (XPS, PHI 5000 VersaProbe) was used to perform elemental analysis. The structural properties of the AlN films were analyzed using grazing incidence angle X-ray diffraction (GIAXRD, Rigaku D/MAX2500) with CuKα radiation, $\lambda = 1.5418$ Å, 35 kV, and 30 mA. The electrode area was 0.785 mm^2 (a circle with a diameter of 1 mm), as deposited by a shadow mask consisting of thin steel (0.05 mm).

3. Results and discussion

To examine the effect of top electrode type on resistive switching, the sputtering gas ratio ($N_2/(Ar+N_2)$) was fixed at 40% to deposit an AlN film with a 100-nm thickness on the Pt/Ti/SiO_2/Si(100) substrate. The electron affinity and band gap of AlN are 1.9 and 6.2 eV, respectively. The work function of Pt is 5.56 eV. The barrier height is 3.66 eV (2.54 eV) as electrons (holes) are injected from Pt to the conduction (valence) band of AlN. The energy band diagram of metal/AlN/Pt is shown in Fig. 1.

A Pt/AlN/Pt device with symmetrical electrodes was fabricated to verify the function of the bottom Pt electrode. The *I–V* characteristics are shown in Fig. 2. No resistive switching was observed, and the currents were all lower than 1 pA. This indicates that the efficiency was poor, regardless of whether holes or electrons were injected from Pt. Therefore, the selection of the top electrode is important. Three different electrodes (Al, Ti, and Ag) were deposited to compare their effects on carrier injection from the top electrode to clarify the possible switching mechanism.

Regarding carrier type, holes could be blocked by the barrier height (2.54 eV) between Pt and the valence band of AlN. Because Pt has a high work function, it is difficult to select a metal top electrode with a work function higher than that of Pt. The work functions of Al, Ti, and Ag are 4.26, 4.33, and 4.63 eV, respectively, which are all lower than that of Pt. The barrier between the valence band of AlN and the work functions of the three metals are high, leading to hard injection of holes from the three metals. Therefore, for (Al, Ti, Ag)/AlN/Pt memory cells, electrons are the dominant carriers.

Fig. 3 shows the typical *I–V* characteristics of the (Al, Ti, Ag)/AlN/Pt memory cells with a current compliance of 100 mA. The applied voltage was gradually increased along the negative *x*-axis (black line). The current significantly increased at approximately -3 to -8 V, and the devices were changed to the low resistive state (LRS). This process is called the formation process, and the voltage at this moment is called the formation voltage. After the

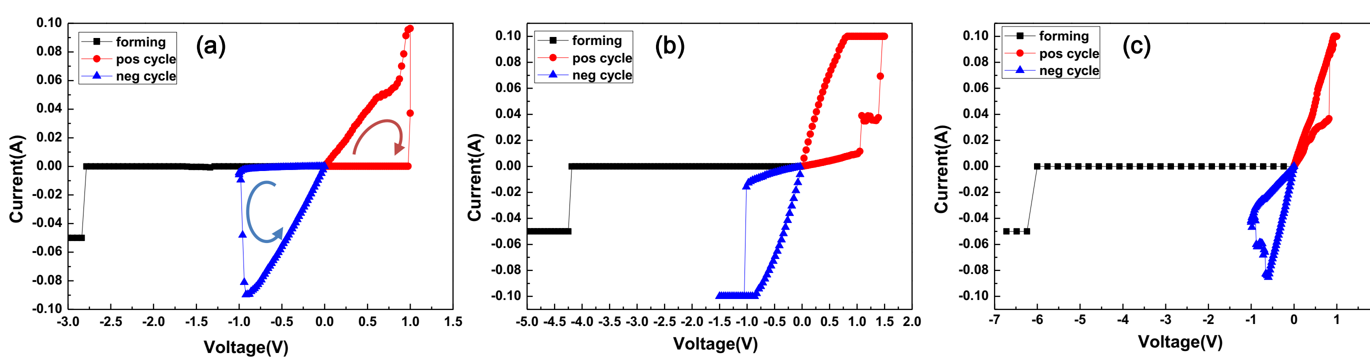

Fig. 3. Typical *I–V* curves of (a) Al/AlN/Pt, (b) Ti/AlN/Pt, and (c) Ag/AlN/Pt memory cells. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)