GDOES depth profile analysis for the investigation of the thermal stability and the degradation mechanisms of Ta based diffusion barriers for Cu metallization systems

René Hübner [1], Michael Hecker [1], Volker Hoffmann [1], Hans-Jürgen Engelmann [2], Henning Heuer [3], and Klaus Wetzig [1]

[1] *Leibniz Institute for Solid State and Materials Research Dresden*
[2] *AMD Saxony LLC & Co. KG Dresden*
[3] *Dresden University of Technology*

11. GDS-Anwendertreffen, Dresden, September 13-14, 2004

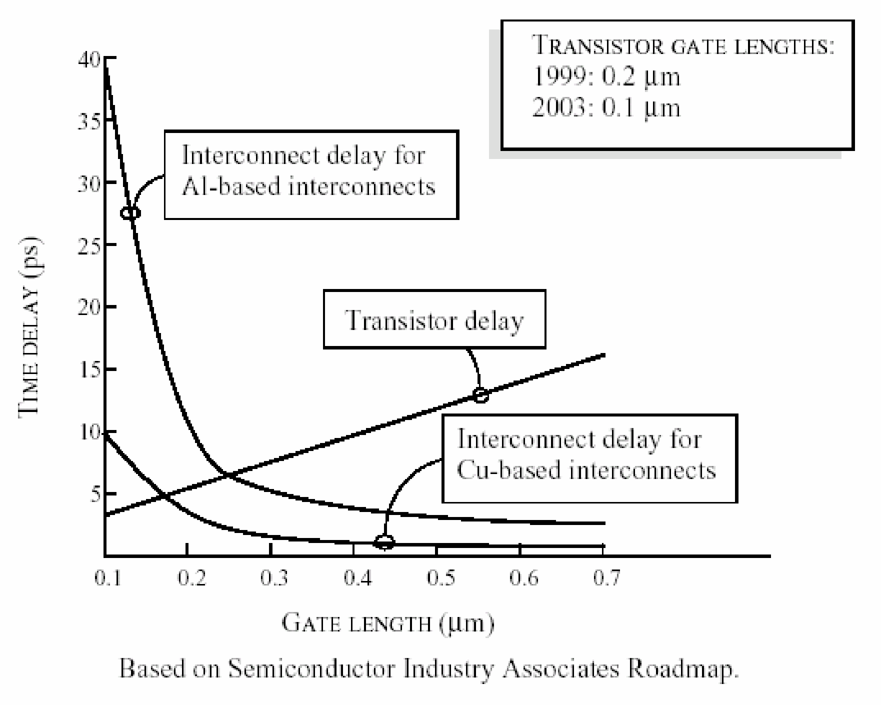
Outline

1. Motivation of the investigations
2. Sample preparation and investigation methods
3. Thermal behavior of various metallization systems during annealing:

   $Cu/Ta/SiO_2/Si$
   $Cu/TaN/SiO_2/Si$
   $Cu/Ta/TaN/Ta/SiO_2/Si$
   $Cu/Ta_{73}Si_{27}/SiO_2/Si$

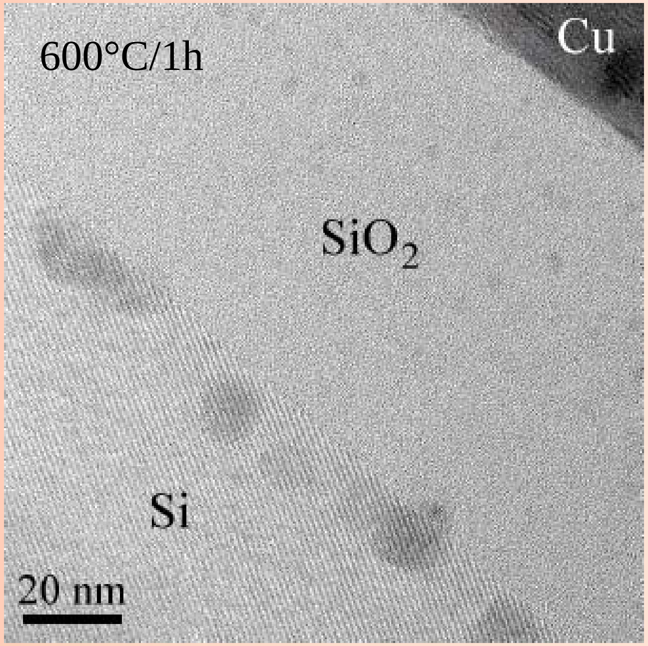
4. Summary

Advantages and disadvantages of copper as interconnect material



Based on Semiconductor Industry Associates Roadmap.

Cu/SiO$_2$/Si - TEM



Compared to aluminum:

- ☺ Lower electrical resistivity
- ☺ Higher thermal conductivity
- ☺ Higher electromigration resistance
- ☺ Better stress migration behavior

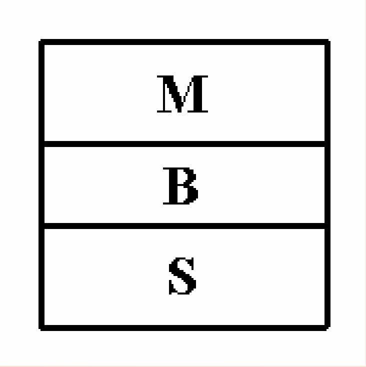
- ☹ High diffusivity of Cu in Si and SiO_2
- ☹ Cu_3Si formation at $T \approx 200$°C

⇒ Need for diffusion barriers between Cu and interlayer dielectric

IFW
Leibniz Institute for Solid State and Materials Research Dresden *René Hübner*

Barrier layer requirements

- Defect-free microstructure of B and its thermal stability
- Low diffusion coefficients of M in B and of S in B
- High chemical stability of the interfaces between M and B as well as between S and B
- High electrical conductivity of B
- High thermal conductivity of B
- Good adhesion of B on S as well as of M on B
- Good mechanical properties (low residual stresses)
- Conformal deposition of B



Tantalum diffusion barriers:

☺ High melting point ($T_{m,Ta}$ = 3020 °C)

☺ High chemical stability of Ta/Si and Ta/SiO_2 interfaces

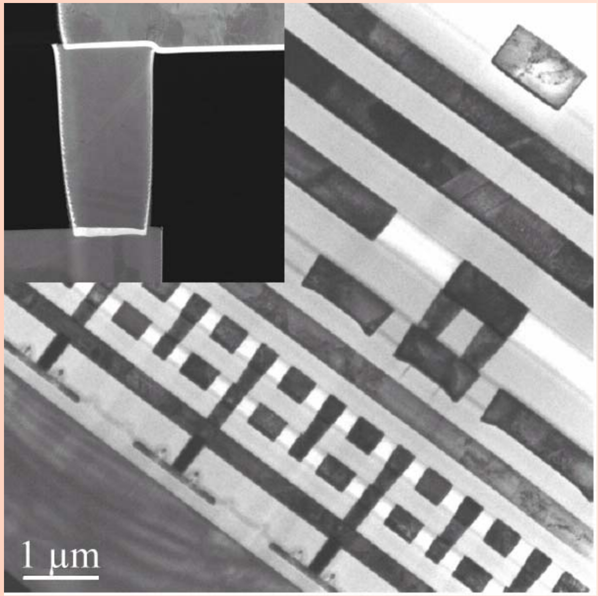
☺ Very low solubility of Cu in Ta and vice versa

☺ No reaction between Cu and Ta

☺ High electrical conductivity (especially for α-Ta phase)

☹ Polycrystalline microstructure ⇒ Cu diffusion

⇒ Need for more stable diffusion barriers

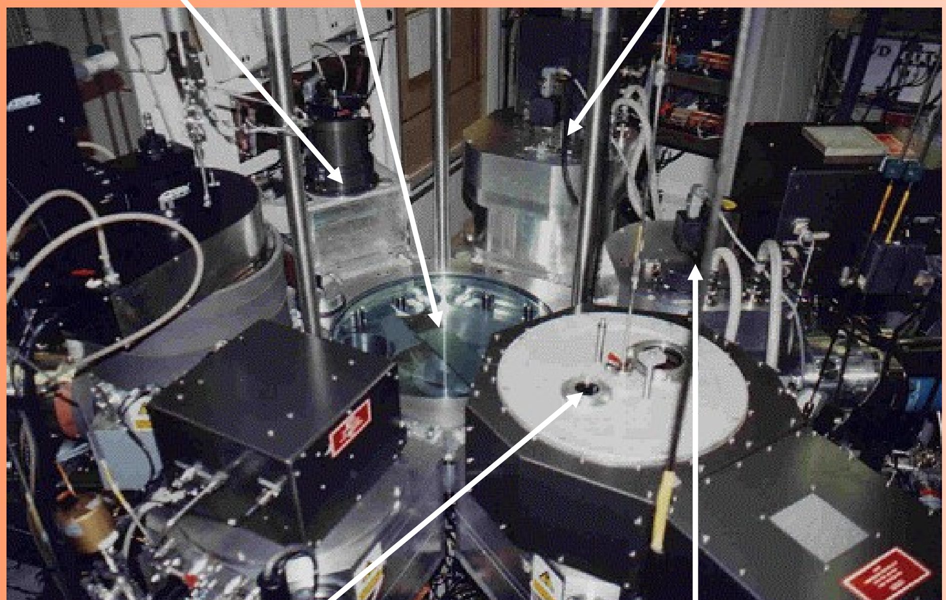


Sample preparation

Cluster Tool

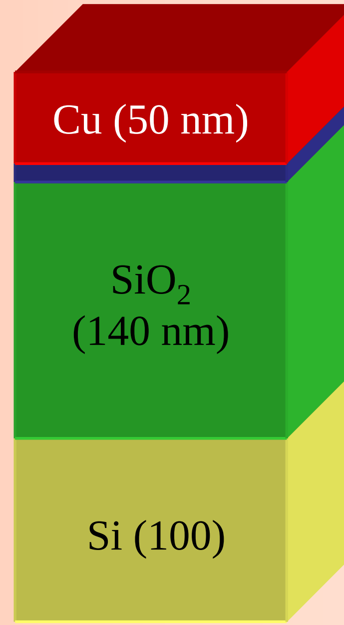
Load lock **Dealer**

PVD copper chamber
$p_0 < 2*10^{-5}$ Pa, d.c. magnetron sputtering, P = 1000 W



ICP soft etch chamber
Ar plasma, P = 200 W

PVD barrier chamber
$p_0 < 2*10^{-5}$ Pa, Ta / Ta_5Si_3 target, r.f. magnetron sputtering, P = 1000 W, different N_2/Ar flow ratios

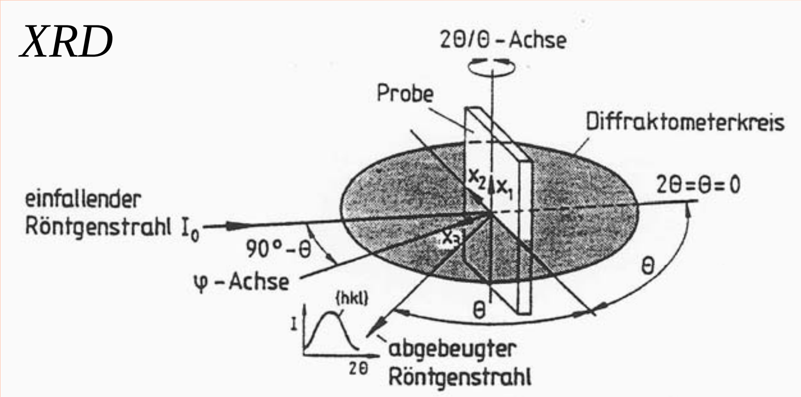


Ta based barrier (10 nm)

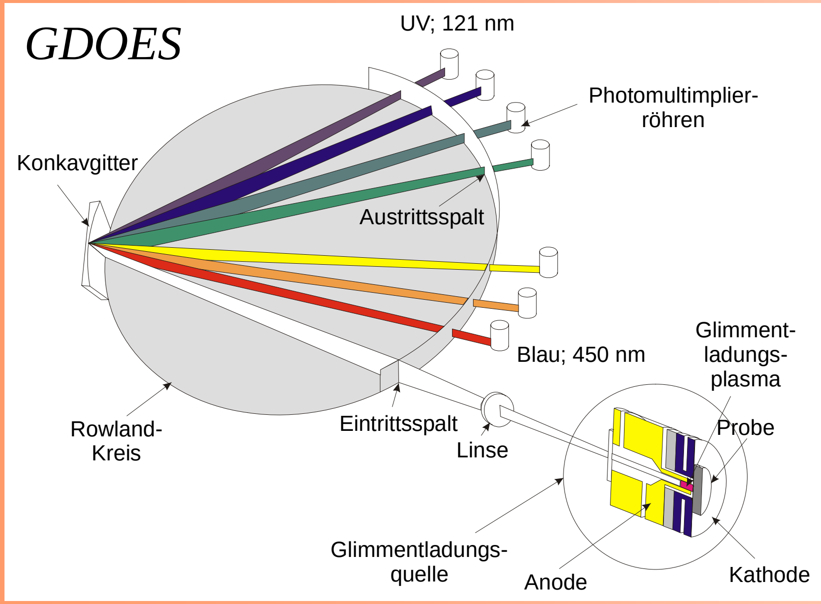
After sputter deposition annealing under vacuum conditions ($p \approx 10^{-4}$ Pa) at various temperatures and annealing times

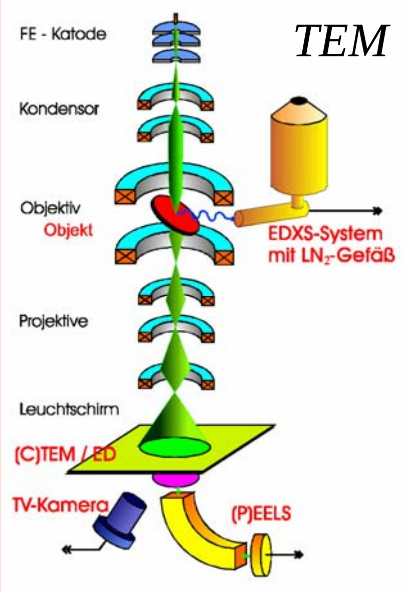
Investigation methods

X-Ray Diffraction (XRD)
Phase formation behavior



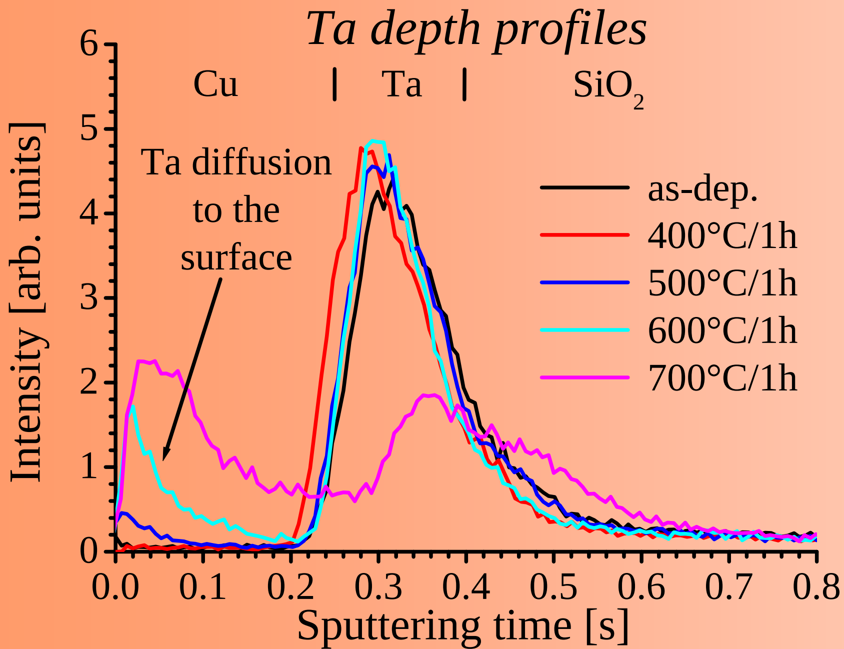
Glow Discharge Optical Emission Spectroscopy (GDOES)
Depth profile analysis

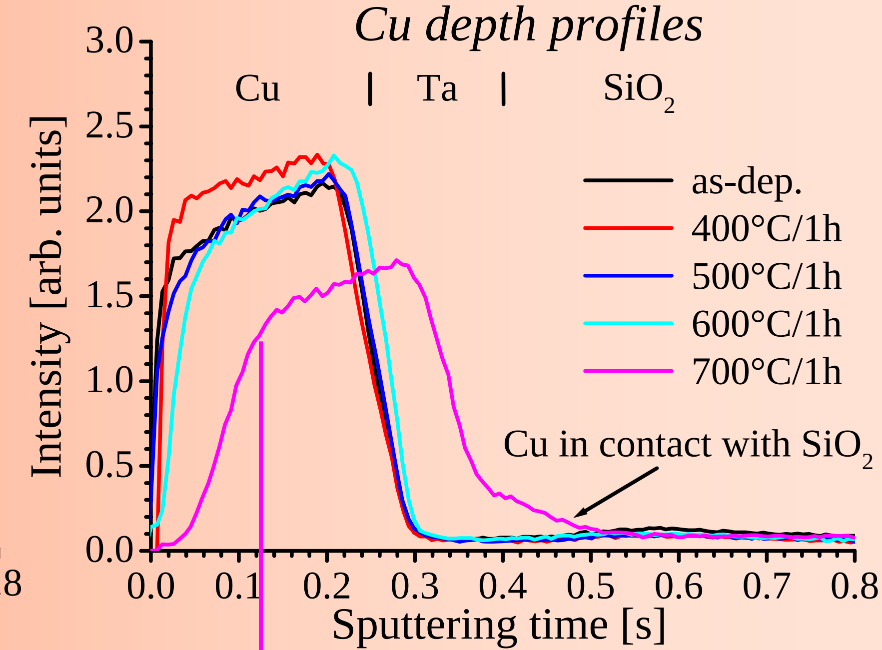




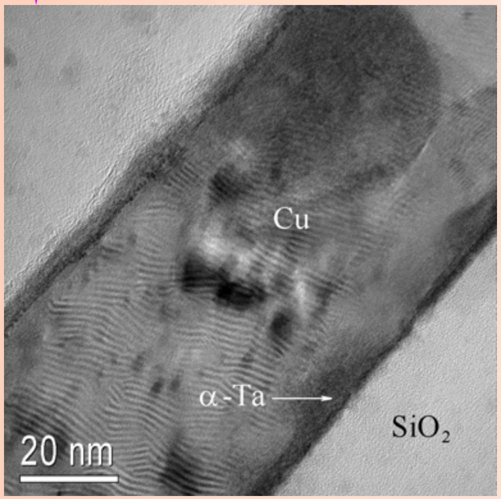
(Analytical) Transmission Electron Microscopy (TEM)
Local microstructure

$Cu/Ta/SiO_2/Si$

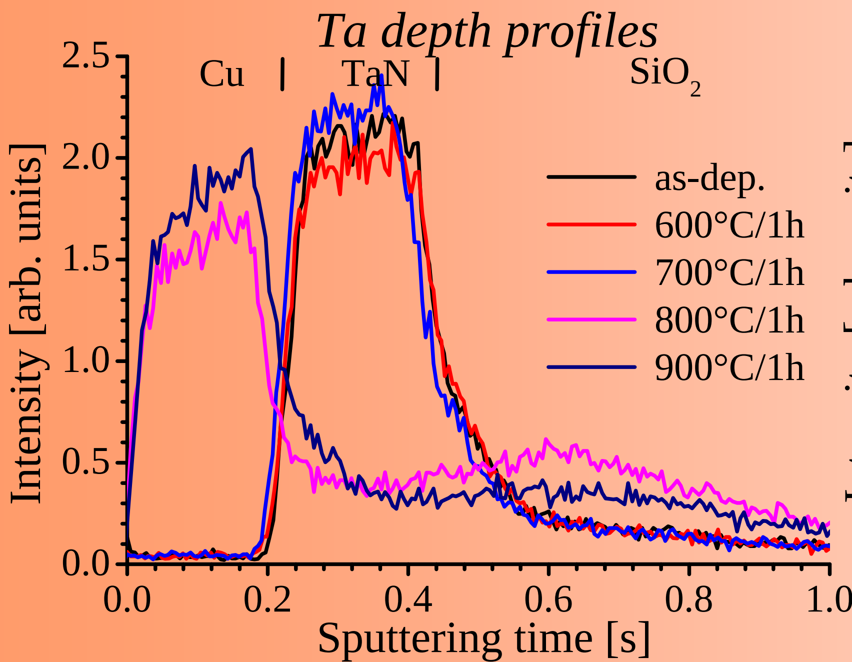


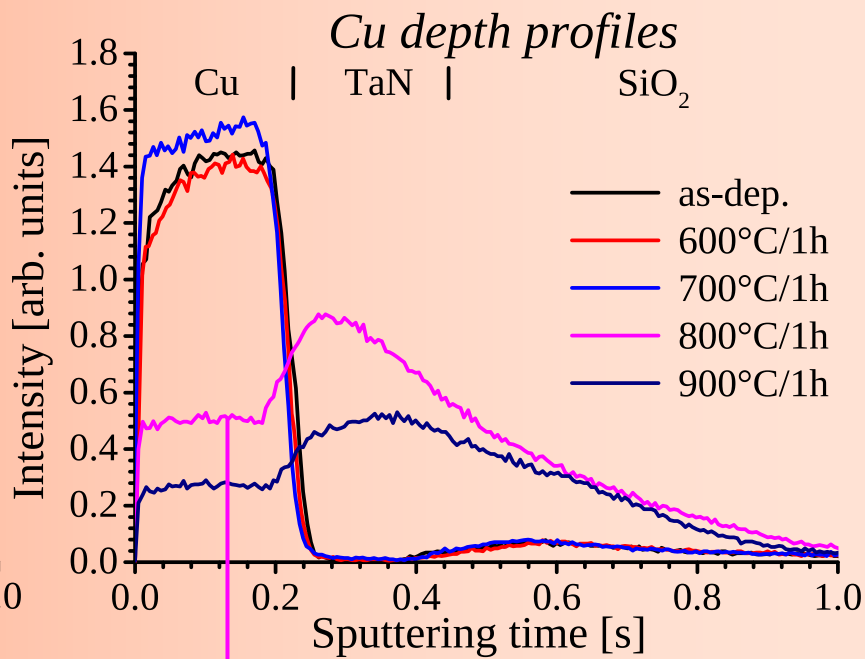


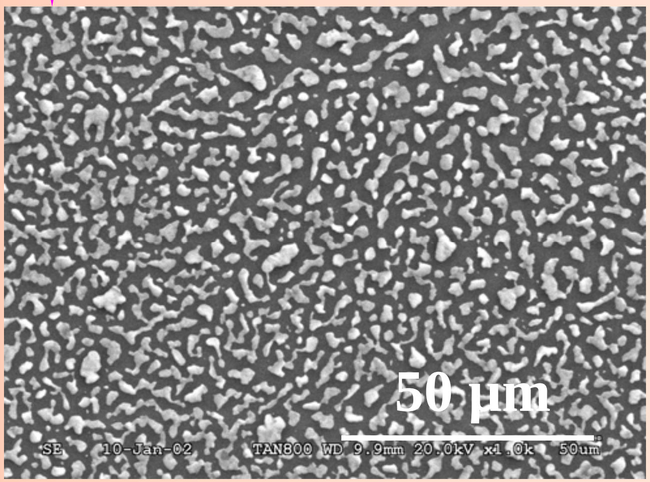
- *500°C/1h:* Ta diffusion to the surface
- *700°C/1h:* α-Ta crystallite growth, Cu in contact with SiO_2 ⇒ Cu diffusion



Cu/TaN/SiO_2/Si



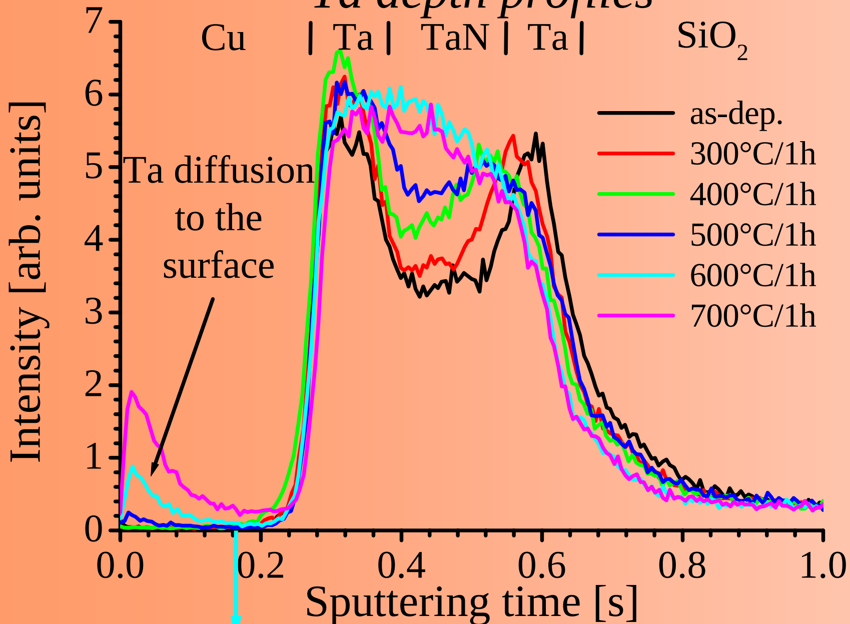




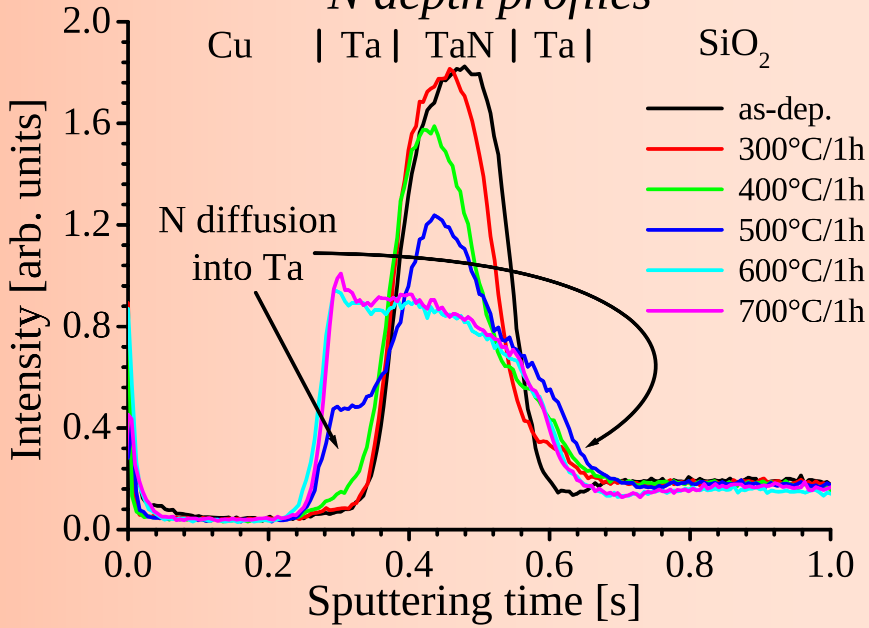
- No Ta diffusion to the surface
- *800°C/1h:* Cu agglomeration – not to be mistaken for Cu diffusion!

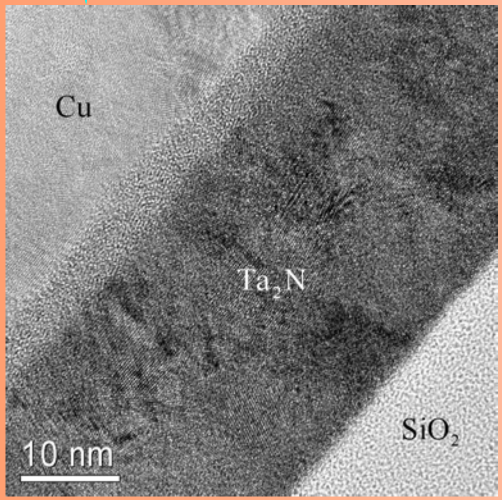
Cu/Ta/TaN/Ta/SiO_2/Si

Ta depth profiles



N depth profiles

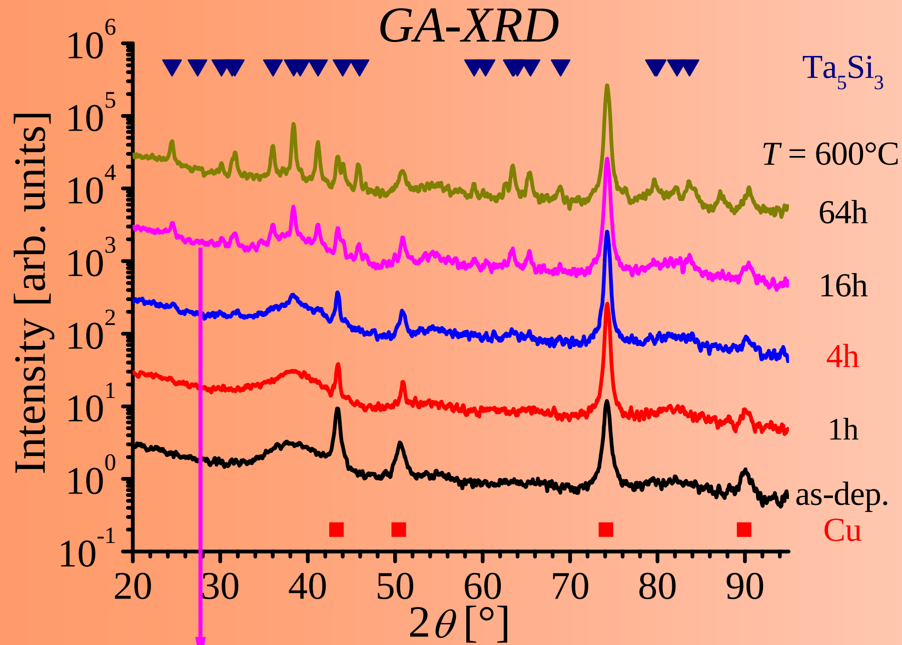


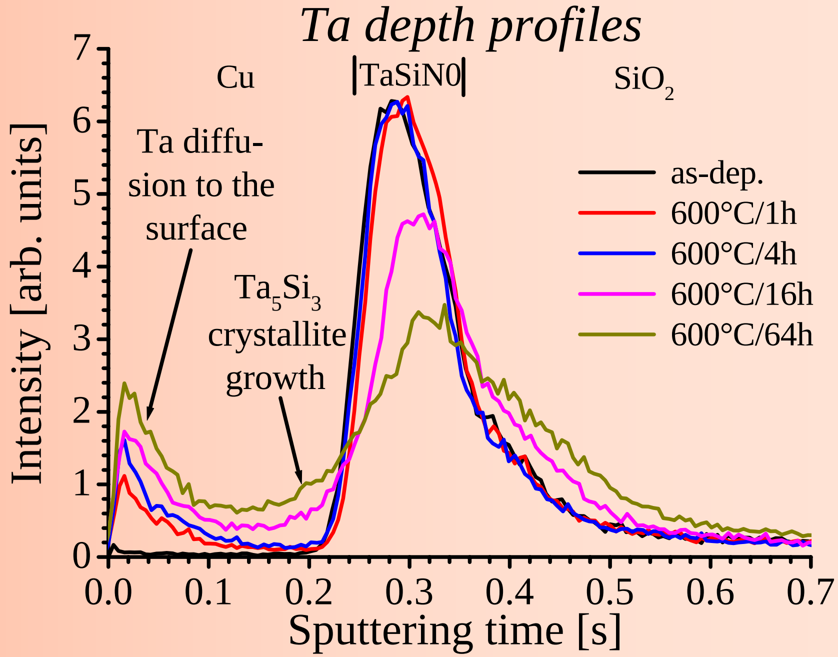


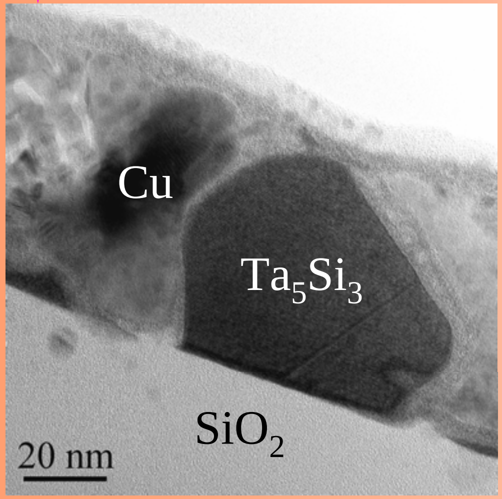
- *300°C/1h:* N diffusion into both Ta layers
- *500°C/1h:* Ta diffusion to the surface; Ta_2N formation ⇒ destruction of the nanocrystalline TaN microstructure ⇒ reduced thermal stability compared to TaN

*(R. Hübner et al., Thin Solid Films **437** (2003) 248-256.)*

$Cu/Ta_{73}Si_{27}/SiO_2/Si$







- *600°C/1h:* Ta diffusion to the Cu surface
- *600°C/≥4h:* Premature barrier crystallization into Ta_5Si_3; Cu diffusion into SiO_2

*(R. Hübner et al., Thin Solid Films **458** (2004) 237-245.)*

11. GDS-Anwendertreffen, Dresden, September 13-14, 2004

Summary

- GDOES depth profile analysis – simultaneous and quick acquisition of element distributions with sufficiently high depth resolution ⇒ quick and comparative characterization of the setup of Cu metallization systems in the as-deposited state and after annealing
- In particular analysis of various diffusion processes: N redistribution within graded Ta-TaN barriers, Ta diffusion out of the barrier to the sample surface, Cu diffusion through the barrier into the substrate ⇒ in conjunction with other methods (XRD, TEM) determination of the thermal stability and the degradation mechanisms of Ta-based diffusion barriers
- Interpretation of the element depth profiles – separation of methodically caused effects from sample properties