

Prototype 16:

3-omega thermal characterization chip

(Device C')

Lead Partners: Berliner Nanotest und Design GmbH, Germany and VTT-Technical research Centre of Finland

This measurement system is suitable for measuring the thermal conductivity of fluids, gels, pastes and bulk samples. The method used is an extension of the 3-omega method, which allows for the measurement of thermal properties of samples for which the traditional 3-omega method is not applicable. For the traditional 3-omega method a thin metal heater line must be deposited on the sample, which is often impractical and even impossible for samples such as fluids, gels, pastes or samples with rough surfaces. In our 3-omega measurement system the sample is applied onto a chip in which the 3-omega sensor is already integrated. A schematic of the measurement setup is shown in Figure 1.

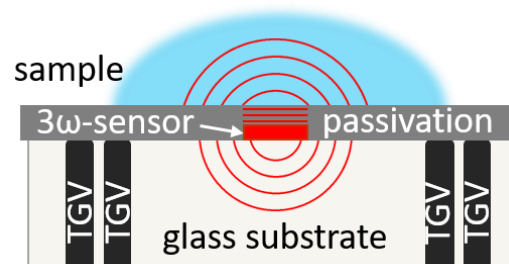


Figure 1: Schematic measurement setup for thermal conductivity measurements with 3-omega thermal characterization chip.

For the 3-omega measurements an alternating voltage $V(t) = V_0 \cos(\omega t)$ is applied to the sensor. The Joule heating in the 3-omega sensor generates an additional voltage oscillation at the sensor at 3ω , the so-called 3-omega voltage, $V_{h,3\omega}$. This voltage is related to the temperature oscillation at the sensor $\Delta T = \frac{2V_{h,3\omega}}{dR/dT I_0}$, where dR/dT is the slope of the temperature-dependent electrical resistance of the 3-omega sensor and I_0 the current in the sensor. Using a bi-directional model in which the materials below and on top of the sensor are considered allows to draw conclusions about the thermal conductivity and diffusivity of the material on top (Lubner, et al., 2015). Photographs of the chip holder for the 3-omega measurements are shown in Figure 2.

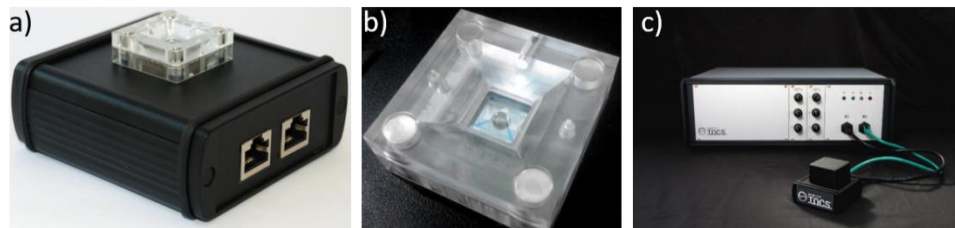


Figure 2: a) and b) Chip holder with spring probes connecting the chip to RJ45 connectors. c) 3-omega measurement setup.

Instrument Specifications

The substrate material for the 3-omega thermal characterization chips is BOROFLOAT®33-Borosilicate glass with tungsten through-glass vias (TGVs). The 3-omega sensors are made of aluminium. The vias connect the pads of the 3-omega sensor to gold pads on the back side of the chip. The top side of the chips is covered with a 54 nm thick Al_2O_3 passivation layer, which was grown by atomic layer deposition. Optical microscopy images of a chip are shown in Figure 3. The chip contains three 3-omega sensors of width $3\ \mu\text{m}$ and length $1200\ \mu\text{m}$. The voltage probes are positioned at $1/4^{\text{th}}$ of the total sensor length away from the edges of the sensor. Geometric dimensions of the 3-omega sensors are given in Table 1 and Figure 6. The 3-omega sensors were designed according to the design rules for 3-omega measurements given by C. Dames (Dames, 2013). In addition, there are two broad meander-shaped heaters at the chip with which the samples can be optionally heated or a temperature gradient can be created between two sides of the chip.

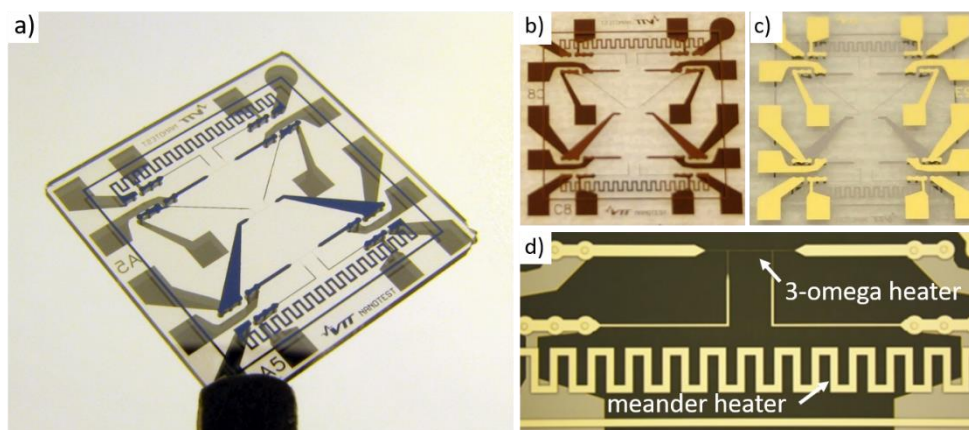


Figure 3: Optical microscopy images of the 3-omega thermal characterization chip. a) chip, b) top side c) back side, d) area on top side with one 3-omega sensor and one meander heater.

Table 1:

Chip substrate material	BOROFLOAT®33-Borosilicate glass (Schott Hermes wafers)
3-omega sensor material	Aluminium
Passivation material	Al ₂ O ₃
Passivation thickness	54 nm
3-omega sensor length	1200 μm
3-omega sensor length between voltage probes	600 μm
3-omega sensor width	≈ 3 μm
Substrate thickness	1100 μm
Resistance of meander heater	120 Ohm

Geometric dimensions of the 3-omega sensors.

Applications

- Thermal conductivity measurements of fluids, gels, pastes, polymers, thermal interface materials, biological samples and bulk samples.
- Thermal conductivity measurement of heated samples.

Measurement procedure

1. Insertion of the chip into the chip holder shown in Figure 2 a) and b).
2. Determination of the temperature coefficient of resistance dR/dT of the 3-omega sensor.
3. Connection of the chip holder to the 3-omega measurement setup shown in Figure 2 c).
4. Application of a voltage $V_{osc}(t) = V_0 \cos(\omega t)$ for a certain desired power at the 3-omega sensor

$$P = \frac{(V_{s,1\omega})^2}{R_h} \text{ is between 0.1 mW and 4 mW.}$$

5. Adjustment of the potentiometer such that the voltage difference between the voltage across the potentiometer and the 3-omega sensor equals zero, $(V_s - V_p)_{1\omega} = 0$.
6. Iteratively readjust the power at the 3-omega sensor and the potentiometer to $(V_s - V_p)_{1\omega} = 0$.
7. Measurement of $V_{s,1\omega}$ and $V_{3\omega}$ at at least 5 different frequencies between $4 \text{ Hz} < f < 2 \text{ kHz}$ using lock-in technique.
8. Application of the sample onto the chip.
9. Measurement of $V_{s,1\omega}$ and $V_{3\omega}$ at several different frequencies $f_{min} < f < f_{max}$ kHz (see below) using lock-in technique.
10. Analysis: Calculate the amplitude of the temperature oscillation at the 3-omega sensor by

$$\Delta T = \frac{2V_{h,3\omega}}{\frac{dR}{dT}I_0}$$

The determination of the thermal conductivity and diffusivity from $\Delta T(\omega)$ is performed either by the slope method or the full bidirectional model (Lubner, et al., 2015).

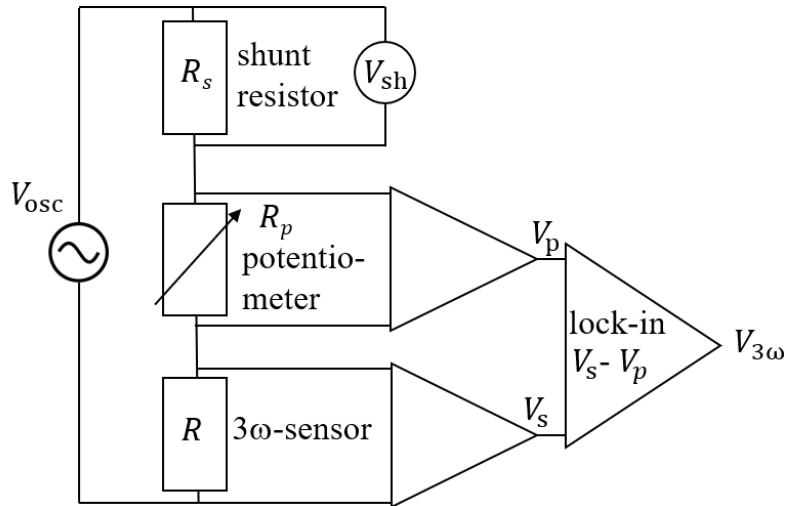


Figure 4: Schematic measurement setup for the 3-omega measurements with the thermal characterization chip. The use of a potentiometer in series with the 3ω sensor allows for a common mode subtraction for the correct determination of the 3-omega voltage $V_{3\omega}$.

Other information



Figure 5: CAD-drawing of chip holder with spring probes connecting the chip to RJ45 connectors.

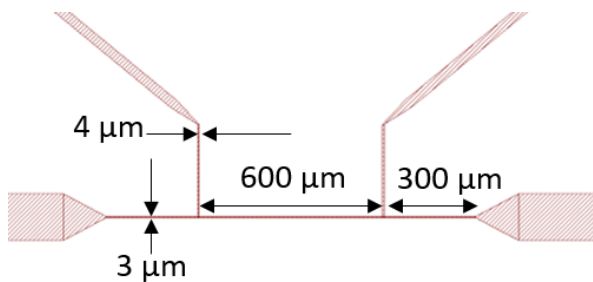


Figure 6: Magnified drawing of the 3-omega sensor in the centre of the chip.



References

Dames, C. (2013). Chapter 2: Measuring the thermal conductivity of thin films: 3-omega and related electrothermal methods. Begell House.

Lubner, S. D., Choi, J., Wehmeyer, G., Waag, B., Mishra, V., Natesan, H., . . . Dames, C. (2015). Reusable bi-directional 3ω sensor to measure thermal conductivity of 100- μm thick biological tissues. *Rev. Sci. Instrum.* 86, 014905.

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