Effect of MIM type selection device on readout margin of cross-point bipolar ReRAM

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1. Introduction
To maximize memory density, 4F²-type cross-point memory is the best candidate. However, to meet the read and program/erase margin, selection devices are necessary which consume large device area. In case of unipolar ReRAM with filament type resistive switching behavior, conventional p-n diode was proposed as a selection device. It is known that the switching uniformity of bipolar ReRAM with interface switching behavior is much better than that of unipolar device with filament-type switching behavior. However, conventional asymmetric p-n diode is not applicable for bipolar cross-point memory.

In this paper, we introduced ALD ultrathin-TiO₂ based MIM selection device for bipolar cross-point memory. To calculate readout margin, we converted the cross-point memory array to a simple circuit model.

2. Experiments
Pt/TiO₂/TiN stack was fabricated as a selection device. 4 nm-thick TiO₂ layer was deposited onto 250 nm diameter via hole at 150 °C using atomic layer deposition (ALD) system. Then, Pt top electrode was deposited by RF magnetron sputtering. Bipolar type resistive memory was fabricated with Pt/TiO₂/TiN/W structure. TiO₂ and TiO₂-x layer were deposited at 250 °C using ALD system and sol-gel spin-coating method, respectively. Then Pt top electrode was deposited at room temperature.

3. Results & Discussion
In the cross-point memory array, load resistors (Rₙ) are located at the end of bit lines for the read operation (Fig. 1 (a)). As shown in Fig. 1(b) we proposed a simple circuit model to investigate the readout margin [1, 2]. In order to read the resistance state of a selected cell of cross point memory array, we need to monitor the current through Rₙ or the voltage drop across Rₙ. Considering the worst case in the read operation, all unselected cells are assumed as LRS. As shown in Fig. 2(a) the ReRAM without selection device shows a very high LRS current for unselected device (V₁=0.5V̇) which in turn causes significant reduction of readout margin. By adopting a selection device, we can significantly improve readout margin as shown in Fig. 2(b). To obtain a selection device with non-linear I-V curve, we have investigated MIM device with ultrathin TiO₂.

As shown in Fig. 3(a), large area MIM device shows ohmic type behavior. In contrast, we observed a non-linear and asymmetric I-V curve for nano-scale devices which can be explained by reduction of defect density. As shown in Fig. 4, we can control a current density by modulating film thickness and injection time of oxidizer. By changing the injection time of oxidizer in TiO₂-ALD process, the ratio of lattice to non-lattice oxygen was controlled. The amount of oxygen vacancies is proportional to a ratio of non-lattice oxygen. Fig. 5 shows I-V fitting using Schottky emission type transport equation. From Schottky diode equation, ideality factor (n) was extracted at room temperature (Pt/TiO₂ : n~2.3, TiN/TiO₂ : n~3.7) (Fig. 6). Richardson’s plot was adopted to extract effective Schottky barrier height of TiN/TiO₂ to be 0.32 eV. And effective Schottky barrier height of Pt/TiO₂ was expected to be 1.42 eV, considering the difference in workfunctions between Pt (5.6 eV) and TiN (4.5 eV) (Fig. 7(a)) [3]. With increasing measurement temperature, ideality factor (n) of Schottky barrier is decreased (Fig. 7(b)) [4]. Fig. 8(a) is a schematic diagram of resistive memory device with a selection device. The selection device which has Pt/TiO₂/TiN structure shows asymmetric I-V characteristics, because of its different Schottky barrier height at Pt/TiO₂ and TiN/TiO₂ interfaces, respectively (Fig. 8(b)). Fig. 8(c) represents the switching mechanism of a bi-layer TiO₂ resistive memory device. The oxygen exchange between oxygen deficient and oxygen rich layer leads resistive switching in this device [5, 6].

By connecting the resistive memory and a selection device in series, we obtained the IV characteristics as depicted in Fig. 9. The LRS current in the unselected cell was significantly reduced after adopting a selection device (Table 1). It indicates that sneak path through unselected cells was under control. From the value of Table 1, we calculated readout margin using the method as shown in Fig. 1(b). Using superposition theory, we obtained the load resistor current (Fig. 10(a)). According to an existence of selection device we could calculate load resistor current respectively. From these results, readout margin (% of applied Vₙₐ₀) also could be obtained depending on the number of words and existence of a selection device as shown in Fig. 10(b). By applying a selection device, we can increase a memory density about 2³ (2¹ x 2²) times at certain readout margins (% of applied Vₙₐ₀).

4. Summary
MIM type device which has back to back Schottky barrier can be used as a selection device for bipolar resistive memory. The I-V characteristics of nanometer scale selection device can be explained by Schottky emission mechanism. Based on modeling and measurement, TiO₂ based selection device shows sufficiently improved readout margin for cross-point memory array.

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References
[4] Minseok Jo et al., Symposia on VLSI, (will be presented)
Fig. 1 (a) The schematic of 4x4 cross-point memory. (b) The equivalent circuit model for the read operation.

Fig. 2 As a worst case (all unselected cells : LRS), I-V model according to an existence of a selection device. (a), (b) Without & With a selection device.

Fig. 3 (a), (b) The schematic and I-V characteristics of 50 x 50 μm device. (c), (d) The schematic and I-V characteristics of 250 nm diameter device.

Fig. 4 (a) The thickness dependence of 250 nm diameter device. (b), (c), (d) Oxygen vacancy dependence of 250 nm diameter device.

Fig. 5 A linear fitting of Schottky emission theory, ln(J) ~ \sqrt{V}.

Fig. 6 I-V characteristics at R.T (300K) to extract ideality factor(s) in MIM structure.

Fig. 7 (a) The effective Schottky barrier height(\(\Phi_{eff}\)) of Pt/TiO\(_2\) and TiN/TiO\(_2\) from Richardson's plot. (b) n values depending on temperature by Schottky diode equation.

Fig. 8 (a) The diagram of ReRAM device with a selection device. (b) The mechanism of a selection device. (c) The mechanism of ReRAM.

Fig. 9 (a) I-V characteristics of ReRAM device and a selection device. (b) I-V characteristic of ReRAM device with a selection device.

Fig. 10 (a) R\(_L\) current depending on the number of Words & existence of a selection device by I-V results. (b) Readout margin according to the number of words with a selection device & without a selection device by I-V results.

< Table. 1 > The resistance value without a selection & with a selection device of an unit cell for the read operation.