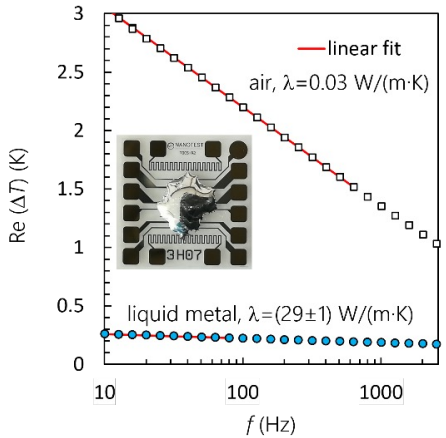
TOCS®

Three-Omega Characterization System

NANOTEST
simply measured

Motivation

- Thermal conductivity of thermal interface materials can be critical for thermal management in microelectronic systems
- Thermal conductivity usually measured by steady-state method ASTM D5470 (e.g., TIMA®), but
  - Measurement during curing is not easily possible (because relatively high ΔT must be applied for measurement)
  - Not well suitable for high thermal conductivity materials and time-consuming preparation for cured samples, because samples of different thicknesses must be prepared
- Bidirectional 3-omega method is an alternative to the standard method for measuring thermal conductivity
  - Sensitive
  - Rapid (≈ 1 minute)
  - Temperature and time-dependent measurements during curing
  - Suitable for low and high thermal conductivities



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Fast-paced thermal material characterization

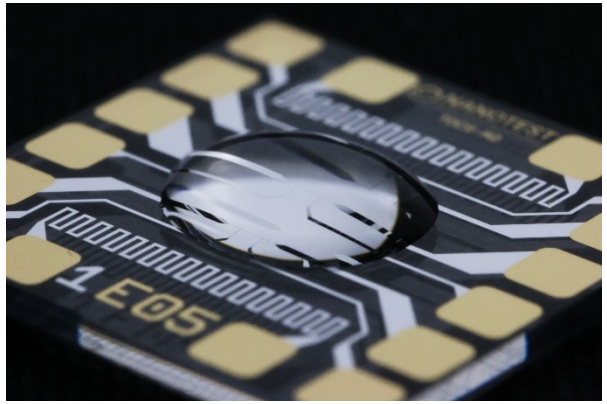
Material parameters

- Bulk thermal conductivity
- Thermal diffusivity

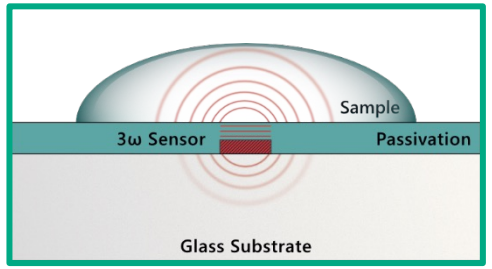
Feasible samples

- Liquids
- Gels
- Pastes
- Soft solids

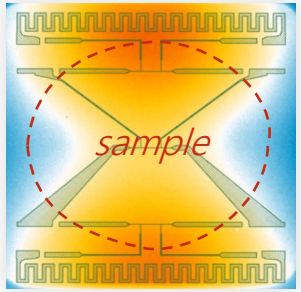
*Sample material is **simply applied** on the test chip and tested with a **mere buttonpress**.*

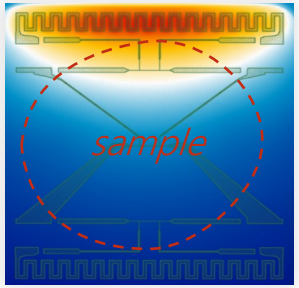


Measurement x-section



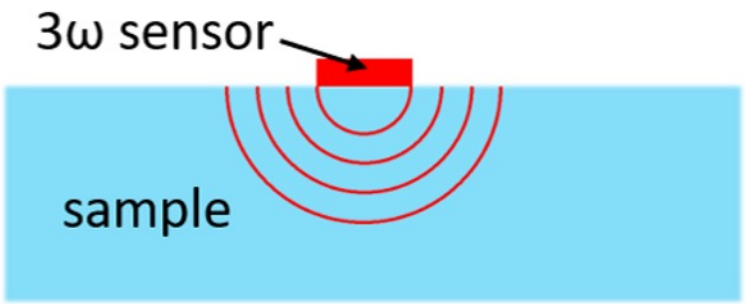
Custom temperature profiles





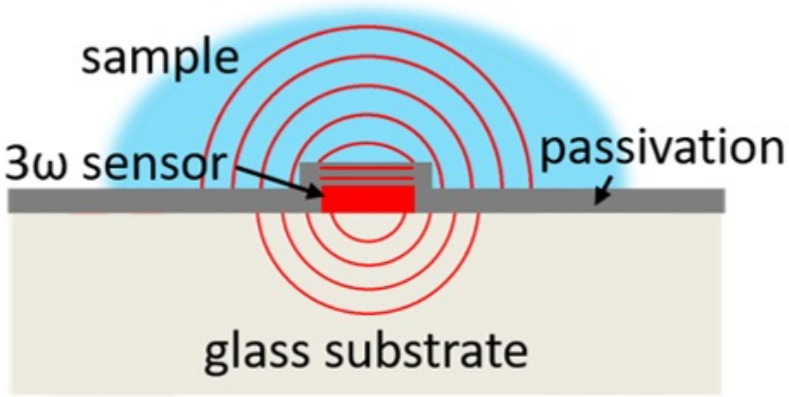
New approach using three-omega method

Conventional 3ω-method



Sensor **on top** of sample

Bidirectional 3ω-method



Sample **on** chip

» Requires 3ω sensor for each sample

» Only for solid materials

» Taking 3ω-method from lab to industrial application

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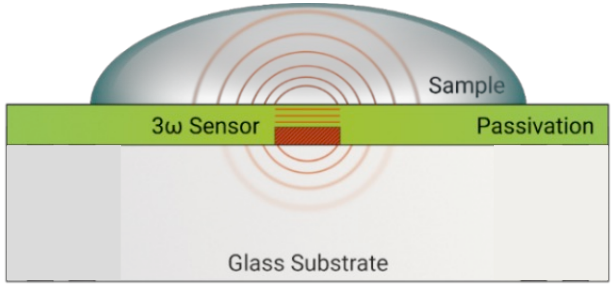
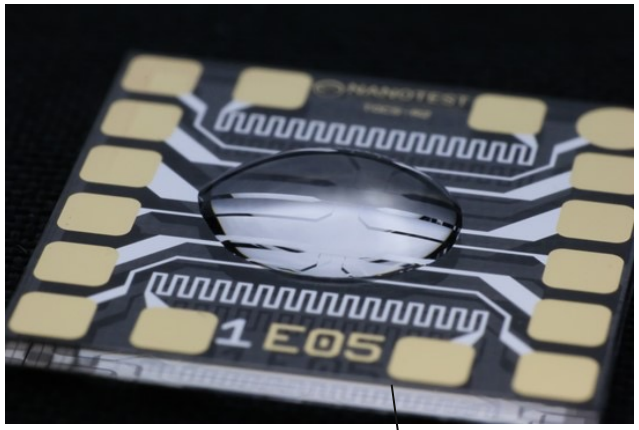
One-minute-thermal conductivity

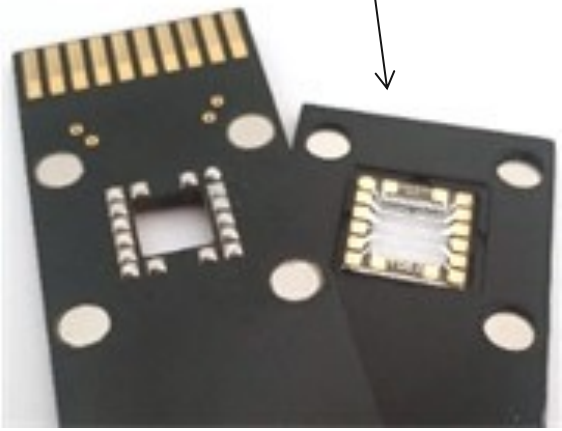
» highly-sensitive measurement platform for thermal conductivity and diffusivity measurements based on the 3ω method



3ω from lab to industrial level



Results in < 1 min



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Method

TOCS® physical basics

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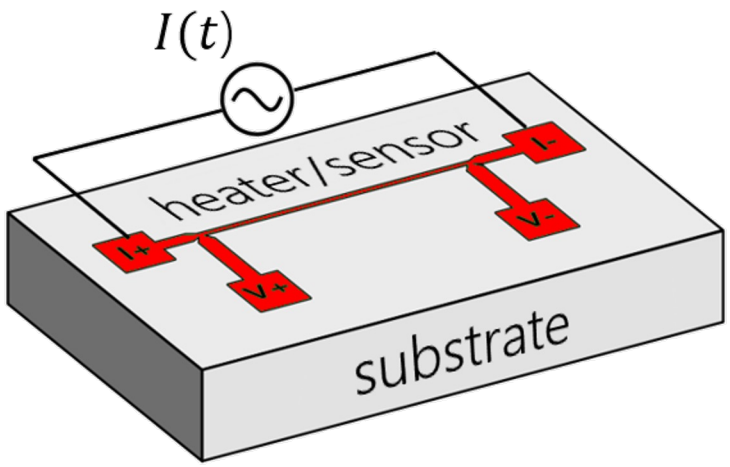
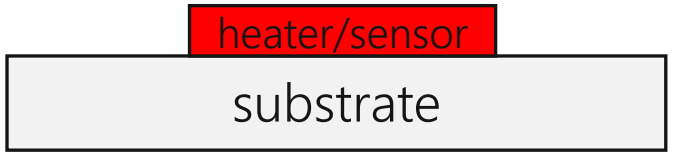
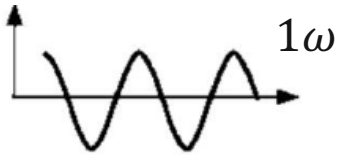
Three-Omega Method used by TOCS®





$$\Delta T = \frac{2V_{3\omega}}{I_0 \mathrm{d}R/\mathrm{d}T}$$

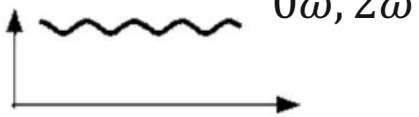
Current $I(t) = I_0 \cos(\omega t)$



Heating $P(t) = I^2(t)R$

Temperature $\Delta T \propto P$

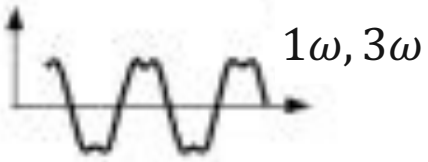
Resistance $R(t) = R_0(1 + TCR \cdot \Delta T(t))$



Voltage $V(t) = \underbrace{I(t)R(t)}$

$V_{1\omega}$ $V_{3\omega}$

Lock-in measurement



[1]

[1] Dames C. *et al.*, *Rev. Sci. Instrum.* **76**, 124902 (2005).

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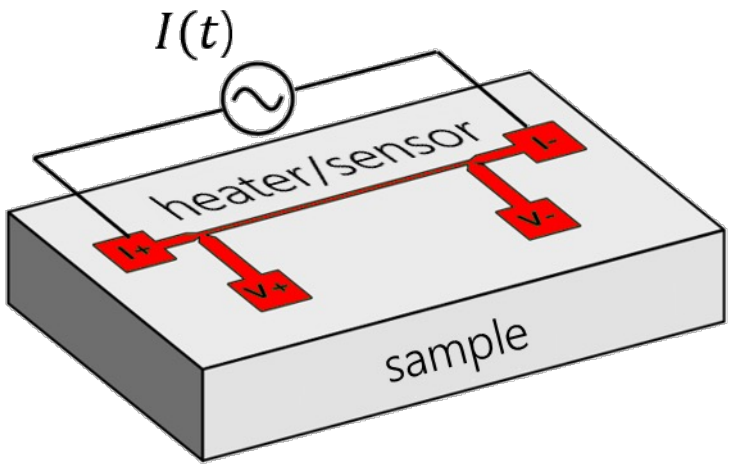
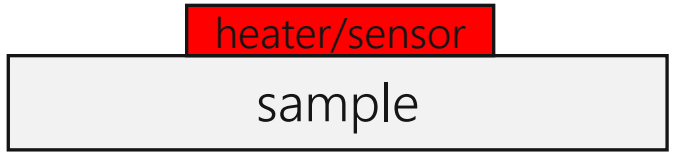
Three omega method: substrate calibration





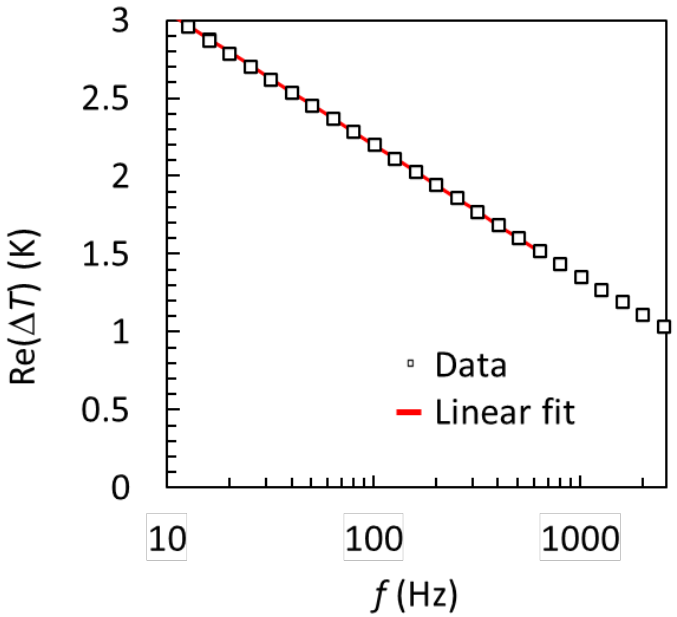
Model by Cahill, 1990 [1]:

$$\Delta T = \frac{2V_{3\omega}}{I_0 \mathrm{d}R/\mathrm{d}T}$$

If substrate thickness $d_s > 5\mu$ and $\mu < L/5$ [2], where $\mu = \sqrt{\alpha/2\omega}$ (= penetration depth):

$$\Delta T = \frac{P}{\lambda \pi L} \int_0^\infty \left(\xi^2 + \frac{i2\omega}{\alpha}\right)^{-1/2} \frac{\sin^2(\xi b)}{(\xi b)^2} d\xi$$

λ: sample thermal conductivity
α: sample thermal diffusivity
P: power
L: sensor length, b: sensor half width.



Boundary mismatch approximation ($L \gg b$, $\mu > b$) [1,2] :

$$\lambda \cong \frac{-P}{2\pi L}\left(\frac{\mathrm{d}(\mathrm{Re}(\Delta T))}{\mathrm{d}(\ln(\omega))}\right)^{-1}$$ "slope method"

[1] Cahill D. G., *Rev. Sci. Instrum.* **61**, 802-808 (1990).
[2] Dames, C., *Ann. Rev. Heat Transfer.* **16**, 7-49 (2013).

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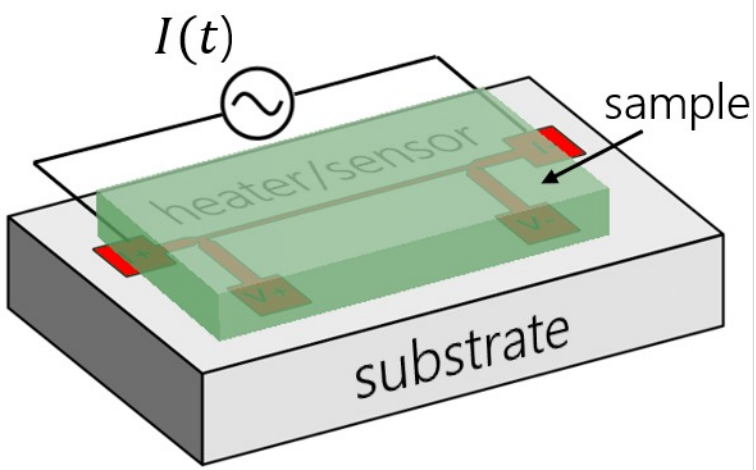
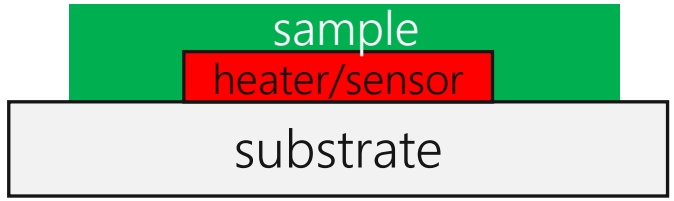
Three Omega Method: measurement of sample on top of chip





If thickness of substrate ($j = 1$) and sample ($j = 2$) $d_j > \mu_j$ and sensor length $L > 5\mu_j$, with $\mu_j = \sqrt{\alpha_j / 2\omega}$ [1]:

$$\Delta T = \frac{P}{\pi L} \int_0^\infty \frac{1}{\Upsilon_1 + \Upsilon_2} \frac{\sin^2(\xi b)}{(\xi b)^2} d\xi$$

$$\Upsilon_j = \lambda_j \sqrt{\xi^2 + i \frac{2\omega}{\alpha_j}}$$

λ_j: thermal conductivity of material j
a_j: thermal diffusivity of material j
b: sensor half width, L: sensor length
R_0: sensor resistance.

Boundary mismatch approximation ($L \gg b$, $\mu_{1,2} > b$) [1] :

Thermal conductivity of sample: $\boxed{\lambda_2 = "\lambda_{1+2}" - \lambda_1}$ "slope method"

[1] Lubner, S. D. *et al.*, *Rev. Sci. Instrum.* **86**, 014905 (2015).

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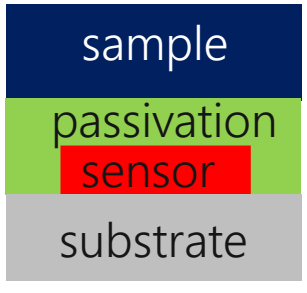
Bidirectional 3ω-method with passivation



$j = 2$

$j = p$

$j = 1$

» Homogeneous sensor line with $L > 5\mu_j$, $b_j < 5\mu_j$ where $\mu_j = \sqrt{\alpha_j/2\omega}$ [1]:

$$\Delta T = \frac{P}{\pi L}\int_0^\infty \frac{\cosh(\Upsilon_p R_p)+\sinh(\Upsilon_p R_p)\Upsilon_2/\Upsilon_p}{(\Upsilon_1+\Upsilon_2)\cosh(\Upsilon_p R_p)+\left(\frac{\Upsilon_1\Upsilon_2}{\Upsilon_p}+\Upsilon_p\right)\sinh(\Upsilon_p R_d)}\frac{\sin^2(\xi b)}{(\xi b)^2}\,d\xi,$$

with $\Upsilon_j = \lambda_j\sqrt{\xi^2 + i\frac{2\omega}{\alpha_j}}$, with $j = 1,2,p$ and $R_p = t_p/\lambda_p$

P: power
$2b$: sensor width, L: sensor length, R_0: sensor resistance
α_j: thermal diffusivity of material j
λ_j: thermal conductivity of material j
t_p: thickness of passivation

Boundary mismatch approximation ($L \gg b$, $\mu_j > b$, $t_p << \mu_j$) [1] :

Thermal conductivity of sample: $\boxed{\lambda_2 = "\lambda_{1+2}" - \lambda_1}$ "slope method"

[1] Lubner, S. D. *et al.*, *Rev. Sci. Instrum.* **86**, 014905 (2015).

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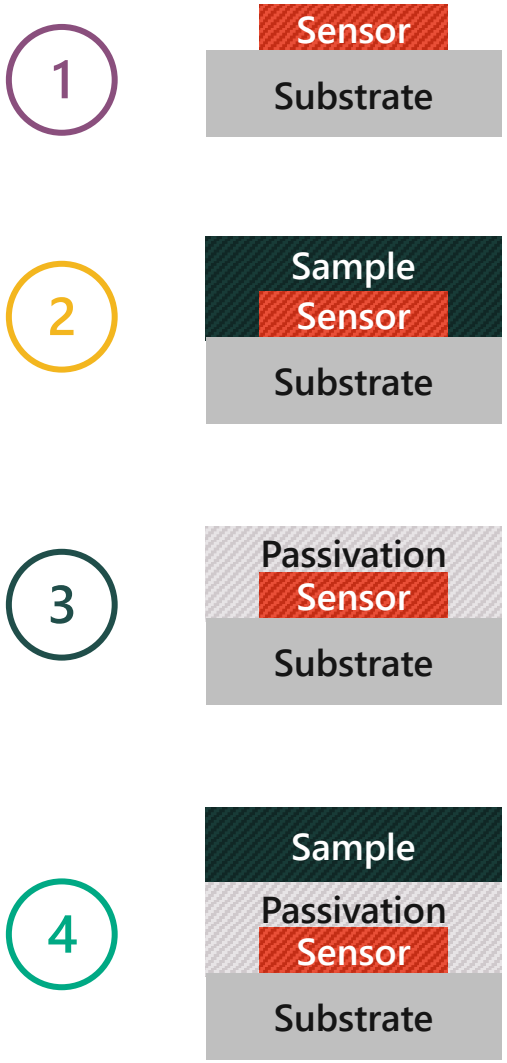
Analysis models of TOCS®

#	Fit model	Results	Remarks	Use case
[0]	Linear fit	Thermal conductivity of substrate and sample	Passivation is neglected “slope”-method	**all**
[1]	Cahill model (only substrate)	Thermal conductivity & diffusivity of substrate	Air or vacuum as sample	1
[2]	Bidirectional w/o passivation	Thermal conductivity & diffusivity of samples	To be used for chip w/o passivation	2
[3]	Fit passivation parameters	Thermal conductivity & diffusivity of chip passivation	Results to be used as input for fit model 4	3
[4]	Bidirectional w/ passivation fit conductivity + diffusivity	Thermal conductivity & diffusivity of samples		4
[5]	Bidirectional w/ passivation fit diffusivity	Thermal diffusivity of samples	Conductivity should be known or measured with other model	4
[6]	Bidirectional model w/ passivation short	Thermal conductivity & diffusivity of samples	Passivation assumed as Rth (offset)	4



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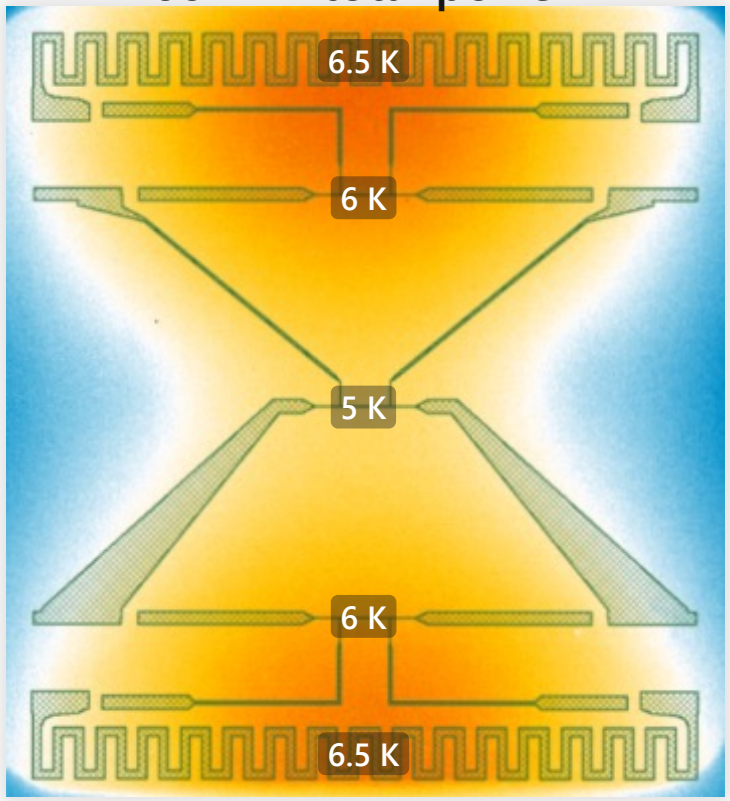
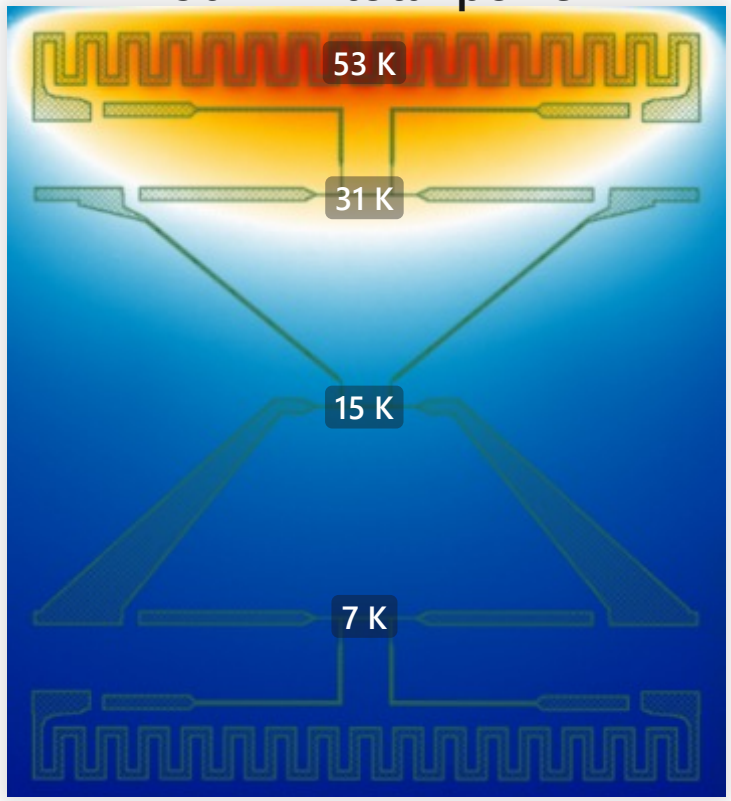
On-Chip heating options

double-sided heating
88 mW total power



single-sided heating
190 mW total power



temperature rise relative to ambient temperature

- → Heating of chip, for temperature-dependent thermal conductivity measurement
- → Chip temperature up to 180°C

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Measurement examples

TOCS® in action

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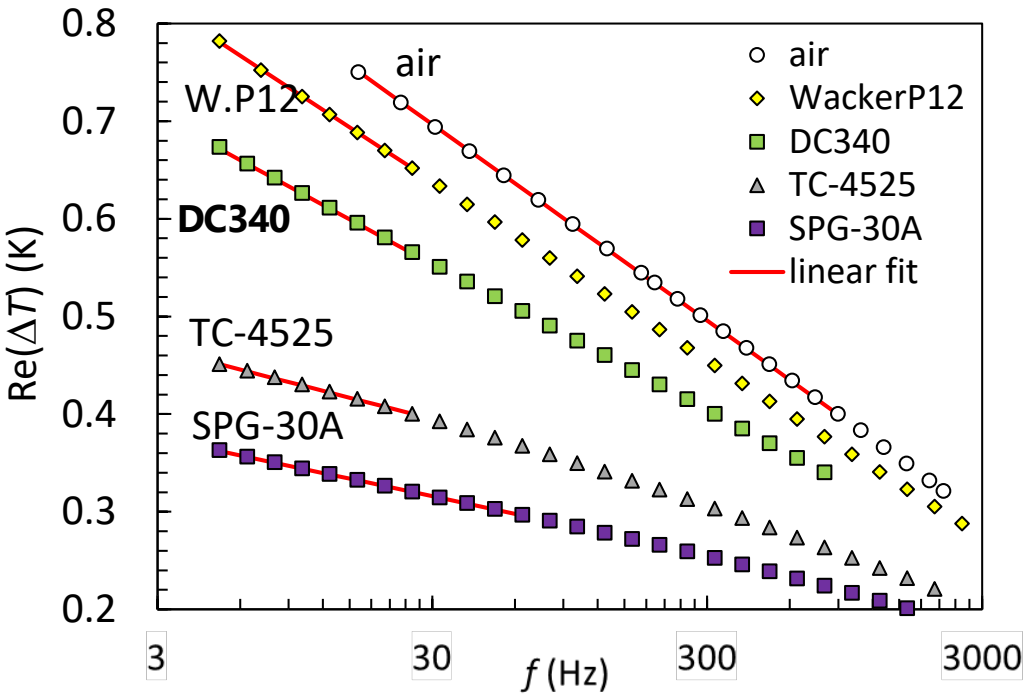
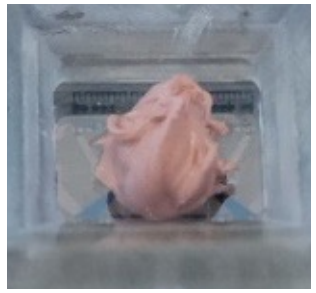
Thermal interface materials

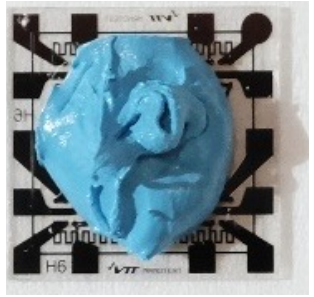
- » Different pastes have been characterized
- » Three non-cured thermal greases
- » One cured two components gap filler
- » Pastes dispensed on the top of the chips
- » Gap filler has been cured at 150°C for 1h directly on the chip
- » Data fitted with model [0]



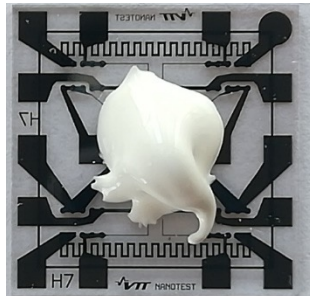
Sarcon® SPG-30A



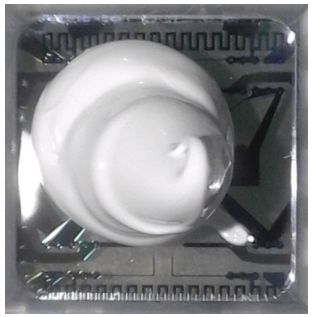
Dow® TC-4525



Wacker® P12



Dow Corning® 340



Material	λ TOCS W/(m·K)	λ Datasheet W/(m·K)
P12	0.58 ± 0.02	0.81
340	0.79 ± 0.04	0.67
TC-4525	2.40 ± 0.20	2.6
SPG-30A	3.81 ± 0.05	3.2

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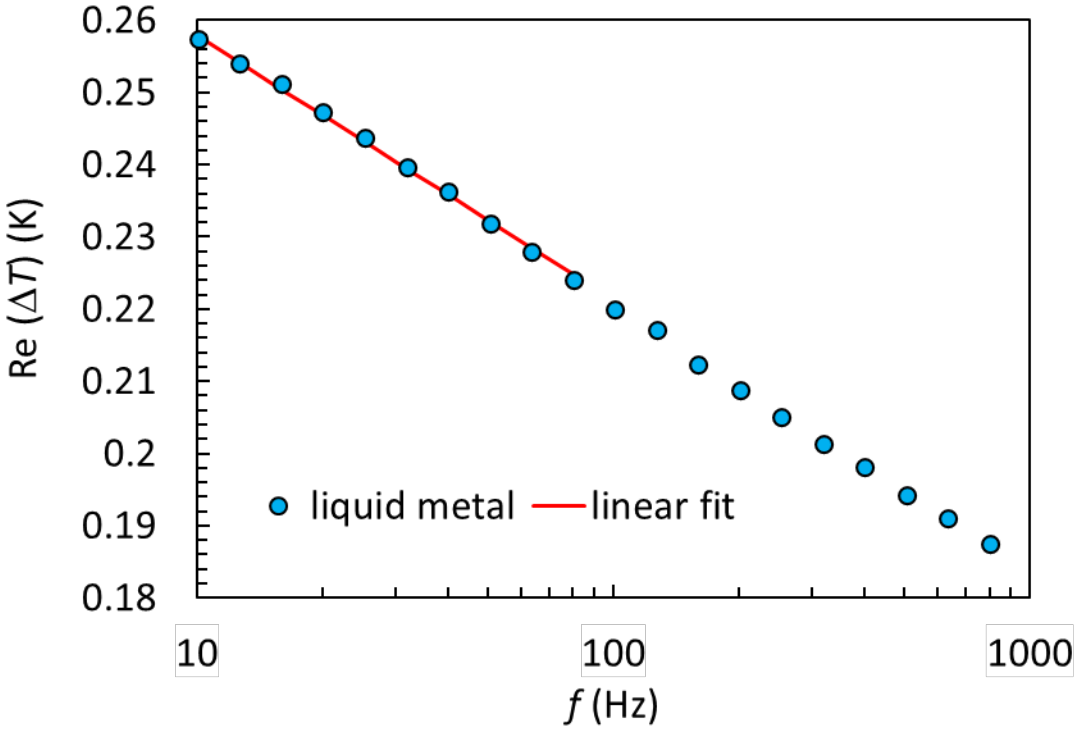
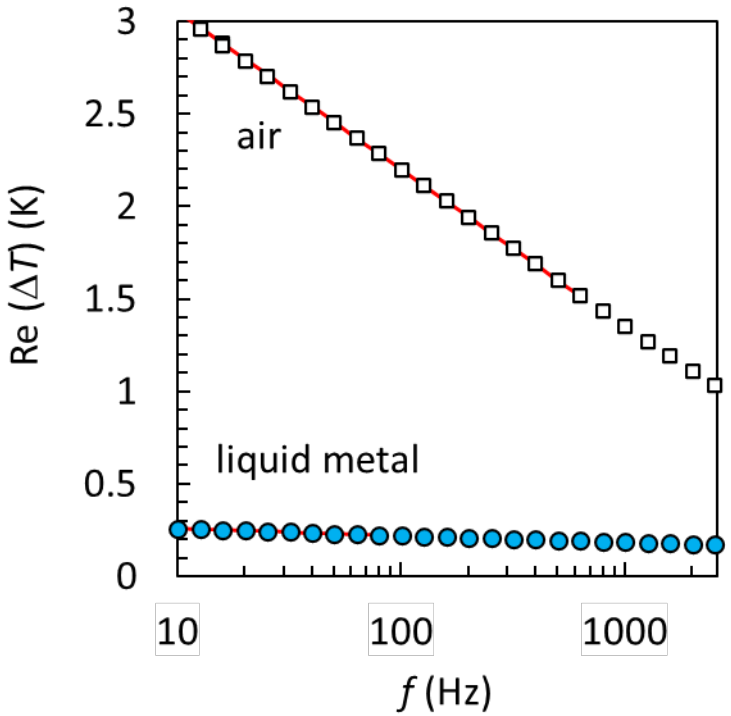
Liquid metal





Indalloy® 46L
61% Ga | 25% In | 13% Sn | 1% Zn

λ = 29 ± 1 W/(m·K)

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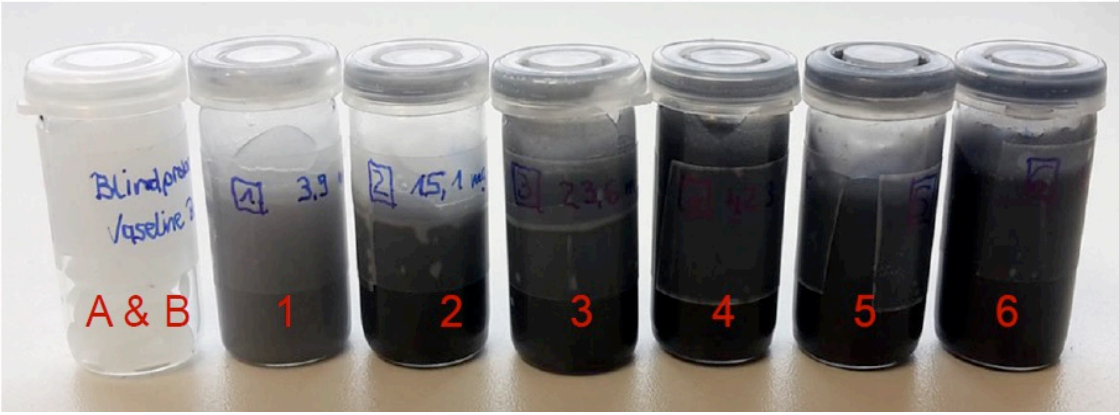
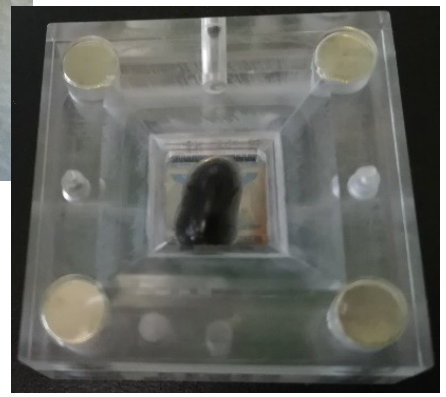
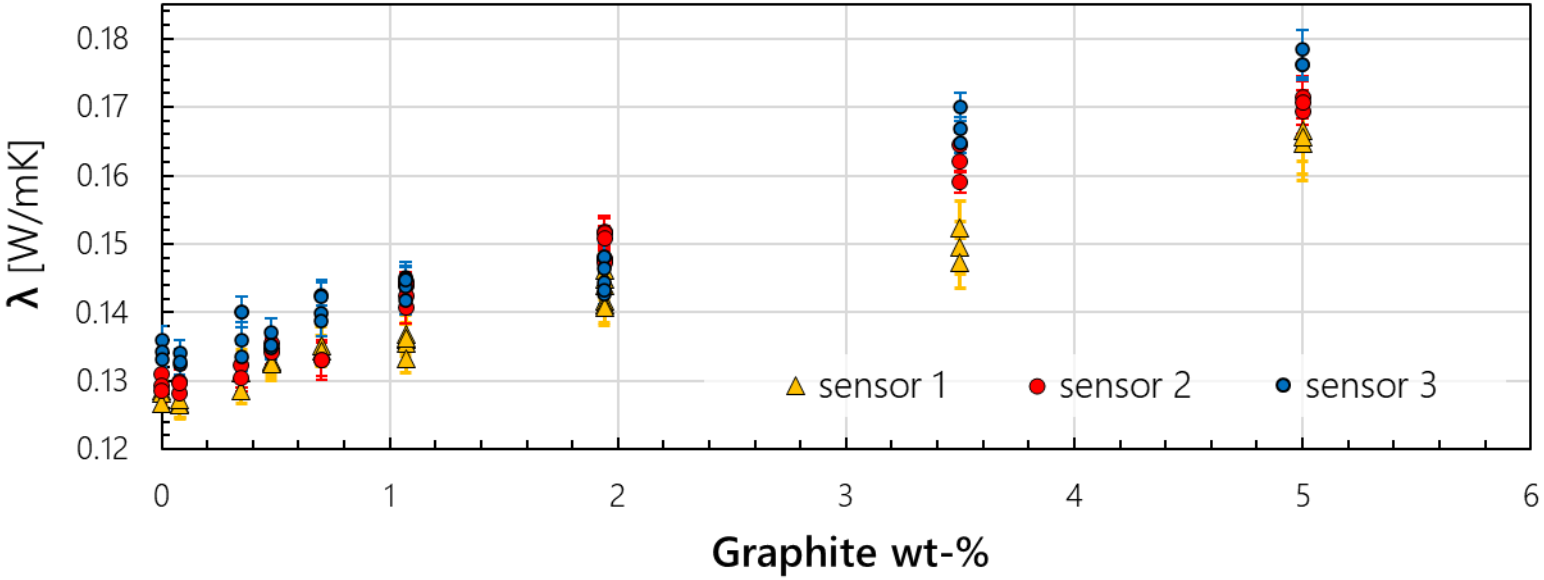
Graphite dispersed in Vaseline



Graphite (99% pure, 15-20 µm particle size) in Vaseline





Clear trend!

~ 0.01 W/mK per wt-%

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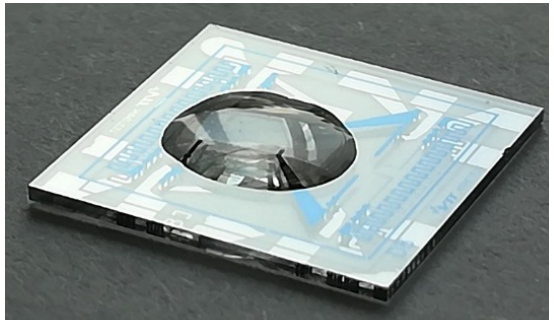
Thermal conductivity of epoxy during curing



2-component gap filler

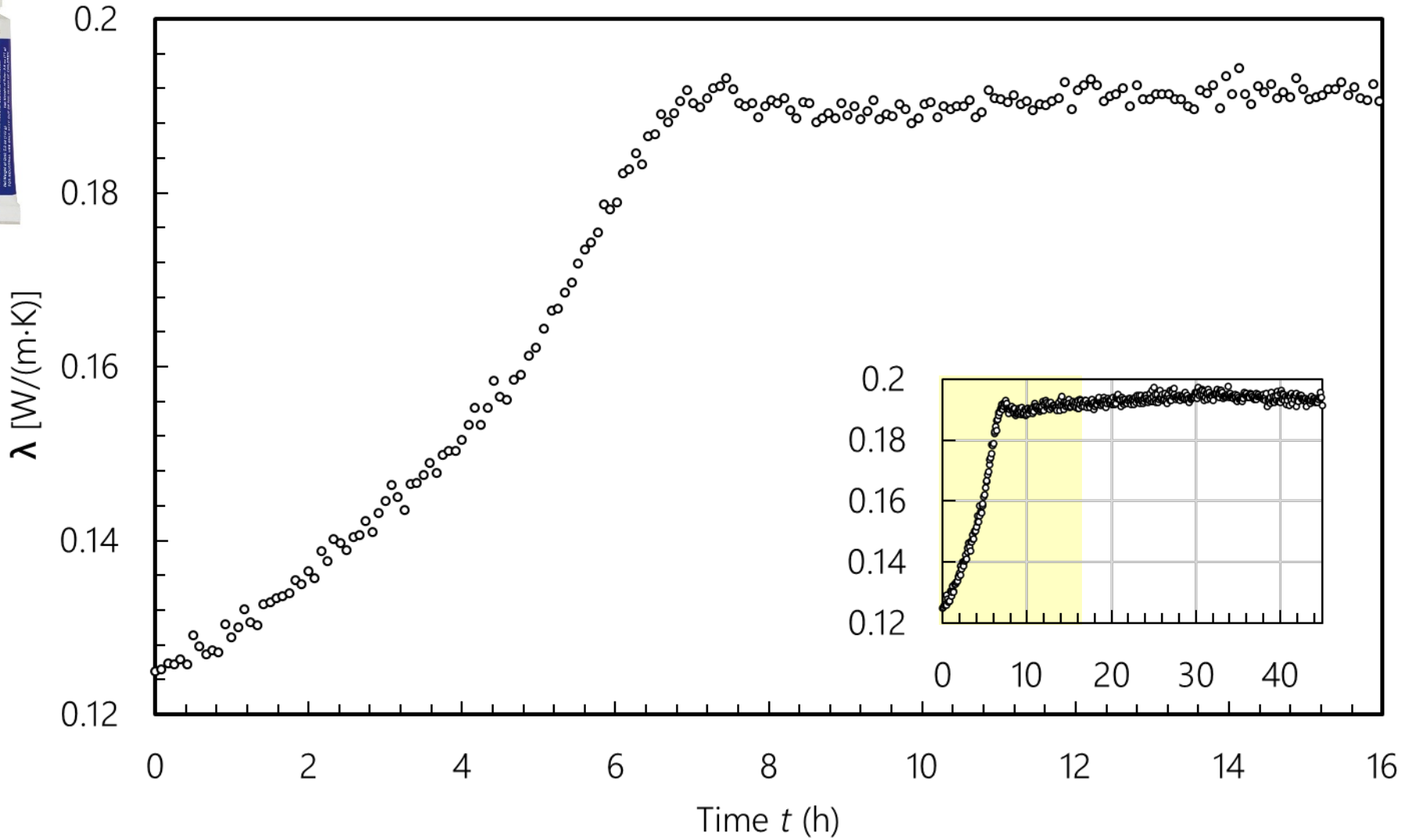
- Room temperature
- 48 hours curing
- Room temperature
- Continous measurement

Initial:

- 0.124 ± 0.004 W/(m·K)

After 8h:

- 0.191 ± 0.004 W/(m·K) (+54%)
- No more (thermal) curing



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TOCS® Conclusions

Features	Limits
» Fast and easy	» Pressure-less only
» Highly sensitive	» Only liquids + pastes
» Conductivity + diffusivity	» Sample thickness > 100 µm (depending on sample type)
» Monitoring over temperature	» Not standardized
» Monitoring over time	
» External curing	

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