S-curve Engineering for ON-state Performance using Anti-ferroelectric/Ferroelectric Stack Negative-Capacitance FinFET

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Abstract—This work investigates the S-curve engineering by exploiting the anti-ferroelectric (AFE)/ferroelectric (FE) stack negative-capacitance FinFET (NC-FinFET) to improve both the subthreshold swing and ON-state current (I_{ON}). The capacitance matching and ON-state performance are evaluated by using a short-channel AFE/FE stack NC-FinFET model. Our study indicates that the AFE/FE gate-stack can theoretically achieve surprising improvements to the OFF-state current (I_{OFF}) and I_{ON} relative to IRDS projections. There is significant long-term advantage to IC power consumption and speed if materials with certain AFE and FE characteristics can be developed and introduced into IC manufacturing.

Index—metal-ferroelectric-insulator-semiconductor (MFIS)-type negative-capacitance field-effect transistor (NCFET), anti-ferroelectric

Terms—FinFET, (MFIS)-type negative-capacitance field-effect transistor (NCFET), anti-ferroelectric

I. INTRODUCTION

NEGATIVE-capacitance field-effect transistor (NCFET) [1]-[12], especially NC-FinFET [2]-[10] has garnered substantial interest as the next-generation logic transistor because it can provide steeper subthreshold slope ($SS < 60$ mV/dec.) and much reduced short-channel effects [7]-[12]. However, the performance of the NCFET depends on the capacitance matching between the ferroelectric capacitance (C_{fe}) and the internal capacitance (C_{int}), which is challenging because both are strongly bias dependent [6]. **Fig. 1(a)** illustrates that for an NCFET with a single-layer ferroelectric, it is very difficult to obtain good capacitance matching all the way from subthreshold to strong inversion by changing the ferroelectric properties such as the remnant polarization (P_r). The ON-state performance of the NCFET is usually degraded due to the degraded internal-voltage amplification (A_V) [6] in strong inversion. It is possible to obtain the anti-ferroelectric (AFE) phase of doped HfO_2 in addition to the ferroelectric (FE) orthorhombic phase [13]-[17]. In this paper, with the aid of a

Figure 1. Capacitance matching at source end (i.e., $y=0$) with various P_r and schematic for MFIS-type (a) single-layer and (b) AFE/FE stack NC-FinFET. Fig. 1(a) indicates that, albeit reducing P_r improves capacitance matching in the subthreshold region, it degrades capacitance matching in strong inversion. The doping concentrations of source/drain and channel (N_{ch}) are $1E20\text{ cm}^{-3}$ and $1E15\text{ cm}^{-3}$, respectively. Abrupt junction is assumed. T_{AFE} , T_{FE} and T_{IL} are thicknesses of anti-ferroelectric, ferroelectric and interfacial-layer, respectively.

developed short-channel AFE/FE stack NC-FinFET model, we propose to boost the ON-state performance by engineering the S-curve of the metal-ferroelectric-insulator-semiconductor (MFIS) type AFE/FE stack NC-FinFET. [Fig. 1(b)]

This paper is organized as follows. In Section II, we present our methodology for constructing the MFIS-type AFE/FE stack NC-FinFET model. In Section III, by using a short-channel AFE/FE stack NC-FinFET model calibrated with published FinFET data [19], the capacitance matching and ON-state performance of the AFE/FE stack NC-FinFET are evaluated. Based on IRDS [20] parameters, the projection of the performance of the AFE/FE stack NC-FinFET for future technology nodes will be investigated in section IV. Finally, Section V draws the conclusion.

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II. METHODOLOGY

In this section, a short-channel MFIS-type AFE/FE stack NC-FinFET model compatible with BSIM-CMG is developed. Without an internal metal between the ferroelectric and interfacial layer, **Fig. 1(b)** shows a schematic sketch of the MFIS-type AFE/FE stack NC-FinFET structure modeled in this work. Note that different from the MFIS-type NC-FinFET with a uniform polarization charge distribution in the ferroelectric, the internal charge in the MFIS-type gate stack varies with the channel position y (which is known as the MFIS-specific distributed charge effect) [8][9]. Based on the surface potential-based scheme of BSIM-CMG, the internal charge, Q_{int} , and internal voltage, V_{int} , of the NC-FinFET can be determined as follows:

$$Q_{int}(y) = C_{ox} \left(V_{int}(y) - V_{fb} - V - V_t \ln \left(\frac{8\epsilon_s V_t N_{ch}}{qn_i^2 W_{fin}^2} \right) - 2V_{th} \ln \left(\frac{\beta}{\cos \beta} \right) - \varphi_{per} \right) \quad (1)$$

$$Q_{int}(y) = \frac{4\epsilon_s V_{th}}{W_{fin}} \times \sqrt{\frac{\beta^2 \left[\frac{e\varphi_{per}/V_{th}}{\cos^2 \beta} - 1 \right]}{+ \frac{\varphi_{per}}{V_{th}^2} \{ \varphi_{per} - 2V_{th} \ln[\cos \beta] \}}} \quad (2)$$

$$V_{int}(y) = V_{gs} - V_{AFE}(y) - V_{FE}(y) \quad (3-a)$$

where V_{fb} is the flat-band voltage, ϵ_s the permittivity of the channel, n_i the intrinsic carrier concentration, V_{th} the thermal-voltage given by $k_B T/q$ and V the quasi-Fermi potential. Note that the internal-voltage (V_{int}) varies with the channel position, which is related to the voltage drop across the anti-ferroelectric (V_{AFE}) and ferroelectric (V_{FE}). We describe the anti-ferroelectric and ferroelectric properties by using the Kittel model [15][21] and Landau-Khalatnikov (L-K) equation [22], respectively:

$$V_{AFE}(y) = T_{AFE} \left[\begin{array}{c} (2\alpha_p + \alpha_n + 12\beta_{AFE} P_a^2) Q_{int}(y) \\ -P_a(\alpha_n + 18\beta_{AFE} Q_{int}^2(y)) \\ -\beta_{AFE}(2P_a - Q_{int}(y))^3 + 7\beta_{AFE} Q_{int}^3(y) \end{array} \right] \quad (3-b)$$

$$V_{FE}(y) = T_{FE} [2\alpha_{FE} Q_{int}(y) + 4\beta_{FE} Q_{int}^3(y)] \quad (3-c)$$

where α_p , α_n , β_{AFE} and P_a are anti-ferroelectric parameters, while α_{FE} and β_{FE} are ferroelectric parameters.

The Kittel model [Eqn. (3-b)] and L-K equation [Eqn. (3-c)] have been seamlessly integrated into a unified surface potential equation. By self-consistently solving Eqn. (1), (2) and (3) under a given bias condition, the internal charge, Q_{int} , can be iteratively determined.

We have verified our Q-V model using TCAD numerical simulation [24]. **Fig. 2(a)** and **(b)** show the Q_{int} and corresponding V_{int} at the source end. It can be seen that the Q_{int} [**Fig. 2(a)**] for the AFE/FE stack case is larger than that of the single-layer one. Due to the negative capacitance effect, the internal voltage change can be greater than the change in applied voltage. With the impact of AFE, the $\Delta V_{int,AFE/FE}$ is larger than the $\Delta V_{int,FE}$ for a given gate-bias change (ΔV_{GS}) [as

Figure 2. Calculated (a) internal charge, Q_{int} , and (b) internal voltage, V_{int} , at the source end with varying V_{GS} . $\Delta V_{int,AFE/FE}$ and $\Delta V_{int,FE}$ in (b) are the changes in V_{int} for the AFE/FE stack and the single-layer FE, respectively, due to the change in V_{GS} . (c) Vertical electric field in the ferroelectric stack and interfacial layer at the source end. (d) Verification of capacitance matching at the source end for the single-layer FE case. The thicknesses of ferroelectric stack and interfacial-layer are 3.6 nm and 1 nm, respectively.

shown in **Fig. 2(b)**]. In addition, **Fig. 2(c)** further shows the vertical field in the ferroelectric stack and interfacial layer at the source end. It can be seen that the vertical field in the ferroelectric stack is opposite to that in the interfacial layer, and the average vertical field of the AFE/FE stack is larger than the single-layer FE one. **Fig. 2(d)** shows the comparison of our model-calculated capacitance matching with TCAD simulation [24] for the single-layer FE case.

Using the surface potential-based scheme, the drain current can be derived [8]:

$$I_{ds} = \frac{2\mu_n H_{fin}}{L_g} [F(Q_{int,d}) - F(Q_{int,s})] \quad (4)$$

where

$$F(Q_{int}) = A_4 Q_{int}^4 + A_3 Q_{int}^3 + A_2 Q_{int}^2 + A_1 Q_{int} \quad (5-a)$$

$$A_1 = V_{th} \quad (5-b)$$

$$A_2 = -T_{AFE} \left[\frac{1}{2} (2\alpha_p + \alpha_n + 24\beta_{AFE} P_a^2) + 12\beta_{AFE} P_a q N_{ch} W_{fin} - 3\beta_{AFE} q^2 N_{ch}^2 W_{fin}^2 \right] - T_{FE} \left[\alpha_{FE} + \frac{3}{2} \beta_{FE} q^2 N_{ch}^2 W_{fin}^2 + \frac{1}{2C_{ox} T_{FE}} \right] \quad (5-c)$$

$$A_3 = T_{AFE} (16\beta_{AFE} P_a - 8\beta_{AFE} q N_{ch} W_{fin}) - 4T_{FE} \beta_{FE} q N_{ch} W_{fin} \quad (5-d)$$

$$A_4 = -6T_{AFE} \beta_{AFE} - 3T_{FE} \beta_{FE} \quad (5-e)$$

Figure 3. Our model has been calibrated with the Intel 14-nm node ultra-low power (ULP) FinFET technology [19]. Intrinsic I_{ON} can be further improved for the AFE/FE stack NC-FinFET.

Figure 4. P-V curves for (a) 100% FE with various α_{FE} , (b) 100% AFE with various α_n , and (c) the AFE/FE stack. The symbols in (c) shows the operating points at different V_{GS} , indicating that the AFE/FE stack can extend the negative capacitance region and improve the A_V in strong inversion.

In addition, the V_{DS} and gate-length dependences in SS and V_T [10][11] are physically modeled with the analytical short-channel Q_{int} model [8].

The model is calibrated against the data of the Intel 14-nm node ultra-low-power (ULP) FinFET [19]. **Fig. 3** shows a good agreement with the experiment data of FinFET. It also shows the hysteresis-free I_{DS} - V_{GS} for both AFE/FE stack and

Figure 5. (a) Equivalent capacitance network of the AFE/FE stack NC-FinFET. The C_{afe} , C_{fe} and C_{int} are the anti-ferroelectric capacitance, ferroelectric capacitance and the internal capacitance, respectively. (b) Capacitance matching comparison at source end shows that the AFE/FE stack improves the high A_V region toward high V_{GS} .

single-layer NC-FinFETs simulation results are achieved by our model. Here 3.6 nm ferroelectric thickness and 1 nm interfacial-layer thickness are used for hysteresis-free operation. It can be seen that, after the action of negative capacitance, the subthreshold swing can be improved from 61 to 48 mV/decade for single-layer NCFET and to 49 mV/decade for AFE/FE stack NCFET, respectively. Besides improved SS and OFF-state current (I_{OFF}), AFE/FE stack (with 10% AFE) NC-FinFETs can achieve higher ON-state current (I_{ON}) compared to that of the single-layer NCFET and non-NC FET. In this paper, 10% AFE means the thickness of AFE (T_{AFE}) is 10% of the total ferroelectric thickness ($T_{FE} + T_{AFE}$). The anti-ferroelectric parameters used in this paper were obtained based on the saturation polarization ($P_s = 20 \mu C/cm^2$) and dielectric constant ($\epsilon_{AFE} = 25 \epsilon_0$) in [14]. The ferroelectric parameters of HfZrO used in this paper are: $\alpha_{FE} = -3.8 \times 10^9$ m/F, $\beta_{FE} = 3.37 \times 10^{11}$ m⁵/F/C², and $\gamma_{FE} = 0$ m⁹/F/C⁴. These values of α_{FE} , β_{FE} , and γ_{FE} were obtained based on the remnant polarization (P_r) and coercive field (E_c) data of HfZrO in [23].

III. S-CURVE AND CAPACITANCE MATCHING OF AFE/FE STACK NC-FINFET

By using the MFIS-type AFE/FE stack NC-FinFET model calculation, we investigate the impact of anti-ferroelectric on S-curve and capacitance matching for AFE/FE stack NC-FinFET in this section.

Fig. 4(a) and **(b)** show the P-V curves for 100% FE and 100% AFE films, respectively. It can be seen that the negative capacitance region (negative slope of P-V curve) for 100% FE [**Fig. 4(a)**] starts from zero voltage and the magnitude of C_{FE} decreases (i.e., A_V increases) with increasing α_{FE} . Different from the ferroelectric, the anti-ferroelectric exhibits a double negative-capacitance region [as shown in **Fig. 4(b)**] occurring at higher voltage. Moreover, the magnitude of C_{AFE} decreases with increasing α_n . Therefore, if the AFE and FE are stacked in series, it is possible that by carefully choosing the parameters α_{FE} and α_n , the AFE/FE stack can exhibit negative capacitance over a larger voltage range than that of the single-layer FE.

In this work, $\alpha_{FE} = -3.8 \times 10^9$ m/F and $\alpha_n = -1.2 \times 10^{10}$ m/F are used for the AFE/FE stack NC-FinFET to achieve larger A_V with hysteresis-free operation. **Fig. 4(c)** shows the P-V curve

Figure 6. The output characteristics for (a) single-layer and (b) AFE/FE stack NC-FinFETs. The AFE/FE stack NC-FinFET exhibits higher I_{DS} with increasing V_{GS} .

Figure 7. (a) Intrinsic I_{ON} ratio for AFE/FE stack to single-layer NC-FinFET with various V_{DD} and % of AFE. (b) Capacitance matching at source end and (c) S-curve comparison for AFE/FE stack NC-FinFET with various % of AFE.

comparison for the 100% FE and the AFE/FE stack cases. It can be seen that the trajectory from $V_{GS} = 0$ to 0.7 V are all in the negative capacitance region for the AFE/FE gate-stack. However, the operating point at $V_{GS} = 0.7$ V for the single-layer FE case moves away from the NC region, resulting in degraded A_V . In other words, the AFE/FE gate-stack can be utilized to enable large gains in strong inversion for NC-FinFETs.

Fig. 5(a) shows the equivalent circuit of the AFE/FE stack NC-FinFET. Although the single-layer NC-FinFET leads to internal-voltage amplification in the subthreshold region, the increasing $|C_{FE}|$ at high V_{GS} degrades the voltage-gain ($A_V = |C_{FE}| / (|C_{FE}| - C_{int})$) in strong inversion. Note that a higher A_V can be obtained if $|C_{FE}|$ is closer to C_{int} . Therefore, by adding some anti-ferroelectric, the effective ferroelectric capacitance (C_{FE}) is the series combination of the two capacitors (i.e. $C_{FE} = C_{fe} \parallel C_{afe}$) and can be engineered to improve ON-state current (I_{ON}). With first choosing the C_{fe} to optimize the subthreshold swing, the AFE can be chosen to extend the negative C_{FE} into the

Table 1. IRDS for 2020 to 2031 technology node [20].

Year (node)	FinFET		Gate-all-around (GAA)		
	2020 (5)	2022 (3)	2025 (2.1)	2028 (1.5)	2031 (1)
Mainstream device	FinFET	FinFET	LGAA	LGAA	LGAA
L_g (nm)	18	16	14	12	12
Fin width, W_{fin} (nm)	7	6			
Fin height, H_{fin} (nm)	50	60			
GAA width, W_{GAA} (nm)			25	20	15
GAA thickness, T_{GAA} (nm)			7	6	5
# of stacked GAA			3	3	4
Effective width, W_{eff} (nm)	107	126	192	156	160
V_{DD} (V)	0.7	0.7	0.65	0.65	0.6
SS (mV/dec.)	78	82	80	75	75
Intrinsic I_{ON} ($\mu A/\mu m$) (w/ $I_{OFF} = 1e-8$)	1733	1950	1670	1975	1696

Figure 8. I_{DS} - V_{GS} characteristics comparison for NC-FinFET and FinFET in (a) 2020 and (b) 2022 node. (c) Comparison of intrinsic I_{ON} for NC-FinFET and 2020/2022 FinFET.

strong inversion region to obtain the overall good capacitance matching. **Fig. 5(b)** shows the comparison of capacitance matching at the source end for different gate-stacks. It can be seen that the NC-FinFET with AFE/FE stack achieves a relatively flat negative capacitance at higher V_{GS} , achieving high- A_V in that region.

Fig. 6 shows the output characteristics of the single-layer and AFE/FE stack NC-FinFETs with various V_{GS} . It can be seen that the AFE/FE stack NC-FinFET can achieve larger I_{DS} than that of the single-layer due to the better capacitance matching and higher A_V in strong inversion. In reality, source-drain series resistance will make such high I_{DS} impractical. The likely strategy is to use lower V_{DD} to achieve much lower power consumption.

Fig 7(a) shows the ratio of intrinsic I_{ON} for AFE/FE stack to single-layer NC-FinFETs ($I_{ON,AFE}/I_{ON,FE}$) with varies V_{DD} and % of AFE. It can be seen that the optimum % (higher $I_{ON,AFE}/I_{ON,FE}$) of AFE is about 10% for $V_{DD} > 0.5$ V. As AFE

Figure 9. I_{DS} - V_{GS} characteristics comparison for NC-FinFET and GAA in (a) 2025 and (b) 2031 node. Inset: schematic of stacked GAA for each node.

Figure 10. Comparison of (a) intrinsic I_{ON} and (b) total intrinsic I_{ON} for NCFinFET and 2025~2031 stacked GAA. Here the fin-height for NC-FinFET is 60 nm (spec. of IRDS in 2022 node).

increases beyond the optimum %, $I_{ON,AFE}$ degrades rapidly. This is because the capacitance matching is dominated by AFE in strong inversion. **Fig. 7(c)** shows that, the slope of S-curve at low-voltage increase with % of AFE, which degrades the A_V in the threshold region and moves the high- A_V region to higher V_{GS} [**Fig. 7(b)**]. Furthermore, for low V_{DD} (< 0.5 V) condition, the capacitance matching is dominated by FE due to the A_V degradation of AFE at low voltage.

IV. PROJECTION BASED ON IRDS

The projection of IRDS for future FinFET and GAA are shown in [20] (**Table. I**). Using the parameters in the table, we simulate the potential performance improvement that FE and 10%-AFE/FE stack can theoretically achieve if AFE and FE materials assumed in our study are available. Our model is calibrated with each IRDS high performance 2020~2031 node through TCAD simulation before the FE or AFE-FE stack is introduced. Besides, in order to meet the tight pitch requirement for future advanced nodes, 1.8 nm T_{FE} and 0.5 nm T_{IL} are used in this section.

Fig 8(a) and **(b)** show the I_{DS} - V_{GS} characteristics FinFET and NC-FinFETs (single-layer and AFE/FE) for the 2020 and 2022 nodes, respectively. NC-FinFETs can theoretically achieve steeper SS and reduce OFF-state current (I_{OFF}), which can significantly reduce the static-power. Besides, AFE/FE stack NC-FinFETs have higher I_{ON} (I_{DS} at $V_{GS}=V_{DD}$) than the single-layer counterparts. The comparison of intrinsic I_{ON} for NC-FinFETs and 2020/2022 FinFET are shown in **Fig. 8(c)**. It can be seen that the intrinsic I_{ON} of NC-FinFET with AFE/FE stack can be further improved $\sim 2.6X$ than the single-layer, which means that the AFE/FE stack may reduce the pressure in fin-height up-scaling.

The IRDS **Table. I** shows that the mainstream device would change from FinFET to gate-all-around (GAA) due to electrostatic integrity requirement. The I_{DS} - V_{GS} characteristics comparison in **Fig. 9** shows that the NC-FinFET can exhibit superior subthreshold IV than GAA counterparts for 2025 and 2031 nodes. Furthermore, **Fig. 10(a)** shows the comparison of intrinsic I_{ON} for NC-FinFET and 2025~2031 GAA. It can be seen that, while the intrinsic I_{ON} for the single-layer NC-FinFETs is potentially larger ($\sim 1.5X$) than that of GAA, the intrinsic I_{ON} for the NC-FinFETs with AFE/FE stack can be further improved to $\sim 2X$.

Fig. 10(b) shows the comparison of total intrinsic I_{ON} for 2025~2031 GAA (inset in **Fig. 9**) and NC-FinFET. Here the fin-height for NC-FinFET is 60 nm (spec. of IRDS in 2022 node). It shows that, due to the technology process limitation of fin-height for NC-FinFET, the total intrinsic I_{ON} for single-layer is comparable to the stacked GAA in 2025 node. By adding some AFE, the total intrinsic I_{ON} can be further improved $\sim 2.3X$ for the AFE/FE stack NC-FinFET. Besides, the total intrinsic I_{ON} of GAA slightly decreases from 2028 to 2031 node. The AFE/FE stack NC-FinFET can help to improve I_{ON} . In other words, NC-FinFET with AFE/FE stack has the potential to sustain I_{ON} improvement for 2025~2031 nodes. It should be noted that this theoretical study assumes the availability of materials with certain AFE and FE properties, and the AFE/FE stack is purely capacitive. In reality, implementing such a thin AFE/FE stack without resistive components is very challenging, and demands more research in the future.

V. CONCLUSION

In this work, we report that the AFE/FE gate-stack can be utilized to engineer the S-curve for boosting the I_{ON} of NC-FinFET. By using a short-channel BSIM-CMG compatible AFE/FE stack NC-FinFET model, the capacitance matching and ON-state performance for AFE/FE stack NC-FinFETs are investigated. Our study indicates that, the AFE/FE gate-stack can be used to improve the capacitance matching in strong inversion at higher gate-bias. Therefore, impressively higher ON-state current (compared to single-layer) can be achieved. In reality, source-drain series resistance will make such high I_{DS} impractical. The more likely strategy is to use lower V_{DD} to achieve much lower power consumption (and reduced vertical fields). While the transient NC effect [25][26] also needs to be carefully investigated, this study suggests significant long term benefits to V_{DD} scaling if materials with certain AFE and FE properties are developed and introduced in IC manufacturing in the future.

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