Ferroelectric Polarization Switching Behavior of Hf$_{0.5}$Zr$_{0.5}$O$_2$ Gate Dielectrics on Gallium Nitride High-Electron-Mobility-Transistor Heterostructures

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Ferroelectric (FE) materials have strong polarization effects and are switchable by the applied electric field, making them attractive candidates for polarization engineering in GaN-based devices. Herein, the FE response of Hf$_{0.5}$Zr$_{0.5}$O$_2$ (HZO) deposited by atomic layer deposition (ALD) on AlGaN/GaN high-electron-mobility transistor (HEMT) heterostructures is characterized and analyzed in both metal–ferroelectric–semiconductor (MFS) and metal–ferroelectric–oxide–semiconductor (MFOS) configurations. Strong 2D-electron gas (2DEG) channel modulation from FE polarization switching is observed. Significant FE polarization switching as well as distinct polarization recovery behavior is observed for the first time in GaN transistor structures. The polarization recovery appears to be related to the presence of significant coupling between the FE layer and the 2DEG channel at the AlGaN/GaN heterointerface. These results have significant implications for the design of devices exploiting FE effects in GaN and related materials.

1. Introduction

Ferroelectric (FE) materials have attracted increased attention due to the potential for a wide range of device applications, including memory devices, steep slope transistors, and devices for neuromorphic computing. Extensive research has been devoted to FE-based devices on silicon, including evaluation of FE-based devices for possible low-voltage device performance optimization or nonvolatile memory applications. However, an area of particular interest and potential impact is the combination of FE materials with III-nitrides. The strong polarization of the nitrides along with the switchable polarization nature of FEs provides new possibilities of polarization engineering in GaN-based high-electron-mobility transistors (HEMTs) for enhanced 2D-electron gas (2DEG) channel modulation as well as dynamic threshold voltage control.

GaN and related compounds are very promising semiconductors for next-generation high-power and high-speed applications due to their superior material properties. However, conventional GaN-based HEMTs are depletion-mode (normally on) devices due to the strong polarization discontinuity between the barrier and channel layers. Many studies have focused on achieving enhancement-mode (normally off) operation for its advantages in circuits. Approaches explored have included cascade configurations, p-GaN gate, and recessed metal–insulator–semiconductor HEMT (MISHEMT) structures. In contrast to traditional dielectrics used in GaN MISHEMTs, FE materials have strong polarization effects and are switchable by the applied electric field, making them great candidates for polarization engineering to enhance the 2DEG channel modulation and to realize threshold voltage control. By taking advantage of the switchable polarization of a FE gate dielectric, the threshold voltage of the device can be modulated dynamically: when the FE polarization direction is aligned with that of the nitride polarization, the 2DEG channel carrier concentration would be increased, and the threshold voltage would shift to more negative values. On the contrary, when the FE polarization is switched to oppose the nitride polarization, the 2DEG channel would be depleted and the threshold voltage shifts to more positive values. The polarization engineering flexibility enabled by combining the FE gate stack with the nitride channel offers a new method for dynamic threshold voltage control in GaN HEMTs.

In this article, FE gate stacks on AlGaN/GaN HEMT heterostructures have been experimentally studied in both metal–ferroelectric–semiconductor (MFS) and metal–ferroelectric–oxide–semiconductor (MFOS) configurations. The FE polarization switching behavior of Hf$_{0.5}$Zr$_{0.5}$O$_2$ (HZO) on AlGaN/GaN HEMT heterostructures has been measured and discussed. Strong 2DEG channel modulation originating from FE gate stack has been observed. Significant FE polarization switching as well as distinct polarization recovery behavior has also been demonstrated. These results have significant implications for...
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2. Experimental Section

Schematic cross sections of the HZO FE-based MFS and MFOS devices on AlGaN/GaN HEMT heterostructures are shown in Figure 1. The HEMT epitaxial layers were a conventional metal organic chemical vapor deposition (MOCVD)-grown AlGaN/GaN heterostructure, consisting of (from the surface) a 20 nm Al$_{0.24}$Ga$_{0.76}$N barrier, a 400 nm undoped GaN channel, and a 2 μm GaN buffer layer, on a SiC substrate. For MFS devices, 10 nm of HZO was deposited on the as-grown HEMT heterostructure by atomic layer deposition (ALD) at 250°C. For MFOS devices, 4 nm of Al$_2$O$_3$ was grown by ALD at 250°C on the HEMT heterostructure, followed by deposition of 10 nm of HZO in the same ALD system without breaking vacuum. Top electrodes were formed by sputtering and liftoff of 100 nm of W. Annealing at 500°C for 30 s in N$_2$ ambient was performed for FE crystallization. For all devices reported here, the top electrode area was 100 μm × 100 μm. High-resolution transmission electron microscopy (TEM) (Figure 1d) revealed crystalline grains of the FE HZO on the AlGaN/GaN HEMT heterostructures.

3. Results and Discussion

3.1. Ferroelectricity of HZO

A metal–ferroelectric–metal (MFM) test structure was used to characterize the properties of the ALD-deposited HZO thin film. The schematic cross section of an HZO MFM capacitor is shown in Figure 2a. The current–voltage and obtained P–V characteristics of FE MFM capacitors as measured with a Keithley 4200 parameter analyzer are shown in Figure 2b,c, demonstrating a remanent polarization $2P_r$ of 51 μC cm$^{-2}$. As shown in Figure 2c, the W–HZO–WFE capacitor achieves good polarization switching behavior.

3.2. Ferroelectric Response of MFS/MFOS on GaN

The FE responses of both MFS and MFOS devices were characterized using triangular waveform measurements. The

![Figure 1](image1.png)

**Figure 1.** Schematic cross sections of a) AlGaN/GaN HEMT structure; b) MFS device structure; c) MFOS device structure; and d) high-resolution cross-sectional TEM image of MFOS device.

![Figure 2](image2.png)

**Figure 2.** a) MFM device schematic cross section; b) I–V characteristics of MFM capacitor measured with triangular waveforms of amplitudes ±3 V with 4 ms period; double triangular waveforms measurements also carried out to permit exclusion of displacement and leakage current contributions. c) P–V loop obtained for W–HZO–W MFM test structure.
measured current–voltage characteristics of typical MFS and MFOS devices on the GaN HEMT heterostructures are shown in Figure 3a,b. As shown in figures, both the MFS and MFOS devices exhibit nontrivial responses. First, significant FE switching current peaks are observed at positive bias, indicating that strong FE polarization effects are present. In the negative bias regime, however, no FE switching current peak was observed. This is attributed to the 2DEG channel depletion at negative bias.

As shown in figures, both the MFS and MFOS devices exhibit nontrivial responses. First, significant FE switching current peaks are observed at positive bias, indicating that strong FE polarization effects are present. In the negative bias regime, however, no FE switching current peak was observed. This is attributed to the 2DEG channel depletion at negative bias. The applied voltage is dropped primarily across the semiconductor due to the significantly reduced channel capacitance, so the electric field in the FE layer is too low to reverse the FE polarization. At the same time, a leakage plateau for gate voltages higher than 5 V can also be observed in the curves.

As shown in Figure 3, MFS and MFOS devices exhibit similar current–voltage characteristics, with the primary difference being that MFOS devices show smaller FE switching current than MFS devices under the same bias conditions. This is because the voltage drop across the FE layer in MFOS devices is smaller than that in MFS devices (due to the additional capacitive voltage division from the Al₂O₃). As a result, relatively weaker FE switching (i.e., smaller switching current) is observed for the same applied gate voltage waveforms. In addition, this effect also results in a lower FE charge concentration. As discussed in Section 3.3, this results in a lower polarization recovery rate than in the MFS devices.

To exclude leakage current and isolate the FE switching current component, both DC and double triangular waveform measurements were carried out, as shown in Figure 4. The DC measurement results (shown in Figure 4c) confirm that the plateaus observed at higher gate voltage in both MFS and MFOS devices originate from DC gate leakage current. The leakage plateaus originate from carrier injection from the channel to the gate under positive gate bias. As discussed in Section 3.3, the level of the plateaus corresponds directly to the DC measured gate current in these devices (Figure 4c). It can also be noticed that MFOS devices show lower gate leakage current as well as higher

Figure 3. I–V characteristics of a) MFS devices and b) MFOS devices measured with triangular waveforms with 4 ms period and varied voltage amplitudes.

Figure 4. I–V characteristics of a) MFS and b) MFOS devices. Data were measured with double triangular waveforms with varied voltage amplitudes; c) DC I–V sweep results of both MFS and MFOS devices, indicating the onset of gate leakage under forward bias.
triggering voltage compared with MFS devices, which is attributed to the voltage drop associated with the additional 4 nm Al₂O₃ layer. For the double triangular waveform measurements (shown in the inset of Figure 4a), ideally, the polarization switching would occur during the first pulse. As the voltage polarity remains unchanged, there should be no FE switching during the second pulse, but only displacement and leakage current. However, as shown in both Figure 4a,b, appreciable FE

![Figure 5](image1)

**Figure 5.** MFOS device I–V characteristics measured with repetitive unipolar triangular waveforms: a) positive pulses only measurements, showing full polarization recovery without reverse-bias reset pulses. b) Negative pulses only measurements, showing 2DEG channel modulation from ferroelectric gate.

![Figure 6](image2)

**Figure 6.** MFOS device I–V characteristics measured with double triangular waveforms of varying pause time \(t_p\) between triangular pulses.
switching current peaks are observed during the second “non-switching” triangular pulse, suggesting that significant polarization recovery has occurred in the interval between the pulses.

### 3.3. Ferroelectric Polarization Recovery Behavior

To assess the observed polarization recovery behavior, repeated unipolar triangular waveform measurements have been carried out. As shown in Figure 5a, for positive pulses, a smaller current peak is measured during the second pulse, indicating that partial polarization recovery has taken place between adjacent pulses. The difference in magnitude between the initial and second current peak indicates the degree to which the FE polarization has recovered. On the contrary, inclusion of a pause in the measurement (as shown in Figure 5a) results in a current peak that is nearly the same as the original one (see the third pulse as shown in Figure 5a), indicating that full polarization recovery takes place over time without the need for any reverse bias reset pulses. For negative pulses, however, only small positive/negative displacement current can be observed. For gate voltage, more negative than −3 V, the displacement current falls abruptly to near zero, suggesting that the 2DEG channel in GaN is depleted. These results provide direct evidence that the FE gate stack can strongly modulate the 2DEG channel in a GaN HEMT for threshold voltage control or achieving enhancement-mode operation.

The details of the time dependence of the polarization recovery have also been studied. Figure 6 shows the measured current–voltage characteristics of MFOS devices for triangular waveforms with varied pause time, \( t_p \), between pulses. One can see that HZO on AlGaN/GaN HEMT heterostructures exhibits significant polarization recovery over time. The polarization recovery rates of both MFS and MFOS devices are shown in Figure 7. In total, 80% polarization recovery (\( P_{\text{recover}}/P = P_{\text{2nd pulse}}/P_{\text{1st pulse}} \)) was reached for an 800 ms pause, whereas full polarization recovery was reached after about 1 s. As voltage drop across the FE layer in MFOS devices is smaller than in MFS devices under the same bias condition (due to the voltage drop associated with the 4 nm Al\(_2\)O\(_3\) dielectric layer), MFOS devices show lower FE charge concentration and correspondingly lower electric field within the AlGaN barrier layer at the same gate bias. This reduced field results in reduced thermionic emission of carriers from the 2DEG into the gate stack, and thus a lower polarization recovery rate than in MFS devices. It should be also noted that in MFOS devices with the FE layer in series with a dielectric layer, due to the large difference between the remanent polarization charge density of the FE layer and the maximum charge density supported by the dielectric (due to the limited critical field strength), significant leakage through the dielectric layer can be expected\(^{[22]}\) unless very thick dielectric films are used.

To illustrate the physical mechanism of this polarization recovery behavior, energy band diagrams for an MFOS structure obtained through solving Poisson’s equation in 1D\(^{[26]}\) are shown in Figure 8. In these calculations, the polarization charge of the HZO layer, as extracted from experimental results, was included in the simulations. As shown in Figure 8a, once the FE

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**Figure 7.** MFS and MFOS polarization recovery \( P_{\text{recover}}/P \) as a function of pause time \( t_p \) for triangular waveform amplitude of 4 V.

**Figure 8.** Simulated MFOS band diagram under different conditions: a) after polarization switching at 2 V, b) depolarization behavior at 0 V bias after partial recovery, and c) without polarization switching at −2 V. Polarization is shown as blue arrows, whereas electron injection/trapping is also indicated with red arrows. The shallow electron trap of oxygen vacancy in HZO is also indicated with gray dashed line.
polarization is switched toward the device channel (positive bias regime), the FE polarization of the HZO significantly enhances the electric field within the oxide and AlGaN (compared with negative bias regime, Figure 8c), which results in electron injection from the 2DEG channel into the FE layer, likely into deep states originating from oxygen vacancies in the HZO.[27,28] The injected electrons then lead to local charge compensation and polarization recovery of the FE layer. This significant coupling between the FE layer and the 2DEG channel in FE devices based on GaN is responsible for the observed FE polarization recovery behavior.

4. Conclusions

In this work, the FE response of HZO on AlGaN/GaN HEMT heterostructures has been characterized and analyzed. Strong 2DEG channel modulation from FE polarization switching has been observed. Significant FE polarization switching as well as distinct polarization recovery behavior has been demonstrated for the first time in both MFS and MFOS configurations. The significant polarization coupling between the FE layer and 2DEG channel in GaN has been highlighted. These results have significant implications for the design of devices exploiting FE effects in GaN and related materials.

Acknowledgements

This work was supported in part by ASCENT, one of six centers in JUMP, Semiconductor Research Corporation (SRC) program sponsored by DARPA.

Conflict of Interest

The authors declare no conflict of interest.

Keywords

AlGaN/GaN high-electron-mobility transistors, ferroelectric, Hf$_2$O$_3$, Zr$_2$O$_3$, polarization switching

Received: August 29, 2019
Revised: October 19, 2019
Published online: November 20, 2019

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