Stress gradients in capped Cu films

Paul R. Besser,[1] Conal Murray,[2] Christian Witt[3] and Jean Jordan-Sweet[2,4]

1) Unity Semiconductor Corporation, Sunnyvale, CA.
2) IBM T.J. Watson Research Center, Yorktown Heights, NY
3) GLOBALFOUNDRIES, T.J. Watson Research Center, Yorktown Heights, NY
4) NSLS, Brookhaven National Lab, Upton, NY

pbesser@unitysemi.com

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Contributions

- This work was executed when I was an employee of Advanced Micro Devices, Inc, and most of it has been published since I left AMD.
- The contributing authors are:
  - Dr. Conal E. Murray, IBM T.J. Watson Research Center, Yorktown Heights, NY.
  - Dr. Christian Witt, GLOBALFOUNDRIES, Yorktown Heights, NY.
  - Dr. Jean L. Jordan-Sweet, IBM T.J. Watson Research Center, Yorktown Heights, NY and NSLS, Brookhaven National Lab, Upton, NY

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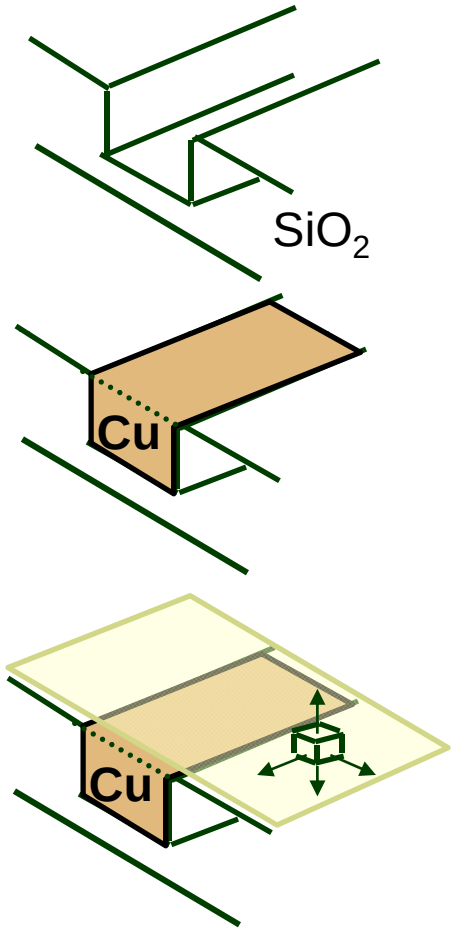
Outline

- Introduction to stress development and Cu capping
- Introduction to GIXD
- Sample description
- Stress determination with XRD and GIXD
- Stress effects from capping
- Effects of Temperature
- Conclusions

Introduction: Mechanical stress in Cu lines

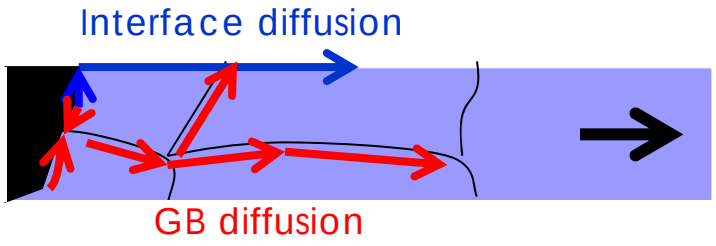
- Mechanical stresses and their determination are well understood in inlaid Cu lines-
  - Besser et al., MRS Symp. Proc. 563 (1999) and AIP Conf. Proc. 491, 229 (1999).
  - Kasthurirangan et al., AIP Conf. Proc. 491, 304 (1999).
  - Besser et al., J. Electron. Materials 30(4), 320 (2001).
- Stresses arise from a CTE mismatch between Cu and the substrate and dielectrics. $CTE_{Cu} >> CTE_{Si}$
- The stresses in Cu lines are smaller than that in Al lines of the same aspect ratio.
- Inlaid fabrication technique alters the stress state.
- The stresses at RT are triaxial and tensile. Stresses are linear with temperature.
- Stress is linearly dependent upon post-plating anneal temperature.

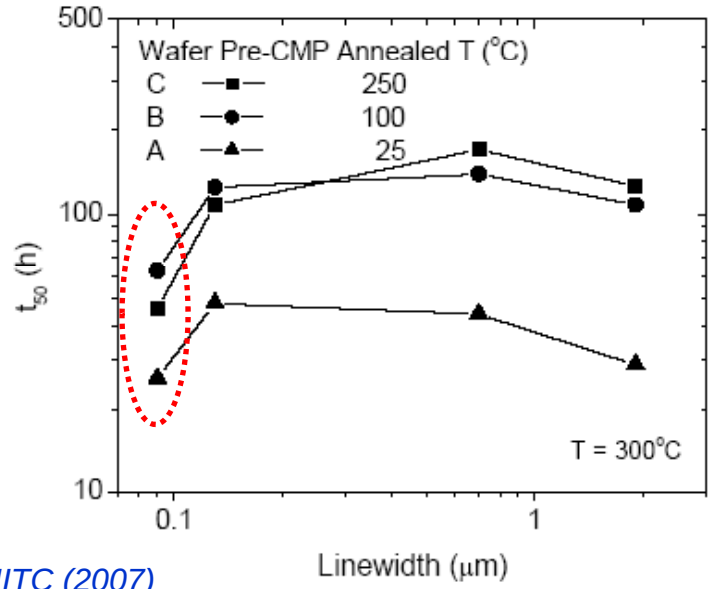


Besser et al., 2004 Workshop on Stress-induced Phenomena in Metals (2004)

Reliability materials challenges

- Current density increases with generation.
  - Lifetime drops by ½ in every generation.
- At 32nm, the mechanism of EM fundamentally changes!
  - 90/65/45nm: interface diffusion dominates, but as linewidth decreases the contribution from grain boundary diffusion is larger.
  - 32nm: EM resistance of narrow lines is dominated by grain boundary diffusion
  - Restrictive design rules at 32nm





Figures from C-K Hu et al., IITC (2007)

Options for improving EM reliability

- EM Reliability must be improved without degrading TDDB

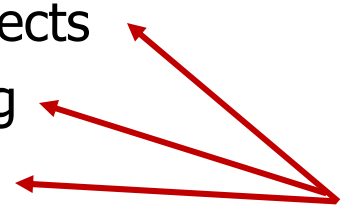
- Ensure good Cu fill in narrow features
- Ensure good barrier integrity

} **Must happen**

- Lower the current density
- Reduce the operating temperature

} **Not gonna happen??**

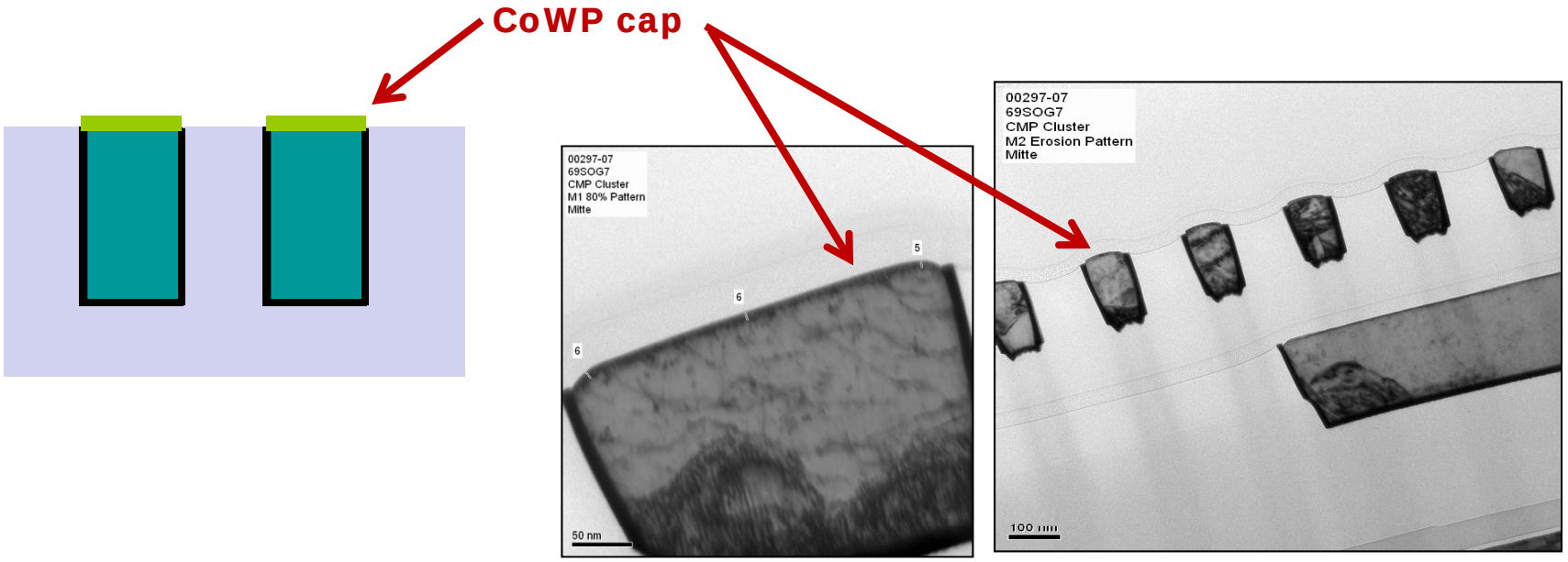
- Encourage grain growth in narrow features (<100nm)
- Short-line effects
- Metal capping
- Cu alloys



Important research areas

Reliability Potential Solution = Metal Caps

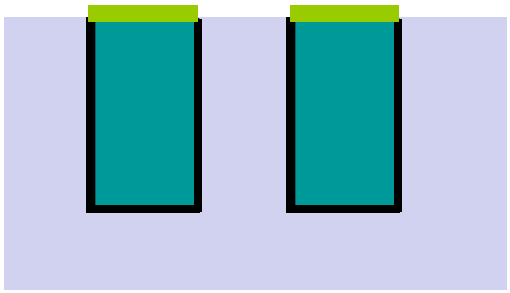
- Selective electroless deposition of a ternary alloy with barrier properties and good conductivity (~60 μΩcm) as a metal cap on the Cu lines.
- The metal cap reduces diffusion along the interface.

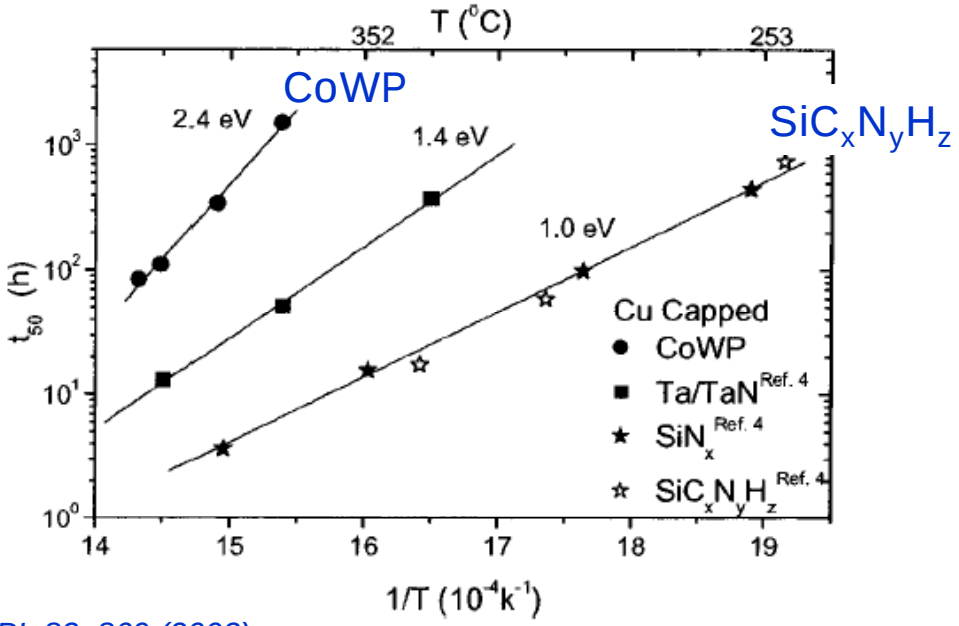


Besser et al., Proc. Adv. Metal. Conf (2008).

Reliability Potential Solution = Metal Caps

- How to improve reliability:
  - $SiC_xN_yH_z$ deposition on the lines provides good reliability
  - Selective electroless deposition of a ternary alloy with barrier properties and good conductivity (~60 μΩcm) as a metal cap on the Cu lines improves reliability
- The metal cap reduces diffusion along the interface and provides >100X increase in MTF over control

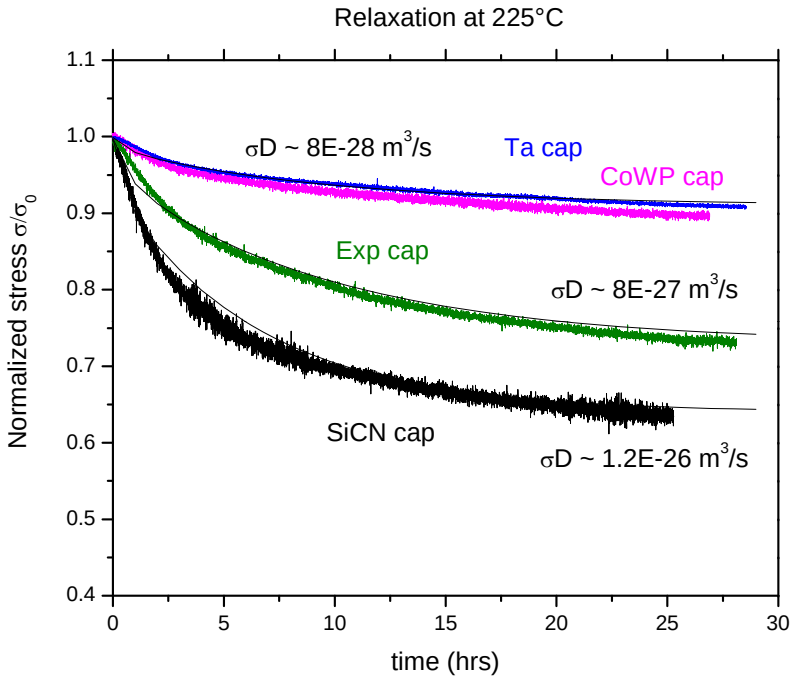




C-K Hu, APL 83, 869 (2003)

Cap Development - Stress Relaxation

- Work to understand the relaxation mechanisms in capped Cu films has revealed that the stress relaxation rates are a function of cap layer, due to reduced diffusivity.
  - CoWP capping of Cu films is effective in reducing stress relaxation.
- But does the stress at the surface change with relaxation and are there stress gradients in the films?



C. Witt et al., SIP Workshop (2008).

Diffusion path	Diffusivity, δD (m^3/s)		
	179 °C	210 °C	247 °C
Grain boundary	1.3×10^{-26}	7.5×10^{-26}	4.7×10^{-25}
SiN/Cu	2.8×10^{-29}	7.7×10^{-29}	6.0×10^{-28}
SiC/Cu	3.3×10^{-28}	6.6×10^{-28}	1.3×10^{-27}
SiCN/Cu	1.2×10^{-28}	2.2×10^{-28}	8.1×10^{-28}
Metal cap/Cu	8.2×10^{-30}	1.5×10^{-29}	5.8×10^{-29}

Gan and Ho, JAP 97 (2005)

Advantages of GIXD

- Grazing-incident X-ray diffraction (GIXD) has been applied to investigate depth-dependent stress distributions for many crystalline materials.
  - The depth from which diffraction information is collected can be controlled by choosing the incident and diffracted beam angles with respect to the film surface.
  - For incident angles close to the critical angle for total external reflection, the 1/e penetration depth associated with the diffracting volume can be several nanometers.
- GIXD of Cu films with a free surface
  - Lower in-plane stress at the free surface was observed, or a small increase (less than 40 MPa), possibly due to oxidation at the surface.

This work investigates the effects of capping materials, which serve as oxidation barriers, on the mechanical stress of blanket Cu films, particularly near the Cu / capping layer interface

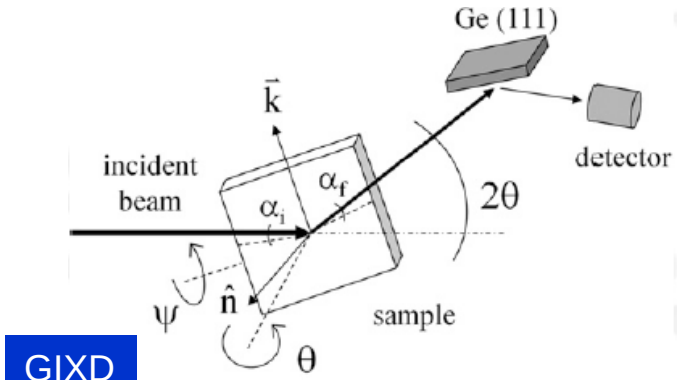
T. Himuro and S. Takayama, MRS Symp. Proc. 854 (2005).
S. Takayama, M. Oikawa and T. Himuro, MRS Symp. Proc. 795 (2004).

Sample description

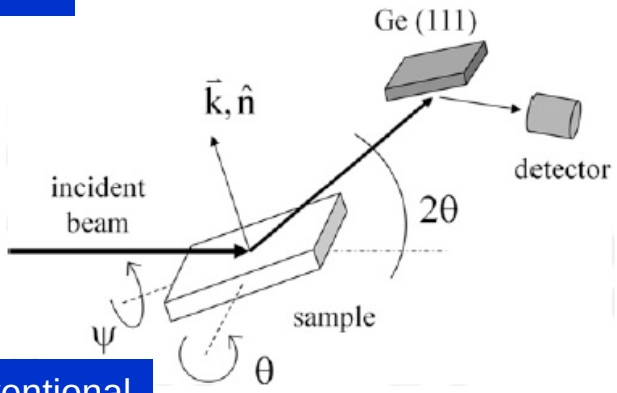
- 10nm Ta/TaN barrier + 30 nm Cu were sputter deposited onto oxidized 300 mm Si (001) substrates.
- Cu films were then electroplated and annealed at 100°C for 30 minutes in a forming gas atmosphere.
- Films were chemical mechanical polished to a final Cu film thickness of ~650 nm.
- Samples received either:
  - 35 nm thick $SiC_xN_yH_z$ capping film, deposited at 350°C,
  - Electrolessly deposited 7.5 nm CoWP film, or
  - 7.5 nm CoWP film followed by a 35 nm $SiC_xN_yH_z$ cap.

XRD measurement details

- X-ray diffraction measurements were conducted at Brookhaven National Laboratory's National Synchrotron Light Source X20A beam-line.
  - Photon energy = E = 8.6 keV (λ = 1.4417Å).
  - Vertical Soller slits collimate the incident beam in the horizontal direction.
  - Diffractive optics: double-crystal Ge(111) monochromator & single-bounce Ge(111) analyzer crystal.
  - Angular width of the incident beam at the detector was measured to be 0.012° FWHM in the diffraction plane.
- Cu (220) peak was measured in grazing-incidence as a function of the incident beam angle above the surface, and Cu (222) peak was measured in the conventional XRD geometry.

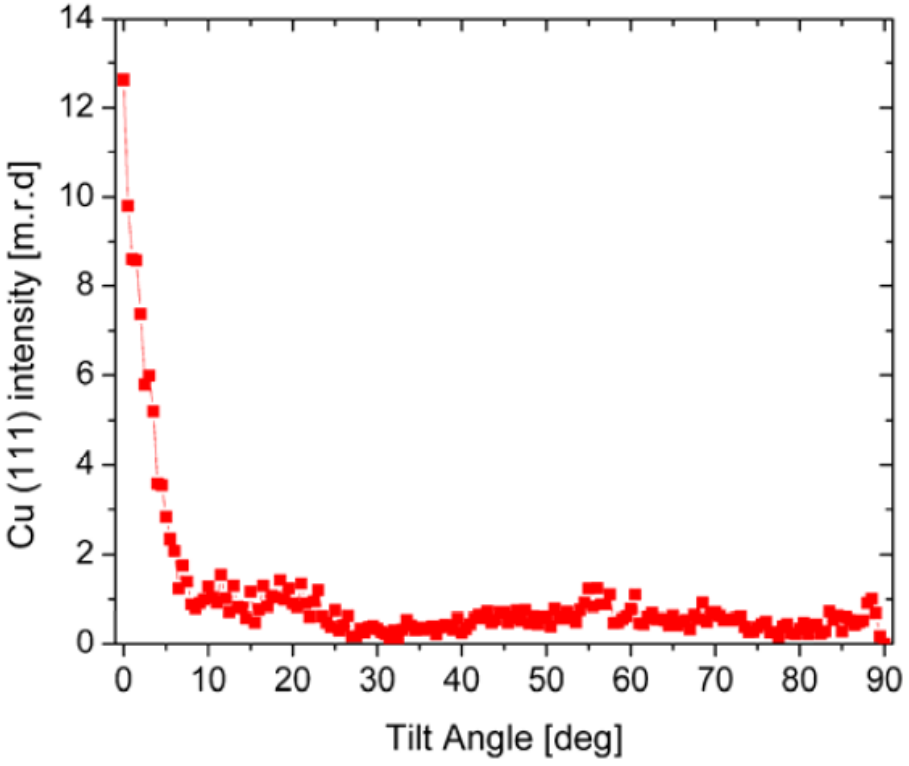


GIXD



conventional

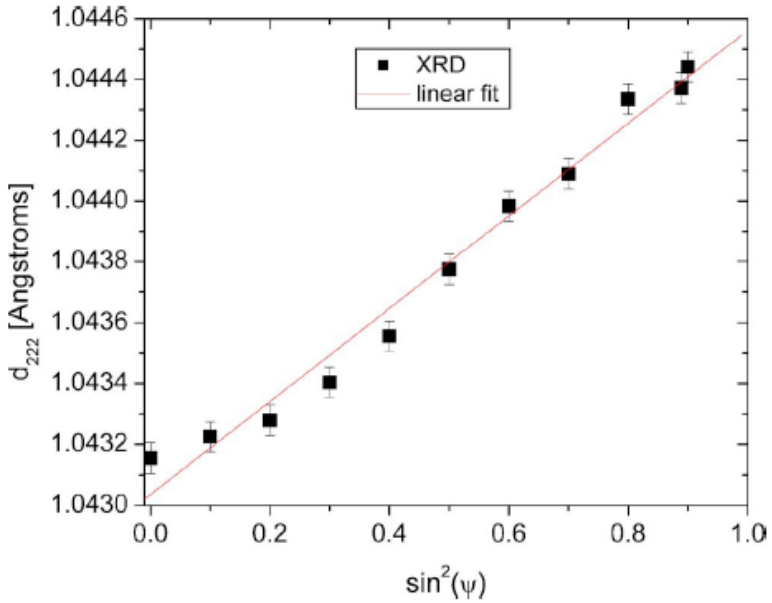
Cu (111) Fiber texture



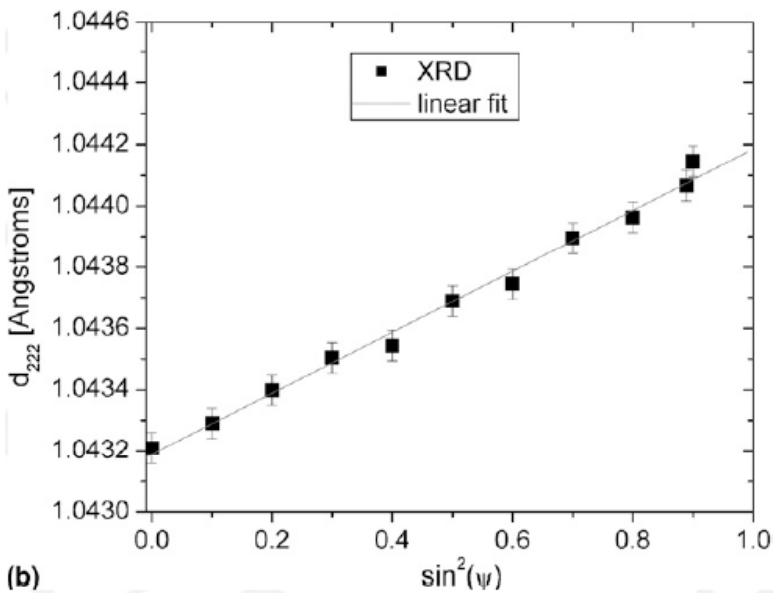
- The Cu films with SiCxNyHz-cap have a strong Cu(111) fiber texture.
- In the plot, the Cu (111) intensity was corrected for absorption and plotted as a function of a multiple of random distribution (m.r.d) where a value of 1 corresponds to a random texture.
- Cu (220) peak was measured in GIXD and Cu (222) peak was measured in the conventional XRD geometry.

d vs. $\sin^2\psi$ for capped Cu

SiCxNyHz-capped Cu



CoWP-capped film



- ψ is the tilt angle between the surface normal and diffraction vector
- Note that d is linear with $\sin^2\psi$.

Murray, Besser, Witt, and Jordan-Sweet: Appl. Phys. Lett. 93, 221901 (2008).

Determining stress from strain

$$\frac{\partial d_{222}}{\partial \sin^2(\psi)} = d_0 \left(\frac{1+\nu}{E} \right)_{XEC} \sigma_{bulk}$$

- Cu (222) interplanar spacing, d, is measured as a function of ψ, based on Gaussian fits. NOTE: Cu(222) is normal to Cu (111).
- An isotropic, biaxial in-plane stress state was assumed.
- The in-plane biaxial stress, σ_{bulk}, for a quasi-isotropic elastic material, is calculated from the slope of the d vs. $\sin^2(\psi)$ measurement.
  - E and v are Young's modulus and Poisson's ratio.
  - The Cu unstressed lattice spacing, d_0, was found from the intercept ($\psi = 0^0$) of the d_{222} vs. $\sin^2(\psi)$ fitted line in order to minimize the uncertainty for d_0 for each sample. Any error is placed in the pre-factor, and is estimated to be less than 0.1%.
  - XEC = x-ray elastic constants were calculated using the Neerfeld-Hill limit, (average of Voigt and Reuss values). For Cu(222), $(1+v)/E = 7.912 \times 10^{-3}$ GPa^{-1}.

Surface stress calculation

- The grazing incidence measurements of the (220) reflection primarily occur from the Cu (111) textured grains.
- The in-plane normal stress σ_{surf} can be calculated from the near-surface lattice spacings measured with GIXD.

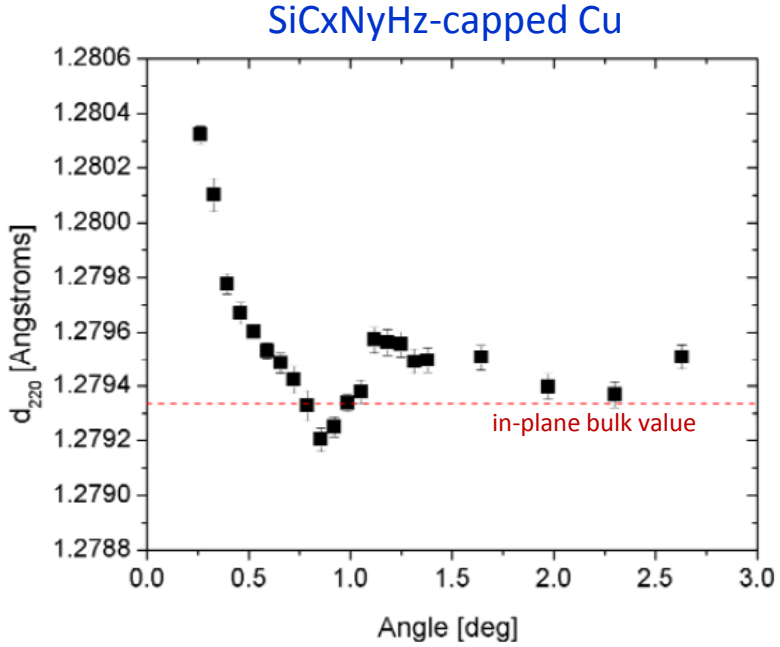
$$\sigma_{surf} = \sigma_{bulk} + \left(\frac{d_{220}^{surf} - d_{220}^{bulk}}{d_{220}^{bulk}} \right) \Big/ \left(\frac{1-\nu}{E} \right)_{XEC}$$

determined from d vs. $\sin^2\psi$ plot

Constant

(1-ν) /E = 4.238×10^{-3} GPa^{-1}

$d_{(220)}$ as a function of incidence angle

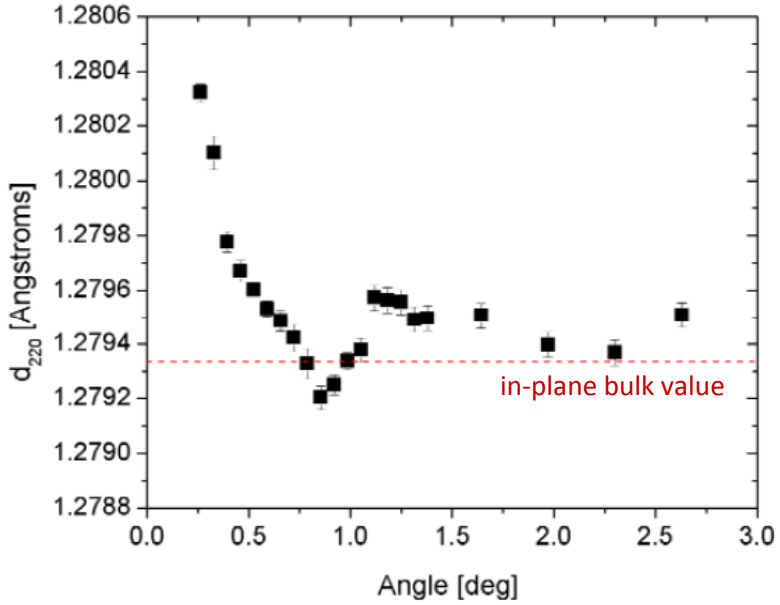


- Notes:
  - The interplanar spacing change is small and needs to be measured precisely.
  - GIXD measurements represent a volume average through the penetration depth of the X-rays, so the depth of the diffracting volume increases rapidly as the incident angle increases above the critical angle.
  - The average in-plane lattice spacing reaches a minimum at ~0.80°, which is the 1/e penetration depth of half of the Cu film thickness.

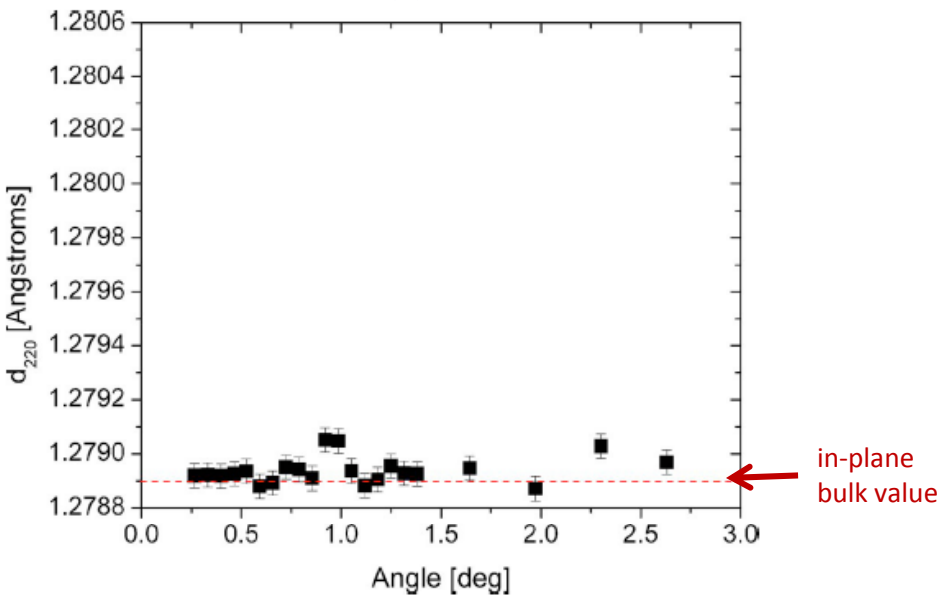
Murray, Besser, Witt, and Jordan-Sweet: Appl. Phys. Lett. 93, 221901 (2008).

$d_{(220)}$ as a function of incidence angle

SiCxNyHz-capped Cu



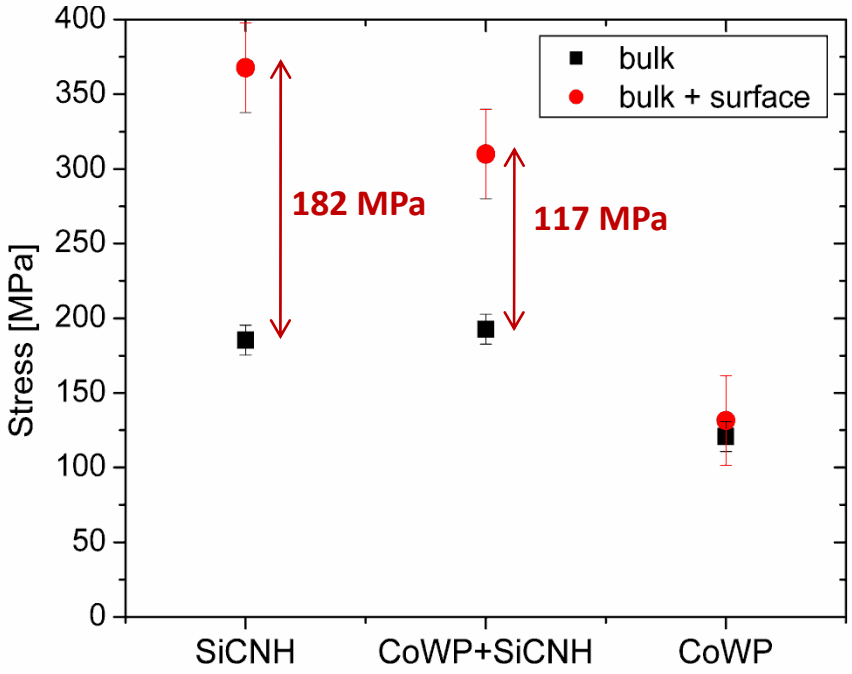
CoWP-capped film



- $SiC_xN_yH_z$-capped Cu:
  - A gradient in the Cu lattice spacing is evident at small incidence angles.
  - A larger in-plane lattice spacing is observed near the top surface of the Cu film.
- CoWP –capped Cu:
  - no discernable difference through the thickness of the Cu film

Murray, Besser, Witt, and Jordan-Sweet: Appl. Phys. Lett. 93, 221901 (2008).

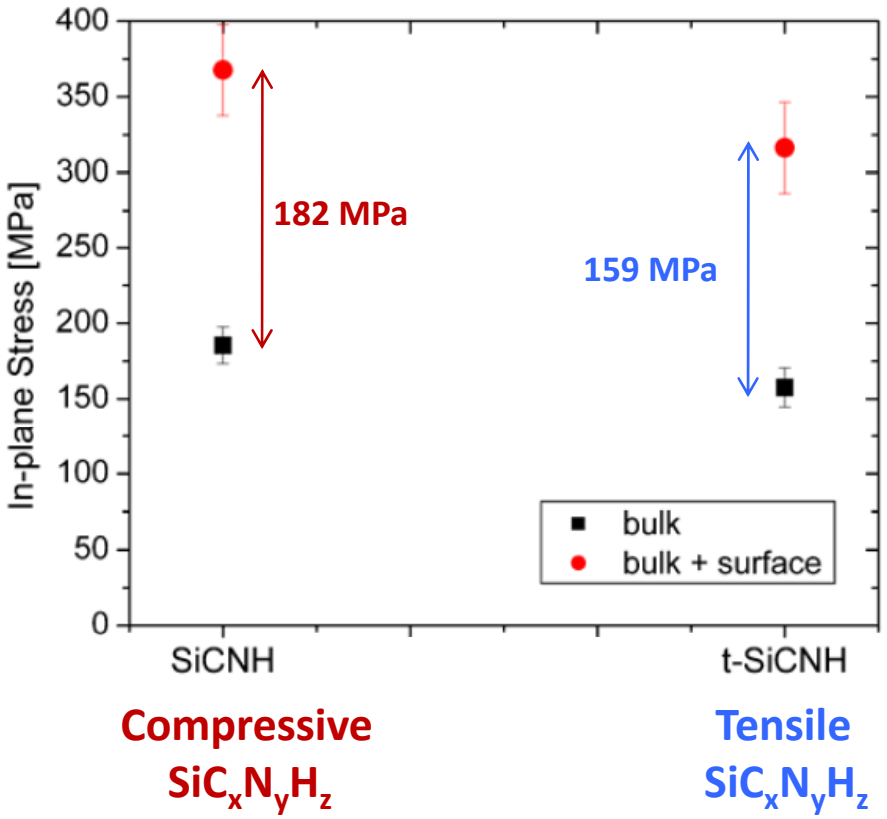
Stress as a function of capping layer



- There is a large increase in stress near the top Cu surface for $SiC_xN_yH_z$-capped films.
- The $SiC_xN_yH_z$-capped Cu film has the greatest increase in tensile stress in the near-surface region.
- CoWP-only capped Cu exhibited a negligible increase in tensile stress near the surface.
- CoWP is deposited at a low temperature (elastic deformation). Plastic deformation (stress gradients) occur only after annealing at elevated temperatures.
- The increase in tensile stress for the Cu film with both a CoWP and $SiC_xN_yH_z$ cap is lower than that for $SiC_xN_yH_z$ capping case. This reduction may be explained by the 7.5 nm distance between the $SiC_xN_yH_z$ and the Cu film due to the CoWP cap, which acts as a buffer layer to reduce the net force.

Murray, Besser, Witt, and Jordan-Sweet: Appl. Phys. Lett. 93, 221901 (2008).

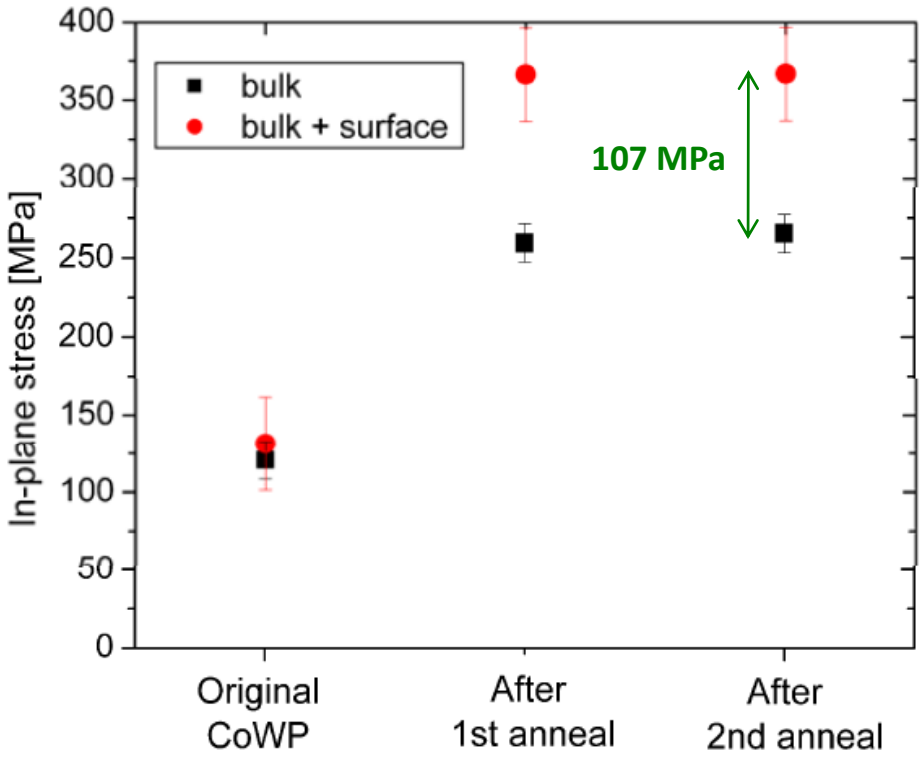
Effect of stress in capping layer



- The stress at the Cu/cap interface for the sample with a tensile $SiC_xN_yH_z$ cap (t-$SiC_xN_yH_z$) exhibited an increase of approximately 159 MPa.
- The stresses in bulk and near-surface regions of Cu films capped with compressive and tensile $SiC_xN_yH_z$ films are similar.
- The net force of the capping layer is primarily accommodated by the underlying Si substrate for blanket samples.

Murray, Besser, Witt, and Jordan-Sweet, J. Mater. Res., Vol. 25, No. 4, (2010)

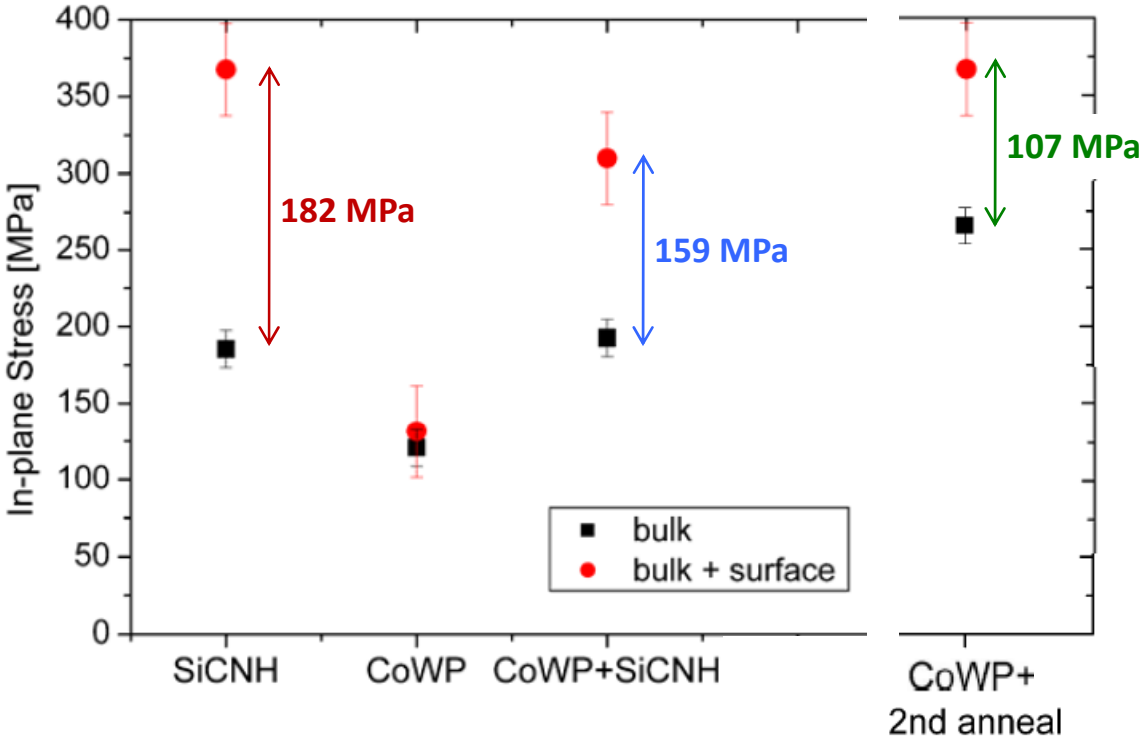
Effect of post-anneal on stress



- CoWP films were annealed at 350°C for 5 min, then an additional 15 min, at NSLS.
- The in-plane stress values in CoWP-capped Cu film in bulk increases from 120 to 259MPa, and the near-surface region stress increases significantly resulting in a stress gradient of 107MPa after a first anneal.
- The stress does not change after additional anneal.

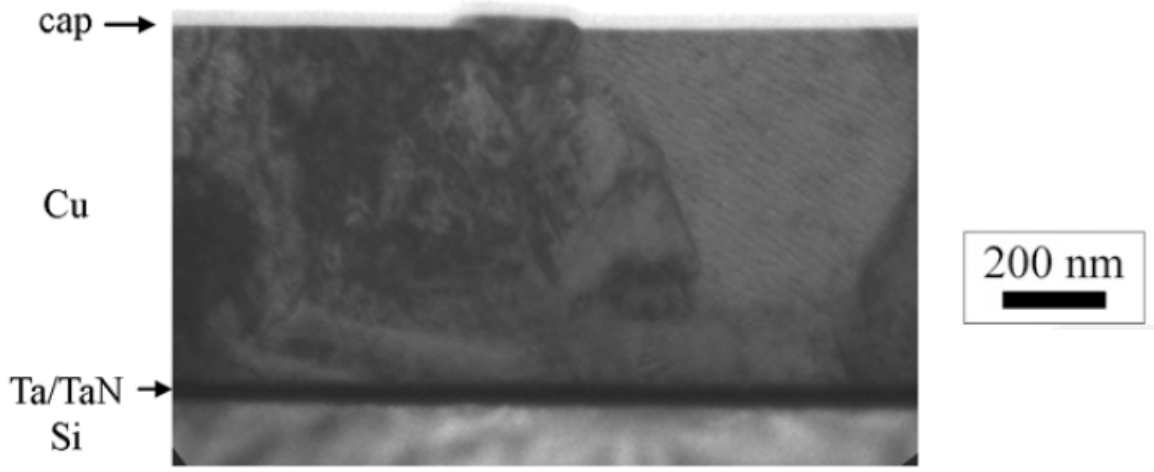
Murray, Besser, Witt, and Jordan-Sweet, J. Mater. Res., Vol. 25, No. 4, (2010)

Effect of post-anneal on stress



- The bulk stresses of the Cu with a CoWP cap + anneal are higher than those observed with $SiC_xN_yH_z$ caps.
- The stress gradient through the thickness is smaller.
- The difference can be attributed to anneal cycles:
  - NSLS: slow ramp and cool (hours)
  - $SiC_xN_yH_z$: fast ramp and short time

Physical Analysis = TEM



- Cross-sectional TEM image of $SiC_xN_yH_z$ -capped Cu film.
- Shallow extrusions were found in all samples that received $SiC_xN_yH_z$ capping. The $SiC_xN_yH_z$ caps followed the underlying morphology of the top Cu surfaces.
- No extrusions were observed in the sample with only an electrolessly deposited CoWP cap

Murray, Besser, Witt, and Jordan-Sweet, J. Mater. Res., Vol. 25, No. 4, (2010)

Summary

- In-plane stress near the top surface of Cu films capped with either $SiC_xN_yH_z$ or CoWP (or a combination) has been measured using GIXD.
- $SiC_xN_yH_z$ capped Cu films:
  - The in-plane surface region exhibits a larger value than that of the bulk Cu.
  - The $SiC_xN_yH_z$ layer constrains the near surface region, limiting the extent of plastic deformation during cooling after $SiC_xN_yH_z$ deposition.
  - Extrusions observed at the top surface of Cu films that received $SiC_xN_yH_z$ caps confirmed that significant plastic relaxation of the compressive stress induced by the CTE mismatch occurs prior to cap deposition.
- CoWP capped Cu films:
  - did not show a gradient in the Cu stress; however, these films did not receive the same thermal treatment: only elastic deformation occurs during dep.
  - Subsequent thermal excursions to elevated temperatures induced a tensile stress gradient (i.e. plastic deformation) in the CoWP-capped Cu films.
- The increase in tensile stress is an important reliability issue where the near-surface regions of the Cu films can be susceptible to stress-voiding phenomena.