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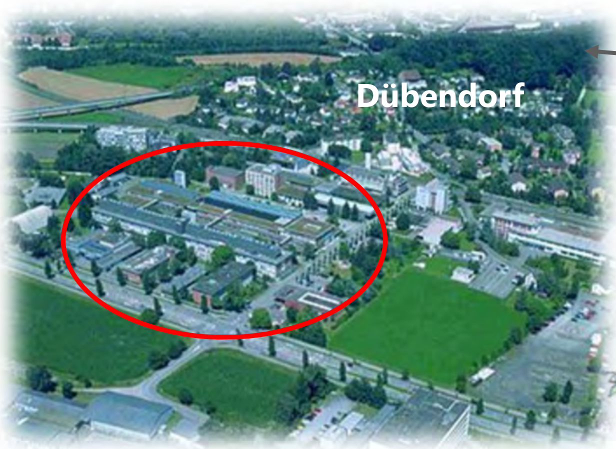
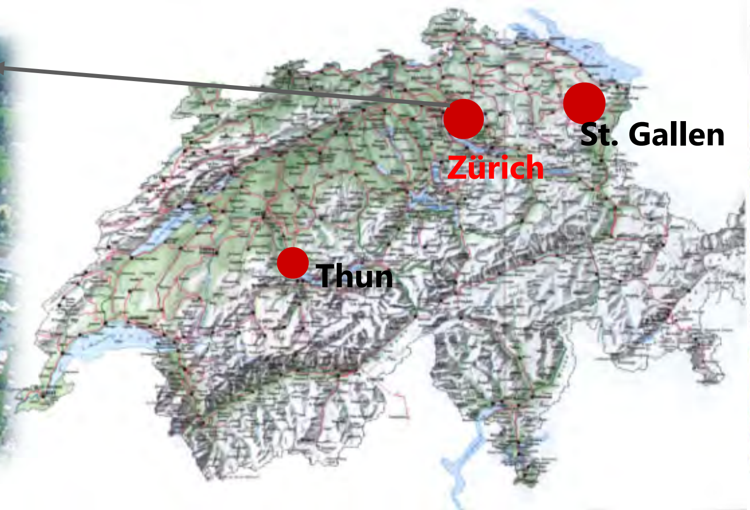
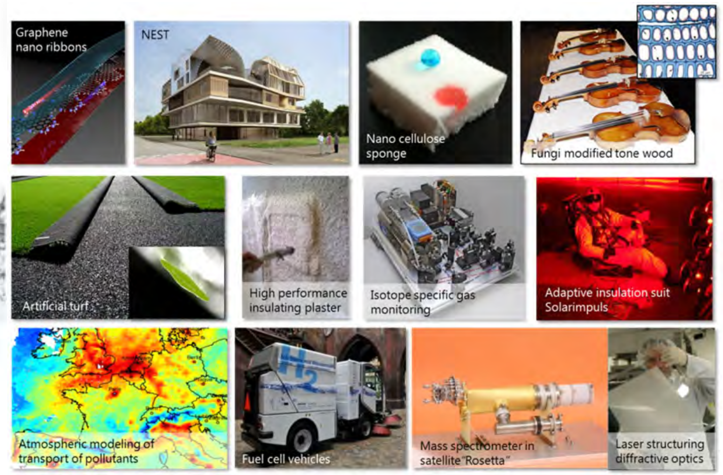


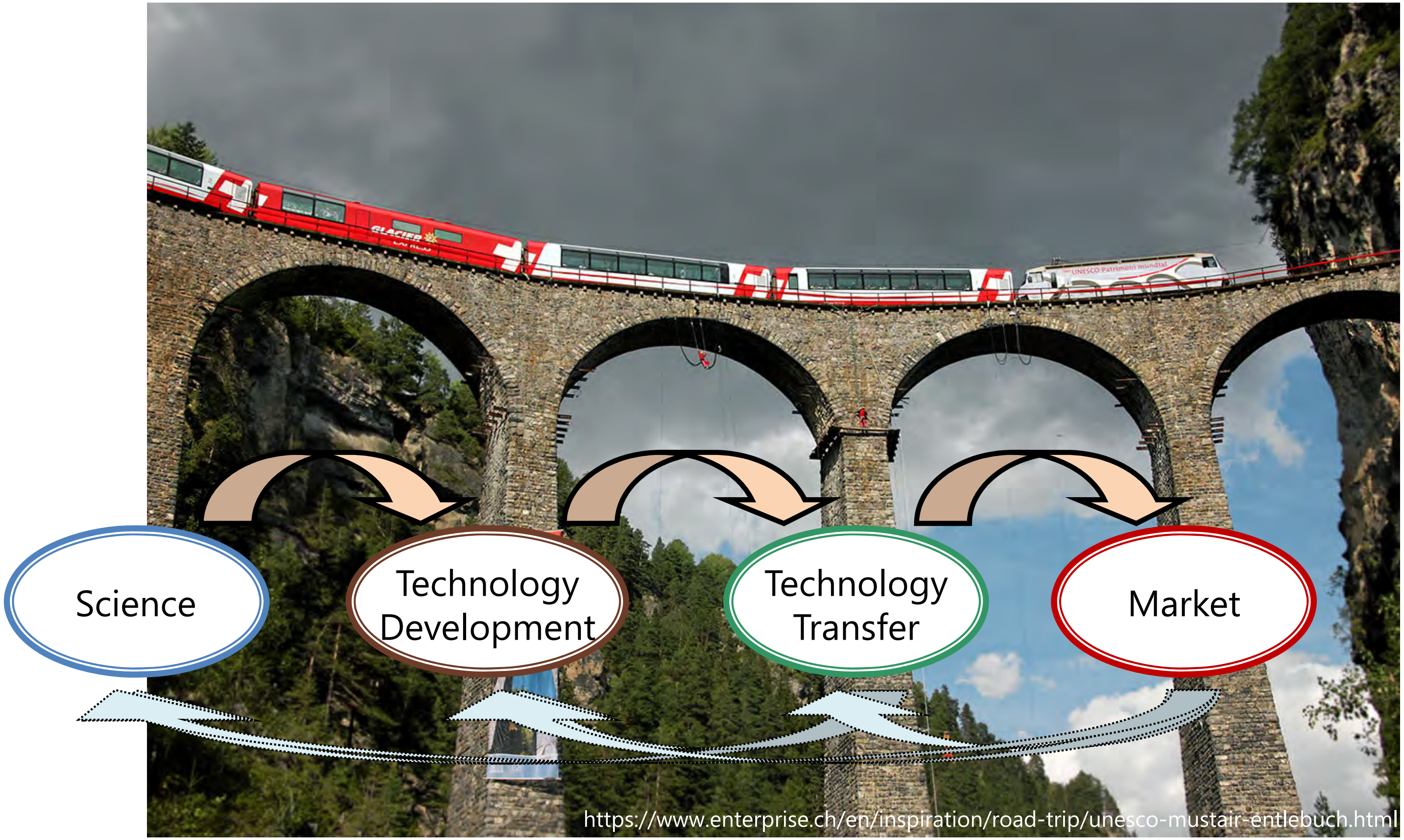




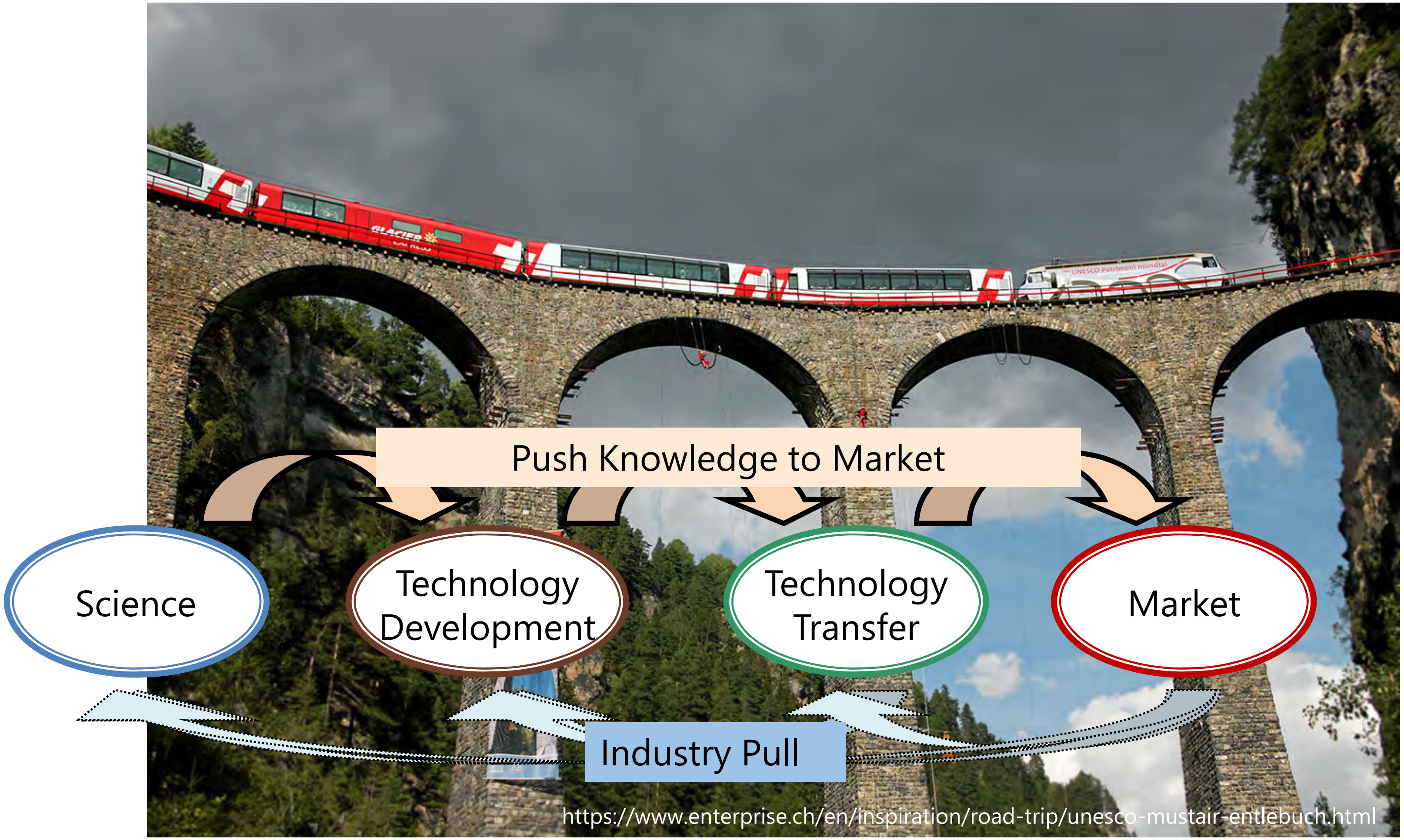
Bridging fundamental science with application, and universities with industry

https://www.enterprise.ch/en/inspiration/road-trip/unesco-mustair-entlebuch.html

Bridging fundamental science with application, and universities with industry



Bridging fundamental science with application, and universities with industry



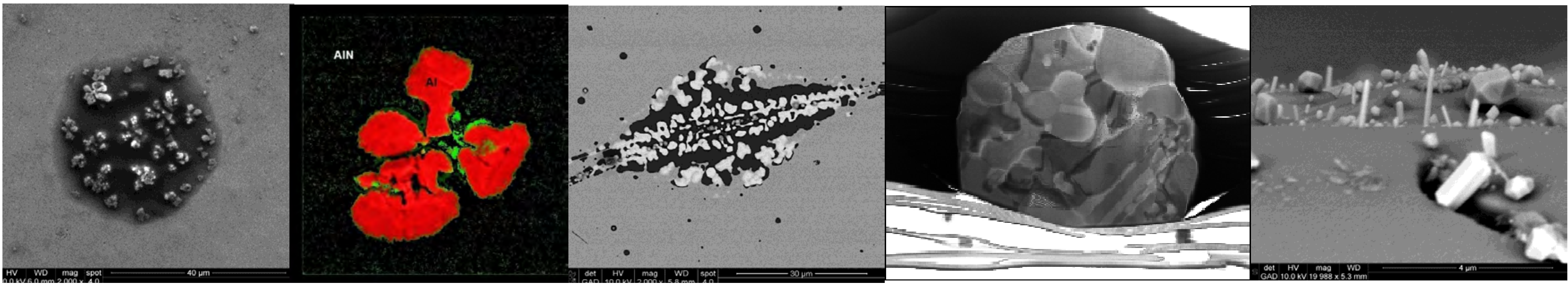
Exploring nanomultilayers for joining technology applications

and > 15 years of collaboration with WUT

Jolanta Janczak-Rusch

Empa, Swiss Federal Laboratories for Materials Science and Technology,

Joining Technologies & Corrosion, 8600 Dübendorf, Switzerland



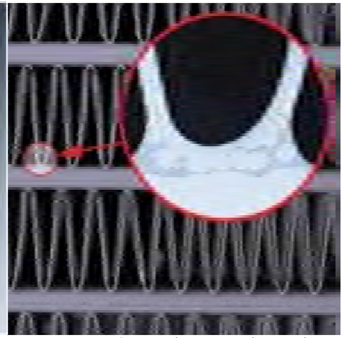
Content:

our journey through the exploration of nanomultilayers

- **Case Study 1**: Development of **Al-Si** brazing filler based nanomultilayers (NMLs)
  - *How to overcome the technological limits by brazing of Al heat exchangers?*
- **Case Study 2**: **Ag-Cu** brazing filler**/AlN** barrier NMLs
  - *Melting, phase separation, melting behavior, control of the mass transport*
- **Case Study 3**: **Ag/AlN** nanomultlilayers
  - *Anomalous fast diffusion under oxygen atmosphere*
- **Case study 4**: **Cu/W** nanomultilayers
  - *Brazing and in-situ formation of nanocomposites*

Case study 1:
AlSi/AlN nanomultilayers

Courtesy: MAHLE Behr GmbH & Co., Stuttgart



Source: www.innovaltec.com/brazed-aluminium-heat-exchangers/

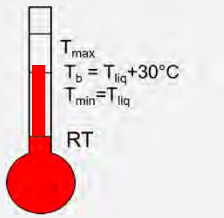
Brazing of Al heat exchangers

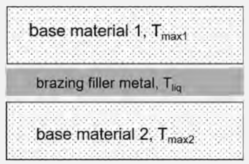
Industrial request (2003-2008)

How to overcome the technological limits by brazing Al heat exchangers?

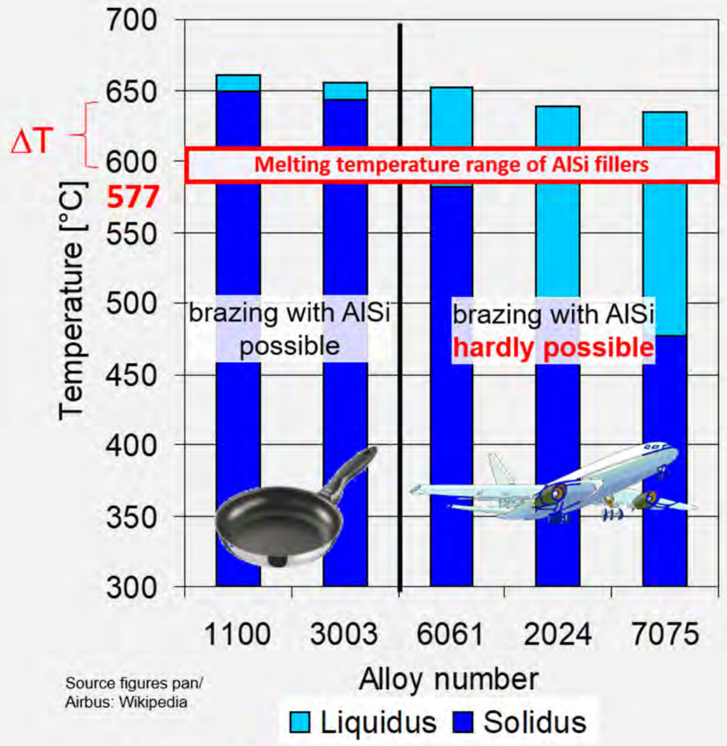
Brazing of **Al-alloys** with AlSi filler metal alloys is limited by the relatively high brazing temperature

- AlSi brazing filler alloys (T_b > 577°C) are general purpose fillers





- Small ΔT between core and filler metal → challenging process control, heat effects on the base metal
- Limited number of suitable core metals for brazing
  - Brazeability of high strength alloys? Innovation?
  - Solidus temperature of some high strength alloys as low as 485°C
- Need of energy- and cost-saving, environmentally friendly processes



Source figures pan/
Airbus: Wikipedia

(Janczak-Rusch et al.:
DVS-NAS-Congress Berlin, Nov. 2011; IBCS April 2012)

Melting Point Depression (MPD) in nanoparticles and thin films

MPD of nanolayers

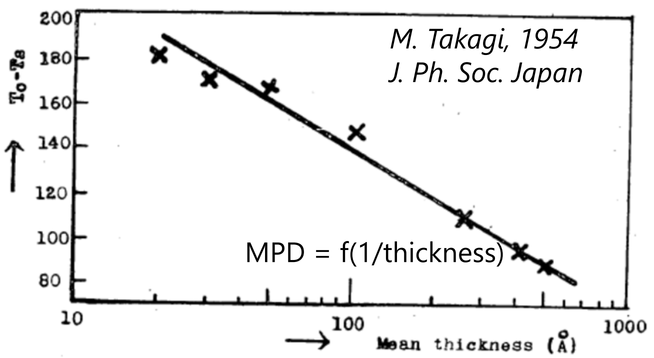
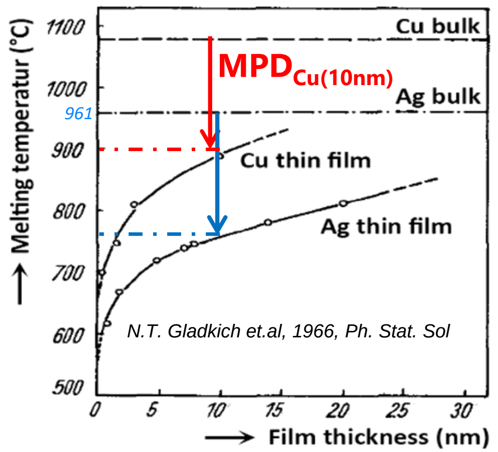
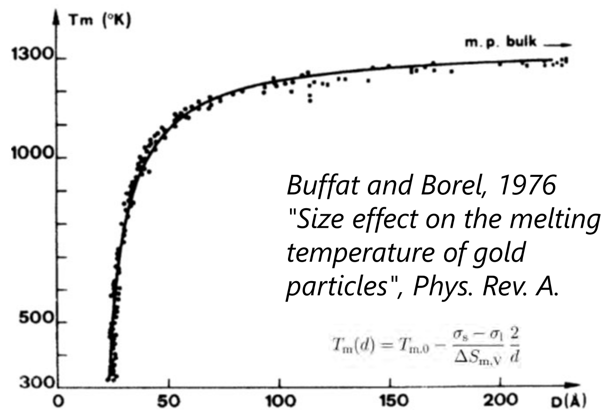


Fig. 3. $(T_0 - T_s)$ for various thickness of Pb films.



$$MPD = T_{m\ bulk} - T_{m\ nano}$$

MPD of nanoparticles



nanoparticle diameter D

- ✓ It is well-known that the melting point of nanostructures decreases with decreasing size in the nano-scale regime (i.e. <20 nm)
  - Large surface to volume ratio of nanometals alters thermodynamic and thermal properties
- ✓ MPD in order of tens to hundreds of degrees can be achieved for metals with nanodimensions.

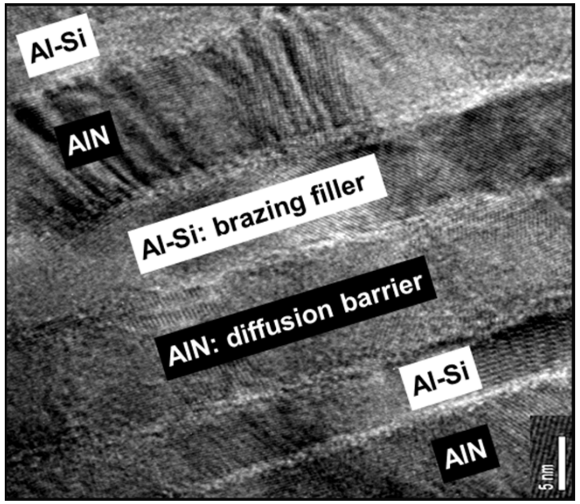
Can we reduce the brazing temperature by using a nanostructured brazing filler metal (alloy) ?

Nanolayered AlSi12 brazing filler (AlSi/AlN NML): methods

NMLs deposition

Magnetron sputtering

- alternated deposition of AlSi and AlN layers
- reactive sputtering of AlN



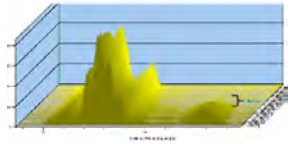
TEM image of cross-section of as-deposited $AlSi12/AlN_{10nm}$ (10x) NML

Behr-/ EMPA- Patent DE102008050433.5

Determination of the melting point

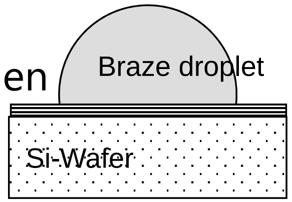
- **HT XRD investigation:** in-situ measurements (PANalytical X'Pert PROMP Diffractometer, HT Chamber), T>300°C, steps of 20°C using CuKα radiation

  Criteria: dissaperence of the strongest crystalline peaks of the brazing filler phases (e.g. 111 or 200)



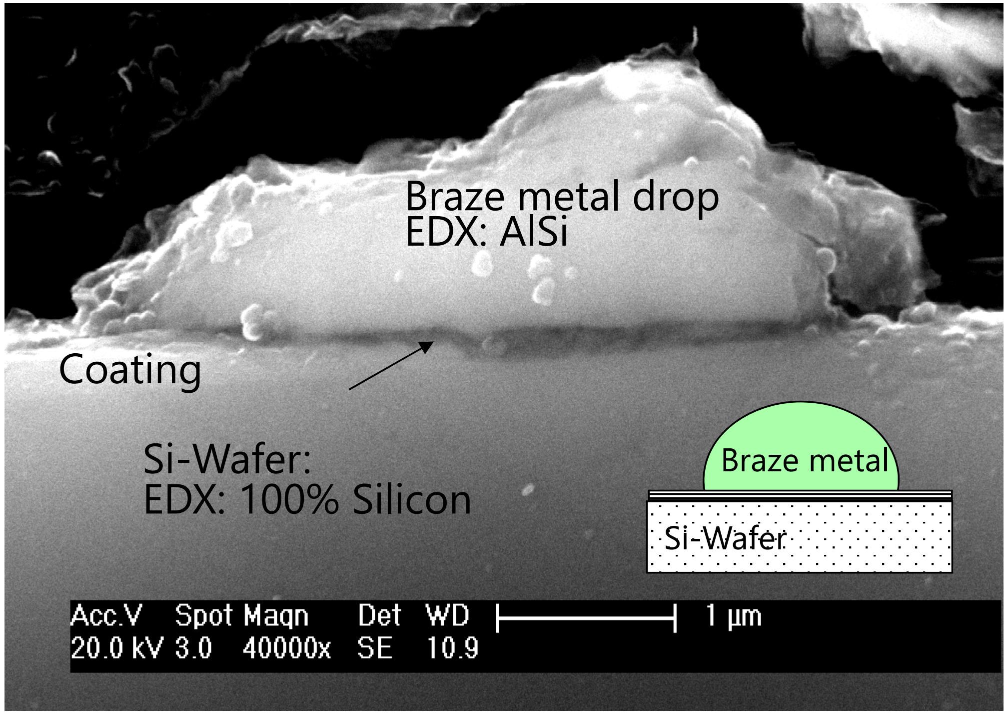
- **Melting experiments**: annealing (T=300 … 600°C, hold time: 5min, hetaing rate: 5K/min, Ar 6.0) followed by SEM investigations and thickness measurements

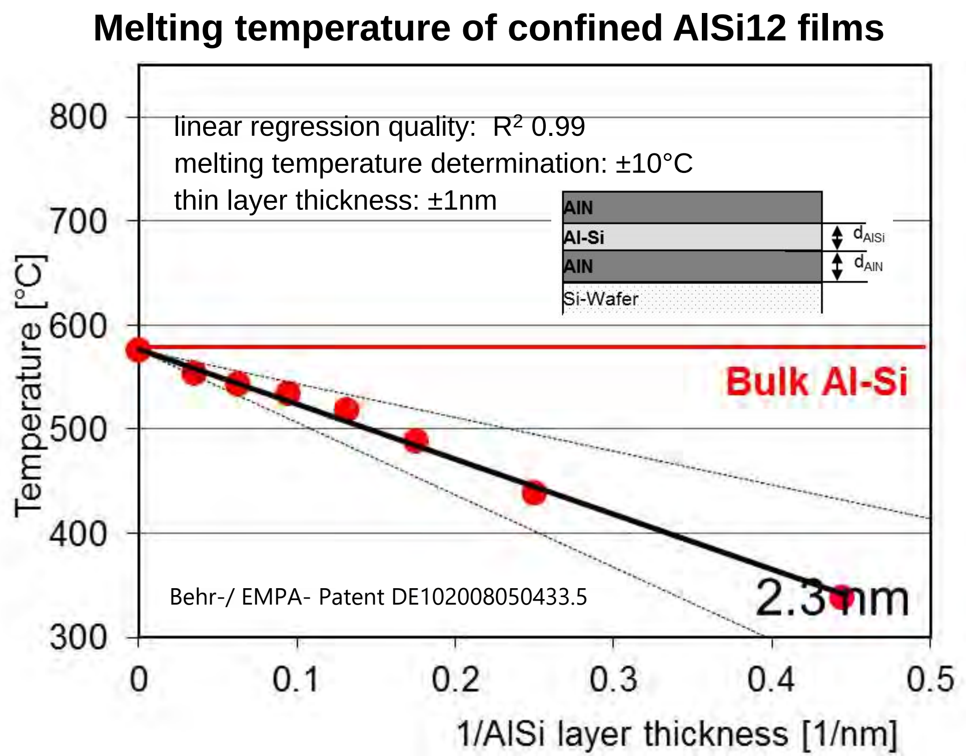
  Criteria: appearance of braze droplets at the specimen surface, change in multilayer thickness



- Correlation of the results of both investigations

Melting of nanolayered AlSi12 brazing filler (AlSi/AlN NML)





Ultra-thin Al-$Si_{12at.\%}$ films confined between AlN layers exhibit size-dependent MPD and allows brazing at reduced temperatures!

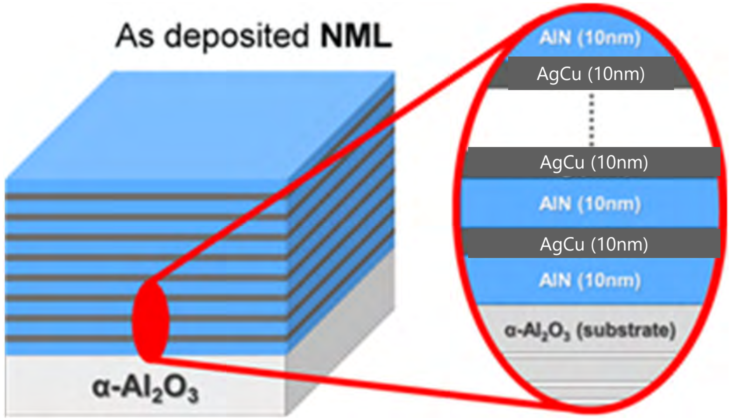
Lessons learned from the case study 1

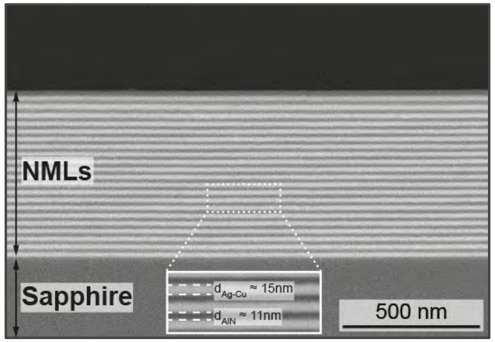
- NMLs offer great opportunities (not only for joining applications)
- **Al-Si/AlN:** a significant MPD can be achieved for nano Al-Si brazing filler
  - It scales with the filler thickness
- The relationships are very complex: many interplaying parameters (meaning also huge design opportunities)
  - Significant effect of the diffusion barrier material observed

Main practical question related to joining with NMLs:

how to intensify the outflow of the braze material to the NML surface?

Case study 2:
Ag-Cu/AlN nanomultilayers





Model system: Ag-Cu_{10nm}/AlN_{10nm} (20x)

Collaboration with INMAT WUT and IMIM PAN
PhD Thesis Vinzenz Bissig Empa/WUT

Ref: J Mater Chem C 4 (2016), 4927

Fundamental study on Ag-Cu/AlN nanomultilayers

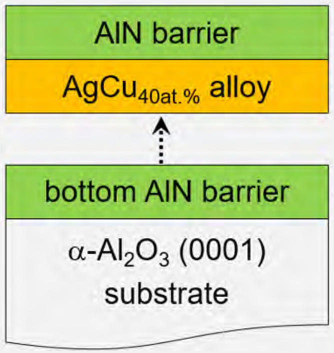
Materials

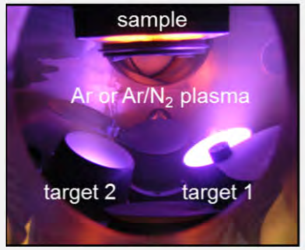
- Silver-based braze alloy have wide range of brazing applications (relatively low T_b)
- Silver-copper eutectic alloy Ag-28Cu (wt.%) is a "key" brazing alloy (representative of virtually every other braze/solder filler alloy).

Name	Analysis (wt%)	Melting point °C	EN 1044	DIN
Eutectic	Ag-28Cu	**778**	AG 401	L-Ag 72

- Representative equilibrium phase diagram: a simple eutectic system with partial solid solubility in the terminal phases
- Two-phase structure with silver and copper rich lamella
- The solubility of copper in a silver rich phase and vice versa is negligible at room temperature

Deposition of Ag-$Cu_{40at.\%}$ /AlN NMLs

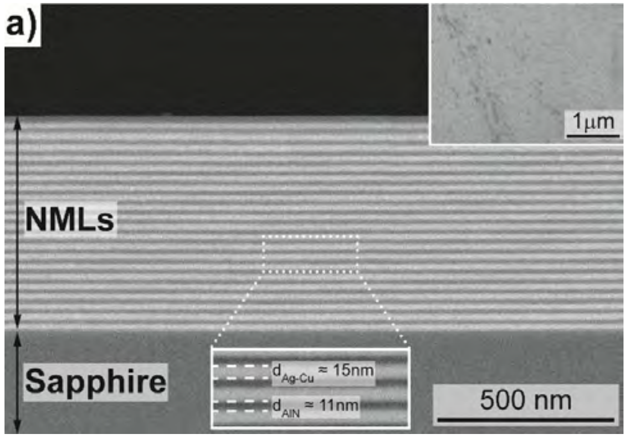




- Ag-40at.% Cu target, applied power: 25 W
- AlN: reactive sputtering of Al in Ar/N_2(g), 0.3 Pa
- Substrate: α-Al_2O_3(0001)
- Single layer thickness: 4-15 nm
- Number of repetitions: 1, 10, 20

As-deposited Ag-$Cu_{40at.\%}$/AlN NML

Morphology by HRSEM

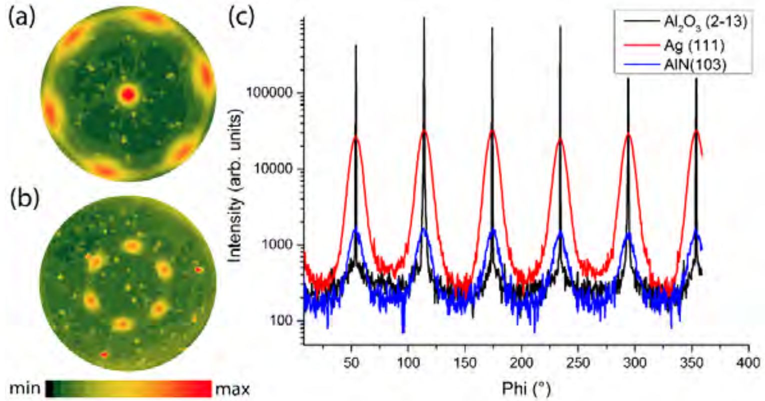


NML cross-section (Ag-Cu: light grey)

SEM micrographs of (**a**) a cross section and (**b**) the surface of an as-deposited Ag-$Cu_{40at.\%}$/AlN NML, as produced by magnetron sputtering.

Texture by XRD

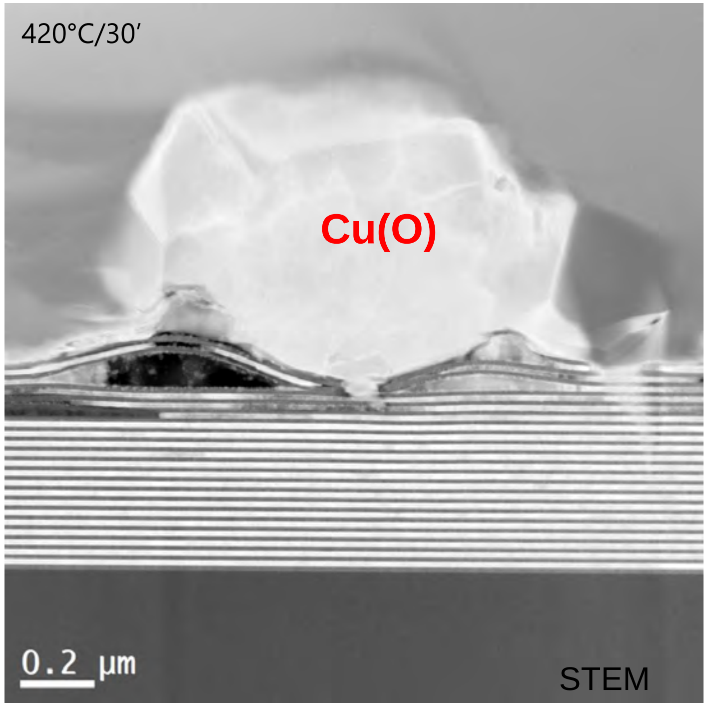
Ref./Source: J. Janczak-Rusch, et.al, Phys. Chem. Chem. Phys., 2015, 17, 28228-28238



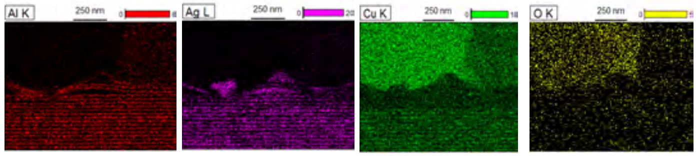
XRD pole figures for (a) the Ag(111) and (b) the AlN(0103) family of planes, as recorded from the $AgCu_{8nm}|AlN_{10nm}$ NML in the as-deposited state. (c) Phi-scans of the α-Al_2O_3(2-1-13), Ag(111) and AlN(10-13) reflections.

- Alternating nanocrystalline Ag-$Cu_{40at.\%}$ and AlN layers are of uniform thickness
- Ag-$Cu_{40at.\%}$ layers consist of fcc matrix of Ag nano-grains supersaturated with Cu
- Strong in-plane and out-of-plane texture, due to the orientation relationship Ag{111}<110>||AlN{0001}<1010>||Al_2O_3{0001}<1010>.

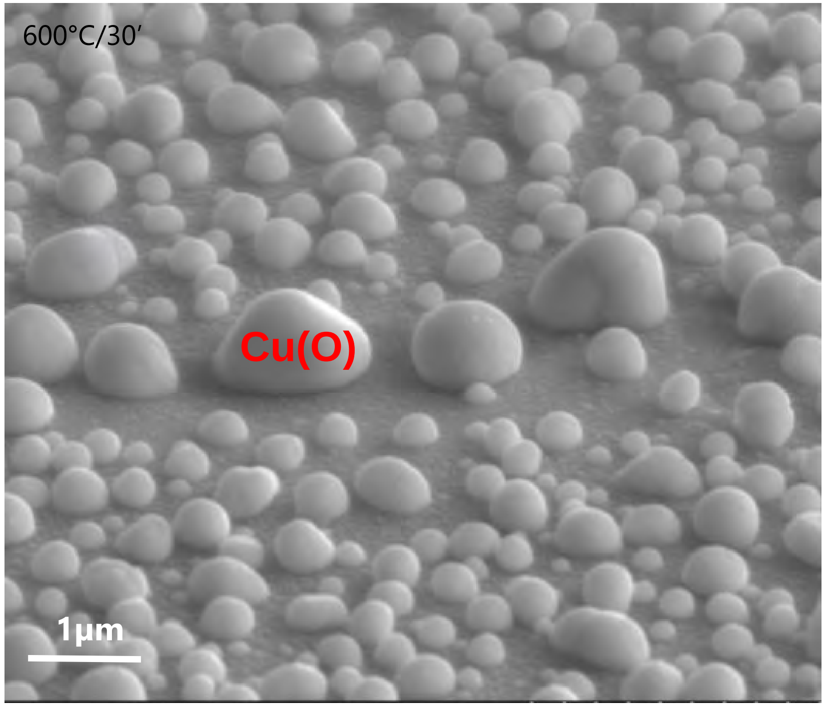
AgCu/AlN after isothermal annealing (420° and 600°C/30′)



NML cross section (TEM image)



TEM investigations: WUT, group of Prof. M.Lewandowska

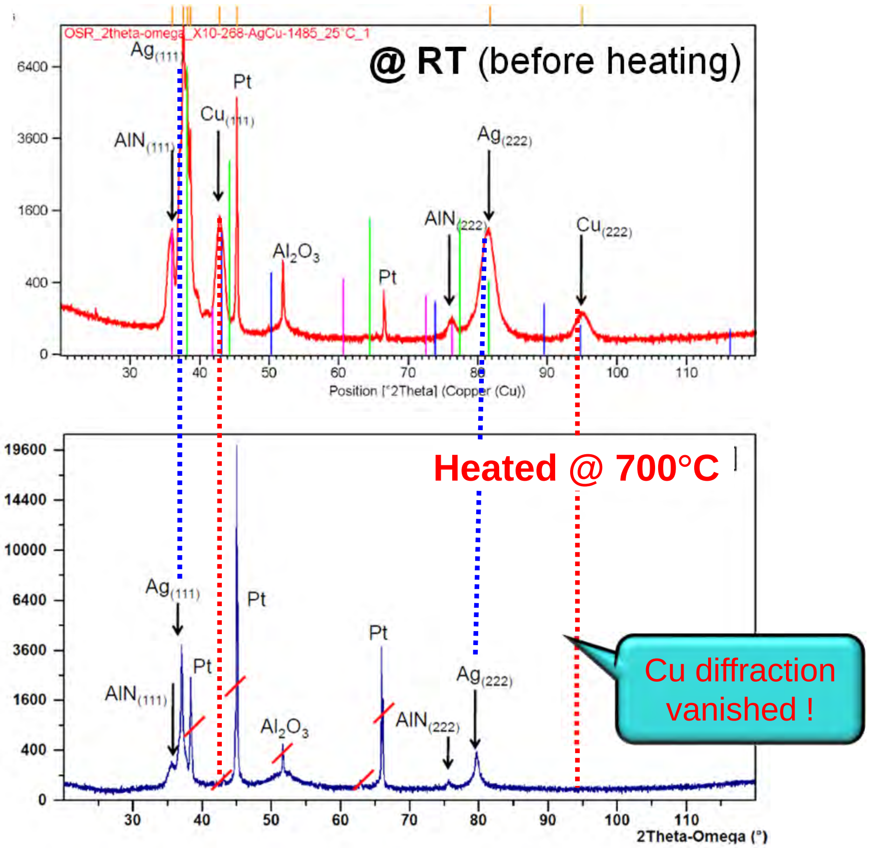


NML top surface (AlN as a top layer)

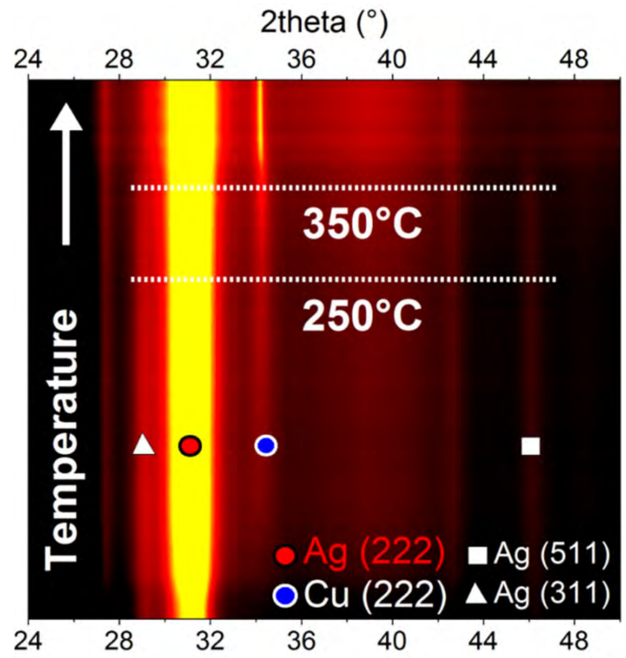
Massive "outflow" of Cu (only)

Melting point depression of confined Ag-Cu by HT-XRD:

HT XRD at CSEM



Real-time XRD at Synchrotron (PSI)



- **Significant structural changes for T>250°C**
- Cu grain size increase from 4nm to 26nm at T=265°C

J. Janczak-Rusch/Exploring nanomultilayers for joining technology applications/22

Ref./Source: J. Janczak-Rusch, et.al, Phys. Chem. Chem. Phys., 2015, 17, 28228-28238

Melting behavior of nanoconfined Ag-Cu/AlN

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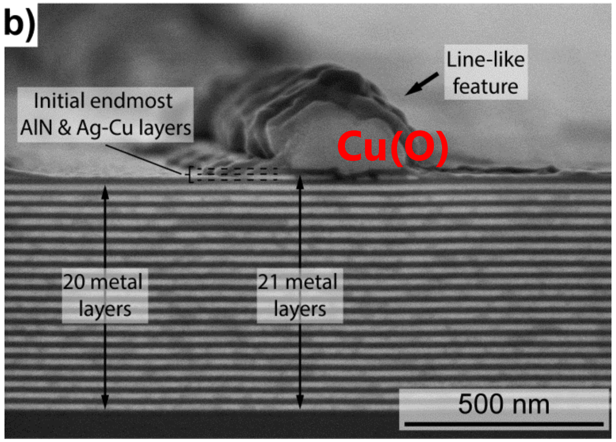
SEM after heating (420°C)



Cu surface protrusions

EDX point measurements			
As-deposited NML			
	Ag (at.%)	Cu (at.%)	O (at.%)
Bare NML	19.0±0.3	12.4±0.5	1.4±0.8
NML after fast heating to 420 °C			
Bare NML	20.3±0.3	10.8±0.4	0.8±0.7
Protrusion	0.7±0.1	**48.7±1.1**	**45.4±3.7**

Findings (XRD, SEM, TEM, EDX)

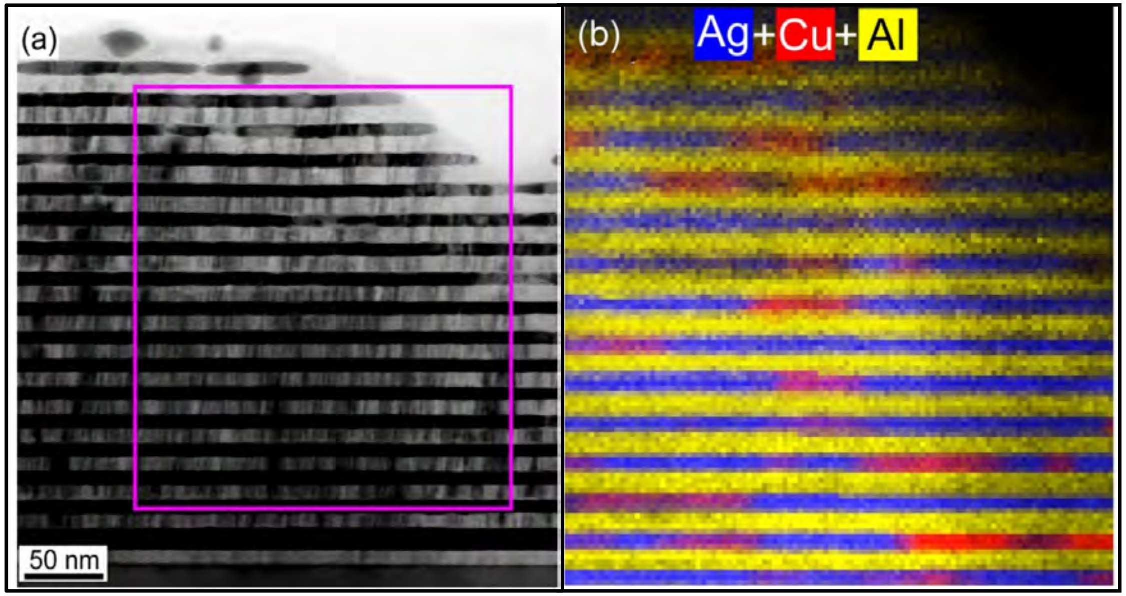
Non-eutectic melting behavior of confined Ag-Cu alloy !

Melting Temperature of	Bulk materials	in NML (layer thickness: 10nm)
Ag-Cu (eutectic)	778°C	heterogeneous melting (420-810°C)
Cu	1084°C	420-560°C
Ag	961 °C	> 700°C

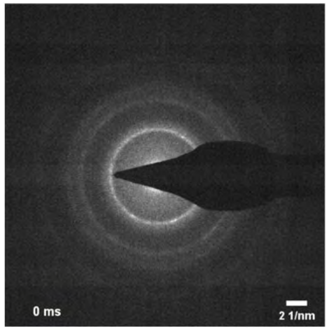
What is the reason for the observed behavior ?
Why the phase with a higher melting point (Cu) melts first?

Ref./Source: J. Janczak-Rusch, et.al, Phys. Chem. Chem. Phys., 2015, 17, 28228-28238

Phase separation in Ag-$Cu_{40at.\%}$/AlN NML



TEM (bright field)/EDS mapping of Ag-Cu_{8nm}/AlN_{10nm} NML after prolonged annealing at T > 250˚C



HT TEM AlN_{10nm}/$AgCu_{16nm}$/AlN_{4nm}, T=350°C, 0.4s

- Phase-separation with coarsening of Ag and Cu domains driven by large enthalpy of mixing and reduction of grain boundary energies
- Onset of phase separation becomes thermally activated at around 250 °C, but does not induce noticeable degradation of the NML structure
- It is a very fast process (~0.4 s); observed also for confined Al-Si alloys

Ref: J Mater Chem C 4 (2016), 4927

Interface's structure in Ag-Cu/AlN (DFT and HR TEM)

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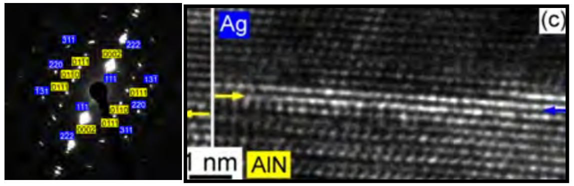
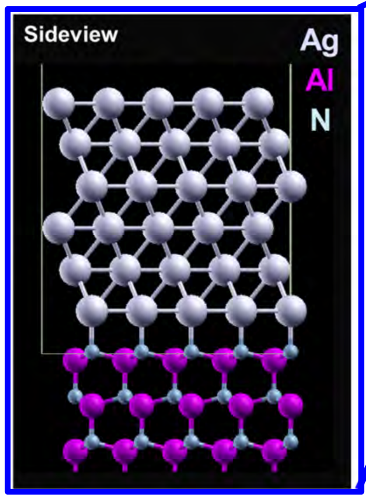
Ag/AlN interfaces

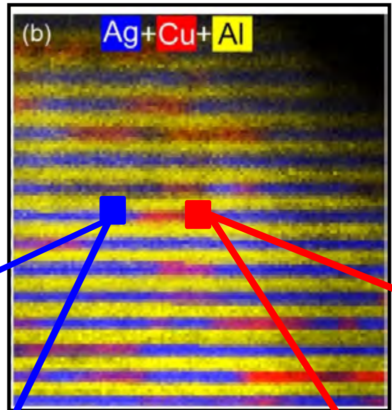


semi- Coherent (stable)



5x5x3-Ag unit cell on 5x5x3-AlN(0001)

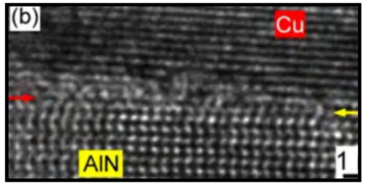
Phase-separated Ag-Cu



Refs: *Phys Chem Chem Phys 17 (2015) 28228, Appl. Phys. Lett. 101 (2012) 181602*

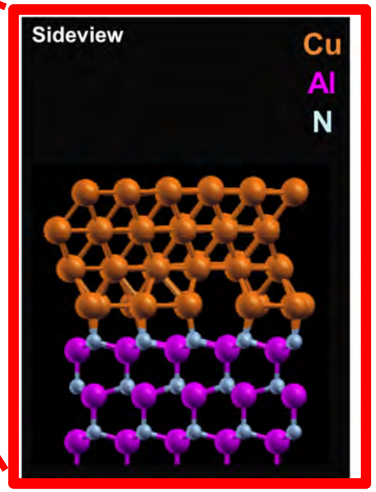
Lower enthalpy of defect formation and higher mobility along Cu/AlN interface, (preferential Cu migration)

Cu/AlN interfaces



HR-TEM

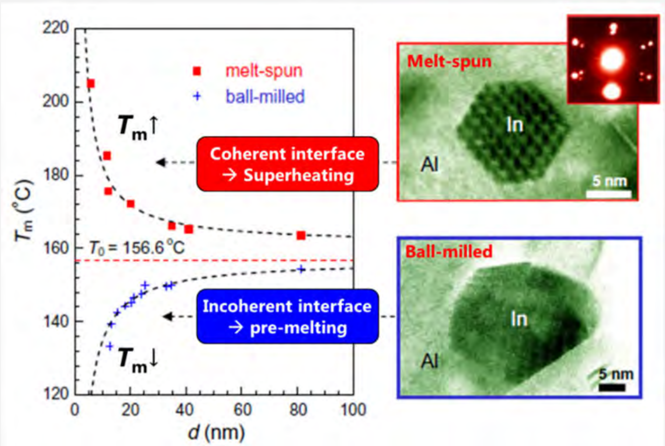
Incoherent (unstable) with strong in-plane disorder



5x5x1/6x6x3-Cu unit cell on 5x5x3-AlN(000$\bar{1}$)

The effect of the interface structure on solid-liquid transition

In particles embedded in a Al matrix (experimental study)

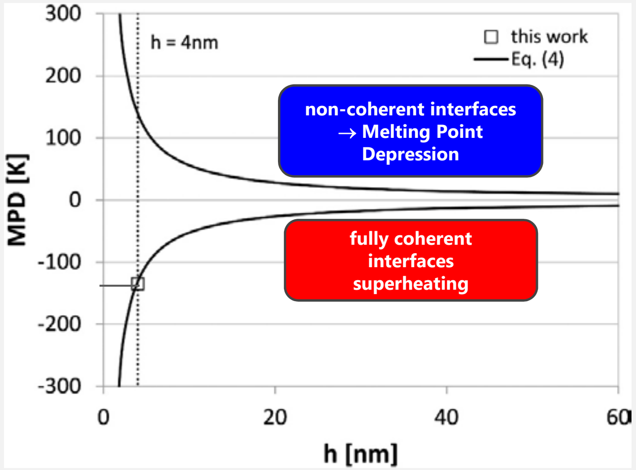


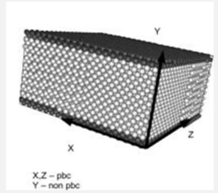
Effect of interface structure on melting of nano-confined metals

Ref: Lu & Jin, Curr. Opin. Solid State Mater. Sci. 5 (2001) 39

Nanoparticles coated by or embedded in a high melting point matrix with incoherent interface, exhibit a melting point higher than that of the bulk counterpart (superheating)

Confined Al thin films (molecular dynamics simulations)





A polycrystalline Al nanolayer (confined between two high-Tm material thin layers)

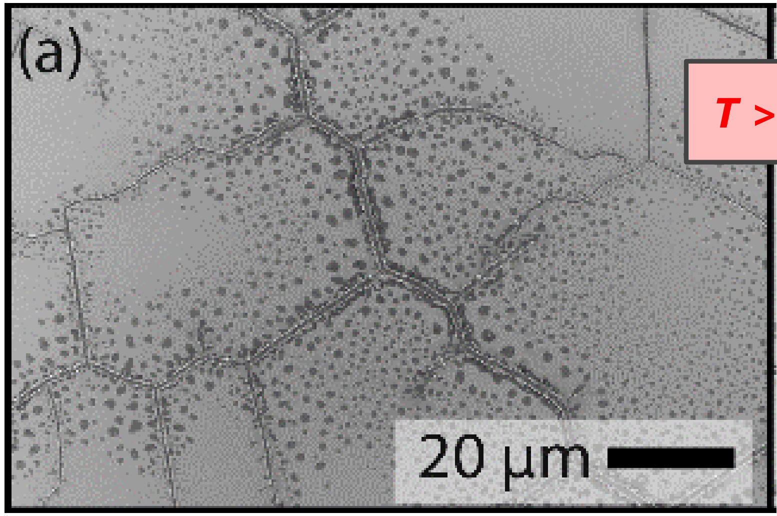
Effect of interface structure on melting point of confined thin aluminium films

Ref: T. Wejrzanowski, M. Lewandowska, K. Sikorski, K. J. Kurzydlowski, 2014. *doi:10.1063/1.4899240.*

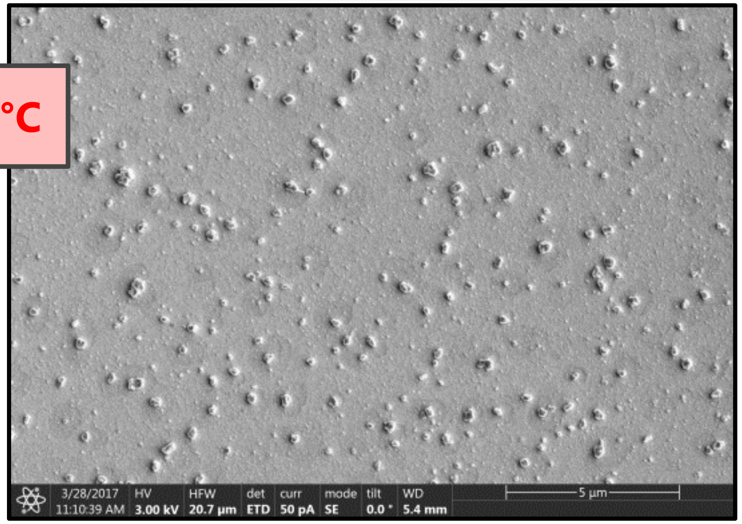
The coherent intercrystalline interface suppress the transition of solid aluminum into liquid, while free-surface gives MPD. Al thin film of 4nm thickness confined between coherent interlayers shows a MP of 131 K by MD higher than defect free infinite crystal

The effect of the barrier layer thickness

Thick AlN barrier (10 nm) → **Thin AlN barrier (4 nm)**



T > 300 °C



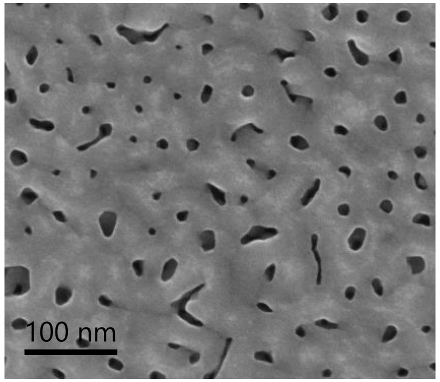
SEM Isothermally annealed Ag-Cu$_{40at.\%}$/AlN NML TEM

- Fast, patterned outflow of Cu
- Void formation
- Fracturing of AlN barrier layers

- Fast, homogenous outflow of Cu and Ag
- No void formation
- Sintering of AlN barrier layers

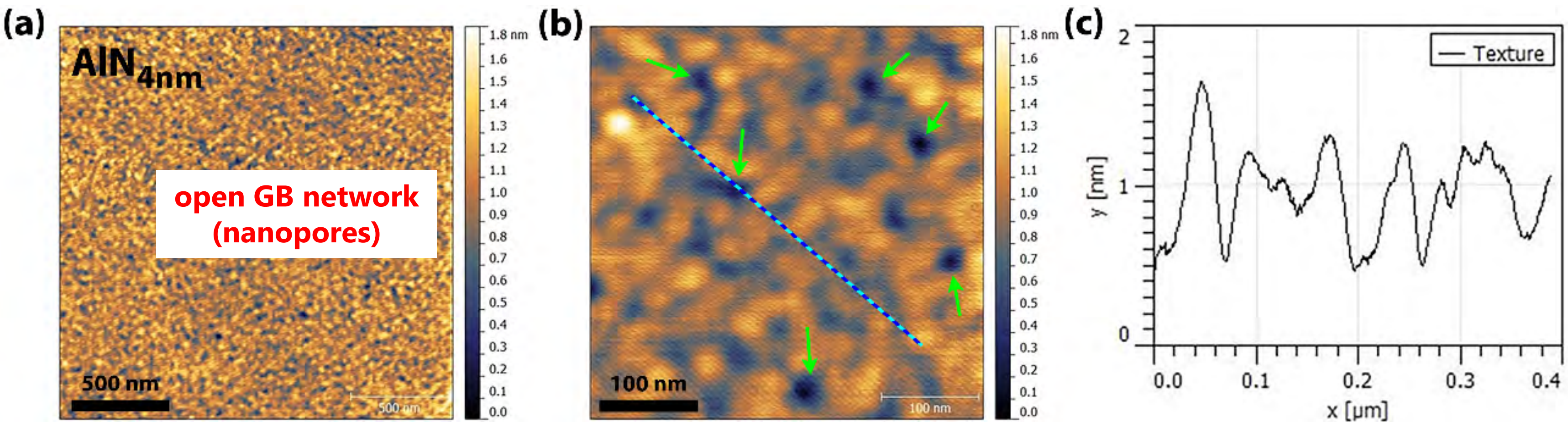
Ref: V. Araullo-Peters et. al. ACS Appl. Mater. Interfaces 116, 6605-6614

Directional mass transport in NMLs with ultra-thin barriers



Surface of thin AlN barrier (4 nm)

Ultra thin AlN nanolayers deposited by magnetron sputtering show open grain boundary structure. The open nano-channels promote the diffusion of confined metals (Cu and Ag) from the entire NML towards the surface.



Ref: V. Araullo-Peters et. al. ACS Appl. Mater. Interfaces 116, 6605-6614

Metal outflow in Ag-$Cu_{40at.\%}$/AlN NML with a thin barrier (4nm)

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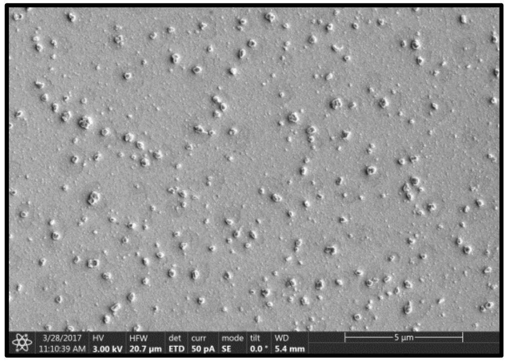
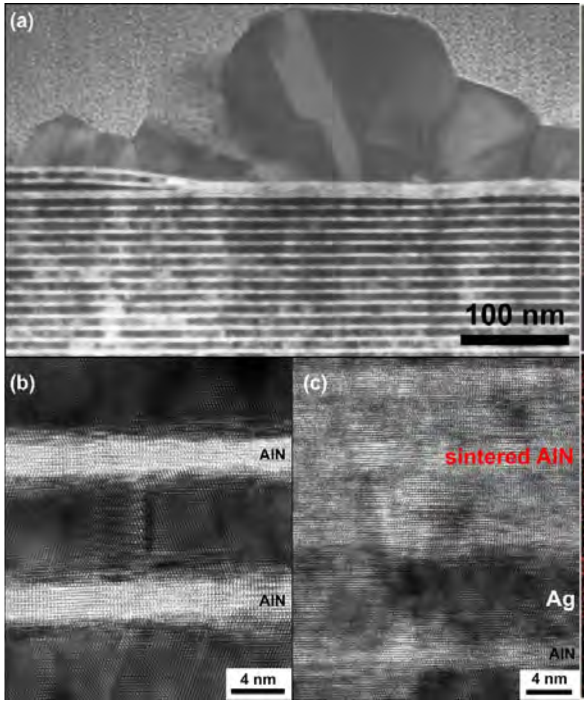
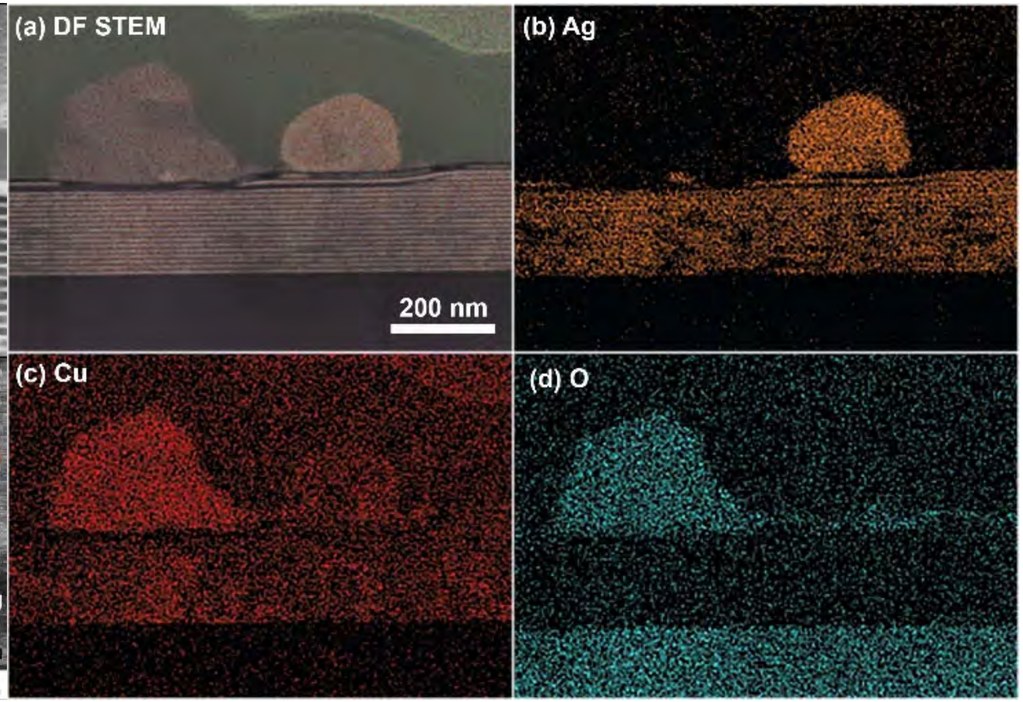


The NML surface is densely and homogeneously covered with submicron and nanometer sized Ag and Cu droplets
(*T* > 300 °C)





STEM micrographs and EDS elemental maps for the $AgCu_{8nm}|AlN_{4nm}$ NML cross-sections after 5 mins of isothermal annealing at 500 °C

Confined voids, as created by mass transport of Cu and Ag, have been closed by the deformation and partially sintering of the remaining AlN barrier layers!

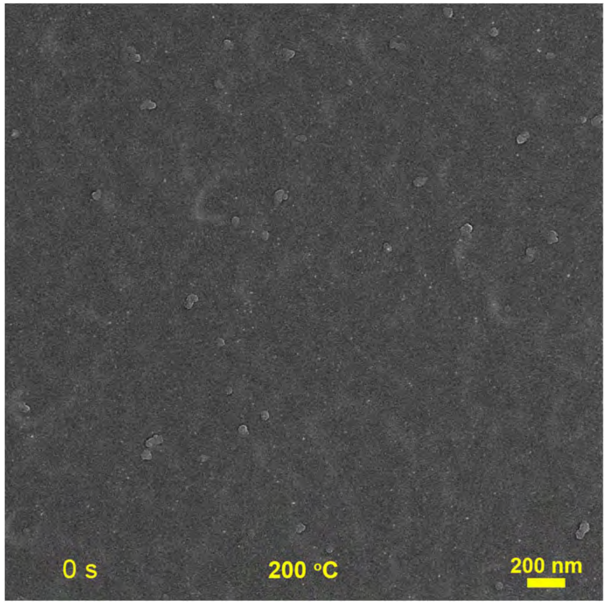
Ref: V. Araullo-Peters et. al. ACS Appl. Mater. Interfaces 116, 6605-6614

Lessons learned from the case study 2

- Nano-confined alloys of bulk eutectic composition can show non-eutectic melting (heterogeneous process).
  - Sputter deposited Ag-Cu/AlN NMLs undergo **phase separation** of Ag and Cu (a very fast process) nano/grains, as driven by large positive enthalpy of mixing.
- Melting point depression strongly depends on the structure of local interfaces and energetics.

•The Cu nano-grains form incoherent AlN interface with AlN, resulting in random in-plane texture and high melting point depression of ~ 500°C.

• The outflow of the confined material can be tuned

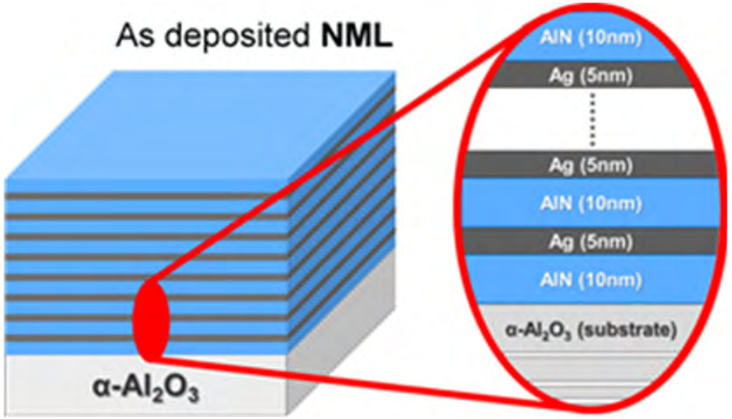


Phase transformations in AlN/Ag-Cu_{18nm}/AlN sandwich 200-400°C (in-situ TEM observations)

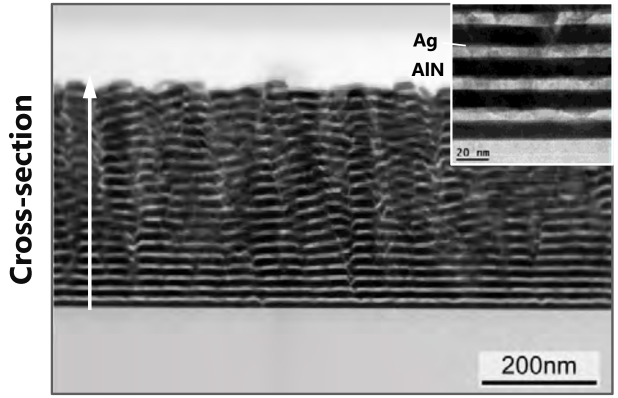
Ref: V. Araullo-Peters et. al. ACS Appl. Mater. Interfaces 116, 6605-6614

Does a nanoconfined “eutectic” alloy offer any advantages in terms of MPD?

Case study 3:
Ag_{5nm}/AlN_{10nm} (20x) nanomultilayer



Collaboration with WUT



Model system: Ag_{5nm}/AlN_{10nm} (20x)

Ref: J Mater Chem C 4 (2016), 4927

The behavior of Ag/AlN nanomultilayers upon heating

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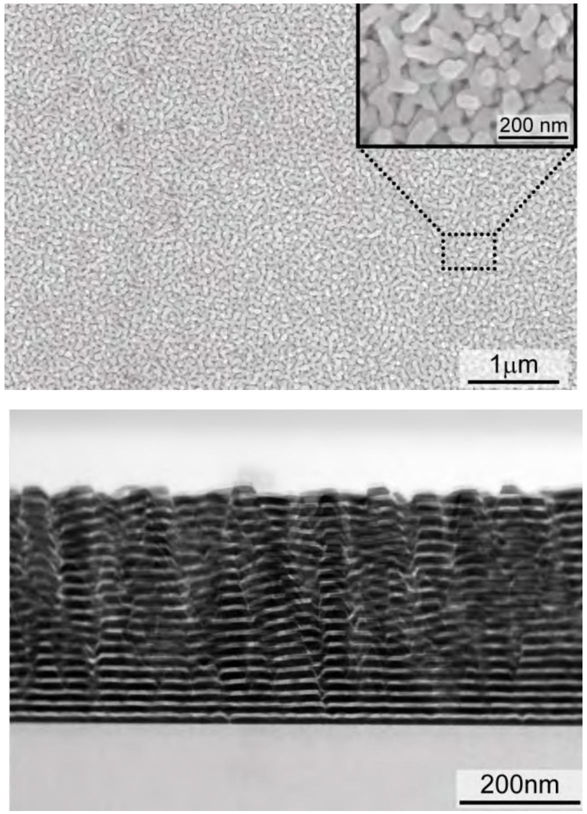
As deposited

Surface

Cross-section

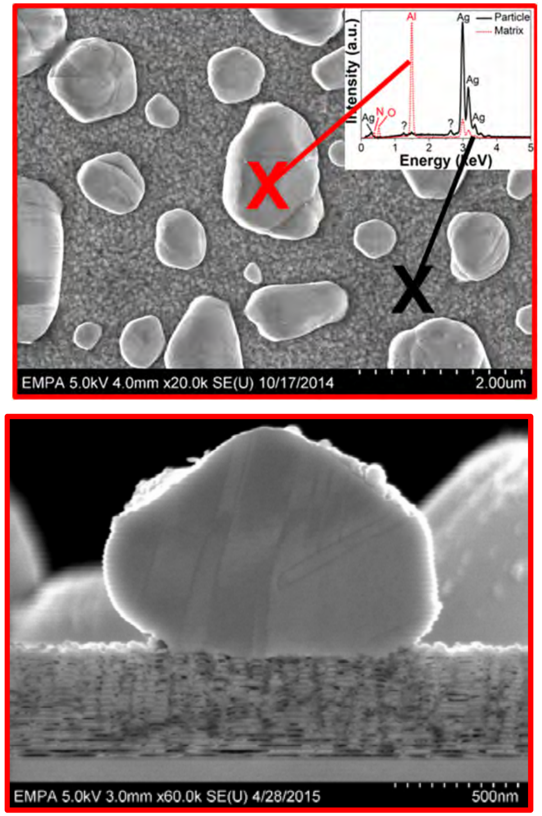


Pronounced island growth of Ag,
significant NML roughness

420°C/30”

in air

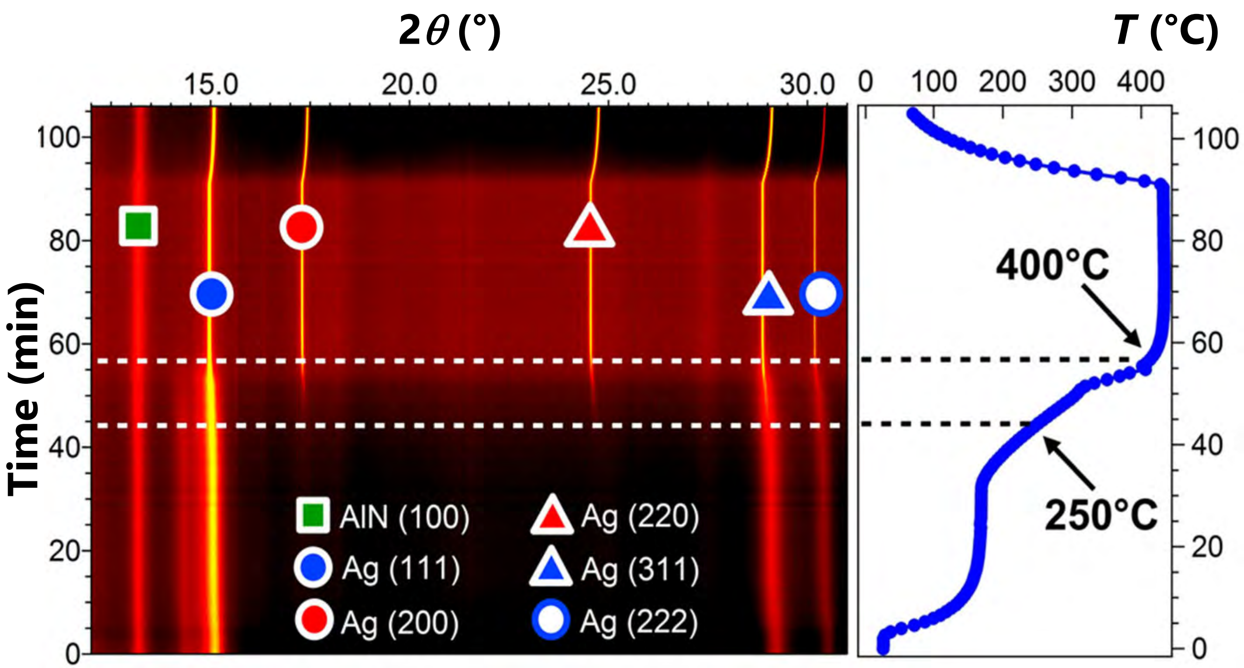
After heating at **420°C/30min**



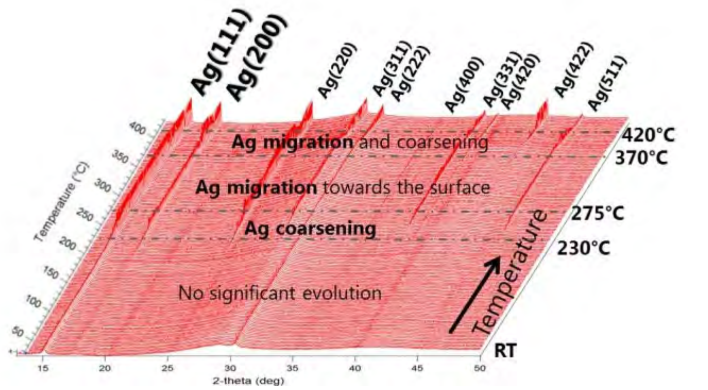
Extensive Ag migration to the NML
surface at T < Tm

Ref: *J Mater Chem C 4 (2016), 4927*

In-situ tracing of the outflow of nanoconfined Ag during heating (XRD at the synchrotron)



Measured diffractograms during heating in air *Heating ramp*



M. Chiodi et. al. Massive Ag migration through metal/ceramic nano-multilayers. J,.Mat. Chem.C, 4[22]2016(4927-4938).

- Initially very broad peaks become narrower upon heating
- Appearance of Ag (200) & Ag (220) reflections (enhanced polycrystallinity!) at T>250°C

In-situ XRD at the synchrotron during heating of Ag/AlN NMLs in air evidences very fast outflow of Ag to the surface at temperatures as low as 250 °C!

In-situ tracing of Ag outflow during heating

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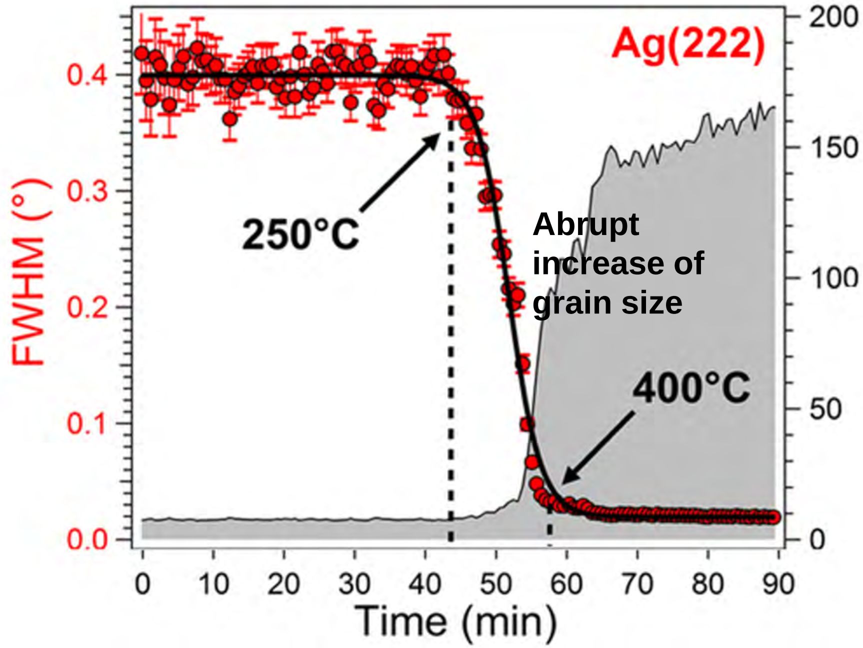
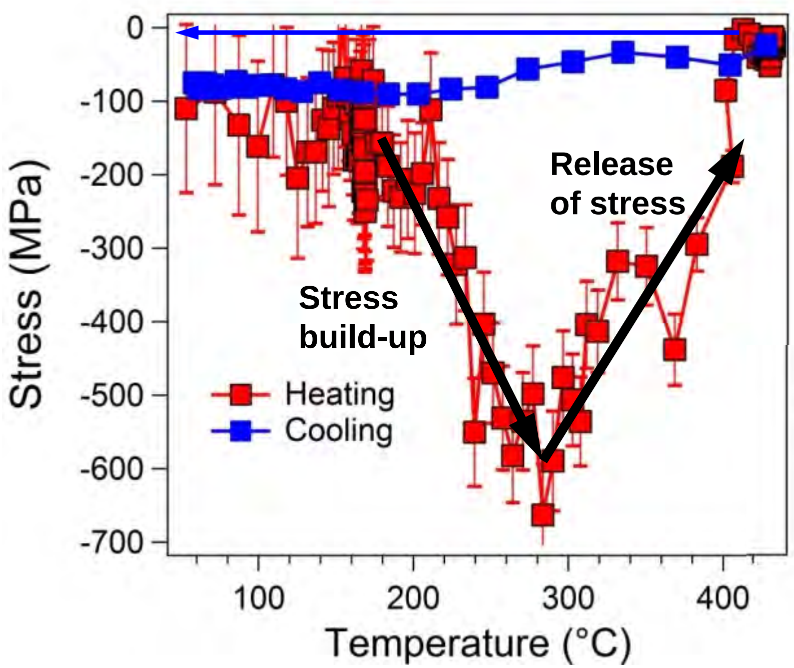
Ag grain-size evolution



Average stress evolution



Ag_{5nm}/AlN_{10nm}

Uniform Stress Deformation Model applied to **Ag(111) and Ag(222)**

$$\beta_{hkl} \cos\theta_{hkl} = \frac{K\lambda}{D} + \frac{4\sigma \sin\theta_{hkl}}{Y_{hkl}}$$

Sherrer formula — Stress-related broadening

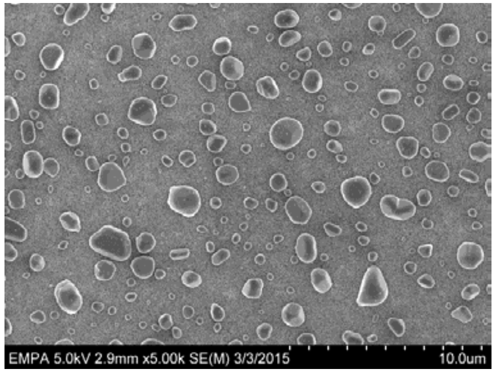
β is the measured **FWHM**
θ is the diffraction **angle**

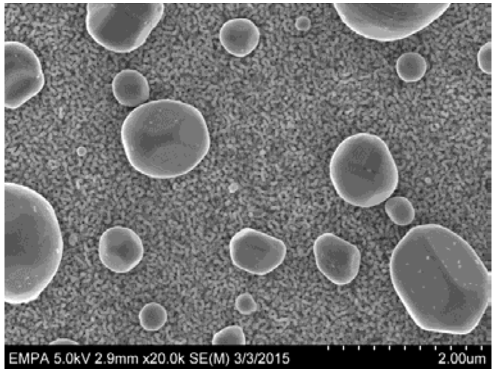
M. Chiodi et. al. Massive Ag migration through metal/ceramic nano-multilayers. J,.Mat. Chem.C, 4[22]2016(4927-4938).

Ag migration is related to the stress-release in the NML

The effect of atmosphere on the Ag outflow and thermal stability of Ag/AlN NMLs

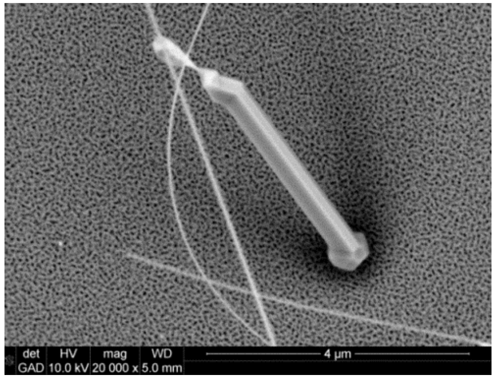
Heating in Air





High number density of surface particles (no whiskers)

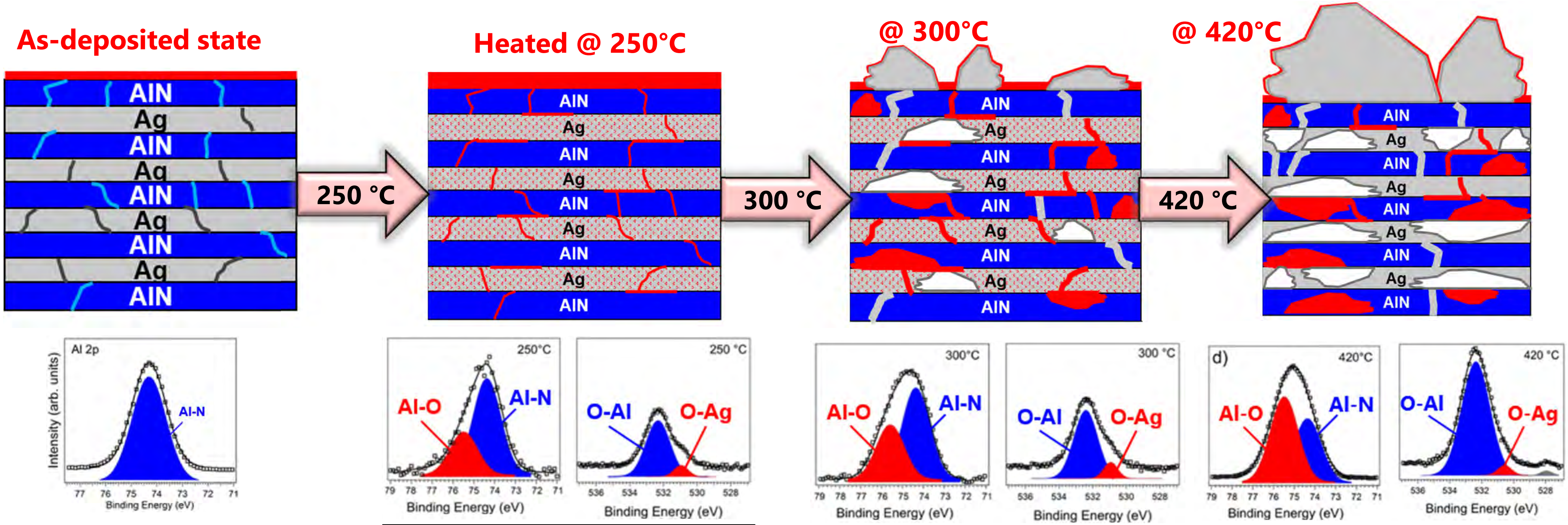
Heating in vacuum (or single layers**)**



Whisker formation by slow solid state diffusion

Ref: J Mater Chem C 4 (2016), 4927

Effect of O_2(g) on thermal stability of Ag/AlN by ex-situ XPS



- NML is oxygen free!

- O inward diffusion along internal interfaces to react with AlN forming AlO_x
- O partially interacts with Ag

- Ag migrates to surface to release accumulated stress (O diluted in Ag enhances the kinetics)
- Coarsening of Ag particles

- Ag is almost entirely relocated to the NML top surface, outflow has stopped

Interaction of O with Ag enhances enthalpy of Ag vacancy formation and thereby the Ag atomic mobility!

M. Chiodi et. al. Massive Ag migration through metal/ceramic nano-multilayers. J,.Mat. Chem.C, 4[22]2016(4927-4938).

A new phenomena of nano-volcanic eruption of Ag orginating in Ag-O interactions

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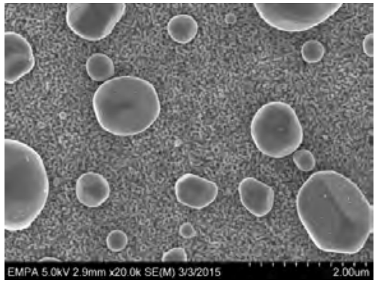
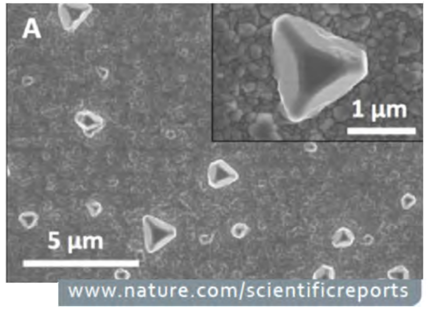


April 2016, Empa, WUT: massive, oxygen enhanced Ag migration in sputtered Ag/AlN NMLs (here: Ag_{5nm}/AlN_{10nm} after annealing at 420°C)

Chiodi, et. al., Massive Ag migration through metal/ceramic nano-multilayers: an interplay between temperature, stress-relaxation and oxygen-enhanced mass transport, J. Mater. Chem. C, 2016

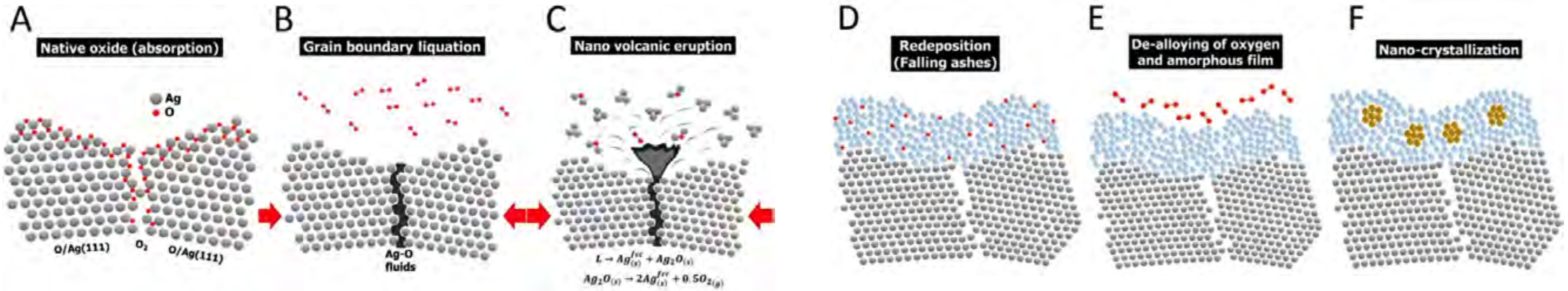
https://www.freepik.com/premium-vector/volcano-eruption-with-lava_9433373.htm

Ag nano-volcanic eruption: abundant Ag hillock formation by several interactions between Ag and O, which can be exactly analogized to a volcanic eruption and the deposition of ash.



Oct. 2016, Osaka University and Cheng Kung University: abundant Ag hillock formation on sputtered Ag films at elevated temperatures (here: 1µm thick Ag thin films sputtered on Ti-coated Si wafers and annealed at 250°C/ 5 min)

Sk. Lin, S. Nagao, E. Yokoi, at al., Nano-Volcanic Eruption of Silver, Scientific Reports (6)2016



The phenomenon involves grain boundary liquation, the ejection of transient Ag-O fluids through grain boundaries, and the decomposition of Ag-O fluids into O_2 gas and suspended Ag and Ag_2O clusters. www.nature.com/scientificreports

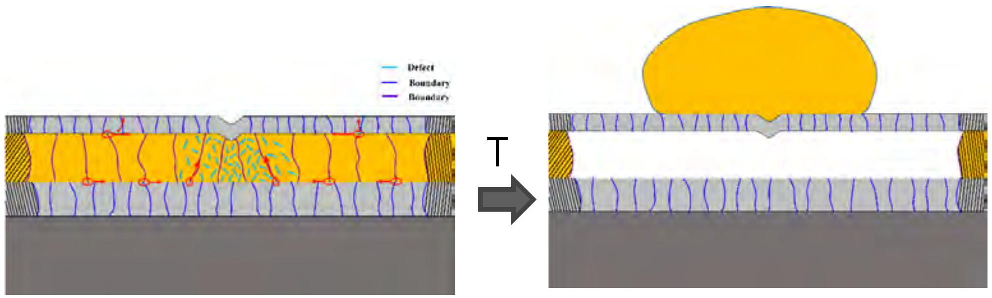
Lessons learned from the case study 3 (Ag/AlN)

- Fast and **extensive migration** of nano-confined Ag at temperatures **T > 250°C** (well below bulk melting point of 962°C) can be evoked by **oxygen**.
- Migration of the nanoconfined metal is related to the stress-release in the NML

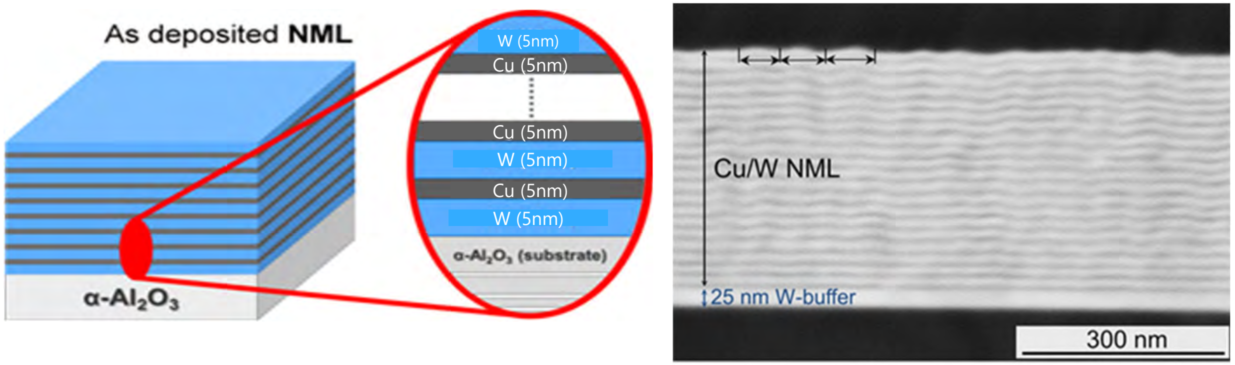
Application-oriented findings:

- New opportunities for the development of joining processes
  - Fast, low-temperature bonding processes with nano-confined brazing fillers are possible
    - no explicit need of melting of the brazing filler or using brazing filler alloys (higher MPD can be practically easier achieved for confined metals than for alloys)
    - use of air as brazing atmosphere can be a choice (low-cost processes)

Can we control the outflow of the confined metal for a localized bonding?



Case study 4:
Cu/W nanomultilayer



How to make high-strength joints of refractory metals at T<750°C?

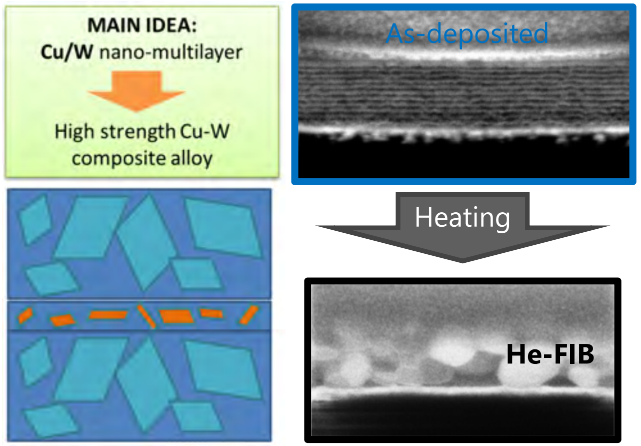
Industrial request (2014-2016) W_{25nm}+(Cu_{5nm}/W_{5nm})x100

Refs.: F. Moszner, et. al. , J. of Mat. Sci. Eng. B 6 (2016) 226-230
C. Cancellieri, et. al. J. Appl. Phys. 2016, 120, 195107
F. Moszner, et. al. Acta Materialia 2016, 107, 345-353

Cu/W nanomultilayer as a brazing filler

Requirements: high-strength joints at T < 750°C

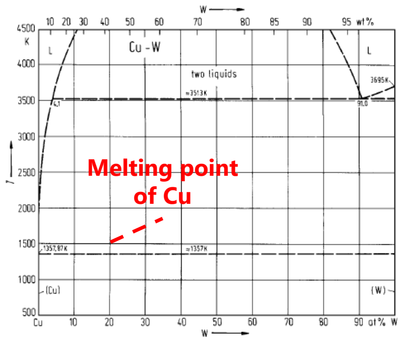
Approach



- Cu alloys reinforced with W-particles offer attractive mechanical properties
- NML approach with to join at relative low temperatures and to form in-situ a high-strength composite (transformation of NML to particular-based composite)

Material System

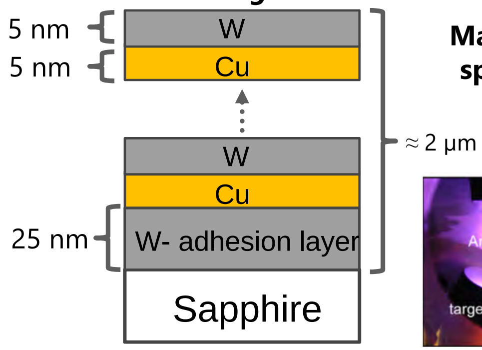
Phase diagram Cu – W



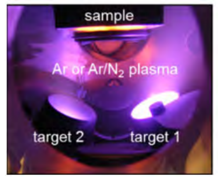
- Immiscible system
- No solid state phase transformations up to the melting point of Cu
- Large CTE mismatch

Methods

NML configuration



Magnetron-sputtering



$W_{25nm}+(Cu_{5nm}/W_{5nm})x100$

- Characterization via SEM, XRD
- Isothermal treatments experiments performed between 400-800°C/100 min (in vacuum)
- Isothermal *in-situ* HT-XRD (675-725°C) to study kinetic of the structural transformation

Refs.:
F. Moszner, et. al. , J. of Mat. Sci. Eng. B 6 (2016) 226-230
C. Cancellieri, et. al. J. Appl. Phys. 2016, 120, 195107
F. Moszner, et. al. Acta Materialia 2016, 107, 345-353

Thermal Stability of Cu/W (SEM investigations)

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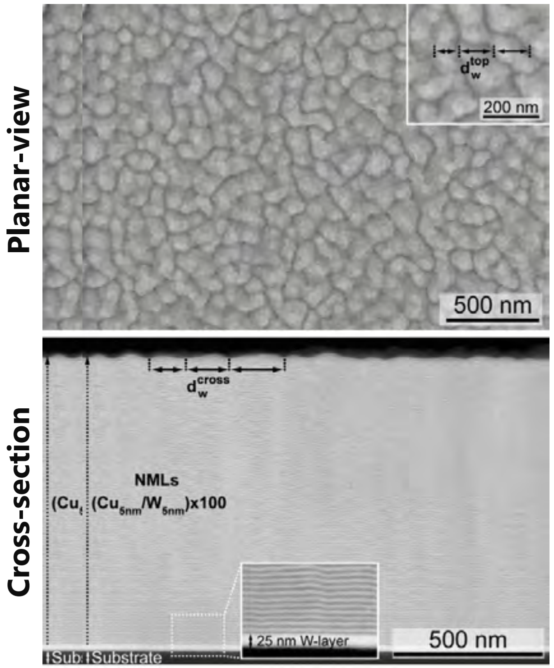
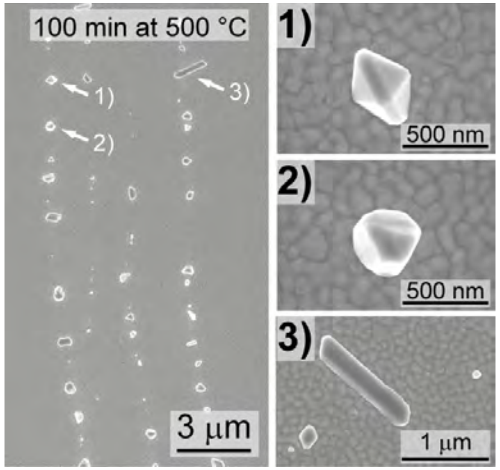
As deposited NML



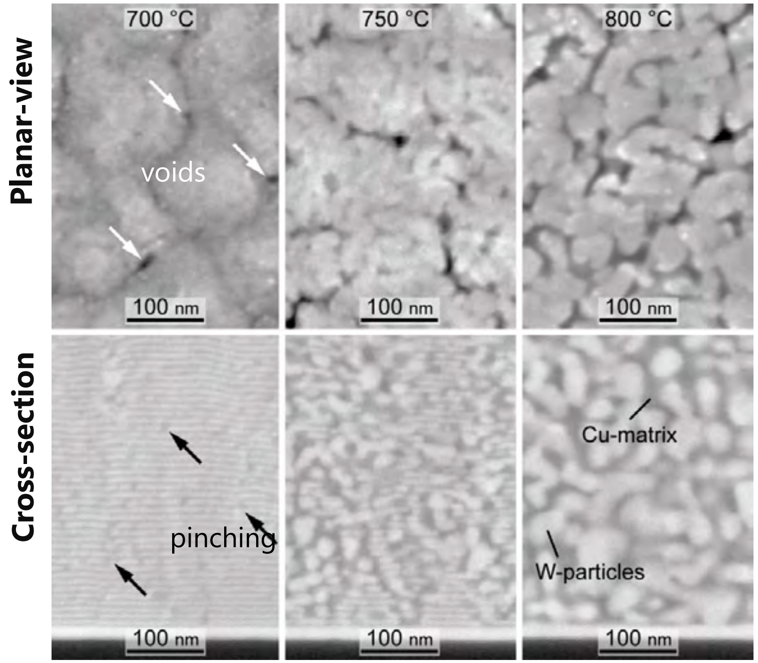
- Increase in layer waviness with increasing number of repetitions
- Semi-coherent interface between Cu and W layers

First structural changes



- Starting from 500°C a high number of lines with facetted Cu particles appear on the surface
- No severe defects (crack, voids)

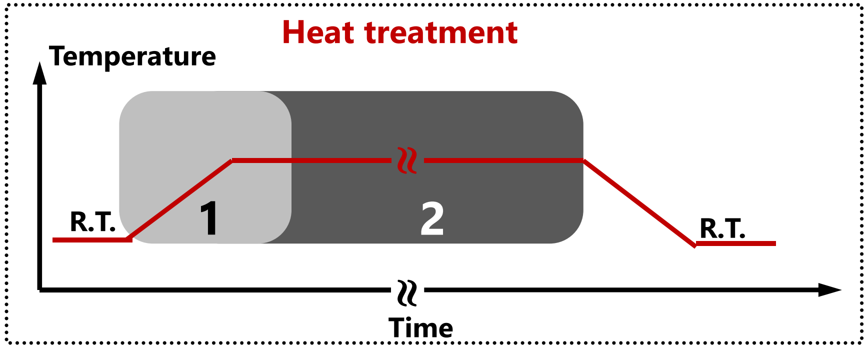
Transformation from NML to nanocomposite

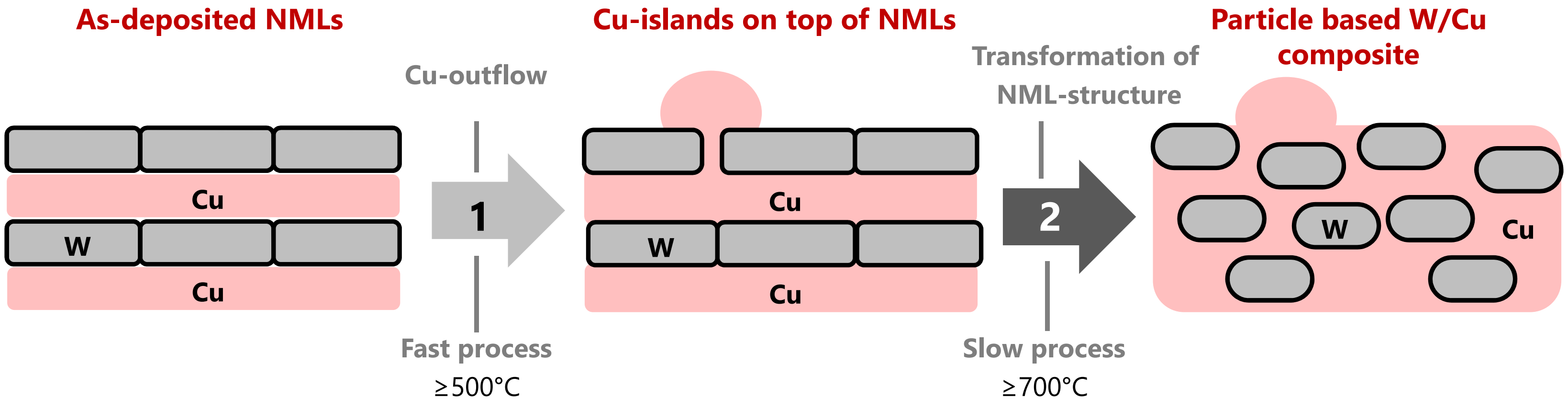


- T>650°C: Degradation of the NML (formation of voids at the surface and pinching of the layers) and formation of a spheroidized Cu-W nano-composite
- NML degradation progresses is completed at 800°C

Refs.: F. Moszner, et. al. , J. of Mat. Sci. Eng. B 6 (2016) 226-230
C. Cancellieri, et. al. J. Appl. Phys. 2016, 120, 195107
F. Moszner, et. al. Acta Materialia 2016,107, 345-353

Structural evolution of Cu/W upon heating



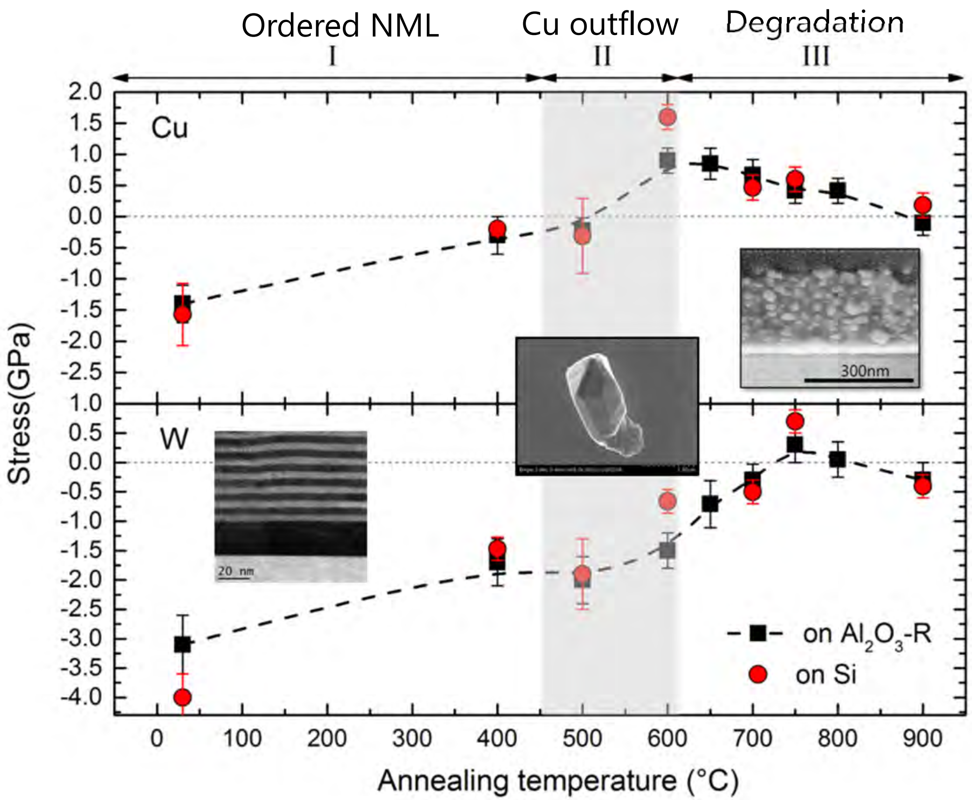


Presumably driven by stresses

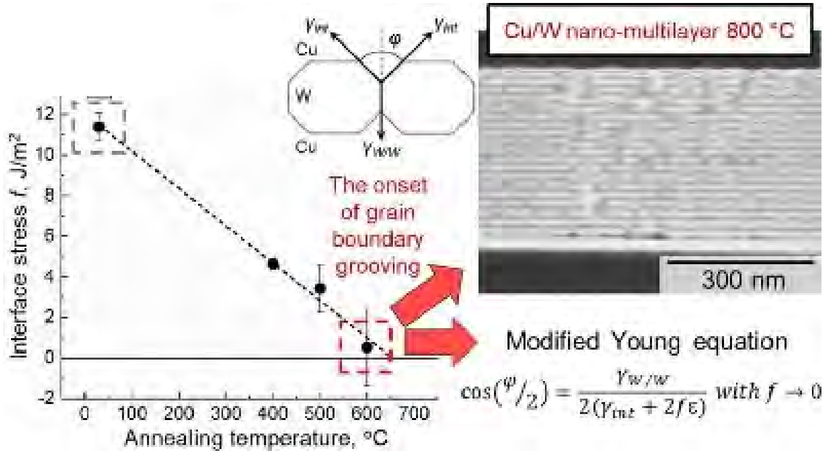
Governed by diffusion along internal interfaces

Refs.: F. Moszner, et. al. , J. of Mat. Sci. Eng. B 6 (2016) 226-230
C. Cancellieri, et. al. J. Appl. Phys. 2016, 120, 195107
F. Moszner, et. al. Acta Materialia, 2016, 107, 345-353

Effect of stress on GB diffusion in Cu/W NMLs

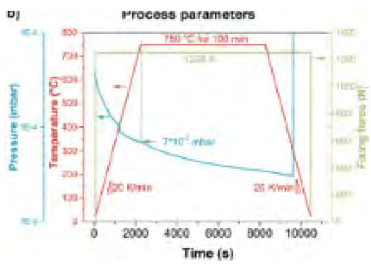


Refs.:
A. V. Druzhinin, et. al. Appl. Surf. Sci. , 2020, 508, 14254
A.V. Druzhinin, et. al., Materialia, 2019, 7. 100400



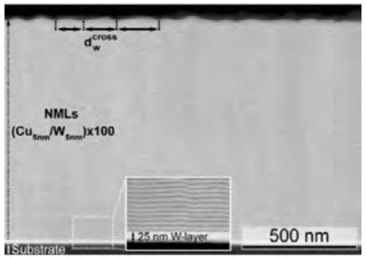
High compressive stresses in the W barrier layer increase the effective activation energy for Cu diffusion in W GBs (by a factor of ~1.5) and considerably slow down the diffusion kinetics

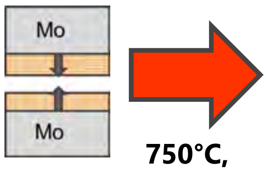
Joining with Cu/W nanomultilayers: proof-of concept



As-deposited NML (SEM image)

Cross-section

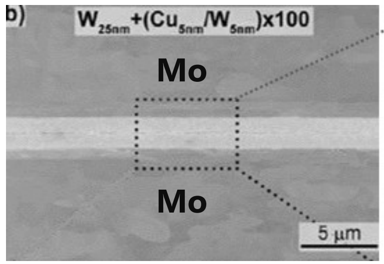


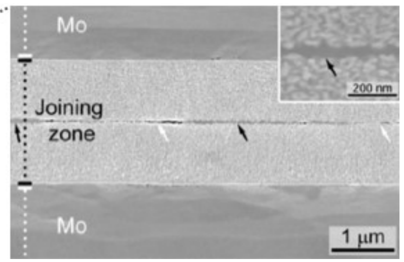


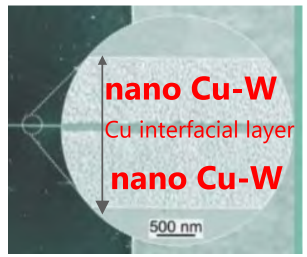
750°C, 30min

High strength refractory metal joints with Cu/W NML @ 750°C

Refs: F. Moszner et al, J Mater Sci Eng B 6 (2016) 226







In-situ formation of a nanocomposite in a joint during brazing process

High strength joints can be achieved with NMLs at reduced brazing temperatures

Lessons learned and outlook case study 4 (Cu/W)

- High strength nanocomposite can be in-situ formed during the bonding process when using NMLs of immiscible metallic systems such as Cu-W as a bonding material
- The temperature of the transformation process can be controlled by the imterfacial stress

Outlook:

- Engineering of NMLs of immiscible metals for joining application and thermal management
  - NMLs with desired functional properties
- Deeper understanding of the behaviour NMLs of immiscible metals
  - In-situ control of internal stresses during the NML deposition
  - Combing experiments with modelling

NMLs offer a great “engineering tool”

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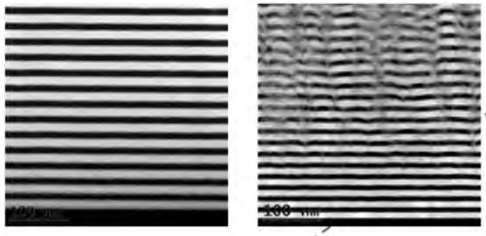
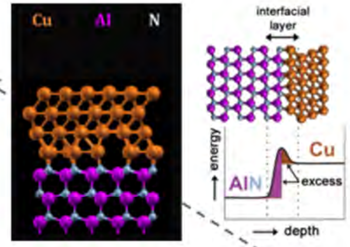
Size



Interfaces
- NML/Base material
- Barrier/Braze
- Grain boundaries...

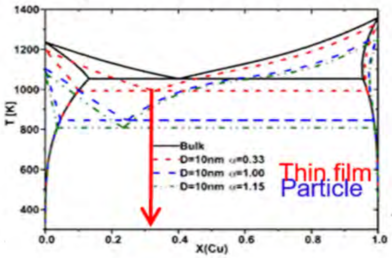


Interface defect structure

Brazing filler metal
- Thickness
- Nanophase diagram
- Phase separation

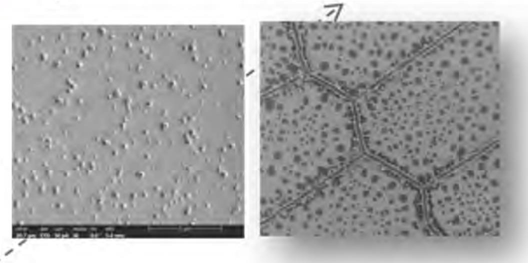
Brazing filler in a multilayer configuration
- Melting and diffusion behaviour

Barrier layer
- “Compatibility” with the braze material
- Joint properties



Composition

Deposition process
- uniformity of the layers
- growth mode
- layer roughness



Stresses

but the new phenomena and complex relationships between the design parameters need to be fully understood

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Current Joining Team

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- ✓ Dr. Bastian Rheingans
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- ✓ Dr. Hans-Rudolf Elsener
- ✓ Dr. Claudia Cancellieri

Former Team Members

- ✓ Dr. Vicente Araullo-Peters
- ✓ Dr. Vinzenz Bissig
- ✓ Dr. Mirco Chiodi
- ✓ Dr. Joanna Lipecka
- ✓ Dr. Frank Moszner
- ✓ Dr. Giancarlo Pigozzi
- ✓ Dr. Sebastian Siol
- ✓ Benjamin Lehmert

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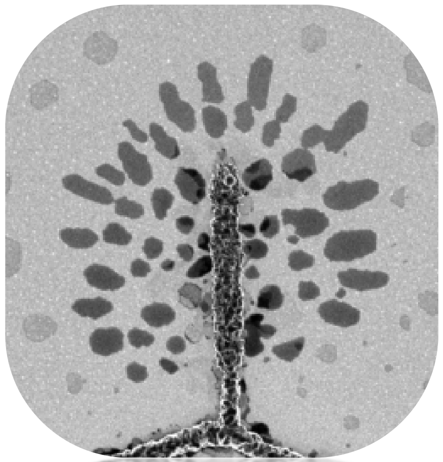
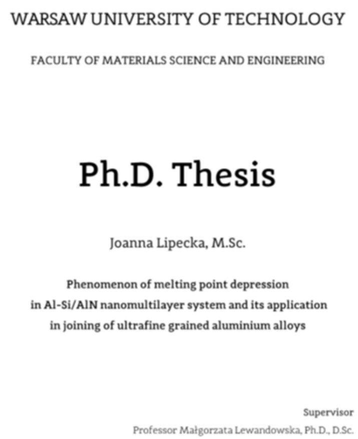


Thank you for your attention!

Follow-up study on Al-Si/AlN NMLs

- The description of underlying mechanisms and microstructural characteristics that govern the phase stability, diffusion and pre-melting behaviour of nano-confined Al and Al-Si alloys in a NML (Barrier: Aln)
- A significant contribution to the understanding of the melting point depression/superheating phenomena and of phase stability of nano-confined alloys



WARSAW UNIVERSITY OF TECHNOLOGY

FACULTY OF MATERIALS SCIENCE AND ENGINEERING

Ph.D. Thesis

Joanna Lipecka, M.Sc.

Phenomenon of melting point depression
in Al-Si/AlN nanomultilayer system and its application
in joining of ultrafine grained aluminium alloys

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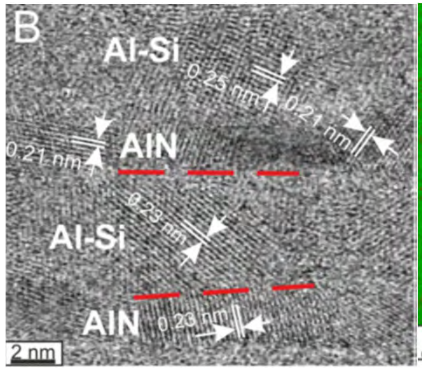

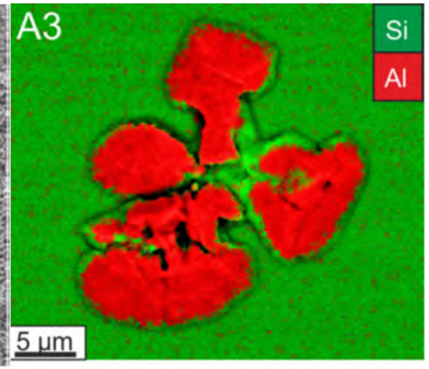

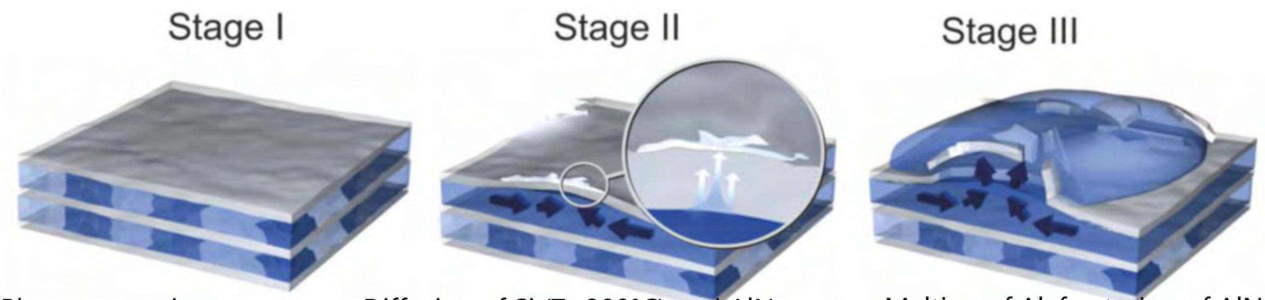

Phase separation

Diffusion of Si (T>200°C) and AlN barrier deformation under large compressive stresses

Melting of Al, fracturing of AlN barrier and "splashing" of liquid Al

Schema of the microstructural changes of an Al-Si12%at.4nm/AlN3nm NML upon heating