

# 博士論文（要約）

## **Study on Ferroelectric-FET with Steep Subthreshold Slope for Low Power LSI Applications**

（低消費電力 LSI 応用に向けた急峻サブスレシヨルド係数を有する強誘電体トランジスタに関する研究）

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Negative capacitance field-effect transistor (NCFET) has become one of the most promising low power transistor solutions with steep subthreshold swing (SS) in the form of ferroelectric field-effect transistor (FeFET) with ferroelectric  $\text{HfO}_2$ . NCFET has many advantages including (1) high on-state current, (2) CMOS-compatible material and process, and (3) minimum circuit design modification.

NCFET/FeFET with sub-60 SS has been experimentally demonstrated by many research groups. However, its physical mechanism is still under debate; how NC effect emerges in ferroelectric thin film is one of the most important questions remained to be answered. The original quasi-static NC (QSNC) theory fails to explain a part of experimental results such as voltage sweep range and measurement time dependent subthreshold characteristics. Therefore, alternative explanation for NC effect and sub-60 SS is necessary for better understanding the operation mechanism of NCFET. Systematic simulation and experimental study are also strongly required for physical understanding of NC effect.

In this dissertation, first, mechanisms of NC effect and steep SS of NCFET are investigated from the perspective of the transient NC (TNC) theory which is different from the original approach. A dynamic ferroelectric model based on classical polarization switching dynamics without traversing the S-curve predicted by Landau theory is developed. The dynamic ferroelectric model is applied to a ferroelectric-dielectric (FE-DE) series capacitor as well as FeFET after calibration and verification by transient measurement of a ferroelectric  $\text{HfO}_2$  capacitor. By investigating current through the FE-DE series capacitor and the gate capacitor of FeFET, we find that incomplete screening of spontaneous polarization charge results in TNC and thus sub-60 SS. In addition, for FeFET, small depletion layer capacitance has an important role to cause strong depolarization effect and thus steep SS. According to the simulation results, the TNC theory provides a reasonable interpretation for the previously reported steep SS of NCFET.

Then, to verify the TNC theory, we have experimentally studied and revealed the direct relationship between polarization switching and subthreshold characteristics of  $\text{HfO}_2$ -based FeFET and anti-ferroelectric FET (A-FeFET) by systematically designing and fabricating devices, and monitoring (gate current)  $I_g$  with high resolution. In the circumstances that charge injection prevents polarization switching from occurring in subthreshold region of FeFET, we have obtained two major findings: (1) Sub-60 SS is observed by adjusting  $V_g$  bias sequence, which is attributed to charge injection assisted by polarization switching. (2) Anti-ferroelectric facilitates to align polarization switching in subthreshold region even with charge injection and SS can be improved in A-FeFET

as a consequence, which verified the TNC theory in nearly quasi-static condition.

Next, we investigate reverse DIBL (R-DIBL) and negative differential resistance (NDR) which are two special phenomena observed in FeFET with steep SS by the previous developed simulation framework with TNC. Simulation results show TNC with polarization reversal and depolarization effect can result in not only sub-60 SS, but also R-DIBL and NDR without the requirement of the S-curve predicted by Landau theory. Moreover, the mechanisms of R-DIBL and NDR based on the TNC theory are discussed in detail. After that, we systematically characterized the  $\Omega$ -gated Fin-FeFET to study the relationship among sub-60 SS, R-DIBL and NDR, which was predicted by former simulation work based on the TNC theory. These three phenomena occurred at the same current level and the physical mechanism of these three phenomena is confirmed to be TNC by taking into account the impact of charge trapping.

Finally, charge trapping and fixed charge are considered in our simulation framework of TNC. The roles of charge trapping and fixed charge on subthreshold characteristics of FeFET are investigated by simulation. The simulation results show that both charge trapping and fixed charge can modulate subthreshold characteristics of FeFET by operation point shift. In addition, sub-60 SS in reverse sweep only with nearly hysteresis-free operation (typical measurement results for NCFET) can be qualitatively reproduced by our simulation framework of TNC, if both charge trapping and fixed charge are well considered.