C-7-05

Extended Abstracts of the 2018 International Conference on Solid State Devices and Materials, Tokyo, 2018, pp217-218

Electrical characteristic of La_2O_3/Si MOSFETs with ferroelectric-type hysteresis

Kiyoshi Endo[1], Kimihiko Kato[1], Mitsuru Takenaka[1] and Shinichi Takagi[1]

[1] Univ. of Tokyo, 2-11-16, Yayoi, Bunkyo-ku, Tokyo 113-0032, Japan

Phone: +81-3-5841-0419 E-mail: takagi@ee.t.u-tokyo.ac.jp

Abstract

Physical origin of hysteresis and reduction in sub-threshold swing (S.S.) of La_2O_3/Si MOSFETs is examined. Hysteresis of MOS C-V curves disappears at low temperature, while that of MIM P-V curves remains. In MOSFETs, apparent S.S. improvement with longer measurement time and the monotonic increase in drain current (I_d) of MOSFETs over 10^3 sec or longer are observed. Faster response time of I_d increase and apparent S.S. improvement are also found at higher temperature. These results strongly suggest that drift of any mobile ions is responsible for the observed hysteresis and S.S. reduction, rather that ferroelectricity of La_2O_3.

1. Introduction

MOSFETs with ferroelectric gate insulators have a strong interest as future lower power logic devices because of the proposal of the concept of the negative capacitance MOSFET [1] and the recent finding of HfO_2-based ferroelectrics [2]. We have recently found that La_2O_3/InGaAs MOSFETs have ferroelectric-type hysteresis and the sub-threshold slope (S.S.) lower than the lower limit of conventional MOSFETs at low temperatures [3, 4]. So far, there has been no report on the ferroelectricity of La_2O_3. However, another interpretation of this hysteresis can be ion drift, as shown in Fig.1. The discrimination of these two origins is important to understand the physical mechanism of the operation of MOSFETs with ferroelectric-type hysteresis.

Thus, in this study, we experimentally examine the physical origin of the ferroelectric-like hysteresis and the impact on the electrical properties of La_2O_3/Si MOS capacitors and MOSFETs through the temperature and time dependencies.

2. Device fabrication

Fig. 2 shows the fabrication process flow of Al/La_2O_3/Si MOS and TiN/La_2O_3/MIM capacitors. Here, La_2O_3 films were deposited at 150 ^{o}C by ALD using La(^{i}PrCp)$_3$ and H_2O. The thickness of La_2O_3 was varied among 15, 10 and 6 nm for the MIS capacitors, while 16 nm for the MIM capacitors. Fig. 3 also shows the fabrication process of TiN/La_2O_3/Si n-MOSFETs. The 15-nm-thick La_2O_3 film was used here.

3. Experimental results

Fig. 4 shows the C-V characteristics of the La_2O_3/Si MOS capacitors with different La_2O_3 thickness. Ferroelectric-type hysteresis can be observed, regardless of the La_2O_3 thickness, which is consistent with La_2O_3/InGaAs MOS capacitors [3, 4]. Fig. 5(a) and (b) show the P-V curves of TiN/La_2O_3/TiN capacitors with changing the maximum scan voltage and frequency, respectively, at room temperature. While hysteresis typical to ferroelectrics is confirmed, the strong frequency dependence suggests the slow response, which can be different from the properties of conventional ferroelectric materials. Here, when mobile ions with thermal activated drift properties cause the ferroelectric-type hysteresis, hysteresis must disappear at low temperature. Fig. 6(a) and (b) show the C-V curves of the MOS capacitors at 293 and 190 K. It is observed that the hysteresis almost disappears at low temperature. On the other hand, the hysteresis of MIM ones still remains at 150 K, as shown in Fig. 7. As a result, it is difficult to fully identify the origin of hysteresis only from the observations of the MIS and MIM capacitors.

Thus, we quantitatively evaluate the electrical characteristics of La_2O_3/Si MOSFETs. Fig. 8(a) and (b) shows the I_d-V_g curves and the resulting S.S.-I_d characteristics, respectively, with changing the V_g scan speed. The I_d-V_g curves show ferroelectric-type hysteresis. It is found that S.S. becomes smaller by taking longer measurement time. This result can be explaining by slow negative shift of V_{th} during the I_d measurement after applying a given V_g. In order to evaluate such slow response of voltage shift, the time dependence of I_d is measured as a parameter of V_g, as shown in Fig. 9. Fig. 10 also shows the effective V_{th} shift, calculated from Fig. 9, as a function of time. It is found that I_d and ΔV_{th} keep increasing with time over 10^3 sec or longer, which is not expected for ferroelectric polarization. As a result, responsibility of mobile ion drift is strongly suggested.

In order to further discriminate the effects of ferroelectricity and ion drift, the MOSFET characteristics at high temperature are evaluated. Fig. 11 shows the I_d-V_g curves at 293, 318 and 368 K. The hysteresis is the largest at 318 K. Fig. 12 summarizes the measurement temperature dependence of hysteresis and the minimum S.S. It is found in a temperature range of 300 to 340 K that the apparent S.S. decreases and the hysteresis increases with increasing temperature. In particular, these S.S. values are lower than the MOSFET lower limit. These facts are explainable not by the ferroelectric nature, but by ion drift. Fig. 13 shows the time dependence of I_d at high temperatures. The faster response time of I_d increase with increasing T is observed, which is another evidence of ion drift. The thermal activation energy of this ion drift, estimated from the response time of I_d (Fig. 14), is around 1.6 eV, which is comparable to drift of K^+ in SiO_2 (1.04±0.10 eV [5]) and H^+ in SiO_2 (0.8 eV [6])

4. Conclusions

Ferroelectric-type hysteresis and apparent improvement of S.S. in La_2O_3/Si MOSFETs can be attributed to drift of any mobile ions, rather that ferroelectricity of La_2O_3, judging from the time and temperature dependence.

Acknowledgements This work was partly supported by JST-CREST Grant Number JPMJCR1332, Japan and the Grant in-Aid for Scientific Research through the MEXT (17H06148).

References [1] S. Salahuddin et al. Nano Lett. **8**, 405 (2007) [2] T. S. Böscke et al., Appl. Phys. Lett. **99**, 102903 (2011) [3] C.-Y. Chang et al., IEDM (2016) [4] C.-Y. Chang et al., AIP adv. **7**, 095215 (2017) [5] G. Greeuw et al., J. Appl. Phys. **56**, 2218 (1984). [6] K. Vanheusden, et al., Nature **386**, 587 (1997).

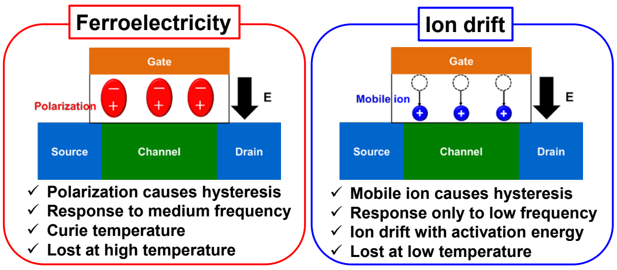

Fig. 1 Schematic diagrams of two possible origins for anti-clockwise hysteresis in MOS structures

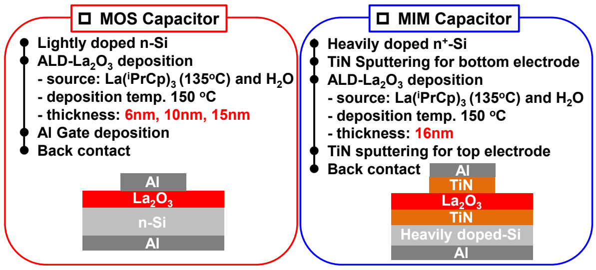

Fig. 2 Fabrication process flow of Al/La_2O_3/Si MOS and TiN/La_2O_3/MIM capacitors.

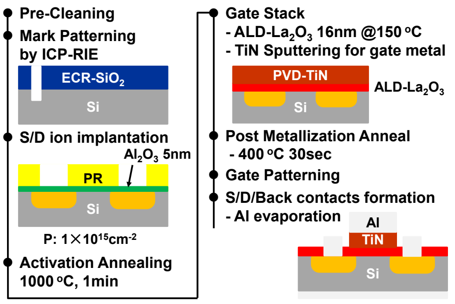

Fig. 3 Fabrication process of TiN/La_2O_3/Si n-MOSFETs with 15-nm-thick La_2O_3.

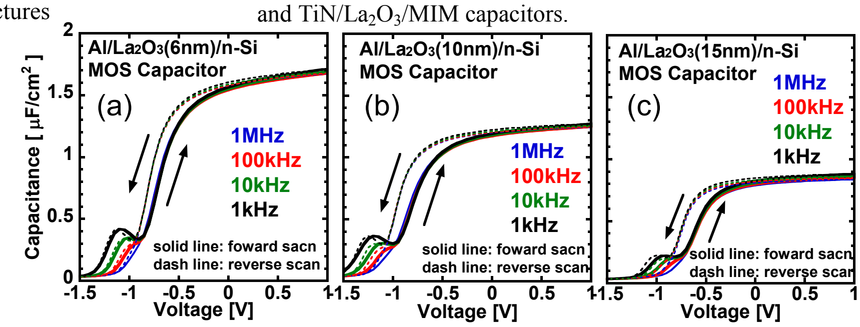

Fig. 4 C-V characteristics of La_2O_3/n-Si MOS capacitors with La_2O_3 thickness of (a) 6 nm, (b) 10 nm and (c) 15 nm.

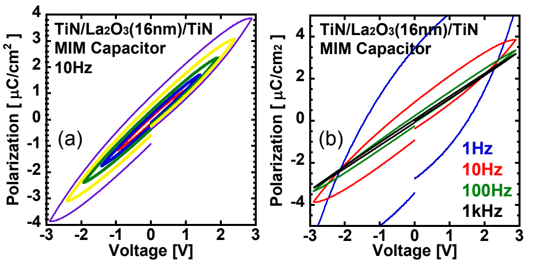

Fig. 5 P-V curves of TiN/La_2O_3/TiN MIM capacitors with changing (a) maximum voltage and (b) frequency.

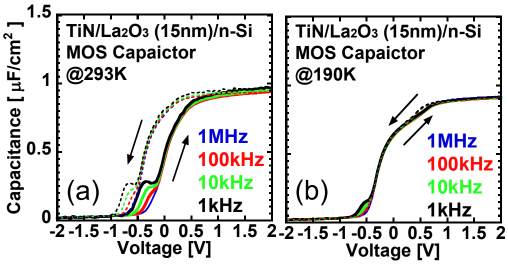

Fig. 6 C-V curves of 15-nm-thick La_2O_3/Si MOS capacitors at (a) 293 K and (b) 190 K.

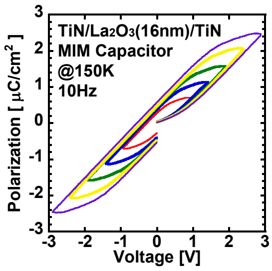

Fig. 7 P-V curves of TiN/ La_2O_3/TiN MIM capacitors at 150 K.

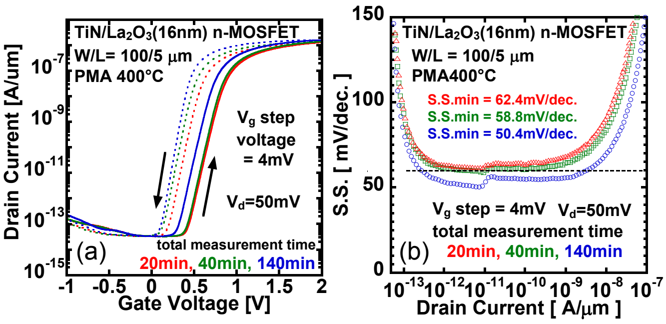

Fig. 8 (a) I_d-V_g curves and (b) S.S.-I_d characteristics of La_2O_3/Si n-MOSFETs at room temperature.

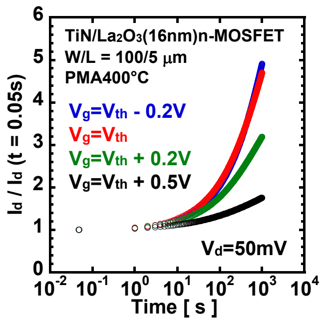

Fig. 9 Time dependence of I_d measured as a parameter of V_g.

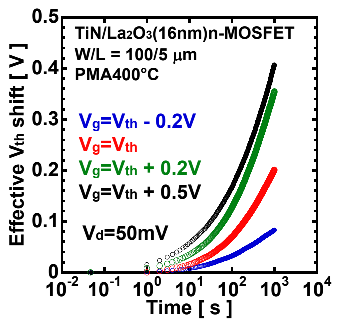

Fig. 10 Time dependence of effective V_{th} shift.

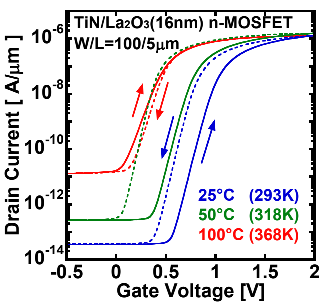

Fig. 11 I_d-V_g curves of La_2O_3/Si n-MOSFETs at 293, 318 and 368 K.

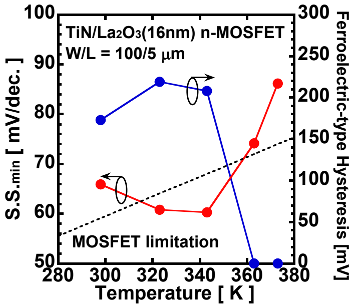

Fig. 12 Measurement temperature dependence of hysteresis and the minimum S.S.

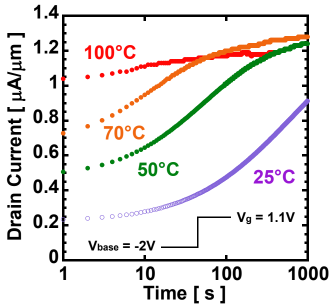

Fig. 13 Time dependence of I_d of La_2O_3/Si n-MOSFETs at 293, 318, 338 and 368 K.

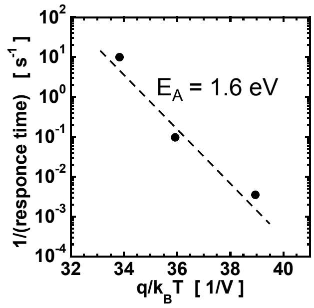

Fig. 14 Thermal activation energy estimated from the response time of I_d.