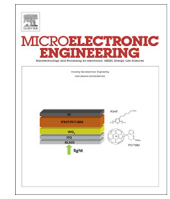
Microelectronic Engineering xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

Microelectronic Engineering

journal homepage: www.elsevier.com/locate/mee



The band-gap energy dependence of metal oxides on non-linear characteristics in the HfO_2-based resistive random access memory

Sangheon Lee, Daeseok Lee, Jiyong Woo, Euijun Cha, Jaesung Park, Kibong Moon, Jeonghwan Song, Hyunsang Hwang *

Dept. of Materials Science and Engineering, POSTECH, Cheongamro 77, Namgu, Pohang 790-784, Republic of Korea

A R T I C L E I N F O

Article history:
Received 22 March 2015
Received in revised form 23 April 2015
Accepted 24 April 2015
Available online xxxx

Keywords:
Non-linearity
ReRAM
Band-gap energy

A B S T R A C T

In this paper, the influence of the band-gap energy of metal oxide layers on the non-linearity of the device had been investigated. The band-gap energy of the metal oxide layer determines barrier height of tunneling between metal oxides and electrodes for tunneling mechanisms. The optimum barrier height between the metal oxides and electrodes exhibits high non-linear characteristics of the device for low leakage current of the cross-point array applications with excellent switching uniformity.

1. Introduction

The resistive random access memory (ReRAM) has been intensively investigated to overcome the limitations of conventional electronic charge-based memories. It has advantages of two-terminal structure and low power operation [1–3]. Particularly, filamentary-type ReRAM has been considered as the most promising non-volatile memory applications. Furthermore, its cross-point array ($4F^2$) is proposed for high-density integration.

However, in the filamentary-type ReRAM, it suffers from high leakage current (I_{LKG}) of low-resistance state (LRS) and variability of resistive switching due to metallic characteristics and random formation [7–10]. The I_{LKG} occurs high-resistance state (HRS) sensing failure when sum of I_{LKG} and I_{HRS} is larger than I_{LRS}. In the case of HRS reading, unselected LRS cells generate I_{LKG} and it is included to I_{HRS}. Thus I_{LKG} and switching variability incur reading failure during reading operation of cross-point array. To overcome an I_{LKG} problem, various selection devices were investigated to reduce current at off-region with structural and compositional complexity [4,5]. In addition, various structures have been reported to mitigate the resistive switching variability of ReRAM [7–10]. Even though various ReRAM structures have been studied, non-linearity and switching uniformity should be more improved. Thus, the non-linear ReRAM has been investigated for low I_{LKG} and switching reliability [6,13–22]. However, the non-linearity controllable factor has not been discovered. The understanding of the non-linearity is important for its optimization.

In this research, the influence of the band-gap energy of metal oxide layers on non-linearity and switching uniformity has been investigated. We evaluated Al_2O_3, Ta_2O_5, and TiO_2 for the non-linearity and uniform switching of the ReRAM. These metal oxide layers were inserted between the switching layer and the bottom electrode (BE) to act as a tunnel barrier and filament growth control. The optimum metal oxide layer effectively exhibit non-linearity owing to its direct and Fowler–Nordheim tunneling [16]. Therefore, careful selection of oxide materials is very important in ReRAM for low I_{LKG} and reliable resistive switching.

2. Experimental

To investigate the effects of the metal oxide layer on the non-linearity, the metal oxide layers were inserted to Pt (top electrode; TE)/Ti/HfO_2/Pt (BE) devices (Ti-top sample). All devices were fabricated in 250-nm via-hole structure. To isolate devices, a 100 nm thickness SiO_2 sidewall layer was deposited on a Pt/Ti/SiO_2/Si substrate by plasma-enhanced chemical vapor deposition. Subsequently, a 250 nm via-hole was defined by a conventional KrF lithography process, and followed by reactive ion etching system as shown in Fig. 1a. To form the barriers of metal oxide layers, we used metal Al, Ta, and Ti targets using RF reactive sputtering in 0.7 and 30 sccm of O_2 and Ar gas for 120 s in room temperature. The HfO_2 switching layer of 4 nm thick was deposited using an atomic layer deposition system, using TEMAH as a precursor and

* Corresponding author. Tel.: +82 54 279 5123; fax: +82 54 279 5122.
E-mail address: hwanghs@postech.ac.kr (H. Hwang).

http://dx.doi.org/10.1016/j.mee.2015.04.120
0167-9317/© 2015 Published by Elsevier B.V.

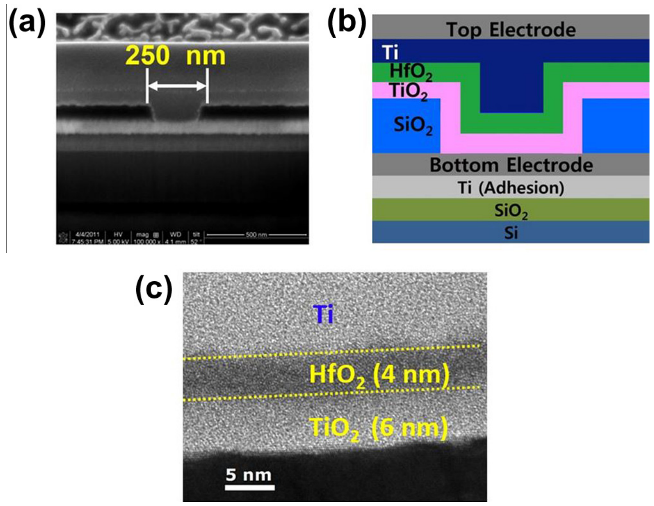


Fig. 1. (a) The cross-sectional SEM image of the 250-nm via-hole structure. All deposited thin film layers were formed in the via-hole. (b) Deposition information of the device structure in via-hole. (c) The cross-sectional TEM image of the Pt/Ti/HfO_2/TiO_2/Pt.

H_2O as an oxidizer at 250 °C. To form the oxygen reservoir layer, the reactive metal Ti was deposited using RF sputtering system. It controls oxygen ion absorption from the HfO_2 switching layer. Finally, the Pt capping layer was deposited with 300 μm. The device in via-hole is described in Fig. 1b and the TEM image was analyzed in Fig. 1c.

3. Results and discussion

Fig. 2 shows LRS current–voltage (*I–V*) characteristics of the devices, which were Al_2O_3, Ta_2O_5, and TiO_2 layers inserted. Once filament is formed in the switching layer, its LRS current is determined by internal or external resistors.

In general, electric field is transferred to the higher resistance state between two serially connected resistors. Therefore, this internal barrier layer determines *I–V* characteristics of the ReRAM [23,24]. Thus the inserted metal oxide layers which can acts as a barrier layer determines *I–V* characteristics in the LRS operations. As shown in Fig. 2, the three different metal oxide layers exhibited totally different non-linear characteristics. The non-linearity is defined in the Eq. (1). It is current ratio between on-and off-states of the device.

$$\text{Non-linearity} = (\mathrm{I}@V_{\mathrm{Read}})/\left(I@\frac{1}{2}V_{\mathrm{Read}}\right) \quad (1)$$

The highest band-gap energy of the Al_2O_3 layer has almost ohmic like behavior. Then, the non-linearity value is increased with lower band-gap energy. Compared to the Al_2O_3 (8.8 eV) layer, the TiO_2 (3.5 eV) layer has much higher non-linearity for the low I_{LKG} at the low voltage level.

The Fig. 3 describes the band-gap diagram of the three metal oxide layers with the Pt electrode [25]. As shown in Fig. 3, the barrier height between the Pt electrode and metal oxide layers are determined by the band-gap energy of the metal oxide layers. The Al_2O_3 layer has the highest barrier height, and the barrier height value is decreased with lower band-gap energy. This barrier height is an important parameter of the non-linear characteristics of LRS in the ReRAM. If the barrier height is too high, the electric field is strongly focused on the barrier layer, and resulted in hard-breakdown of the oxide layer. Then, the permanent conductive path is formed due to oxygen vacancies (V_o) generation in the oxide layer as shown in Fig. 4a. This schematic is based on the LRS *I–V* characteristics of Fig. 2. The lower V_o defect density can exhibits higher non-linearity with the suppressed off-current of low voltage level. The on-current level is almost same, however, the off-current is totally different from the barrier layers. The Al_2O_3 inserted device has ohmic LRS characteristics due to the additional filament formation of the Al_2O_3 layer. The high electric field generates a lot of V_os in the barrier layer and it can be filament during the set operation of the ReRAM. In the case of the Ta_2O_5 inserted device, it has relatively higher non-linearity than that of the Al_2O_3. This is attributed to the relatively lower barrier height value of the Ta_2O_5 layer and the Pt electrode. It can focus lower electric field than the Al_2O_3 layer, and generate very few V_os in the Ta_2O_5 layer. However, its non-linearity is still insufficient to reduce I_{LKG} of the LRS *I–V* characteristics. To maximize the non-linearity of the ReRAM, we additionally assessed the TiO_2 layer.

As shown in Fig. 2, it has the highest non-linearity with the lowest 1.45 eV barrier height. Its optimum value exhibited sufficient non-linearity. In non-linear characteristics, both the sufficient on-current and suppressed off-current are important. To reduce the off-current level, the direct tunneling dominates at low-voltage level while the Fowler–Nordheim tunneling is dominant at the high-voltage level.

Thus we could obtain highly non-linear characteristics of the ReRAM in both positive and negative polarities as shown in

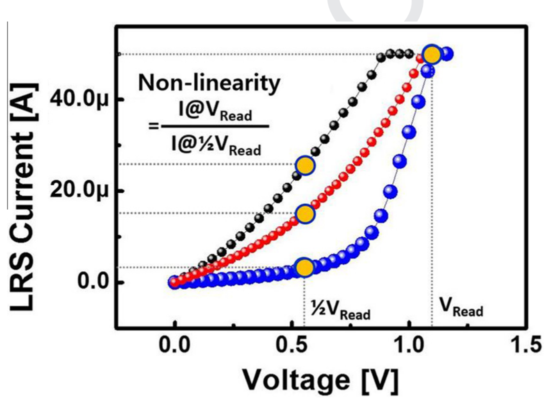


Fig. 2. DC *I–V* characteristics of the LRS of the Al_2O_3 (black), Ta_2O_5 (red), and TiO_2 (blue) inserted devices. All barrier layers were located between the BE and the switching layer. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

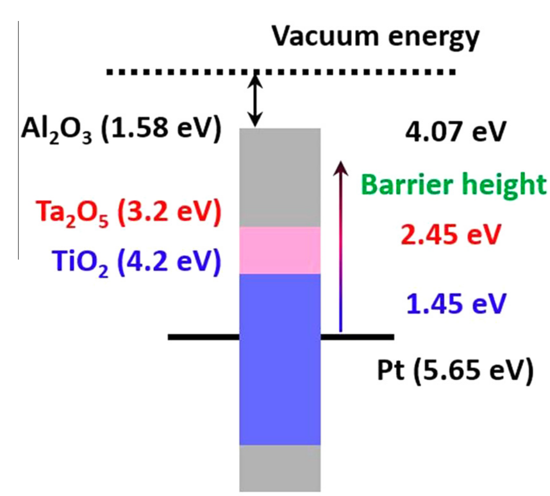


Fig. 3. Band-gap energy dependence of the metal oxide layers on the barrier height with the Pt electrode.