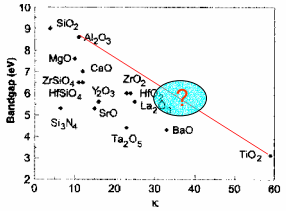
Investigation of Hybrid $TiAlO_x$ as Alternative High-k Gate Dielectric

W. Fan[a,b], O. Auciello[a], J.A. Carlisle[a], S. Saha[a], B. Kabius[a], J.M. Hiller[a], S.Y. Li[b], V.P. Dravid[b], and R.P.H. Chang[b]
a) Materials Science Division, Argonne National Laboratory, Argonne, IL 60439
b) Department of Materials Science and Engineering, Northwestern University, Evanston, IL 60208

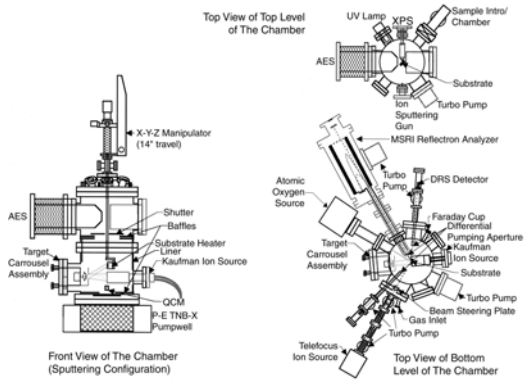
Advantages of $TiAlO_x$ as Gate Dielectric

- High dielctric constant
  $\varepsilon_r = 30 >> \varepsilon_{SiO2} = 3.9$
- Amorphous structure
- Low leakage
- Low oxide formation energy
  Ti (-210 kcal/g·mol O_2)
  Al (-226 kcal/g·mol O_2)
  Si (-192 kcal/g·mol O_2)



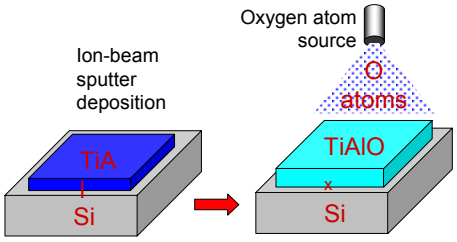
J. Robertson, *MRS Bulletin*, March 219 (2002).

In-situ Thin Film Synthesis & Analysis System



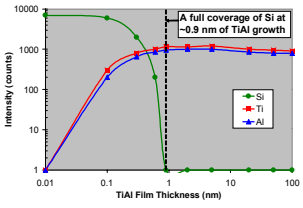
Unique integrated sputter-deposition / time of flight ion scattering and recoil spectroscopy (ToF-ISARS) / X-ray photoelectron spectroscopy (XPS) system for *in-situ* studies of oxide film growth and interface processes with nanoscale resolution

In-situ study of $TiAlO_x$ Layer Growth



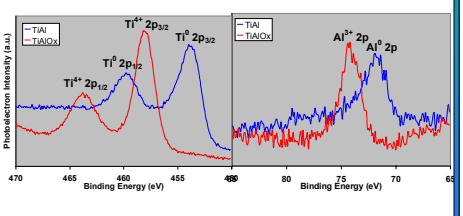
Ultra-thin (3-20 nm) $TiAlO_x$ layers produced by oxidation of TiAl thin films with atomic oxygen

Mass spectrum of TiAl/Si



In-situ MSRI shows complete coverage of Si substrate at ~0.9 nm of TiAl layer growth

XPS of TiAl before and after R.T. oxidation

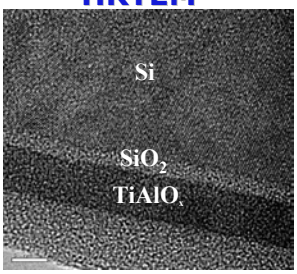


TiAl layer fully oxidized withatomic oxygen at RT

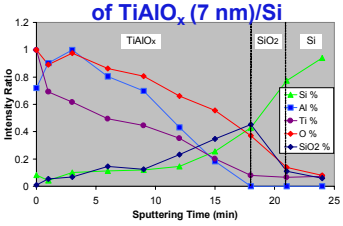
SiO_x Interface Formation

- Uniform $TiAlO_x$ layer along Si surface
- Amorphous $TiAlO_x$ structure
- ~1 nm thin SiO_x interface formation at 500°C
- SiO_x interface layer practically eliminated by RT oxidation of TiAl layer with atomic oxygen

HRTEM



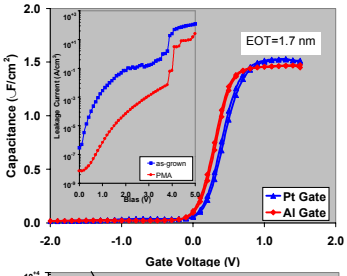
XPS depth profile of $TiAlO_x$ (7 nm)/Si

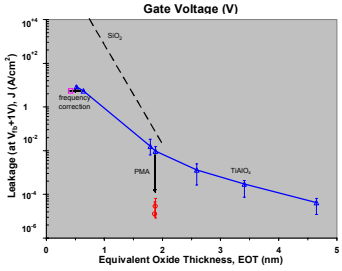


Reduced SiO_x interface formation primarily due to:

- lower Gibbs free energy oxide formation of TiO_2 and Al_2O_3 than for SiO_2
- excellent barrier properties of $TiAlO_x$ with its amorphous structure

Electrical Performance





- $TiAlO_x$ (7 nm) layer grown at 500 °C with 1 nm SiO_x interface shows EOT = 1.7 nm
- SiO_x interface layer suppressed by R.T. oxidation of TiAl
- Very low EOT (0.42-0.48 nm) achieved on 4 nm $TiAlO_x$ layer by RT oxidation.
- Negligible hysteresis behavior in C-V curve
- Low dielectric leakage ~ 10^{4-5} times lower than for SiO_2

Summary

- First ultra-thin $TiAlO_x$ dielectric layers with high permittivity (~ 30) and low leakage demonstrated
- Fully oxidized amorphous $TiAlO_x$ layer produced in wide range of temperature (25 °C to 700 °C) using atomic oxygen
- Formation of SiO_x interface layer as thin as 1 nm with 500 °C oxidation, and suppressed for RT oxidation with atomic oxygen
- EOT <0.5 nm obtained for 4 nm $TiAlO_x$ layer (lowest EOT of high-k layer reported today.
- Leakage current of $TiAlO_x$ layer ~ 10^{4-5} times lower than for SiO_2 layer with similar EOT

O. Auciello, US patent pending (2003)

BES - DOE

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