A 10nm-THICK HAFNIUM ZIRCONIUM OXIDE PIEZOELECTRIC TRANSDUCER FOR EXTREME MINIATURIZATION OF INTEGRATED SENSORS AND ACTUATORS

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ABSTRACT

This paper reports the thinnest ever-reported piezoelectric transducer for realization of extremely miniaturized nanomechanical sensors and actuators. A 10nm hafnium-zirconium-oxide ($Hf_{0.5}Zr_{0.5}O_2$) (HZO) film is engineered through atomic-level stacking, capping with titanium-nitride electrodes, and proper rapid-thermal-annealing treatment to promote non-centrosymmetric orthorhombic crystallization with large piezoelectric properties. The developed 10nm HZO transducer is used for excitation of a silicon-based multi-morph nanomechanical resonator, with an overall thickness of ~350nm. The developed resonator, along with 120nm aluminum-nitride (AlN) transduced counterparts, are also used as test-vehicles to characterize the ferroelectric and piezoelectric properties of the HZO film. Benefiting from large piezoelectric coefficient ($e_{31,HZO} \approx 2.3e_{31,AlN}$), fully conformal deposition, and CMOS-compatibility, ALD-deposited HZO transducer paves the way for radical miniaturization of nano-systems, realization of 3D nano-actuators, and extreme frequency scaling and monolithic integration of RF front-ends for the emerging 5G wireless communication systems.

INTRODUCTION

Over the past decade, piezoelectric films have gained growing interest for realization of micro- / nano-mechanical sensors and actuators. Superior to other integrated transduction schemes, piezoelectric films enable large electromechanical transduction efficiency in small foot-prints; therefore, realizing zero-power sensors [1], large-displacement actuators [2], and wide-band RF filters [3]. However, the forthcoming wave of novel application of M/NEMS including VLSI sensor integration, micro- / nano-robotics, and 5G mm-wave front-end calls for transforming piezoelectric film technologies that enable (a) extreme thickness miniaturization while sustaining large electromechanical coupling; (b) conformal piezoelectric film integration on 3D micro- / nano-structures to enhance actuator displacement flexibility and energy density; and (c) monolithic integration with CMOS.

Currently, no piezoelectric film technology exist that provide these features. Current films are limited to >50-100nm thicknesses (dictated by the nucleation / crystallization processes), and their piezoelectric properties drastically degrade when deposited on sidewalls / non-planar surfaces and are not compatible with CMOS thermal-budget / material restrictions [4]. To address this technological gap, we demonstrate the use of piezoelectric properties of a 10nm atomically-engineered ferroelectric hafnium-zirconium-oxide (HZO) film for transduction of nanomechanical sensors, actuators, and resonators. Though HZO is widely studied for FeFET and FeRAM applications [5], its exploration for piezoelectric transduction are none. ALD deposited HZO films are typically amorphous due to the low thermal budget operation but can be engineered into crystallinity with proper thermomechanical treatment [6].

While conventional ferroelectric films, such as PZT, are known to provide large piezoelectric transduction through proper poling, their fabrication processing techniques are not readily compatible with CMOS manufacturing and are incapable of realizing super-thin films (<70nm) for emerging applications [7]. In contrast, the unique and truly CMOS-compatible fabrication process for HZO, based on atomic layer deposition (ALD), facilitates realization of super-thin films with atomically defined thicknesses over 5nm-25nm, and enables precise control over ferroelectric, and hence piezoelectric, properties of the film through introduction of desirable doping / layering. In this paper, 10nm-thick atomically engineered HZO film with ferroelectric orthorhombic phase are developed and used for electromechanical transduction of a silicon-based nanomechanical resonator. To the knowledge of the authors, this is the thinnest piezoelectric transducer ever reported and paves the way for extreme miniaturization of integrated sensors, actuators, and resonators.

MULTIMORPH RESONATOR DESIGN

A multi-morph nano-mechanical resonator is used for characterization and verification of HZO piezoelectric properties. The resonator is formed from stacking HZO, AlN, and Si films with corresponding electrode layers to realize two-port devices with asymmetric transduction scheme (port-1 AlN, port-2 HZO). Fig. 1 demonstrates the SEM image of the device. Port-1 is created from 120nm AlN film sandwiched between bottom molybdenum (Mo) and top platinum (Pt) electrodes. Port-2 is realized from 10nm- HZO sandwiched between bottom Mo and top titanium nitride (TiN) and Pt electrodes. The HZO transducer stack is deposited atop of the AlN film that is deposited on 70nm Si layer. Details of the individual transducer stack configurations are shown in Fig. 1 (inset). Benefiting from two independent piezoelectric transducers (i.e. HZO and AlN), various drive/sense mechanisms are used, as shown in Fig. 2, for characterization of the device performance and ferroelectric properties. Low frequency measurements using a digital holographic microscope (DHM) are carried out to evaluate the out-of-pane vibration amplitudes of the resonator when actuated with 10nm-HZO and 120nm-AlN transducers. The DHM measurements along with asymmetric transducer design for an individual resonator enable precise extraction of relative piezoelectric properties of HZO and AlN films through comparing vibration amplitudes when actuated at corresponding ports. Fig. 3 details the resonator stack through the high-

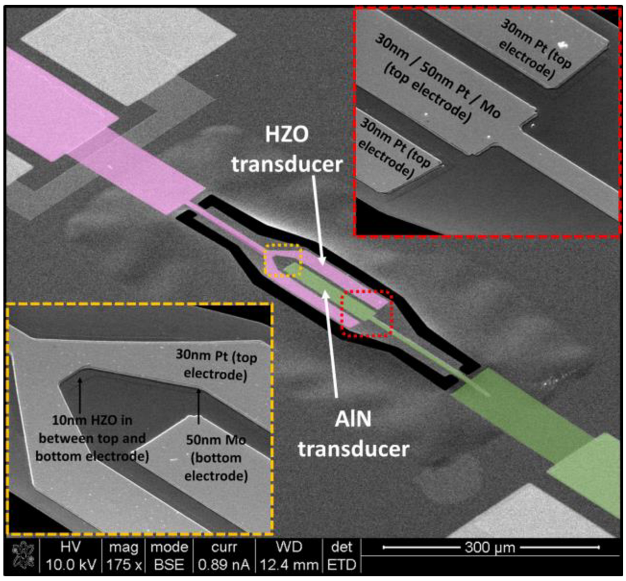

Fig. 1: SEM image of two-port resonator. Port-1 (highlighted in green) is an AlN transducer while port-2 (highlighted in pink) is 10nm HZO transducer. (. (inset-top) shows the IDT electrodes with central AlN transducer and two HZO transducer electrode stack. (inset-bottom) highlights the HZO transducer stack with 10nm HZO in between the top 30nm Pt and bottom 50nm Mo electrodes thus making a viable transduction scheme.

resolution cross-sectional TEM (HR- XTEM) image. The inset shows the diffraction pattern of the HZO film with ferroelectric orthorhombic phase.

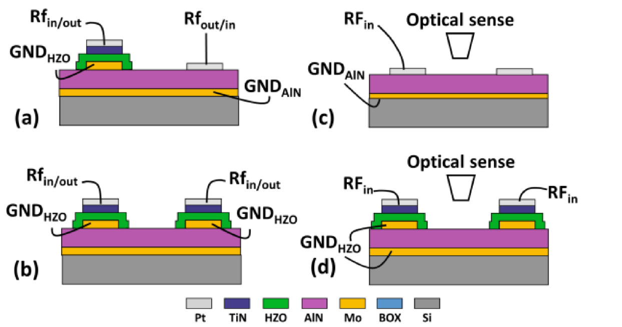

Fig. 2: (a) 2-port measurement set-up for Network Analyzer with AlN-drive and HZO-sense (or vice-versa) (b) 2-port measurement set-up for Network Analyzer with HZO-drive/sense (c) AlN-drive and optical sense of out-of-plane vibration using DHM. (d) HZO-drive and optical sense of out-of-plane vibrations using DHM.

FABRICATION PROCESS

Fig. 4 summarizes the fabrication process used for 2-port (AlN-transduced port-1 and HZO-transducer port-2) asymmetrically transduced waveguide-based resonator. AlN thin film (120nm) sandwiched between top and bottom 50nm molybdenum (Mo) is magnetron sputtered on top of a 70nm device layer SOI substrate. Top Mo is patterned to serve as the ground (GND) for the HZO transduction scheme. An ALD 10nm-HZO / 10nm-TiN

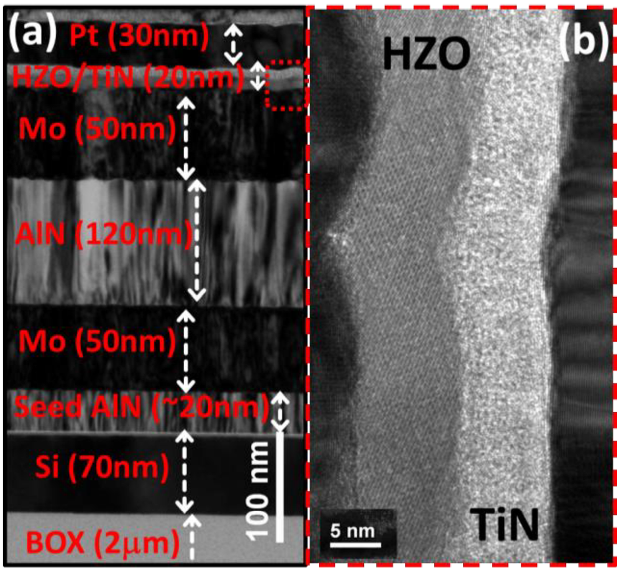

Fig. 3. (a) HR-XTEM image verifying the individual thickness of the materials in the stack. (b) Zoomed-in view of the 10nm/10nm HZO/TiN layers. The crystal diffraction patters are evident in HZO indicating the crystalline form of HZO.

stack is then deposited using alternating series of pulses: tetrakis (dimethylamino) zirconium (IV), followed by a water (H_2O) to oxidize the layer and tetrakis (dimethylamido) hafnium (IV), again followed by H_2O for oxidation. By alternating equal cycles of HfO_2 and ZrO_2 a 1:1 binary of 10nm HZO is achieved. This is followed by tetrakis (dimethylamido) titanium (IV) and nitrogen plasma for 10nm TiN. The TiN capping layer is selectively patterned in the regions for the HZO transduction using Cl_2/H_2 based plasma process. HZO is then consecutively etched back using BOE to get access to AlN in all regions except the HZO transducer area. Following HZO / TiN selective etching, rapid thermal annealing (RTA) at 500^0C for 20s is used to crystalize the HZO in its ferroelectric phase. 30nm platinum (Pt) to serve as $RF_{in/out}$ electrodes is sputtered using a liftoff process. Bottom Mo (serving as GND for AlN transducer) is accessed by dry etch of 120nm AlN outside the device area using Cl_2/Ar based RIE/ICP process. The lateral geometry of the device is then defined with selective etching of 120nm AlN / 50nm Mo / 70nm Si in an RIE/ICP process. Finally, the devices are released from the back side by etching the handle layer Si using DRIE and consecutively etching the buried oxide layer using RIE.

CHARACTERIZATION

Fig. 5 shows the two-port frequency response of the device in Fig. 1, highlighting the resonance peak at ~12MHz. Compared to asymmetric transduced resonator (with a Q_{air} of ~46 and IL=~-80dB), the HZO-only transduced resonator shows significant improvement in insertion loss (IL=~-32dB) owing to higher electromechanical coupling compared to AlN. Besides 2-port electrical characterization, out-of-plane vibration amplitude is also monitored using a DHM and driving schemes shown in Fig. 2(c, d) at ~4MHz, and the results are compared for HZO-only and AlN-only transduced

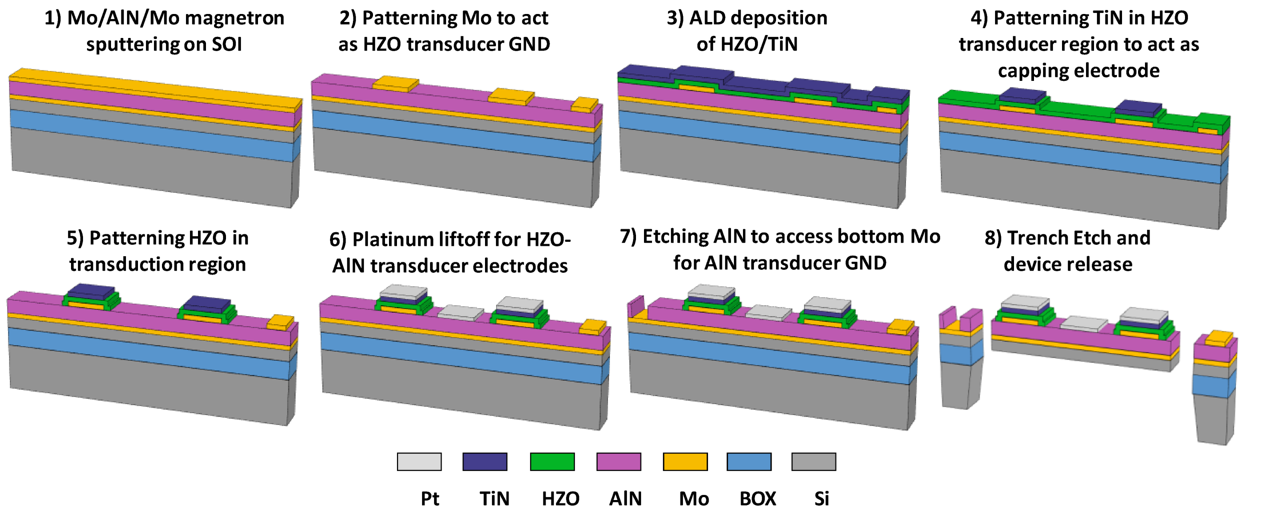

Fig. 4. The fabrication process flow for HZO/AlN dual-transduced 2-port resonator on 70nm Si. Top Mo acts as GND for HZO transducer while bottom Mo serves as GND for AlN transducer.

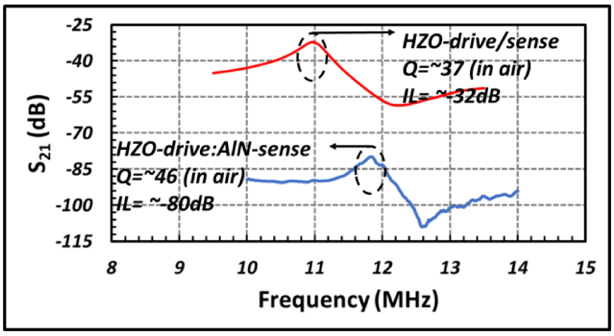

Fig. 5. Measured 2-port frequency response for different transduction schemes as Fig. 2 (a, b). The insertion loss is significantly improved for HZO transduced resonator compared to the AlN-HZO transducer combination due to high piezoelectric coefficient of HZO. Thus, signifying an improved piezoelectric for a10nm film.

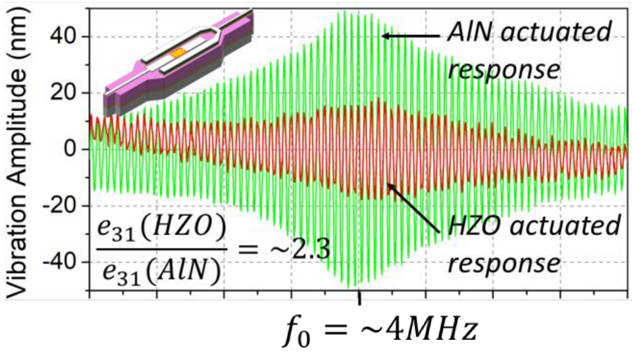

Fig. 6. Out-of-plane vibration amplitude at resonance frequency for resonator actuated using driving mechanisms (Fig. 2(c, d)). The AlN-actuated vibration amplitude is ~50nm while HZO-actuated amplitude is ~20nm. The vibration amplitude comparison indicates $e_{31,HZO} \approx 2.3 e_{31,AlN}$*. (inset) shows the monitoring region for out-of-plane vibration of the resonator under DHM. The Qs derived from the vibration amplitudes is ~50 in both cases suggesting the Q-limiting factor to be geometric than material-induced.*

counterparts (Fig. 6). Such a comparison enables estimation of piezoelectric coefficient of HZO, resulting in $e_{31,HZO} \approx 2.3 e_{31,AlN}$. Fig. 7 shows the two-port frequency response for the first extensional mode of vibration for the device shown in Fig. 1 at ~38MHz with a Q_{air} of ~400 and IL=~-52dB with the driving scheme shown in Fig. 2(a). Fig. 8 shows the P-V response of the HZO film demonstrating strong ferroelectric property of HZO after wake-up. HZO is shown to be ferroelectric in sub-5nm

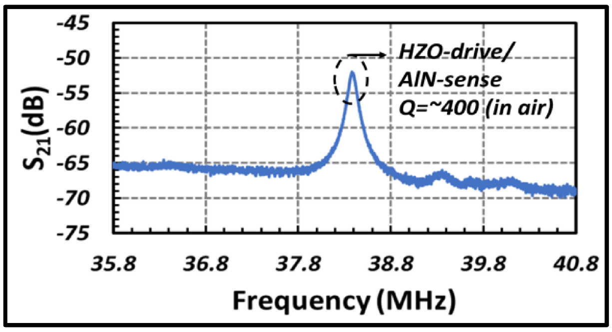

Fig. 7. Measured 2-port frequency response for transduction schemes as Fig. 2(a) for 1st width-extensional mode of vibration. The maximum Q of ~400 (in air) at ~38MHz is observed.

thickness regime [8], thus paving the way for realization of a piezoelectric transducer for extreme miniaturization of integrated sensors and actuators, and frequency scaling of resonators into mm-wave regime.

CONCLUSION

This paper demonstrates the thinnest ever reported CMOS-compatible piezoelectric transducer realized from a 10nm hafnium-zirconium-oxide (HZO) film. Atomically deposited ferroelectric HZO film is engineered to demonstrate large piezoelectric properties and used for excitation of a multi-morph nano-mechanical resonator. Various schemes, including isolated HZO- and AlN-transduction ports, along with different electrical and optical characterization are used to extract ferroelectric and

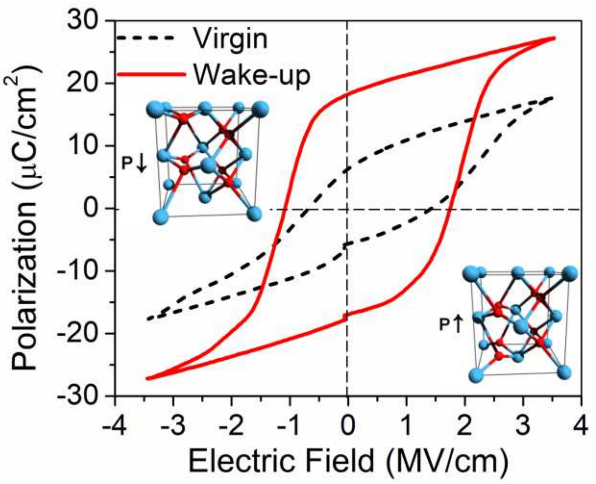

Fig. 8. Hysteresis curves for 10nm HZO film constituting the resonator transducer in the virgin state (dashed) and after wake-up (solid). Wake-up is achieved by 1k cycles of bipolar square wave at 1kHz. The remnant polarization increases after wake-up signifying enhanced ferroelectric properties in film.

piezoelectric properties of the HZO film. The ALD deposited HZO process benefits over the current piezoelectric sputtering / MOCVD deposition techniques by: 1) extreme scalability to sub-25nm thickness without degradation of piezoelectric properties; thus, enabling implementation of cm- and mm-wave resonators for 5G RF front-ends; 2) conformal nature of the deposition process enables realization of sidewall transducers with identical piezoelectric properties to planar films; 3) the capability to engineer ferroelectric / piezoelectric properties by varying doping concentration; and 4) The high-*k* dielectric properties of HZO can be integrated to create a dual electrostatic / piezoelectric hybrid-transducer for low-voltage operation.

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