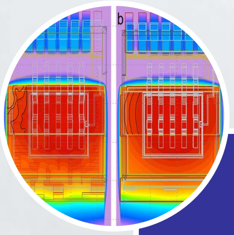
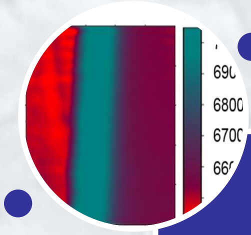
Thermo-physical properties of 500 nm thin Tungsten films investigated with Time Domain Thermoreflectance and Scanning Thermal Microscopy

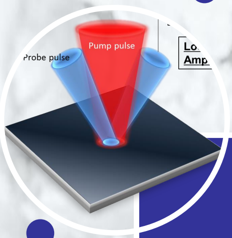
Katrin Fladischer



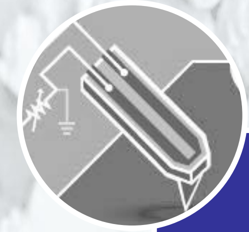
Motivation: Thermal Management @ mcl



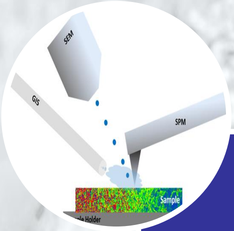
SThM @ mcl



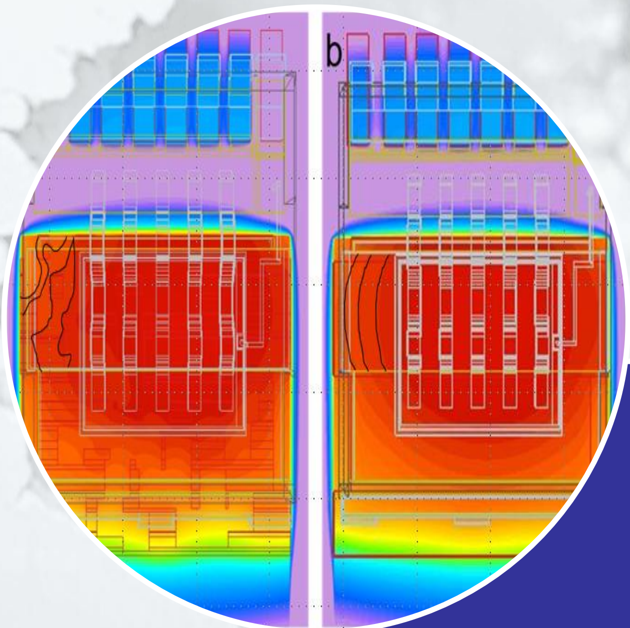
W thin film investigated by TDTR



W thin film investigated by SThM

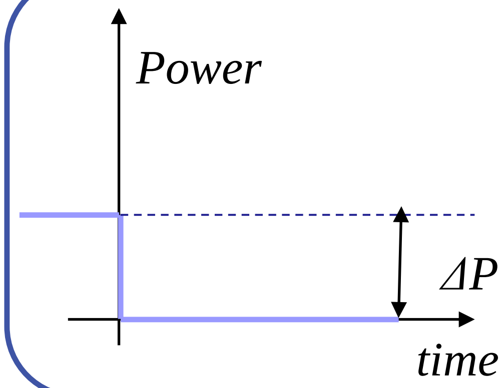


Outlook

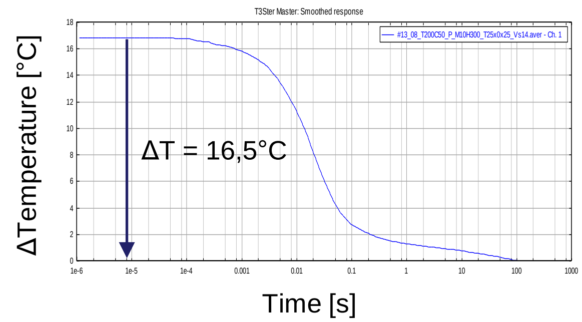


Motivation: Thermal Management @ mcl

Motivation: Thermal Transient Analysis



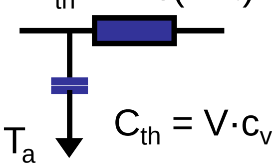
Thermal transient $\Delta T_j(t)$



Time constant spectrum $R_\zeta(\zeta)$

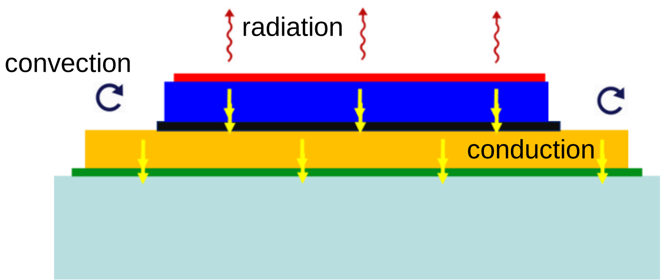
Structure function

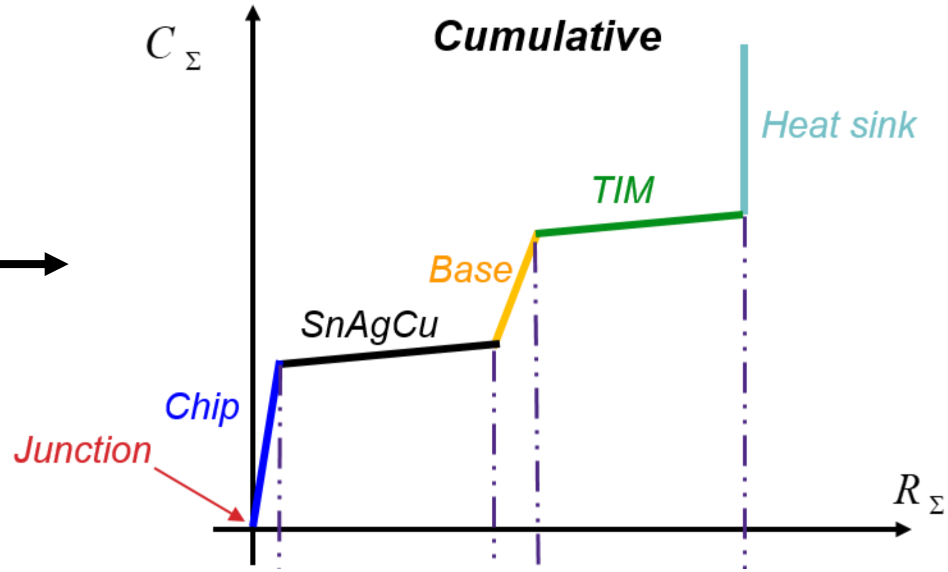
$R_{th} = \Delta L/(A\cdot\lambda)$



$C_{th} = V\cdot c_v$

- Discretize
- Foster -Cauer transformation

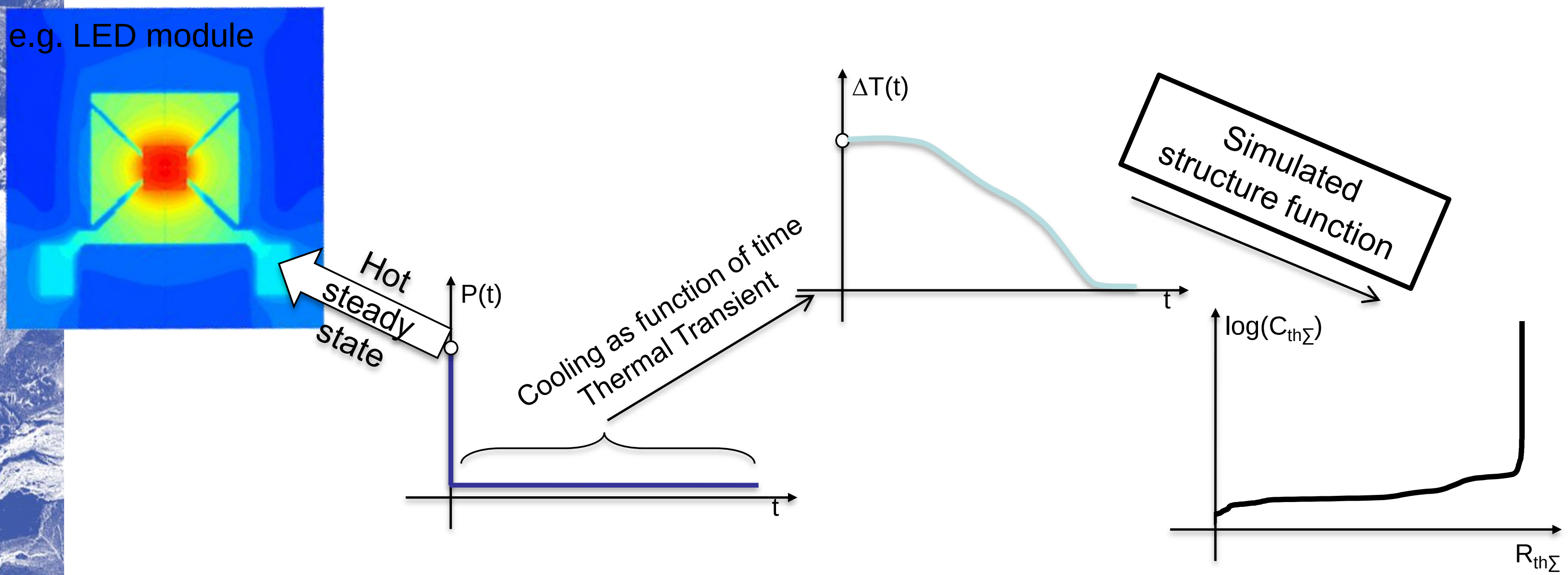




→ can be measured

Motivation: Thermal Transient Analysis - Simulation

Simulation is used to create the thermal transient.



Comparison of simulation and measurements.

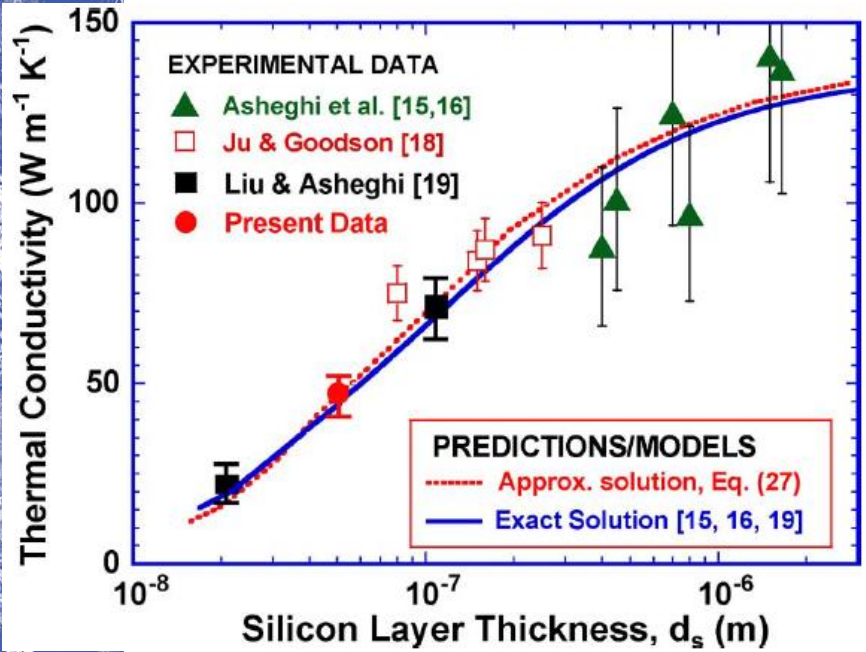
Simulated structure function = measured structure function

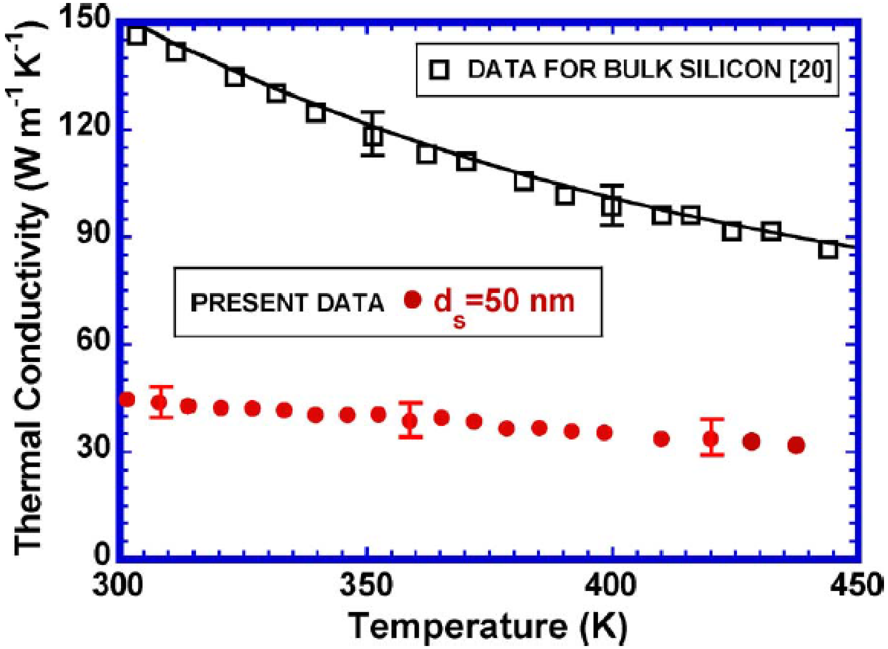
→ Validated system

Adjustment of the module‘s material stack:

Variation of ρ, λ, c_p

Size Effect – Thermal conductivity



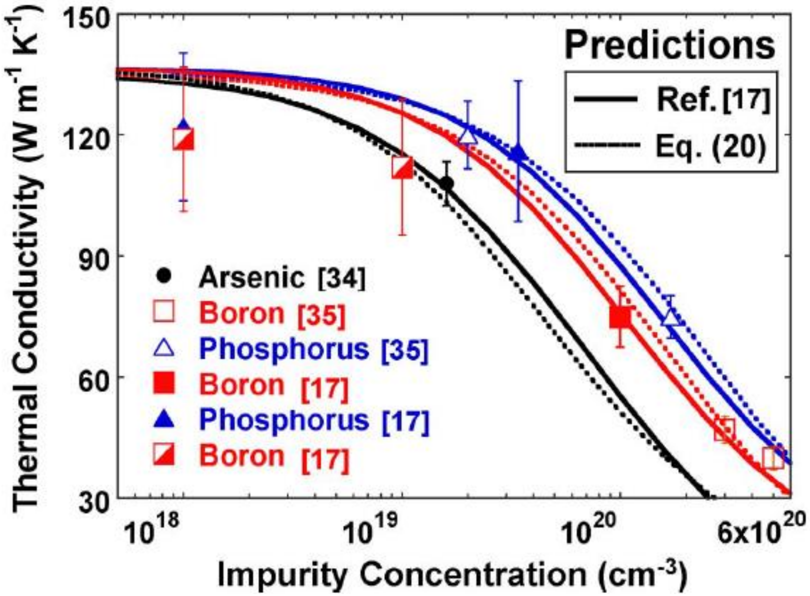


→ Thermal conductivity of 50 nm thin layer of silicon is significantly lower than that of the bulk:
from 150 W/mK to 45 W/mK

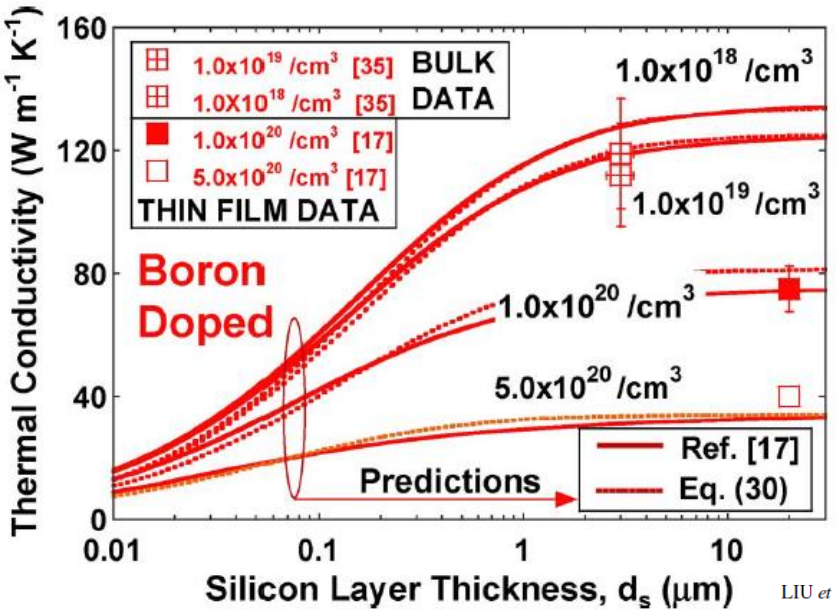
→ Temperature dependency follows different law for bulk and thin layers.

LIU *et al.*: MODELING AND DATA FOR THERMAL CONDUCTIVITY OF SOI LAYERS AT HIGH TEMPERATURE
IEEE TRANSACTIONS ON ELECTRON DEVICES, VOL. 53, NO. 8, AUGUST 2006

Size Effect & Impurities – Thermal conductivity



→ The higher the impurity concentration the lower the thermal conductivity.

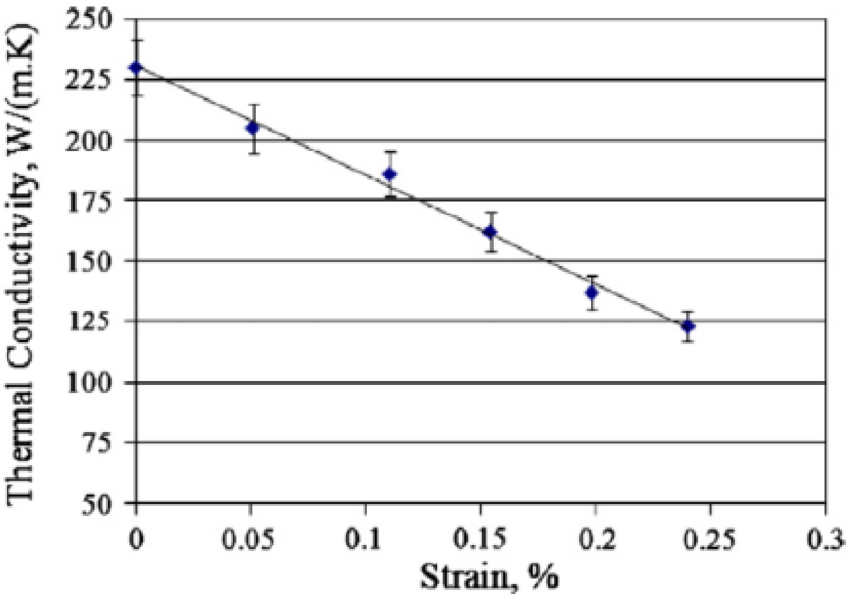


impurity concentration ↑

LIU *et al.*: MODELING AND DATA FOR THERMAL CONDUCTIVITY OF SOI LAYERS AT HIGH TEMPERATURE
IEEE TRANSACTIONS ON ELECTRON DEVICES, VOL. 53, NO. 8, AUGUST 2006

125 nm Al-films with average grain size of 50 nm
(no thickness effect – 3 times the mean free path)

Strain–thermal conductivity coupling:

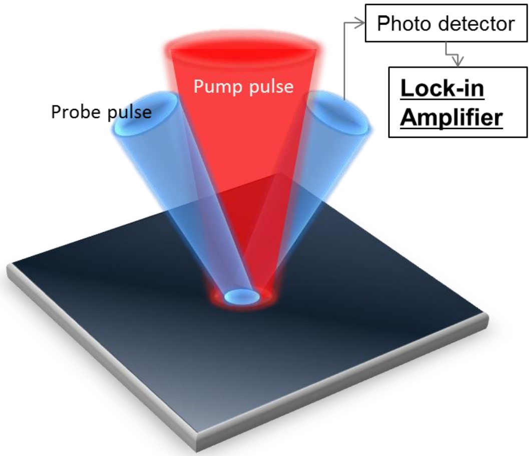


50% reduction in thermal conductivity at ~0.25% strain (~175 MPa of stress)

mechanical strain **decreases the electron mean free path**
→enhanced scattering at the moving grain boundaries

Lee, H. F.; Kumar, S.; Haque, M. A. Role of Mechanical Strain on Thermal Conductivity of Nanoscale Aluminum Films. Acta Mater. 2010, 58, 6619–6627.

Time Domain Thermal Reflectance
TDTR



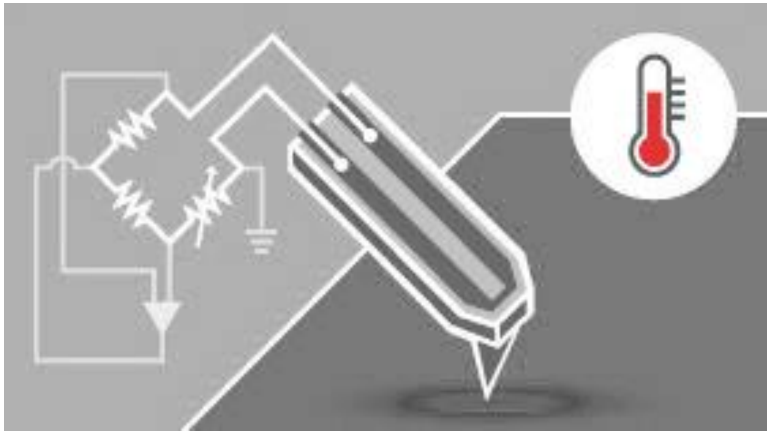
Measurement principle
- Optical reflectivity R changes with the temperature.

What can be measured?
- Thermal effusivity, diffusivity, conductivity and interfacial thermal resistance of layers

On which scale?
- 10 nm to 20 µm thick layers averaged over probe pulse Ø 25 µm

Oven for sample investigation up to 500°C

Scanning Thermal Microscopy
SThM



www.parkafm.com

What can be measured?
- Temperature measurement
- Thermal conductivity
- Topography

On which scale?
- Nanometer scale

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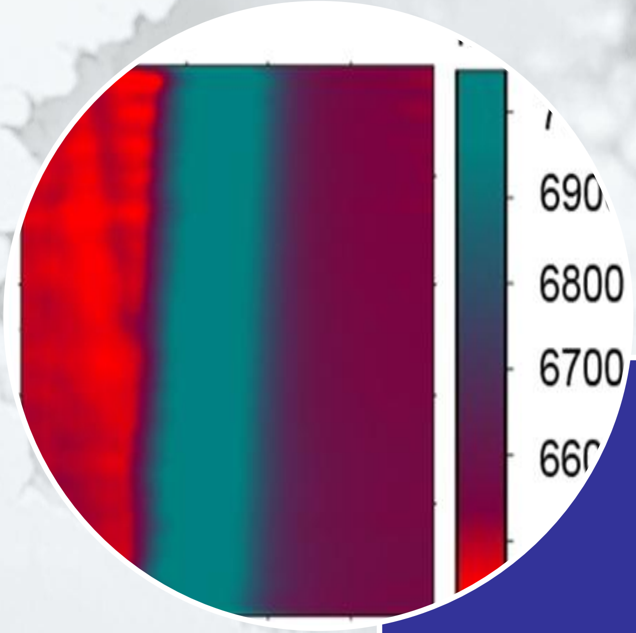


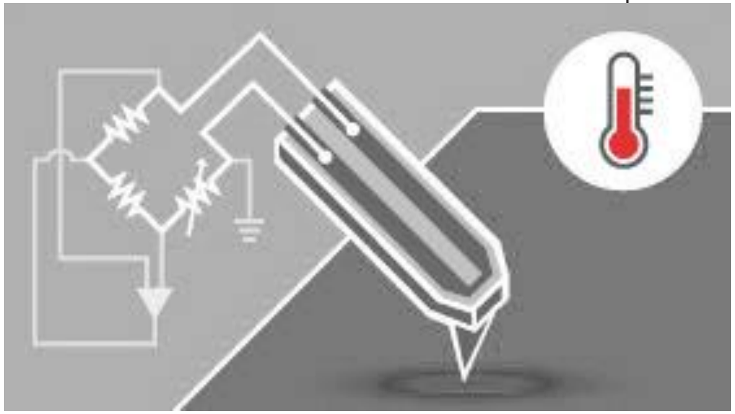
Scanning Thermal Microscopy - SThM

SThM

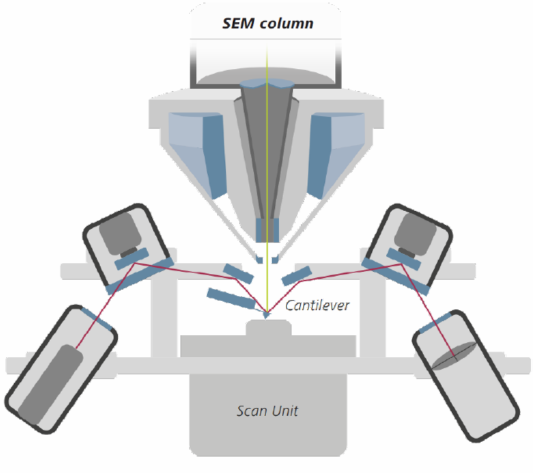
SThM @ MCL: August 2018

Temperatures and thermal conductivities in the sub-100 nm regime

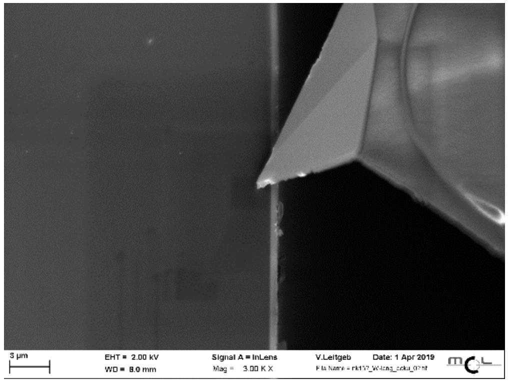
- lateral (in-plane) resolution < 30 nm



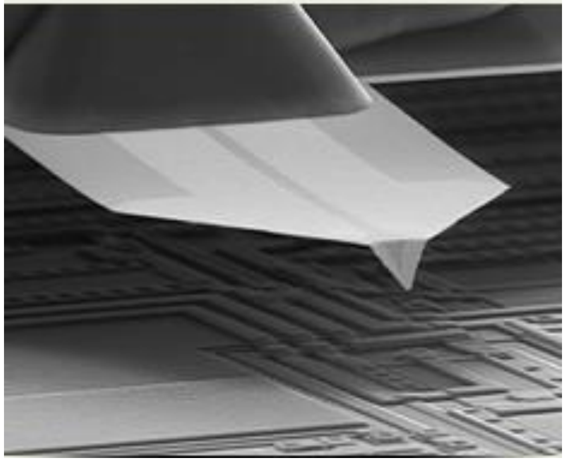
www.parkafm.com



SPM & SEM combination



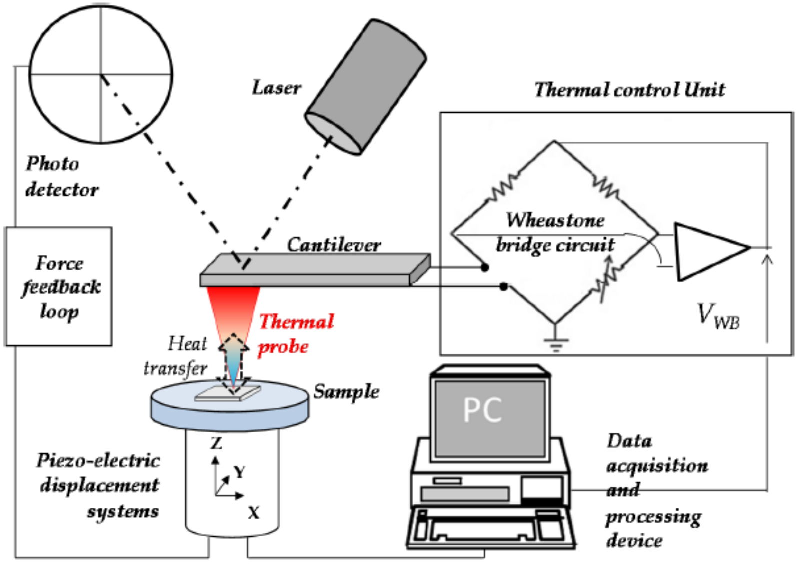
SThM: Working Principle



SEM images of nanolithographed SThM probe from Kelvin Nanotechnology

- Cantilever is made of SiN with a thin-film metal wire. Highest resistance of the wire is near the apex of the tip.
- Electrical resistance of thin-film resistor at probe tip correlates with temperature.

- **Resistive probe** incorporated in Wheatstone bridge
- Frequenzy-modulated measurements
  → 3ω-method (Fiege et al)
  Quantitative results



General layout of a SThM AFM-based system.

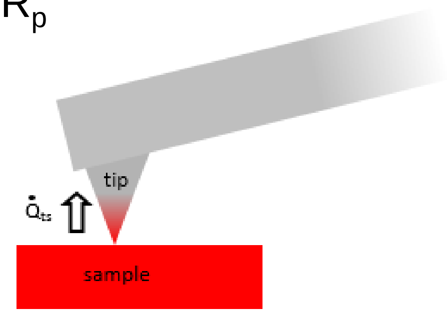
G. Fiege, A. Altes, B. Heiderhoff, L.J. Balk, Quantitative thermal conductivity measurements with nanometre resolution, J. Phys. D-Applied Phys. 32 (1999)

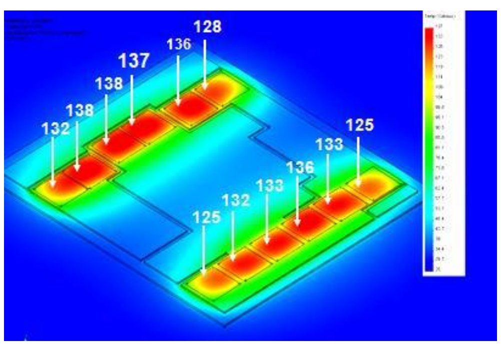
Gomès S., Assy A., and Chapuis P.-O., “Scanning Thermal Microscopy: a review”, 2015, Physica Status Solidi (a) 212

SThM: Operating modes

Thermometry

During a scan, heat flows from the **hot sample** to the probe and changes R_p

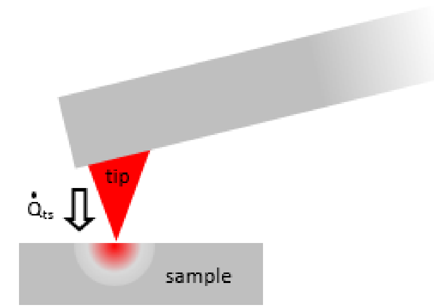


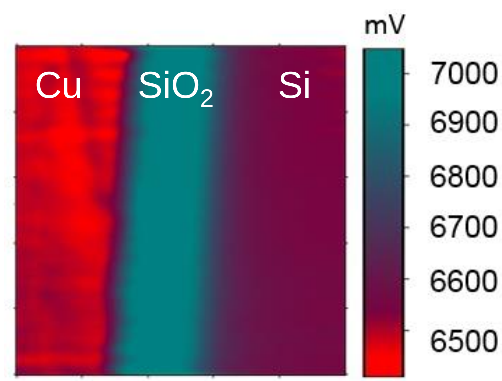


http://www.powerguru.org/heat-transfer-in-power-semiconductor-devices/

Thermal conductivity

Hot tip apex acts as nanoscale heat source



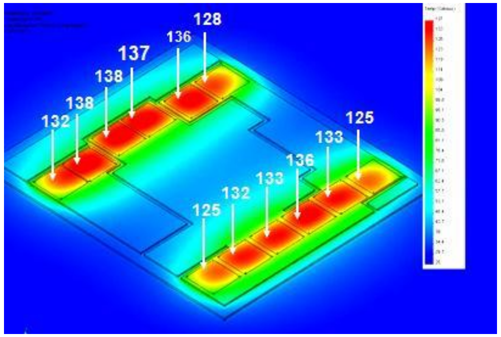


SThM image, 5x5 µm², of Cu-SiO2-Si stack system, scan in vacuum.

SThM: Thermometry

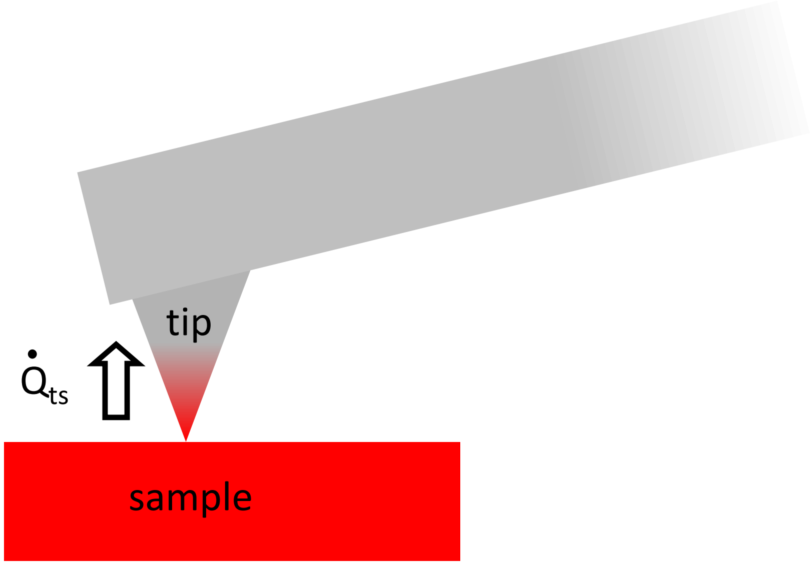
- **Passive mode**

- In this mode, a very small electrical current is passed through the probe
- Results in minimal Joule self-heating and enables measurement of electrical resistance R_p of the probe



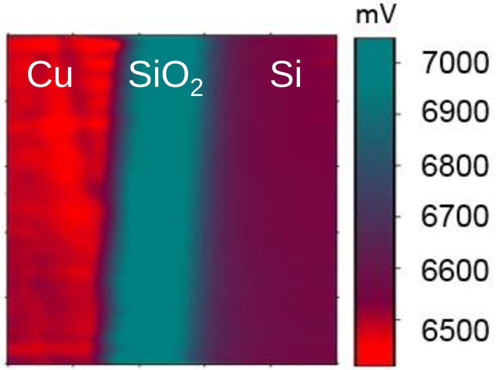
http://www.powerguru.org/heat-transfer-in-power-semiconductor-devices/

- During a scan, heat flows from the **hot sample** to the probe and changes R_p



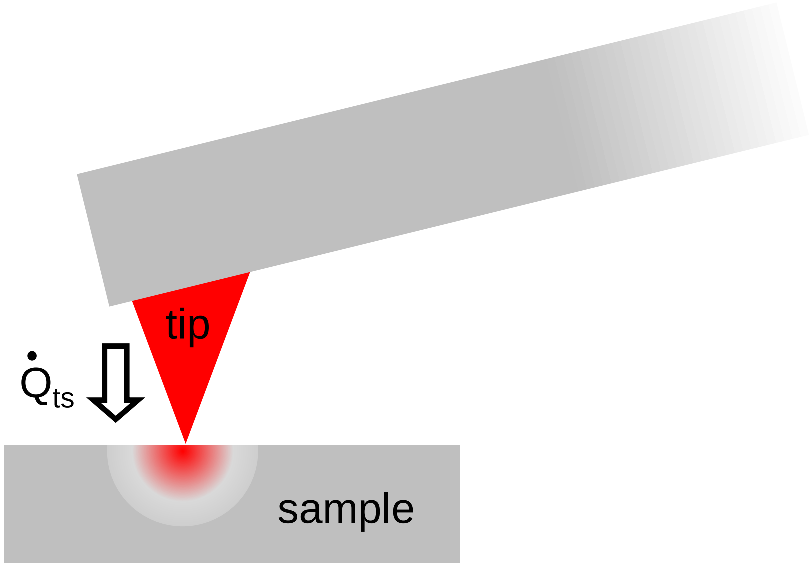
SThM: Thermal conductivity

- **Active mode**
- A larger electrical current is passed through the probe, resulting in a significant Joule heating



SThM image, 5x5 µm^2, of Cu-SiO2-Si stack system, scan in vacuum.

- **Hot tip apex** acts as nanoscale heat source
- Thermal conductivity of sample affects SThM probe



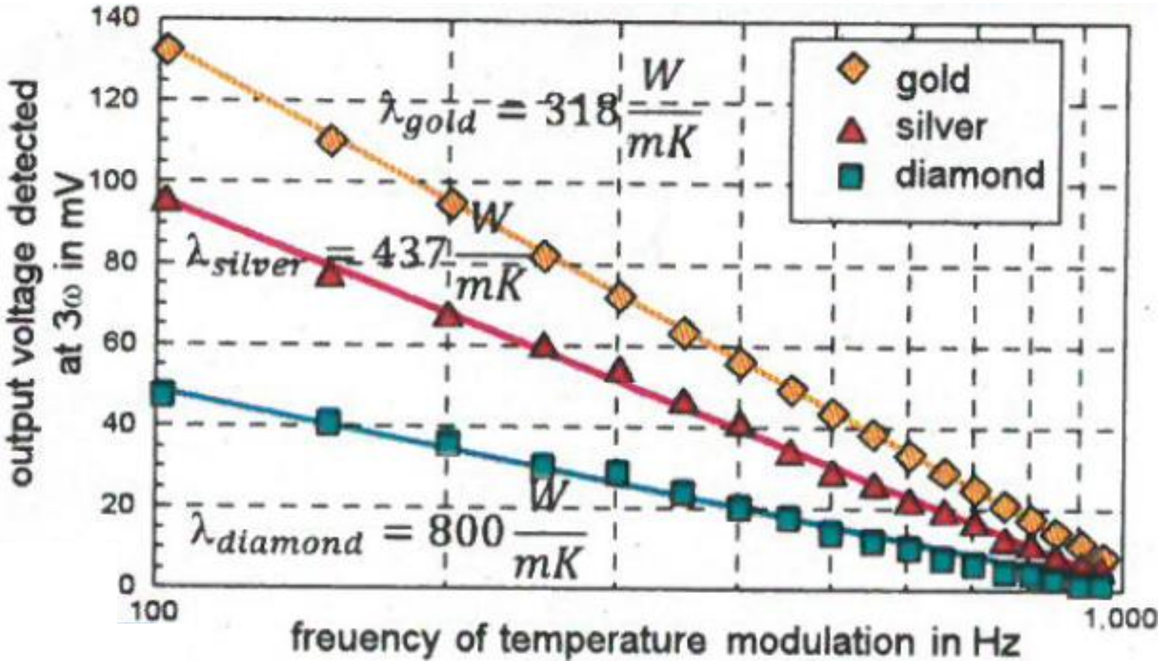
Quantitative measurements of thermal conductivity - 3ω method

Thermal conductivity λ as proportionality factor

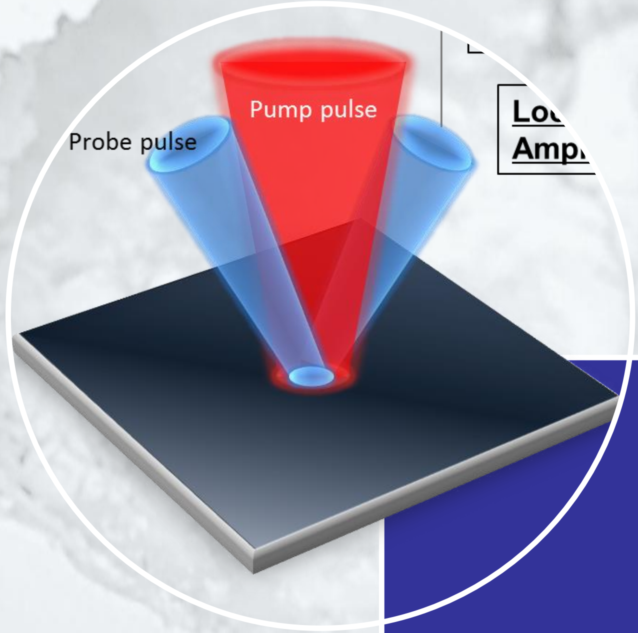
$$\frac{U_{3\omega_1} - U_{3\omega_2}}{\ln(\omega_1) - \ln(\omega_2)} = \frac{1}{4} I_0 \cdot \frac{dR}{dT} \cdot \frac{P}{\pi \cdot \lambda}$$

$\frac{dR}{dT}$ ... temperature coefficient of the probe

P ... power, from probe to sample



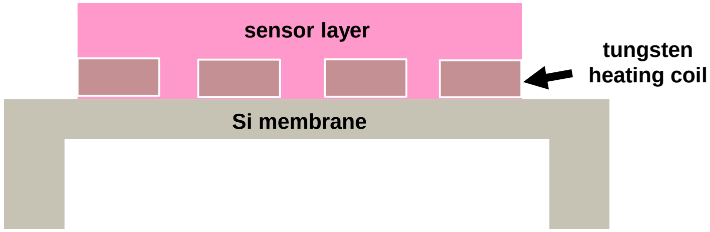
G. Fiege et al., J. Phys. D: Appl. Phys. 32 No 5 (7 March 1999) L13-L17.



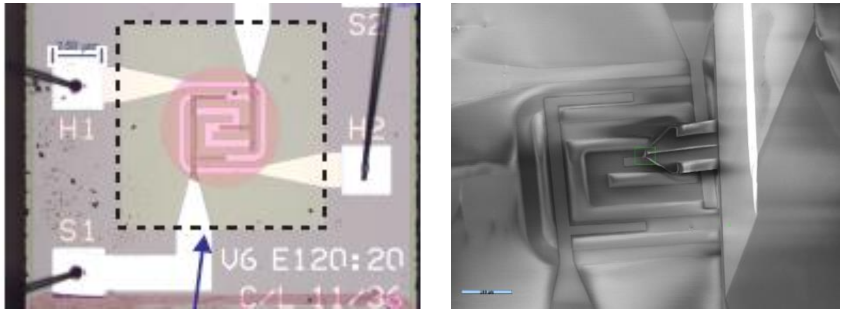
W thin film investigated by TDTR

Thermal conductivities of thin films/ interfaces

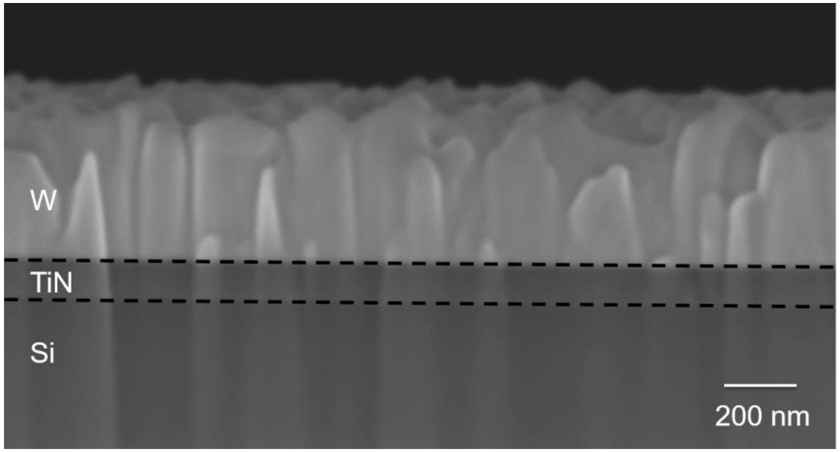
- Heat managment in metal oxide gas sensors



Sideview: Tungsten heating coil for next generation hotplate



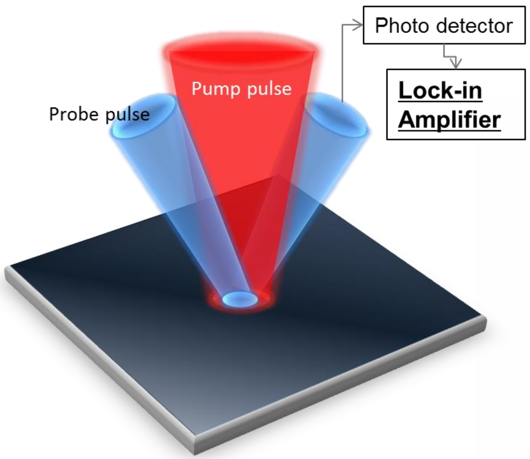
Miniature hotplate: optical image (left) and SEM image (right)

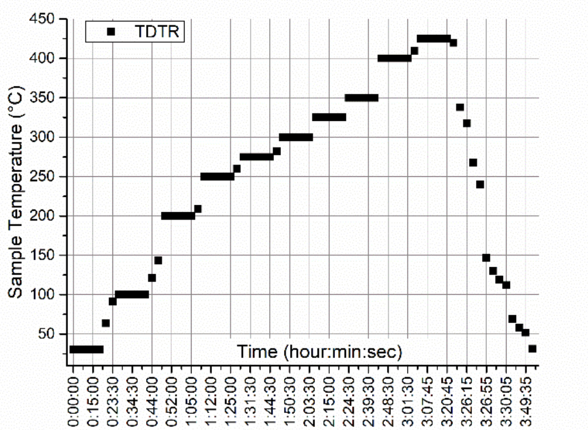


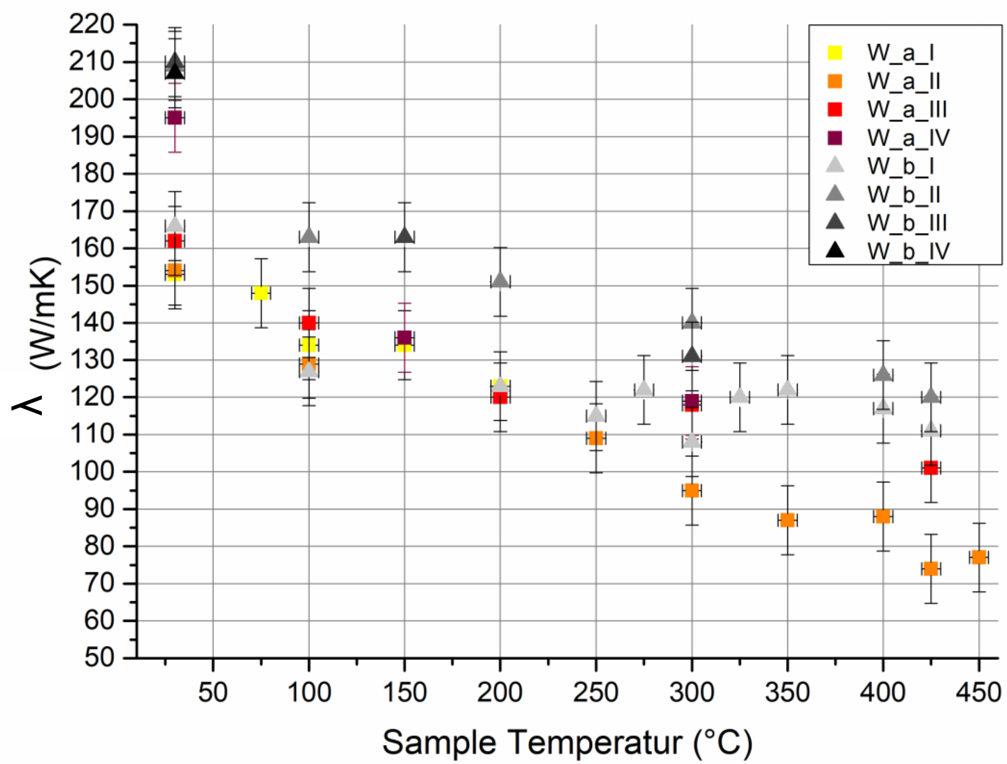
SEM image on cross section of CVD grown 500 nm thick W on a 100 nm TiN layer on (100) Si

TDTR: Tungsten (W) – thin film – temperature dependent

Thermal conductivities (λ) of thin films

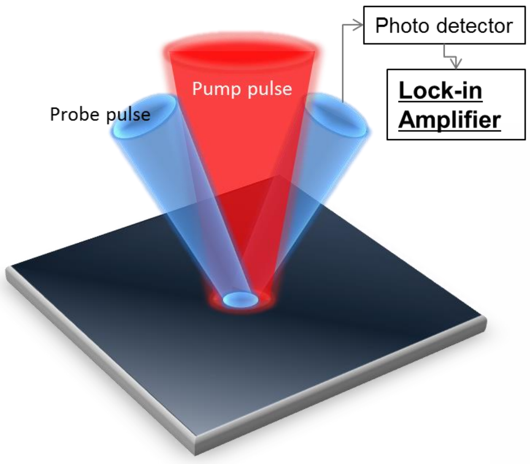


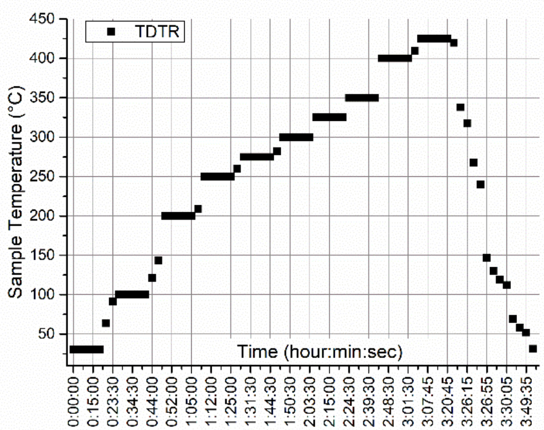


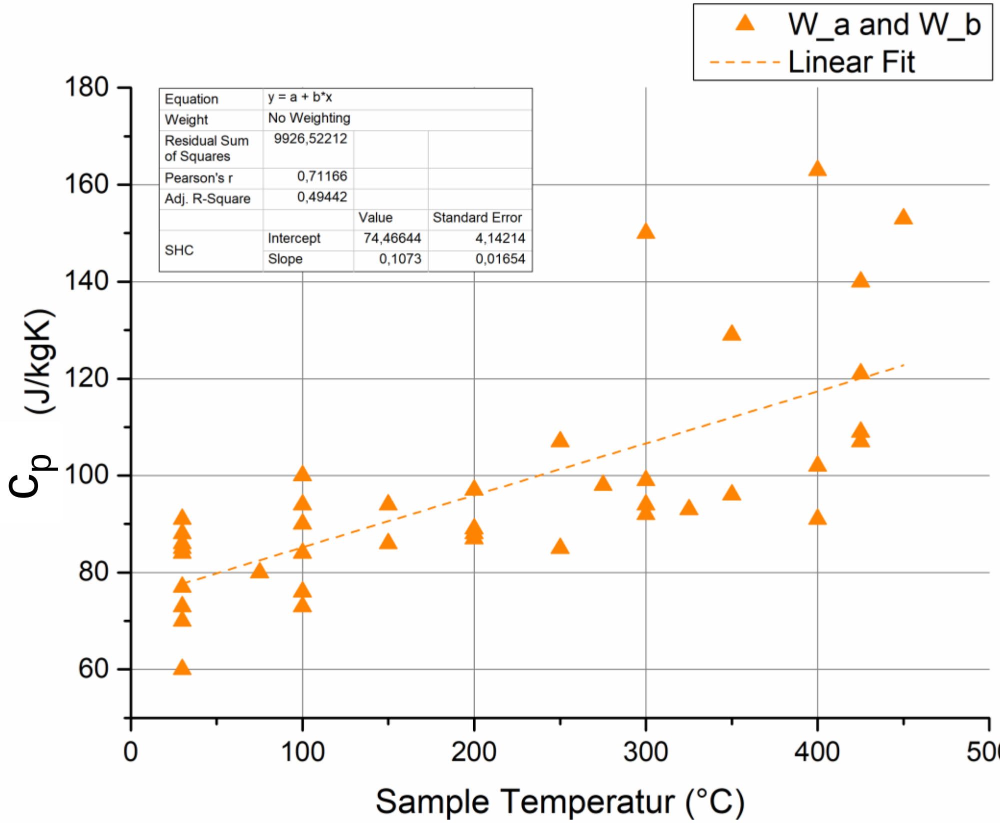


x 4 heating cycles

Specific heat capacity (c_p) of thin films







x 4 heating cycles

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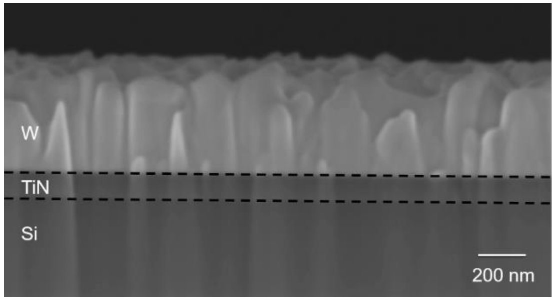
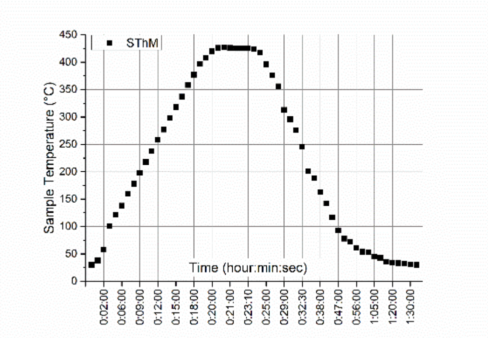
Thermal conductivities of thin films/ interfaces

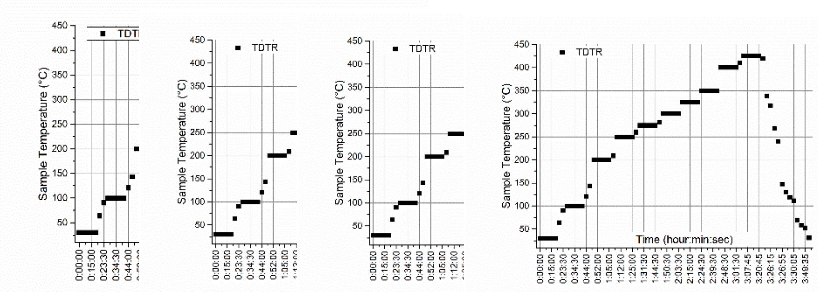
W_native = as deposited



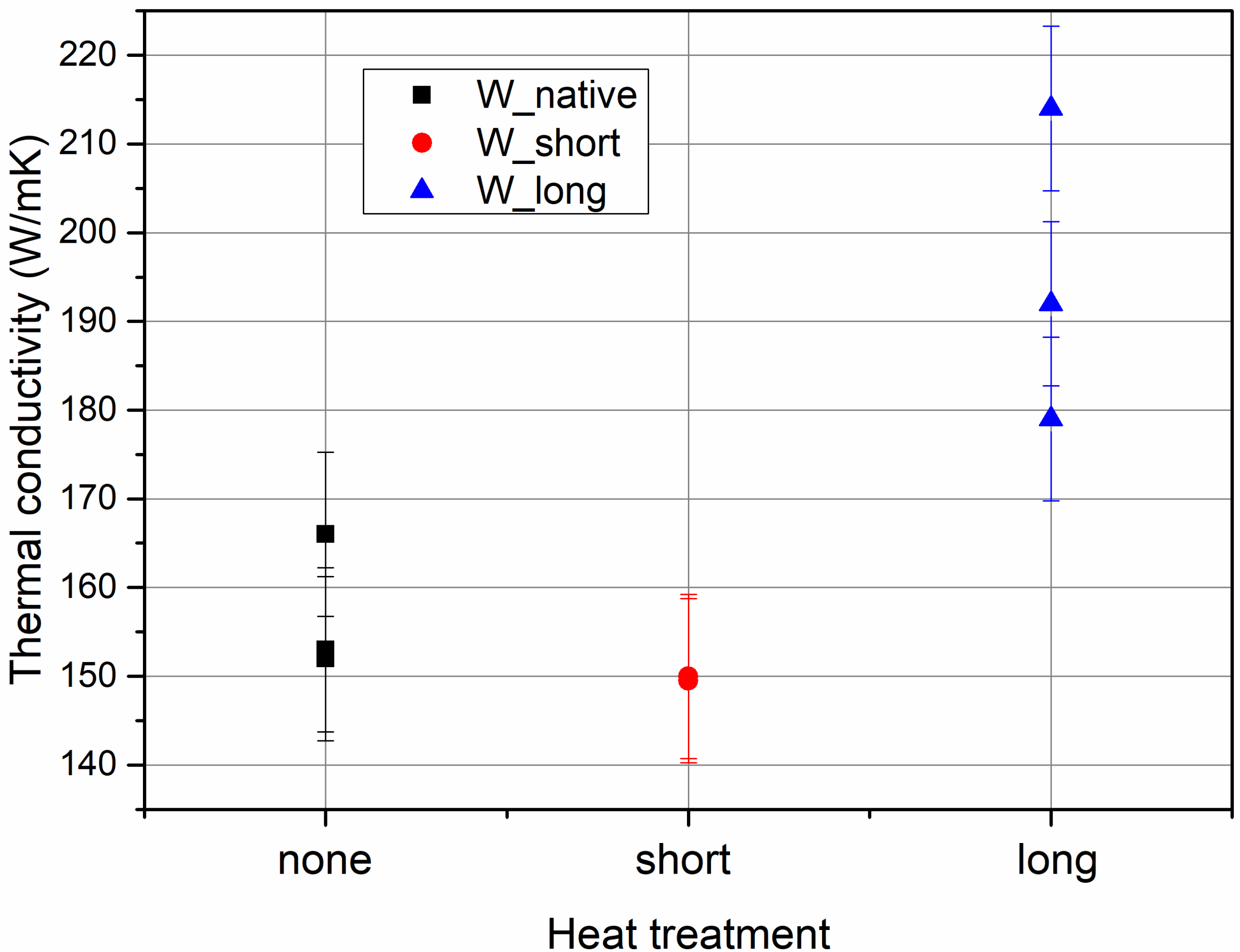
W_short: after a short heat cycle
2.5 min @ 425°C

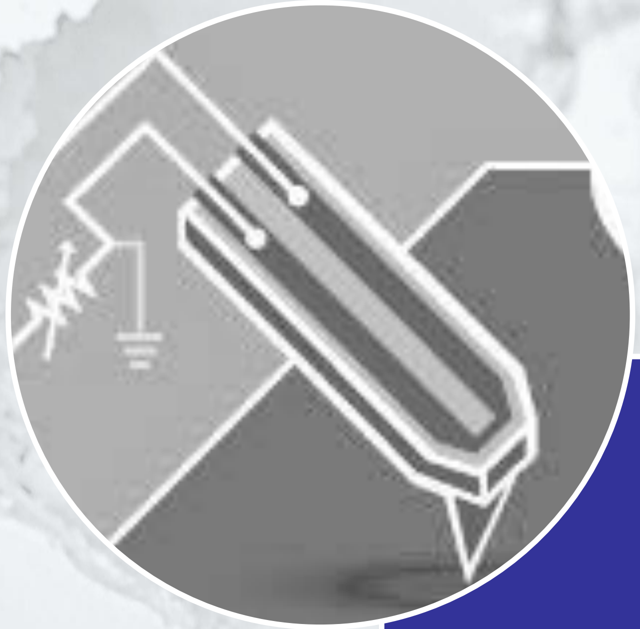


W_long: after a long heat cycle
x 4 heating cycles
up to 425°C



Thermal conductivities of thin films/ interfaces



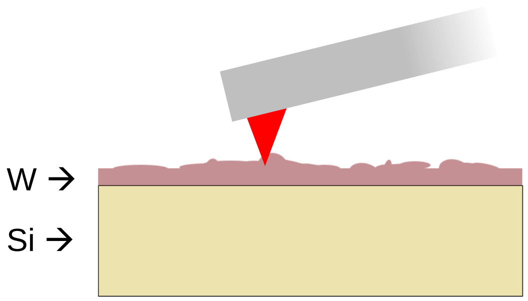


W thin film investigated by SThM

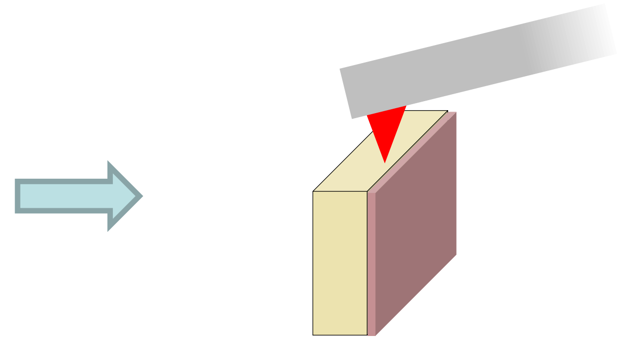
SThM: Tungsten (W) – thin film

Thermal conductivity of tungsten thin layers

Sample preparation



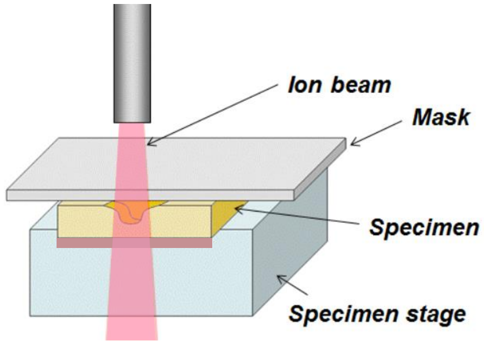
SThM on suface



SThM on cross-section

SThM on cross-section to avoid

- Influence of topography
- Oxidation of surface
- Pollution of surface layer

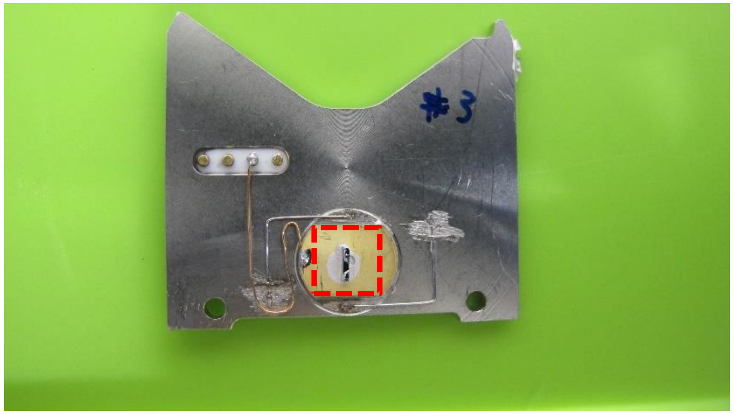


Ion Slicing to get smooth and even surface

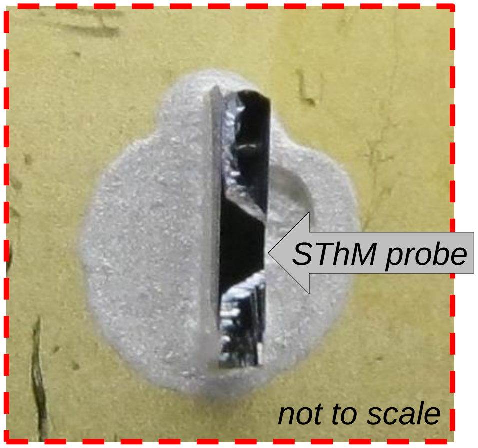
SThM: Tungsten (W) – thin film

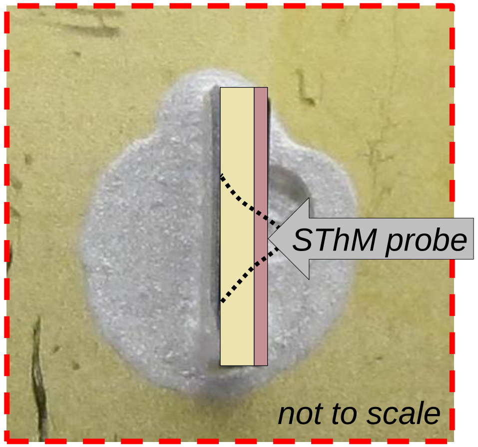
Thermal conductivity of tungsten thin layers

Sample preparation



Tungsten sample on sample holder





SThM on cross-section of tungsten sample

SThM: Tungsten (W) – thin film

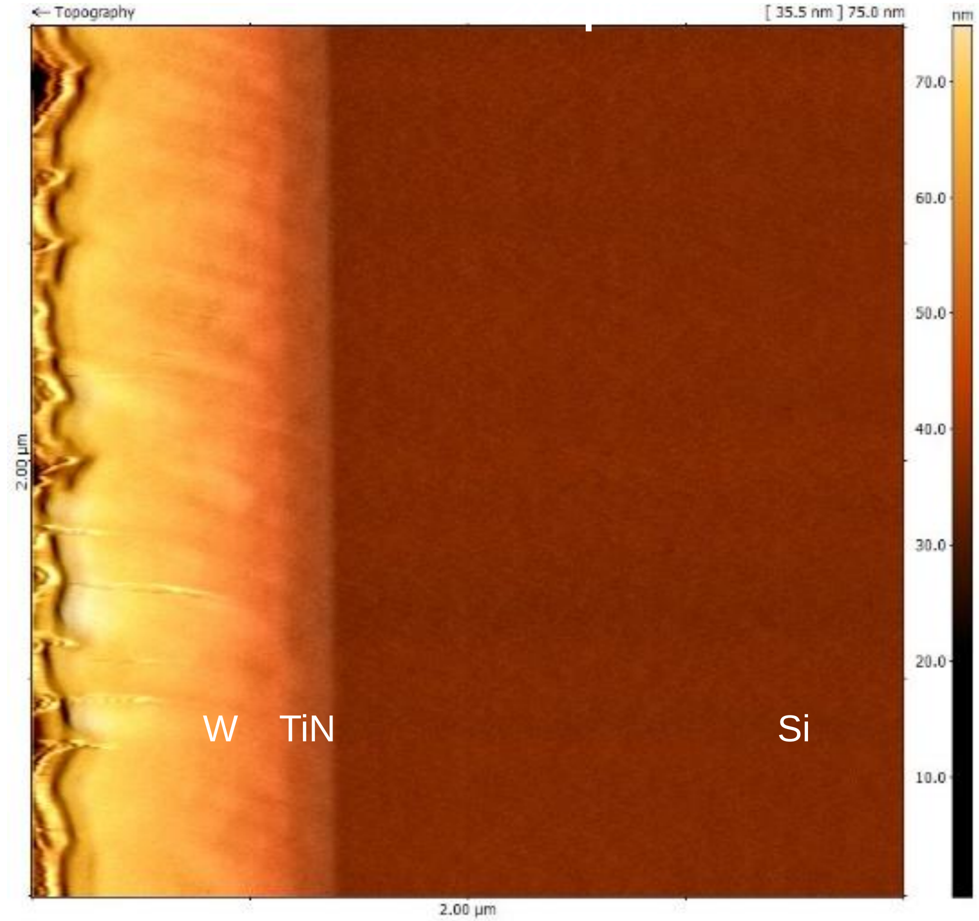
Thermal conductivity of tungsten thin layers

Topography on cross-section:

500 nm W

100 nm TiN

(100) Si substrate



SPM-probe: Arrow-NCR

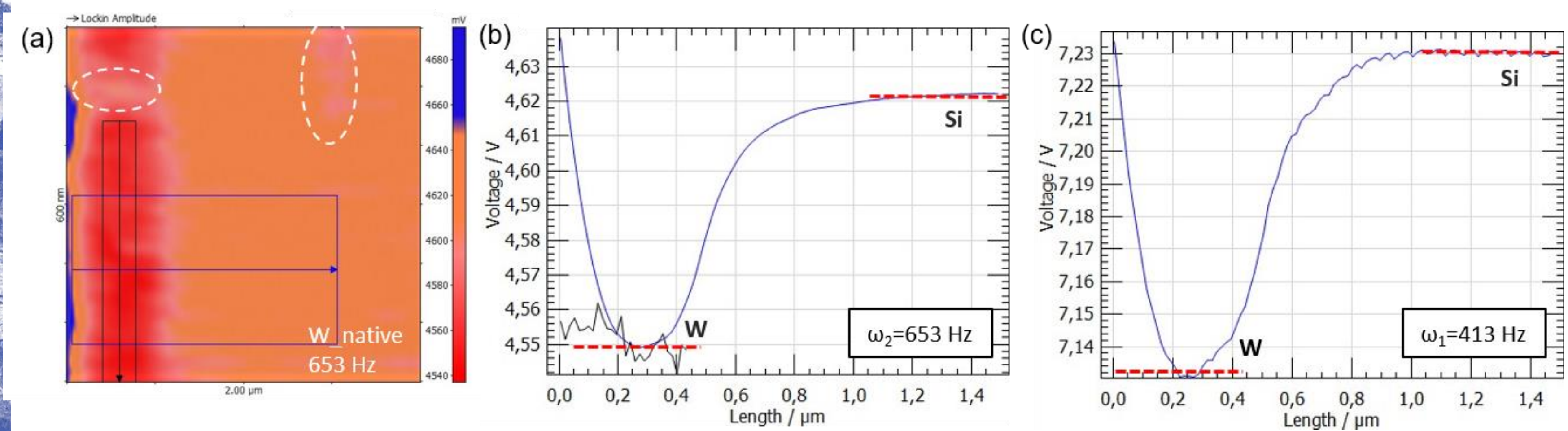
SThM: Tungsten (W) – thin film

Thermal conductivity of tungsten thin layers

SThM on cross-section

Heating voltage 350 mV, in vacuum: $1.1 \cdot 10^{-6}$ mbar

W_native



(a) SThM image
(b) & (c) areas utilized for data evaluation of W and Si at different frequencies

Thermal conductivity, literature values for bulk:

Si ... 149 W/mK
W ... 173 W/mK
TiN ... 19 W/mK

But: TiN layer not visible

$\lambda_{W\_native} = 154.2 \pm 4$ W/mK

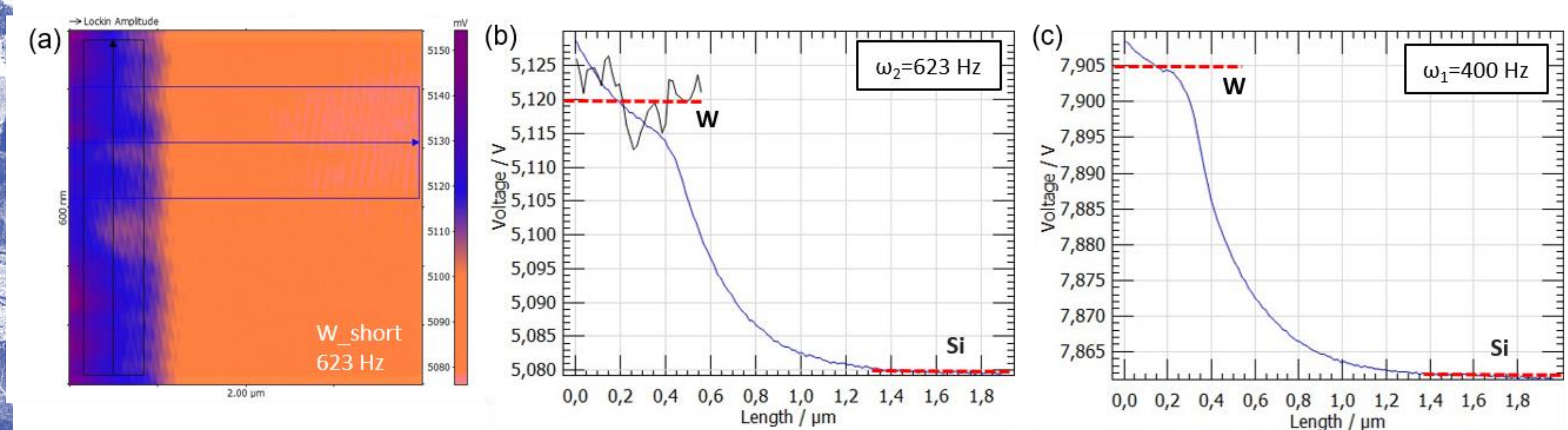
SThM: Tungsten (W) – thin film

Thermal conductivity of tungsten thin layers

SThM on cross-section

Heating voltage 350 mV, in vacuum: 1.1×10^{-6} mbar

W_short



(a) SThM image

(b) & (c) areas utilized for data evaluation of W and Si at different frequencies

λ_{W_short} = 151.8 ±4 W/mK

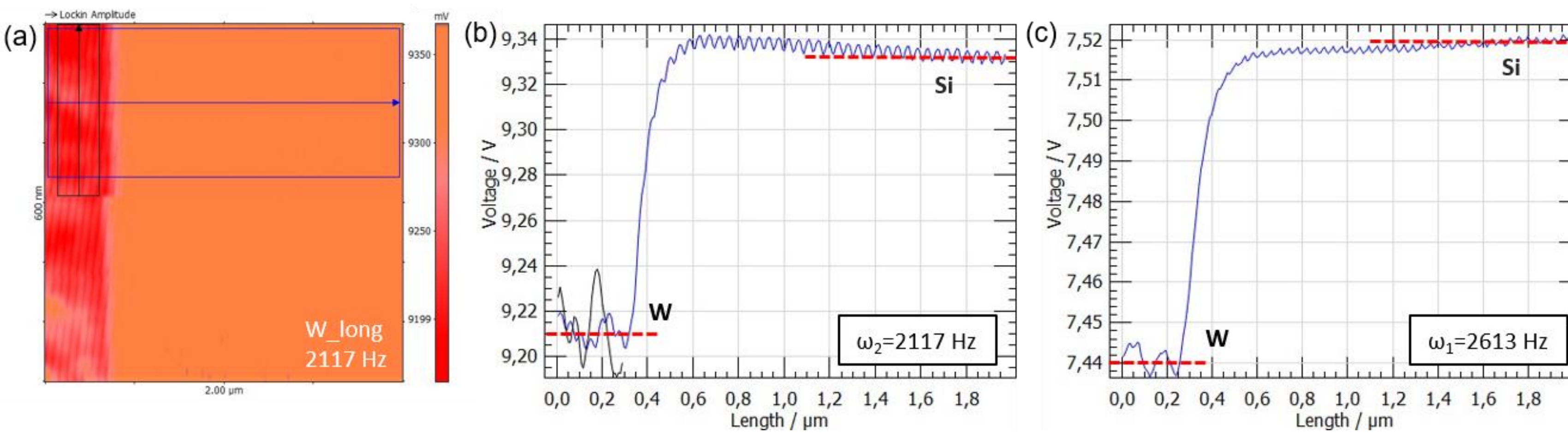
SThM: Tungsten (W) – thin film

Thermal conductivity of tungsten thin layers

SThM on cross-section

Heating voltage 350 mV, in vacuum: $1.1 \cdot 10^{-6}$ mbar

W_long



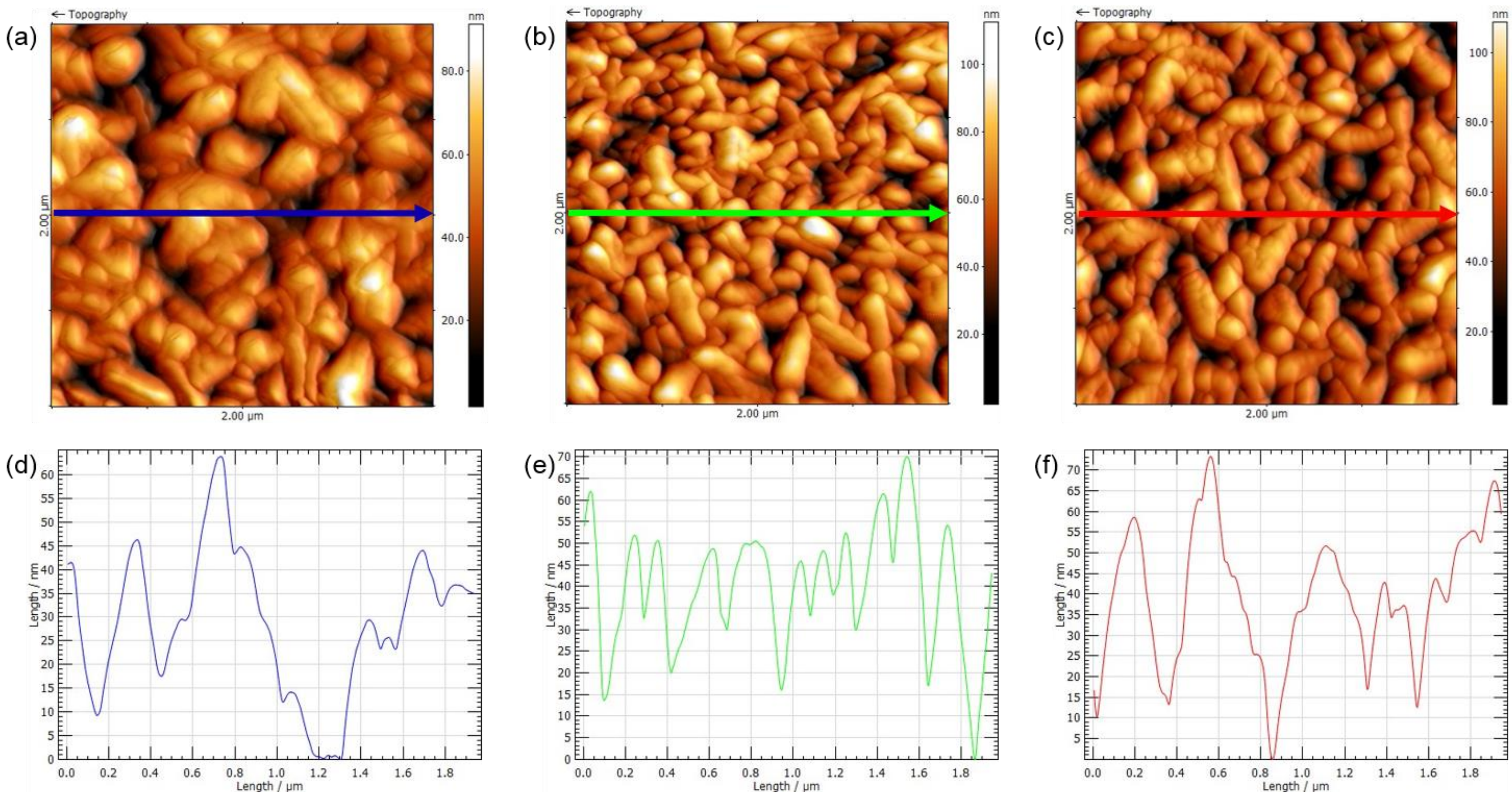
(a) SThM image
(b) & (c) areas utilized for data evaluation of W and Si at different frequencies

$\lambda_{W\_long} = 155.6 \pm 4$ W/mK

Tungsten (W) – thin film – at 30°C

SPM topview – Grain sizes

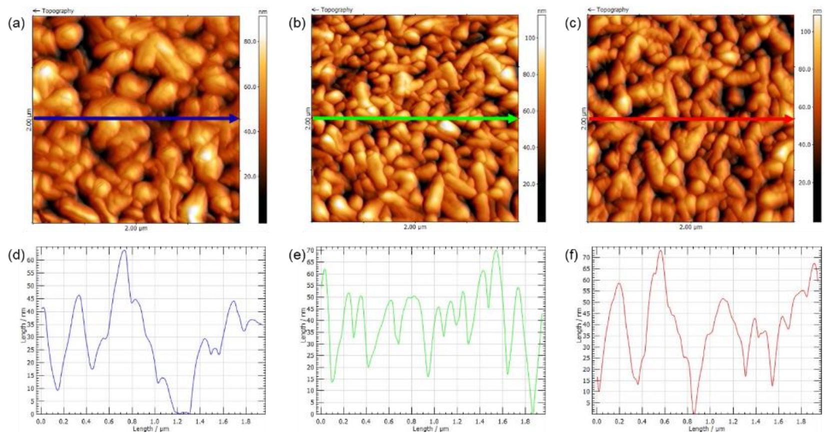
W_native W_short W_long



Tungsten (W) – thin film – at 30°C

SPM topview – Grain sizes

W_native W_short W_long



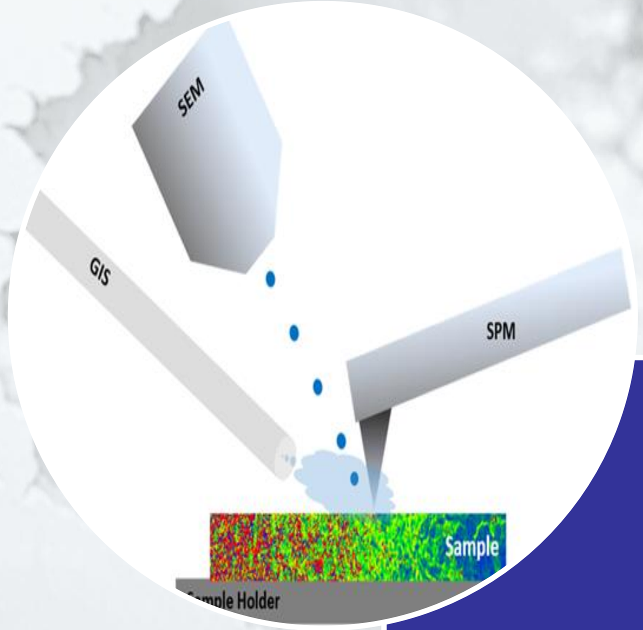
D. Choi, The electron scattering at grain boundaries in tungsten films, Microelectron. Eng. 122 (2014) 5–8. doi:10.1016/j.mee.2014.03.012:

Grain boundary scattering → increase of electrical resistivity due to

- surface scattering (Fuchs-Sonderheimer model $\Delta\ \sigma_{FS}$) and
- grain boundary scattering (Mayadas-Shatzkes model $\Delta\ \boldsymbol{\sigma}_{MS}$)

→ Caclulation of λ_{calc} out of grain size

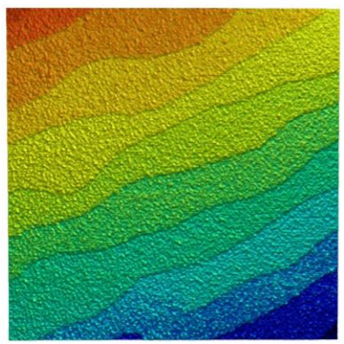
Sample	Average grain size [nm]	λ_{calc} [W/mK]	λ_{TDTR} [W/mK]	λ_{SThM} [W/mK]
W_native	136 ± 51	152^{+5}_{-11}	157 ± 8	153.6 ±4
W_short	105 ± 50	146^{+8}_{-19}	149.8 ± 0.5	151.8 ±4
W_long	177 ± 84	156^{+5}_{-13}	195 ± 18	155.6 ±4



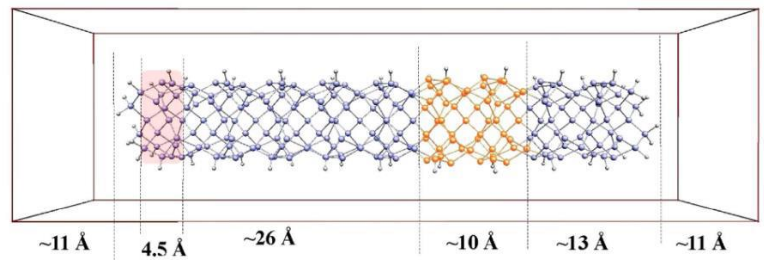
Outlook

Outlook – SThM at MCL

- **SThM & TDTR characterization of multilayer systems and interfaces**
  Record topography and thermal properties simultaneously with nm-resolution
  → Create input to model thermal transport via ab-initio Molecular Dynamics



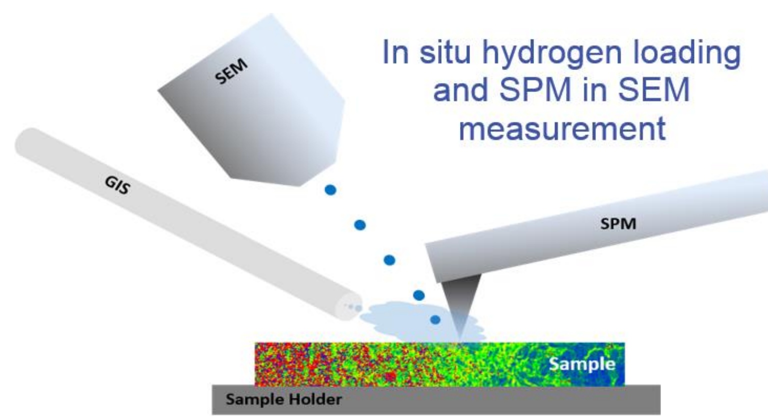
Topography showing steps of strontium titanate; image size 1.1µm



Simulation cell representing layered system. Gibbons, Bebek, Kang, Stanley, and Estreicher, J. of Applied Physics 118 (2015).

https://www.nanosurf.com/en/application/547-topography-strontium-titanate-flexafm

- **SThM - SEM characterization**
  - Study thermal transport mechanism, phonons /electrons?
  - In situ loading of hydrogen etc.



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www.mcl.at

Any questions?

Thank you for your attention!

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