Max-Planck-Institut
für Plasmaphysik

Quaternary tungsten-based alloys as plasma-facing material for fusion reactors

Christian Linsmeier

F. Koch, C. Lenser, M. Balden, M. Rasinski

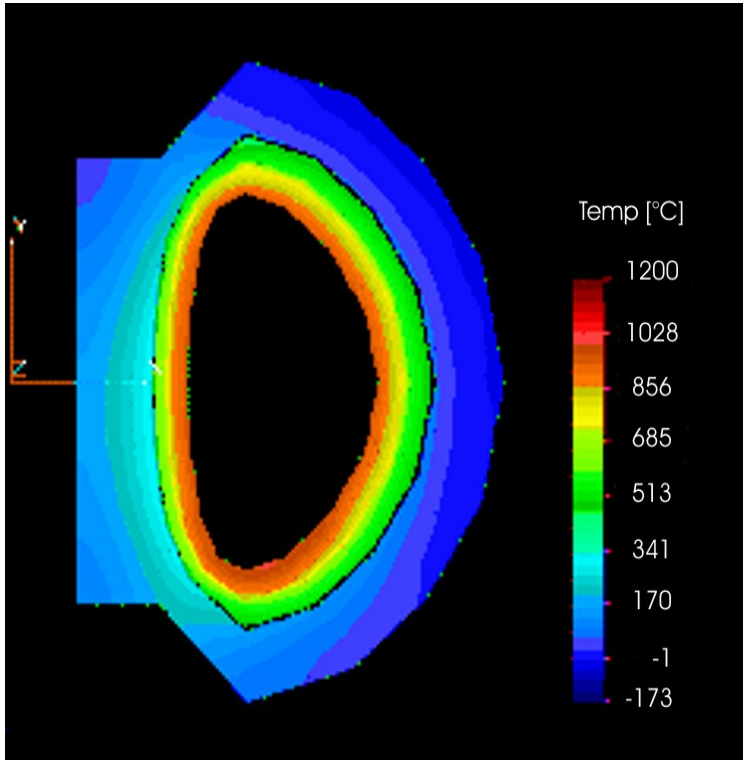
Max-Planck-Institut für Plasmaphysik, Garching b. München, Germany

Outline

- Applications: DEMO (and ITER)
- Self-passivation mechanism
- Characterization of quaternary alloys
- Summary

Accidential loss of coolant in reactor

Power plant conceptual study



Temperature profile in PPCS Model A, 10 days after accident with a total loss of all coolant.

[Final Report of the European Fusion Power Plant Conceptual Study, 2004]

- Accidental loss of coolant: peak temperatures of first wall up to 1200 °C due to nuclear afterheat
- Additional air ingress: formation of highly volatile WO_3
- Evaporation rate: order of 10 -100 kg/h at >1000°C in a reactor (1000 m^2 surface)
  → large fraction of radioactive WO_3 may leave hot vessel

→ Development of self-passivating tungsten alloys

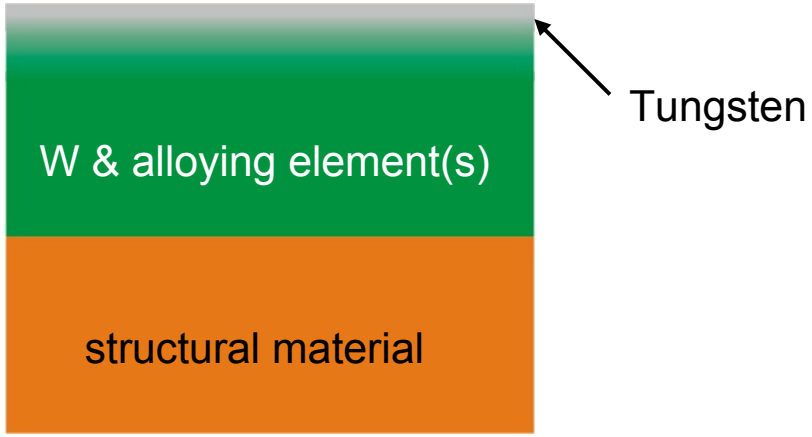
Idea: Tungsten alloys

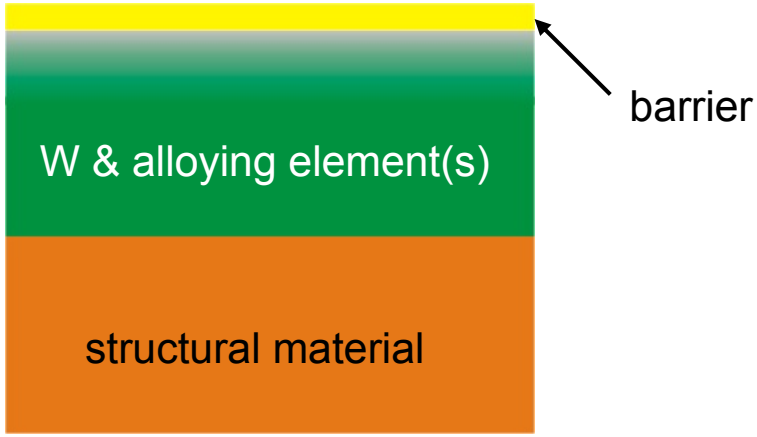
Self passivating tungsten-based alloys:

Surface composition automatically adjusts to the requested property

Normal operation (600°C)**:**
Formation of tungsten surface by depletion of alloying element(s) due to preferential sputtering

Accidental conditions:
(air ingress, up to 1200 °C)
Formation of protective barrier layer





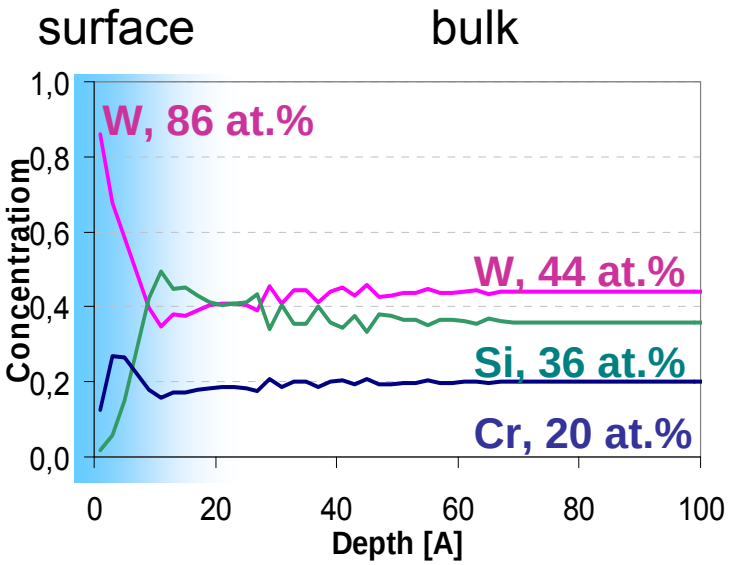
Idea: Tungsten alloys

Self passivating tungsten-based alloys:

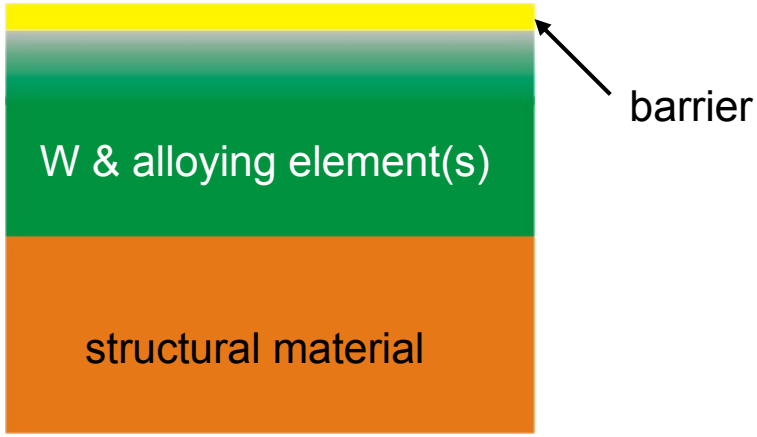
Surface composition automatically adjusts to the requested property

Normal operation (600°C)**:**

TRIDYN numerical simulation of sputter erosion of W-Si-Cr alloy (D ions, 30 eV, fluence 10^{18}/cm²)



Accidental conditions:
(air ingress, up to 1200 °C)
Formation of protective barrier layer



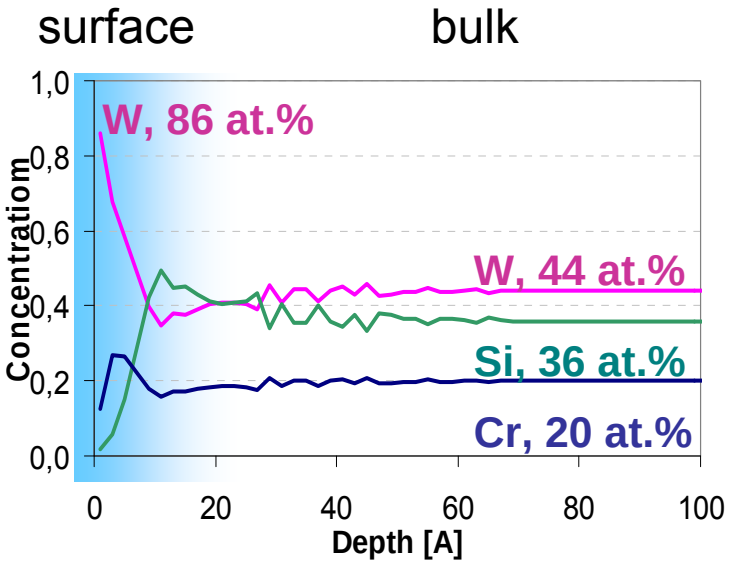
Idea: Tungsten alloys

Self passivating tungsten-based alloys:

Surface composition automatically adjusts to the requested property

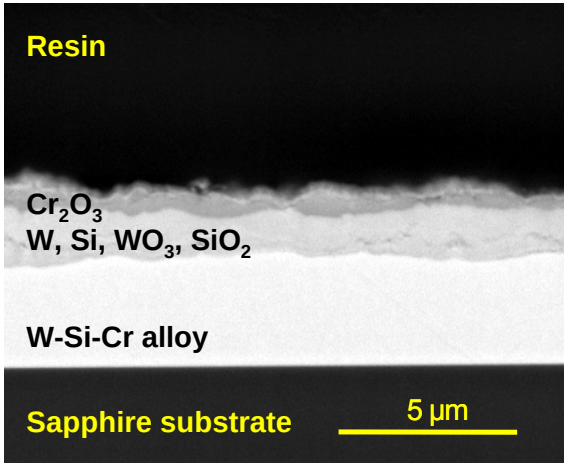
Normal operation (600°C)**:**

TRIDYN numerical simulation of sputter erosion of W-Si-Cr alloy (D ions, 30 eV, fluence 10^{18}/cm²)



Accidental conditions:

Cross section of sputter deposited W-Si-Cr film after oxidation at 1000°C for 1h



Quaternary tungsten based alloys

Addition of reactive elements to W-Si-Cr to improve oxide film formation and adherence

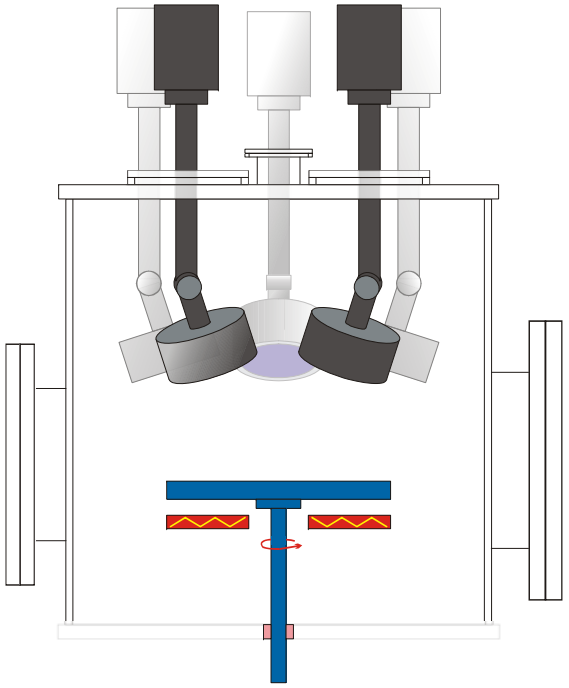
Co-deposition by Magnetron Sputtering

- Film thickness ~ 4µm
- SiO_2 and Al_2O_3 substrates used for oxidation

Investigated systems

- W-Si-Cr-Zr
- W-Si-Cr-Y

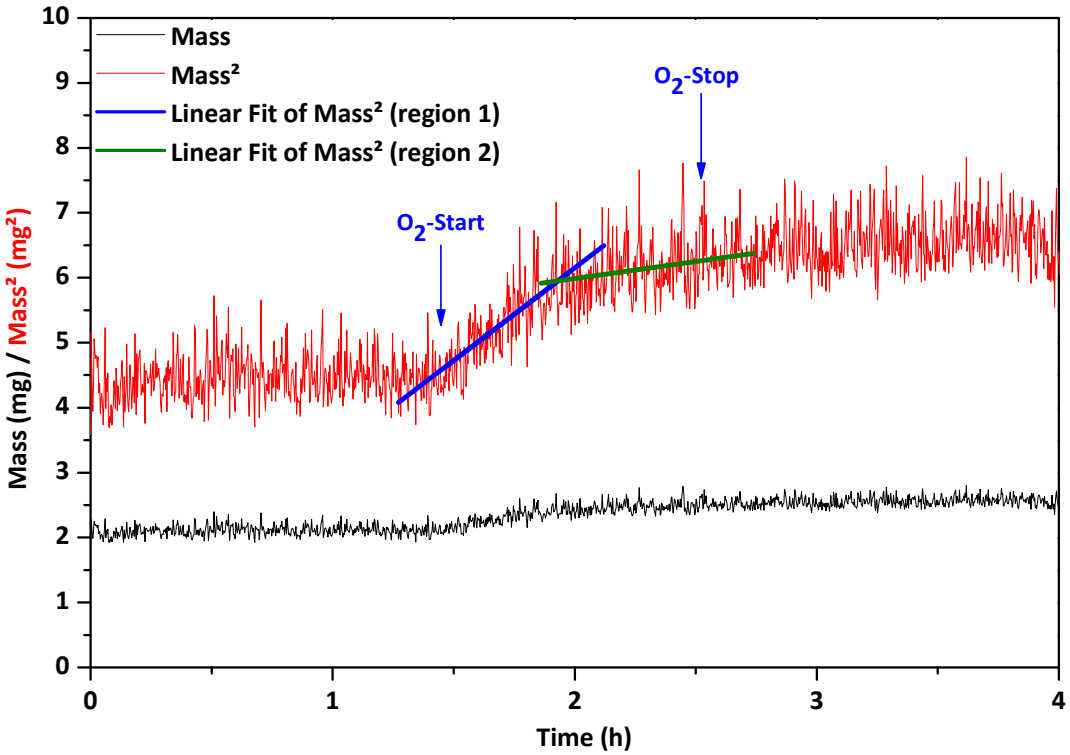
(different concentrations)



Schematic view of deposition facility

Oxidation experiments

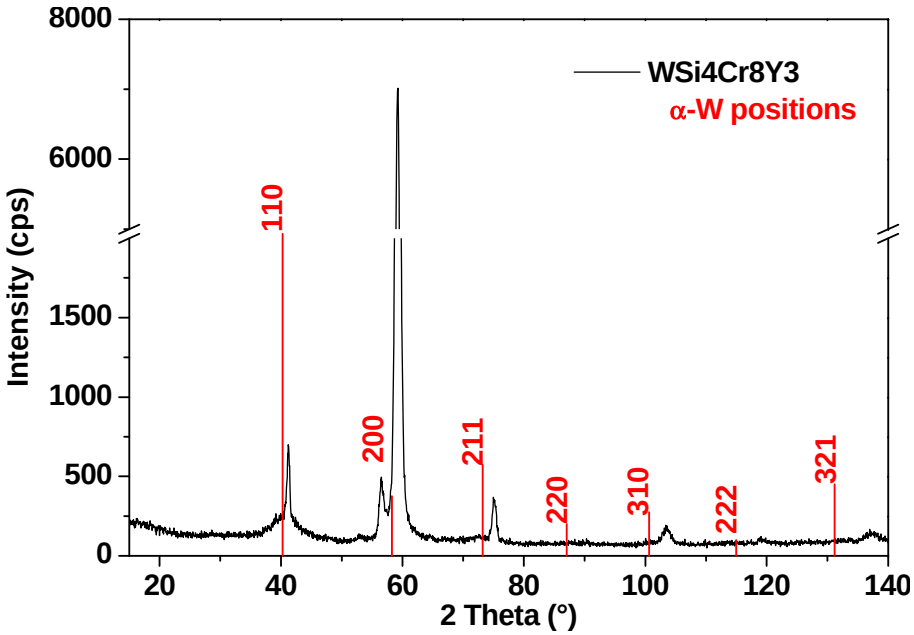
Oxidation of W-Si4-Cr8-Y3 at 1000°C for 1 hours



- Heating under inert gas flow
- Start of oxygen at stable temperature

- Parabolic oxidation rates: $(\Delta m)^2 = k\ t$: → Diffusion-governed process
- Two distinct oxidation rates

XRD analysis: alloys as deposited



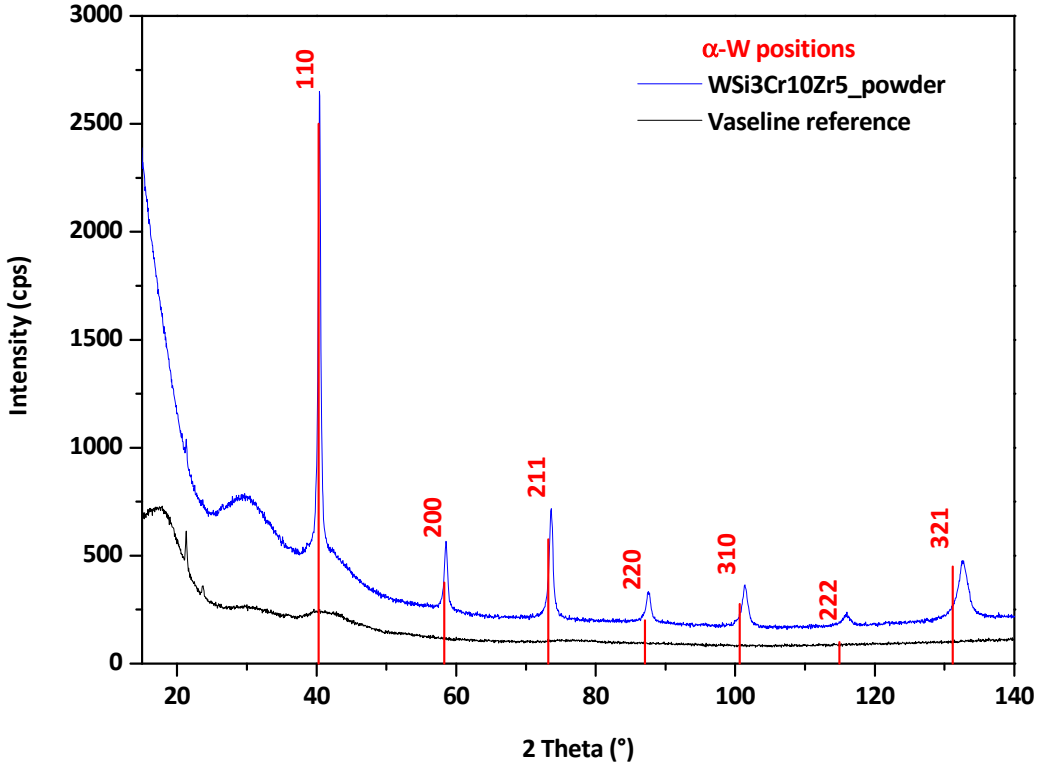
Peak shift due to Lattice Distortion

d	*2θ*	*h*	*k*	*l*
Angström	°			
2,2976	39.177	1	1	0
2,1922	41.1438	1	1	0
1,5567	59.3162	2	0	0
1,3043	72.3989	2	1	1
1,2668	74.8987	2	1	1
0,9823	103.2851	3	1	0
0,8283	136.8753	3	2	1

- Fifth order polynomial by Gust *et* al. used to calculate W concentration in assumed binary W-Cr lattice
- *c*(Cr) = 27.5 at-% from peak shift; *c*(Cr) = 29.2 at-% from RBS

Gust, W.; Predel, B.; Roll, U.: Journal of the Less-Common Metals, 69, pp. 331-353, 1980

XRD analysis: annealed alloys



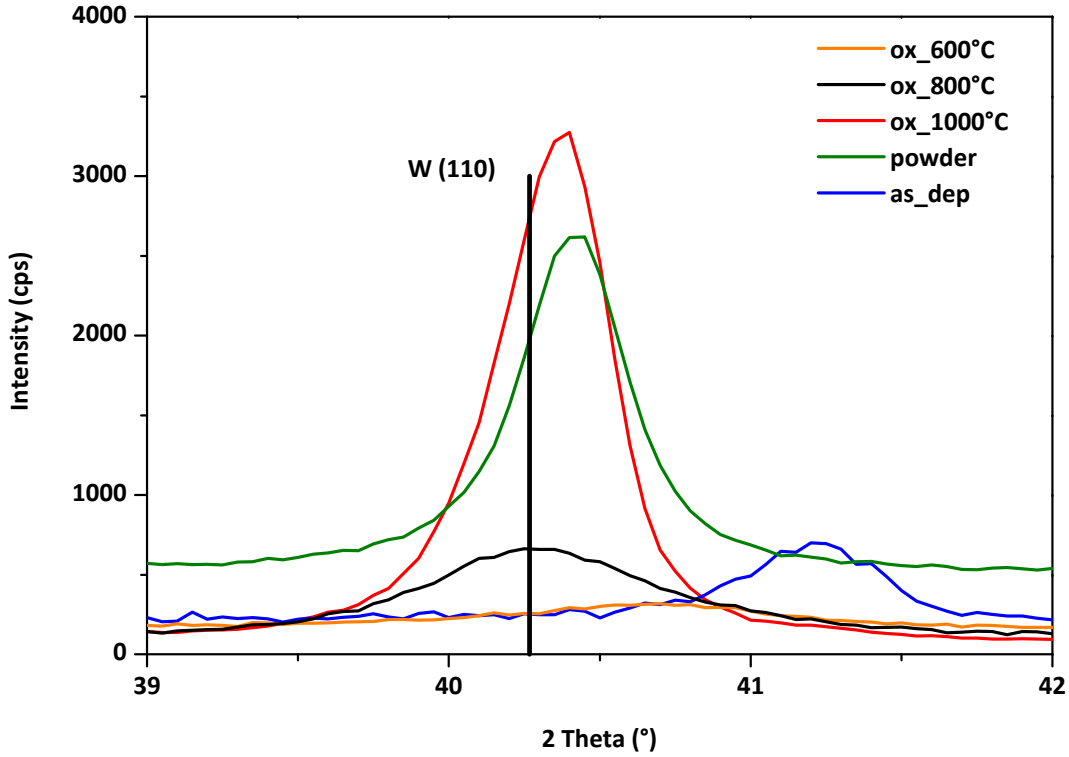
WSi3Cr10Zr5 powder

(annealed at 1000 °C under Ar)

- *c*(Cr) = 24 at-% after deposition (RBS); *c*(Cr) = 6.75 at-% after annealing
- Thermodynamic equilibrium: *c*(Cr) = 7 at-% (Gust et al.)
- Cr precipitates from the binary lattice

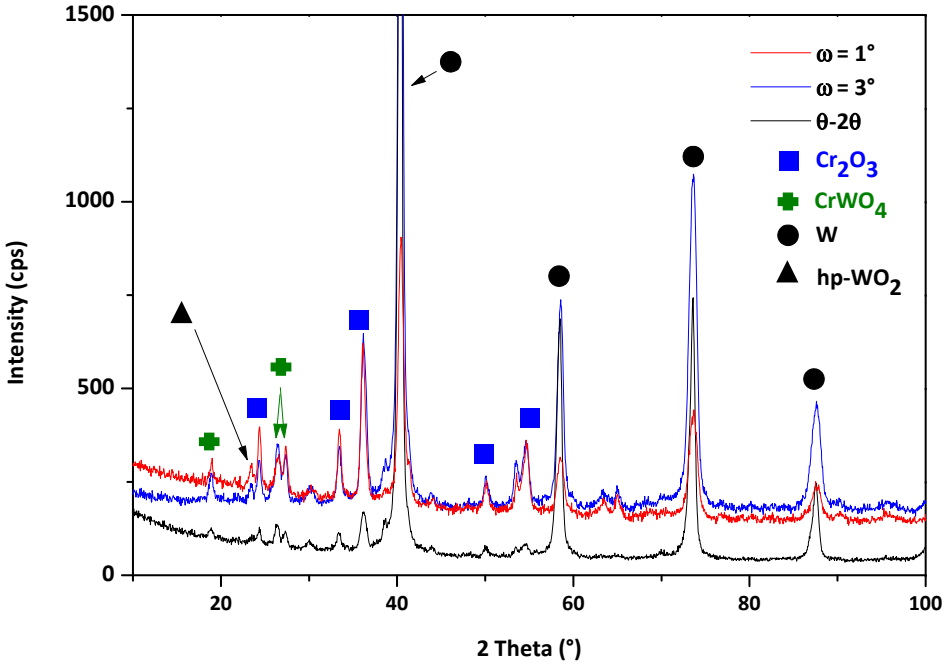
XRD analysis: oxidized alloys

WSi3Cr10Zr5



- Lattice shows strongest distortion after deposition
- Equilibrium concentration of Cr in W lattice is reached at 800°C and 1000°C, but not at 600°C
- Powder has virtually the same peak shift as film -> not stress-related

XRD analysis: oxidized alloys



WSi3Cr10Zr5 (oxidized 1h at 1000 °C)

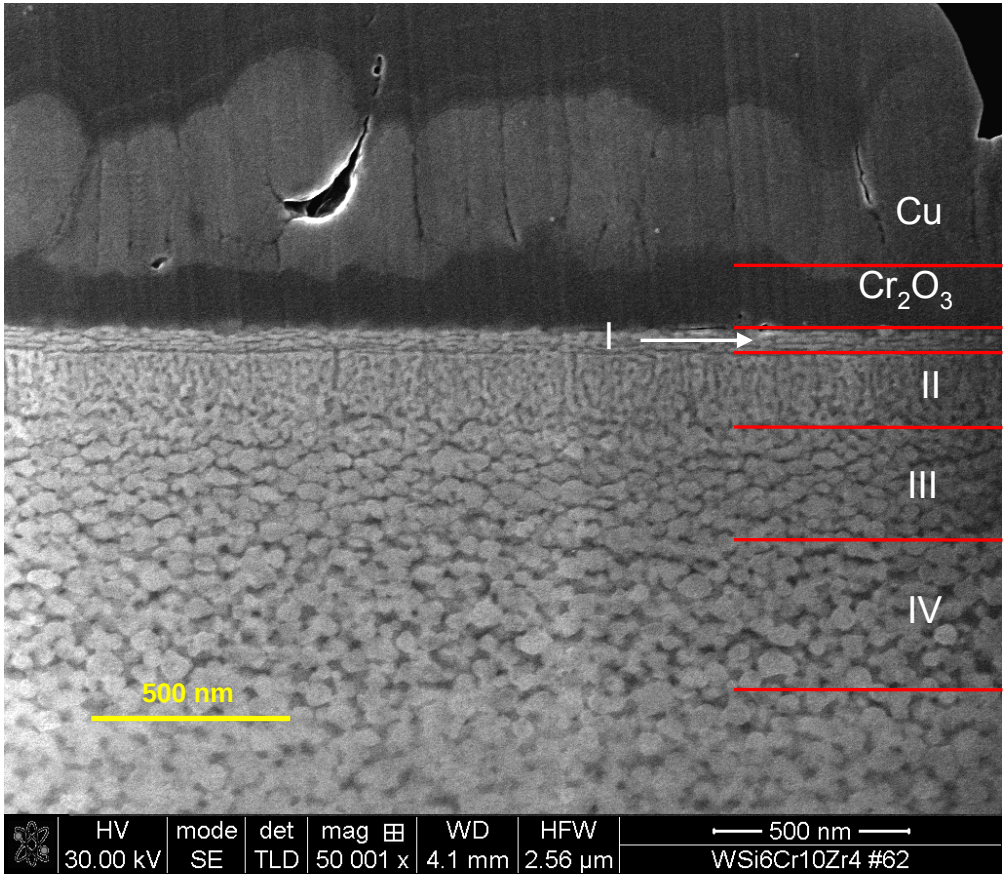
Phases identified by XRD

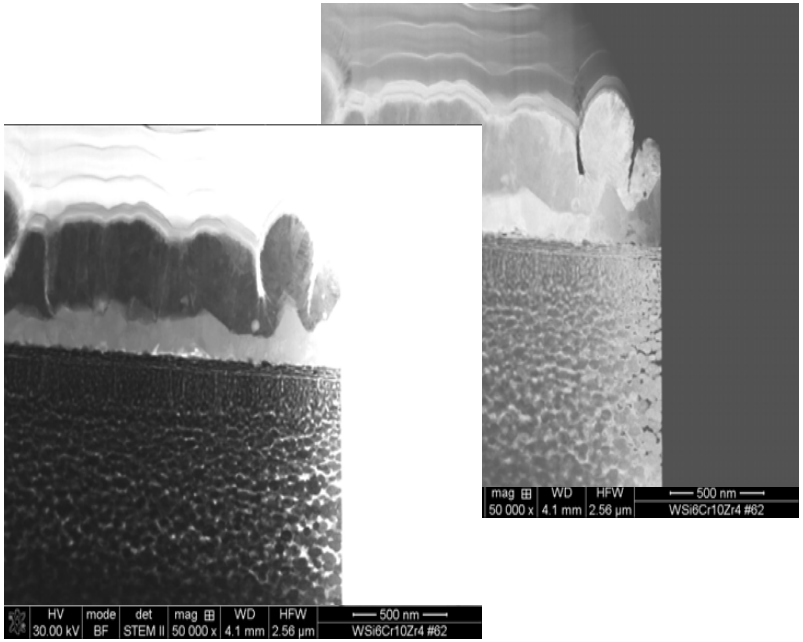
Ox. temp.	600°C	800°C	1000°C
Ox. time	48 h	4 h	1 h
	Cr_2O_3	Cr_2O_3	Cr_2O_3
	$CrWO_4$	$CrWO_4$	$CrWO_4$
	W	W	W
	WO_2	WO_2	
	hp-WO_2	hp-WO_2	hp-WO_2
	$ZrSiO_4$		

→ **no volatile WO_3 formed!**

Microstructure of oxidized alloys

WSi3Cr10Zr5:



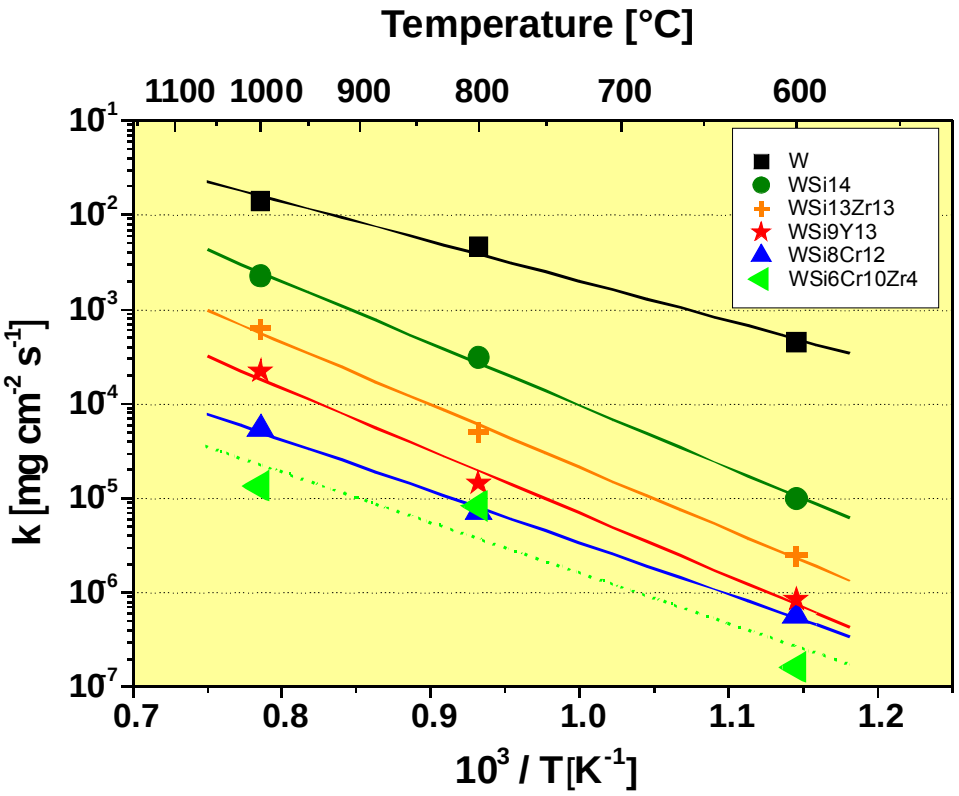


- Dense Cr_2O_3 barrier scale
- Cr is main diffusing species
- Mixed oxide zone(s)
- Cr depletion zone with voids
- No formation of WO_3

SEM of cross section (FIB), 1000°C, 1h

Comparison of oxidation results

Arrhenius plot of oxidation rates of tungsten and tungsten alloys



Oxidation rate (k) has been calculated from weight increase versus time, linear fit.

Alloy	W	Si	Cr	Zr
WSi8Cr12	46	30	24	-
WSi3Cr10Zr5	56	13	24	7

Composition in at.%

Linear oxidation rates of W-Si-Cr & quaternary alloys comparable.

Quaternary alloys show distinct parabolic oxidation behavior at reduced level of alloying elements.

Summary

Conclusions quaternary alloys:

- Quaternary alloys show better passivation behavior than ternary while containing more W
- Active elements (Y/Zr) do not form oxide layers, but improve oxide scale adhesion
- Surface oxide consists of Cr_2O_3
- Oxide phases formed are Cr_2O_3, $WCrO_4$, WO_2 (2 modifications), $ZrSiO_4$ (600°C), but no WO_3 → passivation successful
- Two step-oxidation: switch in oxidation mechanism during oxidation
- Different oxidation mechanisms at different temperatures
- Restructuring induced by the precipitation of Cr from the W lattice