# Beam Studies of Ultra Low-K Film Damage

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# Project Motivation

- As the density of transistors on semiconductor devices increases, technological barriers impede their performance
- New materials help overcome these barriers, but processing remains an issue
- Current processing techniques degrade the properties of new materials, making them perform only marginally better than old ones

# Technological Barriers

- More transistors are being put on wafers, forcing current device sizes to shrink
  - Denser metal lines increase metal-metal capacitance
  - Thinner metal lines increase wire resistance
- Digital switching speed is dependent on the product of metal line resistance and metal-metal capacitance:

$$RC \propto \rho_{met} \frac{k\varepsilon_o L^2}{t_{met} t_{dielectric}}$$

# Solving the Metal Line Capacitance Dilemma

- Decreasing the capacitance between metal lines requires an insulator with a k lower than that of $SiO_2$, but finding a replacement is difficult…
- $SiO_2$ has great chemical and mechanical stability due to strong individual bonds and high bond density…
- But the strongest bonds are often the most polarizable (=higher k), and high bond density also increases k

# A Polymeric Solution?

- Polymers can have much lower k than $SiO_2$
  - But they have poor thermal and mechanical stability unless double and triple bonds are incorporated
    - But double and triple bonds increase k…
  - Pores can be introduced to decrease density, decreasing k
  - Dopants can be added to decrease k

- This research focuses on a porous, MSQ-based ultra low-k polymer

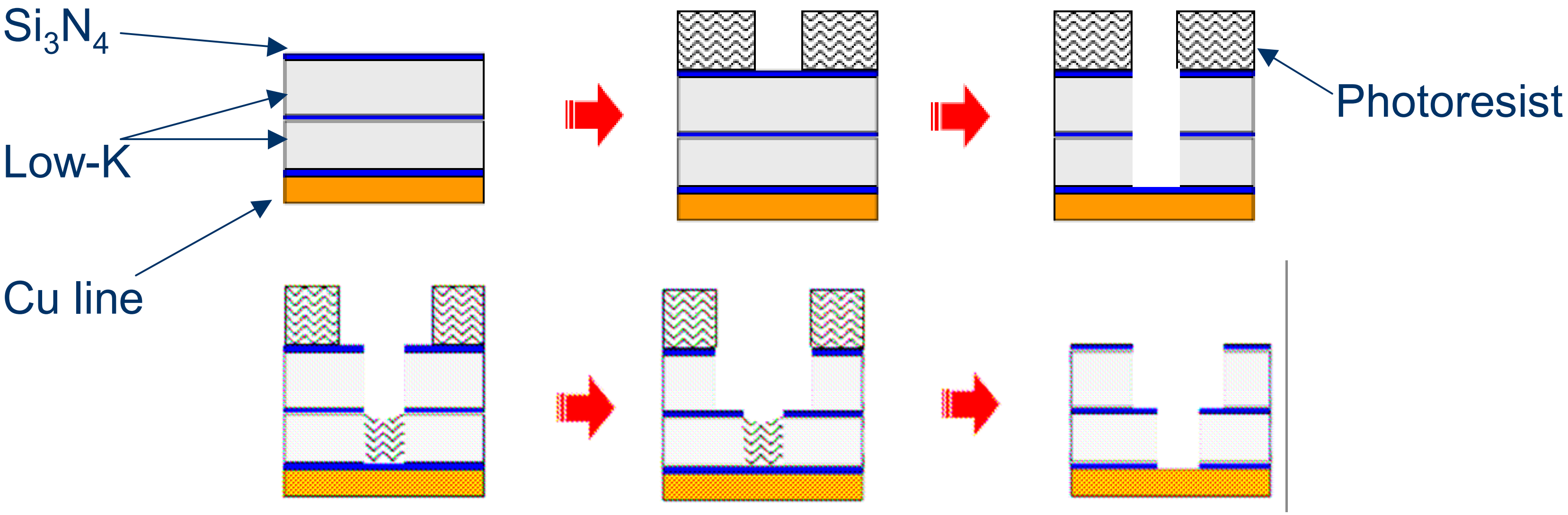
# Back to RC-Time Delay

$$RC \propto \rho_{met} \frac{\varepsilon_{dielectric} L^2}{t_{met} t_{dielectric}}$$

- As metal line dimensions shrink, their resistance increases, requiring the need for lines of lower resistivity
- Metallization has switched from Al(Cu) ($\rho = 3.3\ \mu\Omega$) to Cu ($\rho = 1.9\ \mu\Omega$)

# More Complications

- The move to Cu adds complexity in processing, as Cu cannot be etched in dry processes
  - (Dual) Damascene process for metal wire formation



# Dual Damascene/Low-K Compatibility Issues

- Photoresist can accumulate in porous ILDs, raising K
- With $SiO_2$, photoresist stripping can be easily done in $O_2$ plasma, but this will damage new ILDs
  - $O_2$ plasma will remove carbon from dielectric, raising k

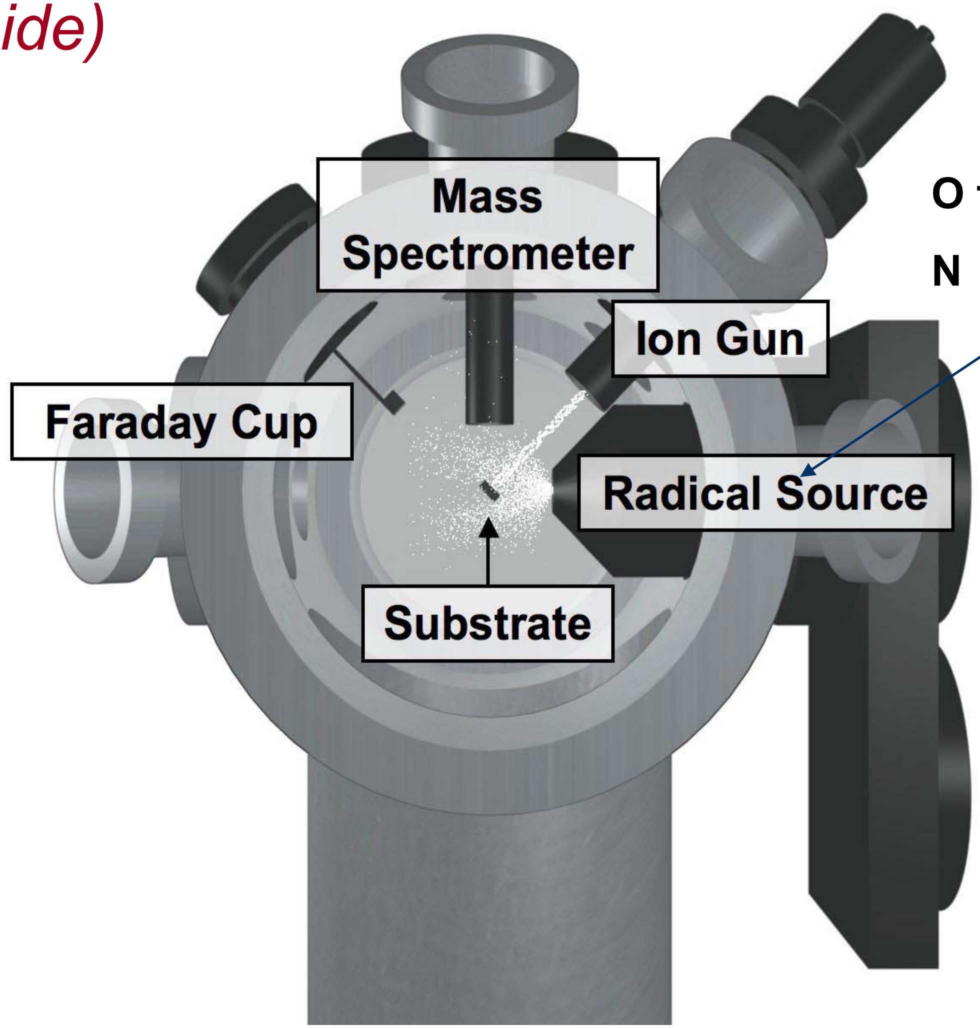
# Processing Chemistries

- Widely known that oxygen plasma destroys dielectric properties of methyl-doped low-k films
  - What can we learn about the degradation?
  - What about nitrogen?
  - Other chemistries?
  - What effect do ions have on the bond structure of the films?

- What conclusions can we draw from beam studies of these films?

# Experimental Setup

*System schematic – view 1 (side)*

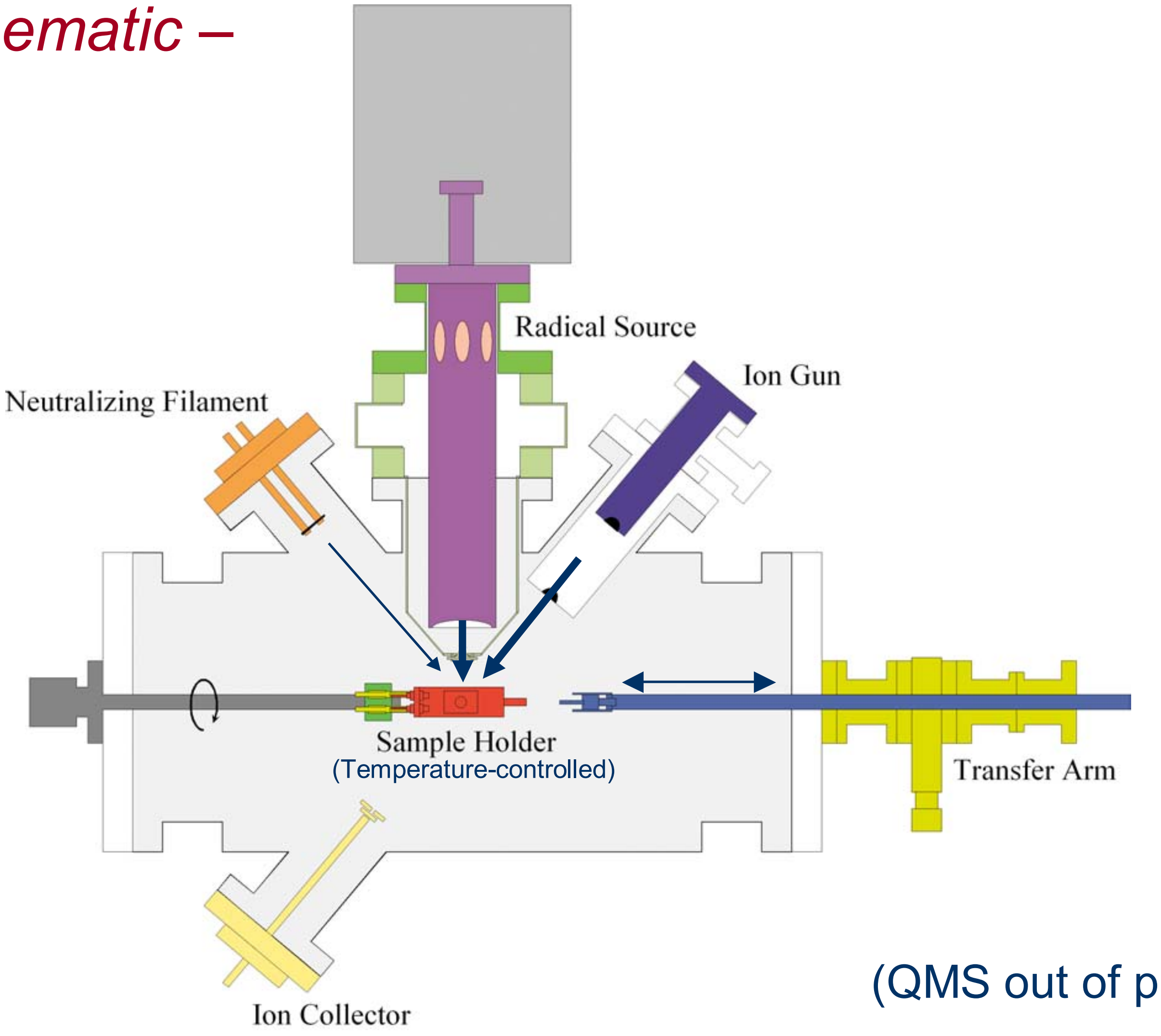


**O fluence ~ $3\text{x}10^{13}$ cm$^{-2}$ s$^{-1}$**

**N fluence ~ 1.5 x $10^{13}$ cm$^{-2}$ s$^{-1}$**

# Experimental Setup (top view)

*System schematic – view 2 (top)*

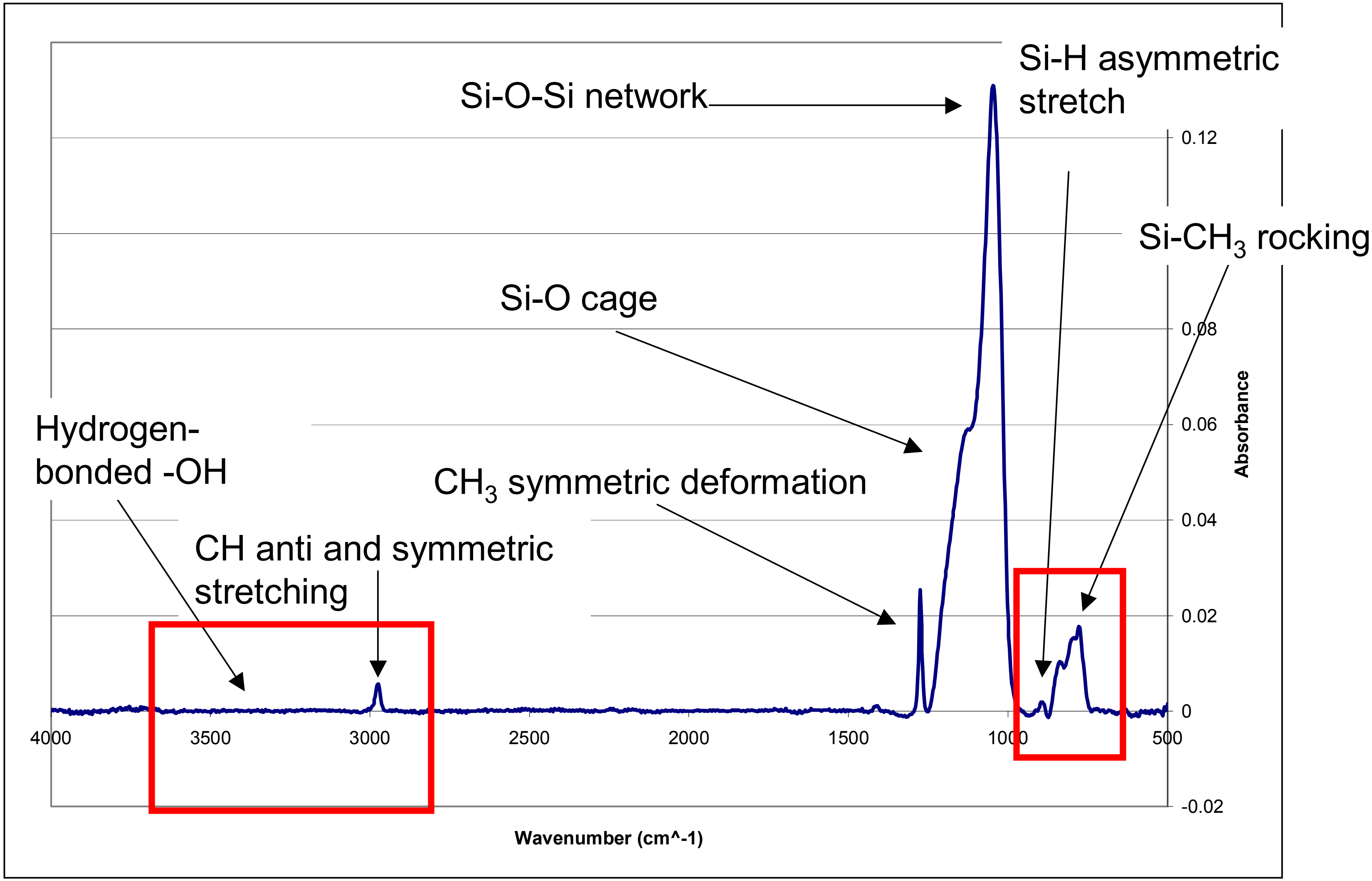


(QMS out of plane)

# Analysis Techniques

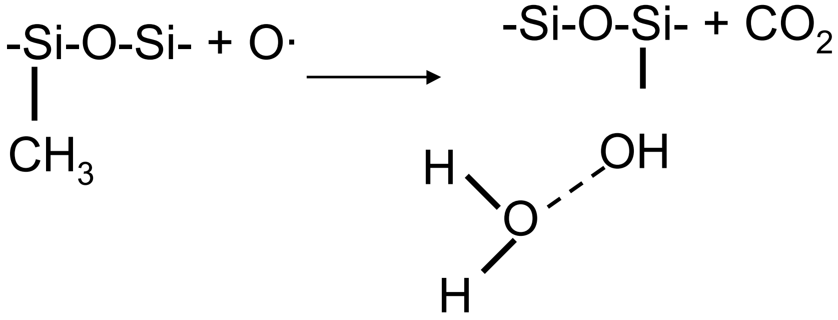
- Main technique is FTIR
  - IR beam is transmitted through sample, and chemical bonds absorb IR light at different wavelengths
  - Spectrum of background Si wafer subtracted off, leaving low-k spectrum
  - Some bonds are more active than others, so comparing the absolute intensities not useful– need to compare relative intensities
  - Peak shifting may occur depending on the environment of the bond

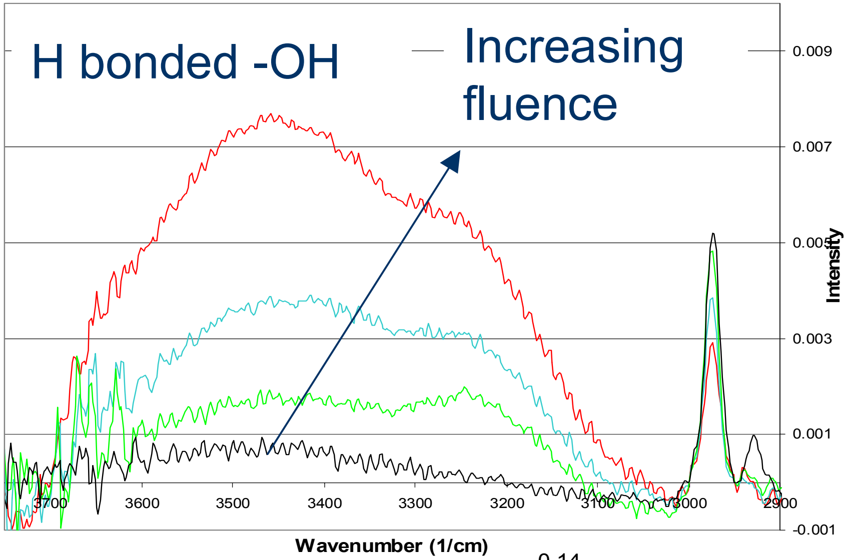
# Unprocessed Low-k Film FTIR Spectrum

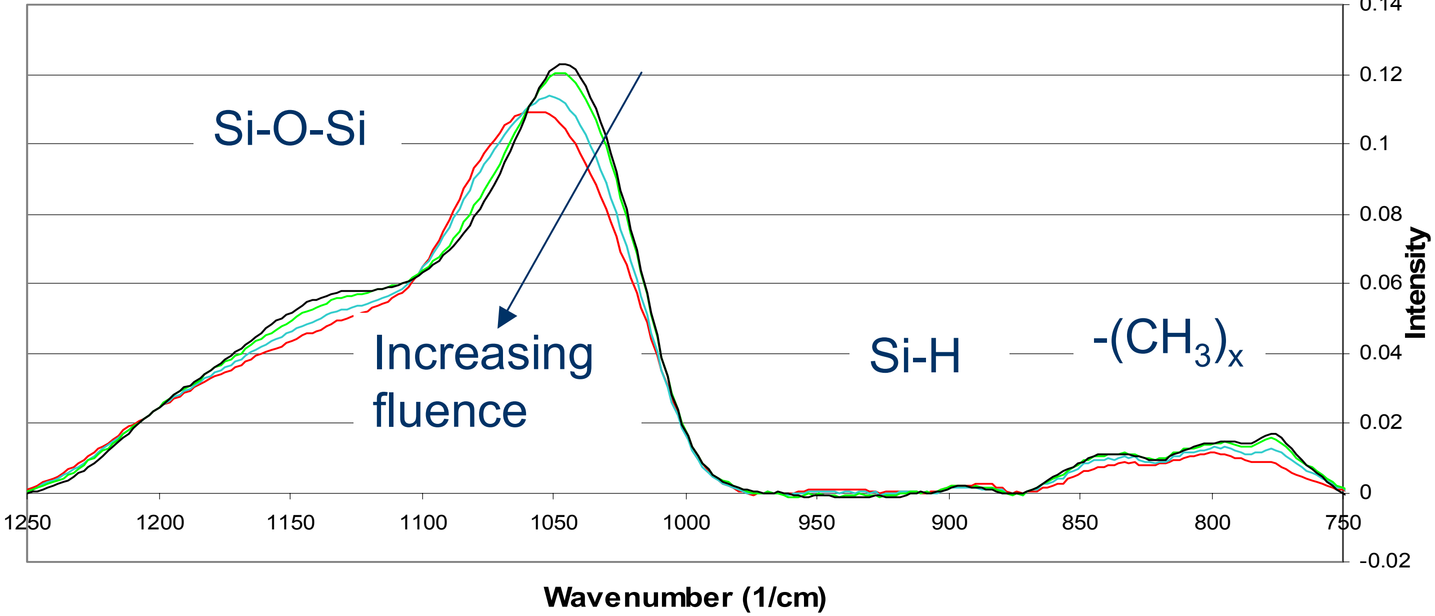


# Experimental Results

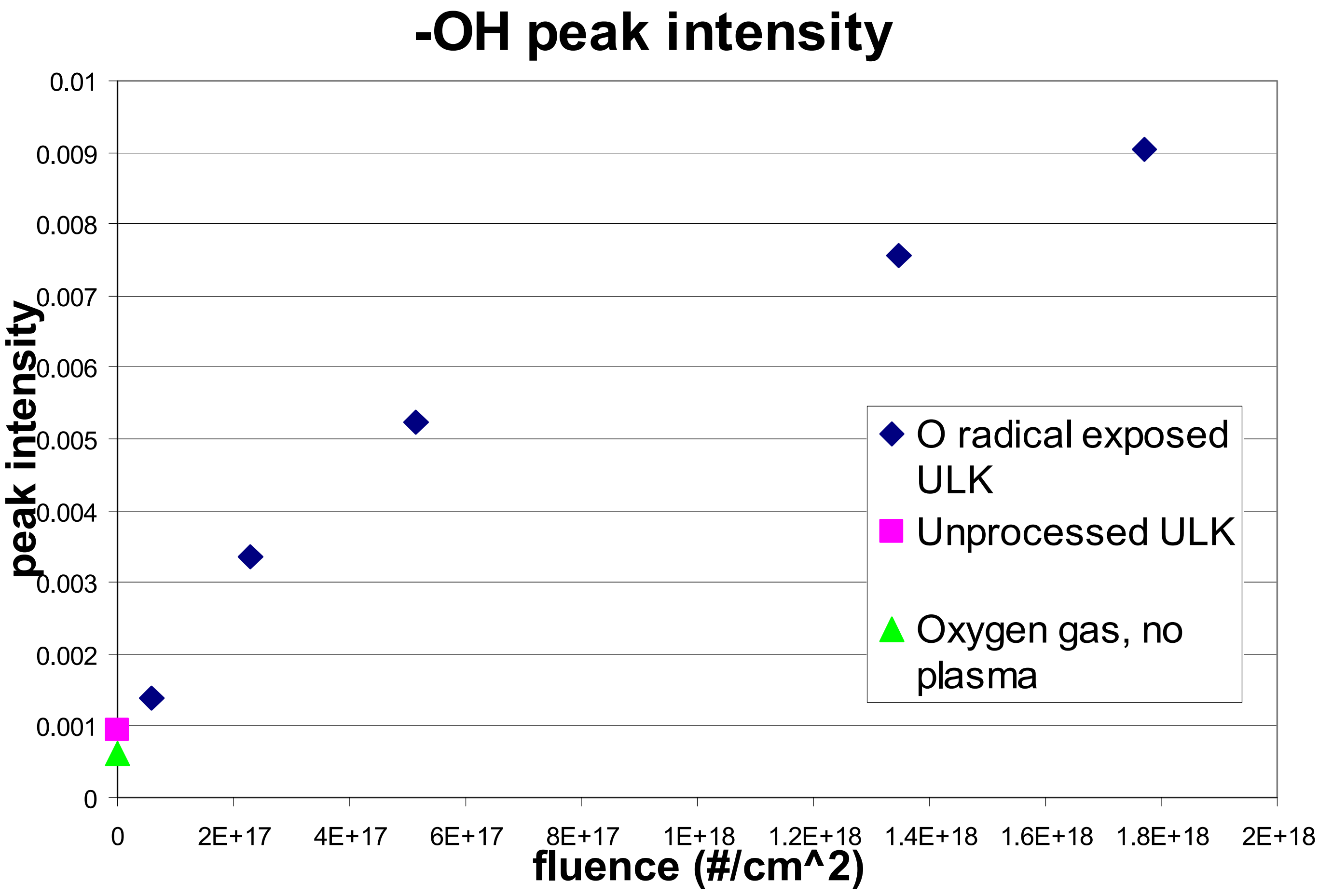
- Oxygen radicals increase $H_2O$ uptake and removing carbon
- Peak shift of Si-O-Si due to change in surrounding bonds





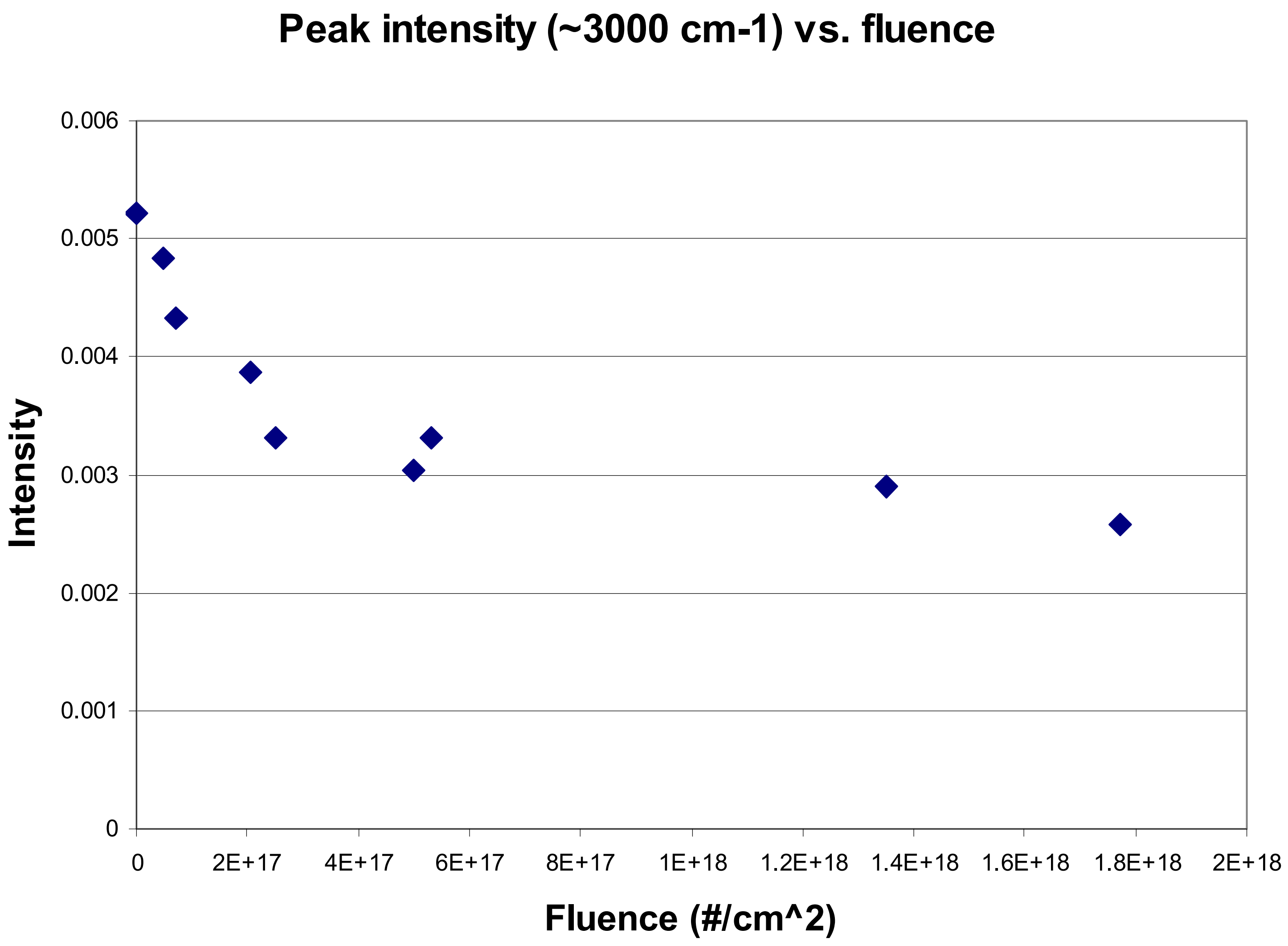


# Diffusion and Reaction of Oxygen Radicals in Low-k Films



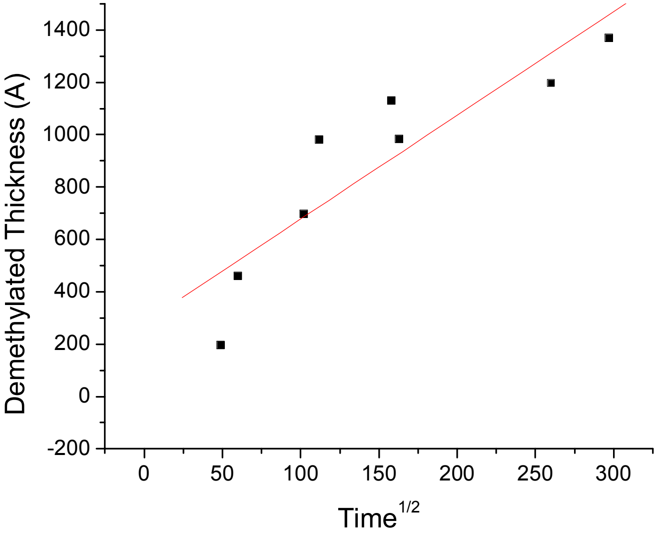
- Peak intensity is proportional to number of Si-OH bonds: indicator of increasing damage.

# Deal-Grove Analysis of Oxygen-Induced Damage



# Deal-Grove Analysis of Oxygen-Induced Damage

- Assume constant radical flux
- Assume that peak intensity is proportional to the number of bonds through the film bulk
  - Convert peak intensity to a methylated (or demethylated) film thickness
- Plot of demethylated film thickness vs. time$^{1/2}$ is approximately linear at longer times



# Deal-Grove Analysis of Oxygen-Induced Damage

- In Deal-Grove model, $x^2 \approx Bt$, where B is the parabolic rate constant,

$$B = \frac{2D_{eff}C^*}{N_i}$$

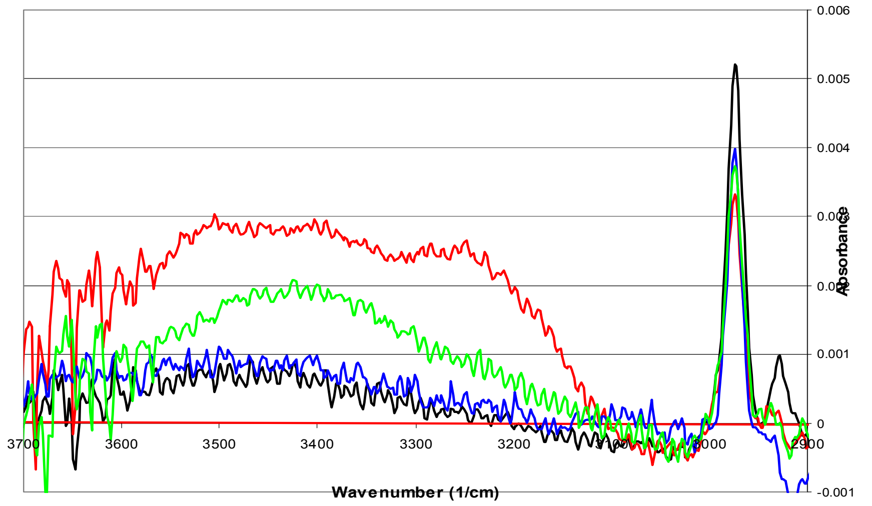
- In our case, B comes from the slope of demethylated thickness vs. time$^{1/2}$ linear fit
- $N_i$ is density of reactive sites
- $C^*$ is surface concentration of radicals

- Find that $D_{eff} \approx 10^{-2}$ cm$^2$/s

# Comparison of Different Radical Chemistries

- At approximately equal fluences, damage trend is

  O > NO w/N > N

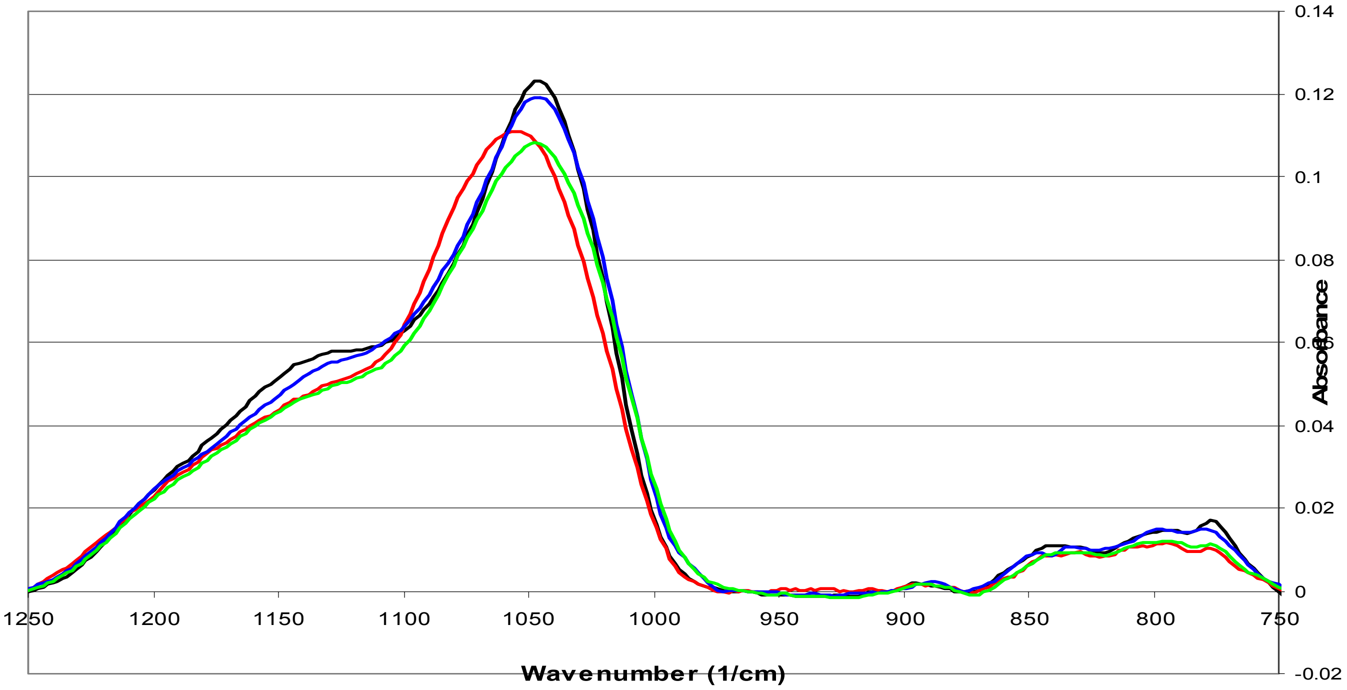


▬ Unprocessed Film

▬ Nitrogen ($3.18x10^{17}/cm^2$)

▬ NO w/N ($3.2x10^{17}/cm^2$)

▬ Oxygen ($2.5x10^{17}/cm^2$)



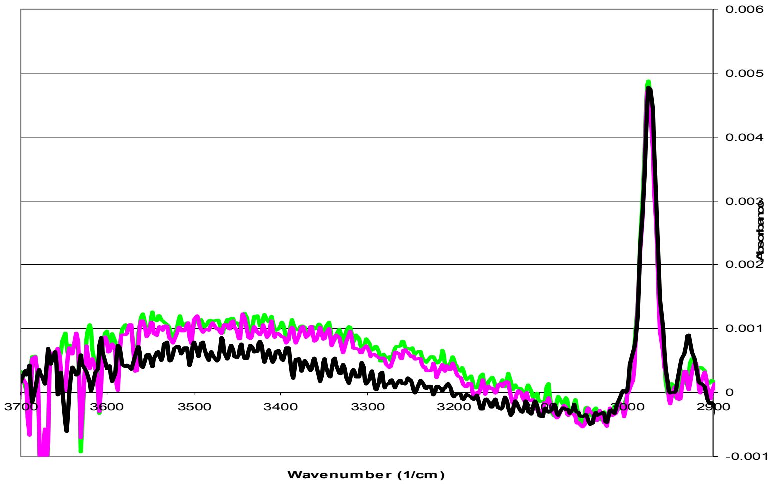
# What Does This Mean?

- Increased –OH peak intensity means more water uptake → higher dielectric constant
- Decreased –$CH_3$ peak intensity means carbon depletion → higher dielectric constant

- Widely known that oxygen-plasma ashing damages low-k films-- less experimental data on nitrogen, and no serious studies of the role of NO have been done

# What Role Do Ions Have?

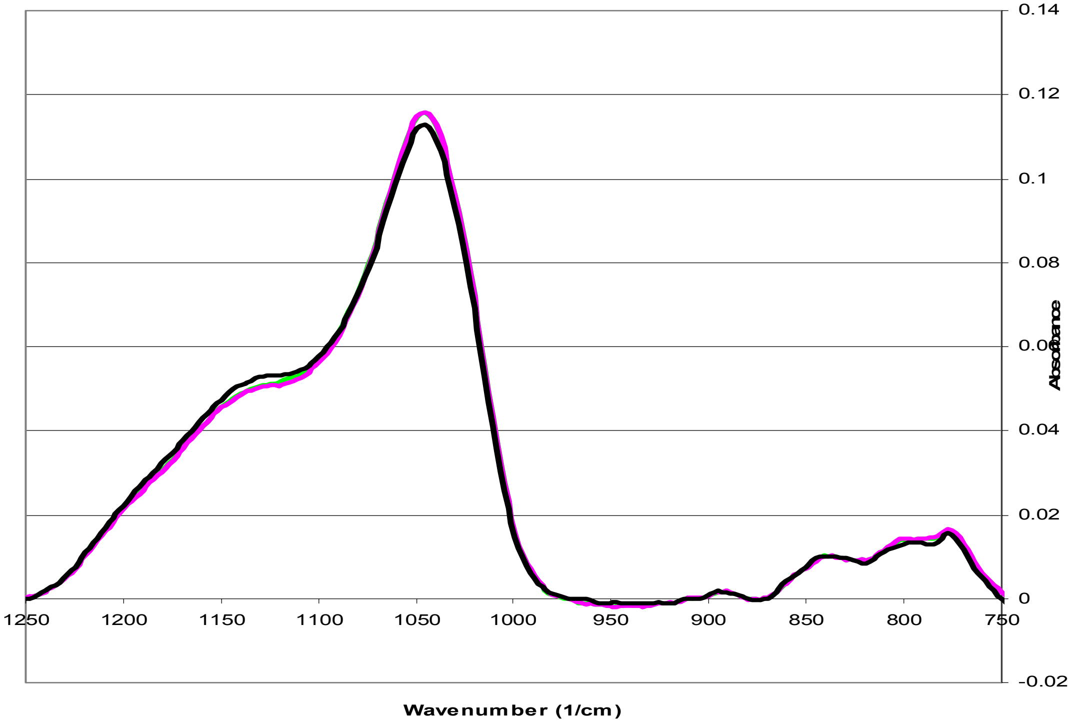
- Shown that radicals damage low-k films, but what about ions? Does ion mass matter? Fluence?



— Unprocessed Film

— Xe+ $2.55\times10^{17}/cm^2$

— Ar+ $2.34\times10^{17}/cm^2$



# Conclusions

- What is happening?
  - Oxygen radicals diffuse into the low-k film, creating a carbon-depleted layer front that moves downward in the film
  - In NO damage, the NO reacts with nitrogen to form $N_2$ and O, and the O attacks the methyl groups
  - Nitrogen radicals do damage the film slightly, much less than similar fluences of oxygen
  - Ions do not penetrate into the film- they damage only the very top layer

# Future Work

- Add separate source of NO to beam system; test effects of NO with and without N from radical source (in progress).
- Study synergistic effects of simultaneous and sequential radical and ion beams (in progress)
- Use $NH_3$ in radical source. Characterize beam and measure damage. (in progress)
- Explore spin-on low k films for use on quartz crystal microbalance: QCM powerful tool in beam system. (proposed)
- Explore post-damage processing to test reversibility of damage. (proposed)
- Explore effects of electrons (and/or photons) in damaging low k films. (proposed)