New Challenges in Etching Ultra Low-k Dielectrics

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think it. apply it.

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APPLIED MATERIALS

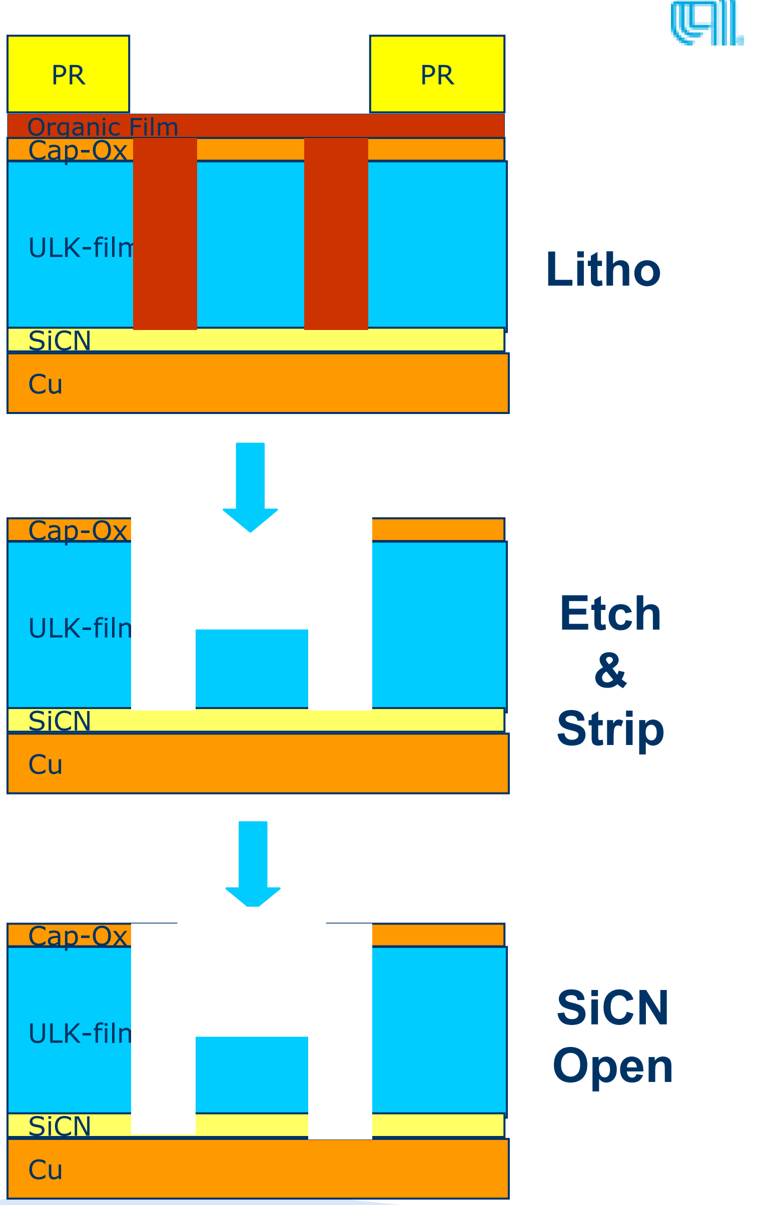
Outline

- Introduction
- New Etch Challenges for ULK
- Plasma Reactor Overview
- Results & Discussions
- Summary

Introduction

- Ultra Low-k (ULK) Dielectrics
  - Integrated for 45nm and beyond
  - Dielectric Constant (k): ≤ 2.5
  - Porosity: > 20%
  - C-concentration: > 20%
  - Si-CH3/Si-O: > 2.5%

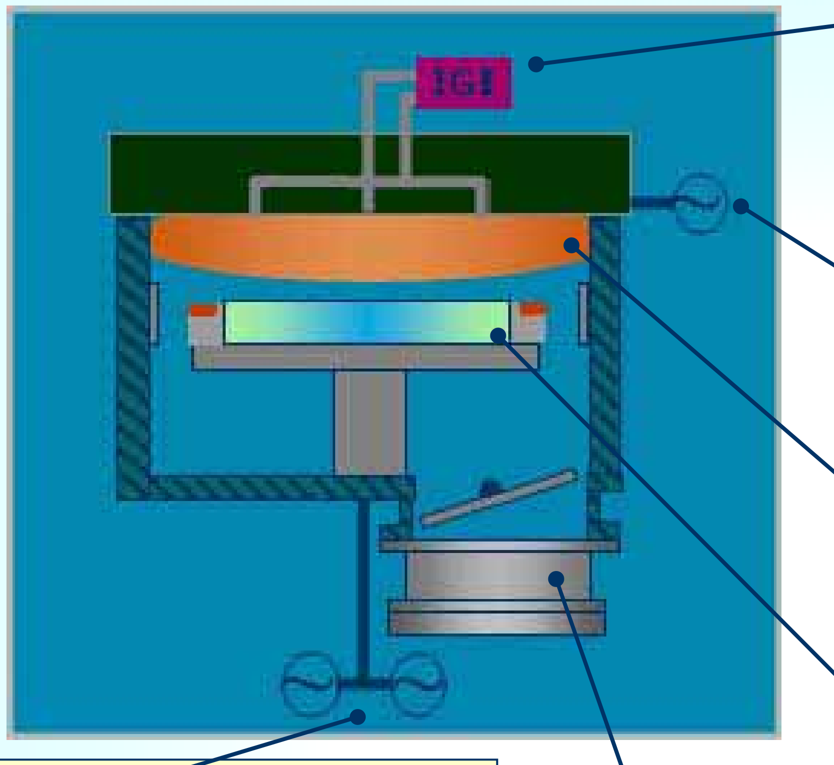
- Etch Process Flow
  - Trench etch with organic mask
  - Strip (ULK exposed)
  - SiCN Open (LRM)



New Challenges in Etching ULK

- Carbon depletion
  - k-increase
- Surface roughness
  - Metal or precursor penetration
  - Increased leakage/Capacitance
  - Degraded device reliability
- Moisture absorption
  - K-increase
  - Degraded Device Reliability

Plasma Reactor Overview



Dual Gas Feed with IGI

- Neutral Species Tuning
- Inner/Outer Gas Flow ratio

VHF Source Density Control

- Independent plasma density control
- Plasma Density: 10^{10} to 10^{11}

Ion Flux Control

- Plasma Uniformity Tuning with magnetic field

Wafer Temperature Control

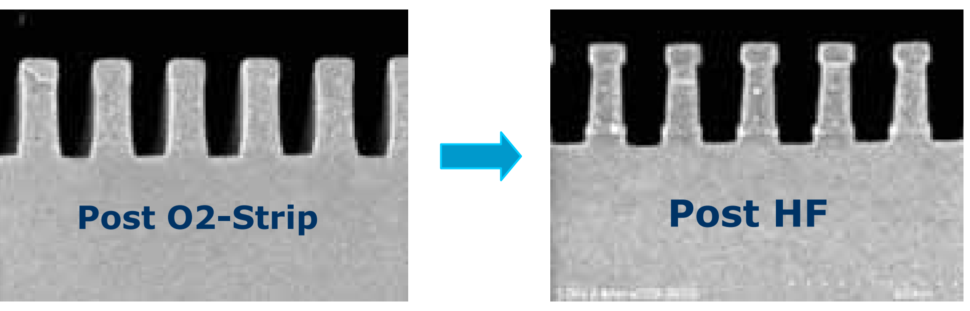
- Dual Zone ESC

Dual Frequency Bias – 2MHz/13.56MHz

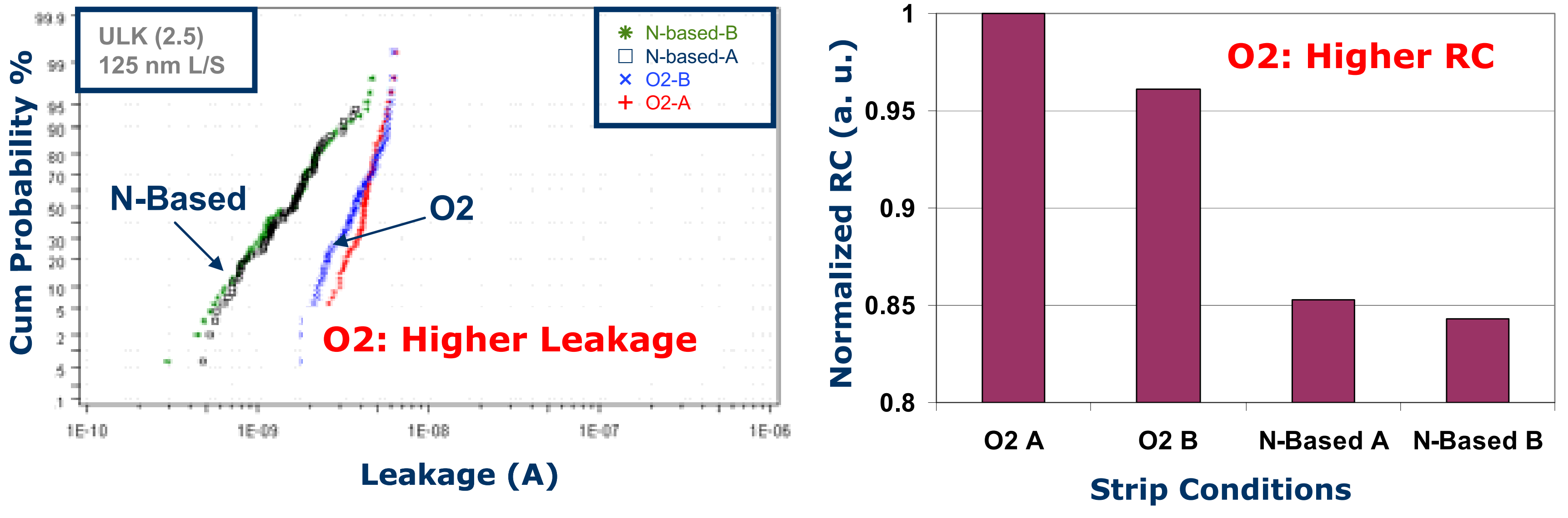
- Tunable Ion Energy Distribution.

3000 LPM Turbo Pump

Issues with O2-Strip for ULK:

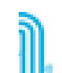


ULK Damage: 15 nm/side

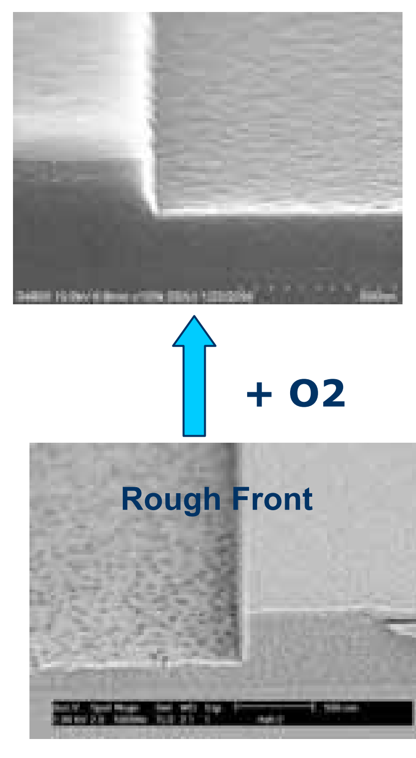


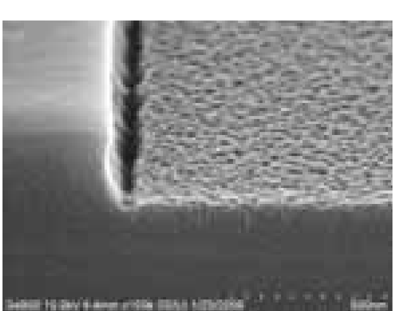
Higher electrical leakage, RC and ULK damage with O2 strip

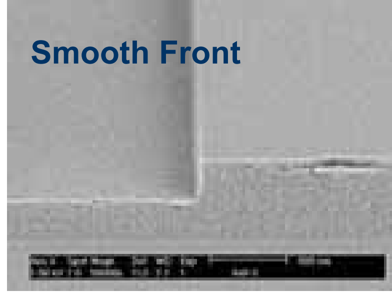
ULK (2.5) Etch Front – Residence Time in N-Based Strip



As-Deposited







R. Time: T sec

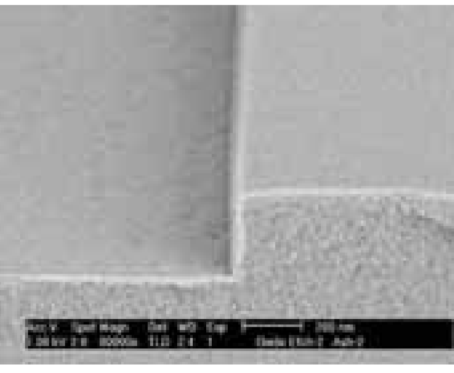
0.1xT sec

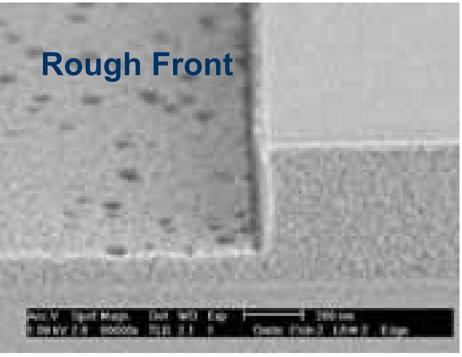
0.03xT sec

Short residence time necessary for smooth ULK etch front

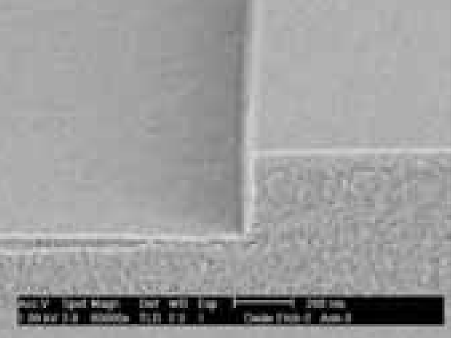
ULK (2.5) Etch Front – W2/Ws in N-Based Strip

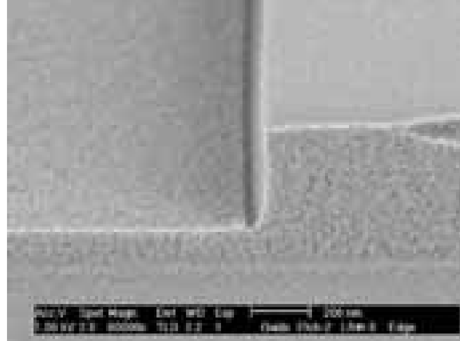
W2/Ws 2:1





W2/Ws 1:1



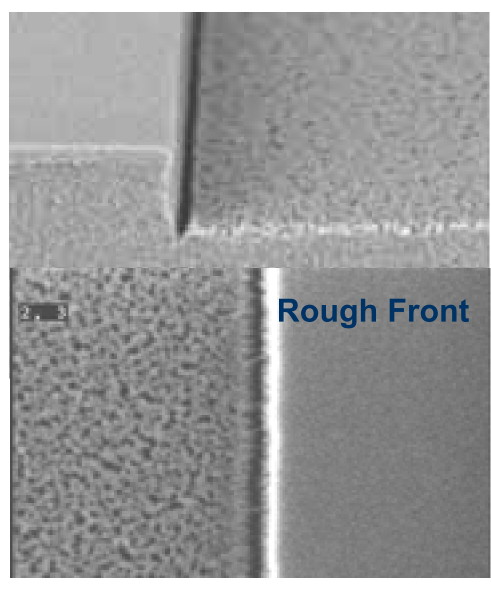


Post Strip

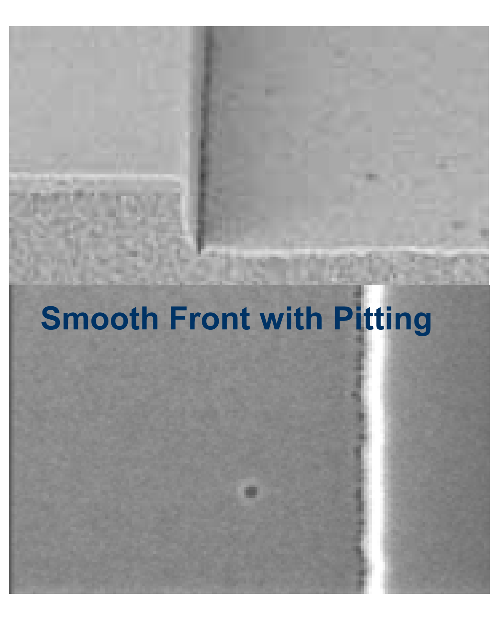
Post SiCN Open

Power ratio in strip affects ULK front after SiCN open

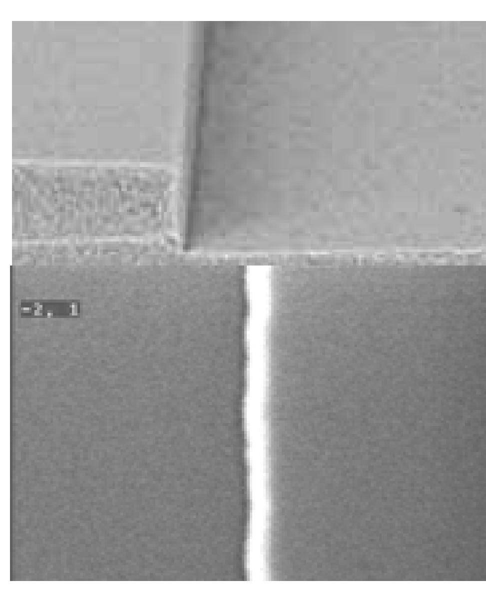
ULK (2.5) Etch Front – Post SiCN Open(CH2F2)



R. Time: T sec



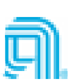
0.5xT sec

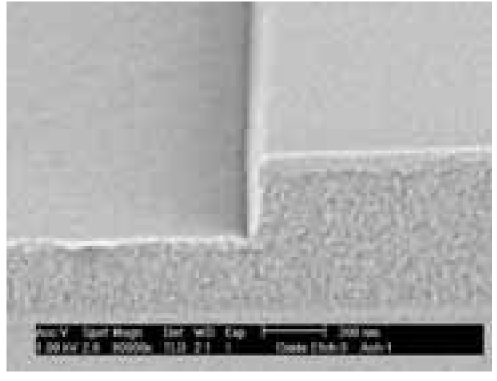


0.25xT sec

Short residence time required for smooth front for H-rich Chemistry

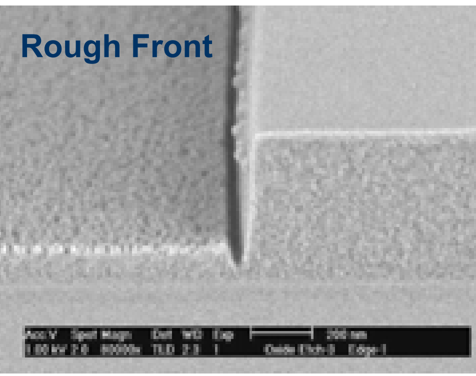
ULK (2.5) Etch Front – Post SiCN Open(CF4)





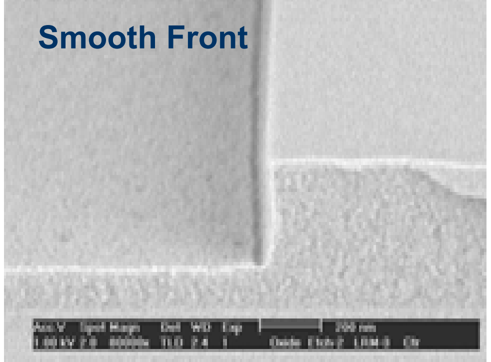
Post Strip

SiCN Open



R. Time:

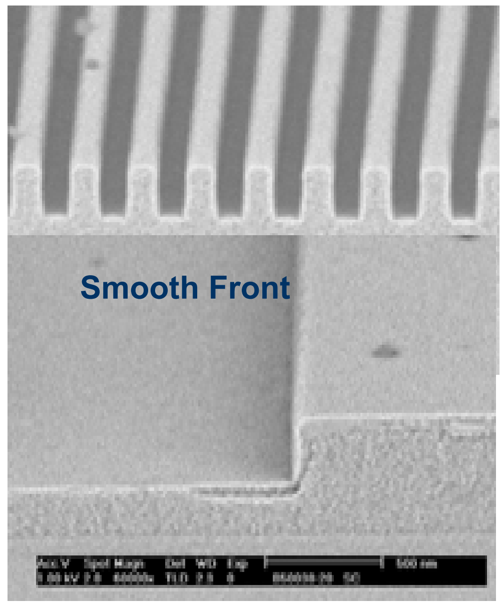
0.25xT sec



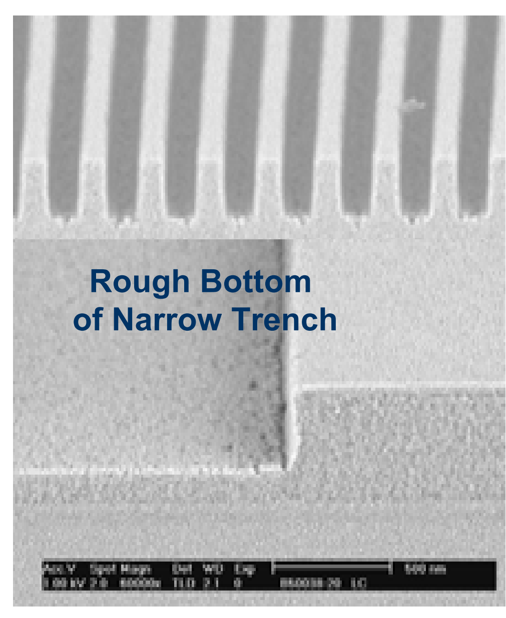
T sec

Longer residence time required for smooth front for lean Chemistry

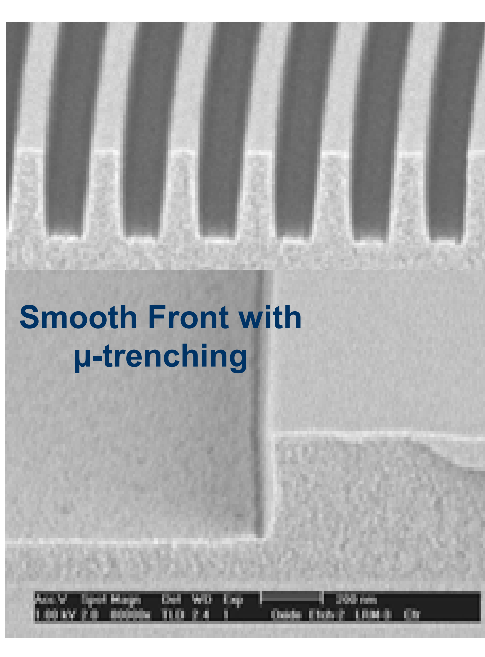
ULK (2.4 & 2.5) Etch Front – Post SiCN Open (CF4)



Post Strip (2.4)



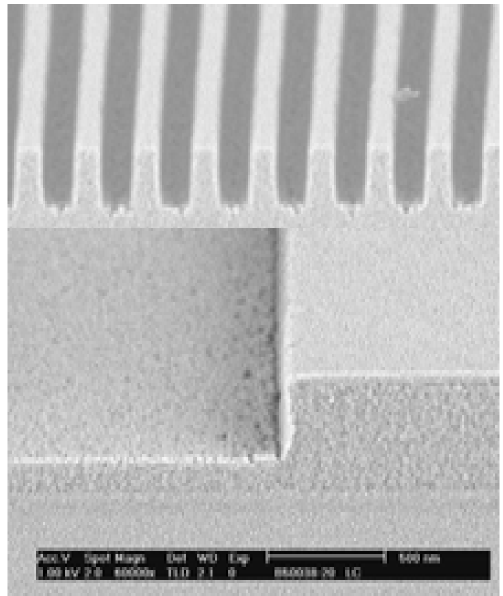
2.4



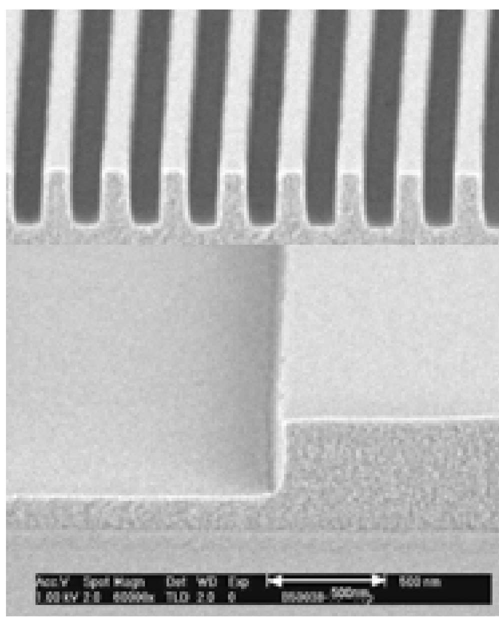
2.5

Narrow process window for ULK etch front

ULK (2.4) Etch Front Improvement:



Post SiCN Open
(LRM)
Rough Bottom
of Narrow Trench



Polymer rich SiCN Open (B)
(LRM-B)
Smooth Front

Smooth front achieved with slightly polymer rich process

Auger Electron Spectroscopy (AES) for ULK (2.4):

C06M398931_1.pro

Sample 20 ASH

O1 C1 Si2 N1.ls1 F1.ls2

Si, O, C, N x10, F x10

Atomic Concentration (%)

Sputter Depth (Å)

Post Strip

Analysis Site

C06M398921_1.pro

Sample 19

O1 C1 Si2 F1.ls1 N1.ls2

Si, O, C, N x10, F x10

Atomic Concentration (%)

Sputter Depth (Å)

Post SiCN Open (B)

Significant difference in C- & O- concentration on the ULK after strip/etch

AES: O/C Ratio for ULK (2.4) Trench:

O/C Ratio vs Depth

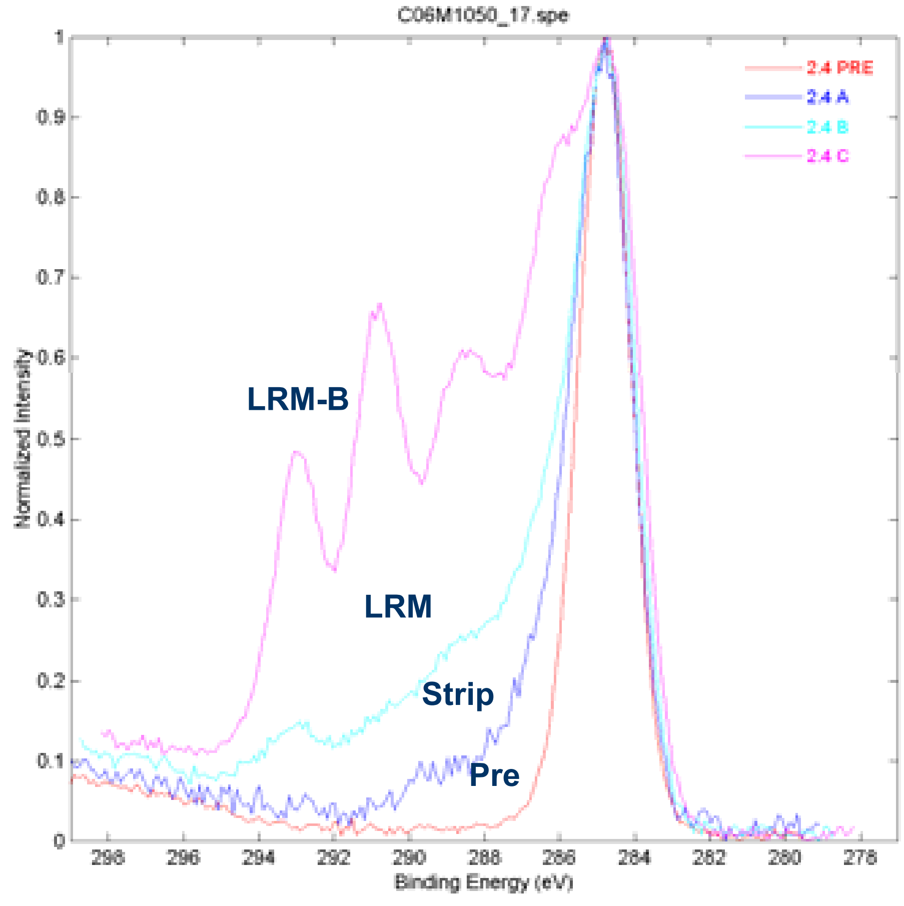
Sputtering Depth (A)	O/C Ratio (a.u.)
Y-axis	0.0, 1.0, 2.0, 3.0, 4.0, 5.0
X-axis	0, 20, 40, 60, 80, 100

Annotations: Post Strip: Smooth; Post LRM: Slight Rough; Post LRM B: Smooth; X 0.2

Axis titles: Supttering Depth (A); O/C Ratio (a.u.)

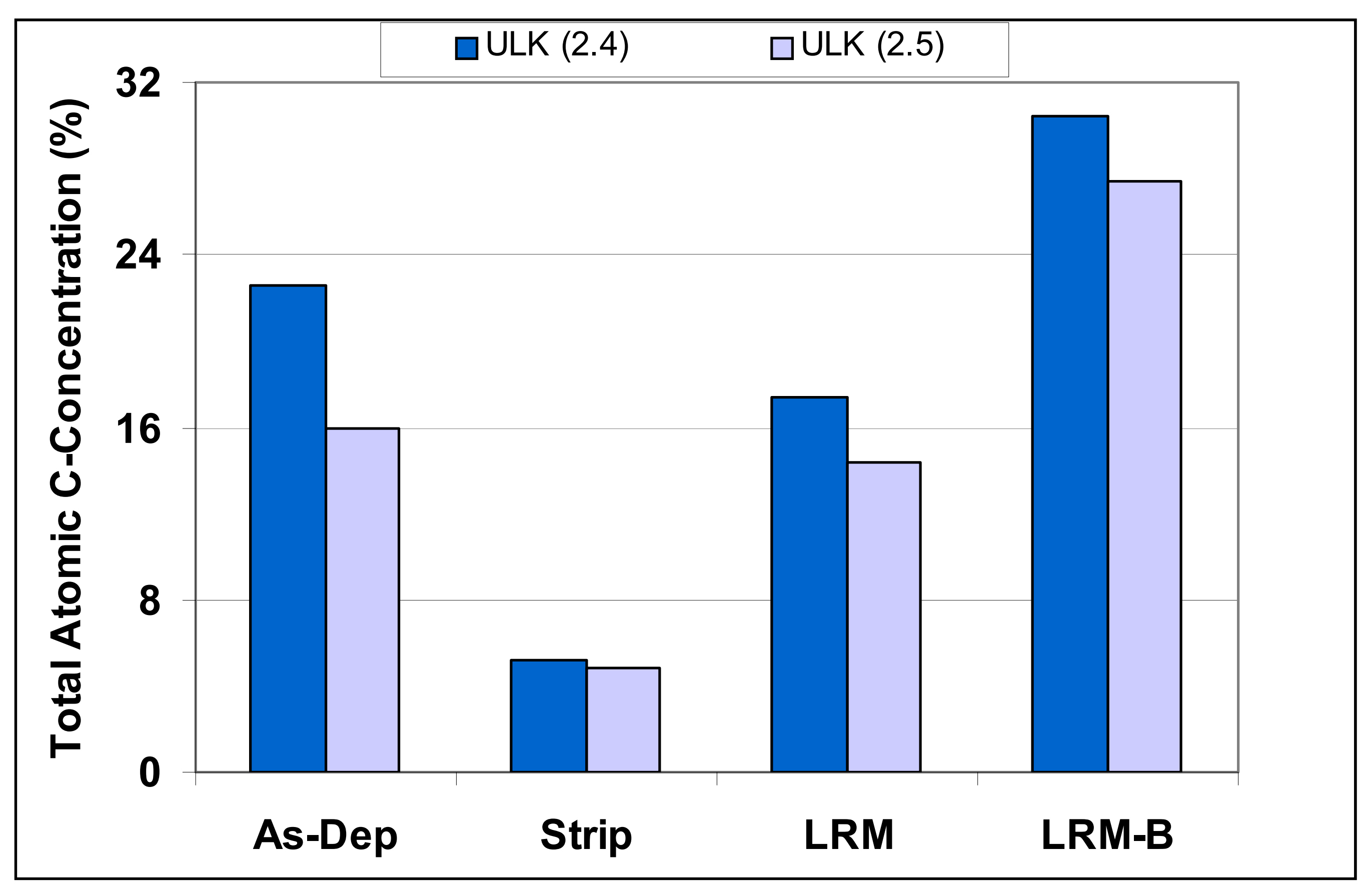
After Strip: ~ 40 Å of C-depletion layer in ULK. Extremely low C at < 20 Å
After LRM: ~ 40 A of C-depletion layer in ULK. Less C-depleted
After LRM-B: No C-depletion layer. Instead, C-concentration is higher

X-Ray Photoelectron Spectroscopy (XPS) for ULK (2.4):



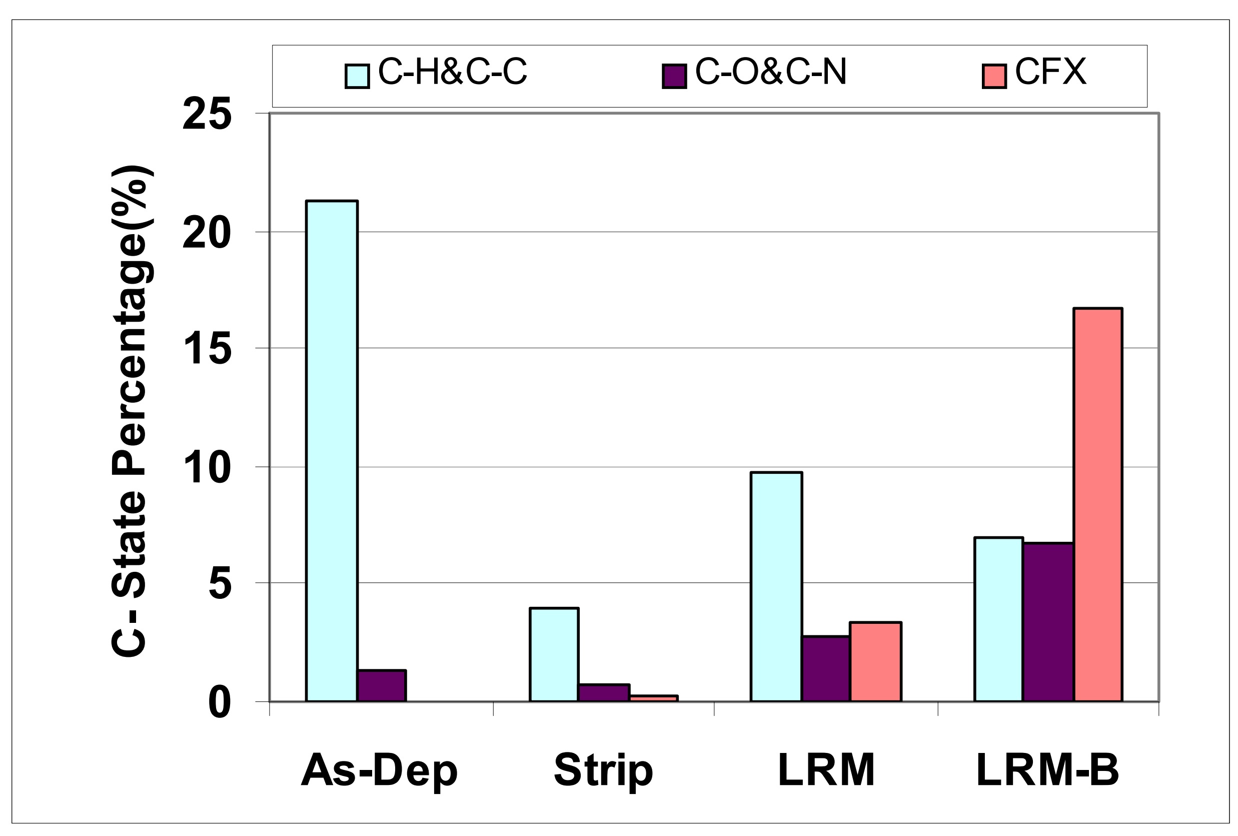
Carbon Chemical State in ULK changes dramatically after plasma processing

XPS: Total Atomic C-Concentration for ULK (2.4 & 2.5):



Lowest Carbon concentration after strip

XPS: Carbon Chemical State Percentage – ULK (2.4)



After ULK is exposed to plasma, C-H/C-C state decreases forming C-O & CFx

ULK Rough Front Formation – Mechanism I:

- **Carbon/Hydrogen Extraction Forming Si-C Skeleton**
  - Formation of small reactive neutrals, like H-atom , is favored at longer residence time
  - These reactive neutrals will react with C or H or CH_3 in ULK films forming Si-C skeleton
  - The plasma process itself has lower etch rate for ULK films than skeleton formation rate
  - These reactive neutrals are very small. They can penetrate the ULK (pore) and extract C or H.

  - For N-based strip & SiCN open with H-rich Chemistry (CH_2F_2):
    -- Rough ULK front forms at long residence time. Formation of H-atom is favored. The H-atoms combine with H or C or CH_3 in ULK forming H_2, or CH_4. On the other hand, more F is scavenged by H which forms Si-C skeleton much faster.

H-Rich Chemistry: Extraction Mechanism

ULK Rough Front Formation – Mechanism II:

- Micromasking
  - Non-uniform polymer formation on ULK
  - The polymer formation favored by the C-concentration in ULK
  - Ion energy decays exponentially with the polymer thickness
  - ULK with less polymer experiences higher etch/sputtering rate
  - The etch rate difference will be exacerbated with high C-containing film

  - For SiCN open with lean chemistry:
    -- Rough ULK front forms at short residence time. This can be explained by high flux of ions that results in non-unif polymer deposition or sputtering

Lean Chemistry: Micromasking Mechanism

Summary

- ULK damage and rough etch front result from surface modifications during plasma strip and etch.
- Carbon concentration on modified ULK film have been quantified and its chemical state changes have also been probed.
- Smooth ULK front leaves either highly C-depleted layer or no C-depleted layer.
- H- & C-extraction or micromasking are two possible mechanisms controlling ULK etch front
- Further studies and electrical tests need to be done to verify the mechanisms.