Extended Abstracts of the 2014 International Conference on Solid State Devices and Materials, Tsukuba, 2014, pp10-11

Effect of Kr/O_2 Mixed ECR Plasma Oxidation on Electrical Properties of Al_2O_3/Ge Gate Stacks Fabricated by ALD

Yuta Nagatomi[1], Yuichi Nagaoka[1], Keisuke Yamamoto[2], Dong Wang[1], and Hiroshi Nakashima[2]

[1]Interdisciplinary Graduate School of Engineering Science, Kyushu University
6-1 Kasuga-koen, Kasuga, Fukuoka 816-8580, Japan
Phone: +81-92-583-8924 E-mail: 3ES14011E@s.kyushu-u.ac.jp
[2]Art, Science and Technology Center for Cooperative Research, Kyushu University
6-1 Kasuga-koen, Kasuga, Fukuoka 816-8580, Japan

Abstract

We investigated the effect of Kr/O_2 mixed ECR plasma oxidation on electrical properties of Al_2O_3/Ge gate stacks fabricated by ALD. It was found that the interface states density was improved by plasma oxidation using Kr/O_2 instead of Ar/O_2, which fell to half at the valence band edge. By using this GeO_x formation under an Al_2O_3 layer, the p-MOSFET with HfGe-source/drain and an EOT of 3 nm was fabricated. The peak field-effect hole mobility was 253 cm^2/Vs, which was higher than that (223 cm^2/Vs) fabricated using Ar/O_2 plasma oxidation.

1. Introduction

Ge is of great interest as a high mobility channel material for future C-MOS devices. However, it is difficult to form shallow source/drain (S/D) junctions with low sheet and contact resistances because of the low dopant solubility. An attractive candidate is metal S/D MOSFET, and to realize high performance, metal/Ge contacts with low electron and hole barrier heights are needed for p- and n-MOSFETs, respectively. We have already established the contact formation techniques using HfGe/Ge and TiN/Ge. [1]

Another important issue is low temperature fabrication of gate stack with a high-quality interface to avoid the degradation of contact properties. Zhang et al. have reported the low temperature fabrication of Al_2O_3/GeO_X/Ge gate stack with a low interface states density (D_{it}) less than 10^{11} $eV^{-1}cm^{-2}$, which was fabricated by ALD and the post oxidation using Ar/O_2 mixed ECR plasma. [2] It was reported that Kr/O_2 mixed high-density microwave-excited plasma has a lower ion energy and a higher ion density than Ar/O_2 plasma, resulting in superior SiO_2/Si dielectric properties. [3] Our group had also found that SiO_2/Si gate stack using Kr/O_2-ECR plasma was much better than that using Ar/O_2-ECR plasma. [4] When Al_2O_3/GeO_X/Ge gate stack is fabricated using Kr/O_2-ECR plasma instead of Ar/O_2, it is possible that the gate stack quality becomes better.

In this paper, we report the electrical properties of the MOS capacitors (CAPs) fabricated by ALD and Kr/O_2-ECR plasma oxidation. For comparison, the properties of MOSCAPs using Ar/O_2-ECR plasma were also studied. The device performances of p-MOSFETs with these two kinds of gate stacks are shown.

2. XPS analysis and MOS device fabrications

A p-type (100) Ge substrate with a resistivity of 0.3Ω·cm was used. The Ge chips were dipped in dilute HF solution followed by rinsing in DI water. The chips were loaded in ALD chamber, and a 1 nm-Al_2O_3 film was deposited at 300°C. (1 cycle: 0.13 nm) After that, plasma oxidation in ECR chamber was carried out at RT for 1 min. The oxidation conditions were a microwave power of 500 W, Kr/O_2 flow rates of 10/1.67 sccm, and Ar/O_2 flow rates of 18/3 sccm. The XPS spectra before and after Kr/O_2 plasma oxidation are shown in Fig. 1. For the sample without the plasma oxidation, an oxidized Ge 3*d* peak was not observed. By contrast, the plasma oxidation sample showed clear oxidized Ge 3*d* peak at 32.0 eV, which is mostly originated from GeO_2. The signal intensity ratio of GeO_X to Ge bulk for the oxidation sample is close to that for 1.0 nm-thick thermally grown GeO_2/Ge sample. Thus, the thickness of GeO_X underlying Al_2O_3 was around 1 nm. The XPS spectrum of an Ar/O_2 plasma oxidized sample was identical to that of Kr/O_2 plasma.

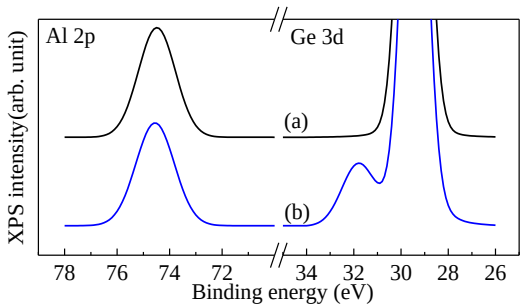

Fig. 1 XPS spectra of 1 nm-Al_2O_3 ALD samples (a) before and (b) after Kr/O_2 plasma oxidation.

For MOSCAP fabrication, a 3.9 nm-Al_2O_3 film was deposited on Al_2O_3/GeO_X/Ge stack by the second ALD, and then PDA was carried out at 400°C for 30 min. A 50 nm-TiN film was deposited, followed by PMA at 350°C for 20 min. Then an Al film was deposited by evaporation and patterned with an area of 2.25×10^{-4} cm^2.

Metal S/D p-MOSFETs were fabricated on n-type (100) Ge substrate with a resistivity of 0.4Ω·cm. After surface cleaning, 10 nm-thick Hf and 10 nm-thick TiN films were deposited using rf sputtering. Metal S/D was patterned by lift-off technique. The gate stack was formed using the same procedure mentioned above.

4. Results and Discussion

Figure 2 shows *C-V* characteristics of MOSCAPs with Kr/O_2 and Ar/O_2 plasma oxidations. The equivalent oxide thickness (EOT), hysteresis (HT) and flat band voltage (V_{fb}) are summarized in Fig. 2. The both MOSCAPs showed well-behaved *C-V* characteristics, showing the same EOTs of 2.9 nm. From the EOT versus the physical thickness of Al_2O_3 for some capacitors with different Al_2O_3 thicknesses, a permittivity of the deposited Al_2O_3 film was determined to be 8.47. By taking into account a GeO_2 permittivity of 0.60, the GeO_X thickness underlying Al_2O_3 was estimated as 1.0 nm, which agreed well with XPS results. The fixed oxide charges deduced from V_{fb} values were $7x10^{10}$ and $6x10^{11}$ cm^{-2} for MOSCAPs with Kr/O_2 and Ar/O_2 plasma oxidations, respectively. Furthermore, HT of the MOSCAP with Kr/O_2 oxidation was smaller compared with that with Ar/O_2. The D_{it} distributions for both MOSCAPs, measured by constant temperature DLTS measurement [5], are shown in Fig. 3. It was found that D_{it} in the lower half of the band gap was reduced by Kr/O_2 oxidation, in particular, the D_{it} near the valence band edge fell to half. From comparison of the electrical properties for both MOSCAPs, it is concluded that Kr/O_2 plasma oxidation is effective to improve interface properties of $Al_2O_3/GeO_x/Ge$ gate stack. Note that *J-V* characteristics for both MOSCAPs were no significant difference, showing high electric breakdown field of 16 MV/cm.

Figure 4 shows I_D-V_D and I_D (I_S)-V_G characteristics of p-MOSFETs with HfGe-S/D and EOTs of 3 nm fabricated using Kr/O_2 and Ar/O_2 plasma oxidations. The MOSFET with Kr/O_2 plasma oxidation showed higher current drivability compared with that with Ar/O_2. The subthreshold slopes of MOSFETs with Kr/O_2 and Ar/O_2 oxidations were 74.3 and 76.3 mV/dec, respectively, corresponding to D_{it}s of 1.1 $x10^{12}$ and $1.5x10^{12}$ $eV^{-1}cm^{-2}$, which were almost the same as DLTS results. The peak field-effect hole mobilities before and after the S/D parasitic resistance correction were 237 and 253 cm^2/Vs for the Kr/O_2 oxidation, and 209 and 223 cm^2/Vs for the Ar/O_2, respectively. This difference would be attributed to the quality improvement of GeO_X interlayer by the Kr/O_2 oxidation.

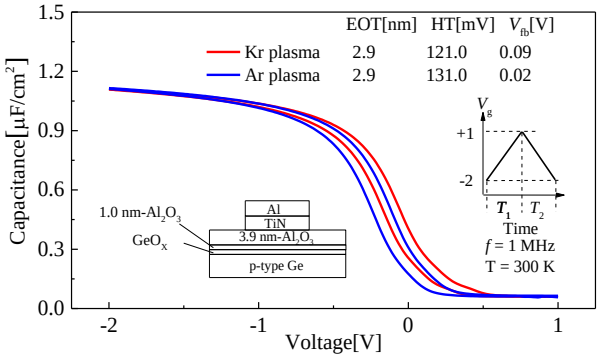

Fig. 2 *C-V* characteristics of $Al/TiN/Al_2O_3/GeO_X/p$-Ge MOSCAPs fabricated by Kr/O_2 and Ar/O_2 plasma oxidation.

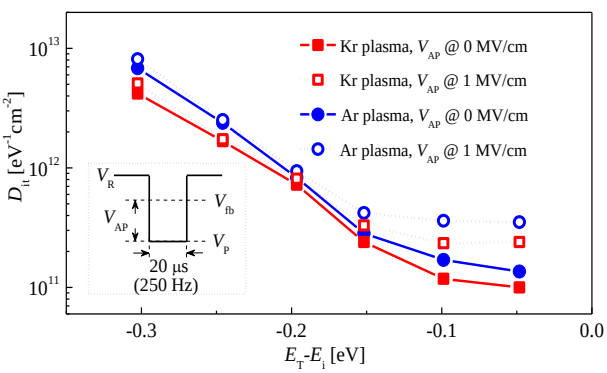

Fig. 3 D_{it} distributions of MOSCAPs with Kr/O_2 and Ar/O_2 plasma oxidations. Solid symbols: accurate D_{it}s. Open symbols: D_{it}s including slow trap component. [5]

5. Conclusion

We demonstrated usefulness of Kr/O_2 plasma oxidation for fabricating $Al_2O_3/GeO_X/Ge$ gate stacks from a comparative study with Ar/O_2 plasma oxidation. The interface properties of MOSCAP with Kr/O_2 plasma oxidation were much better than that of Ar/O_2 oxidation. The peak hole mobilities of MOSFETs were 253 and 223 cm^2/Vs for the Kr/O_2 and Ar/O_2 oxidations, respectively. These results indicated that Kr/O_2 plasma oxidation is a promising method as GeO_x formation under the Al_2O_3 film.

References

[1] K. Yamamoto et al., APEX. **5** (2012) 051301.
[2] R. Zhang et al., APL. **98** (2011) 112902.
[3] K. Sekine et al., IEEE Trans. ED **48** (2001) 1550.
[4] J. Wang et al., JJAP **42** (2003) 6496.
[5] D. Wang et al., JAP **112** (2012) 083707.

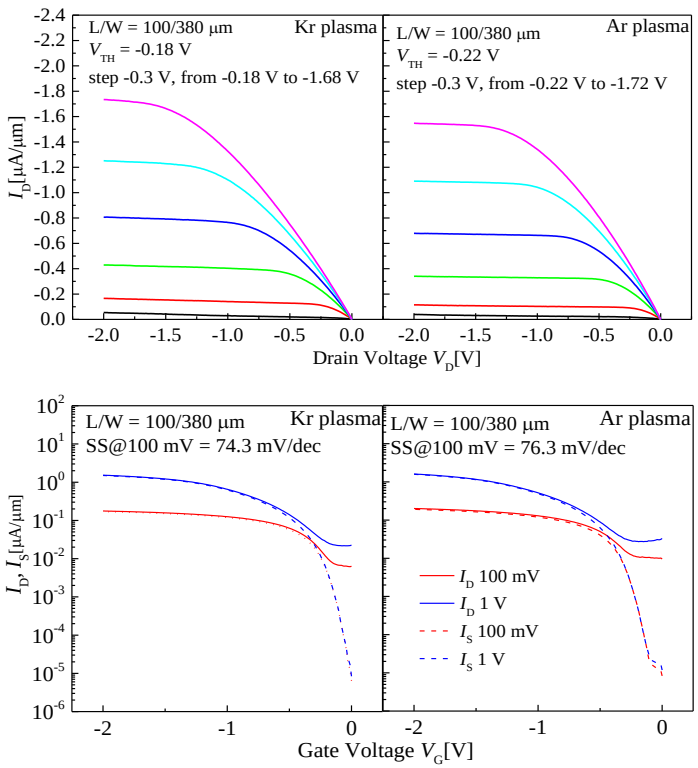

Fig.4 I_D-V_D and I_D (I_S)-V_G characteristics of HfGe-S/D Ge p-MOSFETs with $Al_2O_3/GeO_X/Ge$ gate stacks fabricated using Kr/O_2 and Ar/O_2 plasma oxidations.