

# High-k transition metal elemental and complex oxides: engineering options for implementation into nano-CMOS devices

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The end of an era has passed, and SiO<sub>2</sub> is no longer a viable gate dielectric for advanced Si devices. This is a result of the Moore's Law requirement for scaling-down the effective oxide thickness, EOT, to <1.0 nm where tunneling leakage  $\sim 100 \text{ A-cm}^{-2}$  is detrimental to CMOS circuit operation. Transition metal oxides, e.g., HfO<sub>2</sub>, have emerged as candidates for nano-scale devices with EOT reduced to <1 nm. The HfO<sub>2</sub> dielectric constant permits significant increases in physical thickness, so that tunneling currents can be reduced to meet semiconductor roadmap targets. However other factors, such as 10-50 fold increases in electron and hole trapping have forced several companies to cancel plans to introduce HfO<sub>2</sub> dielectrics in 2007.

Nanocrystalline HfO<sub>2</sub> displays significant asymmetries for hole and electron trapping, and these can degrade operation of CMOS ICs. Spectroscopic studies have demonstrated that these traps are intrinsic to nanocrystalline HfO<sub>2</sub>, and other high-k dielectrics as well. Studies that combine laboratory vacuum ultra-violet spectroscopic ellipsometry, and photo-conductivity, with synchrotron soft x-ray absorption and photoemission spectroscopies, have demonstrated that the intrinsic defects are O-atom vacancies clustered on nanocrystalline grain boundaries.

Two engineering solutions have emerged and offer pathways to aggressive scaling. Spectroscopic studies, combined with electrical measurements, have demonstrated that i) clustered O-vacancies are not intrinsic defects in non-crystalline Hf/Zr Si oxynitride alloys, and ii) clustered vacancy defects can be chemically passivated in ultra-thin HfO<sub>2</sub> dielectrics. These two dielectrics, subject to development of stable gate metals, can meet semiconductor roadmap requirements for the 32 nm node in 2010, and future generations of nano-CMOS devices as well. As such, spectroscopic studies, coupled with advances in gate metal processing, have the potential to provide a science base to carry nano-scale CMOS devices well into the 21st century.

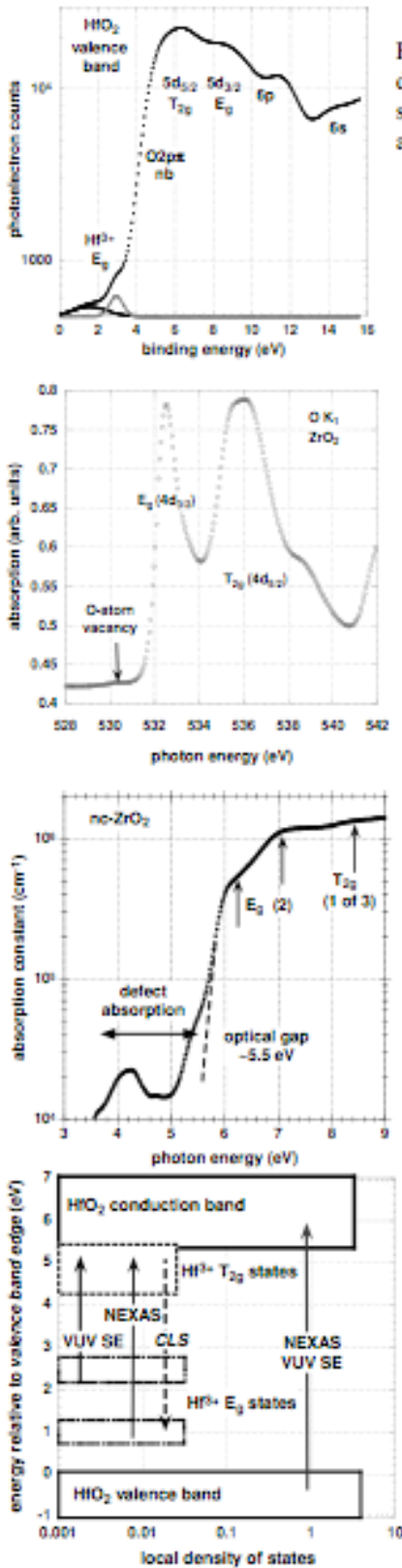


Fig.1 Top - SXPS valence band spectrum for HfO<sub>2</sub> with band edge defect center for hole trapping. Upper Middle - NEXAS OK1 spectrum for ZrO<sub>2</sub> indicating band edge defect for electron trapping and transport.

Fig. 3 (a) FTIR and (b) derivative O1s XPS for low content Si<sub>3</sub>N<sub>4</sub> Zr Si oxyntirde alloy and (c) FTIR and (d) derivative O1s XPS for high content Si<sub>3</sub>N<sub>4</sub> Zr Si oxyntirde alloy.

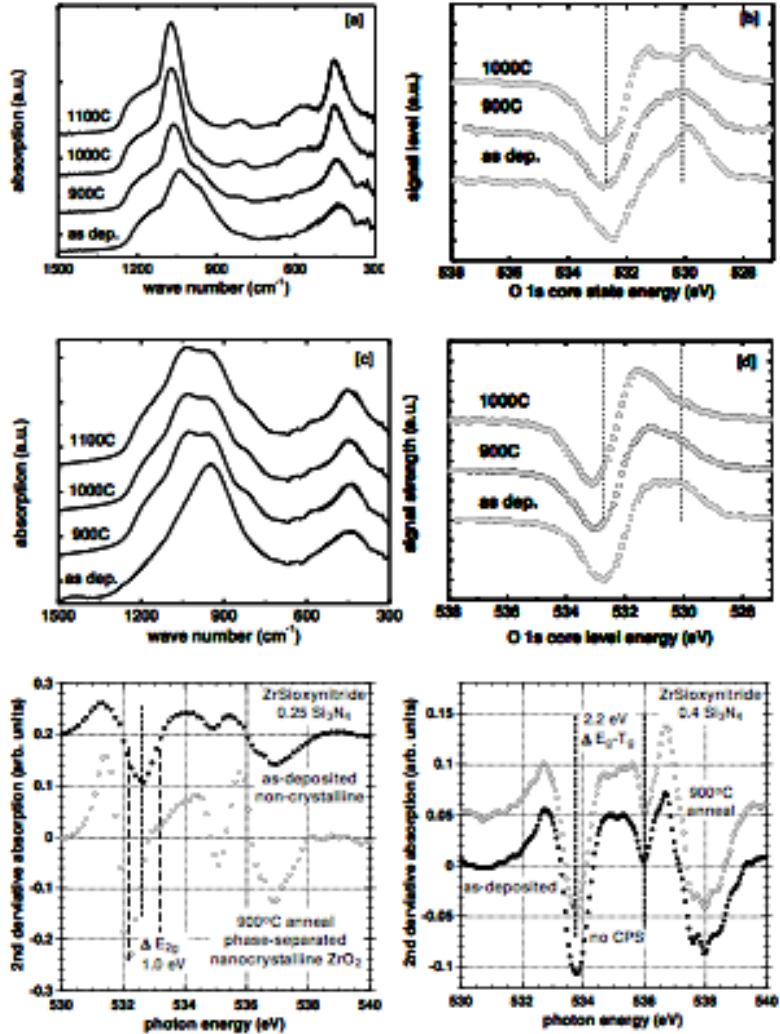


Fig. 4 2nd derivative NEXAS for low and high content Si<sub>3</sub>N<sub>4</sub> Zr Si oxyntirde alloys.

Fig.2 Lower Middle - VUV SE absorption constant spectrum indicating band edge defect states for ZrO<sub>2</sub>. Bottom: Electronic band edge structure of HfO<sub>2</sub> (and ZrO<sub>2</sub>) indicating defect states above the valence band edge, and below the conduction band edge.