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Study of Thermal Diffusivity of Dielectric-Metal Interfaces at Low Temperatures

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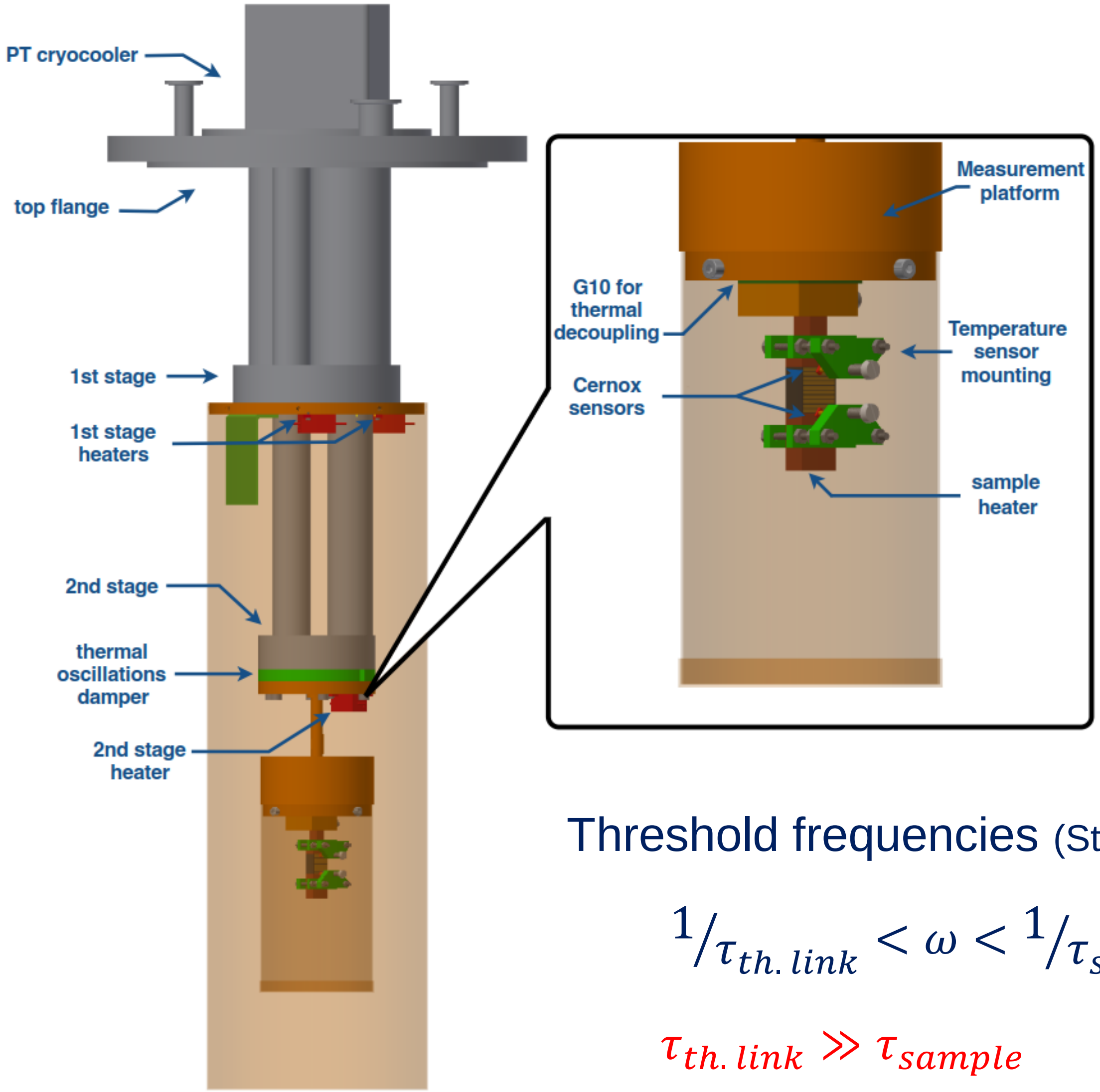
Content

- Introduction to the test set-up
- Method applied and samples
- Measurements and numerical modelling
  - Copper as reference sample
  - Dielectric to metal interfaces
    - Indium or titanium on sapphire
    - SC cable via epoxy impregnation
- Comparison: amplitude vs. τ- method
- Conclusion

Thermal conductivity / diffusivity set-up



Features:

- 3 temperature sensors calibrated to each other + offset compensation
- Stepwise change of platform temperature 1 K - 2 K
- ΔT on sample 0.2 K to 0.3 K
- Passive thermal attenuator between cryocooler and thermal platform

Threshold frequencies (Stewart *et al.*, Rev. Sci. Instrum. 54, 1 (1983)):

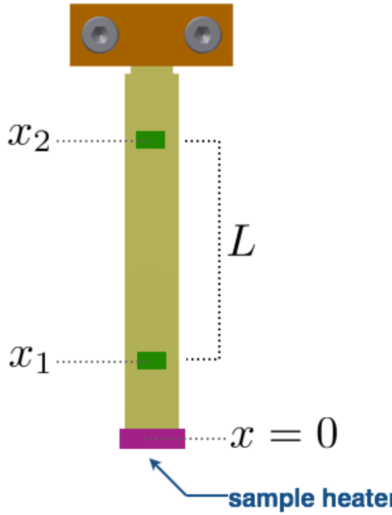
$$^{1}/_{\tau_{th.\,link}} < \omega < {}^{1}/_{\tau_{sample}} \qquad with \quad \tau = RC = \frac{C}{\Lambda}$$

$$\tau_{th.\,link} \gg \tau_{sample}$$

Measurement methodology I

Thermal conductivity: $$\lambda = \frac{\dot{Q} \cdot L}{A \cdot \Delta T}$$

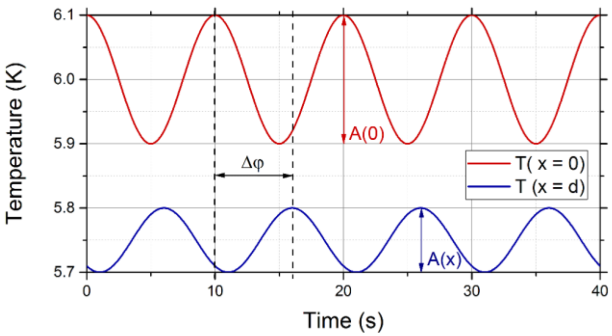
- λ - thermal conductivity
- $\dot{Q}$ - heat load
- L - length along x
- A - cross section
- ΔT - temperature difference



Thermal diffusivity: $$D = \frac{\lambda}{c \cdot \rho}$$

- D - thermal diffusivity
- c - heat capacity
- ρ - density

$$\frac{\delta T}{\delta t} = D \cdot \frac{\delta^2 T}{\delta x^2} \Rightarrow T(L,t) = T_0 \left(1 + e^{-\frac{L}{\mu} cos\left(\omega t - \frac{L}{\mu}\right)}\right)$$



Phase shift method

$$\mu_{phase} = \frac{L}{\phi_0 - \phi_x}$$

$$\phi\ (rad) = \frac{\Delta t\ (s) * 2\pi}{Period\ time}$$

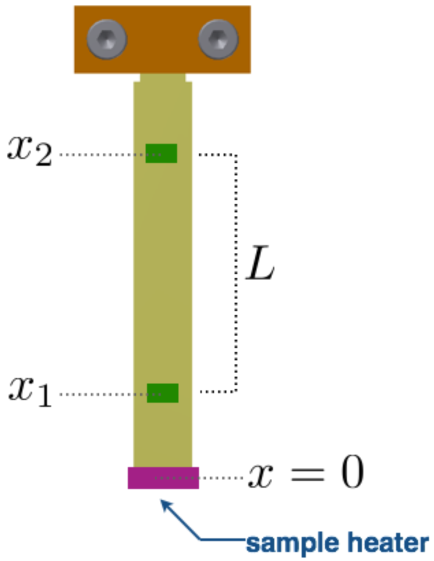
$$D = \frac{\mu^2 \cdot \omega}{2}$$

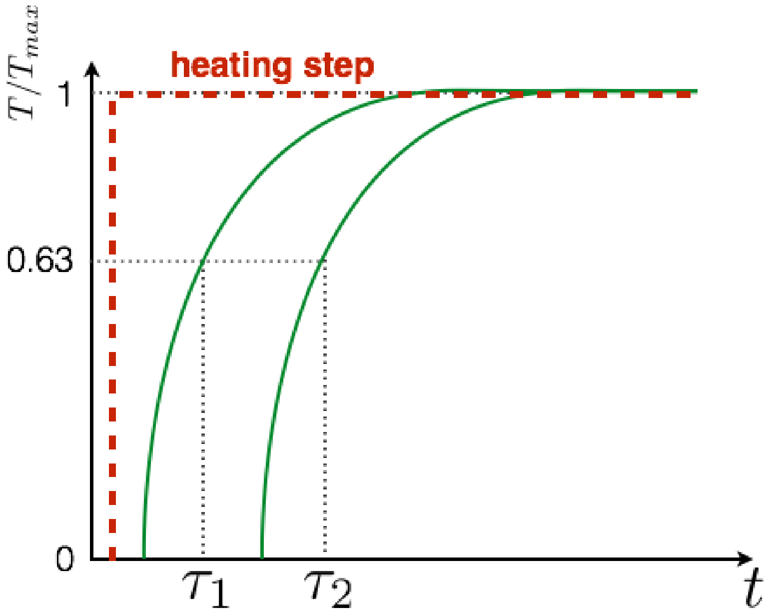
Amplitude method

$$\mu_{atten.} = \frac{L}{ln\left(\frac{A_0}{A_x}\right)}$$

- D - thermal diffusivity in m^2/s
- L - length in m
- μ - thermal diffusion length in m

Measurement methodology II

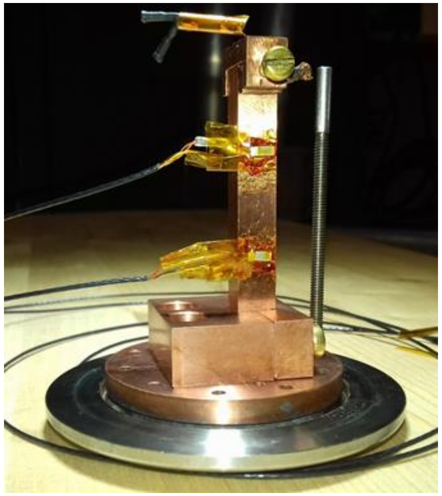




$$\tau = R \cdot C = \frac{m \cdot c}{A/x \cdot \lambda} = \frac{x \cdot V \cdot \rho \cdot c}{A \cdot \lambda} = \frac{x}{A} \cdot \frac{V}{D} = \frac{x^2}{D}$$

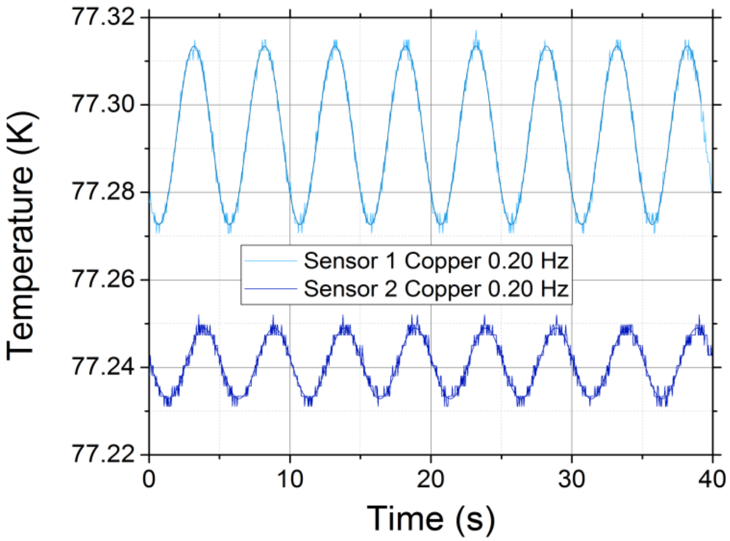
$$D^* = \frac{L^2}{\Delta\tau}$$ τ - method

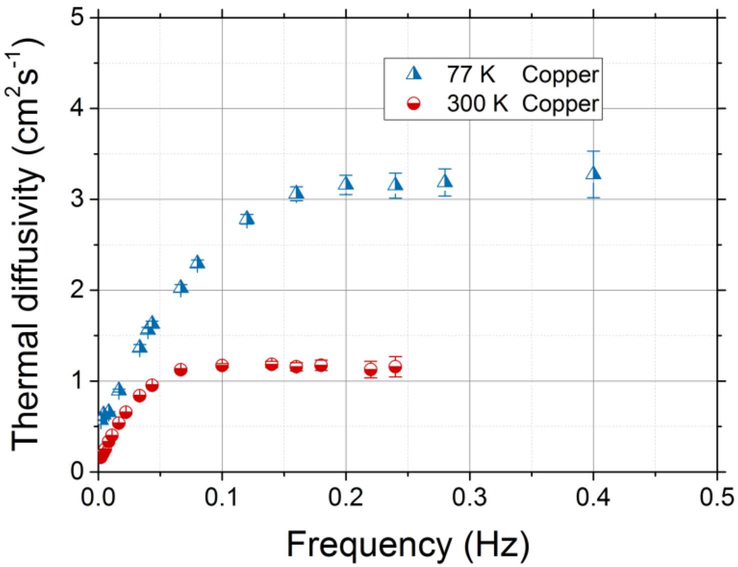
Diffusivity measurements on reference sample Cu-OFHC

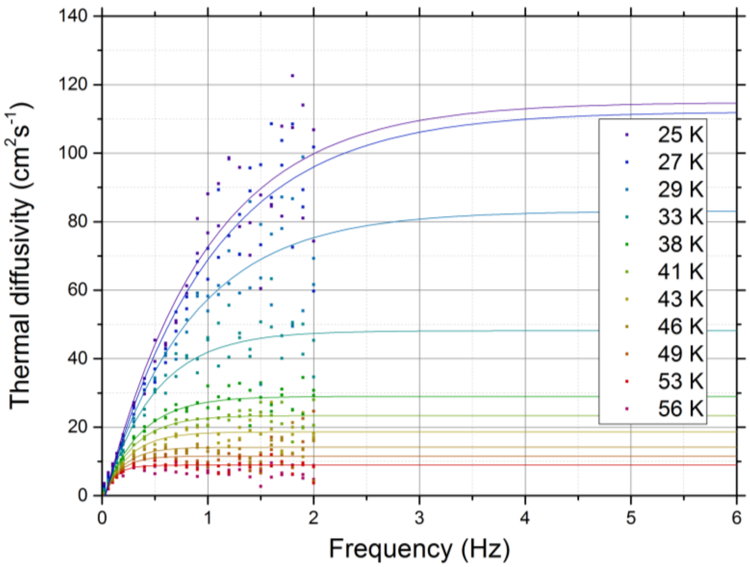


Oxygen-free high-conductivity (OFHC) copper

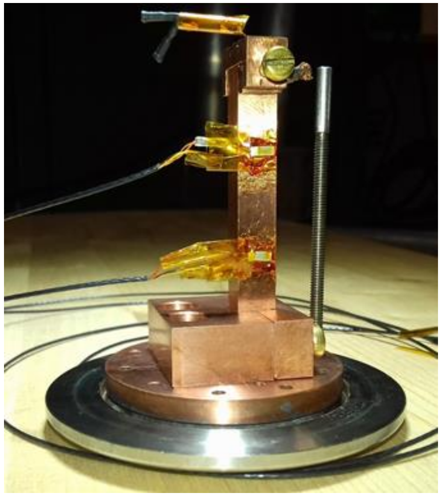
Dimensions:
8 x 8 x 50 mm^3

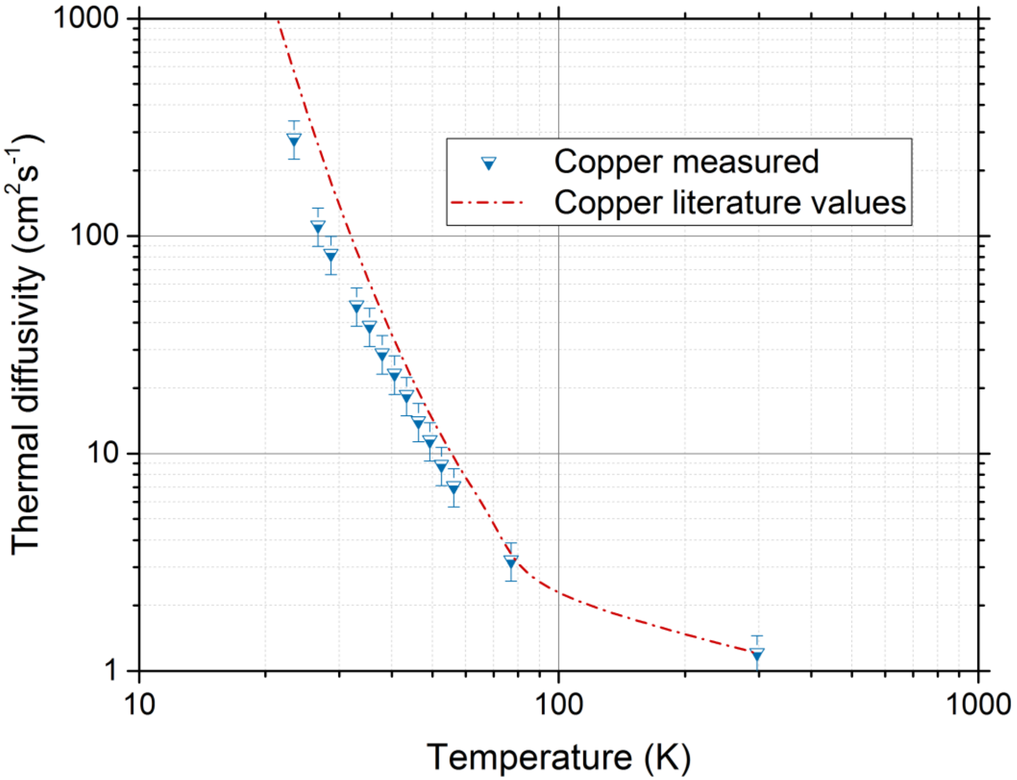






Diffusivity measurements on reference sample Cu-OFHC





D(T) measured is in good agreement with literature values.

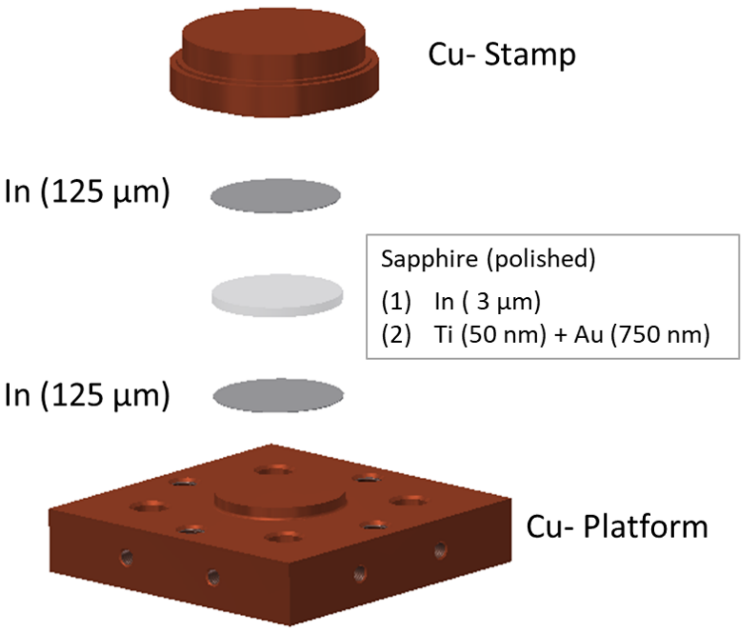
→ Amplitude method can be used for more complex samples

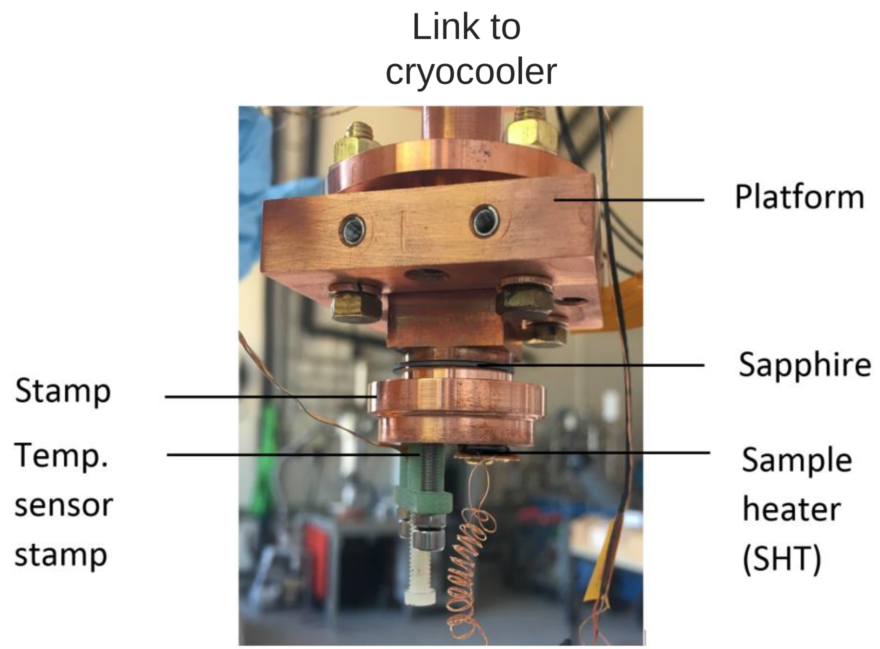
→ Samples and interfaces need to be adapted

Literature data from: J. E. Jensen *et al*., Thermal Diffusivity, Brookhaven National Laboratory Selected Cryogenic Data Notebook, Brookhaven National Laboratory (1980).

OFHC copper tested RRR~100 from th. conductivity results

Thermal diffusivity of a Cu-In- sapphire and Cu-In-Au-Ti-sapphire sandwich





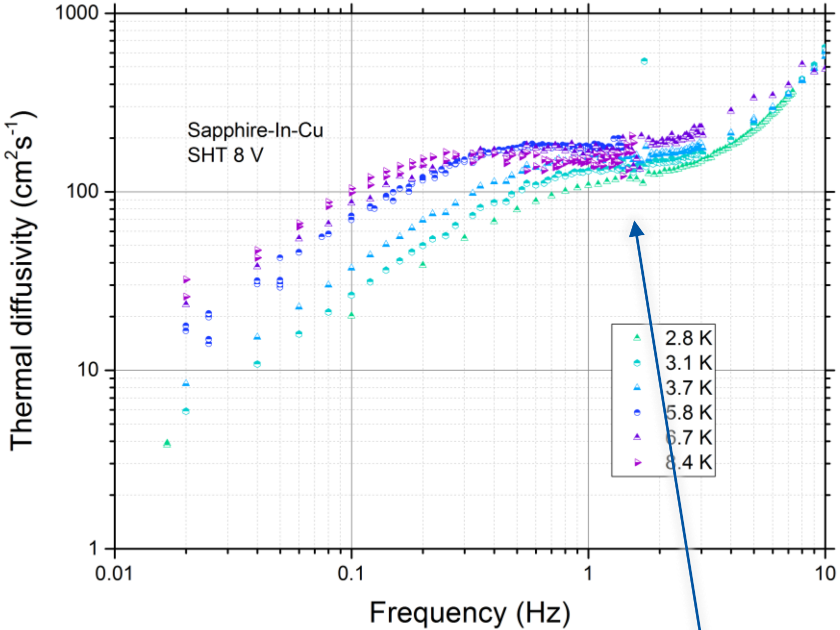
Indium sample :	Cu-In-sapphire-In-Cu
Ti-Au sample:	Cu-In-Au-Ti-sapphire-Ti-Au-In-Cu

See results presented by J. Liberadzka
in her talk: E-09: 32

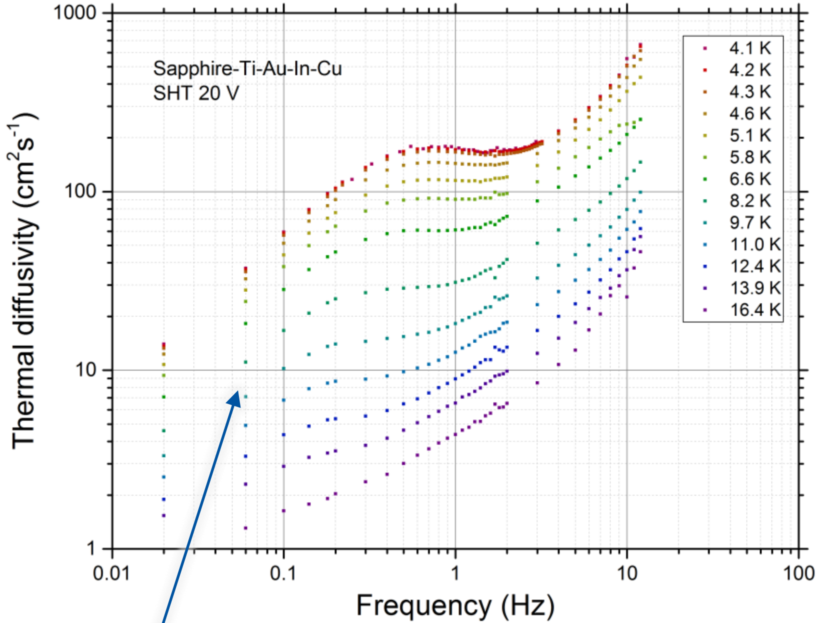
Definition of a diffusivity-like value (due to the presence of interfaces) => D^*

Thermal diffusivity of a Cu-In-sapphire and Cu-In-Au-Ti-sapphire sandwich

Cu-In-Sapphire



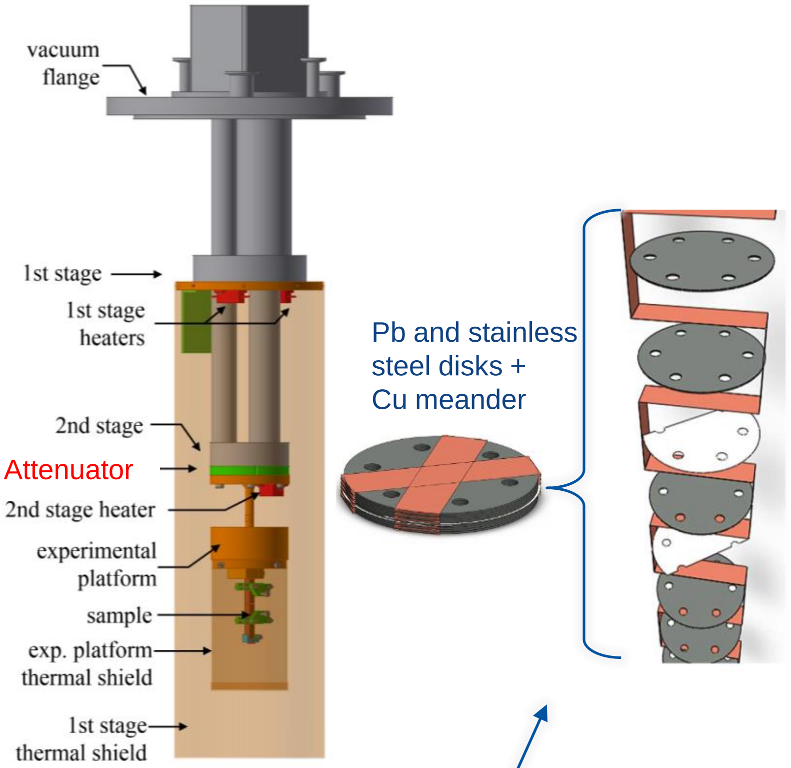
Cu-In-Au-Ti-Sapphire



Influences by the cryocooler frequency and threshold frequency are visible

There is a clever solution to attenuate the cryocooler oscillations and increase $\tau_{th.\,link}$

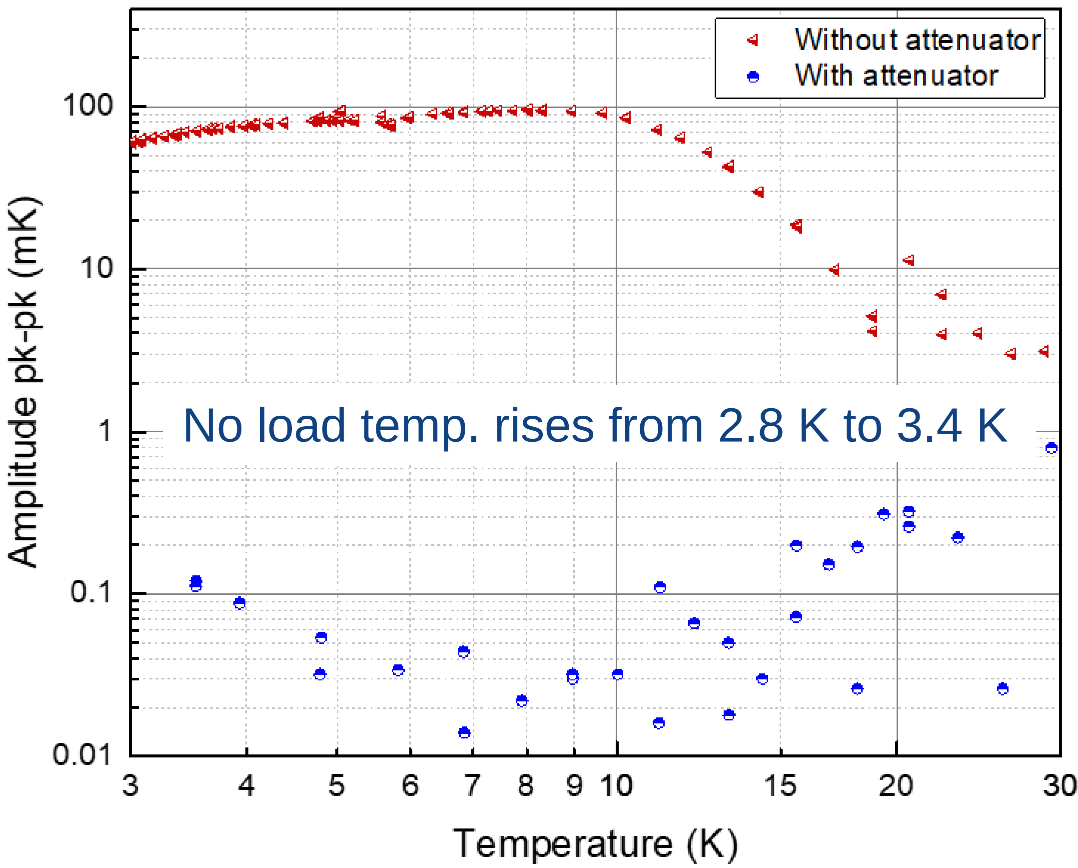
Passive thermal attenuator (G. Dubuis)



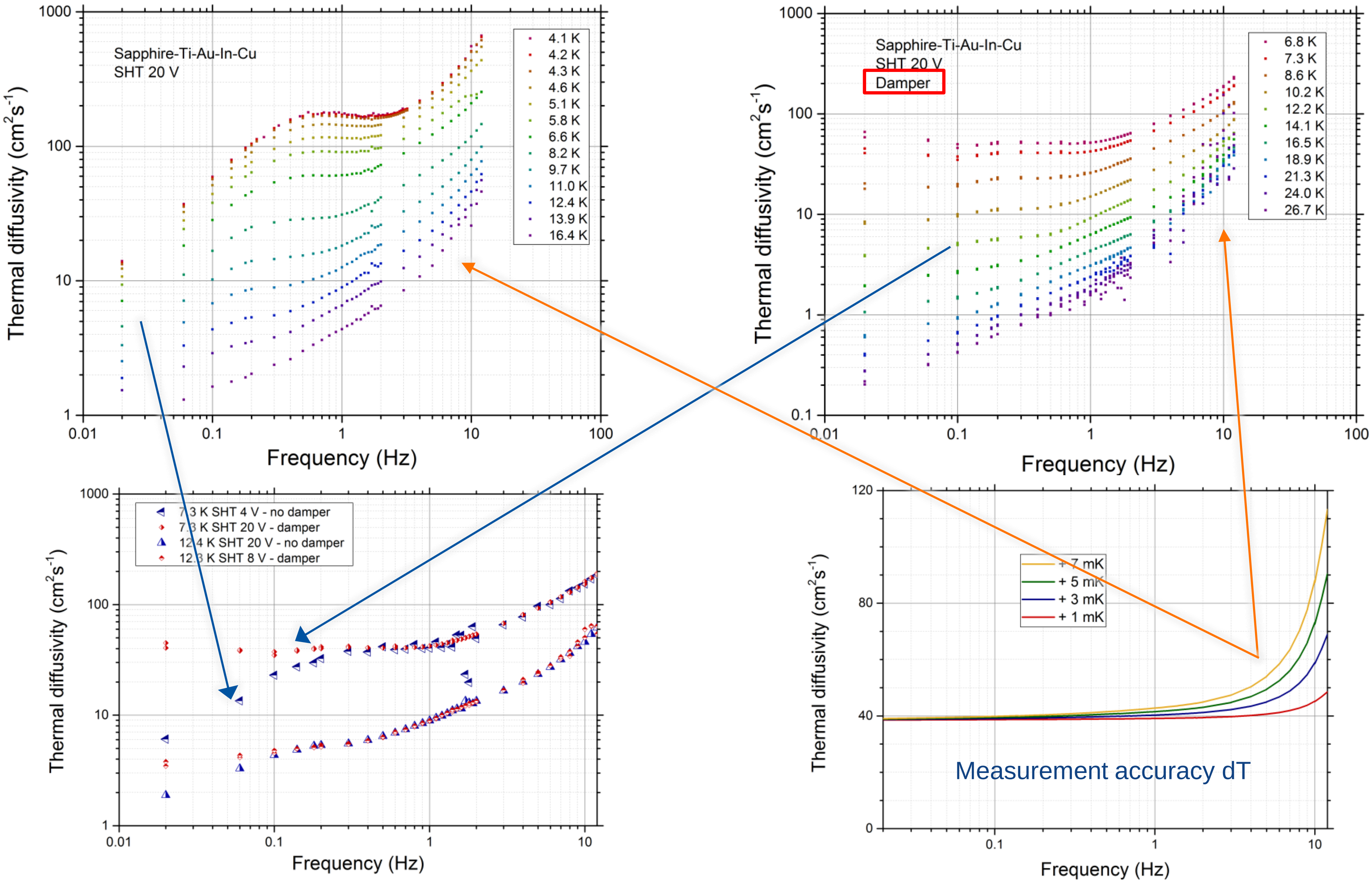
Courtesy: G. Dubuis, X. He, and I. Božovic, Sub-milliKelvin stabilization of a closed cycle cryocooler, Rev. Sci. Instrum. 85, 103902 (2014).

Our version CERN Cryolab with:

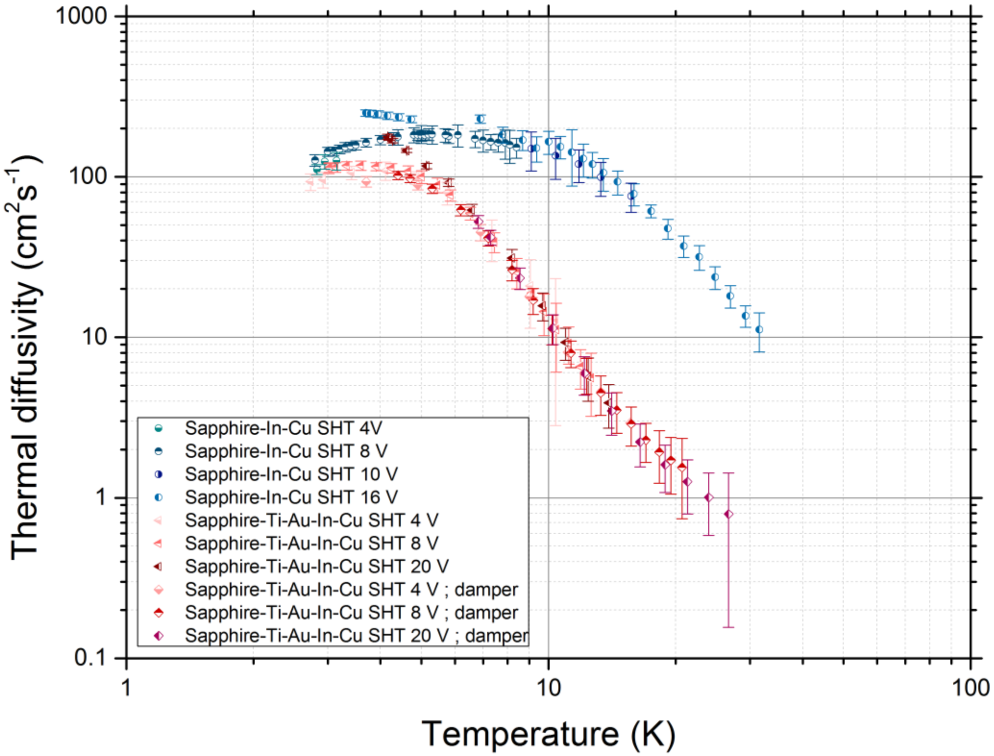
Cryocooler SHI RP-082B2 oscillations at f_{op} = 1.725 Hz



Thermal diffusivity of a Cu-In-sapphire and Cu-In-Au-Ti-sapphire sandwich



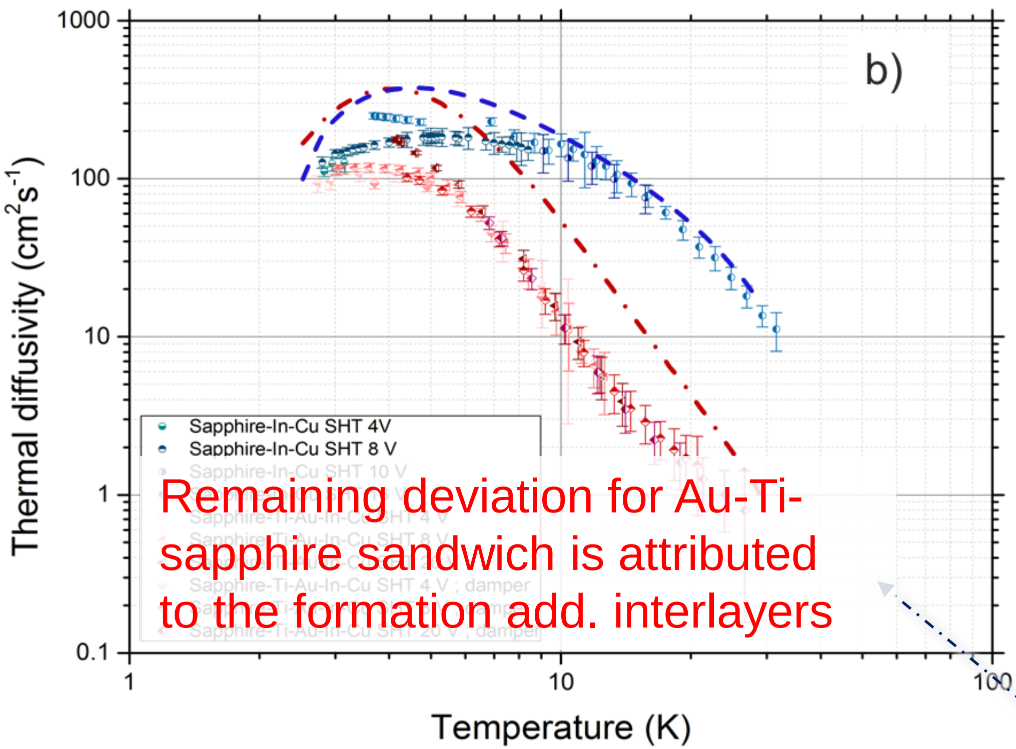
Thermal diffusivity of a Cu-In- sapphire and Cu-In-Au-Ti-sapphire sandwich



- $D^*_{Cu\text{-}In\text{-}Sapphire} > D^*_{Cu\text{-}In\text{-}Au\text{-}Ti\text{-}Sapphire}$
- $D^*_{max,Cu\text{-}In\text{-}Au\text{-}Ti\text{-}Sapphire}$ is at lower T
- Curves almost merge at about 3 K
- Cu-In-Au-Ti-Sapphire has additional interfaces → additional thermal resistance

Numerical modelling of that structure =>

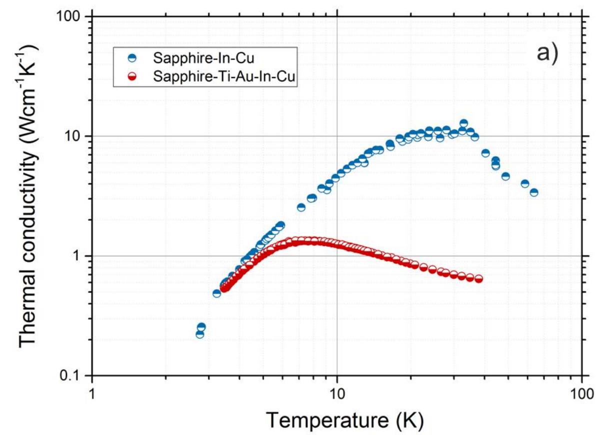
Thermal diffusivity of a Cu-In-sapphire and Cu-In-Au-Ti-sapphire sandwich



Remaining deviation for Au-Ti-sapphire sandwich is attributed to the formation add. interlayers

Numerical modelling =>

measured thermal conductivity



$$R_s = R_{sap} + R_{In} + R_{Cu} + R_{InSapIn}$$

$$R_{InSapIn} = \frac{1}{225} T^{2.5-3.0}$$

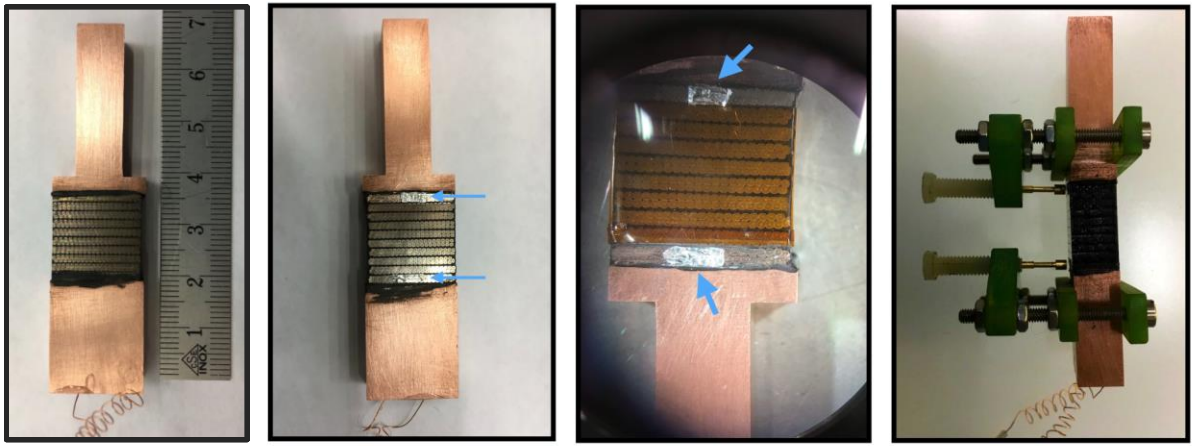
Geometry + $c_s \cdot \rho_s = \sum_i \frac{x_i}{d} \cdot c_i \cdot \rho_i$

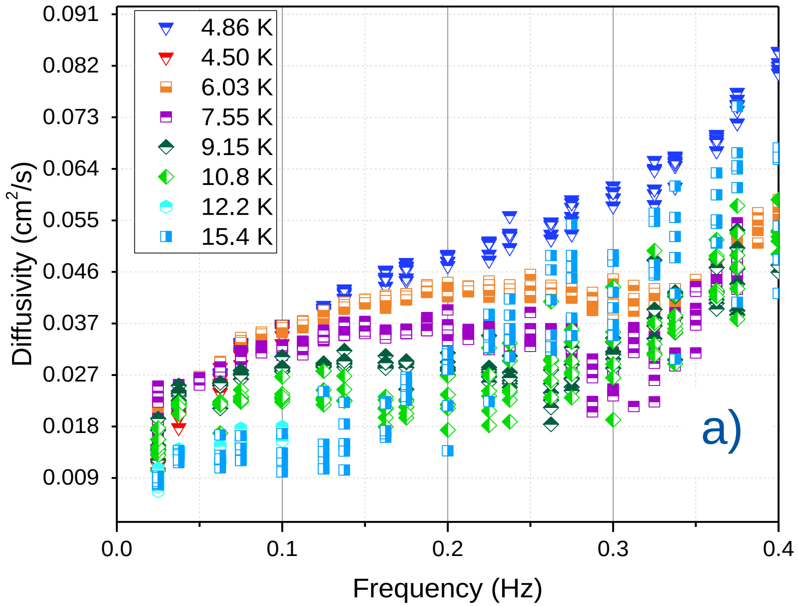
$$D^* = \frac{d}{A \cdot R_s \cdot c_s \cdot \rho_s}$$

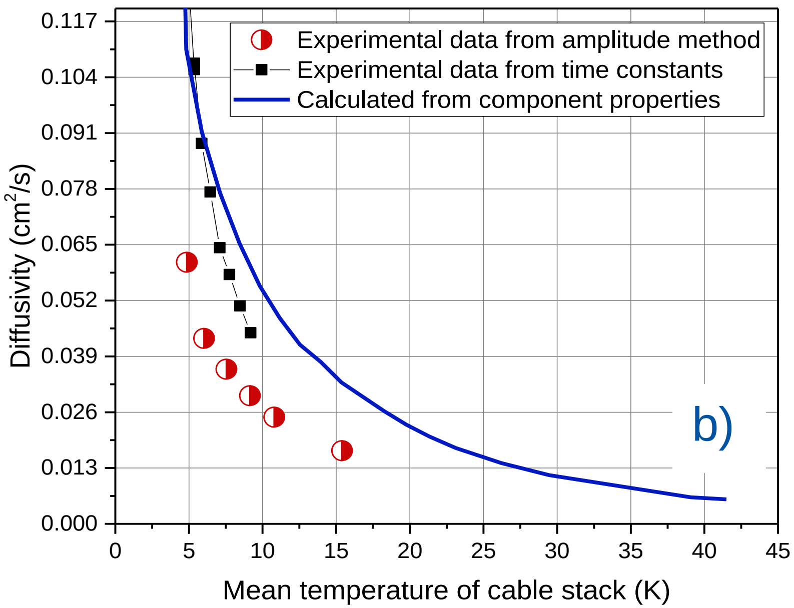
Comparing methods: amplitude attenuation vs. step function

Sample:

Nb_3Sn Rutherford type cable stack of 11 T dipole, fully impregnated

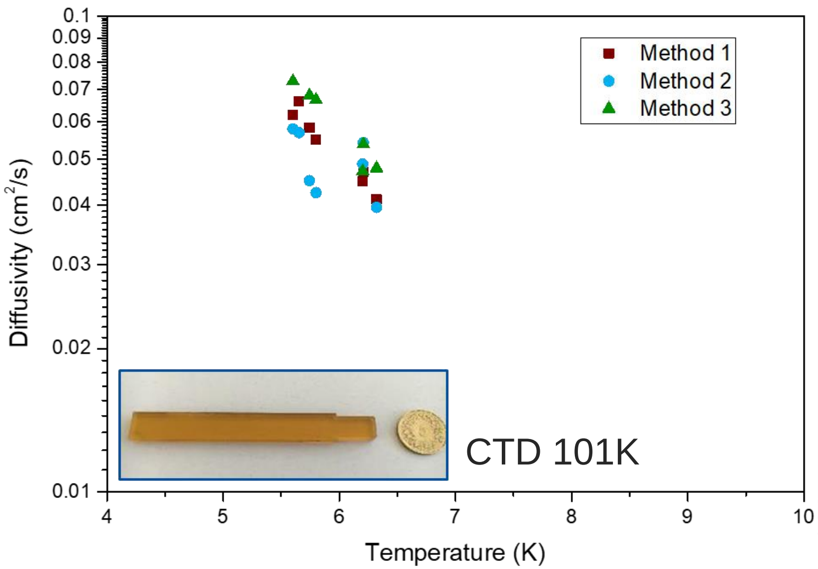


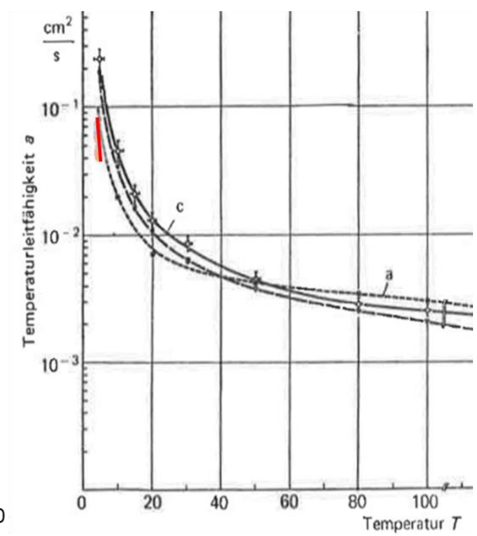




Conclusion

- ✓ Evaluation of measurement methods
- ✓ OFHC-copper measurement and comparison with literature values
- ✓ Inhomogenous stackd with dielectric-metal interfaces
- ✓ Comparison of methods for bulk samples
- ✓ Amplitude attenuation and step methods seem to be complementary





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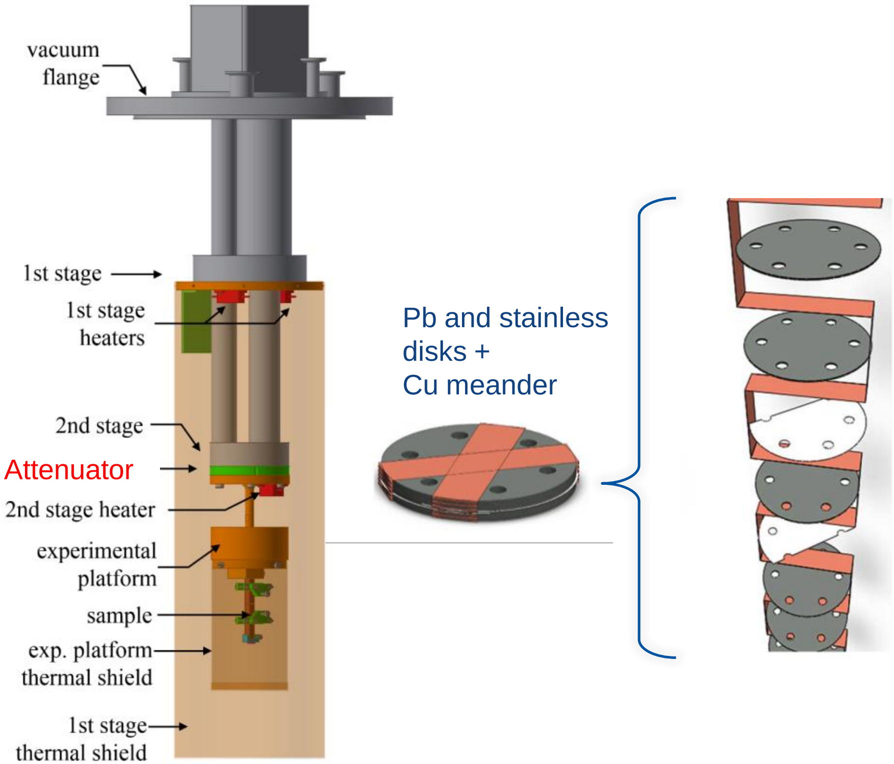
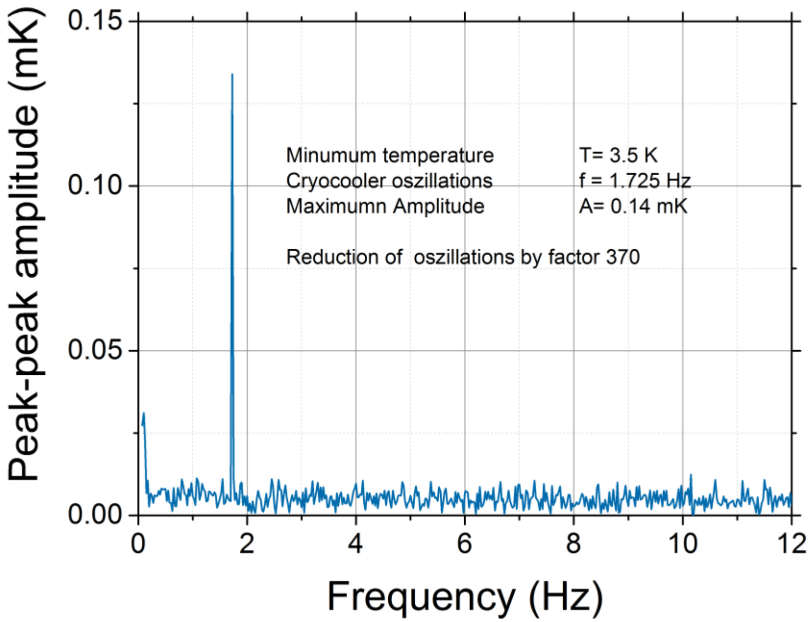
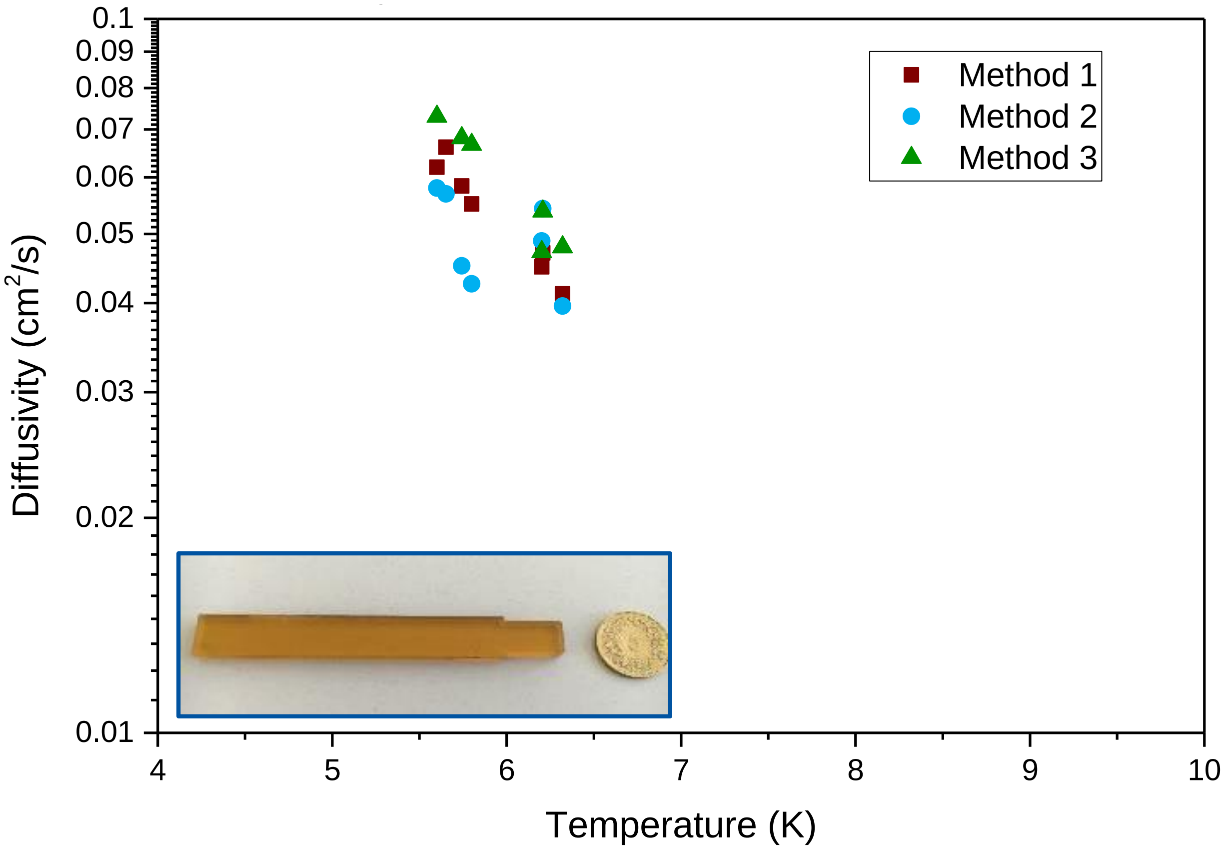
Passive thermal attenuator

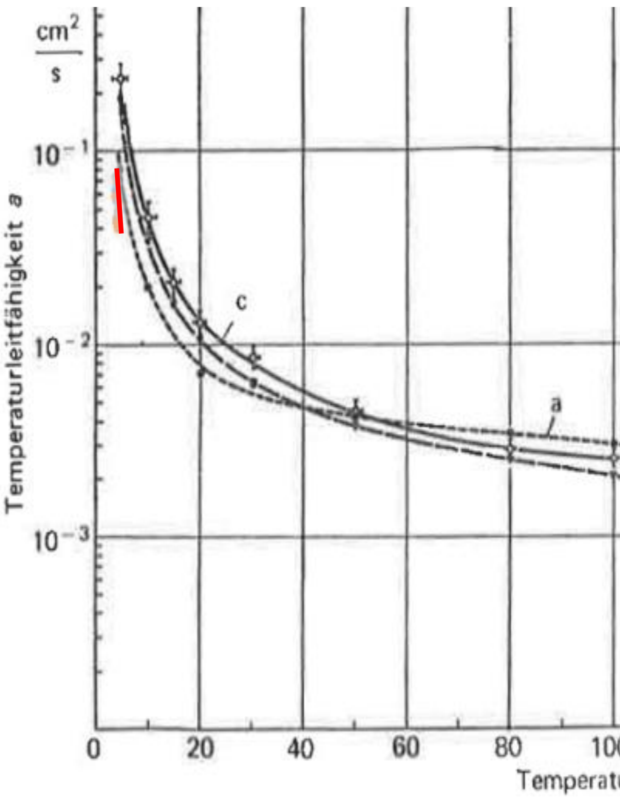




Courtesy: G. Dubuis, X. He, and I. Božovic, Sub-milliKelvin stabilization of a closed cycle cryocooler, Rev. Sci. Instrum. 85, 103902 (2014).

HiLumi LHC$_{11\ T\ Nb_3Sn\ Dipole}$ => CTD-101K bulk epoxy sample

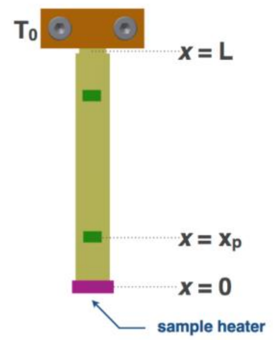


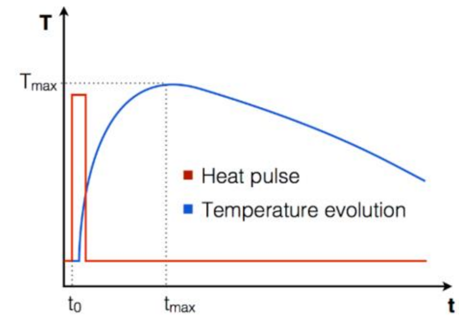


From: Frey, H. and Haefer, R. A., *Tieftemperaturtechnologie*

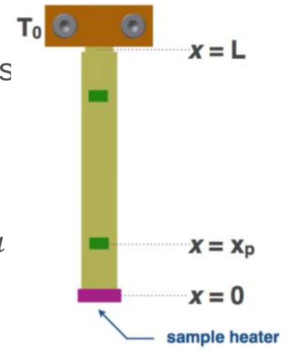
Further diffusivity measurement methods

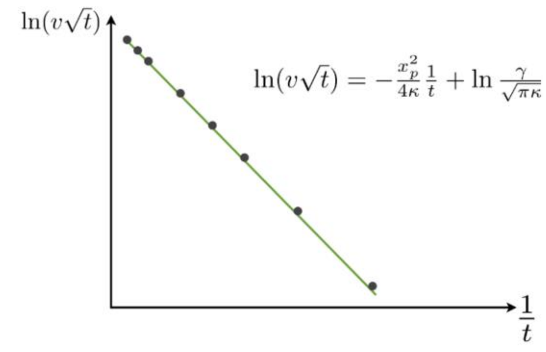
- **Pulse:** $\kappa = \frac{x_p^2}{2t_{max}}$
  - x_p is the distance between the heater and the s
  - t_{max} is the time at which the temperature at x_p
- **Pulse 2:** $\kappa = \frac{x_p^2}{4a}$
  - $v = T_1 - T_0$ is the experimental temperature ris
  - Plot $\ln(v\sqrt{t}) = -\frac{x_p^2}{4\kappa}\frac{1}{t} + \ln\left(\frac{\gamma}{\sqrt{\pi\kappa}}\right) = -a\frac{1}{t} + b,$
  - diffusivity can be extracted through the slope a
- **Step:** $\kappa = 1.38\, {x_p}^2/\pi^2 t_{1/2}$
  - plot $V = T(x_p, t)/T_{max}$ as a function of
  - $t_{1/2}$ is the time when $\mathrm{T}(x_p)$ reaches half of the
- 3 ω method and more …



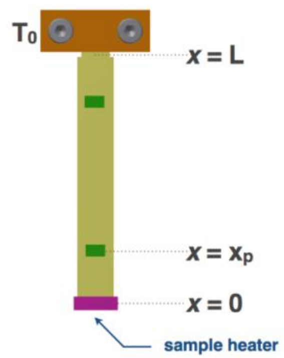


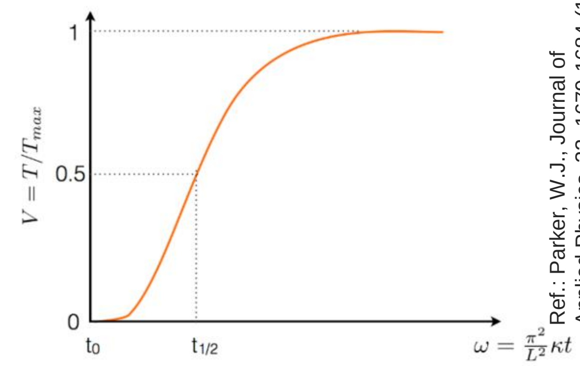
Ref.: Hunklinger, S., Low Temperature Physics, Springer, 2005.





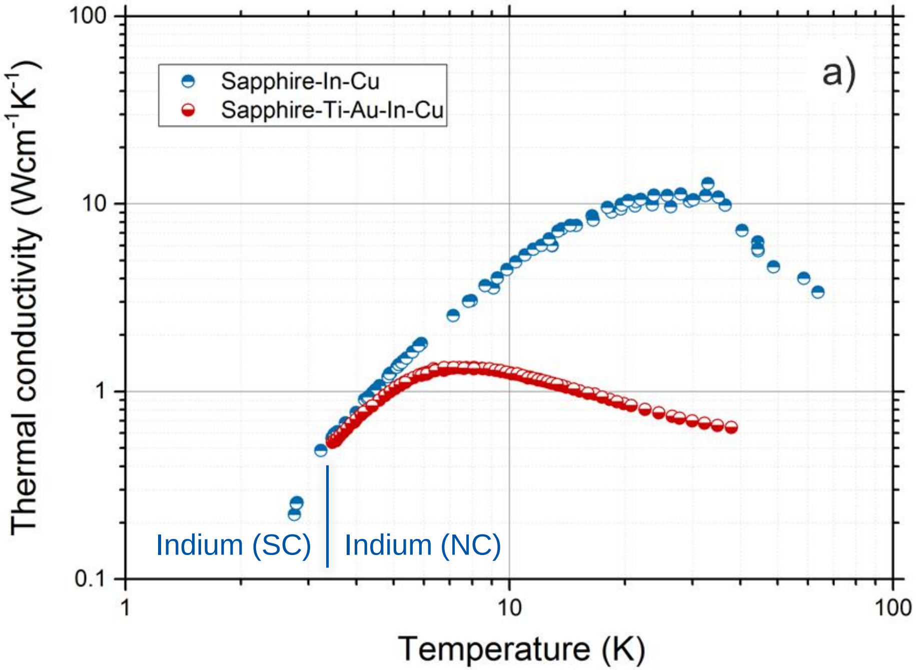
Ref.: Krüger, R. et al., Phys. Stat. Sol. (a) 17: 471–478 (1973)

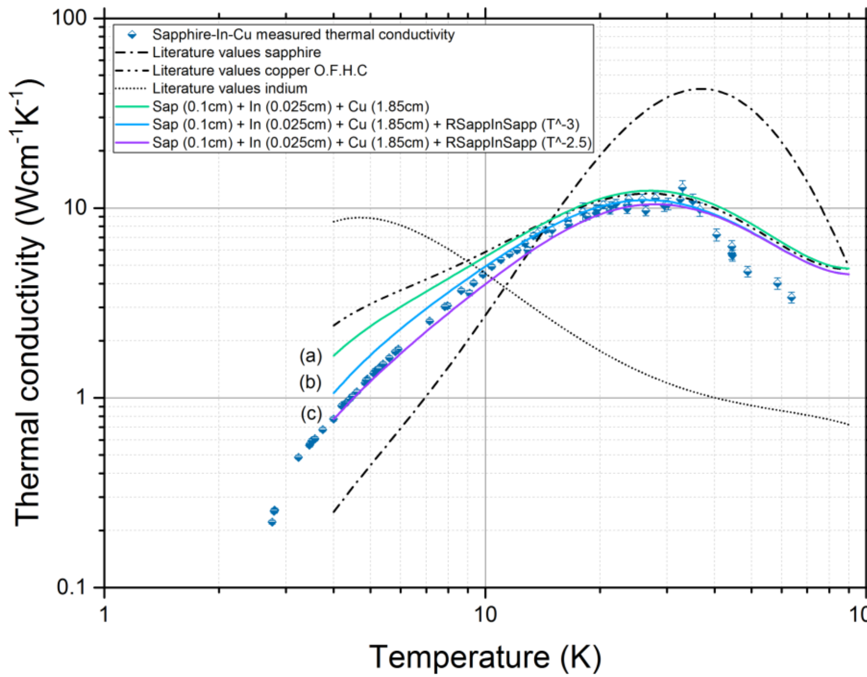




Ref.: Parker, W.J., Journal of Applied Physics, 32, 1679-1684 (1961)

λ and κ^* of a Cu-In-sapphire and Cu-In-Au-Ti-sapphire sandwich





Modelling of thermal conductivity including the boundary resistances e.g. Cu-In-sapphire:

$$R_i = \frac{d}{\lambda \cdot A} \qquad R_s = R_{sap} + R_{In} + R_{Cu} + R_{InSapIn}$$

$$with \quad R_{InSapIn} = \frac{1}{225} T^{2.5-3.0} \quad in \ \frac{m^2}{WK}$$

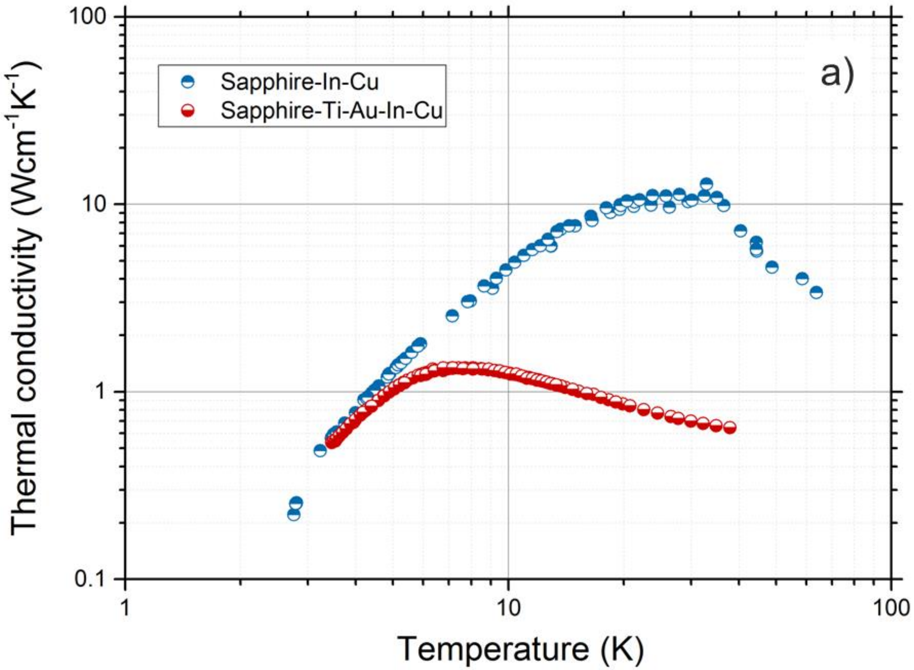
Gmelin et al., J. Phys. D: Appl. Phys. 32 (1999) R19–R43.

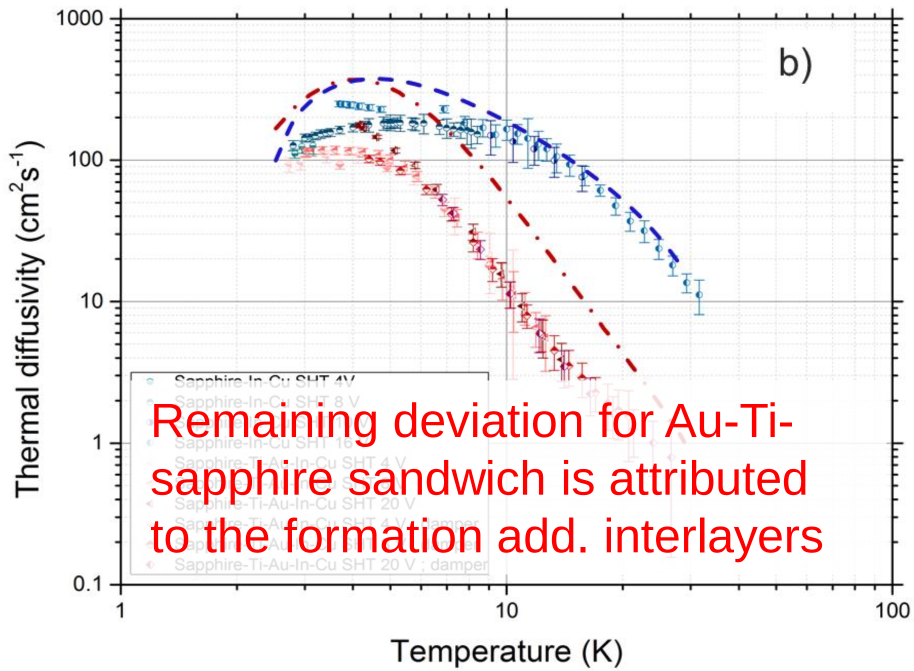
Modelling of diffusivity including λ measured ! of Cu-In-sapphire:

$$c_s \cdot \rho_s = \sum_i \frac{x_i}{d} \cdot c_i \cdot \rho_i$$

$$\kappa^* = \frac{d}{A \cdot R_s \cdot c_s \cdot \rho_s}$$

λ and κ^* of a Cu-In-sapphire and Cu-In-Au-Ti-sapphire sandwich





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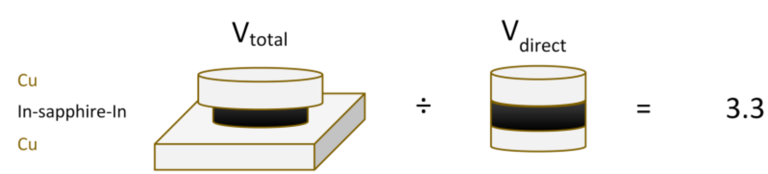
Gmelin et al., J. Phys. D: Appl. Phys. 32 (1999) R19–R43.

Geometry factor: static vs. transient



Cu-In-Au-Ti-sapphire = (2.7)