Modification of the Drain Current on a Metal-Oxide-Semiconductor Field-Effect Transistor with Ferrite Gate Oxide

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($\text{Mn}_{0.24}\text{Zn}_{0.09}\text{Fe}_{0.67}$) Fe_2O_4 (MZF) thin films were grown on Si substrates without and with MOSFETs by pulsed laser deposition (PLD). The deposition of MZF films was carried out by the following two procedures: (1) “1-step deposition,” in which 300-nm-thick MZF film was deposited at 800°C, and (2) “2-step deposition,” in which 10-nm-thick MZF film was deposited at 800°C and 300-nm-thick MZF film was deposited at 27°C followed by post-deposition annealing at 800°C for 1 h under an O_2 pressure of 1.3×10^{-3} Pa. For both preparation procedures, epitaxial growth of MZF thin film with (111)-orientation was observed. The saturation and remanent magnetization of MZF thin film depends on the preparation procedure, and the highest magnetization was obtained for film prepared by 1-step deposition. A microfabrication process in which preparation of MZF thin film was limited to the gate areas of Si-MOSFETs was attempted, using a combination of the abovementioned processes and etching processes: (1) 1-step deposition followed by wet chemical etching, and (2) 2-step deposition. In the 2-step deposition, a lift-off process was inserted before 27°C deposition. I_D - V_{DS} characteristics before and after magnetization of the MZF thin film was measured. As a result, modification of the drain current was observed. The modification was brought about by the Lorentz force, which was caused by the magnetic field induced by remanent magnetization. For MZF/Si-MOSFETs fabricated by 1-step deposition, the modification of the drain current was on the order of several μA when the gate voltage was 5 V. For MZF/Si-MOSFETs fabricated by 2-step deposition, the modification of the drain current was on the order of a few dozen pA when the gate voltage was 0.8 V. It was also clarified that the degree of modification increases with decreasing gate length. These results suggest that this principle could be used in a novel nonvolatile memory application.

Key words: metal-oxide-semiconductor field-effect transistor, modification of drain current, ferrite thin film, fabrication process, epitaxial growth, novel magnetic recording

1. Introduction

The effect of an external magnetic field on metal-oxide-semiconductor field-effect transistors (MOSFETs) is currently known as MAGFETs¹⁻⁴⁾. However, MAGFETs are magnetic sensors using the lateral Hall effect. We have proposed a concept of drain current (I_D) modification in MOSFETs using the Lorentz force from an external magnetic field and a magnetic field induced by remanent magnetization^{5,6)}. It was found that the magnetic field increased the I_D when the carriers were pushed away from the interface, and that a magnetic field with the opposite direction increased I_D slightly. This phenomenon was related to the potential change and carrier mobility⁶⁾. The carrier mobility in the channel of MOSFETs is approximately related to the scattering by bulk and surface phonons, Coulomb scattering, and surface roughness scattering⁷⁾. Therefore, these scattering factors decrease the mobility near the interface, and the scattering is less in the bulk. We expect that this concept will be useful in the design of novel memory devices. The principle of such a memory device is schematically shown in Fig. 1. In the configuration, ferromagnetic thin film is deposited on the gate areas of MOSFETs. An external magnetic field is applied to the ferromagnetic layer, and is then removed. The ferromagnetic layer is then magnetized to generate a magnetic field induced by

remanent magnetization. The magnetic field exerts a Lorentz force on the carriers in the channels of MOSFETs.

The purpose of this work is to establish microfabrication of MZF thin film on the gate areas of Si-MOSFETs, and to examine the degree of drain current modification generated by the principle. The effect of the gate length was also examined in order to increase the modification of I_D .

Fig. 1 Schematic drawing of the principle of the new memory: an external magnetic field is first applied to magnetize the ferromagnetic layer, and is removed.

(a) A downward Lorentz force, which is caused by the magnetic field induced by the remanent magnetization, pushes the carriers in the channel into the bulk to increase mobility.

(b) An upward Lorentz force pushes the carriers toward the interface to decrease mobility.

2. Experimental method

($\text{Mn}_{0.24}\text{Zn}_{0.09}\text{Fe}_{0.67}$) Fe_2O_4 (MZF) thin films were grown on Si substrates with and without MOSFETs by pulsed laser deposition (PLD). The deposition of MZF thin films was carried out by the following two procedures:

(1) “One-step deposition,” in which 300-nm-thick MZF films were deposited at 800°C in 1.3 Pa O_2 . Prior to the deposition of the MZF thin film, 8-nm-thick yttria-stabilized zirconia (YSZ, 800°C in 7.3×10^{-2} Pa O_2), 6-nm-thick CeO_2 (800°C in 7.3×10^{-2} Pa O_2) and 8-nm-thick ZnCo_2O_4 (600°C in 1.3 Pa O_2) layers were deposited. The YSZ layer was essential for realizing epitaxial oxide film preparation on Si(001) substrate⁸. The CeO_2 layer was introduced to improve crystallinity. ZnCo_2O_4 was used to improve the magnetic properties⁶.

(2) “Two-step deposition,” in which 10-nm-thick MZF film was deposited at 800°C in 1.3 Pa O_2 , cooled to 27°C and 300-nm-thick MZF thin film was deposited at 27°C in 1.3 Pa O_2 . Prior to the deposition of the MZF thin film, a 5-nm-thick YSZ thin layer was deposited. Since this process was rather complicated, deposition of CeO_2 and ZnCo_2O_4 layers was not carried out. The 2-step deposition films were annealed at 800°C for 1 h in 1.3×10^{-3} Pa O_2 .

X-ray diffraction analysis, in-situ reflection high-energy electron diffraction (RHEED) observation, and M - H hysteresis curve measurements using a vibrating sample magnetometer (VSM) were carried out for MZF thin films deposited on Si substrates without MOSFETs.

Microfabrication of MZF thin film on the gate areas of Si-MOSFETs was also carried out. Two kinds of microfabrication were attempted:

[1] Wet chemical etching

[2] Lift-off process

These two methods are related to the above two preparation procedures.

Wet chemical etching was carried out after 1-step deposition was finished. We found that YSZ and CeO_2 films are insoluble in 32% HCl solution, while ZnCo_2O_4 and MZF films are soluble. By using the difference in solubility, removal of MZF/ZC films except for the gate areas was carried out by photolithography and wet chemical etching. No annealing was carried out after wet chemical etching. A lift-off process was introduced after 10-nm-thick MZF film was deposited at 800°C and cooled to 27°C. At 27°C, lift-off resist (LOR) was coated on the surface of Si substrate with MOSFETs except for the gate area. 300-nm-thick MZF film was deposited at 27°C in 1.3 Pa O_2 , and the LOR was then removed. Subsequently, microfabrication of MZF/YSZ thin film on the gate area was carried out. Finally, the film was annealed at 800°C for 1 h in 1.3×10^{-3} Pa O_2 .

After processes [1] and [2], Pt electrodes were fabricated on

the pads of source, gate, and drains by dc magnetron sputtering at 27°C followed by a lift-off process. Figure 2 shows schematic cross-sections and laser microscope photographs of MOSFETs after these processes.

Fig. 2 Schematic cross-section of MOSFETs with MZF thin film on the gate area fabricated by (a) 1-step deposition followed by a wet chemical etching process and (c) 2-step deposition followed by a lift-off process. (b) and (d) show laser microscope images after corresponding processes.

The Si substrates with MOSFETs were specially ordered ones (n-channel enhancement type with a gate width (W) of 10 μm , and gate lengths (L) of 0.8, 1, 2, 5, 10, 100, and 300 μm). The I_D - V_{DS} characteristics of the MOSFETs were measured by using a pA meter. The thickness of the film was determined by using both a surface profile meter and X-ray fluorescent spectroscopy.

3. Results and discussion

X-ray diffraction results indicate that the MZF films deposited on Si(001) by both 1- and 2-step depositions show (111)-orientation. Figure 3(a) shows an *in-situ* RHEED image of 60-nm-thick-MZF thin film deposited at 800°C by 1-step deposition. A streak pattern shows that the film is epitaxially grown. Figure 3(b) shows a (100) X-ray pole figure image of MZF thin film deposited at 800°C by 1-step deposition. The observed twelve poles indicate that MZF thin film is epitaxially grown. However, the epitaxial growth consists of four crystallographic domains of MZF coexisting with every 30°

rotation along the ϕ axis, because only three poles are expected to be observed every 120° for a single-crystallographic-domain epitaxial MZF(111) thin film. Figures 3(c) and 3(d) show *in-situ* RHEED images of 10-nm-thick MZF thin films deposited at 800°C and 300-nm-thick MZF thin film deposited on (c) at 27°C . Though the RHEED pattern shown in Fig. 3(d) is rather diffuse, a streaky pattern was also observed. This means that epitaxial growth continued even after 27°C deposition. Actually, the X-ray pole figure pattern after 2-step deposition was the same as that after 1-step deposition, shown in Fig. 3(b). Such low-temperature epitaxial growth of nickel zinc ferrite (NZF) and MZF has also been reported in the literature⁹.

Fig. 3 RHEED image of (a) 60-nm-thick MZF thin film deposited at 800°C (1-step deposition). (b) a (100) X-ray pole figure image of MZF thin film deposited at 800°C (1-step deposition). RHEED images of (c) 10-nm-thick MZF thin film deposited at 800°C and (d) 300-nm-thick MZF thin film deposited on (c) at 27°C (2-step deposition).

Fig. 4 M - H hysteresis curves of MZF thin film prepared by (a) 1-step deposition and (b) and (c) 2-step deposition before and after annealing at 800°C , respectively.

Figure 4(a) shows room-temperature M - H hysteresis curves of

MZF thin film deposited by 1-step deposition. This film exhibited a remanent magnetization of 370 emu/cm^3 . Figures 4(b) and 4(c) show room-temperature M - H hysteresis curves of MZF thin film deposited by 2-step deposition before and after annealing at 800°C for 1 h. This figure shows that the remanent magnetization of as-deposited 2-step deposition MZF thin film before and after annealing was 50 and 260 emu/cm^3 , respectively.

Figure 5(a) shows the I_D - V_{DS} characteristics of MZF/Si-MOSFETs thin film fabricated by 1-step deposition followed by wet chemical etching. The film was as-deposited before application of an external magnetic field. For this MOSFET, the gate length L and gate width W were 5 and 10 μm , respectively, and the gate voltage V_G was 5 V. In this work, an external magnetic field of 0.44 T was applied and removed. Application of an external magnetic field causes remanent magnetization for the MZF thin film, and a magnetic field was induced by the remanent magnetization. It should be noted that the direction of the magnetic field induced by the remanent

Fig. 5 (a) I_D - V_{DS} characteristics of MZF/Si-MOSFET thin film before application of a magnetic field ($L = 5 \mu\text{m}$, $W = 10 \mu\text{m}$, $V_G = 5 \text{ V}$).

Change in ΔI_D with V_{DS} after (b) 1-step deposition followed by wet chemical etching ($L = 5 \mu\text{m}$, $W = 10 \mu\text{m}$, $V_G = 5 \text{ V}$), and (c) 2-step deposition with a lift-off process ($L = 10 \mu\text{m}$, $W = 10 \mu\text{m}$, $V_G = 0.8 \text{ V}$), where ΔI_D is I_D (after magnetic field application)- I_D (before magnetic field application).

Magnetization is opposite to that of the original external magnetic field. In this work, the direction of the magnetic field (induced by remanent magnetization) was selected so as to generate a downward Lorentz force, as shown in Fig. 1(a). Figure 5(b) shows the degree of modification of the drain current (ΔI_D) ($\Delta I_D = I_D(\text{after magnetic field application}) - I_D(\text{before magnetic field application})$) with V_{DS} . The value of ΔI_D was on the order of several μA . Figure 5(c) shows the relationship between ΔI_D and V_{DS} of MZF/Si-MOSFETs thin film fabricated by using a combination of 2-step deposition and a lift-off process. For this MOSFET, the gate length L and gate width W were 10 and 10 μm , respectively, and the gate voltage V_G was 0.8 V. In this case, the ΔI_D was on the order of a few dozen pA. In this figure, a ΔI_D value of 3 pA was observed when $V_{DS} = 0$ V. This finite ΔI_D could be ascribed to the leakage current of MOSFETs at $V_{DS} = 0$ V and the effect of measurement error. Due to the low process yield, it was difficult to compare I_D - V_{DS} characteristics using the same L and V_G for both processes. The difference in the order of ΔI_D is likely to contain several factors such as L , V_G , and process factors. To reduce the number of factors, the change in ΔI_D with gate length was examined in an external magnetic field of 0.4 T (Fig. 6). Figure 6 shows the change in ΔI_D with L . For this experiment, the gate width W was 10 μm , V_G and V_{DS} were 3 and 4 V, respectively, and B was 0.4 T. This figure clearly shows that ΔI_D increases with decreasing L . The results of this work suggest that ferromagnetic thin film fabricated on the gate area of Si-MOSFET could modify the drain current, and that the effect is enhanced by small gate length and high gate voltage.

Fig. 6 Change in ΔI_D with gate length for an Si-MOSFET ($W = 10 \mu\text{m}$, $V_G = 3$ V, $V_{DS} = 4$ V, $B = 0.4$ T).

4. Conclusions

Modification of the drain current of an Si-MOSFET by a magnetic field induced by remanent magnetization of ferromagnetic thin film was investigated. As the ferromagnetic thin film, $(\text{Mn}_{0.24}\text{Zn}_{0.09}\text{Fe}_{0.67})\text{Fe}_2\text{O}_4$ (MZF) was grown on Si substrates with and without MOSFETs by pulsed laser deposition (PLD). The deposition of MZF films was carried out by following two procedures: (1) 1-step deposition, in which 300-nm-thick MZF film was deposited at 800°C, and (2) 2-step deposition, in which 10-nm-thick MZF film was deposited at 800°C and 300-nm-thick MZF film was deposited at 27°C followed by post-deposition annealing. For both preparation procedures, epitaxial growth of MZF thin film with (111)-orientation was observed. The saturation and remanent magnetization of MZF thin film depends on the preparation procedure, and the highest magnetization was obtained for film prepared by 1-step deposition. Microfabrication of MZF thin films in which preparation of MZF thin film was limited to the gate areas of Si-MOSFETs was attempted, using a by the combination of the abovementioned processes and etching processes: (1) 1-step deposition followed by wet chemical etching, and (2) 2-step deposition. In the 2-step deposition, a lift-off process was inserted before 27°C deposition. The I_D - V_{DS} characteristics before and after magnetization of MZF thin film was measured. As a result, modification of the drain current was observed. The modification was brought about by the Lorentz force, which was caused by the magnetic field induced by remanent magnetization. For MZF/Si-MOSFETs fabricated by 1-step deposition, the modification of the drain current was on the order of several μA when the gate voltage was 5 V. For MZF/Si-MOSFETs fabricated by 2-step deposition, the modification of the drain current was on the order of a few dozen pA when the gate voltage was 0.8 V. It was also clarified that the degree of modification increases with decreasing gate length. These results suggest that this principle could be used in a novel nonvolatile memory application.

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