3ω-method in Production Flow for Thermal Flow Sensors

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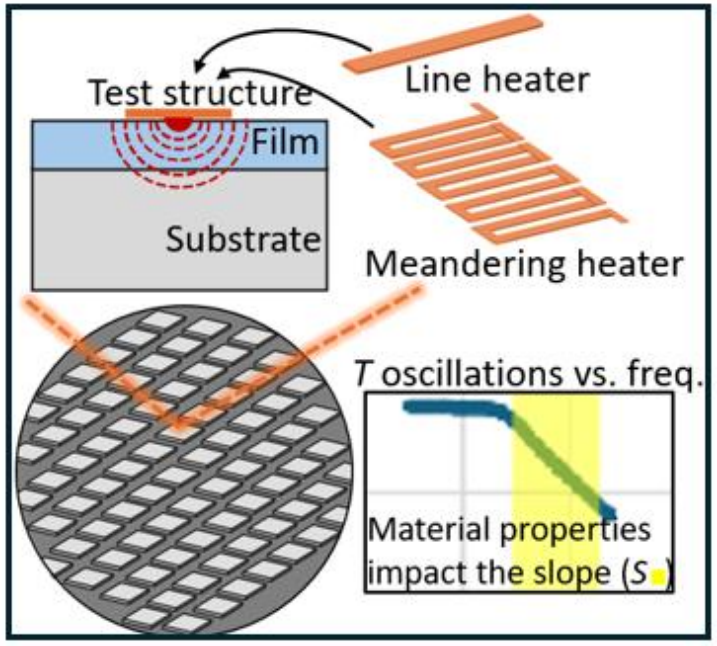
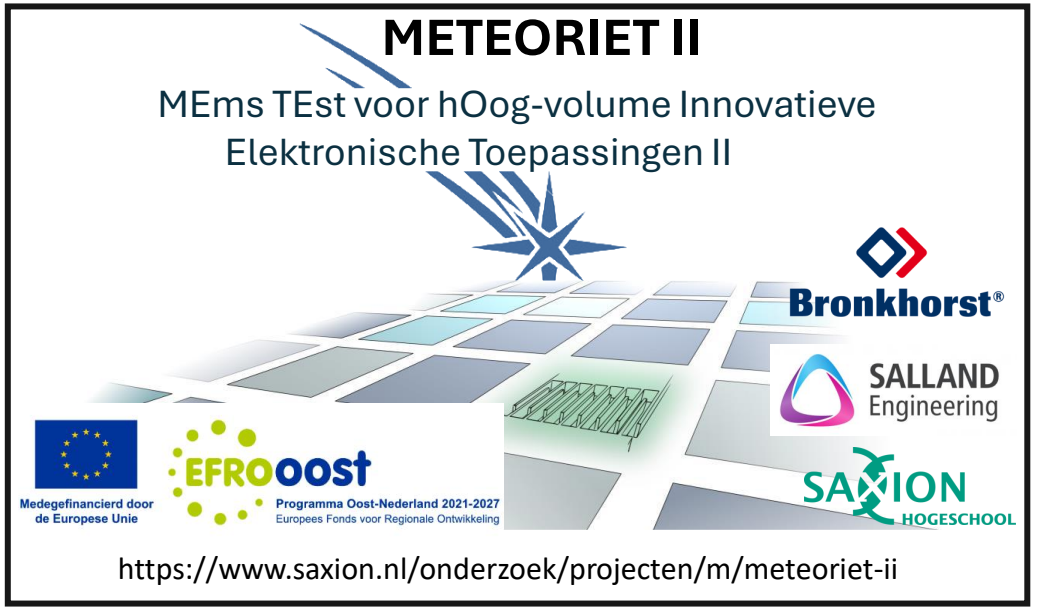
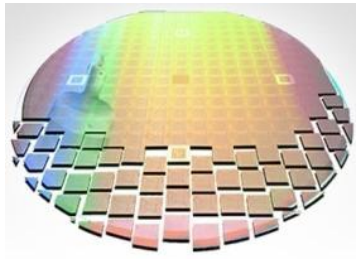


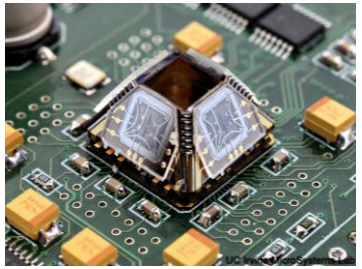


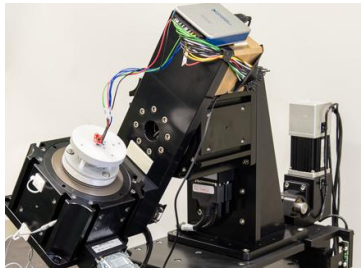
Amsterdam, Comsol Conference, 29-10-2025

General MEMS Production Flow

FRONTEND → **BACKEND** → **ASSEMBLY** → **PRODUCT TEST**

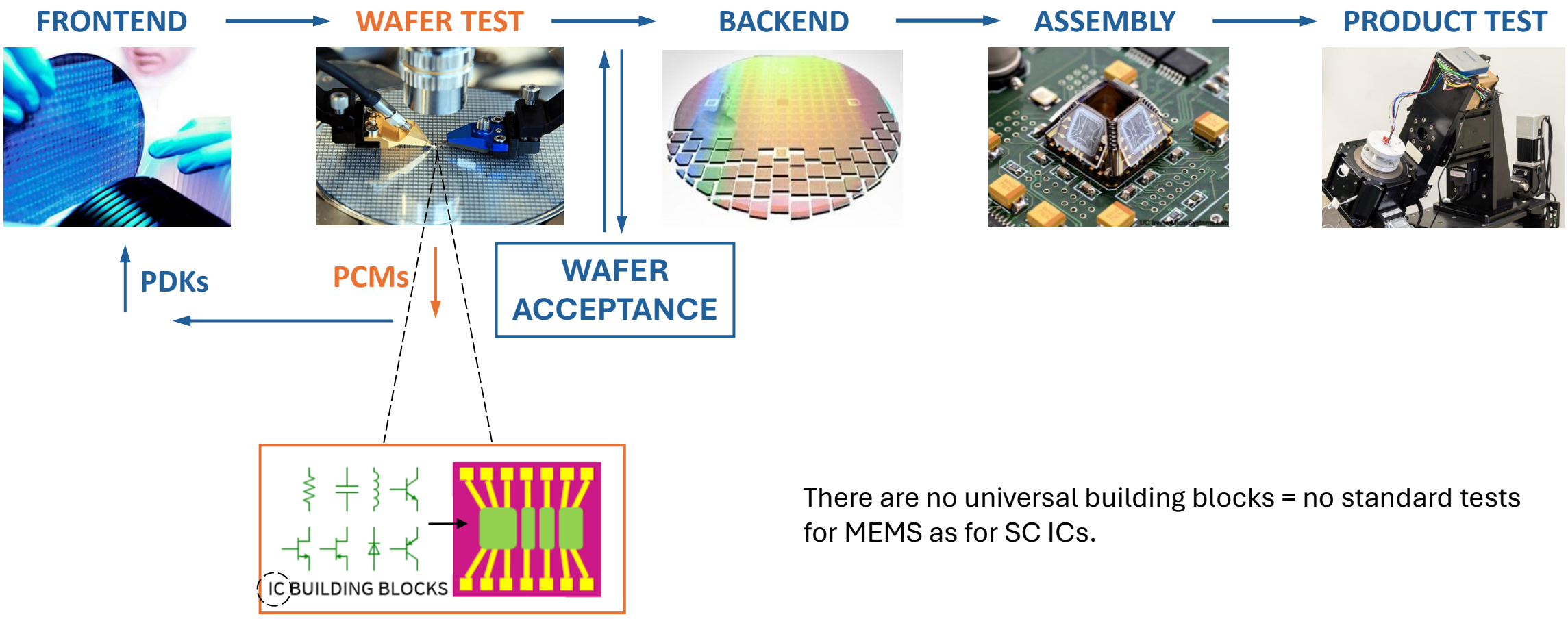






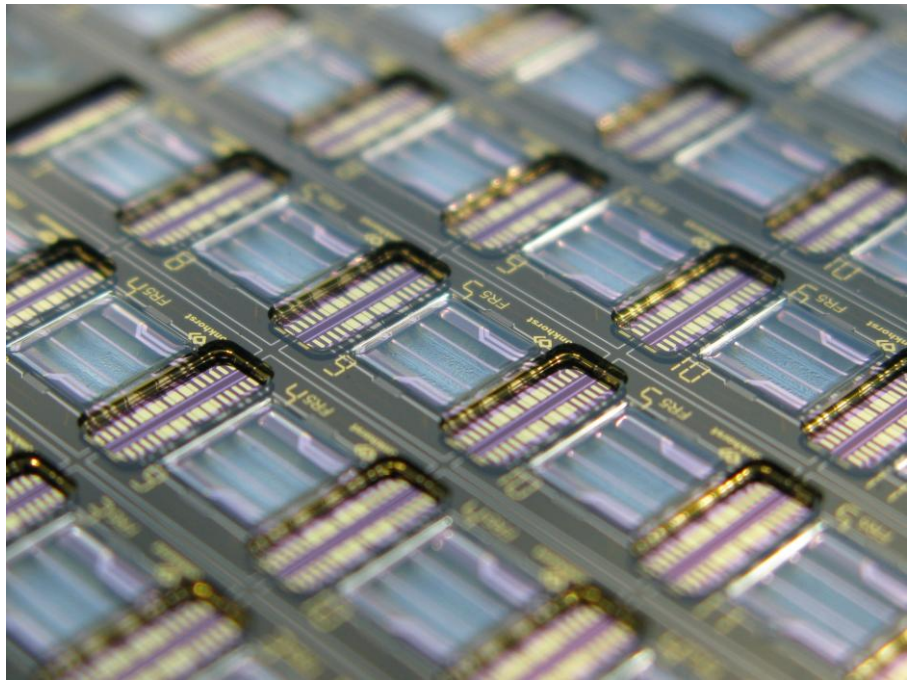
Faulty devices are detected only at the end.

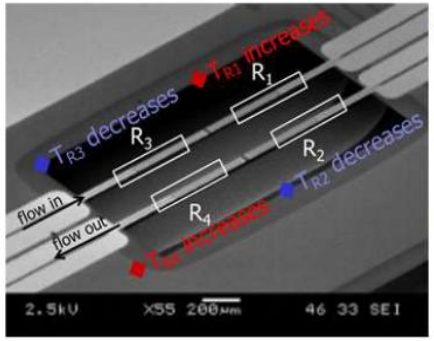
General MEMS Production Flow: challenges

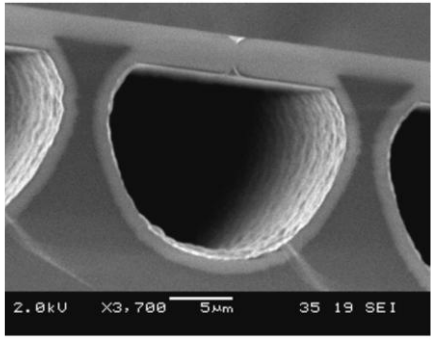


There are no universal building blocks = no standard tests for MEMS as for SC ICs.

Meteorite II: Process control monitors (PCMs) for thermal flow meters







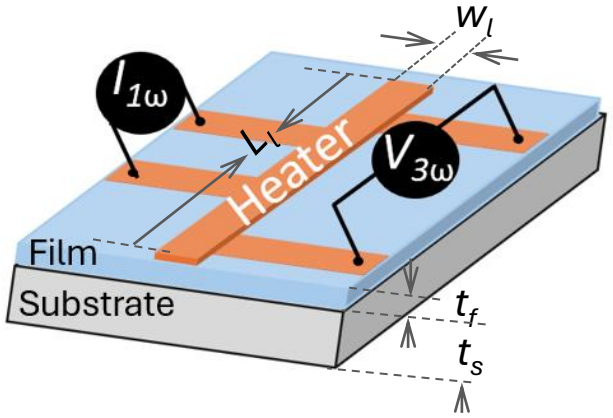
Flexi-Flow products: surface channel technology, flow channels are buried in Silicon.

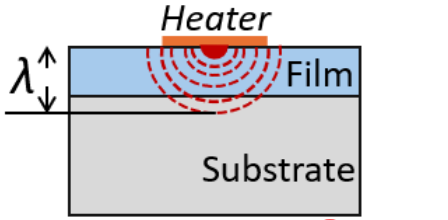
Key impact factors on the performance of the sensor are material properties, which in turn are very sensitive to process variations.

Our goal is to design the tests, the test structures and methodology, to be inserted on a wafer and serve as the PCMs for wafers quality check after front-end.

M Dijkstra *et al* 2007 *J. Micromech. Microeng.* **17** 1971; J. Groenestijn et al. 2017 *Microfluid Nanofluid* 21:127a

3ω-methods: a bit of intro, slope method





$$\lambda = \sqrt{\frac{\alpha}{2\omega}}; \quad \alpha = \frac{k}{\rho C_p}$$

thermal diffusivity
(conductivity and heat capacity)

$$I(t) = I_0 \cdot \cos(\omega t) \equiv I_{1\omega}$$

$$P(t) = I(t)^2 \cdot R_0 \sim P_{DC} + P_{AC}(cos(2\omega t)) \rightarrow \Delta T_{AC}(\alpha, \omega)$$

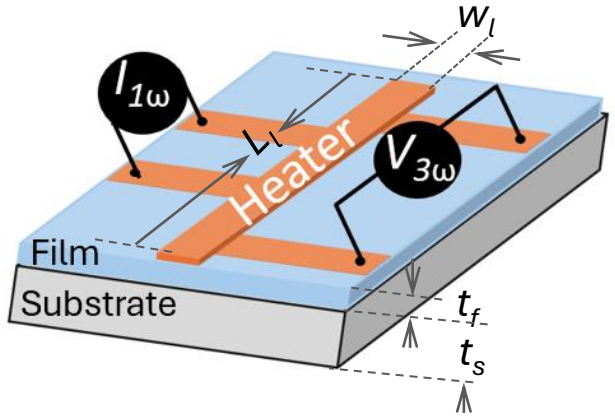
$$R(t) = R_0 \cdot (1 + \underbrace{\alpha_h}_{\text{TCR of heater}} \cdot (\Delta T_{DC} + \Delta T_{AC}))$$

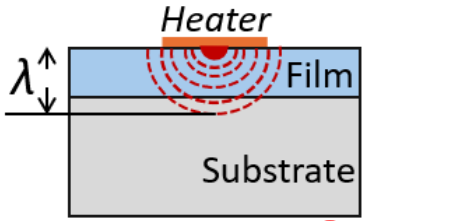
$$V(t) = V_{1\omega} + \underbrace{\frac{1}{2} I_0 R_0 \alpha_h \Delta T_{AC} \cos(3\omega t + \varphi)}_{V_{3\omega}}$$

(we measure in experiments!)

T. Borca-Tascius, A.R. Kumar, and G. Chen, *Rev. Scient. Instr*. 72, 2139 (2001)

3ω-methods: a bit of intro, slope method





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TCR of heater

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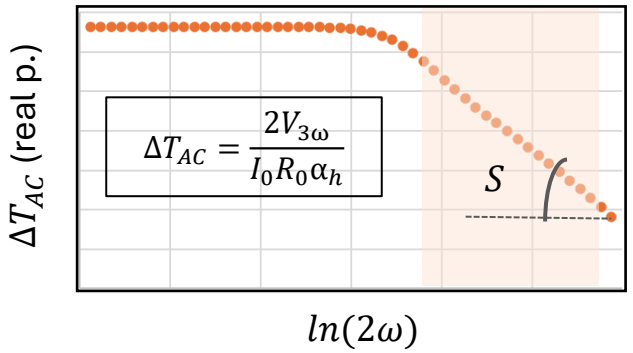


$$k_{sub} = \frac{P_{AC}}{2\pi L_l \cdot S}$$

$$k_{film} = \frac{P_{AC} \cdot t_f}{w_l L_l} [\Delta T_{AC} + 2S]^{-1}_{Aver}$$

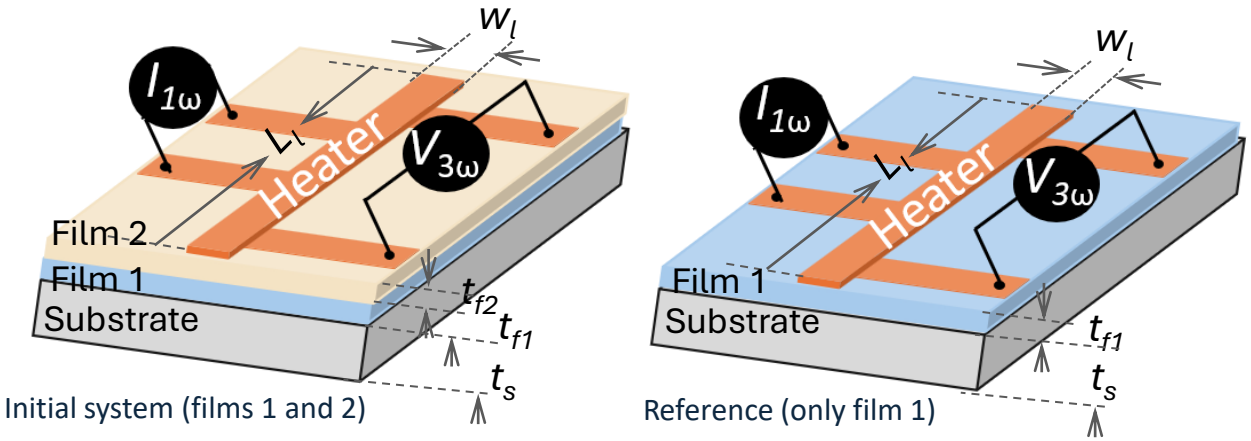
Constraints (1D eqn.; for 1% error)

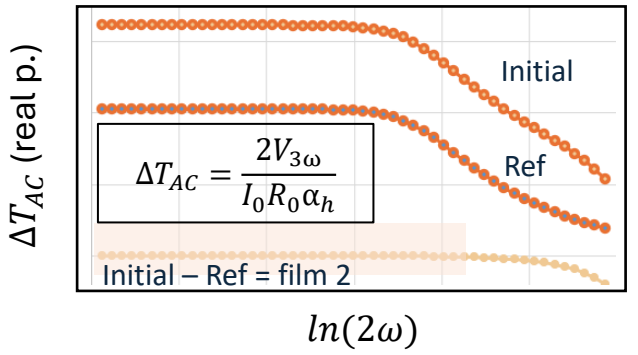
- Line source: $\lambda > {}^5/_2\, w_l$
- Semi-inf. substrate: $\lambda < 5t_s$
- 1D heat flow (isotropy): $\frac{w_l}{2t_f}\sqrt{\frac{k_\perp}{k_\parallel}} > 30$
- Low thermal contrast: $\left(\frac{k_{film}}{k_{sub}}\right)^2 < 0.01$
- ...

3ω-slope method: deviation from the constraints and adding films to the system increases uncertainty.

T. Borca-Tascius, A.R. Kumar, and G. Chen, *Rev. Scient. Instr*. 72, 2139 (2001); C. Dames *AnnRevHT2013*: 3omega and related electrothermal methods (2013)

3ω-methods: a bit of intro, differential method





$$I(t) = I_0 \cdot \cos(\omega t) \equiv I_{1\omega}$$

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(we measure in experiments!)

$$k_{film} = \frac{P_{AC} \cdot t_f}{w_l L_l} \left[\Delta T_{AC,in} - \Delta T_{AC,ref}\right]^{-1}_{Aver}$$

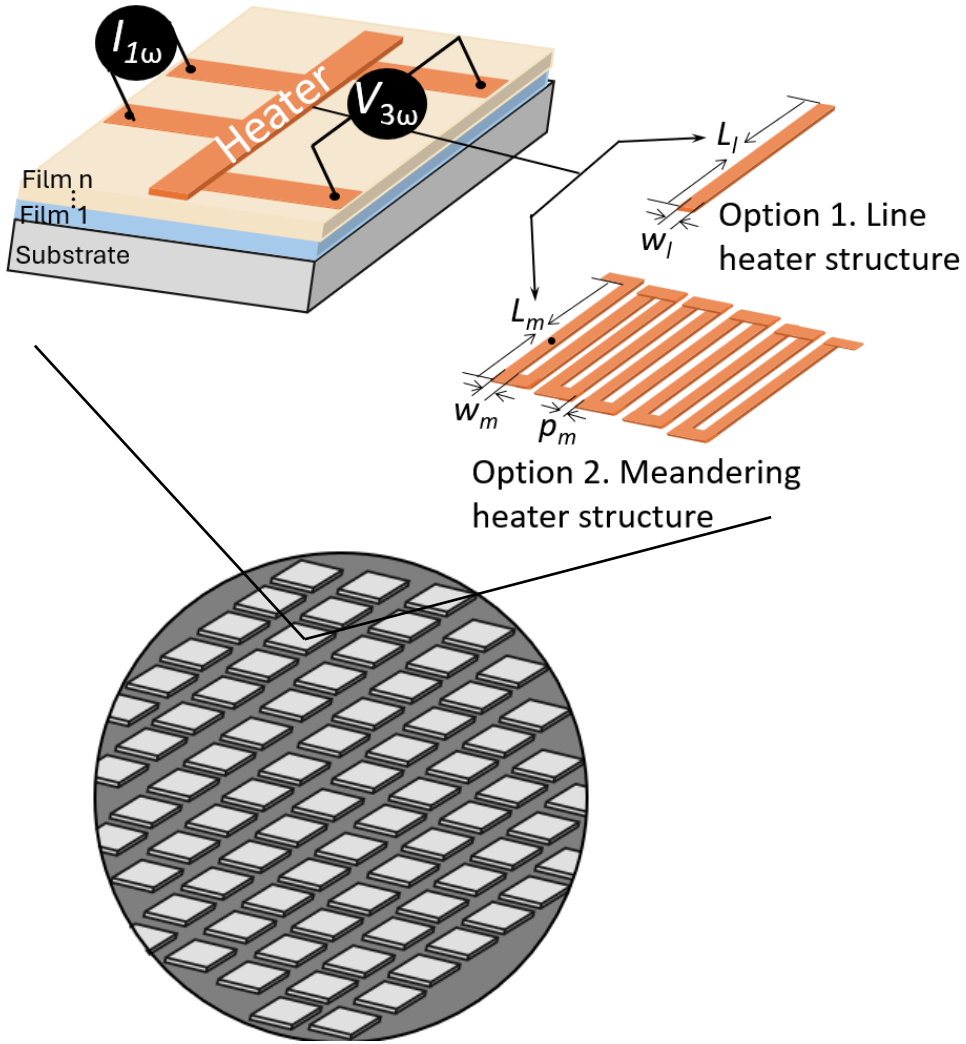
Constraints (1D eqn.; for 1% error)

- Line source: $\lambda > {}^5/_2 w_l$ *
- Semi-inf. substrate: $\lambda < 5t_s$ *
- 1D heat flow (isotropy): $\frac{w_l}{2t_f}\sqrt{\frac{k_\perp}{k_\parallel}} > 30$
- Low thermal contrast: $\left(\frac{k_{film}}{k_{sub}}\right)^2 < 0.01$
- ...

3ω-differential method: some of the constraints * are lifted and basically only experimental uncertainties left, but more space is required.

T. Borca-Tascius, A.R. Kumar, and G. Chen, *Rev. Scient. Instr*. 72, 2139 (2001); J. Alvarez-Quintana, J. Rodriguez-Viejo, *Sens. and Act.* A 142, 232 (2008)

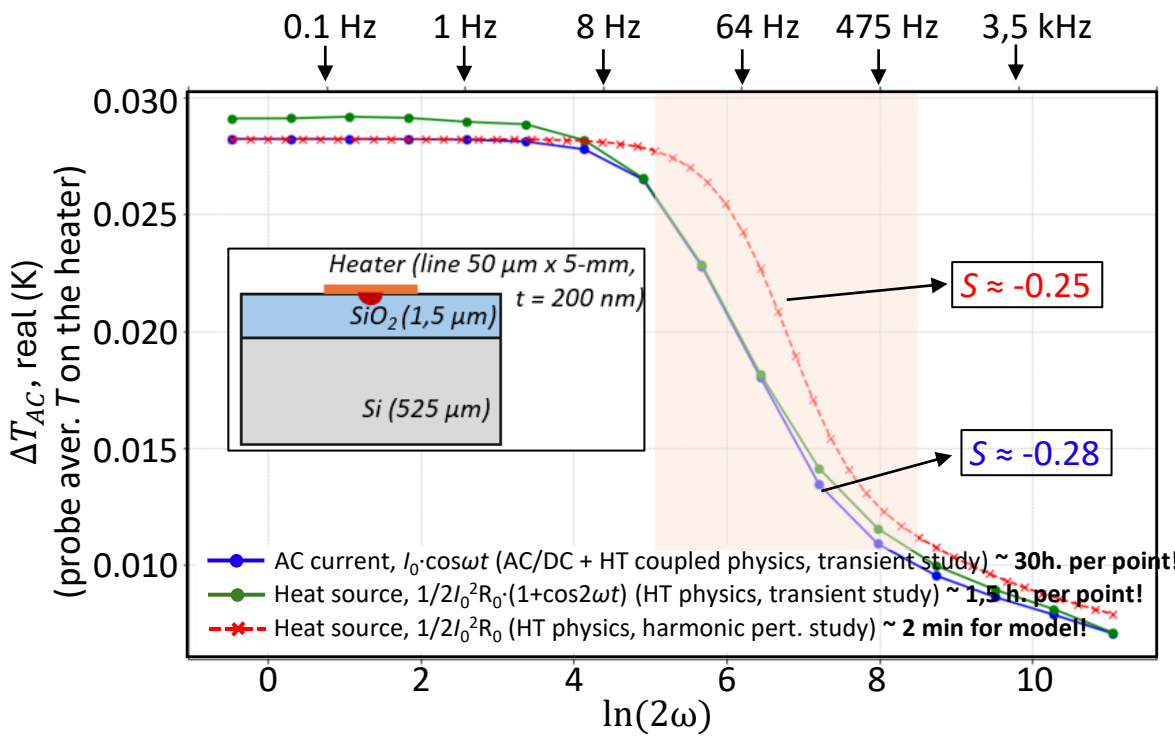
Meteorite II: test insertions under study



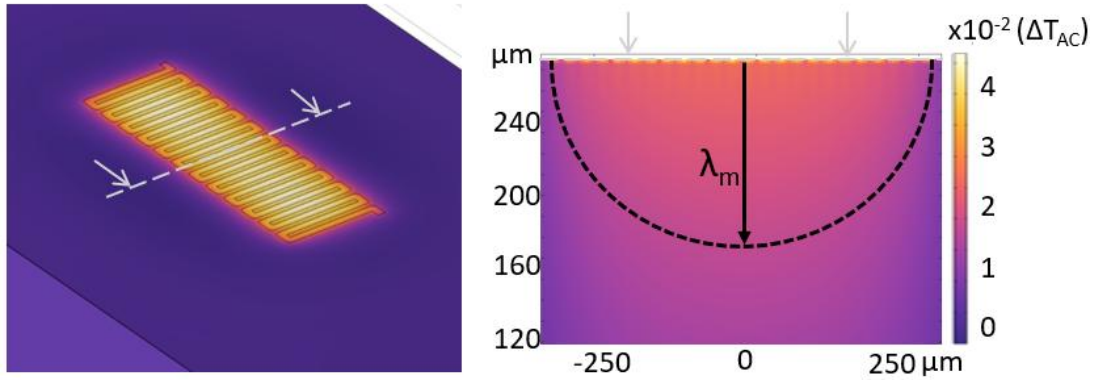
In the production flow not any layer can be added and there are also space constraints, so we are evaluating both 3ω-methods and their combination as well as various test structures options (line and meandering heaters).

Comsol FEM analysis is an integral tool for the design and optimization of the test structures.

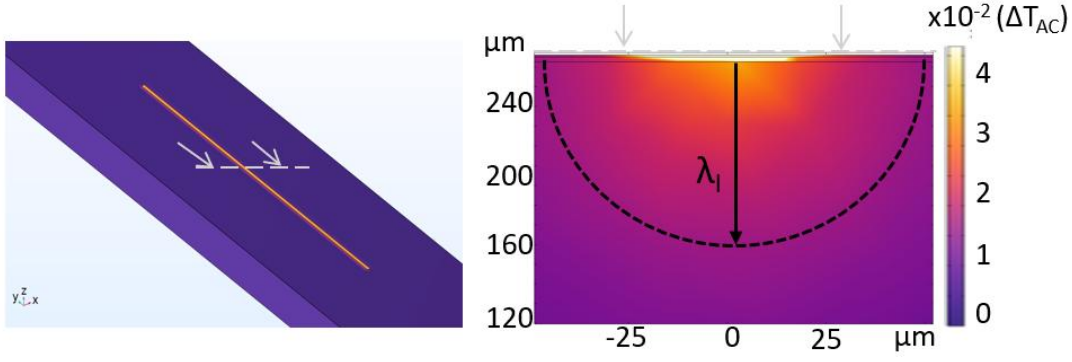
Meteorite II: Comsol models & studies



Coupled physics, akin to experiment approach, shows lower drop-off frequency, otherwise simplified model based on harmonic perturbation captures behavior.

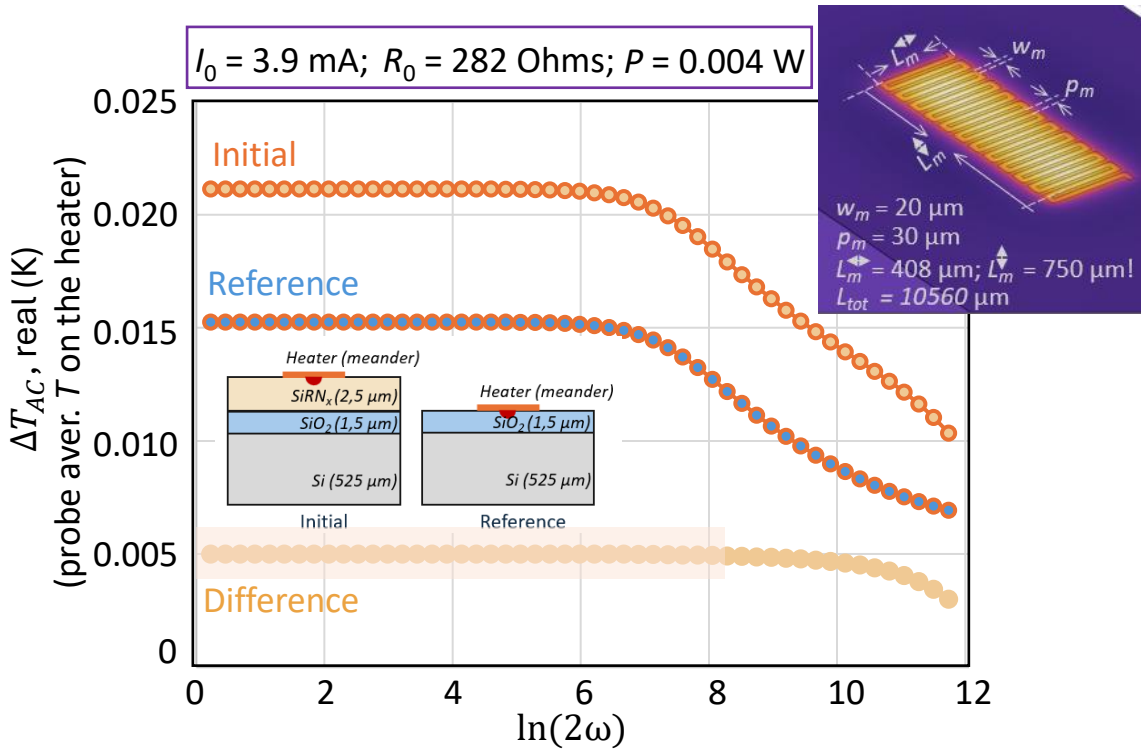


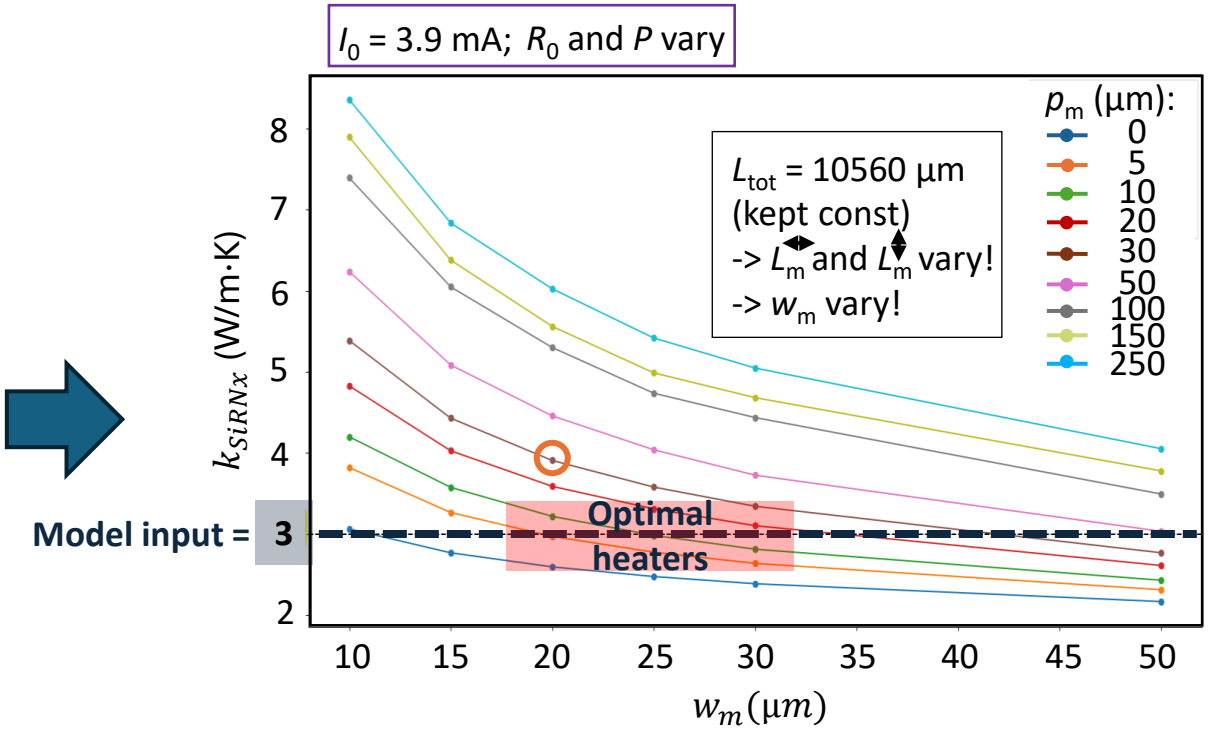
Meandering test structure example (harm. pert. approach)



Line test structure example (harm. pert. approach)

Meteorite II: Comsol models & material properties based on 3ω-methods

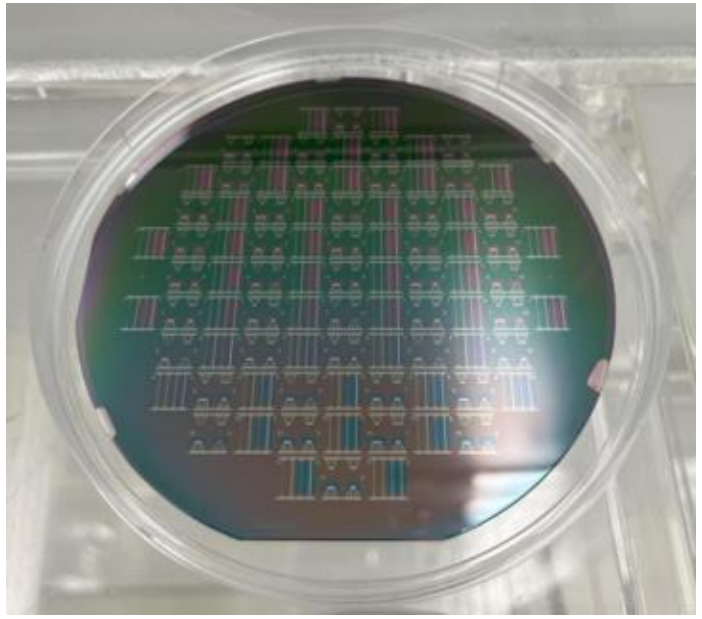


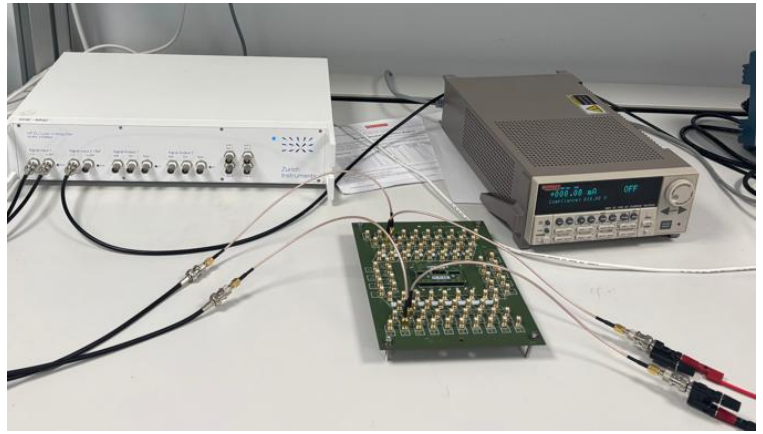


Based on 3ω-differential method (meandering test structure, left) output thermal conductivity for $SiRN_x$ k = 4.22 W/m·K.

Variations of the heating structures' dimensions give the optimized designs (right). Analogous analysis has been done for 3ω-slope method and their combinations for line and meandering heaters and various materials stacks.

Meteorite II: Experimental validation is ongoing





Based on the Comsol analysis we proved high sensitivity of the properties to the test structures designs.

In total 4 wafers have been fabricated with 12 optimized test structures (6 line and 6 meandering heaters) (left).

Currently we are in the process of validation of the proposed designs (the test setup at Saxion, right) and on a few other ideas for a new test run. Based on the results we expect to ‘insert’ chosen test structures on the production wafers.

Acknowledgments to our joint team

Bronkhorst®

SAXION HOGESCHOOL

SALLAND Engineering

Medegefinancierd door de Europese Unie

EFROoost
Programma Oost-Nederland 2021-2027
Europees Fonds voor Regionale Ontwikkeling

https://www.saxion.nl/onderzoek/projecten/m/meteoriet-ii

Thank you!