ZrO$_x$ Negative Capacitance Field-Effect Transistor with Sub-60 Subthreshold Swing Behavior

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Abstract

Here we report the ZrO$_x$-based negative capacitance (NC) FETs with 45.06 mV/decade subthreshold swing (SS) under ±1 V $V_{GS}$ range, which can achieve new opportunities in future voltage-scalable NCFET applications. The ferroelectric-like behavior of the Ge/ZrO$_x$/TaN capacitors is proposed to be originated from the oxygen vacancy dipoles. The NC effect of the amorphous HfO$_2$ and ZrO$_x$ films devices can be proved by the sudden drop of gate leakage, the negative differential resistance (NDR) phenomenon, the enhancement of $I_{DS}$ and sub-60 subthreshold swing. 5 nm ZrO$_x$-based NCFETs achieve a clockwise hysteresis of 0.24 V, lower than 60 mV/decade SS and an 12% $I_{DS}$ enhancement compared to the control device without ZrO$_x$. The suppressed NC effect of Al$_2$O$_3$/HfO$_2$ NCFET compared with ZrO$_x$ NCFET is related to the partial switching of oxygen vacancy dipoles in the forward sweeping due to negative interfacial dipoles at the Al$_2$O$_3$/HfO$_2$ interface.

Keywords: Amorphous ZrO$_x$, Ferroelectric, FET, Subthreshold swing, Negative capacitance

Background

As complementary metal oxide semiconductor (CMOS) devices scaling down constantly, the integrated circuit (IC) technique has entered into the era of “more than Moore era”. The driving force of IC industry and technology becomes the reduction of power consumption, instead of the miniaturization of transistors [1, 2]. However, the Boltzmann tyranny of MOSFETs, more than 60 mV/decade SS has restricted the energy/power efficiency [3]. In recent years, many proposed novel devices have the ability to achieve sub-60 mV/decade threshold swing, including impact ionization MOSFETs, tunnel FETs and NCFETs [4–7]. Due to the simple structure, the steep SS and improved drive current, NCFETs with a ferroelectric (FE) film have been regarded as an attractive alternative among these emerging devices [8–10]. The reported experiments on NCFETs mainly include PbZrTiO$_3$ (PZT), P(VDF-TrFE) and HfZrO$_x$ (HZO) [11–17]. However, the high process temperature and undesired gate leakage current along the grain boundaries of polycrystalline ferroelectric materials have restricted their development for the state-of-the-art technology nodes [18–26]. Recently, ferroelectricity in the amorphous Al$_2$O$_3$ and ZrO$_x$ films enabled by the voltage-modulated oxygen vacancy dipoles has been investigated [27–29]. Compared with the crystalline counterpart, the amorphous ferroelectric-like films have significant advantages in reduced process temperature and leakage current. Thus, there are mass researches on FeFETs with amorphous gate insulator for the non-volatile memory and analog synapse applications [27, 30–34]. However, the systematical investigation on one-transistor ZrO$_x$-based NCFET has not been carried out.

In this work, Ge NCFETs with 5 nm ZrO$_x$ ferroelectric dielectric layer and 5 nm Al$_2$O$_3$/HfO$_2$ ferroelectric dielectric layer have been proposed, respectively. We experimentally observed sub-60 mV/decade steep slope in ZrO$_x$ (5 nm) NCFET, which can be attributed to the
NC effect of ZrO$_x$ ferroelectric layer. And we analyzed the polarization $P$ as function of applied voltage $V$ for the Ge/ZrO$_x$/TaN capacitors. The ferroelectric-like behavior of the Ge/ZrO$_x$/TaN capacitors is induced by the voltage-induced oxygen vacancy dipoles. Moreover, we attributed the improved $I_{DS}$ and the sudden drop of $I_C$ in the Al$_2$O$_3$/HfO$_2$ NCFETs and ZrO$_x$ NCFETs to the NC effect. We also observed the NDR phenomenon in the Al$_2$O$_3$/HfO$_2$ NCFETs and ZrO$_x$ NCFETs. In addition, we further analyzed the physical mechanism of interfacial dipoles-induced decreased NC effect in the Al$_2$O$_3$/HfO$_2$ NCFET. The ZrO$_x$ NCFETs with sub-60 mV/decade steep slope, improved drain voltage and low operating voltage will be suit for the design of NCFETs with low power consumption in the “more than Moore era”.

Methods

Key process steps for NCFETs with ZrO$_x$ and Al$_2$O$_3$/HfO$_2$ fabrication are shown in Fig. 1a. Different gate dielectric insulators, including Al$_2$O$_3$/amorphous HfO$_2$ (5 nm) films and amorphous ZrO$_x$ (4.2 nm) films were grown on n-Ge (001) substrates by atomic layer deposition (ALD) at 300 °C. TMA, TDMAHf, TDMAZr and H$_2$O vapor were used as the precursors of Al, Hf, Zr and O, respectively. The pulse time and purge time of the precursors of Hf and Zr are 1.6 s and 8 s, respectively. A TaN top gate electrode was then deposited on HfO$_2$ or ZrO$_x$ surfaces by reactive sputtering. Source/drain (S/D) regions were defined by lithography patterning and dry etching. After that, boron (B$^+$) and nickel (Ni) was deposited in source/drain (S/D) regions. Finally, rapid thermal annealing (RTA) at 350 °C for 30 s in a 10$^8$ Pa nitrogen ambient was carried out. Figure 1b, d show the schematics of the fabricated Al$_2$O$_3$/HfO$_2$ NCFETs and ZrO$_x$ NCFETs. High-resolution transmission electron microscope (HRTEM) image in Fig. 1c depicts the amorphous HfO$_2$ (5 nm) film on Ge (001) with Al$_2$O$_3$ interfacial layer. HRTEM image in Fig. 1e depicts the amorphous ZrO$_x$ (4.2 nm) film on Ge (001). The C–V curve of ZrO$_x$ NCFETs and the X-ray photoelectron spectra (XPS) of TaN/ZrO$_x$ (4.2 nm)/Ge capacitors were measured in Additional file 1: Fig. S1.

Results and Discussion

Figure 2a shows the measured curves of polarization $P$ v.s. applied voltage $V$ characteristics for the Ge/ZrO$_x$/TaN capacitors at 3.3 kHz. The gate length (L$_G$) of the capacitors are 8 μm. It is observed that the remnant polarization $P_r$ of the Ge/ZrO$_x$/TaN capacitors can be enhanced with larger sweeping range of $V$. The ferroelectric-like behavior of the amorphous ZrO$_x$ film in the Fig. 2a is proposed to be originated from the voltage-driven oxygen vacancy dipoles [35]. Figure 2b shows the measured $P$–$V$ curves for the Ge/ZrO$_x$/TaN capacitors under different frequencies from 200 to 10 kHz. We can see that the ferroelectric-like behavior of the amorphous ZrO$_x$ film remain stable for all frequencies. However, the $P_r$ of the amorphous ZrO$_x$ film is reduced with the increased frequencies. This phenomenon can be explained by the incomplete dipoles switching under high measurement frequencies [36, 37]. As measurement frequencies
Increasing, the time for the direction change of electric field in the amorphous ZrO₂ film decreases. Thus, part of oxygen vacancy dipoles switching is incomplete, providing decreased $P_r$.

Figure 3a shows the measured $I_{DS}$-$V_{GS}$ curves of a ferroelectric Al₂O₃/HfO₂ NCFET at the $V_{DS}$ of −0.05 V and −0.5 V. The $I_G$ of the devices is 3 μm. The hysteresis loops of 0.14 V ($V_{DS} = −0.05$ V, $I_{ds} = 1$ nA/μm) and 0.08 V ($V_{DS} = −0.5$ V, $I_{ds} = 1$ nA/μm) are demonstrated, respectively. The clockwise hysteresis loops are attributed to the migration of oxygen vacancies and accompanied negative charges. The oxygen vacancy dipoles accumulate (deplete) in the Ge/Al₂O₃ interface under positive (negative) $V_{GS}$. Therefore, the threshold voltage ($V_{TH}$) increases (decreases) under forward (reverse) sweeping of gate voltages. As shown in Fig. 3b, the output characteristics of the Al₂O₃/HfO₂ NCFET and the control FET are compared. The saturation current of the Al₂O₃/HfO₂ NCFET exceeds 30 μA/μm, with a rise of 12% compared to that of the control FET at $|V_{GS}| = 1$ V. The improved current enhancement and more obvious NDR prove the enhanced NC effect of the amorphous ZrO₂ film. The NDR effect is caused by the incomplete switching of oxygen vacancy dipoles due to the coupling of drain-to-channel as $V_{DS}$ increases [40, 41]. Figure 3c compares the measured gate leakage $I_G$-$V_{GS}$ curves for the 5 nm Al₂O₃/HfO₂ NCFET at the $V_{DS}$ of −0.05 V and −0.5 V. The sudden drops of $I_G$ only during the reverse sweeping indicate the decreased voltage in the amorphous HfO₂ film and the amplification of surface potential [38, 39]. In addition to current enhancement, the obtained obvious NDR proves the NC effect of the amorphous HfO₂ film. The absence of NC effect during the forward sweeping is caused by the partial switching of oxygen vacancy dipoles in the amorphous HfO₂ film [43]. The different ability to contain oxygen atoms between Al₂O₃ and HfO₂ layer leads to oxygen redistribution and negative interfacial dipoles at the Al₂O₃/HfO₂ interface [44, 45]. Due to the presence of negative interfacial dipoles, it is difficult for the amorphous HfO₂ film to realize complete polarization switching (NC effect) in the forward sweeping (Additional file 1).

Figure 4a shows the measured transfer curves of a ferroelectric ZrO₂ NCFET at the $V_{DS}$ of −0.05 V and −0.5 V. The $I_G$ of the two devices are 4 μm. The clockwise hysteresis loops of 0.24 V ($V_{DS} = −0.05$ V, $I_{ds} = 1$ nA/μm) and 0.14 V ($V_{DS} = −0.5$ V, $I_{ds} = 1$ nA/μm) are demonstrated, respectively. As shown in Fig. 4b, the output characteristics of the ZrO₂ NCFET and the control FET are compared. The saturation current of the ZrO₂ NCFET exceeds 30 μA/μm, with a rise of 12% compared to that of the control FET at $|V_{GS}| = 1$ V. The improved current enhancement and more obvious NDR indicate the enhanced NC effect of the amorphous ZrO₂ film (5 nm) contrast to that of 5 nm HfO₂ film. Figure 4c compares the measured gate leakage $I_G$-$V_{GS}$ curves for the 5 nm ZrO₂ NCFET at the $V_{DS}$ of −0.05 V and −0.5 V. Compared to the sudden $I_G$ drops of Al₂O₃/HfO₂ NCFET only during reverse sweeping in Fig. 3c, the sudden drops of $I_G$ both in forward and reverse sweeping in Fig. 4c also prove the enhanced NC effect in the amorphous ZrO₂ film.

Figure 5a, b shows the point SS as function of $I_{DS}$ for the Al₂O₃/HfO₂ and ZrO₂ NCFET at the $V_{DS}$ of −0.05 V and −0.5 V. As shown in Fig. 5b, sub-60 mV/decade sub-threshold swing (SS) can be achieved during forward or reverse sweeping of $V_{GS}$ at the $V_{DS}$ of −0.05 V and −0.5 V. When $V_{DS}$ is −0.05 V, a point forward SS of 45.1 mV/dec and a point reverse SS of 55.2 mV/dec were achieved. When $V_{DS}$ is −0.5 V, a point forward SS of 51.16 mV/dec and a point reverse SS of 46.52 mV/dec were achieved.
Due to the different ability of scavenging effect for the Al₂O₃/HfO₂ and ZrOₓ layer, the partial dipoles switching is caused in the Al₂O₃/HfO₂ NCFET. Therefore, the more obvious NC effect with sub-60 mV/decade SS is achieved in 5 nm ZrOₓ NCFET.

Conclusions
We report the demonstration of ferroelectric NC ZrOₓ pFETs with the sub-60 mV/decade SS, low operating voltage of 1 V and a hysteresis of less than 60 mV. The impact of the amorphous ZrOₓ films on the ferroelectric behavior is explained by the oxygen vacancy dipoles. The improved I_DS and NDR phenomenon are also obtained in Al₂O₃/HfO₂ NCFETs and ZrOₓ NCFETs compared to the control device. The suppressed NC effect of the Al₂O₃/HfO₂ NCFET can be attributed to partial dipole switching due to interfacial dipoles at the Al₂O₃/HfO₂ interface. The ZrOₓ NCFETs with sub-60 mV/decade steep slope, improved drain voltage and low operating voltage pave a new way for future low power consumption NCFETs design.

Supplementary Information
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Additional file 1. From the C–V curve of ZrOₓ NCFETs in Fig. S1 (a), we can see that the threshold voltage of the ZrOₓ NCFETs is around 0.5 V. From the XPS of TaN/ZrOₓ/4.2 nm/Ge capacitors in Fig. S1 (b), we can see that a TaOₓ interfacial layer formed in the TaN/ZrOₓ interface and oxygen vacancies (ZrOₓ) in ZrOₓ because of the scavenging effect.

Abbreviations
TaN: Tantalum nitride; ZrOₓ: Zirconium dioxide; TDMAZr: Tetrakis (dimethylamido) zirconium; Pₓ: Remnant polarization; E_c: Coercive electric field; MOSFETs: Metal–oxide–semiconductor field-effect transistors; Ge: Germanium; ALD: Atomic layer deposition; B⁺: Boron ion; Al₂O₃: Aluminum oxide; HRTEM: High-resolution transmission electron microscope; Ni: Nickel; RTA: Rapid thermal annealing; I_D: Drain current; V_GS: Gate voltage; V_TH: Threshold voltage; NCFET: Negative capacitance field-effect transistor.
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Authors’ Contributions
SQZ and HL drafted the manuscript and carried out the experiments; YL and JRZ helped to revise the manuscript; YH and GQH supported the study; All the authors read and approved the final manuscript.

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Availability of Data and Materials
The datasets supporting the conclusions of this article are included in the article.

Competing interests
The authors declare that they have no competing interests.

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