Evaluation of surface potential of ferroelectric-gate MOS capacitors by C-V analyses

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【Background】 MOSFETs using HfO_2-based-ferroelectric gate insulators have been expected as a steep slope device, because of the negative capacitance (NC) effect, which could be stabilized when placed in series with a paraelectric insulator in theory [1]. However, the reality of the quasi-static NC effect, predicted by the theory, has still be controversial [2]. In order to verify the quasi-static NC effect, the accurate determination of the surface potential (φ_s) with changing gate voltage (V_g) is necessary. In this study, thus, we examine to evaluate φ_s of metal/ferroelectric/ Si (MFS) and metal/ferroelectric/insulator/Si (MFIS) capacitors with $HfZrO_2$ as a function of V_g and the sensitivity ($\Delta\varphi_s/\Delta V_g$) through the capacitance-V_g analyses.

【Experiments】 Fig. 1 shows the structure and fabrication process of MFS and MFIS capacitors on Si substrates, and SiO_2 MOS capacitors fabricated on the same substrates as the reference. The *C-V* measurement was performed to evaluate φ_s through the comparison with theoretical C-V characteristics under a constant substrate impurity concentration (N_{sub}) [3]. $\Delta\varphi_s/\Delta V_g$ can be determined as a function of φ_s from this estimated φ_s. Note that when the quasi-static NC effect exists, $\Delta\varphi_s/\Delta V_g$ is expected to be larger than 1.

【Results and discussion】 Fig. 2 shows the *C-V* measurement results with different waiting times before backward scanning of all samples. During the waiting time, the maximum positive V_g, corresponding to the inversion condition, is applied. In the SiO_2 MOS capacitor, deep depletion is observed for fast voltage sweep, but disappears under long waiting times (10 s and 100 s) as expected. However, in both MFS and MFIS capacitors, deep depletion does not disappear even at long waiting times, indicating that N_{sub} cannot be directly determined by the C-V curves. It is assumed, thus, that N_{sub} in the MFS and MFIS capacitors is the same as in the SiO_2 MOS capacitor, obtained from the *C-V* characteristics under the inversion condition. Also, small counter-clockwise hysteresis suggests no polarization switching due to the small V_g swing. Fig. 3(a) and (b) show the method to extract φ_s from the experimental results and the estimated $\Delta\varphi_s/\Delta V_g$ as a function of φ_s, respectively. It is observed in a region between the flatland and the midgap that the surface sensitivity is over than 1 for both in the MFS and MFIS capacitors. Note that the *C-V* results in the depletion region can be hardly affected by the minority carrier response under deep depletion. This result could possibly suggest the existence of the quasi-static NC effect in the MFS and MFIS capacitors, whereas further careful considerations including the understanding of the physical origin of the deep depletion behaviors would be needed.

【Conclusion】 It was found that the strong deep depletion occurs in *C-V* curves of both in the MFS and MFIS capacitors even in long waiting times. Under the assumption of the same N_{sub}, the surface sensitivity was estimated and the values higher than 1 was observed in the depletion region. This result possibly suggests that the quasi-static NC effect can exist in the MFS and MFIS structures, while further careful examination on the experimental conditions might be needed.

【References】 [1] S. Salahuddin et al, Nano Lett. **8**, 405, 2008. [2] M. Alam et al., Appl. Phys. Lett. , 2019 [3] H. Katto et al., IECE 57-C, 195 (1974)

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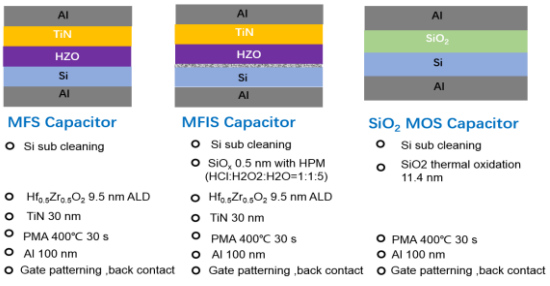

Fig. 1 Sample structure and process flow

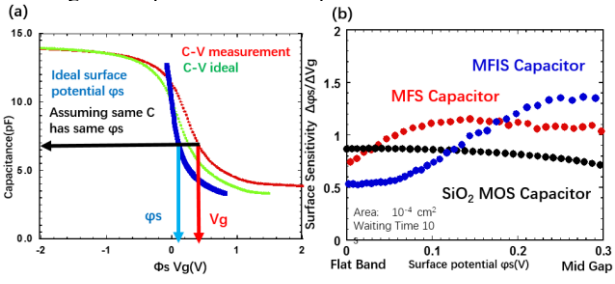

Fig.3 (a) Principle of capacitance analysis. (b) Surface sensitivity of SiO_2 MOS, MFS, and MFIS Capacitors.

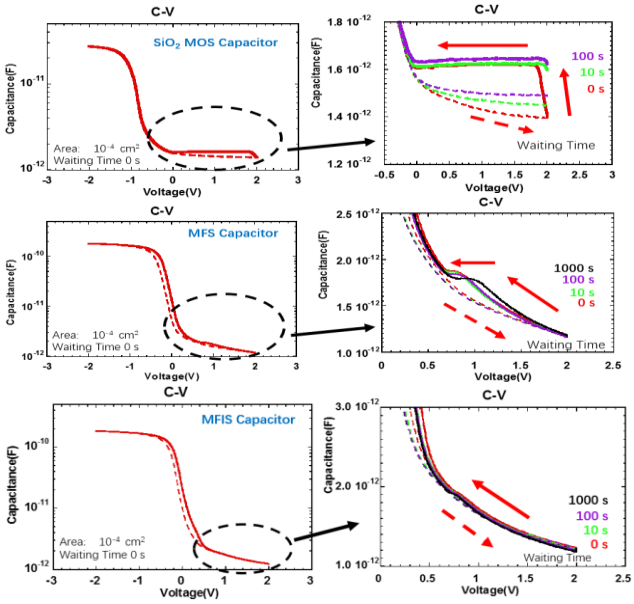

Fig. 2 C-V curves of SiO_2 MOS, MFS, MFIS capacitors with waiting times varied from 0 s to 1000s