Valence-band Structure and Charge Trapping During VUV Irradiation of BEOL Dielectrics *

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Outline

- Introduction
- Experimental Details
- Valence-band Structure of low-*k* Dielectrics
- Charging Response of low-*k* Dielectrics
- Conclusions

Introduction

- Processing plasmas produce significant amounts of vacuum ultraviolet (VUV) radiation which is, among other processes, capable of creating electron-hole pairs within dielectrics.

- As a result, VUV radiation has an impact on the electrical conductivity of dielectrics during plasma processing which can either contribute to or mitigate trapped charge within dielectrics.

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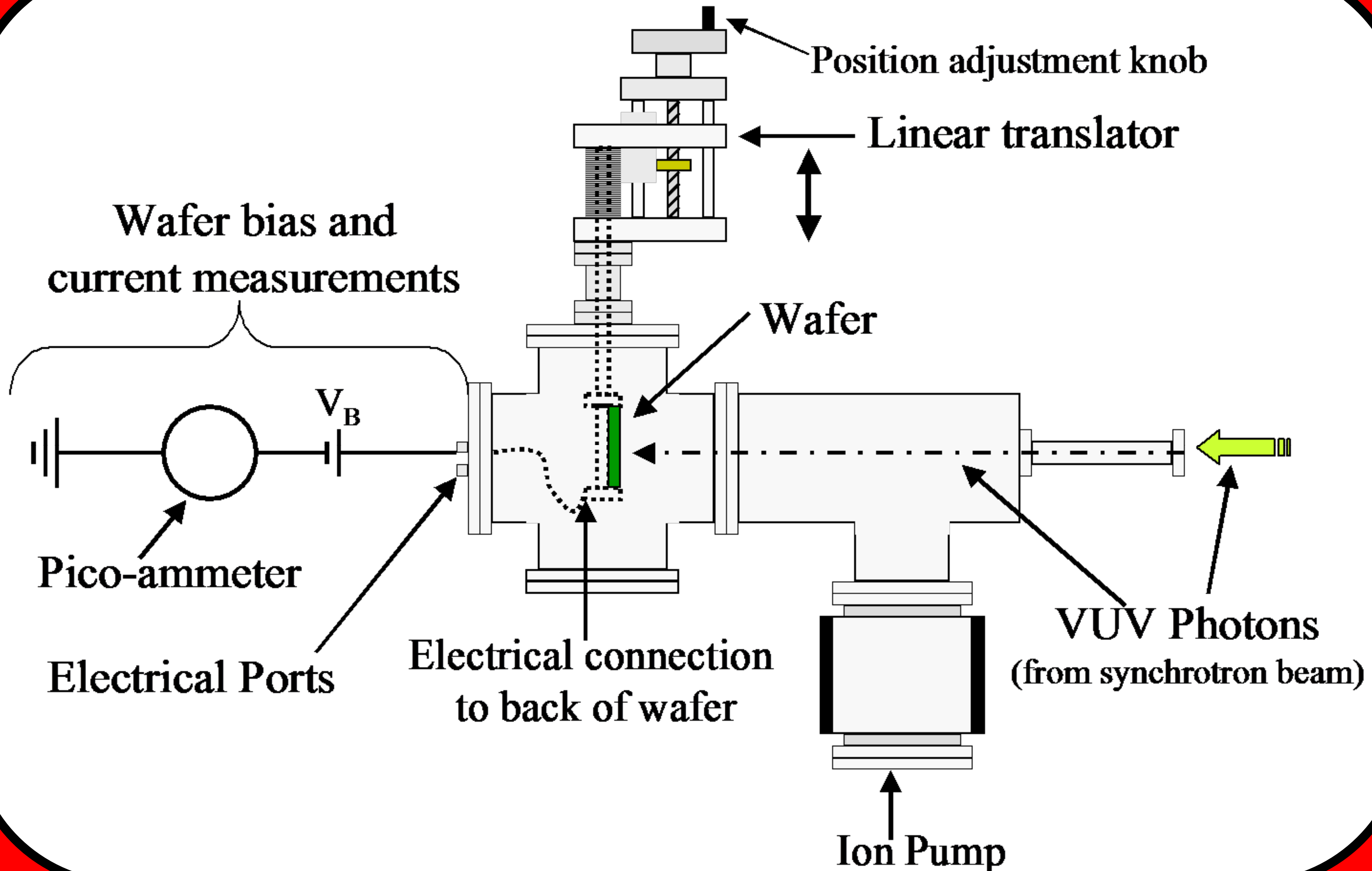
Trapped Charge in Dielectrics

- Traps provide both a path for conduction and modification of the local electric field due to space-charge accumulation.
- Two important parameters that control the magnitude and path of leakage currents within dielectrics are
  - Valence-band structure
  - Traps/defects
- So if we know these parameters, we can explicitly measure the quality of the dielectric.

Significant Findings

- In this work, we measured and compared the valence-band structure and nature of charge trapping within several low-*k* films after VUV irradiation.
  - porous-SiOCH, SiN, SiCO, SiCN, and SiC on Si.
- We determined that the VUV-induced trapped positive charge is located 1.4 eV above the valence-band edge.
  - This implies that the traps are likely to be caused by O-deficient Si defects or dangling Si bonds within the dielectric.
- Although the defects remain, we can anneal out the trapped positive charge with UV radiation.

Experimental Apparatus



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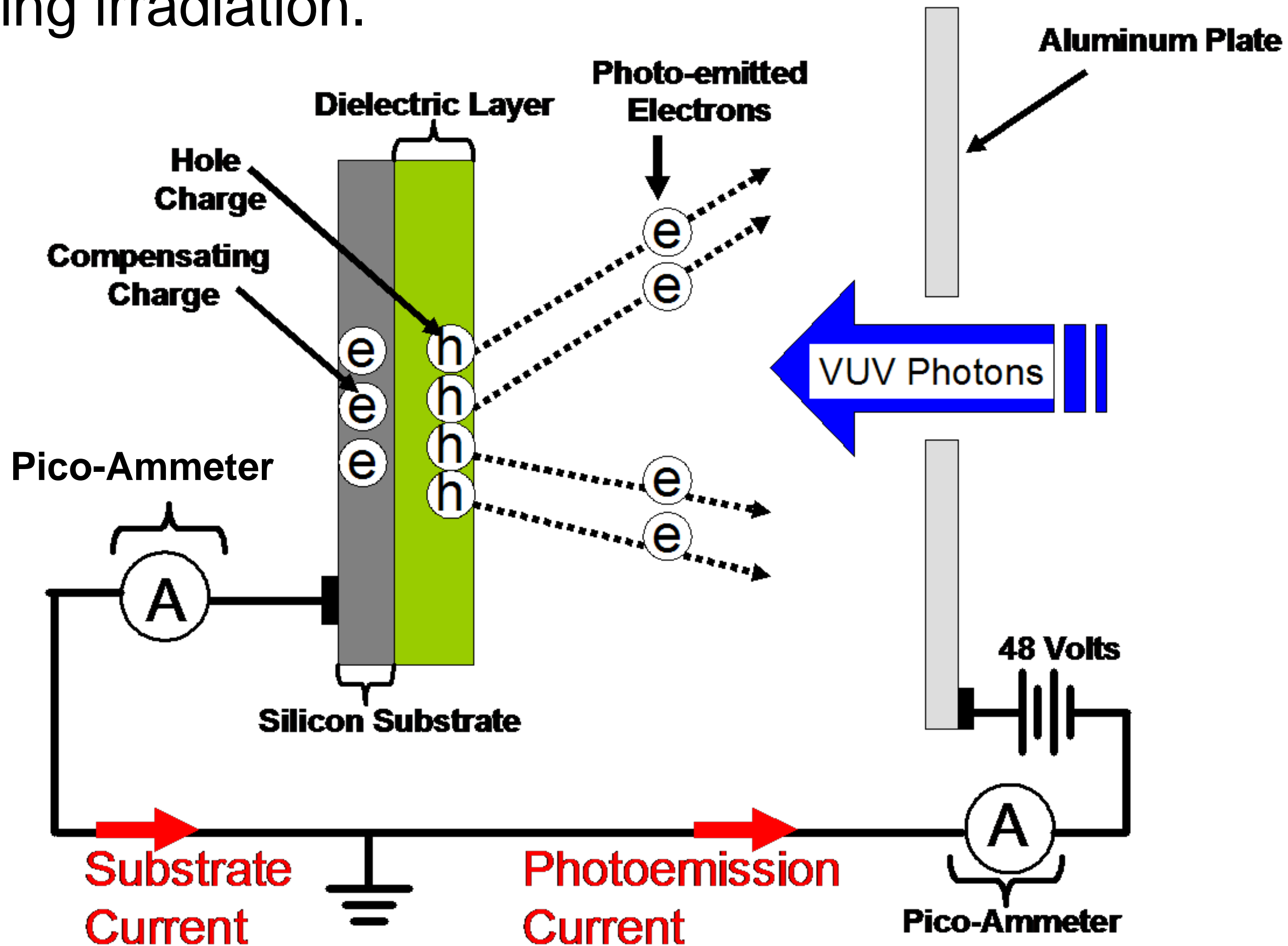
VUV-irradiation Apparatus

- The substrate and photoemission currents are measured during irradiation.



Induced Charging and VUV- spectroscopy

- Charging Response to VUV irradiation (Step 1)
  - The photon energy was fixed while the photoemission and substrate currents were measured as a function of time.
  - Charge accumulation as a function of total VUV-photon dose was evaluated with a Kelvin probe system after VUV irradiation for several dielectric thicknesses.
    - Determine the location within the dielectric the trapped charge is located.
- VUV-spectroscopy (Step 2)
  - Measured the photoemission and substrate currents while the photon energy is scanned between 5 and 15 eV.
    - Determine the location (in energy) where the trapped charge is located.

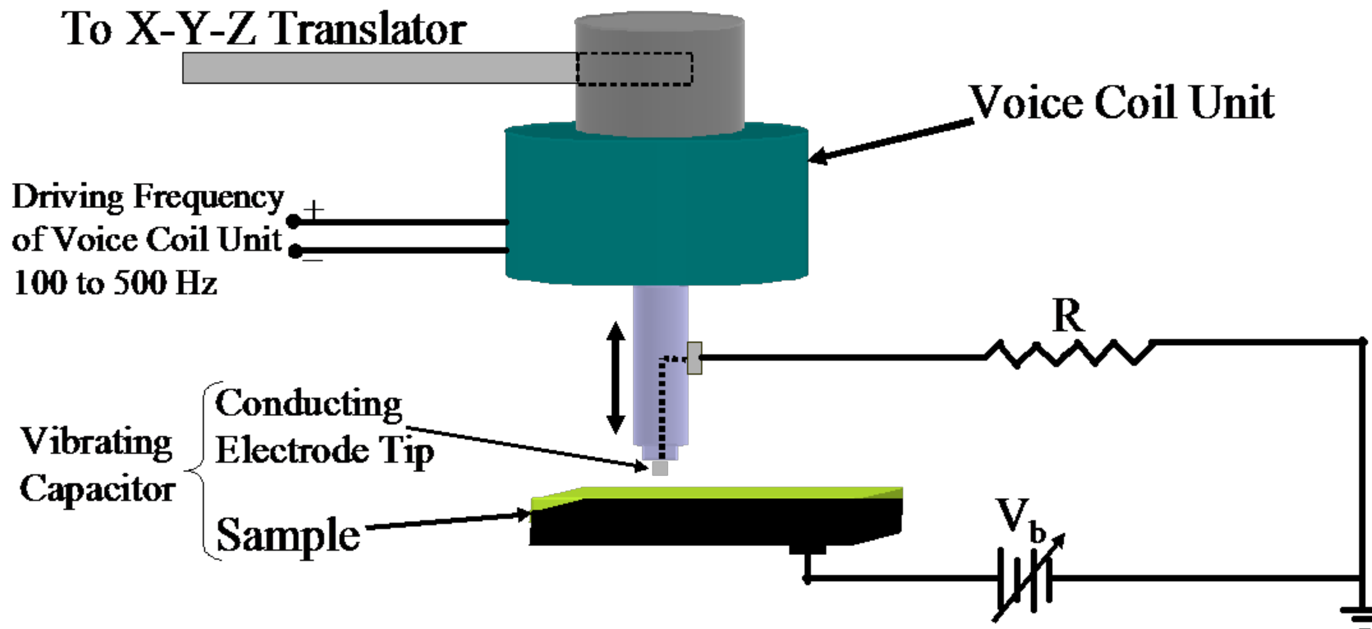
Kelvin Probe System

- When a vibrating electrode (Kelvin Probe) is placed near the surface of a charged dielectric, because of the surface potential V_{SP}, the varying capacitance introduces an a.c. current.

$$i(t) = V_{SP}\, dC/dt$$

- A dc voltage $V_b = -V_{SP}$ nulls the current thereby measuring the surface potential.

$$i(t) = (V_{SP} + V_b)\, dC/dt$$



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Approximate Location of Trapped Charge

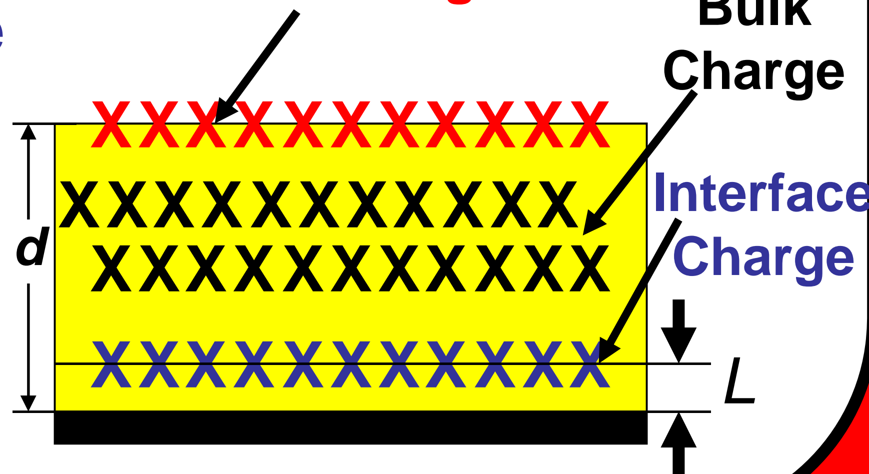
- The general expression for the surface potential due to trapped charges within a dielectric layer of thickness *d* is

$$V_{SP} = \frac{1}{k\varepsilon_0}\int_0^d x\rho(x)dx$$

- Since the distribution of trapped charges within the dielectric layer is unknown, the above equation can be approximated by assuming a physically plausible distribution of trapped charge.

Surface Charge — Bulk Charge — Interface Charge

$$V_{SP} = \frac{Q_S d}{k\varepsilon_0} + \frac{Q_B d^2}{k\varepsilon_0} + \frac{Q_I L}{k\varepsilon_0}$$



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Valence Band of SiOCH (*k* = 2.55)

- The peak at 7.6 eV decays as the photon energy is scanned multiple times on the same location on the wafer surface.
  - Caused by depletion of electrons from the oxygen-deficient Si centers, which are located at 7.6 eV.

O(2p)
O-Deficient Si
Photoinjection
Scan1
Scan2
scan3
Scan4
Scan5
scan6
Normalized Current (a.u.)
1.0
0.8
0.6
0.4
0.2
5.0
5.5
6.0
6.5
7.0
7.5
8.0
8.5
9.0
9.5
10
Photon Energy (eV)

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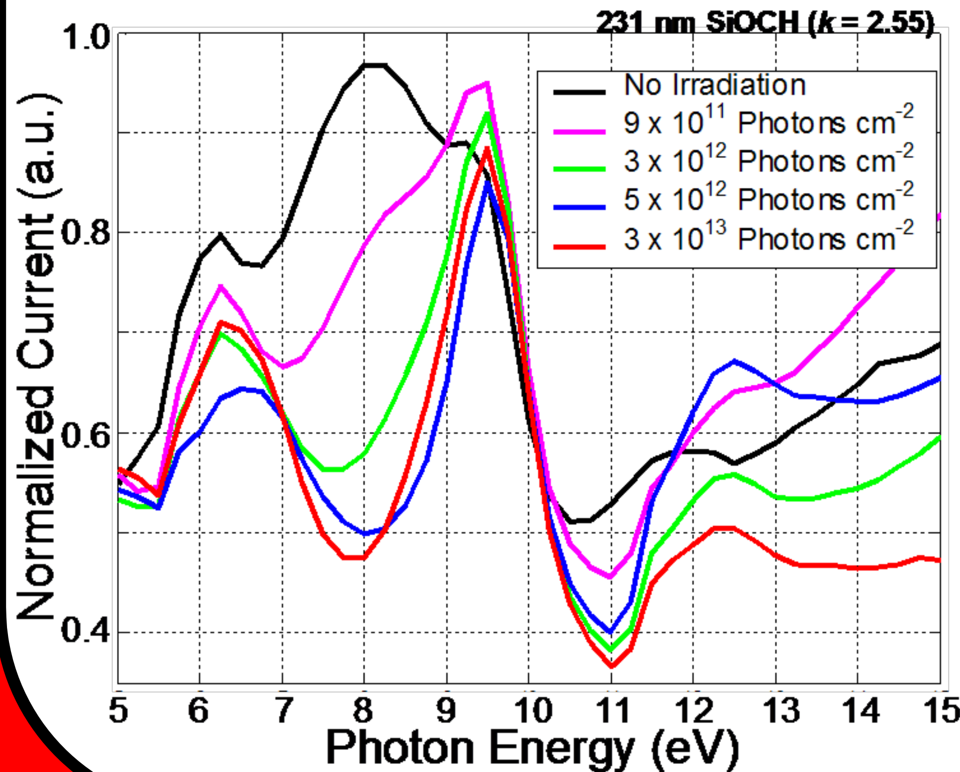
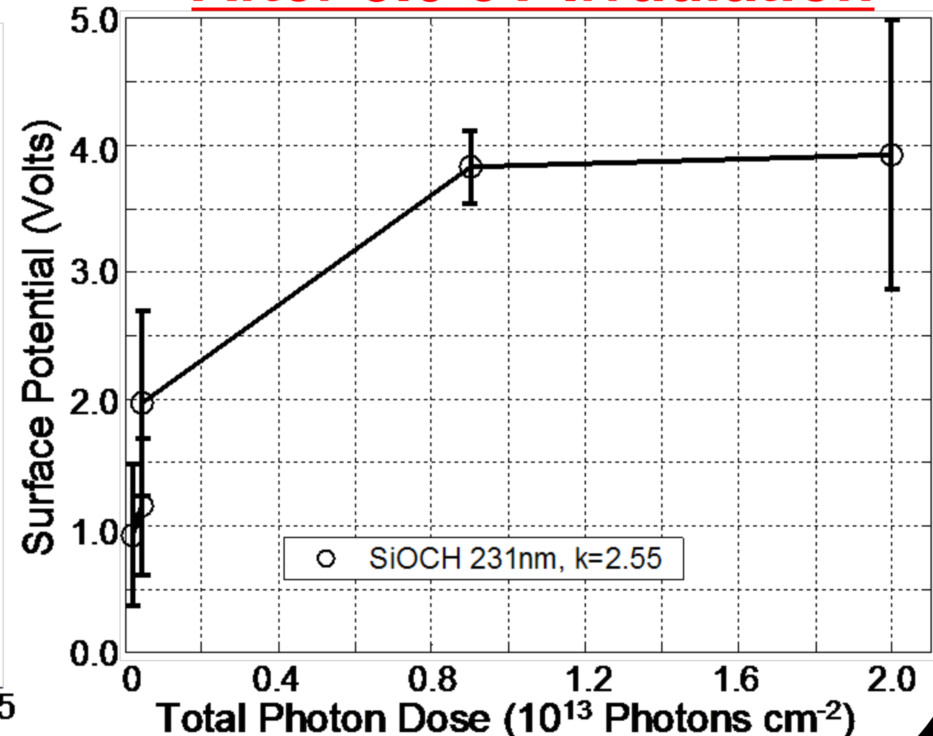
Defect States after 8 eV Irradiation

- The depletion of electrons from the O-deficient Si centers within the 231 nm SiOCH (*k* =2.55) dielectric saturates after a photon flux of 5 x 10^{12} Photons cm^{-2} for 8.0 eV photons.
- Similarly, the surface potential saturates after a photon flux of 8 x 10^{12} Photons cm^{-2}.



After 8.0 eV Irradiation



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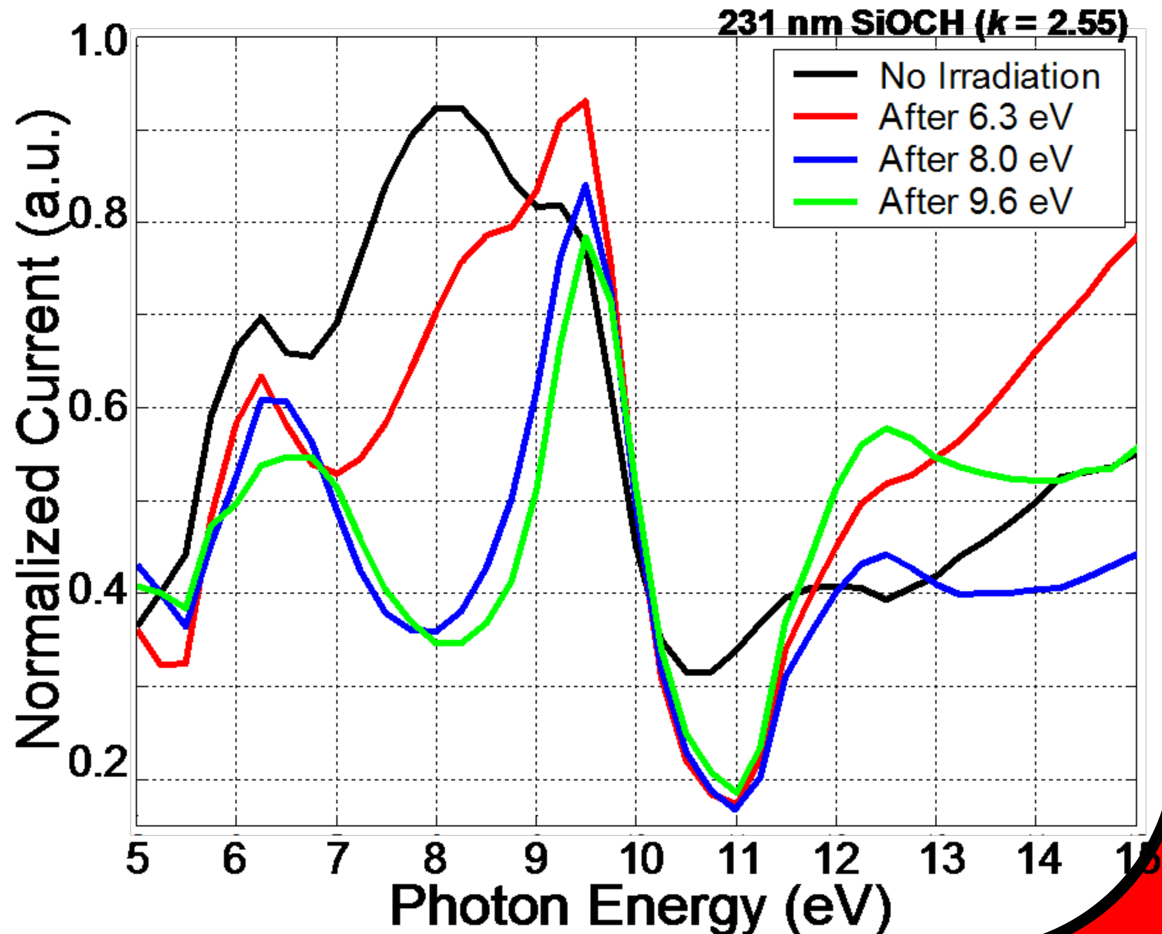
After 6.3, 8.0 and 9.6 eV Irradiation

- The O-deficient Si centers do not decay at the same rate under irradiation with 6.3, 8.0, and 9.6 eV photons for the same total photon dose (3 x 10^{12} Photons cm^{-2}).

8 and 9.6 eV photons are more efficient at depleting the electrons from the O-deficient defects than 6.3 eV Photons.



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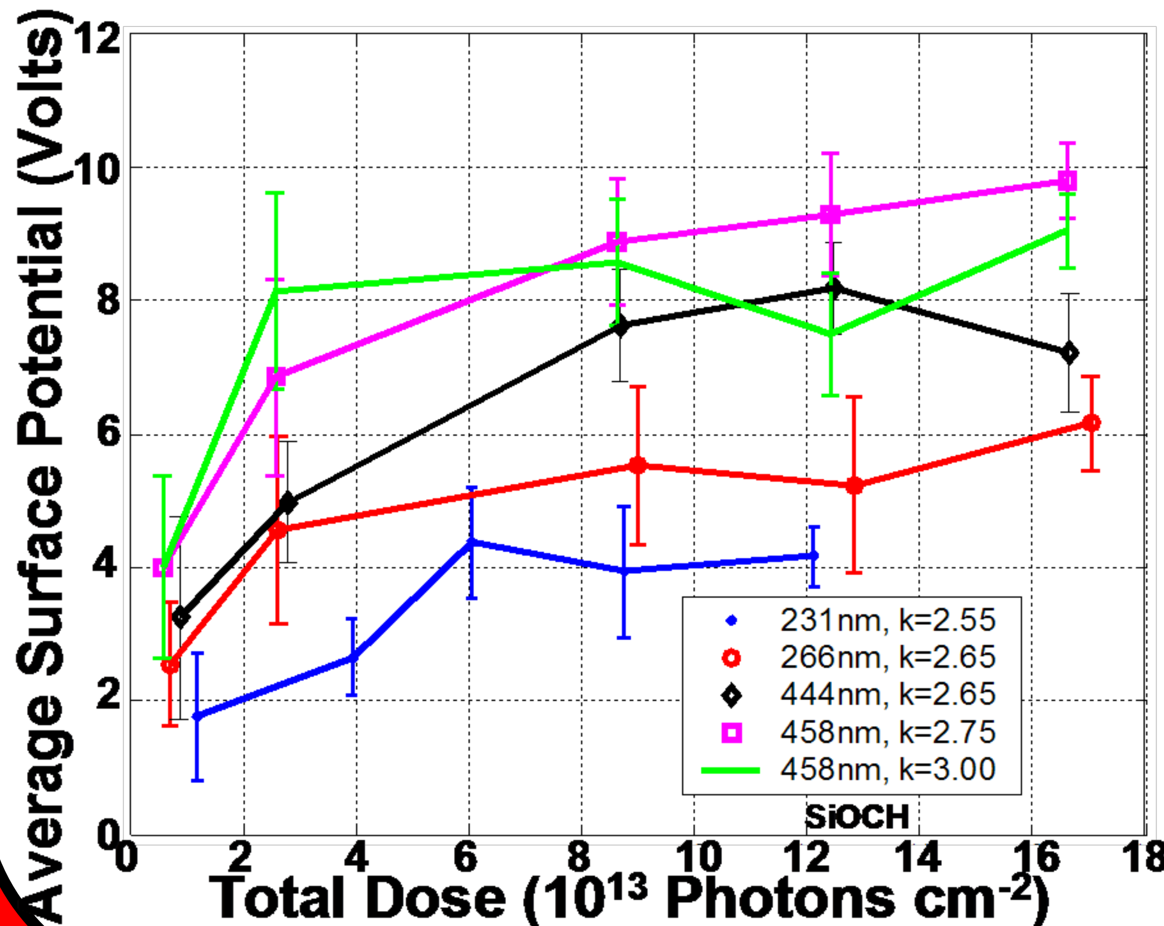
Surface Potential after 9.5 eV Irradiation

- Comparison of surface potential for several *k*-values of SiOCH after 9.5 eV photons.



- On average the surface potential is lower for the lower *k*-values.
- However, the surface potential should increase as *k* decreases for the same amount of charge. V = Q/C

$$V_{SP} = \frac{Q_S d}{k\varepsilon_0} + \frac{Q_B d^2}{k\varepsilon_0} + \frac{Q_I L}{k\varepsilon_0}$$

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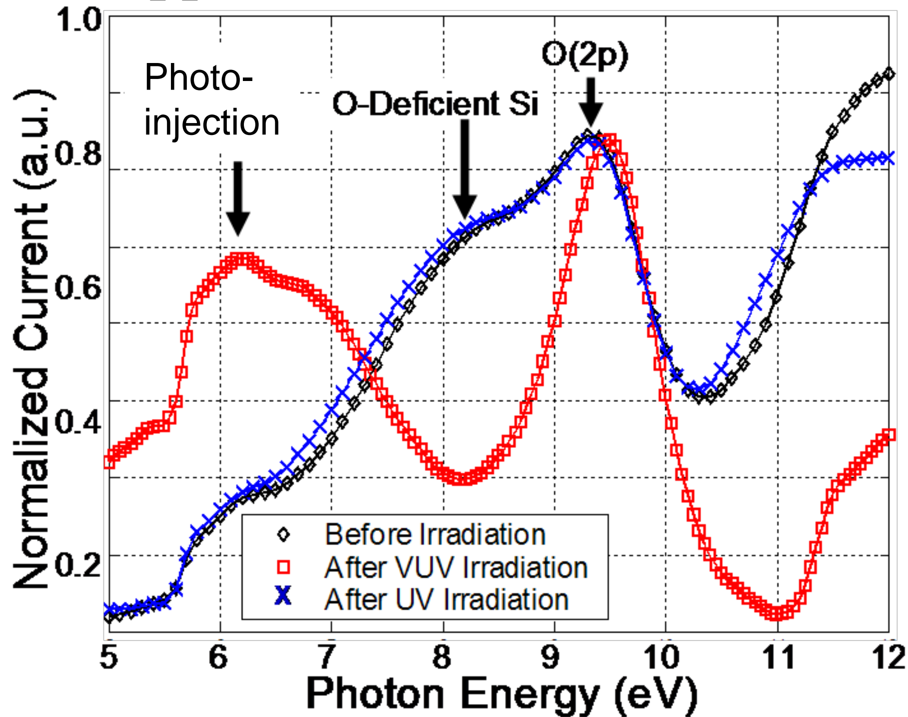
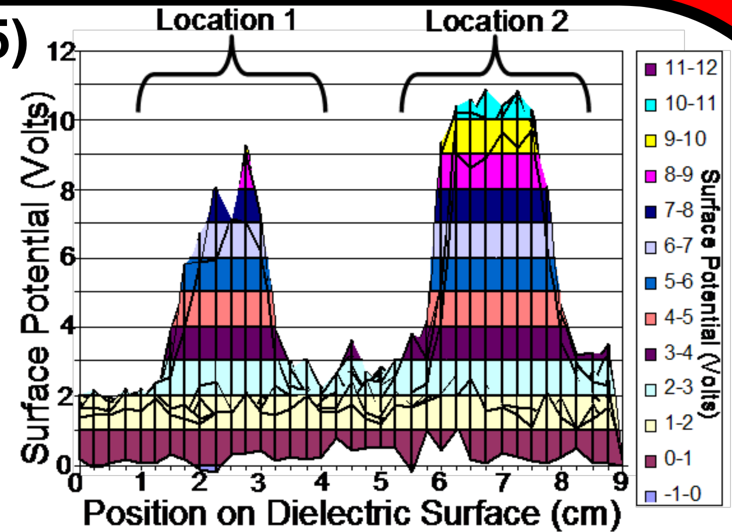
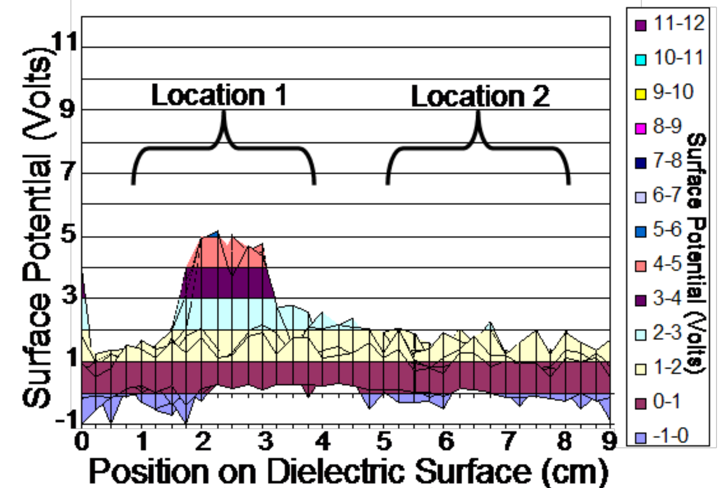
VUV and UV Irradiation

500 nm SiOCH (k = 2.55)

- The peak at 7.6 eV decays after VUV irradiation, however reappears after UV irradiation.







- The surface potential becomes positive after VUV irradiation, however will return to its original background potential after UV irradiation.

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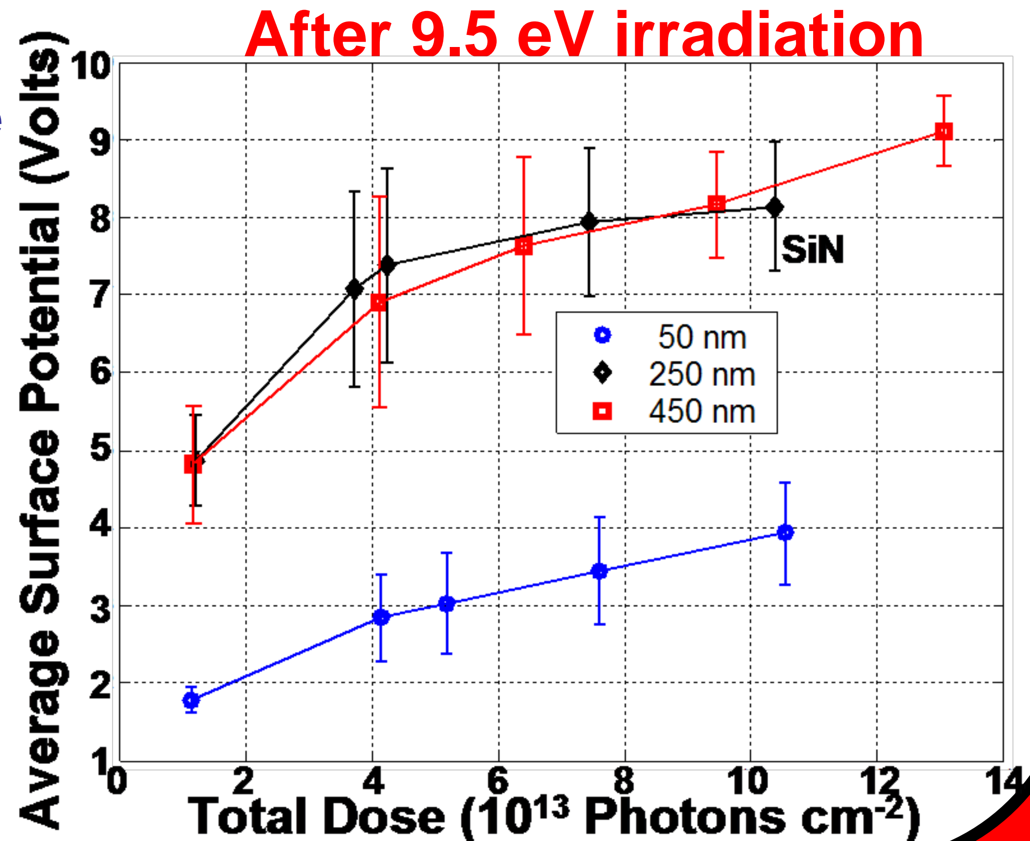
Charging Response of SiN to VUV

- The surface potential on the SiN layer does not change as the dielectric thickness is increased from 250 to 450 nm.
  - Most of the trapped charge must be located near the SiN/Si interface.

Surface Charge **Bulk Charge** **Interface Charge**

$$V_{SP} = \frac{Q_S d}{k\varepsilon_0} + \frac{Q_B d^2}{k\varepsilon_0} + \frac{Q_I L}{k\varepsilon_0}$$

After 9.5 eV irradiation



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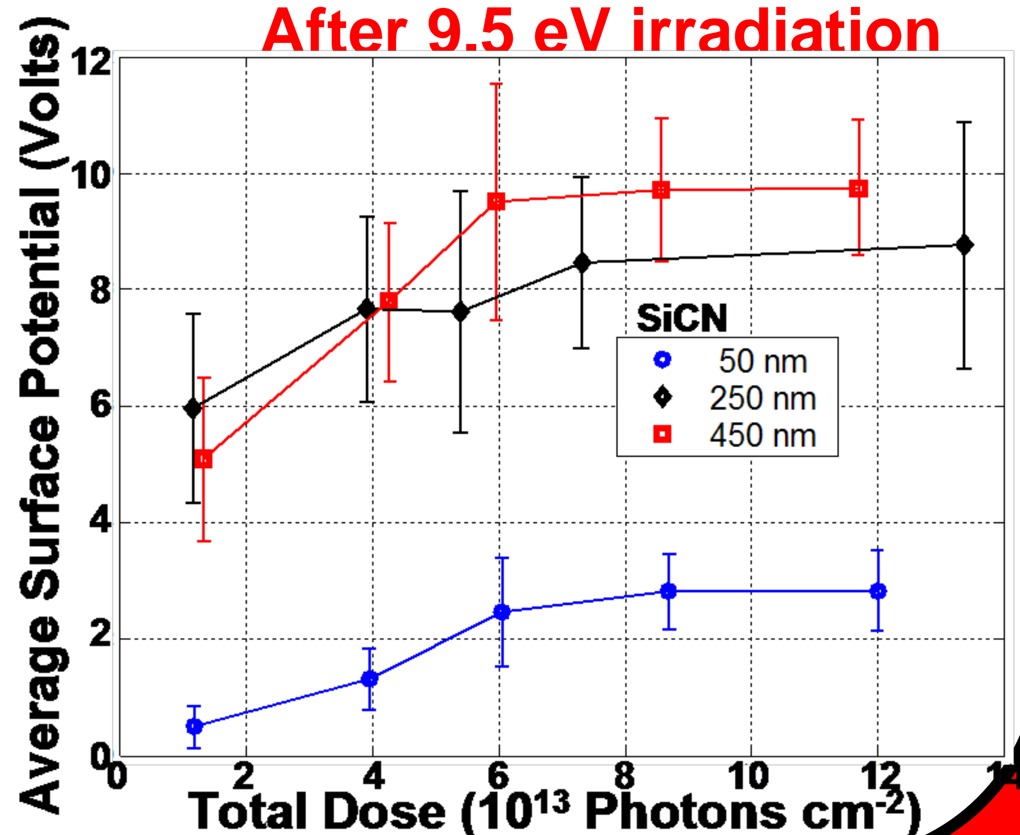
Charging Response of SiCN to VUV

- There is a slight increase in the surface potential between 250 and 450 nm of SiCN.
  - This suggest that there maybe some trapped charge within the bulk or at the surface of the SiCN dielectrics.

Surface Charge | **Bulk Charge** | **Interface Charge**

$$V_{SP} = \frac{Q_S d}{k\varepsilon_0} + \frac{Q_B d^2}{k\varepsilon_0} + \frac{Q_I L}{k\varepsilon_0}$$



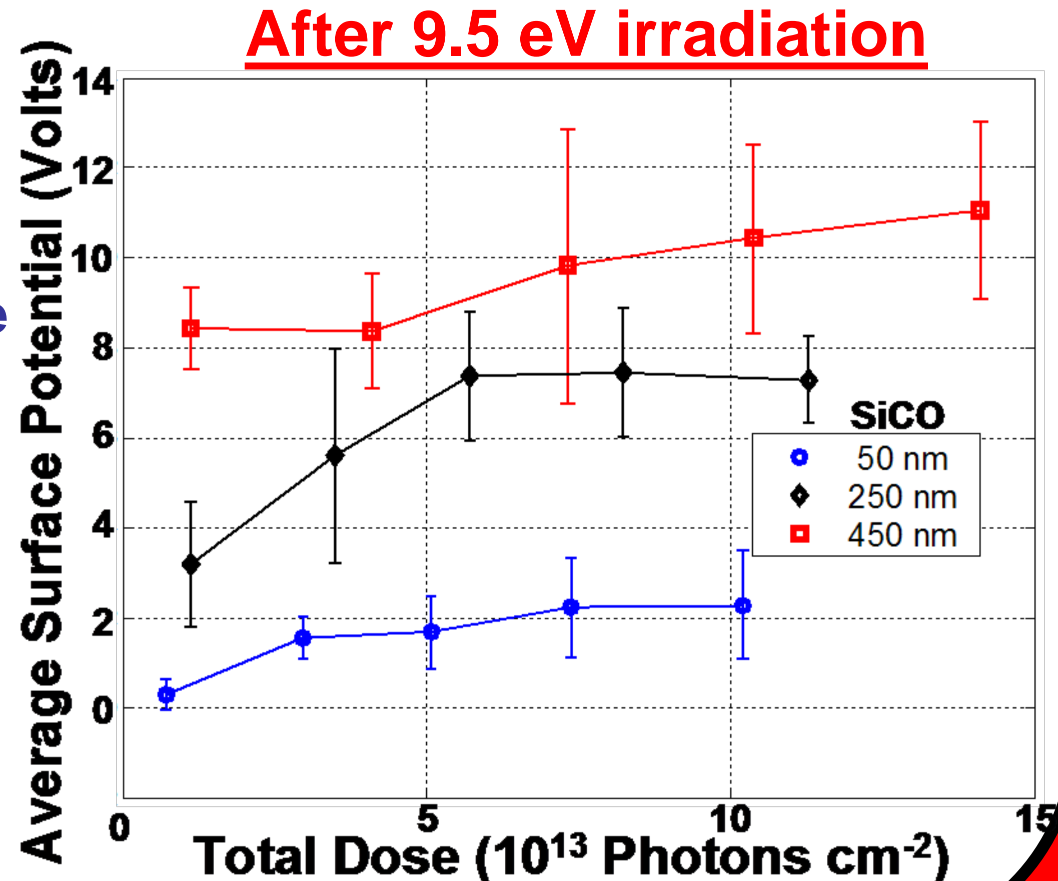
Charging Response of SiCO to VUV

- The SiCO dielectric appears to have trapped charge located at the surface or within the bulk of the dielectric layer.

Surface Charge **Bulk Charge** **Interface Charge**

$$V_{SP} = \frac{Q_S d}{k\varepsilon_0} + \frac{Q_B d^2}{k\varepsilon_0} + \frac{Q_I L}{k\varepsilon_0}$$

After 9.5 eV irradiation



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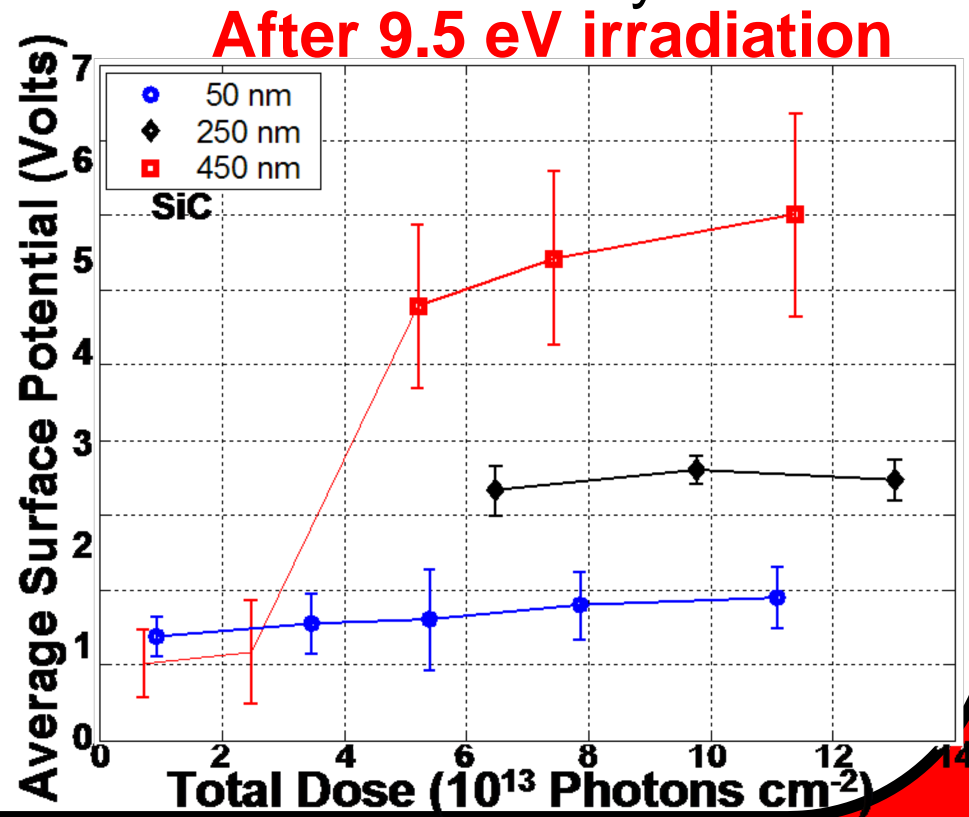
Charging Response of SiC to VUV

- The surface potential is much smaller on the SiC dielectrics compared to the other dielectrics for the same dielectric thicknesses and photon dose.
- The SiC dielectric appears to have trapped charge located at the surface or within the bulk of the dielectric layer.

Surface Charge **Bulk Charge** **Interface Charge**

$$V_{SP} = \frac{Q_S d}{k\varepsilon_0} + \frac{Q_B d^2}{k\varepsilon_0} + \frac{Q_I L}{k\varepsilon_0}$$

After 9.5 eV irradiation



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Conclusions (SiOCH)

- We determined the valence-band structure of low-*k* porous-SiOCH (*k* = 2.55) dielectrics
  - Band gap of 9.0 eV with the valence band edge defined by the O(2p) states.
  - Electronic states due to O-deficient Si centers are located 1.4 eV above the valence-band edge.
  - The O-deficient Si centers are responsible for most of the accumulation of positive charge within the SiOCH dielectric after VUV irradiation.
- The trapped positive charge due to VUV irradiation can be annealed with UV.

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Conclusions (SiN, SiCO, SiCN, SiC)

- The SiN dielectrics have trapped positive charge located mostly near the SiN/Si interface.
- The SiCN and SiCO dielectrics have trapped positive charge located at the dielectric-substrate interface as well as within the bulk and/or on the surface of the dielectric.
  - The SiCO dielectric has the largest surface potential compared to the other dielectrics for the same thickness and photon dose.
- The SiC dielectric had the lowest surface potential compared to the other dielectrics.
  - Most of the trapped charge is located at the surface or within the bulk of the SiC dielectrics.

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Conclusions (Plasma Irradiation)

- From this work, since plasmas generate both UV and VUV, there is a tradeoff between charging and discharging of trapped states.
- By suitably optimizing or supplementing the spectrum of the emitted radiation, it is possible to significantly affect the amount of trapped charge.