INVESTIGATION OF NEGATIVE CAPACITANCE EFFECT FROM DOMAIN SWITCHING DYNAMICS

Kunkun Zhu[1,2]*, Qianqian Huang*[2*]*, Huimin Wang*[2]*, Mengxuan Yang*[2]*,*
Yang Zhao[2]*, Zhongxin Liang*[2]*, Hao Pan*[3]*, Jing Ma*[3]*, and Ru Huang*[2*]
[1]Shenzhen Graduate School, Peking University, Shenzhen 518055, China
[2]Key Laboratory of Microelectronic Devices and Circuits (MOE), Institute of Microelectronics, Peking University, Beijing 100871, China
[3]Department of Materials Science and Engineering, Tsinghua University, Beijing 100084, China
[*]E-mail: hqq@pku.edu.cn; ruhuang@pku.edu.cn

ABSTRACT

In this work, the negative capacitance (NC) effect of a ferroelectric (FE) capacitor is experimentally investigated. Both negative and positive capacitance in FE are observed, and further analyzed from the perspective of domain switching dynamics. It is shown that the negative or positive capacitance in FE depends on the competition between the expansion and contraction forces of new domains. Experimental results indicate that a small and slow voltage drop near the maximum sweeping voltage applied on FE is more helpful to enhance the NC effect.

Keywords—Negative Capacitance effect; domain switching dynamics; polarization switching; domain wall motion; sideways expansion

INTRODUCTION

The negative capacitance (NC) effect has attracted great attention in recent years, which enables the sub-60 mV/decade subthreshold swing (SS) for ferroelectric field-effect-transistors (FeFETs) at room temperature. To verify the NC effect, extensive experiments have been studied in the series systems consisted of the FE capacitor and the external circuits, and the derived negative slope segment in the Polarization-Voltage (P-V) hysteresis loop of FE is considered to be the evidence of the emergence of NC effect [1-3]. However, the fundamental physics of NC effect is still not clear and controversial.

Until very recently, we have observed the NC effect directly in a standalone FE capacitor for the first time and directly verified that the physical origin of NC phenomena is related to domain switching dynamics of FE [4]. Further physical investigation of NC effect in FE is required from the microscopic physical viewpoint, since it is crucial for the device modeling and design optimization.

In this work, the experimental study of NC effect in a standalone FE capacitor is demonstrated. Moreover, both NC and positive capacitance (PC) are obtained, and the dynamic growth process of newly formed domains in the FE film is given to illustrate the physical origin of NC effect.

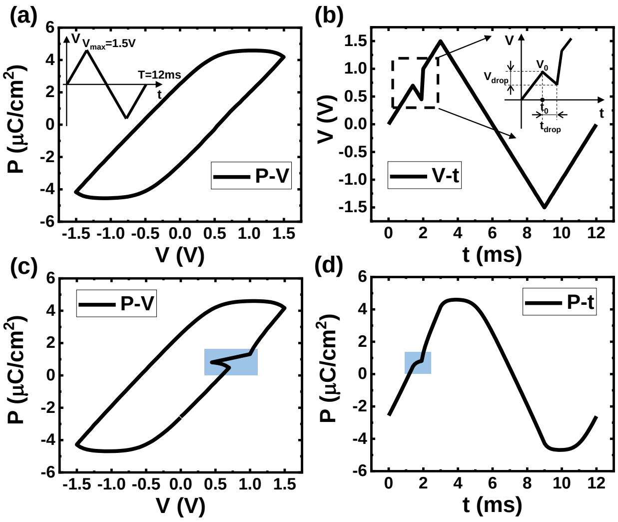

Fig. 1 (a) P-V curve of HZO-based FE capacitor with the applied triangular voltage pulse as the inset shows; (b) Applied voltage versus time. The inset is an enlarged view of the negative slope segment of V-t curve; (c) Measured P-V curve with an obvious negative slope segment; (d) Measured P-t response curve. The highlight area represents the P-t curve during the voltage drop.

DOMAIN SWITCHING DYNAMICS OF NC EFFECT

$Hf_{0.5}Zr_{0.5}O_2$ (HZO)-based FE capacitor is fabricated and measured in this work. When a standard bipolar triangular voltage pulse is applied to the FE capacitor, the measured P-V curve shows the typical hysteresis loop as shown in Fig. 1(a). In the triangular voltage pulse, the period time is 12 ms and the amplitude is 1.5 V. Under the forward sweeping voltage, new domains in the FE film successively undergo four stages, including nucleation, forward growth, sideways expansion and coalescence [5], which correspond to the different parts of P-V curves. At the third stage, the domain wall motion is much slower than the previous stages, which is also known as the creep-type lateral expansion [6]. At the coalescence stage, domain walls move more and more slowly until they finally disappear. Eventually, the polarization of FE film is along the electric field direction, and the entire material becomes the single domain state.

To figure out the voltage division of gate stack in NCFETs, we have investigated the FE-Dielectric (DE) series system and observed a voltage drop across FE layer, even with the increase of total applied voltage, as shown in Fig. 1(b). The inset illustrates the definitions of V_{drop}, t_{drop}, t_0 and V_0 for this voltage drop. In Fig. 1(c), a negative slope segment appears in the measured P-V curve of the FE capacitor. In such case, domain walls continue to creep outwards due to the inability to respond to the change of applied voltage in time, and the polarization will keep increasing with time, which can also be seen from the measured Polarization-time (P-t) curve in Fig. 1 (d). In other words, *d*P is positive when *d*V is negative, which directly indicates the generation of NC effect.

PARAMETER IMPACTS OF NC EFFECT

As mentioned above, it is the voltage drop of FE with an increasing total applied voltage that results in the NC phenomena. Therefore, in this work, to understand the polarization switching dynamic behavior of FE in the process of voltage drop, we measured the P-V and P-t curves of HZO-based FE capacitor under sweeping voltage pulse with three different parameters, namely V_{drop}, t_{drop} and t_0, and the period time and amplitude are 60 ms and 1.5 V respectively.

Reversed nuclei of FE will grow up continuously under an applied voltage at a certain sweeping frequency, and the growth of new domains can be regarded as the consequence of domain wall motion. Originated from the curvature of domain wall, the elastic force causes the outward expansion of domain wall, as implied in [7]. Accordingly, it can be considered that there is an expansion force to induce the nucleation and growth of new domains. Meanwhile, if the variation trend of sweeping voltage suddenly reverses, the motion of domain wall will be pinned by a contraction force, which will trigger new domains to shrink inwards once the duration of voltage drop exceeds the response time of FE [8]. Therefore, it is the competition between expansion and contraction forces that determines how the polarization changes [9, 10].

With the increase of V_{drop}, the contraction force will finally prevail over the expansion force during the growth of new domains. For ease of illustration, the polarization at t_0, i.e. $P(t_0)$, was taken as the reference value, and curves of the difference between polarization thereafter and $P(t_0)$, denoted by ΔP, as a function of V in the voltage drop segment with V_{drop} of 0.125 V, 0.25 V and 0.5 V are shown in Fig. 2(a), and the curves of ΔP varying with t are presented in Fig. 2(b). It is manifest that as V_{drop} increases, the NC effect is getting weaker, and the trend of polarization changing with t gradually slows down. From the point of view of microscopic physics, since the expansion force dominates at first, the polarization will keep increasing due to the continuous expansion of new domains. For a larger V_{drop}, the contraction force replaces the expansion force to dominate the motion trend of domain walls after the response time of FE, resulting in the inward motion of domain walls, thereby the contraction of new domains. Under the circumstances, the polarization and the applied voltage decreases simultaneously with time, and thus the capacitance of FE becomes positive. That is to say the NC state of FE turns into PC state eventually. Hence the smaller V_{drop} is, the more distinct NC effect will be.

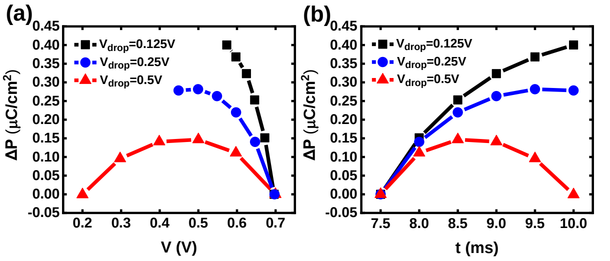

Fig. 2 (a) Response curves of ΔP (the difference between P and $P(t_0)$) versus V with various V_{drop} in the voltage drop segment. (b) Response curves of ΔP versus t with various V_{drop} in the voltage drop segment.

The impact of t_{drop} on the change of FE polarization is related to the response time of domains to applied voltage. Fig. 3(a) shows the curves of ΔP versus V with t_{drop} of 1.5 ms, 2.5 ms and 5 ms in the voltage drop segment. It can be seen that as t_{drop} increases, the polarization ultimately shows a significant decrease, which can also be confirmed from the curves of ΔP versus t with various t_{drop} in Fig. 3(b). However, the moment when polarization begins to decrease is relatively late for the case of t_{drop} = 5 ms, in other words, the time proportion of polarization increases with time is relatively larger. In this process, for the same voltage drop, the larger t_{drop} means the smaller contraction force, and it is more difficult for the contraction force to overwhelm the expansion force. Thus the expansion force will take longer effect on the domain wall motion, and domain walls are more easily to maintain the outward motion, and the polarization is more likely to be enhanced.

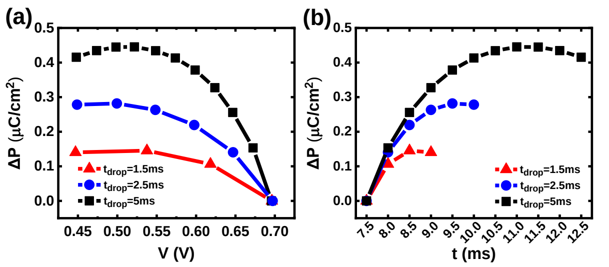

Fig. 3 (a) Response curves of ΔP (the difference between P and $P(t_0)$) versus V with various t_{drop} in the voltage drop segment. (b) Response curves of ΔP versus t with various t_{drop} in the voltage drop segment.

As a consequence, the longer the NC effect lasts. In one word, a larger t_{drop} is preferred for the NC effect enhancement.

Different t_0 corresponds to different starting points of the voltage drop, and can also be interpreted as domain wall motion at different stages. Fig. 4(a) shows the response curves of ΔP versus V with t_0 of 3.5 ms, 7 ms and 10.5 ms in the voltage drop segment. Fig. 4(b) illustrates the response curves of ΔP varying with t correspondingly. It can be seen that before the moment of (t_0+2) ms, the rising trend of polarization remains unchanged regardless of t_0, while polarization decreases at the last point for smaller t_0. The result implies that a larger t_0 is favorable for NC effect, which can be physically explained by the fact that a larger t_0 means the longer it takes for the voltage drop to start working. As domain wall motion slows down over time, the contraction force induced by the voltage drop can hardly work. Especially for the coalescence stage of new domains, the domain walls are too slow to respond to the applied voltage drop in time, which indicates that the expansion force can always enhance the polarization and thus the NC effect is improved. In addition, a larger t_0 also signifies that the voltage drop is closer to the maximum sweeping voltage. Consequently, a voltage drop near the maximum sweeping voltage is more conducive to NC effect.

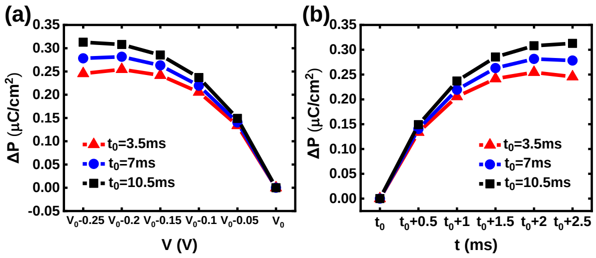

Fig. 4 (a) Response curves of ΔP (the difference between P and P(t_0)) versus V with various t_0 in the voltage drop segment. (b) Response curves of ΔP versus t with various t_0 in the voltage drop segment.

CONCLUSION

In this paper, the NC effect in a standalone FE capacitor is experimentally demonstrated and analyzed from the perspective of domain switching dynamics. Both negative and positive capacitance are observed. It is shown that the negative or positive capacitance depends on the competition between the expansion and contraction forces of new domains. In order to enhance the NC effect, it is essential for the existence of a small and slow voltage drop near the maximum sweeping voltage across FE layer, so that the expansion force can always prevail over the contraction force in the process of domain wall motion.

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