Ultra-thin ALD HfO2 Growth Mechanism Studied By Atomic Force Microscope (AFM)

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Outline

- **Introduction**
- **Description of analytical techniques used in this study**
- **Influence of silicon oxide interface layer (IL) surface chemistry on the HfO2 growth**
  - **Growth rate, surface coverage and morphology**
- **HfO2 growth mechanism**
- **Correlation of HfO2 morphology with leakage current performance**
- **Conclusions**

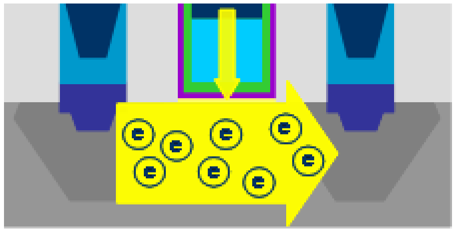
Introduction

▪Incentives of high-k HfO_2 gate dielectric

– Tradition SiO2 and SiON delectrics cannot sustain low gate leakage current (Jg) for EOT below 10 Å

– Higher k dielectrics can afford large physical thickness to reduce Jg

Smaller Jg



▪Why SiO_2 and SiON based dielectrics are hard to replace?

– Natively grown, high purity, conformal, dense and stable!

– Good electrical properties: low defect density and good interface property

▪Challenges of HfO_2 deposition processes

– ALD process for conformal deposition

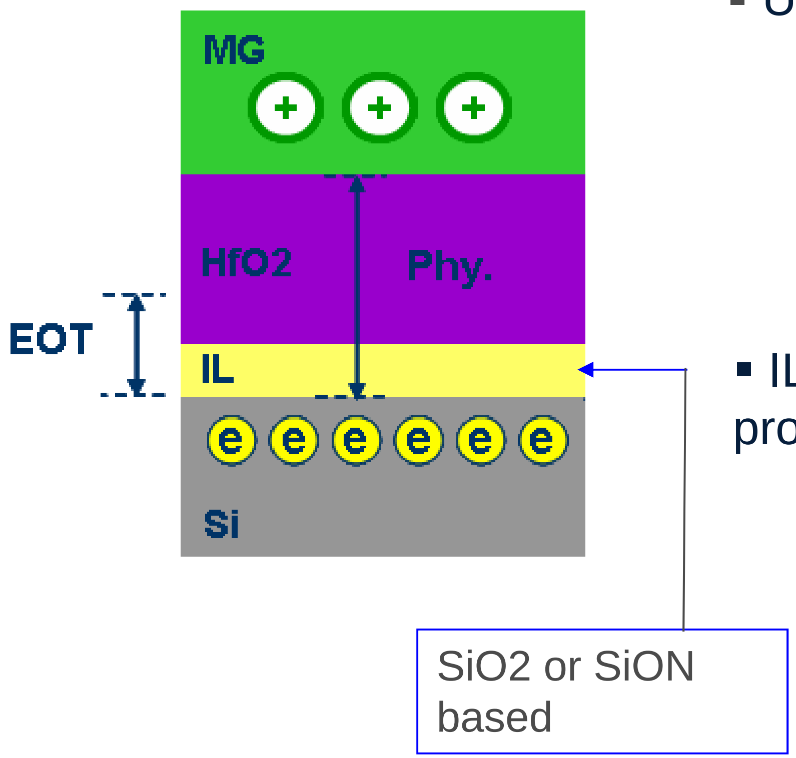
– Control of composition, impurity content, phase and crystallinity

– ***Density and uniformity – affecting current leakage property***

– Interface with Si channel – interface roughness induced carrier scattering

Introduction

Interface engineering is important in high-k/metal gate processing



- Unintentionally formed IL (interface layer)
  - unstable
  - poor interface with Si channel
  - poor electrical properties

- IL engineering to grow good IL with good properties
  - low roughness interface to decrease carrier scattering
  - chemically stable to reduce interface states and traps
  - as thin as possible, not to consume EOT budget
  - ***good surface properties for easy high-k oxide nucleation!***

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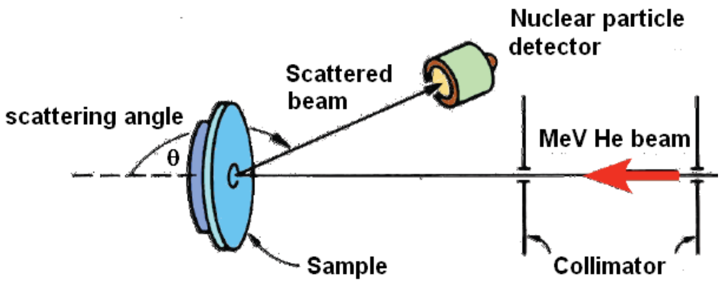
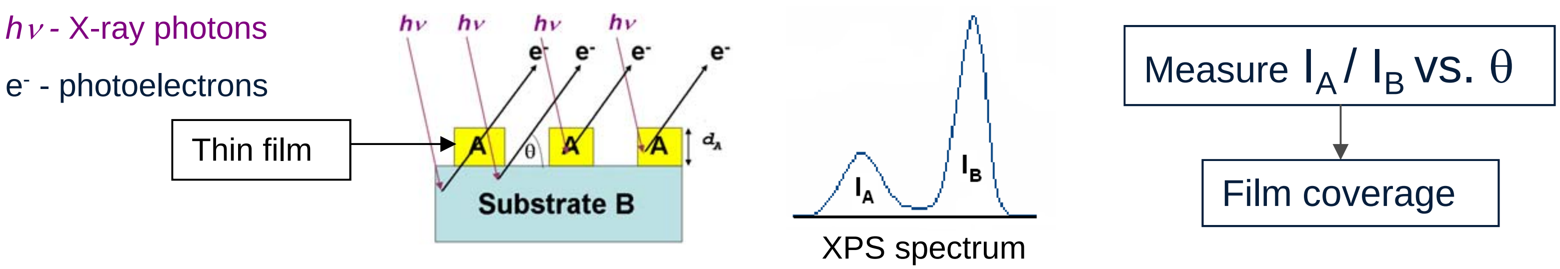
Descriptions of analytical techniques

- **RBS – Measures surface dose of Hf**
  - Energy of scattered He depends on the atomic # of the atoms on surface
  - 10^{11} atoms/cm^2 detection limits for Hf
  - **For determination of HfO2 growth rate**



- **AR-XPS - Measures thin hafnium oxide composition and coverage**



- **Atomic force microscope (AFM, non-destructive)**
  - **Imaging of film morphology at different stages of film growth, best for providing direct film growth mechanism information**
  - Not successfully applied before due to easy tip damage and low image resolution

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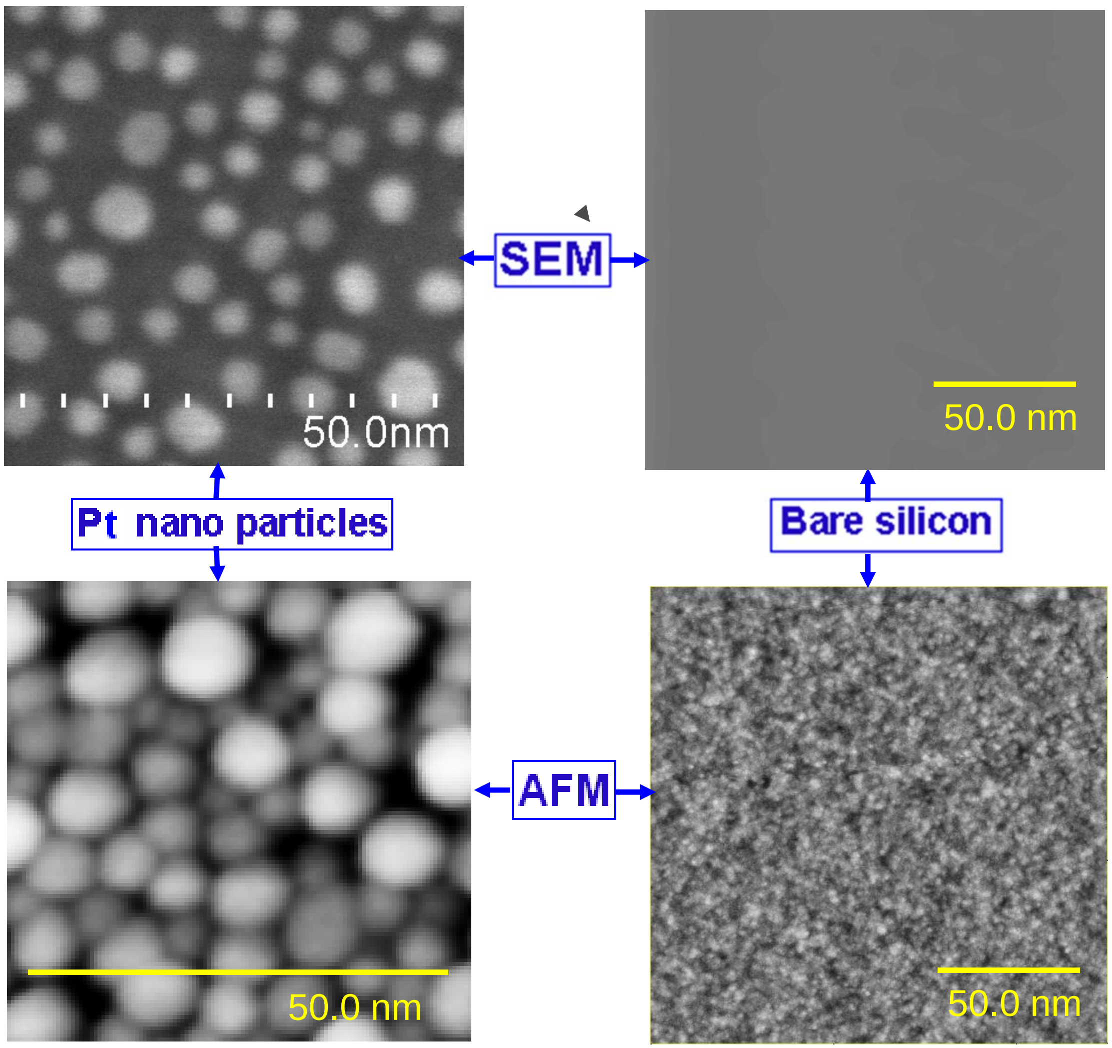
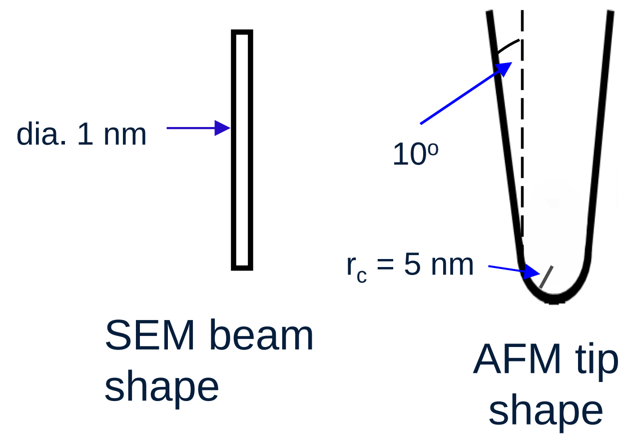
Pros and cons of AFM for high resolution imaging

Comparison with secondary electron microscope





Cons

- *TiP damages easily*
- *Poor lateral resolution*

Pros

- *Good height sensitivity*
- *Non-destructive*

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Low tip damage technique development

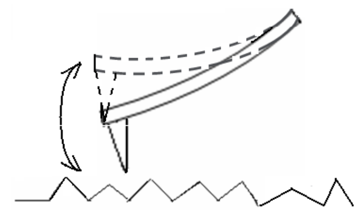
Non-contact AFM

Traditional tapping mode

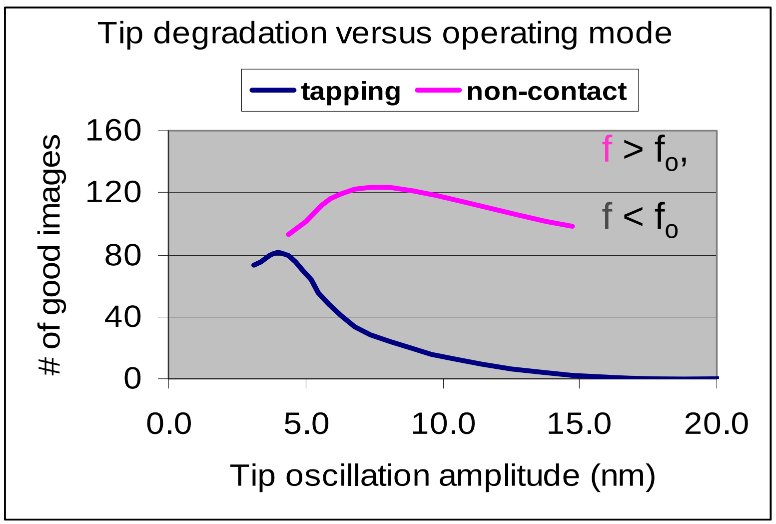
New non-contact mode

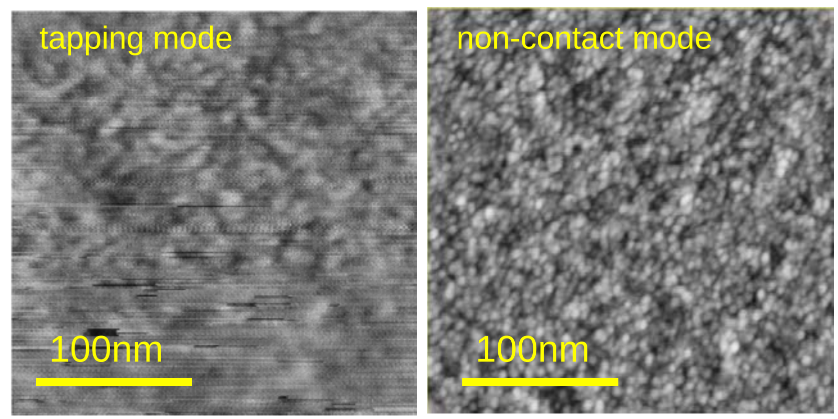
Broken tip

Contaminated tip



Intact tip





AFM images of bare Si

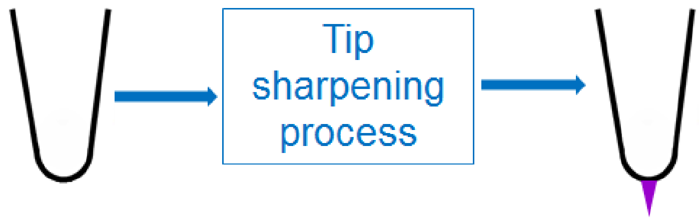
Non-contact AFM technique considerably prolongs tip life and improves image quality

C. C. Wang, Y. Pu, L. Fu, Y. Ma and Y. S. Uritsky, *AIP Conference Proceedings* **788**, 194-199 (2005)

B. Liu, C. C. Wang, P. Huang and Y. S. Uritsky, *Proc. of SPIE* **7729**, 77290O-1-77290O-11 (2010)

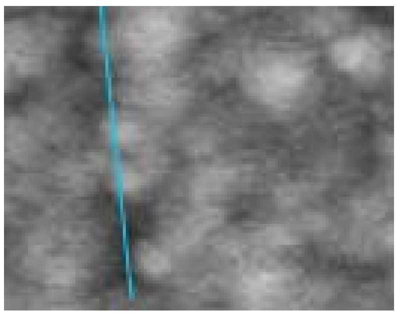
High resolution AFM tip development

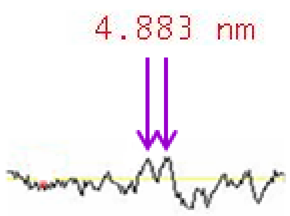
Proprietary AFM tip sharpening technique to improve resolution ≥ 1.5X



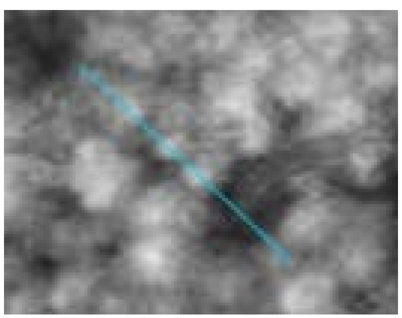
Bare silicon surface

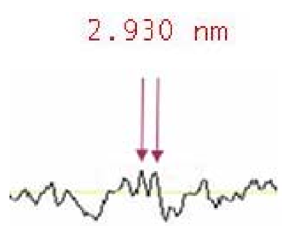
Not sharpened tip





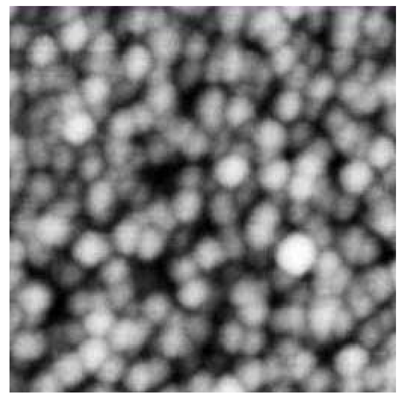
Sharpened tip



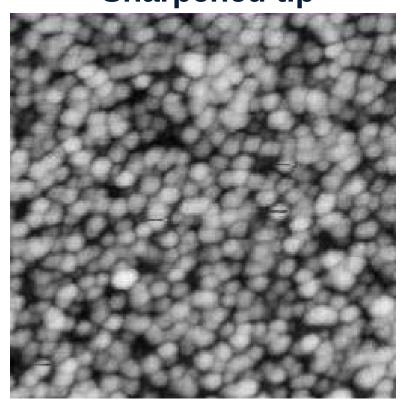


Silicon nano crystals

Not sharpened tip



Sharpened tip



- ***Considerable improvement in lateral resolution.***
- ***In-house tip sharpening avoids shipping, handling and aging damage to AFM tip.***

HfO_2 growth study – descriptions of ALD HfO_2 samples

TABLE 1. Descriptions of the Six IL sample groups, on which ALD HfO_2 films[@] were deposited

Group No.	Group 1	Group 2	Group 3	Group 4	Group 5	Group 6
IL type/thickness^	IL1/10 Å	IL2/15 Å	IL3/15 Å	IL4/15 Å	IL5/15 Å	IL6/12 Å
Oxide process*	T1	T1	T2	T3	T1	ChemOx[#]
Surface treatment	none	none	none	none	SC1(25^{o}C)[+]	none

[@] 0, 5,11, 17 and 23 cycles of ALD HfO_2 films were deposited on the different IL layers to study the HfO2 growth mechanism.

^ Thicknesses of the IL layers were verified by XPS measurements.

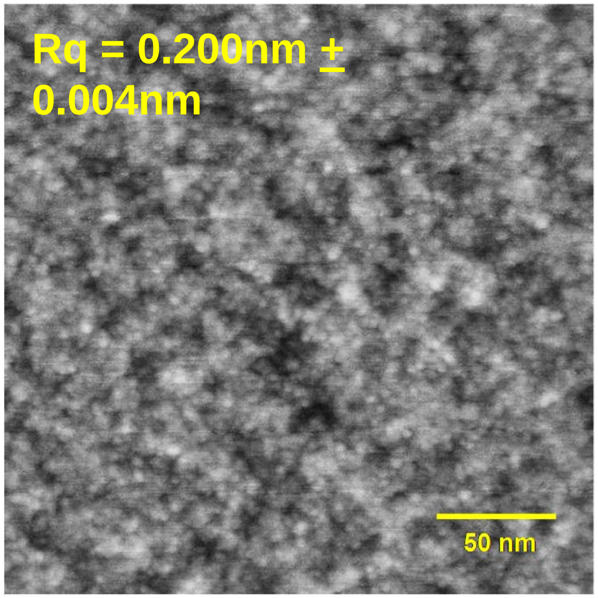
** “T” stands for thermally grown oxide.*

[#] ChemOx is the oxide formed on Si surface by SC1 clean (NH4OH + H2O2 in DI water at 87^{o}C) . It is abundant in OH-terminated sites on surface.

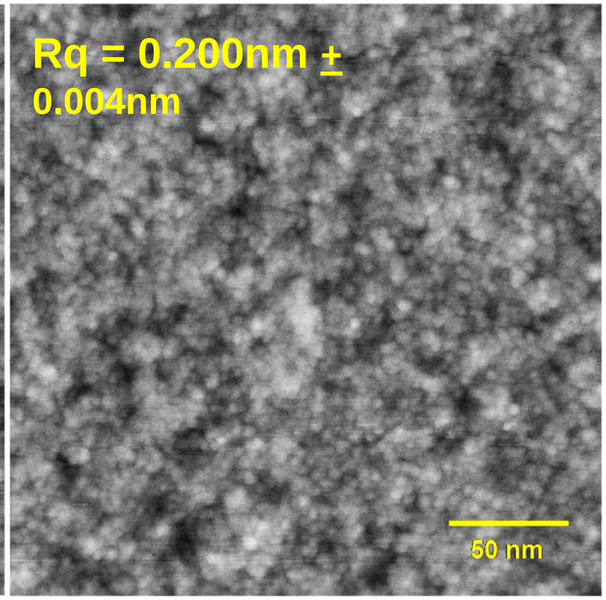
+ IL5 was IL1 dipped in SC1 (25^{o}C) solution for a few seconds then rinsed clean with DI water.

HfO_2 growth study – AFM images of IL with no HfO_2 film

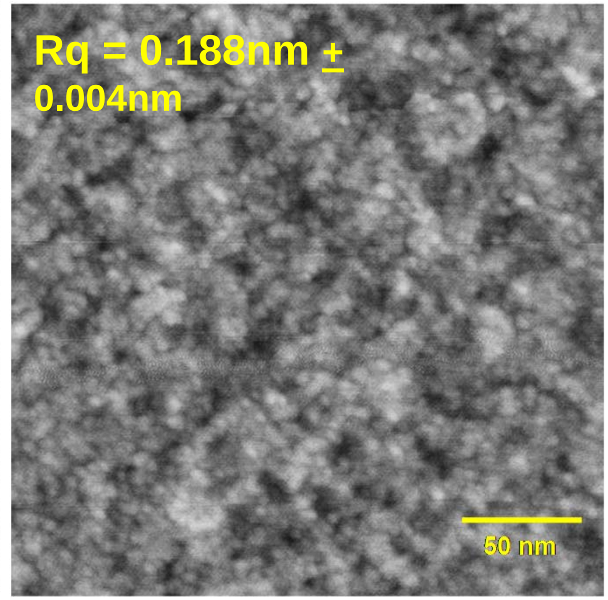
IL1 10Å



IL2 15Å

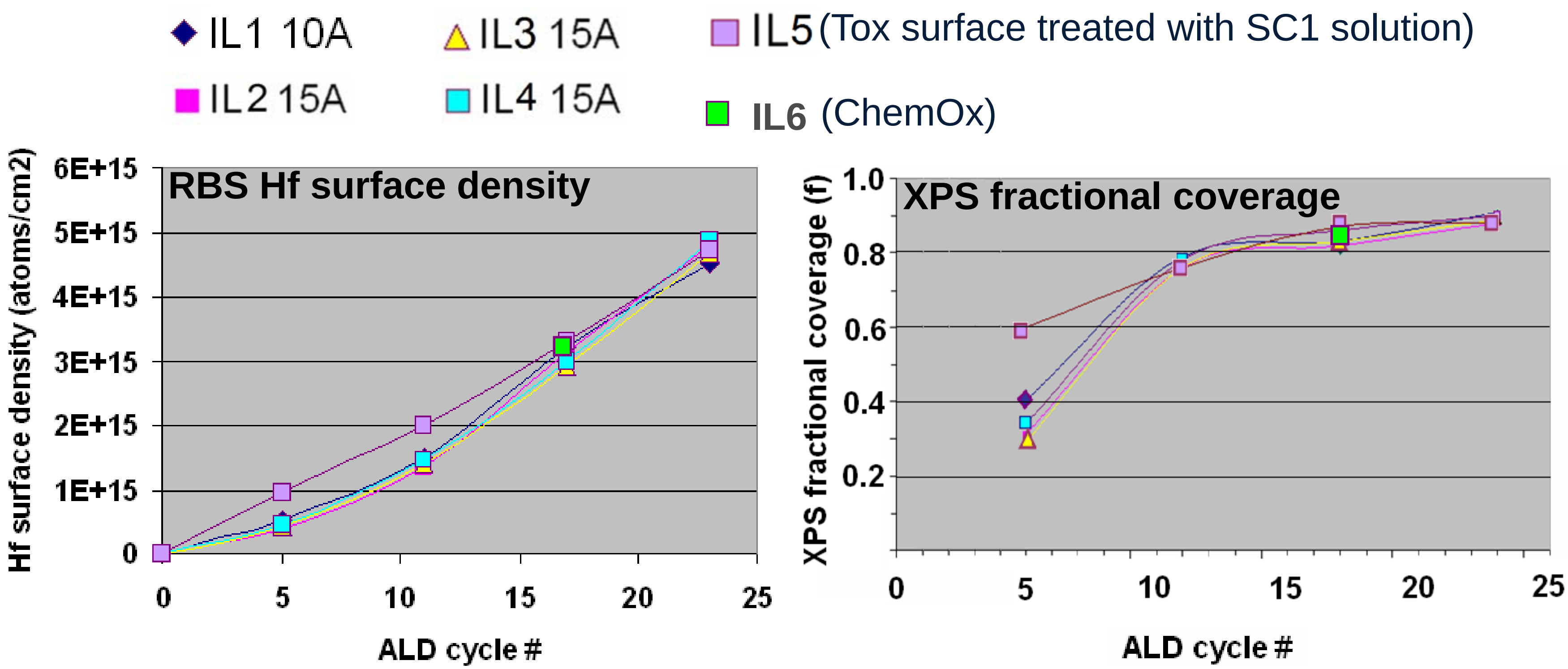


IL5 15Å



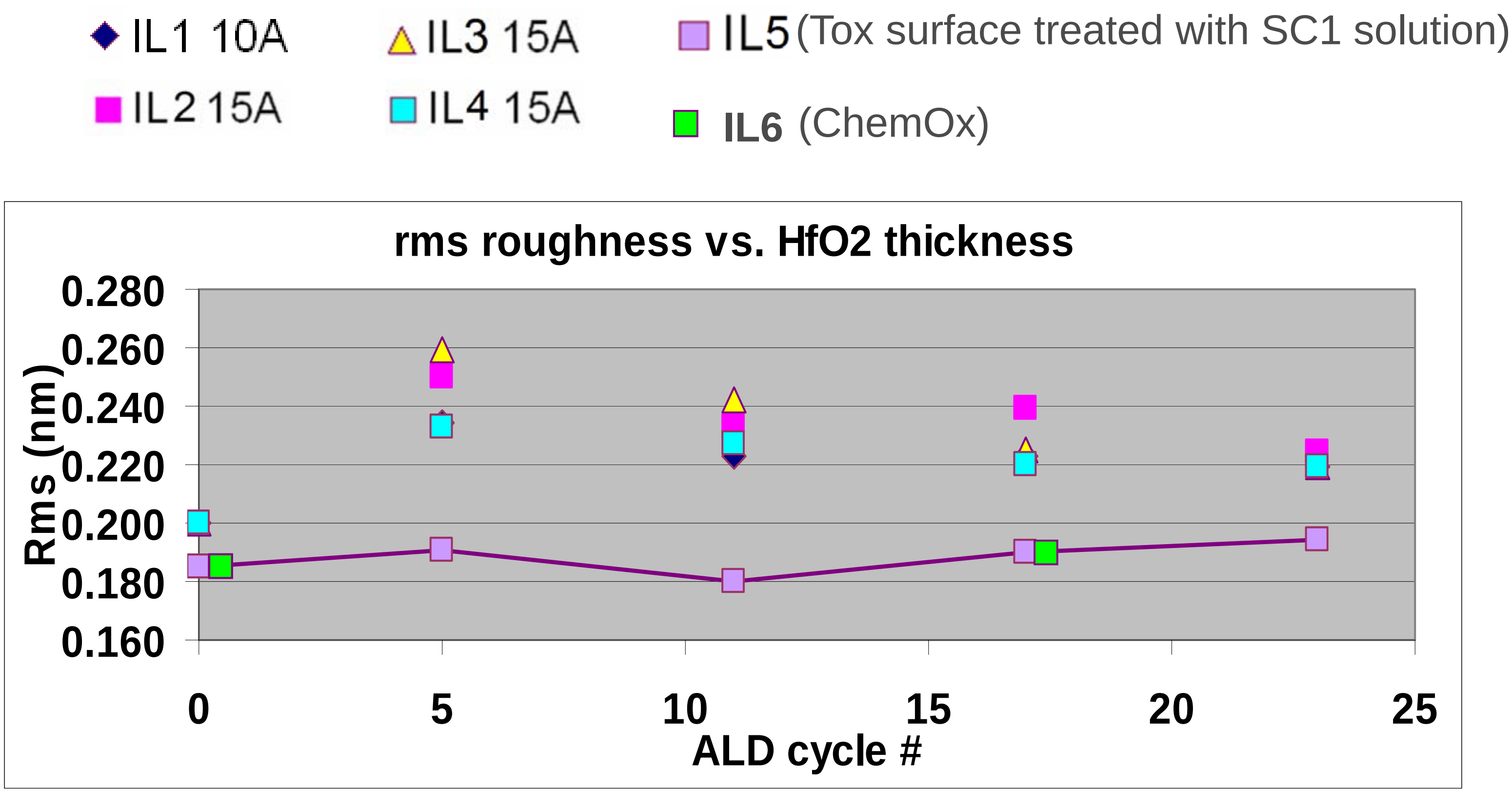
- ***Both IL1 and IL2 surfaces have more tiny protruding features.***
- ***IL5 surface is slightly smoother than both IL1 and IL2 surfaces and is without the tiny protruding features.***
- ***All the surfaces are not atomically flat (rms roughness > 0.5nm).***

HfO_2 growth study – RBS and XPS results



- ***Linear growth rate of HfO_2 film on IL5 is observed.***
- ***Similar growth rates are observed on all the other four thermally grown IL types.***
- ***Initial Growth rate on thermally grown ILs = ½ initial growth rate on IL5 (thermally grown IL with ChemOx treatment).***
- ***XPS coverage study showed that HfO_2 has higher initial coverage on IL5 than on the other four IL types. At higher coverages, XPS coverage failed to distinguish the difference of HfO2 films on the different types of ILs.***

HfO_2 growth study – AFM roughness results



- **HfO_2 films deposited on IL5 shows no increase in roughness with increasing ALD cycle #.**
- **HfO_2 films deposited on all other four types of thermally grown ILs show large increase in roughness at 5 ALD cycles then gradual decrease in roughness with increasing ALD cycle #.**

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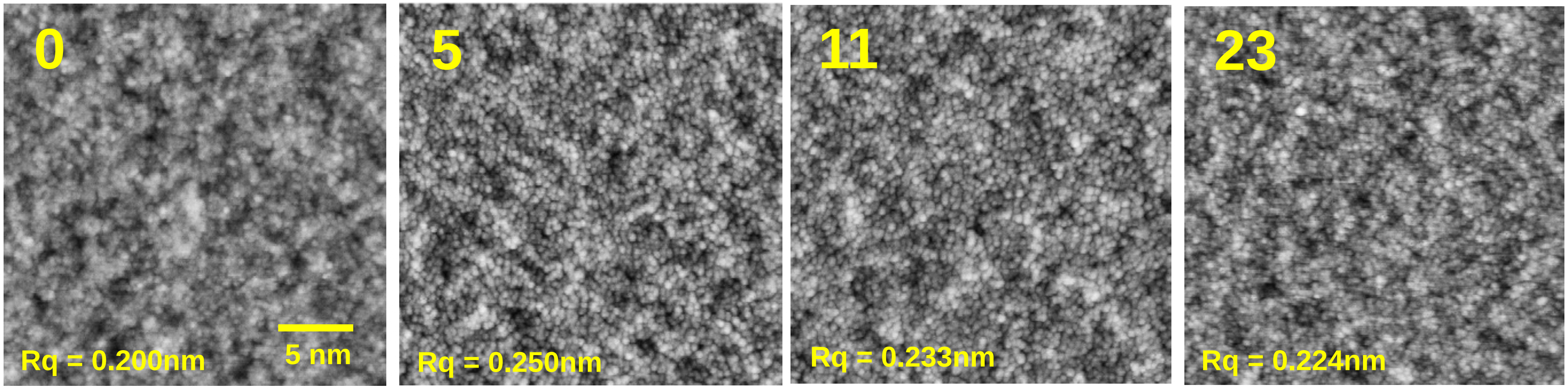
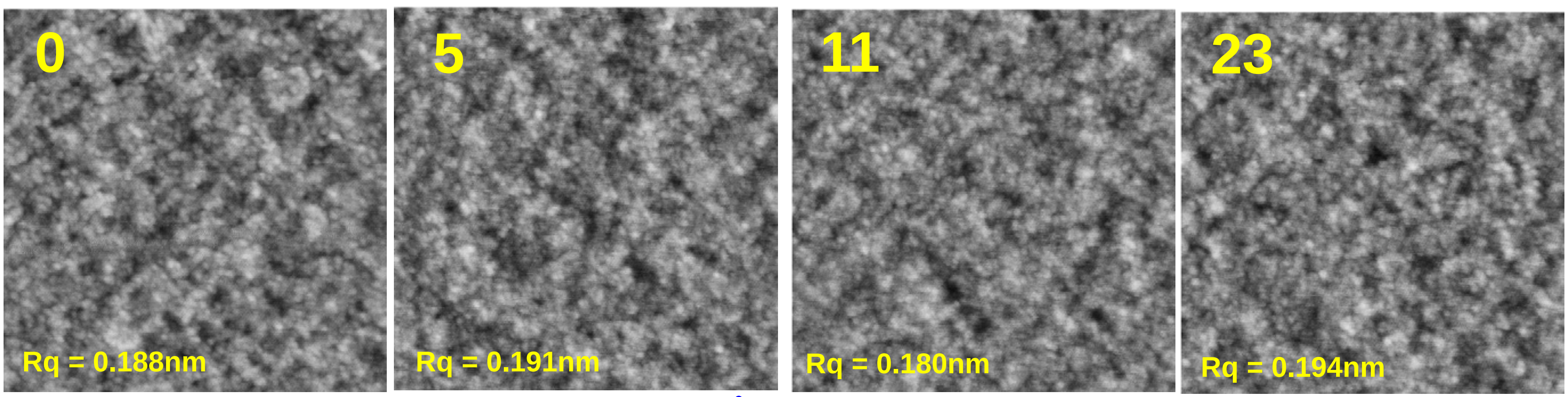
HfO_2 growth study – HfO_2 AFM images

ALD HfO_2 on 15 Å IL1

Yellow # indicates ALD cycle #



ALD HfO_2 on 15 Å IL5

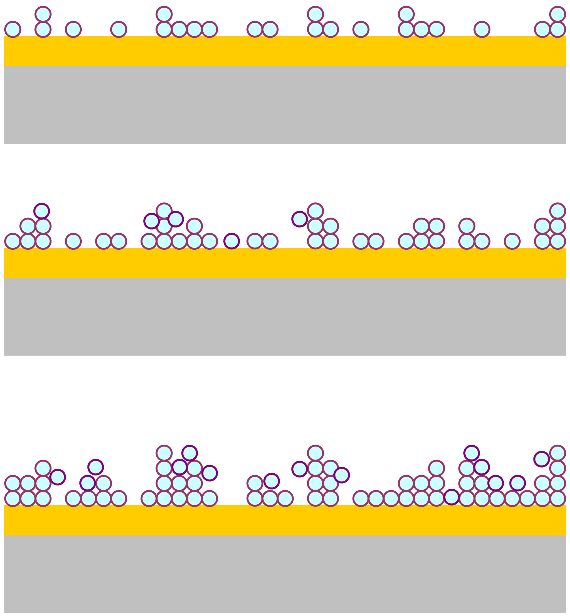


- *Numerous tiny nodules can be seen on 15 Å IL1 after 5 cycles of HfO_2 growth, indicating islands growth mechanism. Such was observed on all the other three thermally grown IL layers.*
- *No morphology change after 5 cycles of HfO_2 on 15 Å IL5, indicating conformal growth mechanism.*

HfO_2 growth study – growth mechanism hypothesis

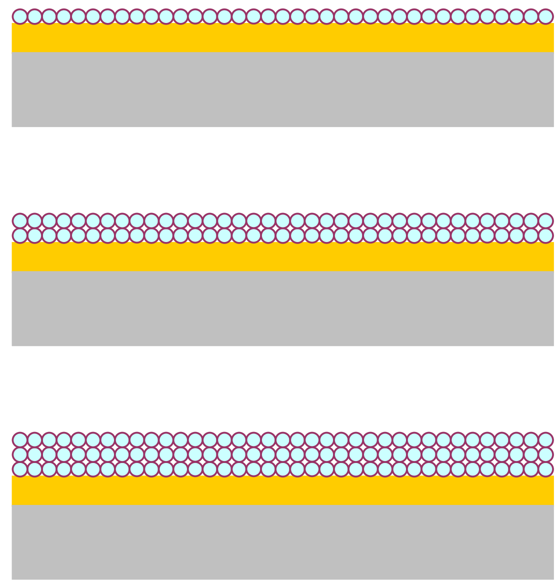
On all thermally grown ILs

Islands (three dimensional) growth – due to scarcity of –OH terminated nucleation sites



On thermally grown IL treated with SC1 (IL5)

Layer by layer (two dimensional) growth – due to abundance of –OH terminated nucleation sites

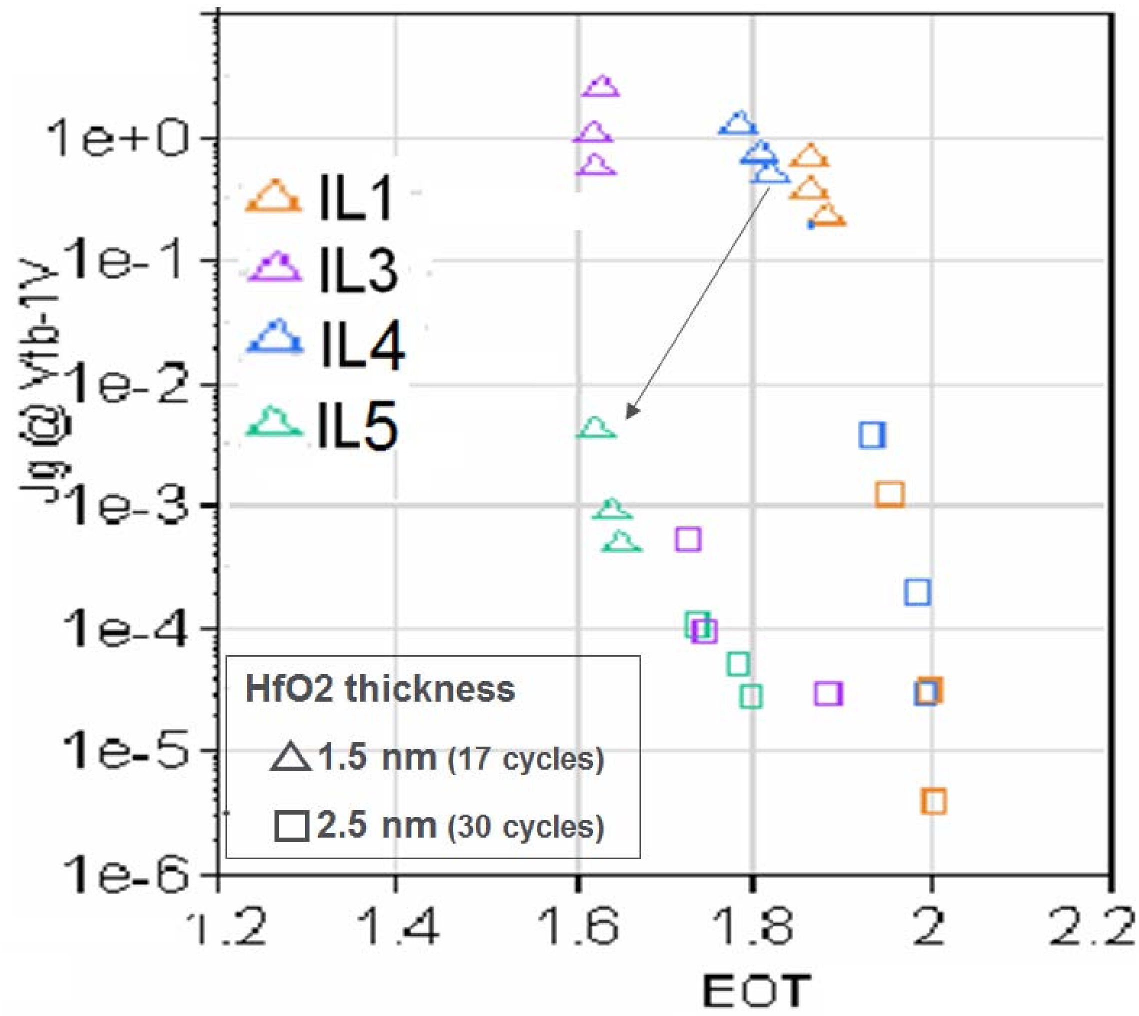


- ***Growth rate increases with the increase of surface area***
- ***HfO2 films are porous and non-uniform***

- ***Growth rate stays the same***
- ***HfO_2 films are dense and uniform***

Justin C. Hackley, Theodosia Gougousia and J. Derek Demaree, JOURNAL OF APPLIED PHYSICS 102, 034101 (2007)

HfO_2 growth study – correlation with electrical tests



Three data points are from center, middle radius & edge of the wafer.

- *The IL5 with 1.5 nm HfO_2 shows X1000 lower Jg than the other ILs with the same thickness HfO_2*
- *The IL5 wafer shows better within wafer uniformity in Jg test.*
- ***Jg data correlates with AFM morphology study results well!***

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Conclusions

- ***New AFM imaging techniques were developed that enables the direct observation of the morphology of ALD films during the initial stages of film growth***

- ***The same technique can be used to study***
  - *the continuity of ultra-thin film*
  - *Morphology of nano-crystalline materials*
  - *2-dimentional materials*

- ***AFM study of the ALD HfO_2 on different ILs***
  - *reveal that Islands growth on thermally grown SiO_2 ILs results in less dense HfO_2 and its higher leakage current*
  - *validates the conformal growth of ALD HfO_2 on SC1 treated SiO_2, which is abundant with hydroxyl (-OH) groups that facilitate the uniform nucleation of the HfO_2 and growth of a dense HfO2 film that in turn results in low leakage current.*