

Effect of Species Density and Ion Scattering During Ashing on Ultra Low-κ Inter-Level-Dielectric (ILD) Materials

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Outline

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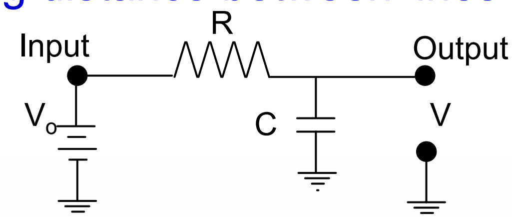
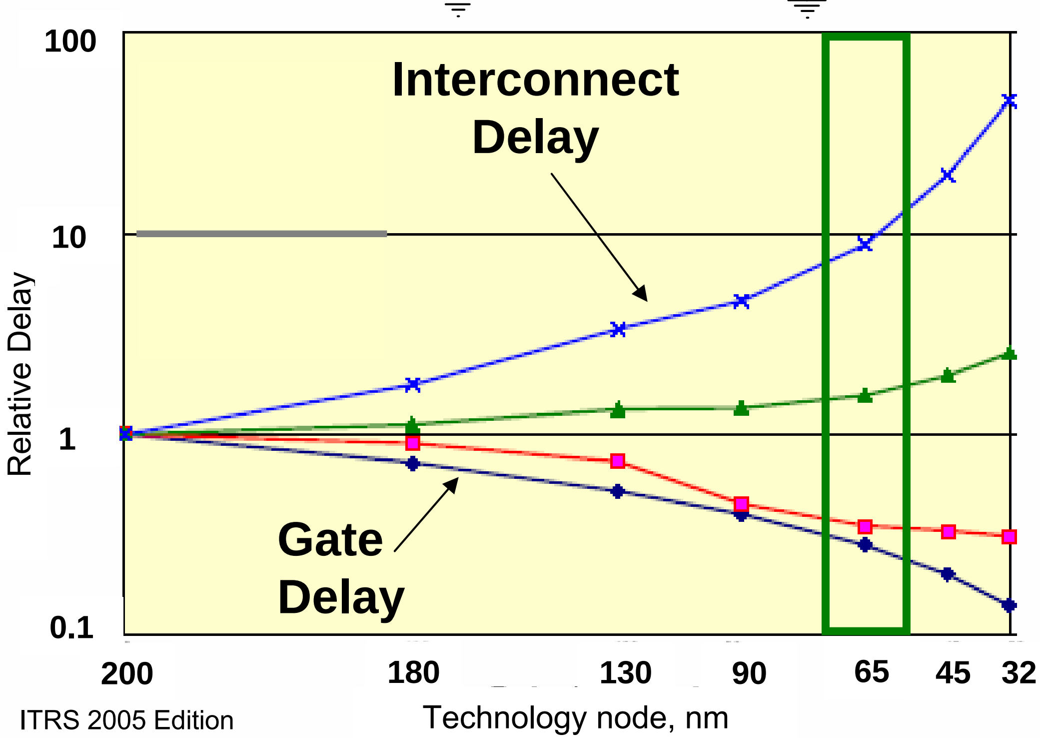
- **Motivation**
  - Low-κ
  - Integration challenges
- **Background**
  - Experimental Setup
  - Analytical Techniques
- **Key Results: Radicals and Ion Impact**
  - Oxygen ash plasma
  - Nitrogen ash plasma
- **Summary and Conclusions**

Motivation: Low-κ

- **Limitation is in interconnects – the wiring structure connecting transistors**
  - Increased number of layers (circuit length) – Increased resistance (R)
  - Shrinking distance between lines - Increased capacitance (C)

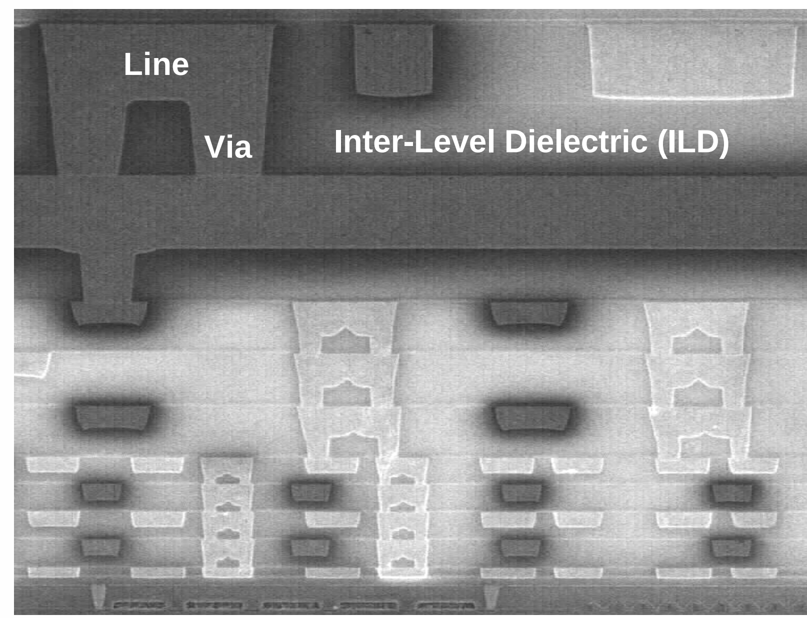


RC Delay



ITRS 2005 Edition

Cross section of chip at 90 nm technology node



D. Edelstein, IITC 2004

Reduce R – Al to Cu

Reduce C – SiO_2 to organosilicate glass low-κ

Motivation: Integration Challenge

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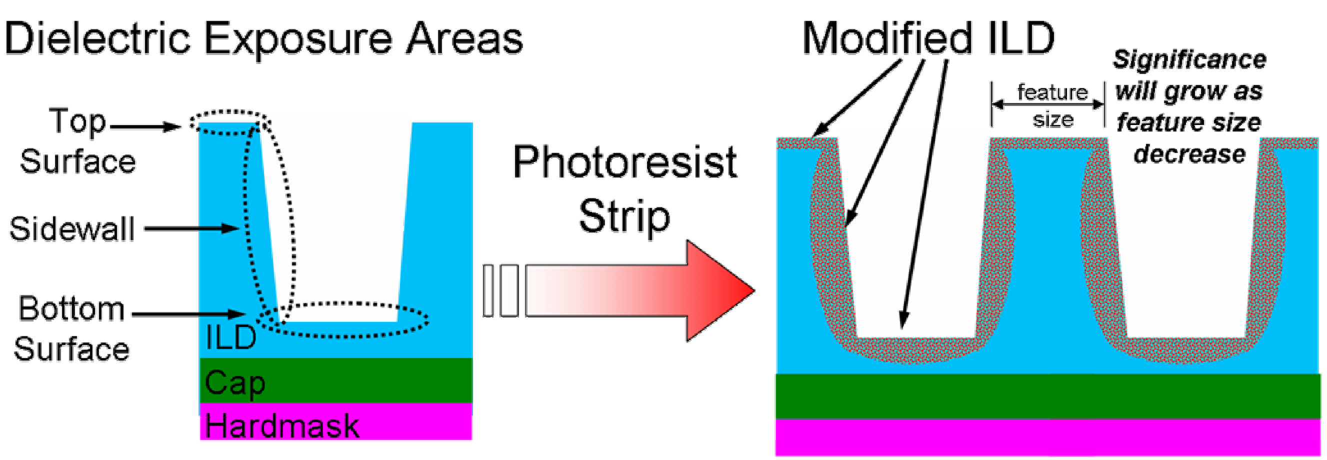
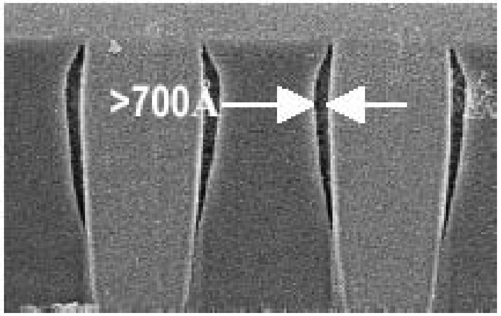
Photoresist ash plasmas have been shown to both

- A) Etch or remove the exposed dielectric
- B) Leave a "skin" or modified layer
  - Deficient in carbon content – "oxide-like"
  - *Increased κ ⟶ performance issues associated with device speed*
  - *More hydrophilic ⟶ reliability issues associated with crack propagation in water, and possibly adhesion*



SEM Image of Damage



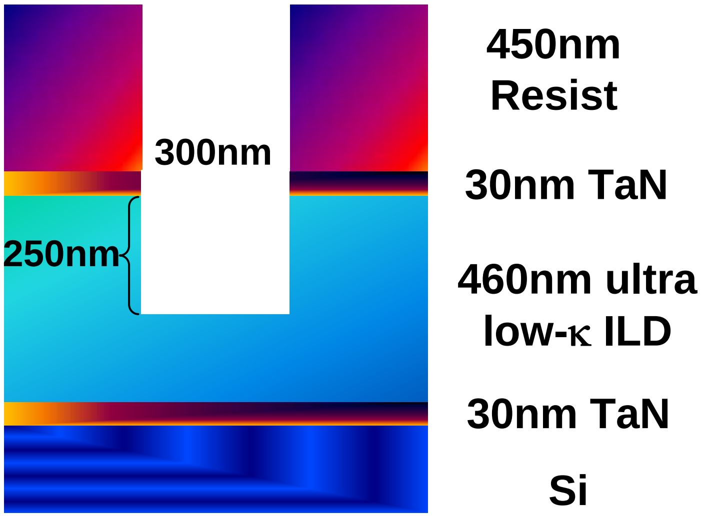
Courtesy of Stephen M. Gates

Background: Experimental Setup

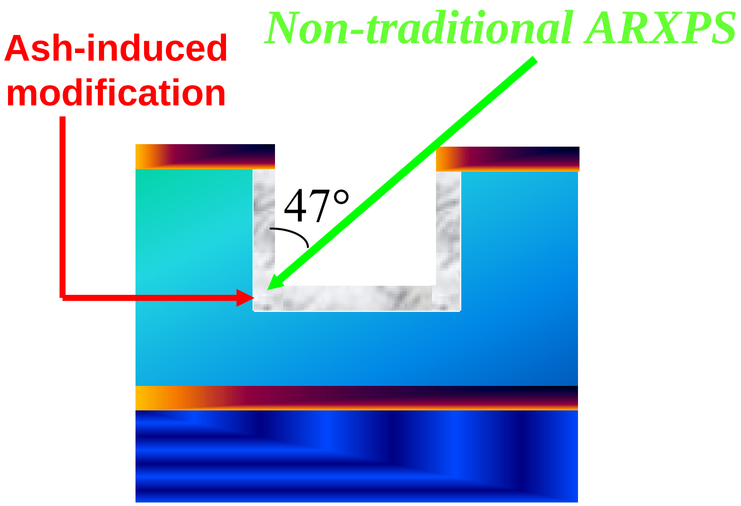
- **Goal: Gain fundamental understanding of how the following factors in ashing plasmas affect ultra low-κ ILD (κ < 2.0) materials:**
  - Radical Species Density
  - Ion Impact

- **Setup:**
  - Plasma Characterization
    - Radical density in dual frequency capacitive (DFC) discharge by OE actinometry
    - Modeling of ion mean free path (λ_i) and sheath thickness (s_m) to estimate ion scattering
    - Modeling of relative ion density to estimate ion current as a function of pressure
  - Test Structure: 450nm PR/30nm TaN/460nm ILD/30nm TaN/ Si substrate
  - Material Analysis
    - Ash samples under various conditions
    - Analyze sidewalls (θ>47°) and trench bottom (θ=0°) by non-traditional ARXPS

Schematic of Test Structure



Schematic after Resist Removal



Experimental Setup: Ion Scattering Model Details

- Use pressure (p) to control mean free path of Ar^+ ions (λ_{Ar+}),

$$\lambda_{Ar^+} = \frac{1}{n_g \sigma_{Ar^+}} \approx \frac{1}{330p} \, (cm)$$

- Use pressure and bias power to control plasma sheath thickness, s_m

$$s_m = \left[\frac{\sqrt{2}(1.68)\varepsilon_0 V^{\frac{3}{2}} \sqrt{\lambda_i} \left(1 + \frac{\pi \lambda_{De}}{2\lambda_i} \right)^{\frac{1}{2}}}{e n_s \sqrt{T_e}} \right]^{\frac{2}{5}}$$

where

V is the sheath voltage

λ_i is the mean free path for ions,

λ_{De} is the Debye length

n_s is the ion density at sheath edge

T_e is the electron temperature.

- Compare: $\lambda_i \ll s_m$ (scattering), $\lambda_i \gg s_m$ (no scattering)

Significance of Ion Scattering Determined

Experimental Setup: Actinometry Details

- Use light emitted from excited state species to determine species concentration. For the electron (e^-) impact excitation on species A,

$$A + e^- \rightarrow A^* + e^- \quad \rightarrow \lambda_A$$
$$A_2 + e^- \rightarrow A + A^* + e^- \quad \rightarrow \lambda_A$$
$$I(A,\lambda_A) = 4\pi\alpha(\lambda)\beta n_e n_A \int_{v_{th}}^{\infty} \sigma(v) v^3 f_e(v) dv$$

where

A = species of interest
α = spectrometer sensitivity
n_A = species density
ν = velocity
β = branching fraction

I = light intensity
n_e = electron density
σ = excitation cross section
f_e = electron energy distribution function

- To determine absolute density must normalize with an actinometer, X, with similar excitation threshold, ν_{th}

$$\frac{I(A,\lambda_A)}{I(X,\lambda_X)} = \frac{b_{A_2,X} n_{A_2} + b_{A,X} n_A}{n_X}$$

Density desired

where $b_{Y/X}$ is the ratio of the excitation rate of species (A or A_2) over the actinometer (X).

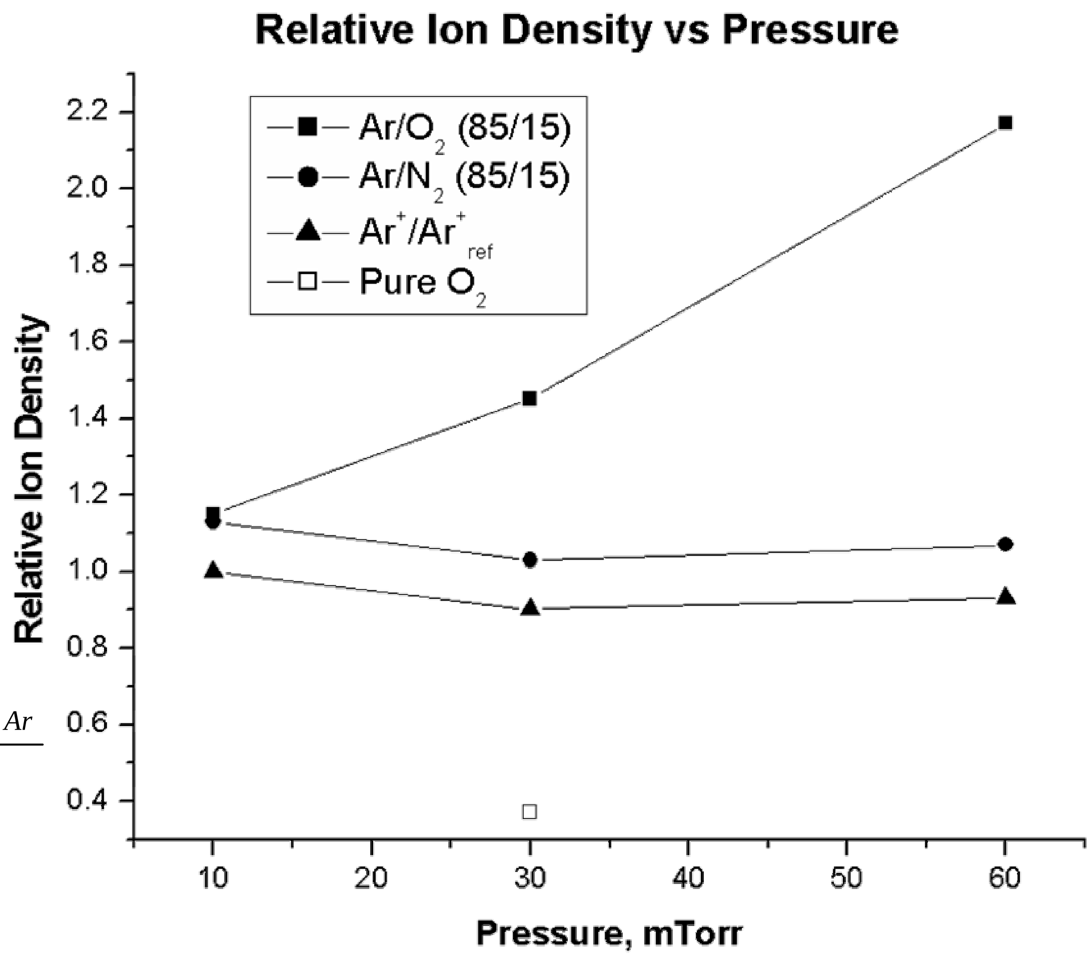
- Use fractional flow Ar and chamber pressure to vary radical density

Reactive Radical Species Densities Measured

Experimental Setup: Ion Density Model

- **Ion Current ~ $n_i u_i$**
- **Relative ion density, n_i, modeled**
  - Ar^+, A_2^+ (A = O or N) – minimal dissociation
  - Ionization cross sections from literature
  - EEPF's from previous study
- **Relative ion velocity, u_i, estimated via V_s**
  - Bias power ($V_{applied}$)
  - Pressure ($V_p \sim 5T_e$)
  - Expect T_e (and therefore ion velocity) to decrease with pressure

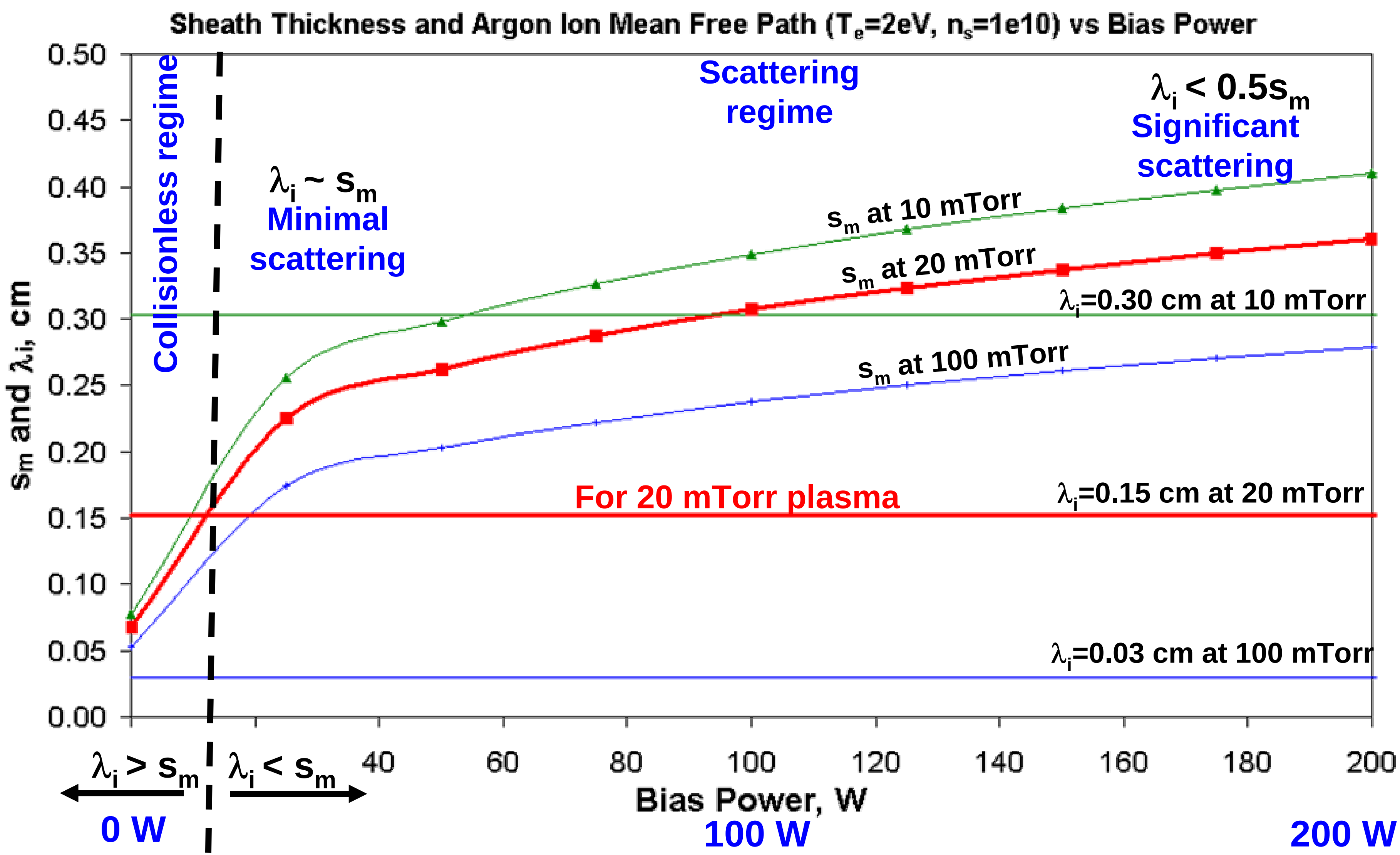
$$n_{ion} \equiv \frac{n_{A_2^+} + n_{Ar^+}}{n_{Ar^+_{ref}}} \approx \frac{k_{iz(A_2)} n_{A_2} + k_{iz(Ar)} n_{Ar}}{k_{iz(Ar_{ref})} n_{Ar_{ref}}}$$



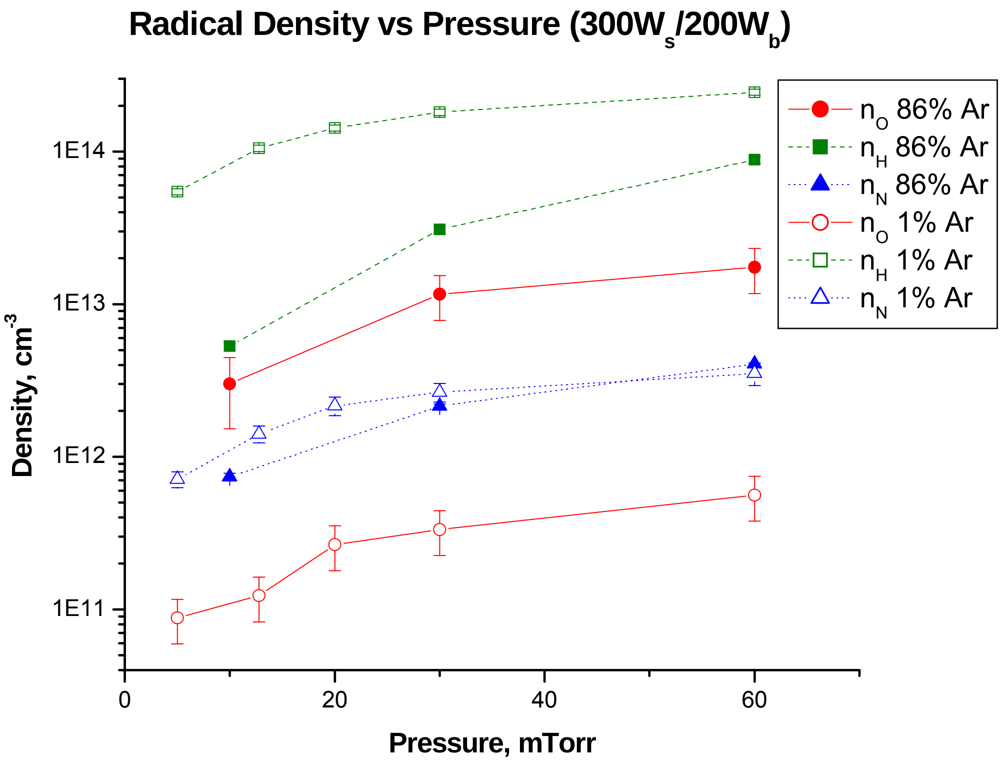
Ion current *increases* with increasing pressure for O_2 plasma

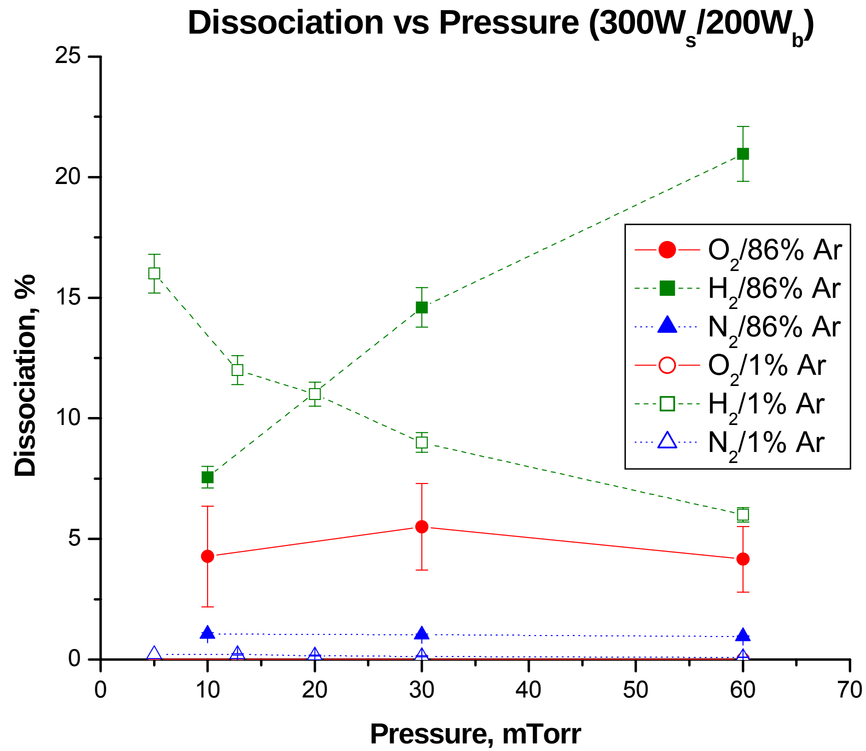
Ion current *decreases* with increasing pressure for N_2 plasma

Ion Scattering Model



Radicals: OE Actinometry – Pressure & Percent Ar





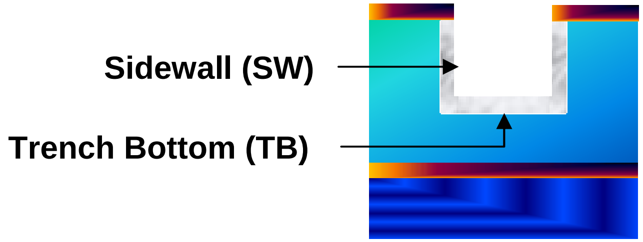
- **Pressure**
  - Radical species density increases with chamber pressure for all species
  - Dissociation behavior of H_2 plasma is unique – EEPF and dissociation cross section function
- **Percent Ar**
  - Radical species density decreases with increasing %Ar for H_2 and N_2 plasma
  - Radical species density and dissociation *increase* with %Ar for O_2 plasma – Penning dissociation

5-60 mTorr allows significant increase in radical species density

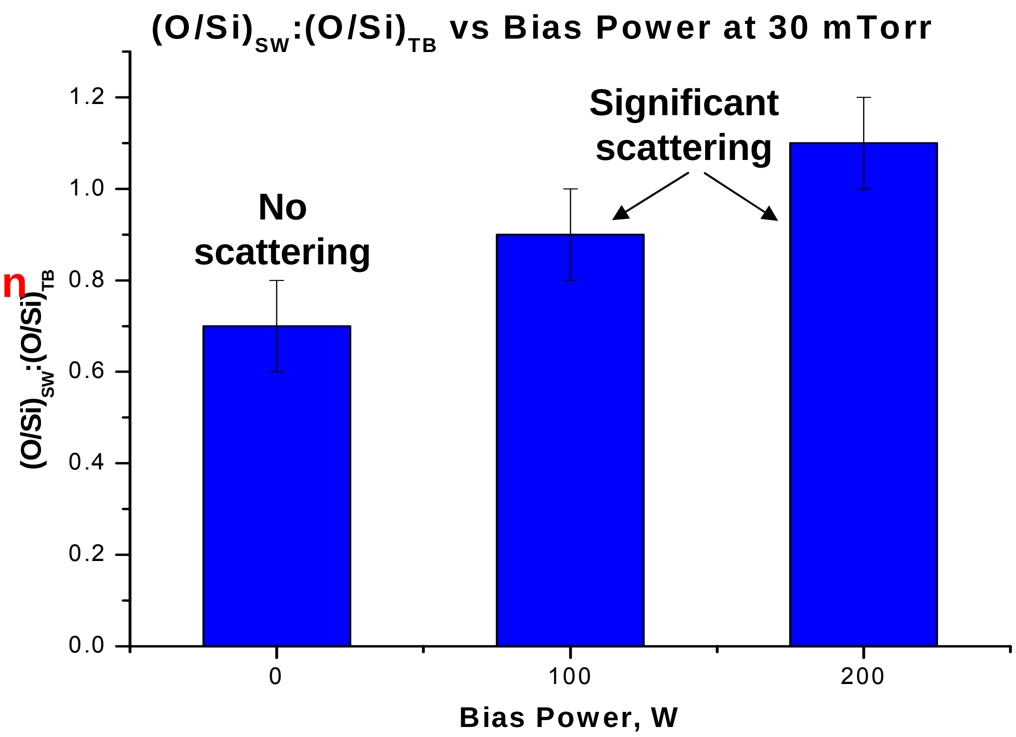
ARXPS Analysis (Ar/O_2) - Bias Power

Ion impact *increases* with bias power (30mTorr)
Radical species density is constant

Test Structure after Ash



- **Damage characterized by increase in O content relative to Si**
  - $(O/Si)_{SW}$:$(O/Si)_{TB}$ ratio is
    - 1 for equal damage
    - <1 for lesser damage to SW
    - >1 for greater damage to SW
- **Effect of ions on sidewall damage in O_2 discharge**
  - 0W: less damage to SW
    - No ion scattering
    - Most damage at trench bottom
  - 100W: increased damage to SW
    - Significant ion scattering
    - Leads to increased SW damage
  - 200W: increased damage to SW
    - Significant ion scattering
    - Leads to increased SW damage



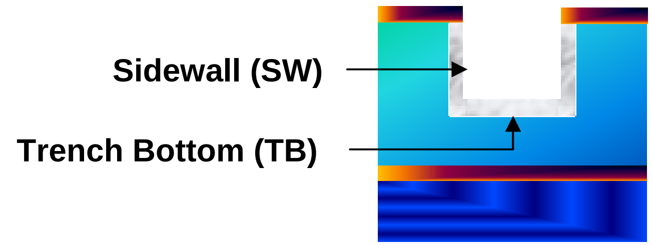
Ion impact causes significant SW damage at 30mT

ARXPS Analysis (Ar/O_2) - Pressure

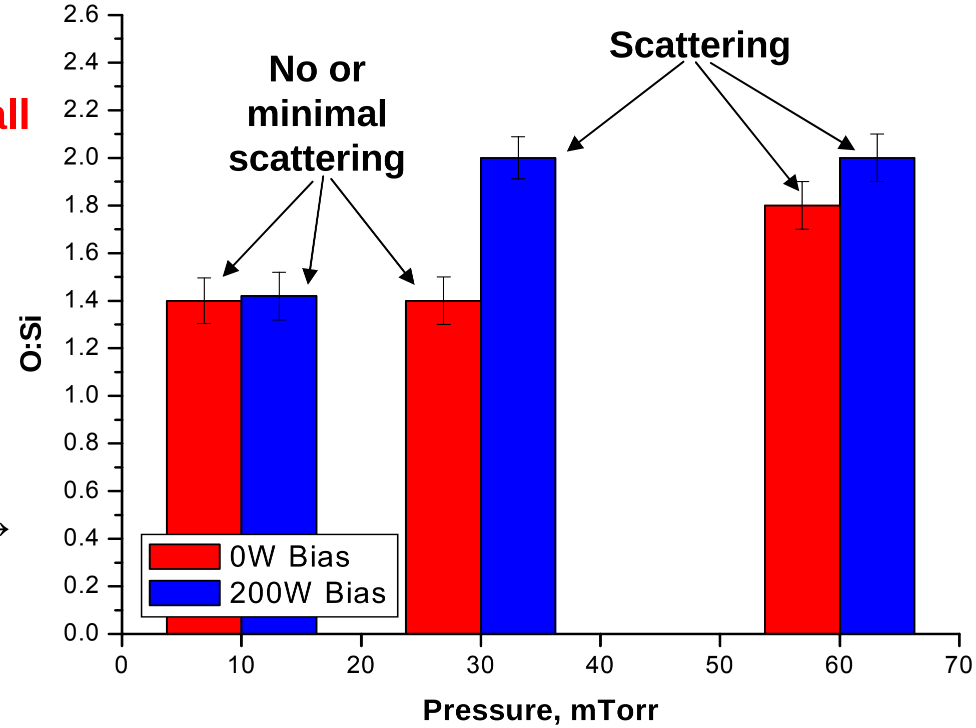
Ion impact *increases* with pressure
Radical species density *increases* with pressure

- **Damage characterized by increase in O content relative to Si**
  - $(O/Si)_{ILD} \sim 1.3$
  - $(O/Si)_{ILD} > 1.3 \rightarrow$ damage
- **Effect of ions and radicals on sidewall damage in O_2 discharge**
  - 10mTorr: little damage to SW
    - No ion scattering
    - Low O density
  - 30mTorr: damage to SW depends on bias
    - No ion scattering at 0W→little damage
    - Significant ion scattering at 200W→ significant damage
  - 60mTorr: increased damage to SW
    - Significant ion scattering
    - High O density

Test Structure after Ash



O:Si at Sidewall vs Pressure



Effect of ion scattering is significant

ARXPS Analysis (Ar/N_2) – Bias Power

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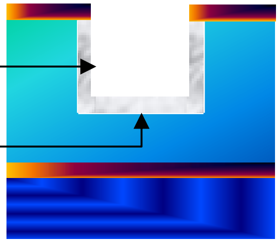
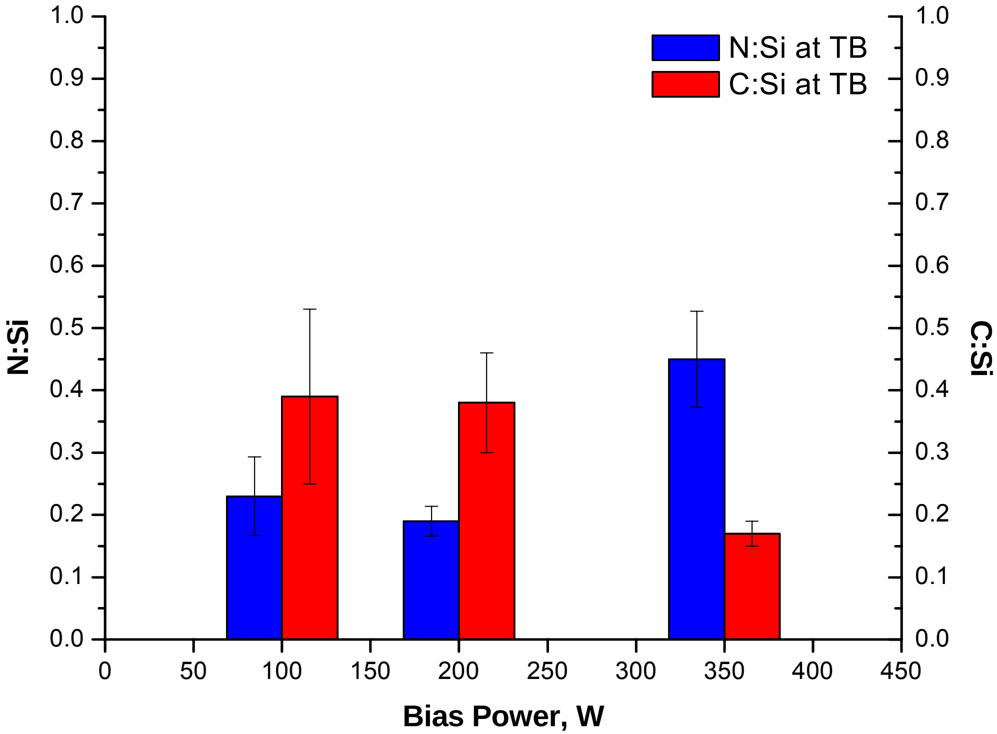
Ion impact *increases* with bias power (scattering regime)
N species density is constant

Test Structure after Ash



- **Damage characterized by increase in N content and decrease in C content relative to Si**
  - $(N/Si)_{ILD} = 0$
  - $(N/Si)_{ILD} > 0 \rightarrow$ damage
  - $(C/Si)_{ILD} = 0.5$
  - $(C/Si)_{ILD} < 0.5 \rightarrow$ damage

- **Effect of ions on damage in N_2 discharge**
  - Similar damage to SW and TB (scattering regime)
  - Damage increases with bias power
    - N:Si increases with power
    - C:Si ratio decreases with power
  - Damage trend follows trend in ion impact

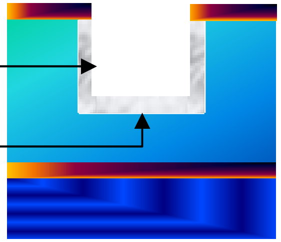


Increased ion impact leads to more damage

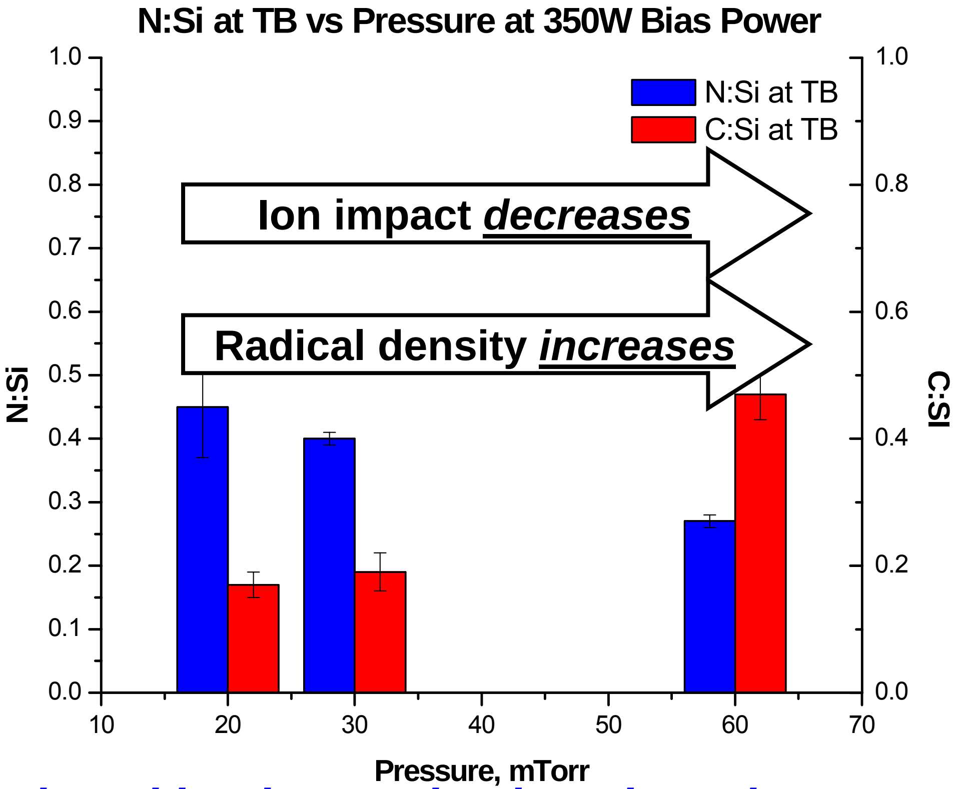
ARXPS Analysis (Ar/N_2) – Pressure

Ion impact *decreases* with pressure (scattering regime)
N species density *increases* with pressure

Test Structure after Ash



- **Damage characterized by increase in N content and decrease in C content relative to Si**
  - $(N/Si)_{ILD} = 0$
  - $(N/Si)_{ILD} > 0 \rightarrow$ damage
  - $(C/Si)_{ILD} = 0.5$
  - $(C/Si)_{ILD} < 0.5 \rightarrow$ damage
- **Effect of ions and radical density on damage in N_2 discharge**
  - Damage decreases with pressure
    - N:Si decreases with pressure
    - C:Si ratio increases with pressure
  - Damage trend *does not* follow radical density
  - Damage trend *does* follow trend in ion bombardment



Reduced ion impact leads to less damage

Summary and Conclusions

- **Identified ion impact as key factor that has significant impact on ash-induced damage**
  - Oxygen ash plasma
  - Nitrogen ash plasma

- **Conclusions for minimal damage**
  - Optimal ash process may be in a reactor that eliminates ion impact
  - If ion impact cannot be eliminated, operate in a regime that minimizes ion impact
    - Low pressures
    - Low bias power

These conclusions focus on minimizing low-κ ILD damage, photoresist removal rate must also be considered in optimizing ash process