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Charge trapping characteristics of Al_2O_3/Al-rich Al_2O_3/SiO_2 stacked films fabricated by radio-frequency magnetron co-sputtering

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ABSTRACT

A thin-film structure comprising Al_2O_3/Al-rich Al_2O_3/SiO_2 was fabricated on Si substrate. We used radio-frequency magnetron co-sputtering with Al metal plates set on an Al_2O_3 target to fabricate the Al-rich Al_2O_3 thin film, which is used as a charge storage layer for nonvolatile Al_2O_3 memory. We investigated the charge trapping characteristics of the film. When the applied voltage between the gate and the substrate is increased, the hysteresis window of capacitance–voltage (C–V) characteristics becomes larger, which is caused by the charge trapping in the film. For a fabricated Al–O capacitor structure, we clarified experimentally that the maximum capacitance in the C–V hysteresis agrees well with the series capacitance of insulators and that the minimum capacitance agrees well with the series capacitance of the semiconductor depletion layer and stacked insulator. When the Al content in the Al-rich Al_2O_3 is increased, a large charge trap density is obtained. When the Al content in the Al–O is changed from 40 to 58%, the charge trap density increases from 0 to $18 \times 10^{18}\ cm^{-3}$, which is 2.6 times larger than that of the trap memory using SiN as the charge storage layer. The device structure would be promising for low-cost nonvolatile memory.

1. Introduction

Nanoscale devices have been widely studied [1–5] for large-scale integration. In particular, TaN–Al_2O_3–SiN-oxide–silicon trap memory devices [3–5] have been attracting increasing attention because they are expected to offer extremely large-scale integration due to their thin tunnel insulator (SiO_2) and thin block insulator (Al_2O_3).

Recently, we proposed a simplified trap memory that uses Al_2O_3 for the tunnelling insulator and blocking insulator and Al-rich Al_2O_3 for the charge storage layer. We clarified that the structure is very effective for nanoscale devices due to its simple structure and thin insulator [6–9]. However, a concern for this device is the interface between the Al_2O_3 and Si. It has been reported that defects near the interface degrade the mobility in field-effect transistors considerably [10,11]. The low mobility causes low operation speed, which is 1/10 that of the conventional value.

In the present work, to resolve the above concern, we fabricated an Al_2O_3/Al-rich Al_2O_3/SiO_2/Si structure using the radio-frequency (RF) magnetron co-sputtering method. The structure has three merits. The first is that SiO_2 is already very widely used as the tunnelling insulator in conventional nonvolatile memory [12] so that its use in the memory device enables us to use the prevailing process, i.e., thermal oxidation. The second is an ideal SiO_2/Si interface, near which there are almost no defects so that the mobility degradation does not occur. The third is that the Al-rich Al_2O_3 layer can produce many trap sites as pointed out previously [6–9].

For the Al_2O_3/Al-rich Al_2O_3/SiO_2/Si structure, capacitance evaluation, or in other words, dielectric constant evaluation, is very important for investigating the electrical field across each layer, which is useful for analyzing band bending when programming and erasing. For the capacitance evaluation, orthodox MIS (metal-insulator-semiconductor) theory would be effective. In this article, we calculate the insulator capacitance of each stacked film and the semiconductor depletion layer capacitance theoretically. Using these values, we estimate the maximum and minimum capacitance in capacitance–voltage (C–V) hysteresis curves. The estimated values agree well with the experimental ones. From this analysis, the capacitance value in each layer is confirmed.

In the Al-rich Al_2O_3 layer, how the charge trap density changes as a function of the Al content is still not fully understood. Therefore, we changed the Al content from 40 to 60% and evaluated the charge trap density. We also examined the data retention of the film.

The rest of this paper is organized as follow. Section 2 presents experimental procedures for the film. Section 3 describes the experimental results, which include the film deposition characteristics (the Al content and leakage current density), C–V characteristics, charge trap density, and data retention. Conclusions are finally described in Section 4.

2. Experiment

In this experiment, we used (100) n-type Si wafers ($\rho \cong 1.5 \times 10^{-2}$ Ωcm) as substrates. As shown in Fig. 1(a), 2.0 nm of SiO_2 was first

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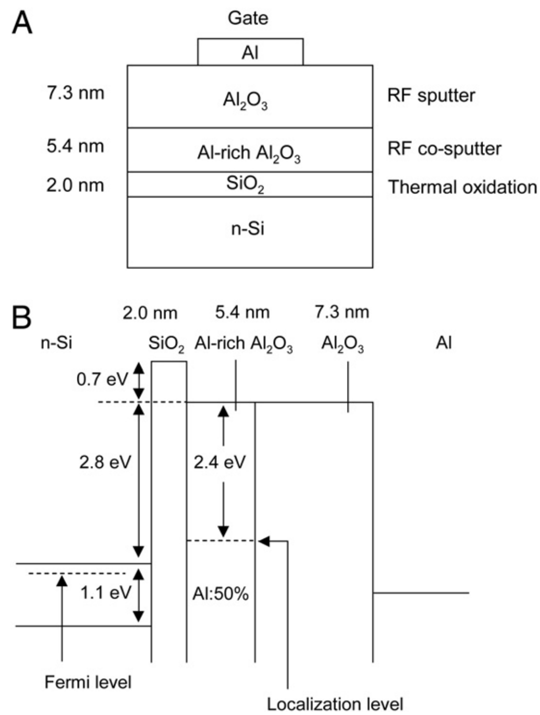

Fig. 1. Memory structure fabricated by RF magnetron co-sputtering: (A) Cross section and (B) energy band diagram.

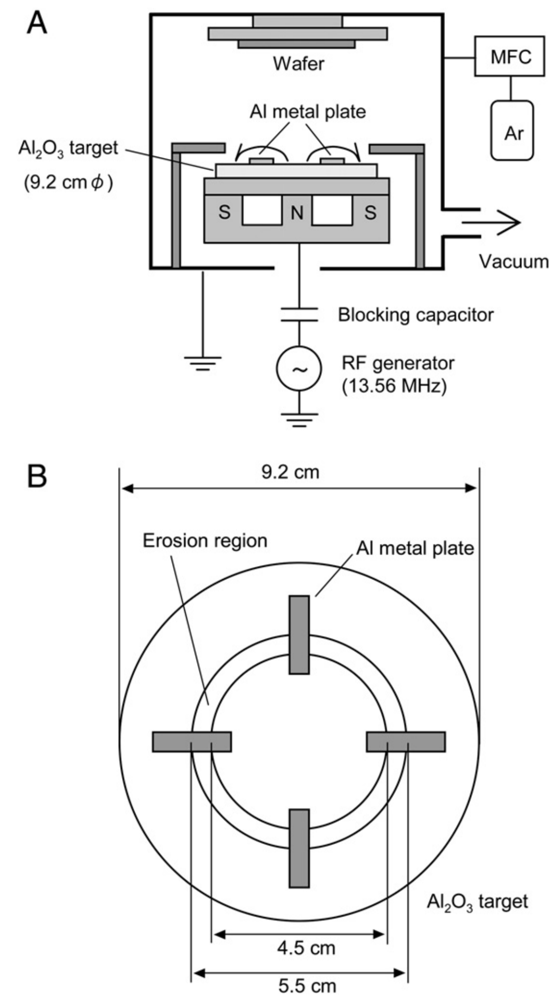

Fig. 2. RF magnetron co-sputtering method: (A) Cross-sectional view and (B) top view.

formed as a tunnel barrier insulator by thermal oxidation. Next, 5.4 nm of Al-rich Al_2O_3 was deposited as a charge storage layer by the co-sputtering method. Finally, 7.3 nm of stoichiometric Al_2O_3 was deposited as the blocking barrier insulator by conventional RF sputtering. The sample was annealed at 200 °C for 1 h effectively during deposition because the substrate temperature was set at 200 °C. In this experiment, annealing at 550 °C as in Ref. [9] was not performed after the Al_2O_3 blocking layer was deposited. A gate electrode with a diameter of 100 μm was formed by thermal evaporation of Al. The band diagram of this structure is shown in Fig. 1(b). Al_2O_3 has a 2.8-eV conduction barrier height [13]. In Al-rich Al_2O_3, the localized level is thought to be about 2.4 eV from the conduction band [14]. Regarding conduction band offsets, the band diagram in Fig. 1(b) is not accepted universally. There is an experimental report that shows much lower values in the case of an ultrathin layer [15]. The conduction band offsets of the ultrathin layer are an important issue. Much research will be necessary to clarify this point.

Here, we explain the co-sputtering method. For the fabrication of Al-rich Al_2O_3, we used RF magnetron co-sputtering equipment [9]. During co-sputtering, Al metal plates (plate size: 2 cm × 0.5 cm) were set on the Al_2O_3 target, which had a diameter of 9.2 cm. The Al content of the Al–O film can be controlled by changing the areal ratio of the Al metal on the target. A schematic representation of the co-sputtering system is shown in Fig. 2, where (a) and (b) are cross-sectional and top views, respectively. Atoms are sputtered from a target and reach wafers as shown in Fig. 2(a). The ratio of sputtered atoms from the target is determined by the ratio of Al plate area in the erosion region area in Fig. 2(b).

During deposition of Al_2O_3 and Al-rich Al_2O_3, Ar gas was used for sputtering. RF frequency was 13.56 MHz. The distance between the target electrode and substrate electrode was about 4 cm. After deposition, the deposited film thickness was measured with a spectroscopic ellipsometer. To investigate the Al content in the Al–O film, we used an electron probe micro-analyzer, which allows us to evaluate the Al content non-destructively by radiating an electron beam to the sample. Acceleration voltage and sample current were 15 kV and 20 nA, respectively. Beam size was 30 μm.

Electrical measurements were performed using a probe at room temperature. Leakage current was measured with a precision semiconductor parameter analyzer (HP4156). Capacitance was measured with a precision LCR meter (HP4284A) at 1 MHz.

3. Results and discussion

3.1. Film deposition

First, we describe the deposition characteristics of RF magnetron co-sputtering. Fig. 3(a) shows the Al content in the Al-rich Al_2O_3 as a function of the areal ratio of Al metal on the Al_2O_3 target. A ratio of zero means that there are no Al metal plates on the target, which corresponds to the deposition of stoichiometric Al_2O_3. A ratio of 100% means the Al_2O_3 target is completely covered with Al plates. It is clear that the Al content changes linearly as a function of the areal ratio. In the experiment, the Al content reached as high as 70%, which can provide sufficiently Al-rich Al_2O_3.

The leakage current characteristics of the structure in Fig. 1 with an Al content of around 50% are shown in Fig. 3(b). When the electric field is smaller than 2×10^8 V/m, leakage current is on the order of 10^{-9} A/cm^2, which is almost the same level as that for Al–O fabricated by electron-cyclotron-resonance sputtering [16] and in our previous work [9].