Al_2O_3 Interlayer Engineering for Stabilizing Ferroelectricity in Thick $Hf_{0.5}Zr_{0.5}O_2$ Films for Photonic Applications

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Abstract

Al_2O_3 Interlayer Engineering for Stabilizing Ferroelectricity in Thick $Hf_{0.5}Zr_{0.5}O_2$ Films for Photonic Applications

Recent advances in artificial intelligence (AI) and high-performance computing have significantly increased the demand for high-bandwidth and energy efficient data transmission systems. Silicon Photonics has emerged as a promising platform for photonic integrated circuits owing to its compatibility with complementary metal-oxide-semiconductor (CMOS) processes and potential for large scale integration. However, the centrosymmetric crystal structure of silicon limits its second-order nonlinear optical responses, which restricts the realization of efficient nonlinear photonic devices. Therefore, CMOS-compatible ferroelectric materials with nonlinear optical properties are highly desirable.

In this study, $Hf_{0.5}Zr_{0.5}O_2$ thin films were investigated as CMOS-compatible ferroelectric materials for photonic applications. In particular, relatively thick HZO films are required to enhance optical confinement and light-matter interaction in photonic structures such as HZO-Au hybrid metasurfaces. However, the ferroelectricity of HZO films generally degrades as the film thickness increases because of grain growth and the formation of the non-ferroelectric monoclinic phase. To address this issue, ultrathin Al_2O_3 interlayers were introduced into thick HZO films to suppress grain growth and stabilize the ferroelectric orthorhombic phase.

HZO-based metal-ferroelectric-metal capacitors were fabricated using atomic layer deposition. The HZO composition was fixed at Hf:Zr =0.5:0.5, and Al_2O_3 interlayers with various thicknesses were inserted after every 10 nm of HZO deposition. The ferroelectric and structural properties of the films were analyzed using polarization-voltage measurements and X-ray diffraction. For HZO films without Al_2O_3 interlayers, the remanent polarization decreased with increasing film thickness, and the 40 nm thick HZO films showed almost no ferroelectric behavior. X-ray diffraction analysis revealed that this degradation originated from the increased formation of the non-ferroelectric monoclinic phase and the reduced fraction of the ferroelectric orthorhombic phase.

By introducing Al_2O_3 interlayers, the ferroelectric properties of thick HZO films were significantly improved. In 30 nm thick HZO films, the remanent polarization increased as the Al_2O_3

interlayer thickness increased up to 0.5 nm and then decreased with further increase in Al_2O_3 thickness. X-ray diffraction and peak deconvolution analyses confirmed that the 0.5 nm thick Al_2O_3 interlayer effectively suppressed the monoclinic phase and promoted the formation of the ferroelectric orthorhombic phase. The effectiveness of this interlayer engineering strategy was further verified in 40 nm thick HZO films, where Al_2O_3 insertion also enhanced ferroelectricity and suppressed monoclinic phase formation.

These results demonstrate that Al_2O_3 interlayer engineering is an effective approach for stabilizing ferroelectricity in thick HZO films. The optimized Al_2O_3/HZO multilayer structure provides a promising route toward CMOS-compatible ferroelectric photonic devices, including nonlinear photonic devices and nonvolatile optical phase shifters.

Keywords : $HfZrO_2$, Al_2O_3 interlayer, ferroelectricity, silicon photonics, CMOS compatibility, nonlinear optics, monoclinic phase, orthorhombic phase

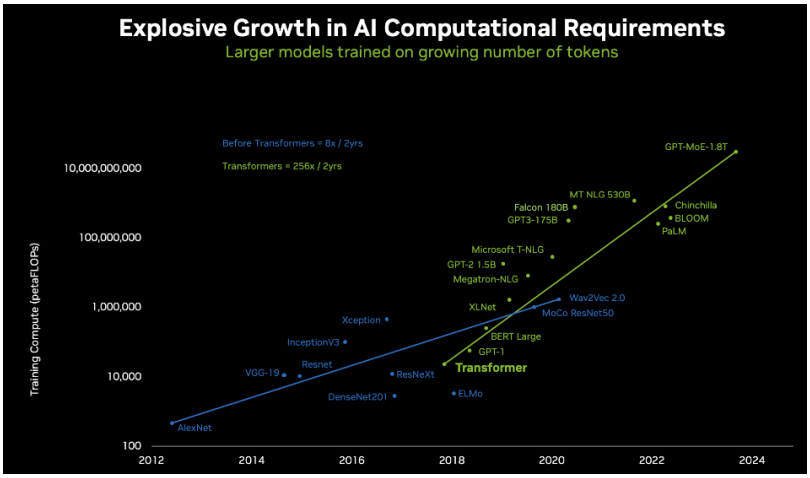
1. Introduction

1.1 Si photonics technology

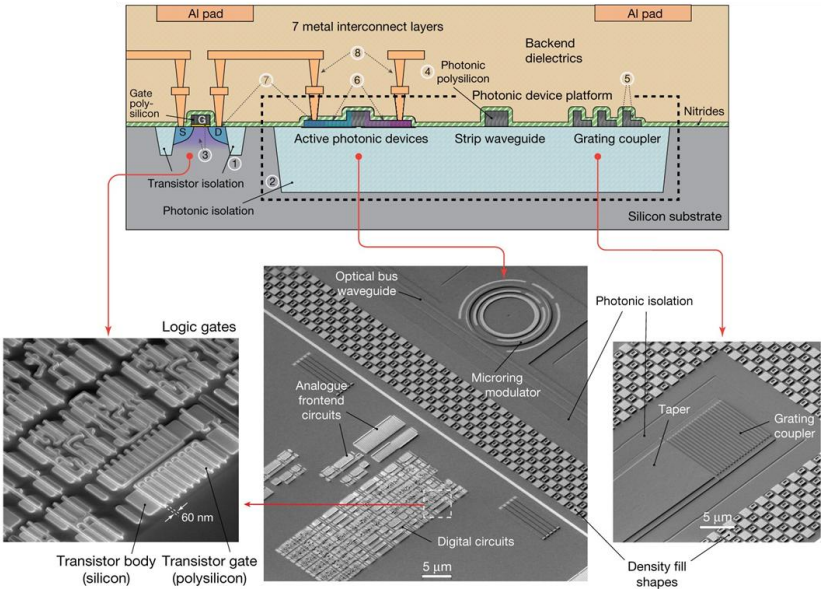
The Recent advances in artificial intelligence (AI) technologies have led to a rapid increase in data traffic. This trend has increased the demand for high-bandwidth and energy efficient data transmission systems. As a result, silicon (Si) photonics has attracted considerable attention as a key technology to overcome the bottlenecks of conventional electrical interconnect based systems [1]. Si photonics enables the integration of optical components, such as optical waveguides and modulators, on a Si complementary metal-oxide semiconductor (CMOS) compatible platform. This compatibility with CMOS processes allows large-scale integration and cost-effective mass production of photonic integrated circuits (PIC) [2].

However, Si has a centrosymmetric crystal structure, which suppresses its bulk second-order nonlinear optical susceptibility, $\chi^{(2)}$. Therefore, $\chi^{(2)}$-based optical properties, such as Pockels effect and second harmonic generation (SHG), are difficult to realize using Si alone [3]. This remains a limitation for active Si photonic devices that require efficient electro-optic modulation or nonlinear optical functions.

To overcome this limitation, ferroelectric materials such as $LiNbO_3$ (LN) and $BaTiO_3$ (BTO) has been integrated with Si photonic platforms [4]. These materials exhibit large electro-optic coefficients and strong nonlinear optical responses due to their non-centrosymmetric crystal structures. However, LN and BTO are not fully compatible with Si CMOS processes, and their integration often involves complex fabrication processes. Therefore, CMOS-compatible materials with nonlinear optical responses are required for scalable Si photonic device [5].



<Fig 1.1> Growth in AI computational requirements



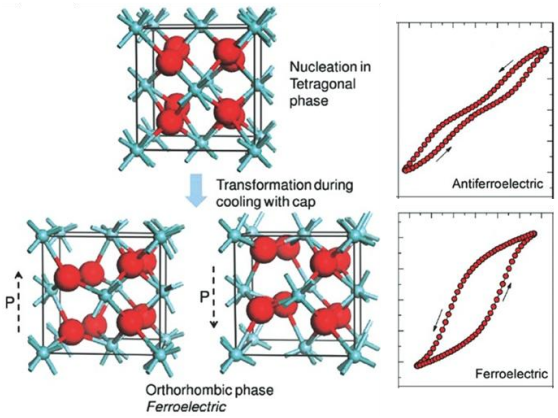
<Fig 1.2> Integrated Si photonics platform

1.2 $HfZrO_2$ ferroelectrics as nonlinear optical materials

Recently, HfO_2-based thin films have attracted considerable research interest because of their compatibility with CMOS processes. HfO_2 generally exhibits non-ferroelectric behavior in the monoclinic phase (m-phase). However, a non-centrosymmetric orthorhombic phase (o-phase) with $Pca2_1$ space group can be stabilized through doping, compositional control, and thermal treatment, resulting in ferroelectric properties [6, 9].

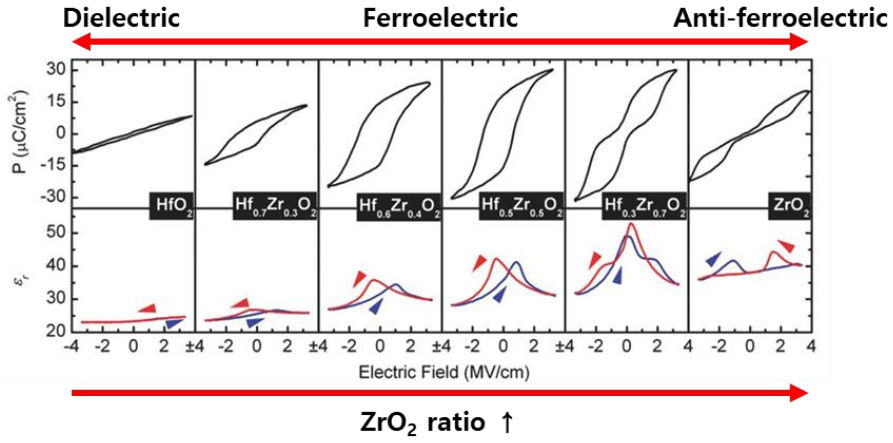
Among various HfO_2-based ferroelectrics, $HfZrO_2$ (HZO) is regarded as a particularly promising material. Zr has chemical and physical properties similar to those of Hf, and HZO can be crystallized at relatively low temperatures. In addition, the phase of HZO can be engineered by controlling the Zr composition, which makes it suitable for investigating phase-dependent properties [8].

Based on these advantages, HZO has been widely investigated for electronic devices such as ferroelectric random-access memory (FeRAM) and ferroelectric field-effect transistors (FeFETs) [10]. In contrast, the optical properties of HZO have been much less explored, particularly its nonlinear optical response associated with ferroelectric polarization. Therefore, integrating HZO into Si photonic platforms as a CMOS-compatible ferroelectric photonic material is important for the development of highly integrated photonic devices.



<Fig 1.3> Phase transformation from tetragonal to orthorhombic phase in HfO_2-based thin films

[7]



<Fig 1.4> Polarization-electric field (P-E) hysteresis curves of $Hf_{1-x}Zr_xO_2$ (x=0-1) films [8]

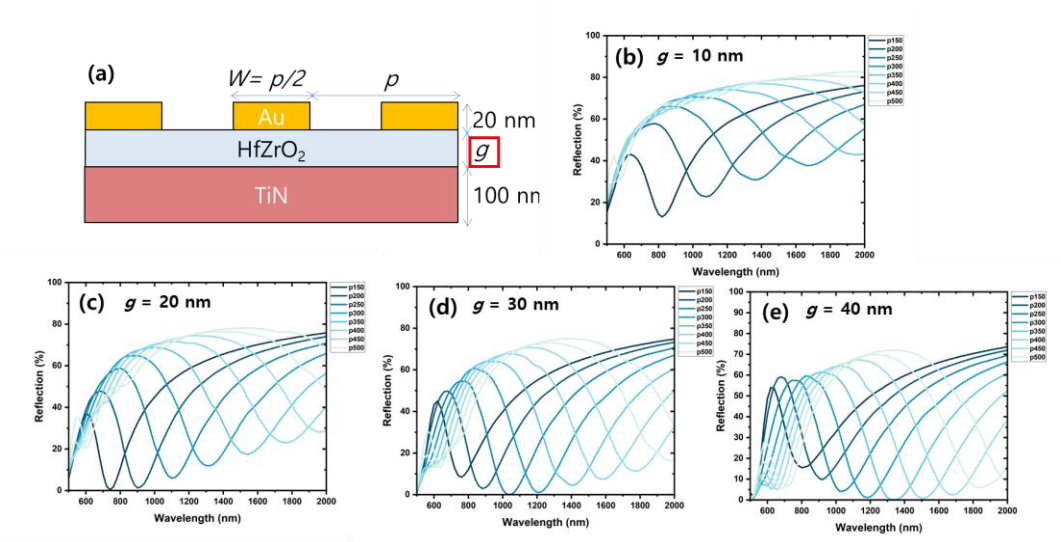
2. Background

2.1 Motivation for thick HZO films in photonic structures

For photonic applications, functional thin films should not only exhibit ferroelectricity but also interact effectively with optical modes. In particular, in structures utilizing local electric-field enhancement, such as metasurfaces, the thickness of the functional film strongly affects the resonance wavelength and the strength of light-matter interaction [11]. Therefore, when HZO is applied to photonic devices, not only its ferroelectric properties but also its optical confinement characteristics in the target wavelength range should be considered.

In this study, resonance simulations were performed for an HZO-Au hybrid metasurface structure to determine an appropriated HZO thickness for optical field confinement [12]. The proposed structure consists of an HZO thin film formed on a TiN bottom electrode, with an Au one-dimensional grating placed on top of the HZO layer. The thickness of the TiN bottom electrode was fixed at 100 nm, while the HZO thickness was varied as 10, 20, 30, 40 nm. In addition, the reflection spectra were compared under different Au grating pitches.

The simulation results showed that the resonance features in the reflection spectra became more pronounced as the HZO thickness increased. This results suggests that an HZO thickness above a certain level can be beneficial for enhancing the optical response of the device structure. Therefore, to realize HZO-based photonic devices, it is important to stabilize ferroelectricity in relatively thick HZO films with thicknesses greater than 20 nm.



<Fig 2.1> (a) Simulated structure. Reflection spectra of $HfZrO_2$ with various thickness (b) 10 nm (c) 20 nm (d) 30 nm (e) 40 nm

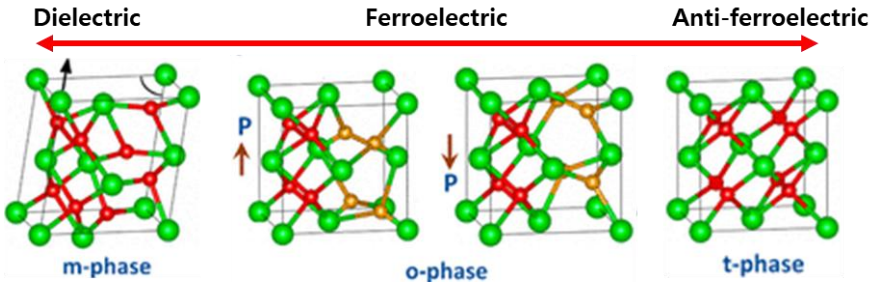
2.2 Thickness problem of HZO

HZO thin films can exhibit a remanent polarization (P_r) of approximately 10-40 μC/cm2 even at an ultrathin thickness below 10 nm. This ferroelectricity is associated with the formation of the non-centrosymmetric o-phase. Since this orthorhombic phase is induced by large tensile stress generated during the island coalescence process in Volmer-Weber type thin film growth, it is regarded as a metastable phase under normal thermodynamic conditions [13].

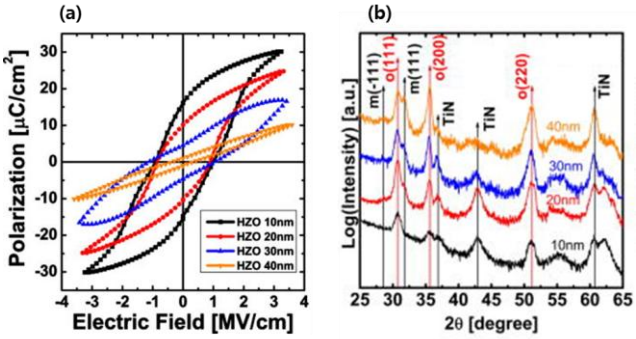
In HZO thin films, grain size plays an important role in stabilizing the ferroelectric phase. When the grain size is sufficiently small, the surface-to-volume ratio increases, making the metastable o-phase or tetragonal phase (t-phase) more favorable than the thermodynamically stable m-phase. In contrast, as the film thickness increases, the grain size also increases, which promotes the formation of the non-ferroelectric m-phase. This phase transition has been reported as a major reason for the reduction in remanent polarization and degradation of ferroelectricity in thick HZO films.

Therefore, to recover ferroelectricity in thick HZO films with thicknesses greater than 20 nm, it is essential to suppress grain growth, minimize the formation of the m-phase, and maintain a sufficient fraction of the ferroelectric o-phase. One effective approach is to insert an ultrathin Al_2O_3 interlayer into the HZO film. Previous studies have reported that the Al_2O_3 interlayer interrupts the continuous grain growth of HZO, reduces the grain size, and consequently suppresses the formation of the m-phase [14].

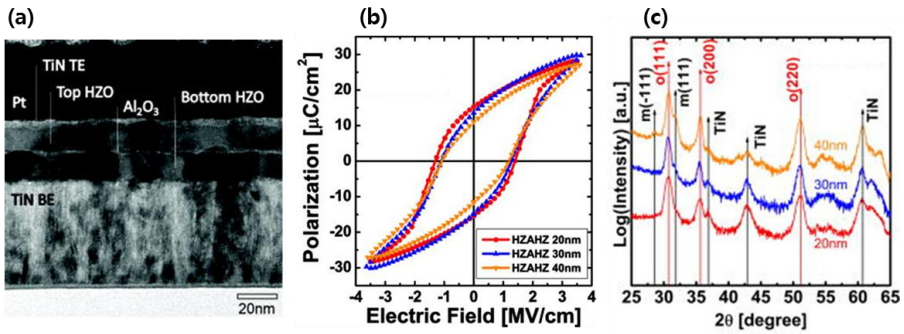
In this study, Al_2O_3 interlayer engineering is introduced to stabilize ferroelectricity in thick HZO films required for photonic applications. In particular, this work aims to obtain HZO films with thicknesses of 30 nm or greater for HZO-Au hybrid metasurface structures while controlling grain growth and maintaining the ferroelectric o-phase through the insertion of Al_2O_3 interlayers. This approach is expected to demonstrate the potential of CMOS-compatible ferroelectric HZO thin films for photonic device applications.



<Fig 2.2> Crystal structures of HfO_2-based phases [13]



<Fig 2.3> $Hf_{0.5}Zr_{0.5}O_2$ films with various thickness (a) P-E curves (b) X-ray diffraction (XRD) pattern [14]



<Fig 2.4> (a) Cross-sectional transmission electron microscope (TEM) image of $Pt/TiN/Hf_{0.5}Zr_{0.5}O_2/Al_2O_3/Hf_{0.5}Zr_{0.5}O_2/TiN$ structure (b) P-E curves and (c) XRD patterns of the $Hf_{0.5}Zr_{0.5}O_2/Al_2O_3/Hf_{0.5}Zr_{0.5}O_2$ films with various thickness [14]

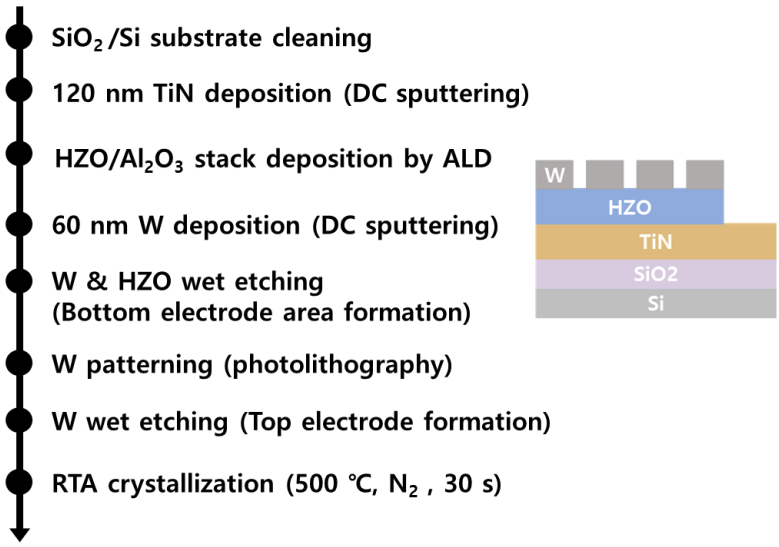
3. Experiment

To achieve this objective, HZO-based metal-ferroelectric-metal (MFM) capacitors were fabricated and characterized. The fabrication process of the capacitors is schematically illustrated in Fig. 3.1.

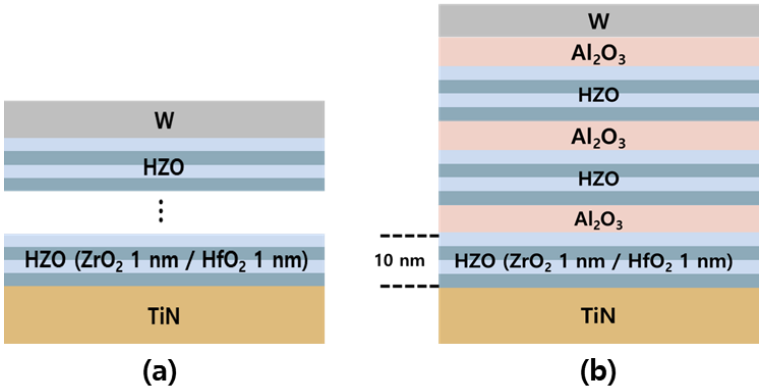
First, Si substrate with a 300 nm thick SiO_2 layer were cleaned with acetone. A 60 nm thick TiN bottom electrode was deposited on the SiO_2/Si substrate by DC sputtering. Subsequently, Al_2O_3/HZO stacked films were deposited by atomic layer deposition (ALD) at a substrate temperature of 250 ℃ using tetrakis(ethylmethylamino)hafnium (TEMAHf), tetrakis(ethylmethylamino)zirconium (TEMAZr) and trimethylaluminum (TMA) as the Hf, Zr, and Al precursors. The HZO composition was set to Hf:Zr = 0.5:0.5. Since the HfO_2 and ZrO_2 sublayers were deposited with a 1:1 ALD cycle ratio, $Hf_{0.5}Zr_{0.5}O_2$ films were obtained.

To control the grain growth of the HZO films, ultrathin Al_2O_3 interlayers with thicknesses of t nm (t = 0, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7 and 1.0 nm) were inserted after every 10 nm of HZO deposition. This Al_2O_3/HZO stacking was repeated three times, resulting in a total HZO thickness of 30 nm. The sample with t = 0 nm corresponds to the reference HZO films without Al_2O_3 interlayers.

After the ALD process, W top electrodes were deposited by DC sputtering. Finally, post-metallization annealing (PMA) was performed using rapid thermal annealing (RTA) at 500 ℃ for 30 s in a N_2 atmosphere to crystallize the films.



<Fig 3.1> Fabrication process of HZO-based MFM capacitor



<Fig 3.2> (a) HZO films (b) HZO/Al_2O_3 stack films

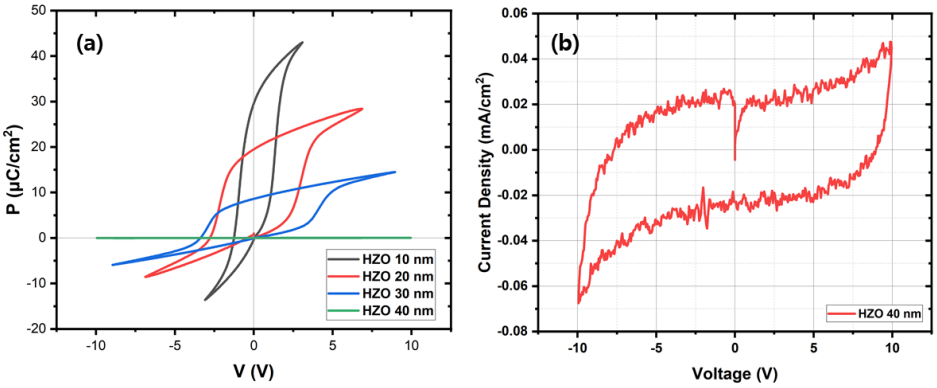
4. Results and Discussion

4.1 Thickness-dependent ferroelectric degradation in HZO thin films

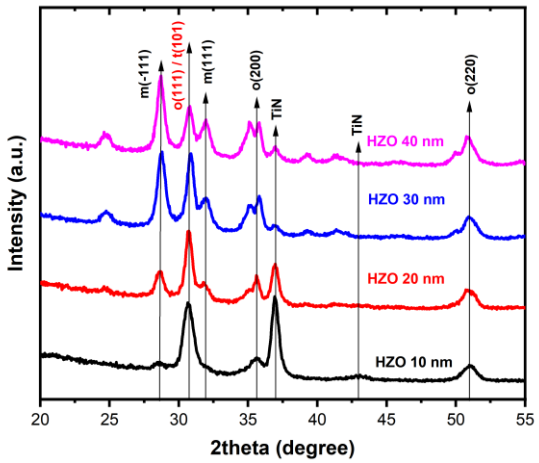
The polarization-voltage (P-V) characteristics and XRD patterns of HZO thin films without an Al_2O_3 interlayer were investigated as a function of HZO thickness. In the P-V measurements, the 10 nm thick HZO film exhibited the largest remanent polarization and a clear ferroelectric hysteresis behavior. However, as the HZO thickness increased, the remanent polarization gradually decreased, indicating degradation of the ferroelectric properties. In particular, the 40 nm thick HZO film showed almost no ferroelectric behavior. This thickness dependent degradation was also supported by the current density-voltage (J-V) characteristics.

The XRD patterns measured in the 2θ range of 20°–55° further support the P-V results by revealing the thickness dependent phase evolution of the HZO films. As the HZO thickness increased, the peak intensity associated with the m-phase of HZO increased. In contrast, the peak intensity corresponding to the o/t-phase decreased with increasing HZO thickness. These results indicate that the formation of the non-ferroelectric m-phase becomes more dominant in thicker HZO films, while the ferroelectric o-phase is suppressed.

Therefore, the degradation of ferroelectricity observed in the P-V measurements can be attributed to the thickness induced phase transition from the ferroelectric o-phase to the non-ferroelectric m-phase. This result confirms that controlling the HZO film thickness and suppressing m-phase formation are essential for maintaining robust ferroelectric properties in HZO thin films.



<Fig 4.1> (a) P-V curves of HZO films with various thickness (b) J-V curve of the 40 nm thick HZO



<Fig 4.2> XRD patterns of HZO films with various thickness

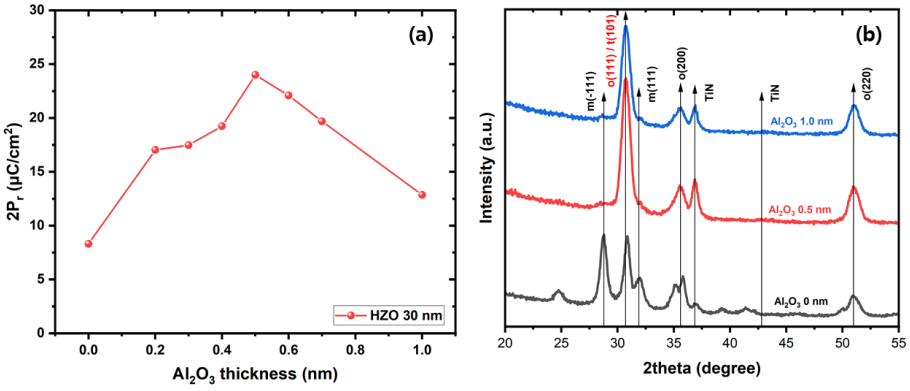
4.2 Effect of Al_2O_3 interlayer on 30 nm thick HZO films

The effect of the Al_2O_3 interlayer on the ferroelectric and structural properties of 30 nm thick HZO films was investigated with P-V and XRD measurements. When comparing the remanent polarization values, the 30 nm thick HZO film with a 0.5 nm thick Al_2O_3 interlayer exhibited the highest remanent polarization. As the Al_2O_3 thickness increased from 0 to 0.5 nm, the remanent polarization gradually increased, reaching its maximum at 0.5 nm. However, with further increase in the Al_2O_3 thickness, the remanent polarization gradually decreased.

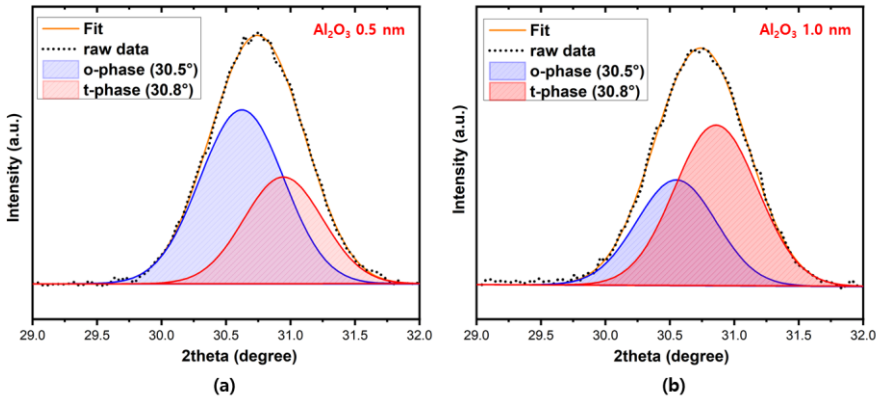
Based on this result, XRD measurements were performed for selected Al_2O_3 thicknesses of 0, 0.5 and 1.0 nm. The XRD results confirmed that the formation of the m-phase was suppressed when the Al_2O_3 interlayer was introduced. Although the peak intensity associated with the o-phase also increased, it is difficult to clearly distinguish the o-phase from the t-phase because of their structural similarity.

To further separate the contributions of the o-phase and t-phase, peak deconvolution analysis was performed. In this analysis, the o-phase peak was assigned at 30.5°, while the t-phase peak was assigned at 30.8°. The deconvolution results showed that a certain fraction of the o-phase was successfully obtained in the Al_2O_3 inserted HZO films. In particular, the 0.5 nm thick Al_2O_3 interlayer exhibited a higher o-phase fraction than the 1.0 nm thick Al_2O_3 interlayer.

These results indicate that inserting an ultrathin Al_2O_3 layer can effectively suppress the formation of the non-ferroelectric m-phase and promote the formation of the ferroelectric o-phase in 30 nm thick HZO films. Therefore, the 0.5 nm thick Al_2O_3 interlayer is considered the optimal condition for improving the ferroelectric properties of 30 nm thick HZO films.



<Fig 4.3> (a) remanent polarization and (b) XRD patterns of 30 nm thick HZO films with Al_2O_3 interlayers of various thicknesses



<Fig 4.4> XRD patterns of 30 nm HZO films showing the intensity distributions of the o-phase (blue) and t-phase (red): (a) 0.5 nm Al_2O_3 interlayer (b) 1.0 nm Al_2O_3 interlayer

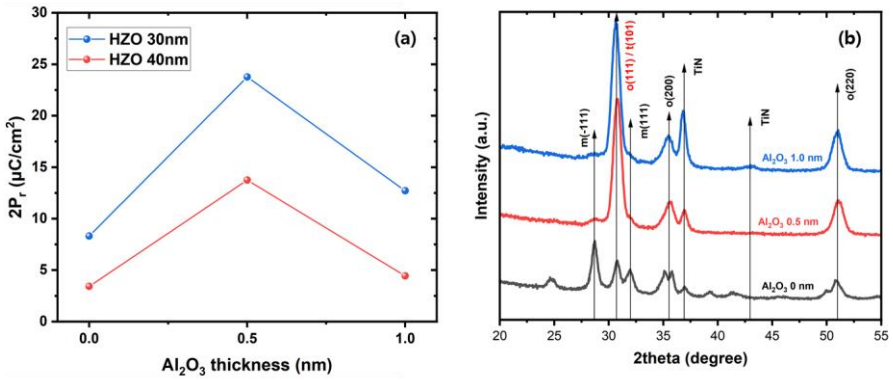
4.3 Verification of Al_2O_3 insertion effect

Based on the previous results, the same multilayer structure with an Al_2O_3 interlayer was applied to 40 nm thick HZO films to verify whether this approach is also effective for thicker HZO films. For comparison, 40 nm thick HZO films without an Al_2O_3 interlayer and those with 0.5 and 1.0 nm thick Al_2O_3 interlayers were prepared and analyzed.

The P-V measurement results showed a trend similar to that observed in the 30 nm thick HZO films. The remanent polarization was improved by introducing the Al_2O_3 interlayer, indicating that an appropriately designed Al_2O_3 interlayer is effective in recovering the ferroelectric properties of thick HZO films.

The XRD results further confirmed the effect of the Al_2O_3 interlayer. In the samples with the Al_2O_3 interlayer, the diffraction peak intensity associated with the o/t-phase increased, whereas the peak intensity corresponding to the non-ferroelectric m-phase decreased. This indicates that the Al_2O_3 interlayer suppresses the formation of the m-phase and promotes a crystal structure favorable for the formation of the ferroelectric o-phase in thick HZO films.

Therefore, these results demonstrate that the multilayer structure using an Al_2O_3 interlayer is an effective strategy for recovering ferroelectricity not only in 30 nm thick HZO films but also in thicker HZO films with a thickness of 40 nm.



<Fig 4.5> (a) remanent polarization of HZO with various Al_2O_3 thickness (b) XRD pattern of 40 nm HZO with various Al_2O_3 thickness

4.4 Future work

In this study, we investigated HZO thin film structures and process conditions applicable to Si photonics platforms. In particular, to mitigate the degradation of ferroelectricity with increasing HZO film thickness, we designed a multilayer structure capable of recovering ferroelectric properties even in relatively thick HZO films. Through this approach, the optimal thickness condition of the Al_2O_3 interlayer was determined.

In future work, the Al_2O_3/HZO-based thin film structure developed in this study will be directly integrated into Si photonic devices to investigate its optical effects. First, the optimized HZO thin film will be incorporated into the simulated structure shown in Fig. 2.1, and the second harmonic generation (SHG) effect will be examined by utilizing the second-order nonlinear optical properties induced by the non-centrosymmetric o-phase of ferroelectric HZO. This study is expected to clarify the correlation between the ferroelectricity of HZO thin films and their nonlinear optical response, thereby evaluating their potential as CMOS-compatible nonlinear photonic materials.

Furthermore, it is necessary to systematically analyze the influence of the polarization components of HZO on its optical properties in order to establish a clear understanding of the mechanism underlying the nonlinear effects in HZO. Through these follow-up studies, we expect to verify that HZO can be utilized as a CMOS-compatible ferroelectric photonic material that can potentially replace conventional ferroelectrics such as BTO and LN. This work may further be extended toward the realization of nonvolatile optical phase shifters, electro-optic modulators, and nonlinear photonic devices.

5. Conclusion

In this study, Al_2O_3 interlayer engineering was investigated as an effective strategy for stabilizing ferroelectricity in thick $Hf_{0.5}Zr_{0.5}O_2$ films for photonic applications. Silicon photonics requires CMOS-compatible materials that can provide nonlinear optical responses, because the centrosymmetric crystal structure of Si limits its second-order nonlinear optical properties. HZO is a promising candidate for this purpose due to its CMOS compatibility and ferroelectricity originating from the non-centrosymmetric orthorhombic phase. However, for photonic structures such as HZO–Au hybrid metasurfaces, relatively thick HZO films are required to enhance optical field confinement and light–matter interaction. This requirement introduces a major challenge because the ferroelectricity of HZO films tends to degrade as the film thickness increases.

To clarify this thickness-dependent degradation, HZO films without Al_2O_3 interlayers were first investigated as a function of film thickness. The P–V measurement results showed that the remanent polarization decreased with increasing HZO thickness. In particular, the 40 nm thick HZO film exhibited almost no ferroelectric behavior. XRD analysis revealed that this degradation was closely related to the increase in the non-ferroelectric monoclinic phase and the decrease in the ferroelectric orthorhombic phase. These results confirmed that suppressing the formation of the monoclinic phase is essential for maintaining ferroelectricity in thick HZO films.

To overcome this issue, ultrathin Al_2O_3 interlayers were inserted after every 10 nm of HZO deposition. In 30 nm thick HZO films, the remanent polarization increased as the Al_2O_3 interlayer thickness increased up to 0.5 nm, while further increase in the interlayer thickness resulted in reduced ferroelectric properties. Structural analysis showed that the Al_2O_3 interlayer effectively suppressed the formation of the monoclinic phase and promoted the formation of the ferroelectric orthorhombic phase. Among the investigated conditions, the 0.5 nm thick Al_2O_3 interlayer provided the most favorable balance for improving ferroelectric properties in 30 nm thick HZO films.

The effectiveness of Al_2O_3 interlayer engineering was further verified in 40 nm thick HZO films. Similar to the 30 nm thick films, the introduction of Al_2O_3 interlayers enhanced the remanent polarization and suppressed the monoclinic phase formation. These results demonstrate that the

Al_2O_3 interlayer can interrupt continuous grain growth and stabilize the ferroelectric phase even in relatively thick HZO films.

Overall, this study demonstrates that Al_2O_3 interlayer engineering is a promising approach for stabilizing ferroelectricity in thick HZO films required for photonic applications. The optimized Al_2O_3/HZO multilayer structure can serve as a CMOS-compatible ferroelectric platform for future Si photonic devices. In particular, this approach is expected to contribute to the realization of nonlinear photonic devices, electro-optic modulators, and nonvolatile optical phase shifters based on ferroelectric HZO films.

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Abstract in Korean

Al_2O_3 중간층 삽입을 통한 두꺼운 $Hf_{0.5}Zr_{0.5}O_2$ 박막의 강유전성 안정화 및 광소자 응용 가능성

최근 인공지능 및 고성능 컴퓨팅 기술의 발전으로 인해 고대역폭 및 저전력 데이터 전송 시스템에 대한 수요가 급격히 증가하고 있다. 이러한 요구에 대응하기 위해 실리콘 포토닉스는 상보성 금속 산화막 반도체 (Complementary Metal Oxide Semiconductor, CMOS) 공정과의 호환성 및 대규모 집적 가능성을 바탕으로 유망한 광집적회로 플랫폼으로 주목받고 있다. 그러나 실리콘은 중심대칭 결정 구조로 인해 2 차 비선형 광학 응답이 제한되며, 이로 인해 효율적인 광소자 구현에 한계가 있다. 따라서 CMOS 공정과 호환되면서 비선형 광학 특성을 가질 수 있는 강유전체 물질의 개발이 필요하다.

본 연구에서는 광소자 응용을 위한 CMOS 호환 강유전체 물질로 $Hf_{0.5}Zr_{0.5}O_2$ 박막을 연구하였다. 특히 HZO-Au 하이브리드 메타표면과 같은 광소자 구조에서는 광 모드 구속 및 빛-물질 상호작용을 향상시키기 위해 비교적 두꺼운 HZO 박막이 요구된다. 그러나 HZO 박막은 두께가 증가함에 따라 결정립 성장이 촉진되고 비강유전성 monoclinic 상이 형성되어 강유전성이 저하되는 문제가 있다. 본 연구에서는 이러한 문제를 해결하기 위해 두꺼운 HZO 박막 내부에 초박막 Al_2O_3 중간층을 삽입하여 결정립 성장을 억제하고 강유전성 orthorhombic 상을 안정화하고자 하였다.

이를 위해 원자층 증착법을 이용하여 HZO 기반 금속-강유전체-금속 커패시터를 제작하였다. HZO 의 조성은 Hf:Zr = 0.5:0.5 로 고정하였으며, HZO 10 nm 증착마다 다양한 두께의 Al_2O_3 중간층을 삽입하였다. 제작된 박막의 강유전 특성과 결정 구조는 분극-전압 측정 및 X 선 회절 분석을 통해 평가하였다. Al_2O_3 중간층이 삽입되지 않은 HZO 박막의 경우, 박막 두께가 증가함에 따라 잔류분극이 감소하였으며, 40 nm 두께의 HZO 박막에서는 강유전 특성이 거의 나타나지 않았다. X 선 회절 분석 결과, 이러한 강유전성 저하는 박막 두께 증가에 따른 비강유전성 monoclinic 상의 증가와 강유전성 orthorhombic 상의 감소에 기인함을 확인하였다.

Al_2O_3 중간층을 삽입한 경우, 두꺼운 HZO 박막의 강유전 특성이 향상되었다. 30 nm 두께의 HZO 박막에서는 Al_2O_3 중간층 두께가 0.5 nm 까지 증가함에 따라 잔류분극이 증가하였으며, 그 이상의 두께에서는 다시 감소하는 경향을 보였다. X 선 회절 및 피크 분리 분석 결과, 0.5 nm 두께의 Al_2O_3 중간층은 비강유전성 monoclinic 상의 형성을 효과적으로 억제하고 강유전성 orthorhombic 상의 형성을 촉진하는 것으로 확인되었다. 또한 동일한 Al_2O_3 중간층을 40 nm 두께의 HZO 박막에 적용한 결과, 강유전 특성이 회복되고 monoclinic 상의 형성이 억제되는 것을 확인하였다.

본 연구 결과는 Al_2O_3 중간층이 두꺼운 HZO 박막의 강유전성을 안정화하는 효과적인 방법임을 보여준다. 최적화된 Al_2O_3/HZO 다층 박막 구조는 향후 CMOS 호환 강유전체 광소자, 전기광학 변조기 및 비휘발성 광 위상 변조기 구현을 위한 유망한 플랫폼으로 활용될 수 있을 것으로 기대된다.

핵심되는 말 : $HfZrO_2$, Al_2O_3 중간층, 강유전성, 실리콘 포토닉스, CMOS 호환성, 비선형 광학, monoclinic 상, orthorhombic 상