Extended Abstracts of the 2018 International Conference on Solid State Devices and Materials, Tokyo, 2018, pp769-770

Junctionless ferroelectric FET with doped HfO_2 on n^+-TiO_2 for three-terminal nonvolatile switch

L. Xu[1], S. Shibayama[1], T. Nishimura[1], T. Yajima[1], S. Migita[2] and A. Toriumi[1]
[1]Department of Materials Engineering, The University of Tokyo, Tokyo 113-8656, Japan
[2]National Institute of Advanced Industrial Science and Technology (AIST), Tsukuba 305-8569, Japan
Phone : +81-3-5841-1907, E-mail: toriumi@material.t.u-tokyo.ac.jp

Abstract

This paper discusses potential opportunities of ferroelectric FETs using doped HfO_2 on oxide semiconductor channel, and demonstrates its nonvolatile FET action. It should offer versatile applications of CMOS compatible Fe-FETs for low power LSI application.

1. Introduction

The ferroelectric FETs (Fe-FETs) have been investigated for many years, because it should offer versatile opportunities in terms of low power nonvolatile FETs operated by keeping its polarization in the absence of an electric field. Perovskite type of ferroelectric films have been so far intensively studied [1]. Recently, ferroelectric HfO_2 was found experimentally [2], and has been investigated for various promising applications, since HfO_2 is now dominantly used for CMOS gate stacks. Substantial challenges of ferroelectric HfO_2 for advanced device design are how to control the interface with semiconductors as well as ferroelectric material properties. It is well known that HfO_2 directly deposited on Si should generate a huge amount of interface states. Therefore, it is critically important to employ appropriate semiconductors for HfO_2 in terms of good gate stack operation. In addition, since the polarization charges are always too high for conventional semiconductor channels, it is required to reconsider semiconductor material as well as appropriate FET structure. This paper demonstrates ferroelectric HfO_2 FETs by overcoming above big challenges.

2. Ferroelectric film, channel material and device structure

(i) Ferroelectric film

There have been so many researches on Fe-FETs using perovskite type of ferroelectric films. In terms of (1) scalability and (2) CMOS compatibility, however, it has not successfully been realized so far. Recently, doped HfO_2 was reported to be ferroelectric. It will make Fe-FETs possible without being worried by above two concerns. Furthermore, we have paid attention to ferroelectric N-doped HfO_2 [3], because very small N is needed to make HfO_2 ferroelectric and N will not degrade the interface as compared with metallic cation as the dopant.

(ii) Semiconductor material

Si is practically the best material for any applications, but when a huge polarization charges (10~100 $\mu C/cm^2$) in ferroelectric films are considered, "high permittivity oxide" channel materials might be better, because electric field inside the channel can be reduced and the interface layer will not be formed. Therefore, we have selected TiO_2 for the channel (k~100). In fact, high mobility (~10 $cm^2/Vsec$) TiO_2 FETs grown by PLD were recently achieved [4].

(iii) FET design

Charge accumulation type FETs are inevitably affected by the interface quality, because mobile carriers are always near the interface and the interface quality determines the carrier transport in FETs. Therefore, we have employed the junctionless type FET, in which carriers are spread over the channel thickness at "on" state, while all carriers are depleted from the interface at "off" state [5].

3. Experimental

N-doped HfO_2 films were grown by rf-sputtering by introducing a controlled amount of N_2 into Ar, flowed by PDA at 600°C. **Fig. 1** shows typical polarization-electric field (P-E) characteristic deposited on p^+Ge (111). Remanent polarization was the same as other cation doped HfO_2, although dopant concentration was much smaller [6]. Next, we fabricated 40 nm 0.34% N-doped HfO_2 film with 10-nm-thick 0.2 wt.% Nb-doped TiO_2 as the n^+-type channel layer. Nb-doped TiO_2 films were grown by PLD, followed by PDA at 600°C, as the semiconductor channel layer on SiO_2/Si substrate. Al was used for source and drain ohmic contacts to TiO_2. A schematic view is described in **Fig. 2**.

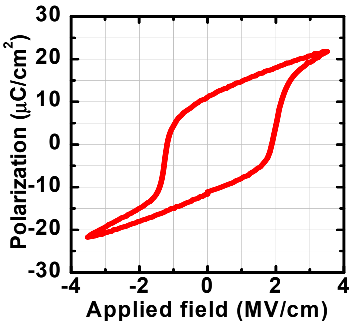

Fig. 1 P-E (100 Hz) characteristic of 28-nm-thick 0.34% N-doped HfO_2 film, which shows a typical ferroelectric hysteresis.

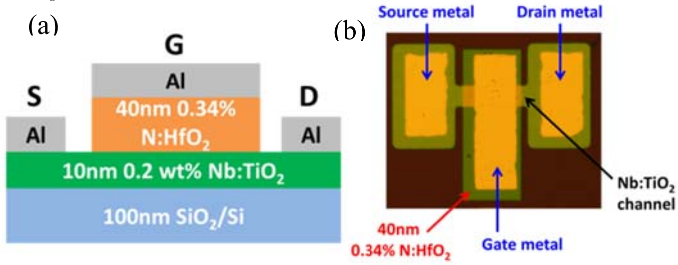

Fig. 2 **(a)** Schematic view of Fe-FET with ferroelectric N-doped HfO_2 (40 nm) on Nb-doped TiO_2 (10 nm). **(b)** Photo-image top view of Fe-FET.

4. Results and Discussion

FET characteristics are shown in **Fig. 3**, in which **(a)** I_{DS}-V_{DS} and **(b)** I_{DS}-V_{GS} characteristics are shown. The saturation behavior is a little degraded in I_{DS}-V_{DS}, while the subthreshold characteristics show counter-clockwise hysteresis and surprisingly low off-leakage current. The hysteresis width is roughly 5 V in this case, because the coercive field of HfO_2 is sufficiently large. This value is adjustable by changing HfO_2 thickness. An appropriate electrode material selection in place of Al is needed to adjust the threshold voltage. To our knowledge, this is the first demonstration of junctionless ferroelectric FET with doped HfO_2 on n^+-oxide semiconductor.

Ferroelectric HfO_2 scalability and reliability have been already investigated in the capacitors, and the remanent polarization gradually increases with the HfO_2 thickness decrease down to 5 nm. Furthermore, thin ferroelectric HfO_2 (~5 nm) has a higher cycling property than thick (30 nm) one [7]. Therefore, both scalability and reliability in thin ferroelectric HfO_2 are very promising for versatile and scaled applications.

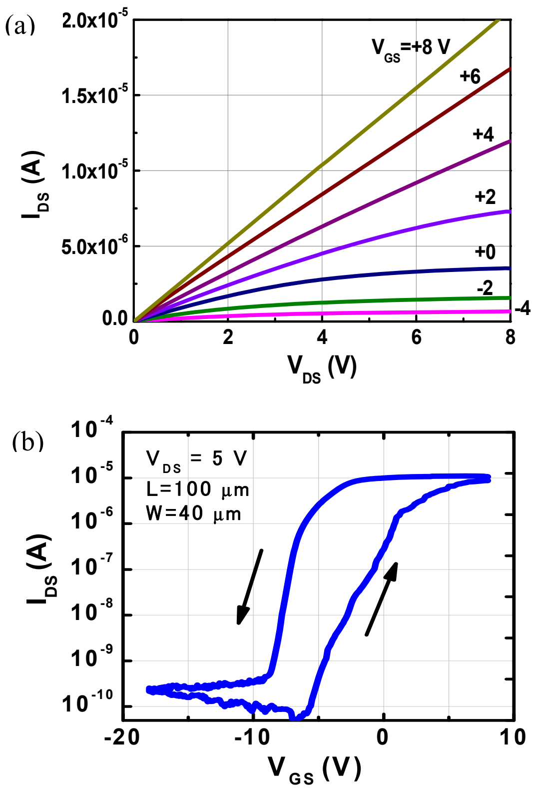

Fig. 3 **(a)** I_{DS}-V_{DS} and **(b)** I_{DS}-V_{GS} characteristics in N-doped HfO_2 on Nb-doped TiO_2. V_{th} is not optimized in this device, but a very stable memory window is shown.

Furthermore, cycling properties in Fe-FETs are shown in **Fig. 4**. 7 V and -13 V were used for writing and erasing, respectively. Although a large number of tests have not been carried out, V_{th} looks stable in spite of the fact that thick (40 nm) HfO_2 was used for the present gate stack.

All of the results obtained so far show that junctionless ferroelectric HfO_2 FETs on n^+-doped TiO_2 will be promising for CMOS compatible functional devices.

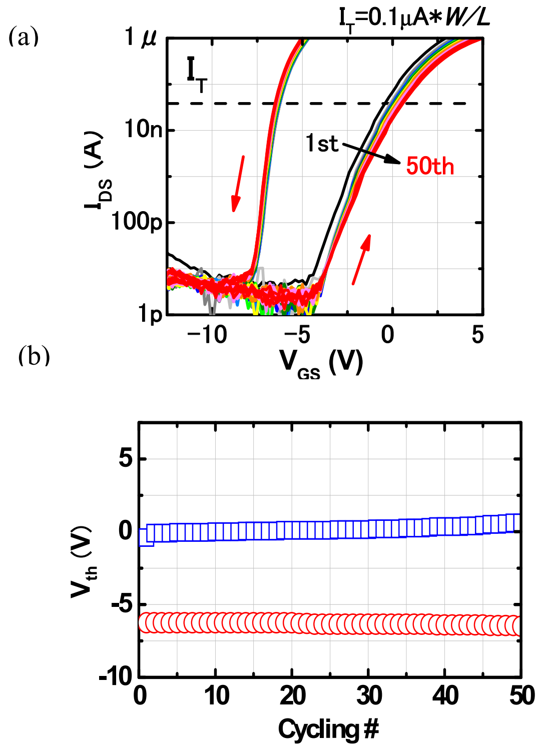

Fig. 4 **(a)** Cycling characteristics in Fe-FET to the 50th repetition. **(b)** V_{th} defined by I_T in (a) as a function of cycling number. Only slight V_{th} shift is observed.

5. Conclusion

Direct ferroelectric HfO_2 on Si or Ge for controlling the surface potential at the interface seems not easy, but well-behaved FET characteristics with ferroelectric HfO_2 on oxide semiconductors have been successfully demonstrated for the first time. The oxygen-terminated interface at HfO_2/TiO_2 is appropriate for making the best use of functional HfO_2 in terms of minimizing the gap-states formation at the FET channel interface. In addition, junctionless FETs exhibit their bigger potential for the present application rather than for ultra-short channel FETs on conventional semiconductors.

Acknowledgement

This work was supported by JST-CREST (JPMJCR14F2).

References

[1] H. Ishiwara, J. Semicon. Tech and Sci. **1**, 1 (20011).
[2] T. S. Boscke et al., APL **99**, 102903 (2011).
[3] L. Xu et al., APEX **9**, 091501 (2016).
[4] T. Yajima et al., Phys. Stat. Sol.A. **213**, 2196 (2016).
[5] J. P. Colinge et al., Nat. Nanotech. **5**, 225 (010).
[6] L. Xu et al., JAP. **122**, 124104 (2017).
[7] X. Tian et al., IEDM (2017).