Ferroelectric HfZrO Films: Process, Characterization and Devices

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Outline

- Introduction
 - Ferroelectric HfZrO
 - Motivation and Methodology of Film Formation
- Physical and Electrical Characteristics
- Applications
 - Memories
 - Digital Logic Devices
 - Neuromorphic Devices
- Summary and Conclusions

Ferroelectric Films

- Two distinct polarization states (remnant polarization)
- Maintained in the absence of an electric field
- Can be switched by an electric field

ABO_3
Perovskite

Centrosymmetric
Linear Dielectric
 $T > T_C$

Non-Centrosymmetric
Ferroelectric
 $T < T_C$

Ferroelectricity in Hafnium Oxide based Thin Films

- Engineered HfO_2
 - Anneal, etc. See: Muller et. al. APL 99, 112901 (2011); Boscke et. al. APL 99, 102903 (2011)
- Doped HfO_2
 - Zr, Al, Gd, La, Si, Sr and Y
- Ferroelectricity in HfO_2 origin is attributed to the non centrosymmetric orthorhombic phase
- Currently Ferroelectric films are considered for Ferroelectric RAM (FeRAM), Ferroelectric FETs and as gate dielectrics for negative capacitance FETs (NCFETs)

Forming Ferroelectric HfZrO

Adapted From: Dey *et. al.* FCMN 2017
Also: Sharma *et. al.* VLSI 2017

5nm TiN/7nm $\text{Hf}_{0.2}\text{Zr}_{0.8}\text{O}_2/\text{Si} + 700^\circ\text{C}$ 30 sec. PMA

X-axes are defined as $x/(x+y)$ for:

Cycle Ratio: $[(\text{TEMAH}/\text{Ox})_x + (\text{TEMAZ}/\text{Ox})_y] \times n$ cycles

Molar Flow: $[(x \text{ TEMAH} + y \text{ TEMAZ})/\text{Ox}] \times n$ cycles

- To form the non-centrosymmetric orthorhombic phase thought to cause ferroelectric behavior specific process sequences are needed depending on the substrate.
- We have observed a strong correlation with peaks attributable to the tetragonal phase, which is anti-ferroelectric and a possible transition state in polarity flips.

Some Ferroelectric Device Possibilities

After positive gate pulse
(polarization down)

Low- V_T state

After negative gate pulse
(polarization up)

High- V_T state

Dunkel, S. IEDM 2017

Florent, K. VLSI 2017

Fig. 2 Schematic view of the FeFET: three polysilicon gates, ferroelectric Al:HfO₂ surrounding a cylindrical vertical channel.

Tunnel Junction (FTJ)

Chen, L. Nanoscale 2018, 10.1039/c8nr0473k

Fig. 3 (a) TEM cross-section. (b) STEM zoom of the bottom opening.

Krivokapic, Z. IEDM 2017

Fig. 4: Capacitance matching between FE capacitors and MOS load line for both IL cases. For IL_A the matching occurs at positive C_{FE} , while for IL_B it occurs for negative C_{FE} .

NCFET

Fig. 6: Variation of SS in the subthreshold regime for various transistor areas.

Sharma *et. al.* VLSI 2017

GI-XRD: (Apparently) Tetragonal correlates to polarization

(PMA; 5nm) TiN/ (CR; 7nm) $\text{Hf}_{1-x}\text{Zr}_x\text{O}_2/\text{Si}$

7nm Films in MIM Structure – Varying Composition

Mukundan accepted MRS Fall 2018

Tetragonal

Orthorhombic

Monoclinic

Correlating GIXRD and Electrical Characterization:

- MIM 7nm $\text{Hf}_{0.5}\text{Zr}_{0.5}\text{O}_2$

Electrical test scheme

$$P_r^- = (Q_1 + Q_2) - (Q_3 + Q_4)$$

$$P_r^+ = (Q_5 + Q_6) - (Q_7 + Q_8)$$

HZO sample shows ferroelectric behavior with a remnant polarization of $\sim 27 \mu\text{C}/\text{cm}^2$ with a necessary electrical activation (drive-in)

7nm $\text{Hf}_{0.5}\text{Zr}_{0.5}\text{O}_2$

MFM Devices

Both MFM and MFIS shows similar ferroelectric behavior
 $\text{Hf}/(\text{Hf}+\text{Zr})\%=50\%$

MFIS Devices

7nm $\text{Hf}_{0.2}\text{Zr}_{0.8}\text{O}_2$

MFM Devices

MFM Devices show Anti-Ferroelectric behavior, indicating Tetragonal HfZrO_3 ; MFIS remains Ferroelectric

MFIS Devices

The observation of antiferroelectric behavior for Thin, High Zr films has been shown previously in the literature.

See: Park et. al. Nanoscale (2017) 10.1039/C7NR02121F

Ferroelectric FETs for Memory applications

(a) Ferroelectric FET NVM operation; (b) Electron/hole trapping within gate stack during erase/program pulse, respectively; (c) Charge trapping narrows MW; (d) V_{TH} distribution without (solid line), and with (dashed line) charge trapping. Charge trapping broadens and shifts distribution.

I_D - V_G characteristics with increasing (a) erase and (b) program voltage amplitude. The inset shows the MW_{expt} as a function of the write amplitude. MW_{expt} monotonically increases with amplitude. Pulse width of 500 ns is applied.

Preventing Breakdown of IL and Optimizing MW

(a) Electric field distribution for 1nm FE/0.8nm SiO₂ IL stack, $E_{IL} > 25$ MV/cm (degrades reliability), while $E_{FE} \sim 1$ MV/cm (reduces MW). (b) Simulated MW and (c) maximum E_{IL} as a function of IL composition/thickness.

- IL is subjected to high electric field during device program/erase leading to early failure
- High K interface layers are proposed as a countermeasure

(a) Design space exploration for four different interlayer dielectrics, bounded by constraints: (1) $t_{IL} + t_{FE} \leq 10.8$ nm, (2) $E_{IL} \leq 12$ MV/cm for La₂O₃ and HfO₂ and $E_{IL} \leq 15$ MV/cm for Al₂O₃ and SiO₂. (b) Maximum memory window satisfying all the constraints for four different interlayer dielectrics. ϵ_{FE} kept at 30 is used for all thicknesses of HZO.

Enhancement of Ferroelectricity Properties Via additional capping

Control

5 nm ALD Hf_{0.5}Zr_{0.5}O₂

w/ Cap

5 nm ALD Hf_{0.5}Zr_{0.5}O₂ / 1 nm Al₂O₃

- Ferroelectricity enhanced by in situ cap
- Ideal for memory application

Switching Dynamic

- Insertion of Al_2O_3 increases MW significantly

Nucleation limited polarization switching

Variation

- Excellent variation property for different pulse widths and amplitudes

Negative Capacitance FET (theory)

$$\frac{1}{C_T} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} \dots$$

Negative?

$$d\psi_s = \frac{C_1}{C_1 + C_2} dV_G \xrightarrow{C_1 < 0} d\psi_s = \frac{|C_1|}{|C_1| - C_2} dV_G$$

- A gain $\frac{d\psi_s}{dV_g} > 1$ is possible
- The amount of gain is dependent upon how well C_2 is matched to $|C_1|$

Negative Capacitance FETs using Ferroelectric Hf/ZrO

Scaled Gate Last Hf/ZrO NCFETs

$I_{DS}-V_{GS}$ Characteristics

Scaling effect

FerroFET

Ferroelectric in a **hysteretic** NCFET

Hysteretic
with
Trapping

Neuromorphic: Ferroelectric Synapse

- Electric-field controlled partial polarization switching in ferroelectrics FETs can be harnessed for synaptic memory with nanosecond updates.

- **FeFETs have potential applications as neuromorphic computing components**
- **Bring memory and computing together**

Summary

■ Accomplishment

- Ferroelectric HfZrO was demonstrated and investigated for logic and memory applications
- Effects of Thickness, Composition, and MIM vs. MIS Structure have been investigated
- Polarization is enhanced by using cap technique
- Cap material dependence of memory windows are evaluated
 - High-k interlayer is better than SiO₂ interlayer both in memory window and breakdown voltage
- Steep SS<60mV/dec. realized during ferroelectric switching (NCFET)
- Stable and Uniform switching characteristics can enable nonvolatile logic for Neuromorphic applications

■ Future plan

- Realizing Ferro-electric phase with < 5 nm thickness
- Understanding how structural effects impact electrical behavior and breakdown
- Expanding memory window

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