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Performance enhancement of Si MOSFETs using anti-ferroelectric thin films as gate insulators

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Abstract

The contribution of anti-ferroelectric (AFE) gate insulators to the on-current (I_{on}) of Si MOSFETs is examined by simulation. A minor loop of P-E characteristics of HZO is found to increase I_{on} of MOSFETs without any hysteresis in the off condition. Also, AFE with P_{AF}/q of 1~2x10^{13} cm^{-2} are expected to significantly improve the performance of MOSFETs. These results suggest the effectiveness of MOSFETs with single AFE gate insulators.

1. Introduction

MOSFETs with ferroelectric (FE) gate insulators have stirred a strong interest recently. In particular, FET operation based on the concept of negative capacitance (NC) [1] is expected to improve the I_{on}/I_{off} characteristics. It has been reported [2] that I_{on} changes systematically by adjusting P_r and E_c of a FE gate insulator. However, it is not fully revealed if the negative capacitance is realized for applied gate voltage near 0 V [3]. If NC would not be available, large hysteresis could appear in I_d-V_g characteristics of FET (Fig. 1), leading to a serious problem in low voltage operation. On the other hand, when an anti-ferroelectric (AFE) material is used as a gate insulator, small hysteresis of I_d-V_g characteristics and increase in I_{on} are expected (Fig. 2). This is because the *P-E* characteristics of AFE show almost no hysteresis loop around 0 V. A theoretical study has reported that the AFE-FE stacks can improve I_{on} of MOSFETs under the existence of NC [4]. However, the effectiveness of AFE stacks only on the MOSFET performance without NC effects has not been revealed yet. In this study, therefore, we study I_d-V_g characteristics of MOSFETs with single AFE gate insulators through simulations using simple analytical models and examine the effectiveness of the increase of I_{on}.

2. Simulation method

The Gibbs free energy of AFE materials can be given by the equation of the polarizations of sub-lattices [5]. The relation between applied electric field and entire polarization of AFE materials can be described by the Cross model [6]. AFE materials have two phases. When electric field is near zero, the AFE phase is stable. With increasing electric field, the AFE-to-FE phase transition occurs at threshold field E_{AF} [7]. Simple analytical *P-E* curves of AFE $Hf_{0.1}Zr_{0.9}O_2$, $Hf_{0.2}Zr_{0.8}O_2$ and $Hf_{0.4}Zr_{0.6}O_2$ films, based on the Cross model, were determined by fitting to experimental ones (Fig. 3) [8] after choosing parameters of forward and backward switching field E_{AF} and E_{FA} and the polarization P_{AF} and P_{FA}. The differential permittivity, defined by the derivative at E = 0 MV/cm, of $Hf_{0.1}Zr_{0.9}O_2$, $Hf_{0.2}Zr_{0.8}O_2$ and $Hf_{0.4}Zr_{0.6}O_2$ were 24.2, 32.2 and 44.1 respectively. The physical thickness of these films, determined so as for EOT to be 0.5 nm, were 3.10, 4.13 and 5.66 nm. The I_d-V_g characteristics of MOSFETs were calculated by combining the result of TCAD simulation with the voltage across AFE gate insulators determined on an assumption that P/q is equal to the surface carrier concentration in MOS inversion layers, N_s.

3. Results and discussion

Fig. 4(a) and (b) show the simulated I_d-V_g characteristics of AFE $Hf_{0.1}Zr_{0.9}O_2$, $Hf_{0.2}Zr_{0.8}O_2$ and $Hf_{0.4}Zr_{0.6}O_2$ MOSFETs. In comparison with MOSFETs with 0.5-nm-thick SiO_2, no improvement in I_{on} is observed, which is attributable to P_{AF}/q much higher than the maximum surface carrier concentration (N_s of 1~2x10^{13} cm^{-2}) available in conventional MOSFETs. It is known, on the other hand, that HfZrO films under electric field weaker than E_c still show smaller hysteresis loops in the *P-E* curves (minor loops) [9]. Therefore, the model of $Hf_{0.4}Zr_{0.6}O_2$ was corrected to fit more to the reported *P-E* curve in low *E* (Fig. 5). It is found that, when the physical thickness is adjusted to provide the same EOT, I_{on} can be improved in the $Hf_{0.4}Zr_{0.6}O_2$ MOSFETs (Fig. 6(a) and (b)). This is attributable to N_s enhanced by the rapid increase in P with an increase in E.

Next, the ideal *P-E* characteristics of AFE were examined in terms of the I_{on} enhancement. Fig. 7(a) and (b) show *P-E* characteristics of imaginary AFE films and the resulting I_d-V_g characteristics of the AFE MOSFETs, respectively. Here, the value of P_{AF}, polarization at the AFE-to-FE phase transition [7], was varied among 6.1, 3.0 and 1.0 cm^{-2} as a parameter. P_{AF} of 6.1 cm^{-2} was the same as in $Hf_{0.4}Zr_{0.6}O_2$. It is found that I_{on} increases with a decrease in P_{AF}. This is because P_{AF}/q approaches the maximum N_s and the rapid increase in P near P_{AF} can effectively contributes to the I_{on} increase. Fig. 8 shows I_{on} of the AFE MOSFETs as a function of P_{AF}. It is found that there is the optimum P_{AF} value for maximizing I_{on}. This result indicates that AFE materials with P_{AF}/q of 1~2x10^{13} cm^{-2}, comparable to the maximum N_s available in conventional MOSFETs, are strongly required for the MOSFET application.

4. Conclusions

The performance of MOSFETs with the AFE only gate stack was studied through simulation. For MOSFETs with existing HZO AFE, the increase in P of a minor *P-E* loop in a low E region can lead to the increase I_{on} of MOSFETs under a give EOT. Also, AFE gate insulators with P_{FA}/q of 1~2x10^{13} cm^{-2} are expected to significantly improve the performance of MOSFETs.

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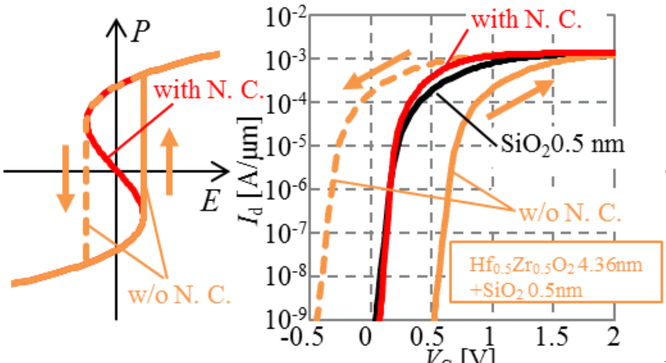

Fig. 1 Schematic P-E curve of ferroelectric film and I_d-V_G characteristics of ferroelectric $Hf_{0.5}Zr_{0.5}O_2$ MOSFET.

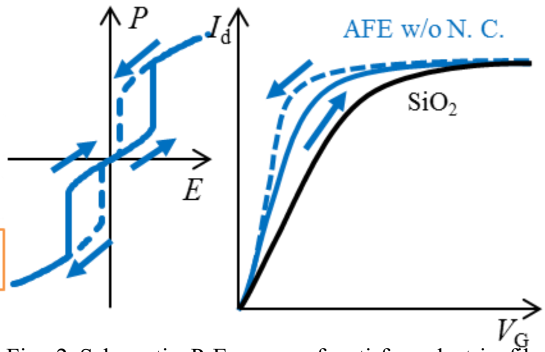

Fig. 2 Schematic P-E curve of anti-ferroelectric film and expected I_d-V_G characteristics of AFE MOSFET.

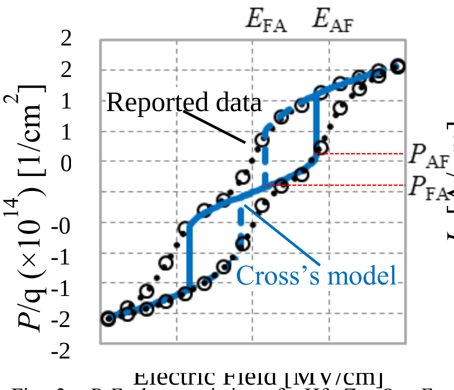

Fig. 3 *P-E* characteristics of $Hf_{0.4}Zr_{0.6}O_2$. E_{FA} represent the backward witching field for inducing the FE-to-AFE phase transition.

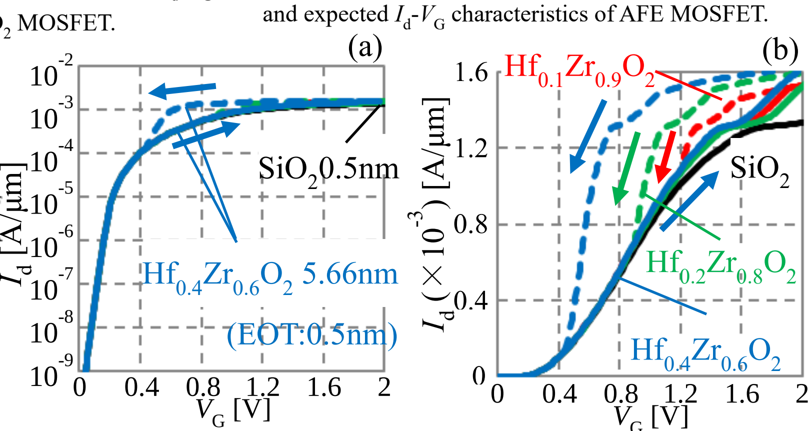

Fig. 4 I_d-V_G characteristics of AFE MOSFET. The physical thickness of $Hf_{0.4}Zr_{0.6}O_2$, $Hf_{0.4}Zr_{0.6}O_2$ and $Hf_{0.4}Zr_{0.6}O_2$ are 3.10, 4,13 and 5.16nm respectively.

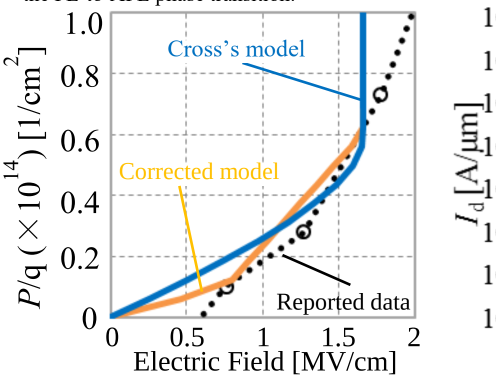

Fig. 5 *P-E* characteristics of corrected model.

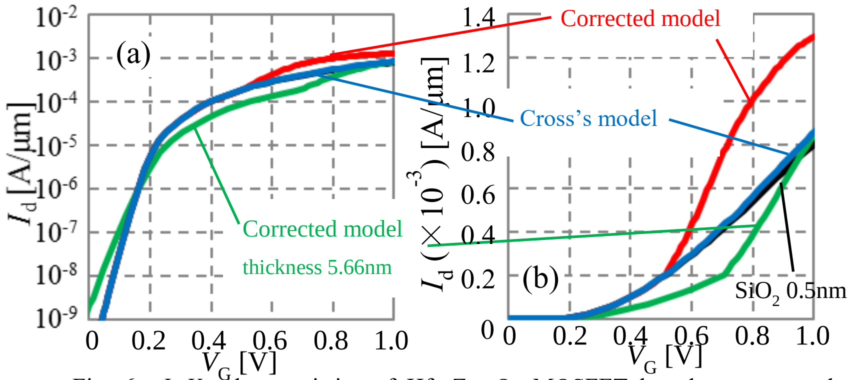

Fig. 6 I_d-V_G characteristics of $Hf_{0.4}Zr_{0.6}O_2$ MOSFET based on corrected model. For comparison, physical thickness is equal to Cross's model (5.66nm) or EOT is equal to Cross's model (physical thickness is 3.13nm).

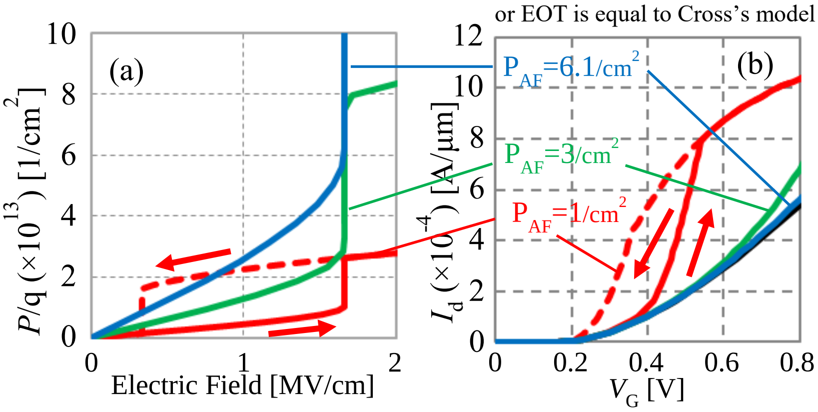

Fig. 7 *P-E* characteristics of imaginal AFE film and I_d-V_G characteristics of AFE MOSFET. When V_G is 0.8 V, hysteretic characteristic exists for switching polarization P_{AF} =1 cm^{-2}.

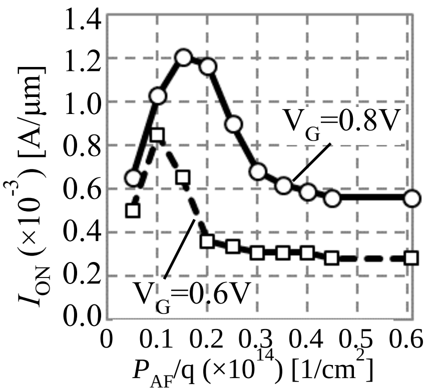

Fig. 8 On-current of AFE MOSFET as a function of switching polarization P_{AF} .