Measurement of thermal boundary resistance by photothermal radiometry

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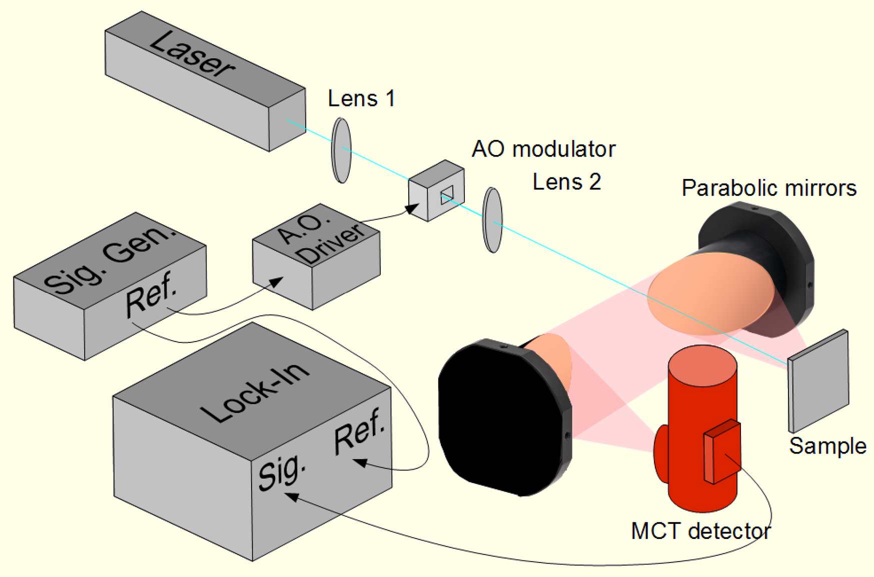
Abstract

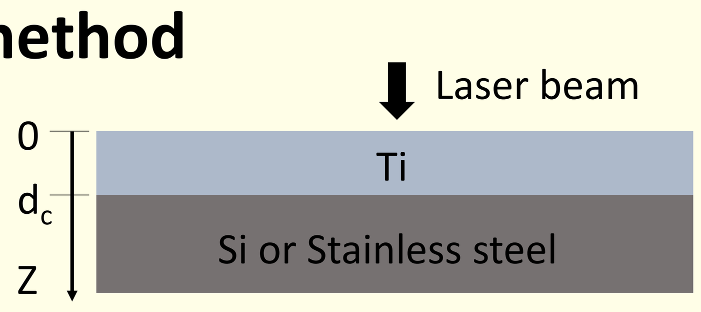
Despite recent progress in the comprehension and modeling of heat transfer across interfaces, experimental values of interfacial thermal resistance R_{th} in various systems present large deviations from theoretical predictions. Moreover, a large variability of R_{th} with the condition of the interface at micro- and nano-scale is observed. However, such data are necessary for the validation of theoretical models and computations. Measuring R_{th} between a film and the substrate is often a challenge for the experimentalist because the available methods have to be adapted to the features of the samples. This work presents the experimental approach we are using including high frequency photothermal radiometry (HF-PTR), the theory of the simulation model and the sensitivity analysis. The current PTR system has been extended for measurements up to 10 MHz. For simple configurations, R_{th} is obtained directly from the experiment and then it can be compared to theoretical predictions. A study of uncertainties led us to minimize ΔR_{th} and to find the optimum film thickness.

Experimental method

- 0.1Hz to 100 Hz for polymer composites: $d \approx 500\ \mu m$[1]
- 1 kHz to 10 MHz for thin films characterization[2,3]
- Photoconductive MCT detector KMPV-11-1
- Heterodyne lock-in amplifier SR844 – 200 MHz
- Increase of sample temperature $<$ few °C ($P_{LASER} = 80$ mW)
- Surface of measurement $\approx 1\ mm^2$



Theoretical method



Using the Fourier transformations the solution of the heat equation in a semi-infinite substrate gives the alternative temperature T_{AC} on the surface of the sample:

$$T_{AC}(f) = \frac{(-1+i)\,q}{2e_1\sqrt{\pi f}} \times \frac{1 - e^{2(1+i)\sqrt{\frac{\pi f}{a_1}}\times d_c \times \frac{\frac{e_2}{e_1}+(i+1)R_{th}e_2\sqrt{\pi f}+1}{\frac{e_2}{e_1}-(i+1)R_{th}e_2\sqrt{\pi f}-1}}}{1 + e^{2(1+i)\sqrt{\frac{\pi f}{a_1}}\times d_c \times \frac{\frac{e_2}{e_1}+(i+1)R_{th}e_2\sqrt{\pi f}+1}{\frac{e_2}{e_1}-(i+1)R_{th}e_2\sqrt{\pi f}-1}}} \quad (1)$$

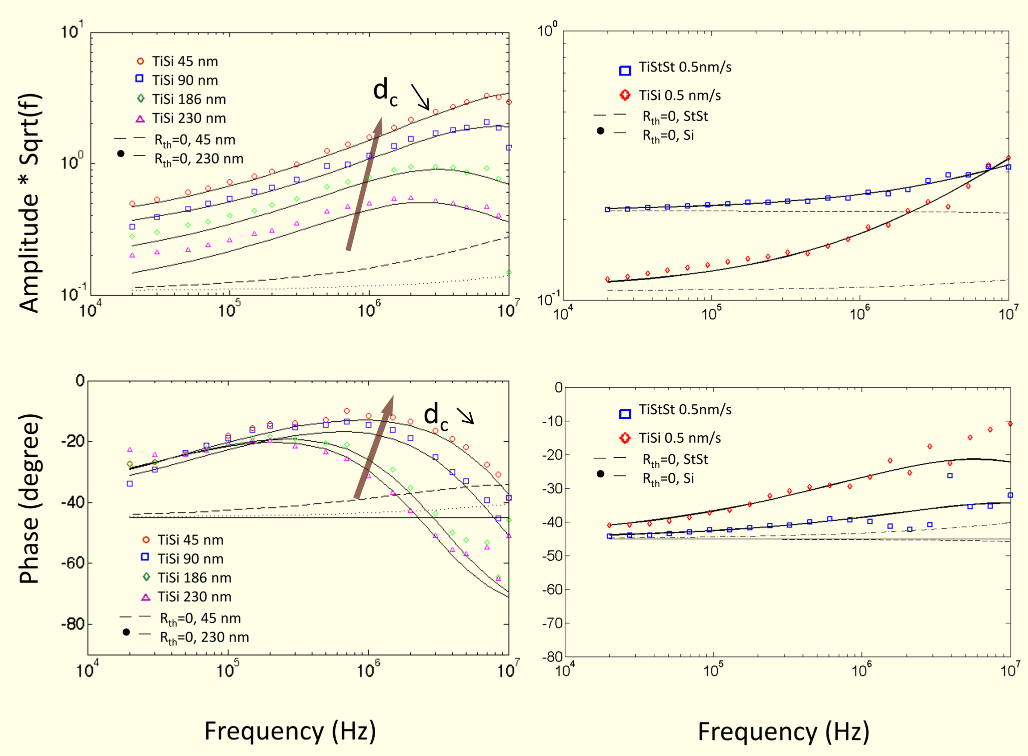
e_1 = Effusivity of the film
e_2 = Effusivity of the substrate
a_1 = Diffusivity of the film
d_c = Thisckness of the first layer
f = Frequency
q = Heat flux
R_{th} = Thermal boundary resistance

Experimental samples

Set 1	Set 2
Titanium coating on silicon substrate	Titanium coating on silicon and Stainless steel substrates
Coating thicknesses d_c : 230, 186, 90 and 45 nm	4 samples with same coating thickness d_c: 50 nm
Substrate thickness : 500 µm	2 different speeds of deposition: 0.5 and 0.1 nms^{-1}
Fabrication process: PVD 'EVA 300' (Alliance Concept)	

Experimental results

Set 1 Set 2



R_{th} results

Set 1		Set 2	
Thickness d_c (nm)	R_{th} ($10^{-8}\ m^2KW^{-1}$)	Sample/speeds of deposition (nms^{-1})	R_{th} ($10^{-8}\ m^2KW^{-1}$)
230	10.8 ± 1.4	Ti / Si – 0.5	1.9 ± 0.2
186	9.4 ± 1.2	Ti / Si – 0.1	1.8 ± 0.2
90	8.0 ± 1.2	Ti / StSt – 0.5	1.1 ± 0.2
45	10.1 ± 2.3	Ti / StSt – 0.1	0.8 ± 0.2

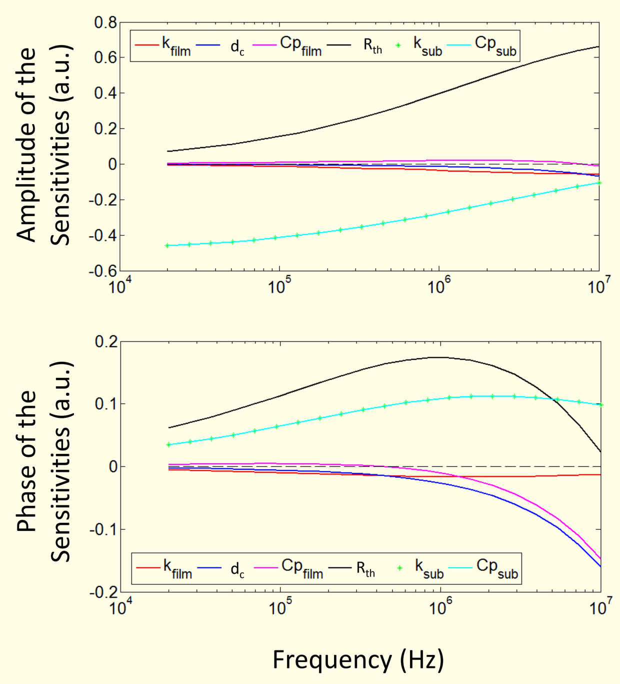
Sensitivity and uncertainty studies

The calculation of the sensitivity is made by using the equations (2) where p represents the parameter and $T_{AC}(p+\Delta p)$ is the temperature using the new measurand.

$$S_p^A = \frac{\partial \ln A}{\partial \ln p} \qquad S_p^{\varphi} = \frac{\partial \varphi}{\partial \ln p} \quad (2)$$

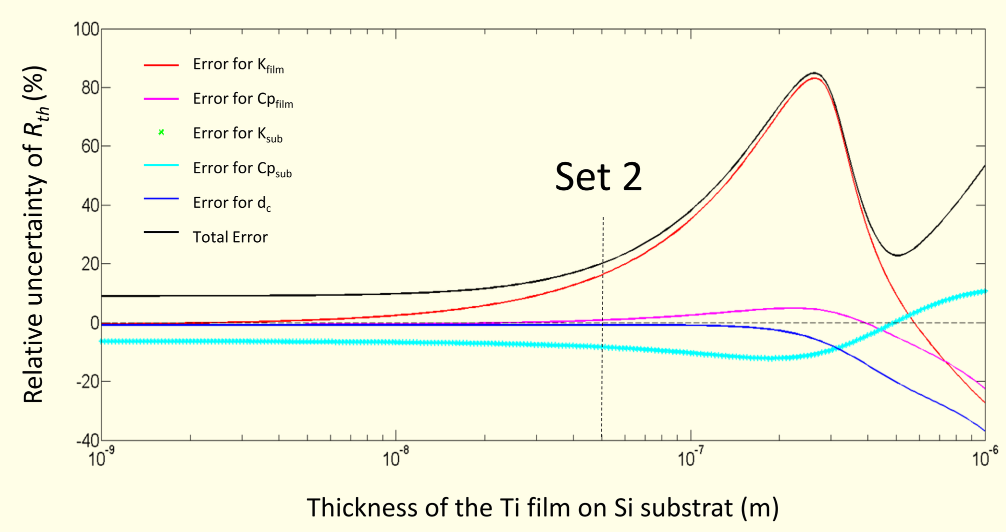
Where A and φ are the amplitude and phase of T_{AC} respectively.

Set 2 Ti/Si



After R_{th} determination for all samples, the uncertainties are calculated using equation (3)[4]. The standard uncertainties for the measurand p supposed know $\Delta R_{th\,i}(p)$ as: 50% for k_{film} ; 10% for Cp_{film} ; 10% for k_{sub} ; 10% for Cp_{sub} and 20% for d_c. The combined standard uncertainty ΔR_{th} is an estimated standard deviation and characterizes the dispersion of the values that could reasonably be attributed to the measurand p.

$$\Delta R_{th}^2 = \sum_{i=1}^{N} \left(\Delta R_{th\,i}^2(p)\right) \quad (3)$$



Conclusions

- High sensitivity to R_{th}, no sensitivity to thermal conductivity of the coating,
- Uncertainties are between 10 and 22%,
- metal/metal interface gives lower R_{th},
- Strong dependence on the nature of the substrate (factor 10),
- No influence of the deposition speed for silicon substrate,
- R_{th} decrease of 25% with lower speeds of deposition on stainless steel substrate,
- High uncertainty on k_{film} gives only 15% of uncertainty on R_{th},
- For better measurements and lower uncertainty it's better to have a thinner film (d_c /2) .

Literature cited

1. N. Horny, et *al.* (2016). Optimization of thermal and mechanical properties of bio-polymer based nanocomposites. *Polymer Degradation and Stability*.
2. J. Pelzl, et *al.* (2015). Correlation Between Thermal Interface Conductance and Mechanical Adhesion Strength in Cu-Coated Glassy Carbon. *International Journal of Thermophysics*, *36*(9), 2475-2485.
3. C. Jensen, et *al.* (2013). Thermal conductivity profile determination in proton-irradiated ZrC by spatial and frequency scanning thermal wave methods. *Journal of Applied Physics*, *114*(13), 133509.
4. http://www.bipm.org/en/publications/guides/gum.html for more information about Evaluation of measurement data - Guide to the expression of uncertainty in measurement, JCGM 100:2008.

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