POLITECNICO DI MILANO

COMSOL
CONFERENCE
EUROPE
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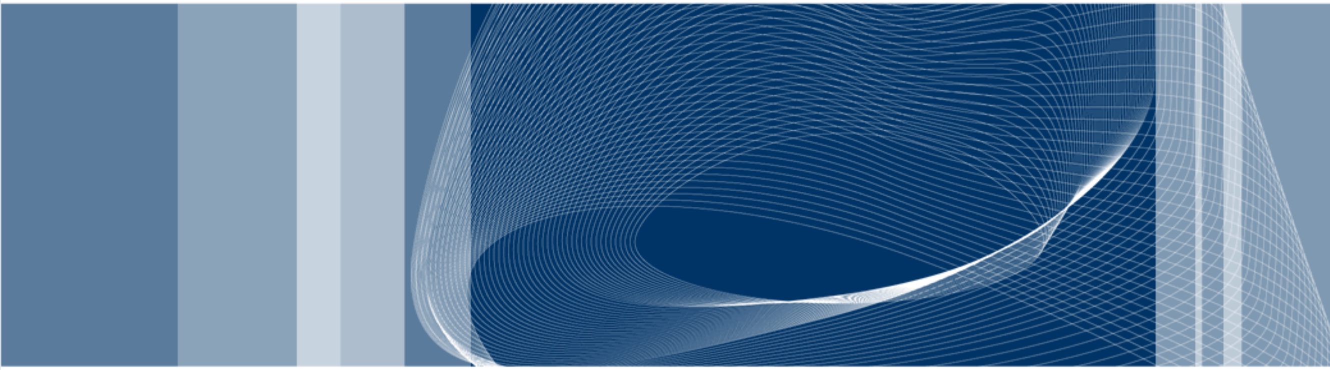

Multi-Physics Simulations for the Design of Probe-Heads Micro-Needles

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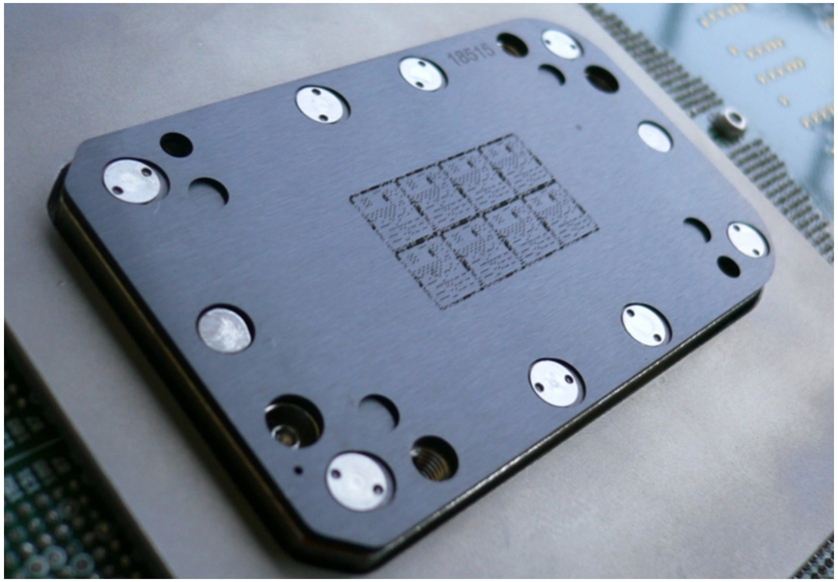
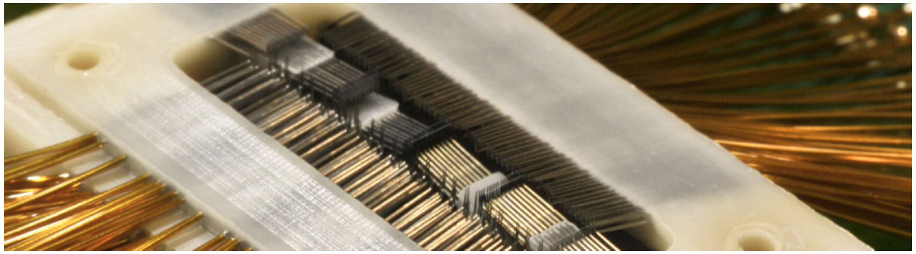
TECHNOPROBE
Wafer Probing Technologies

Excerpt from the Proceedings of the 2012 COMSOL Conference in Milan

Problem

ICs testing applications are more and more demanding in terms of requested fine pitch capability with reduced pad damage risk and increased Current Carrying Capability (CCC) even at high testing temperature

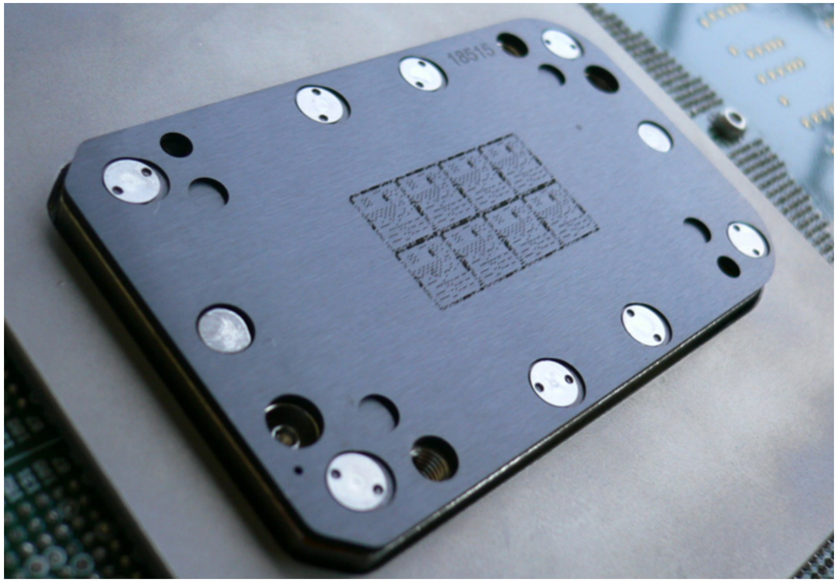




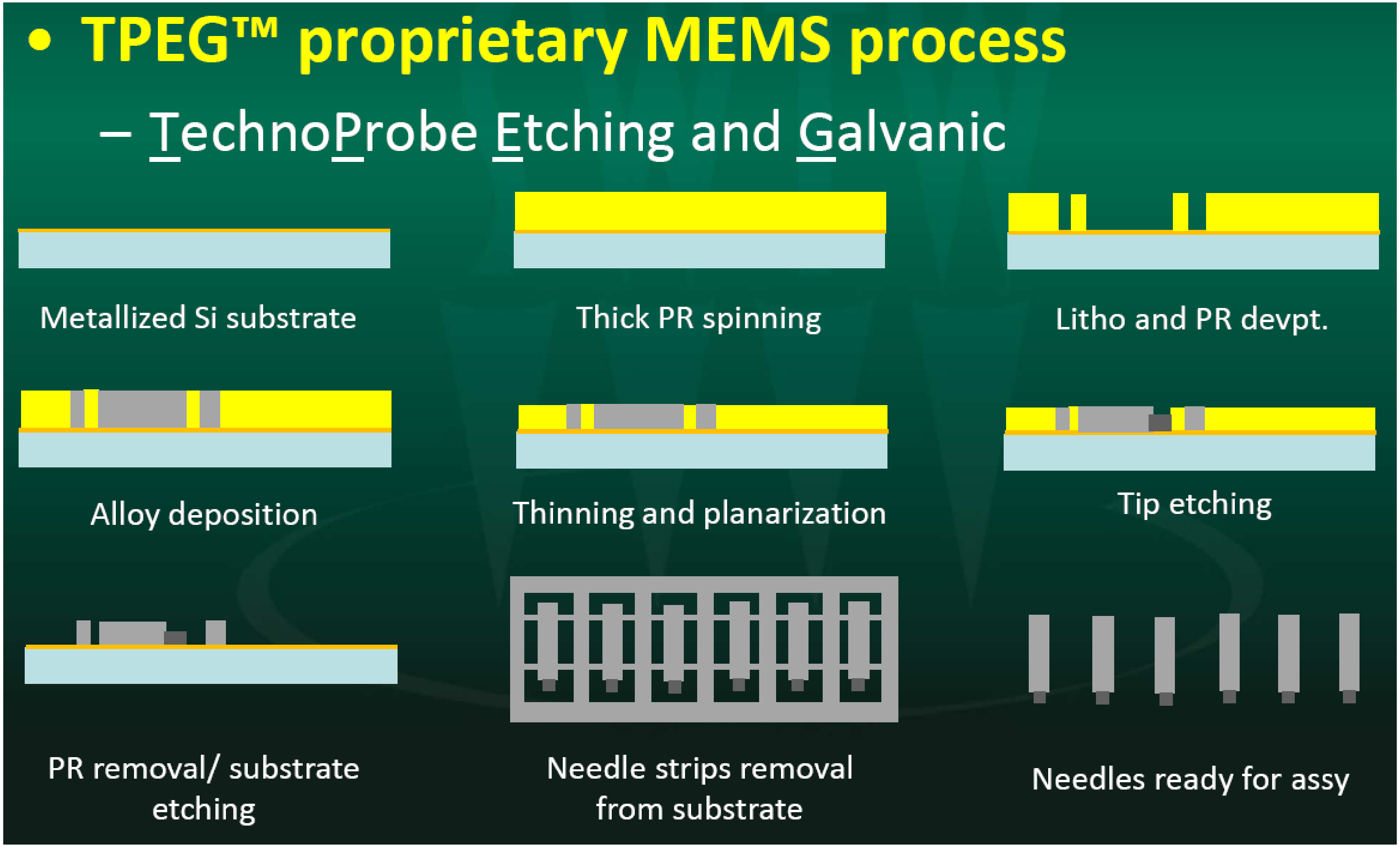
Problem

Typical testing apparatus:

probe card with micro-needles which contact the electric pads on IC wafers to be tested



Micro-needles produced with MEMS process



- TPEG™ proprietary MEMS process
  - TechnoProbe Etching and Galvanic

Metallized Si substrate

Thick PR spinning

Litho and PR devpt.

Alloy deposition

Thinning and planarization

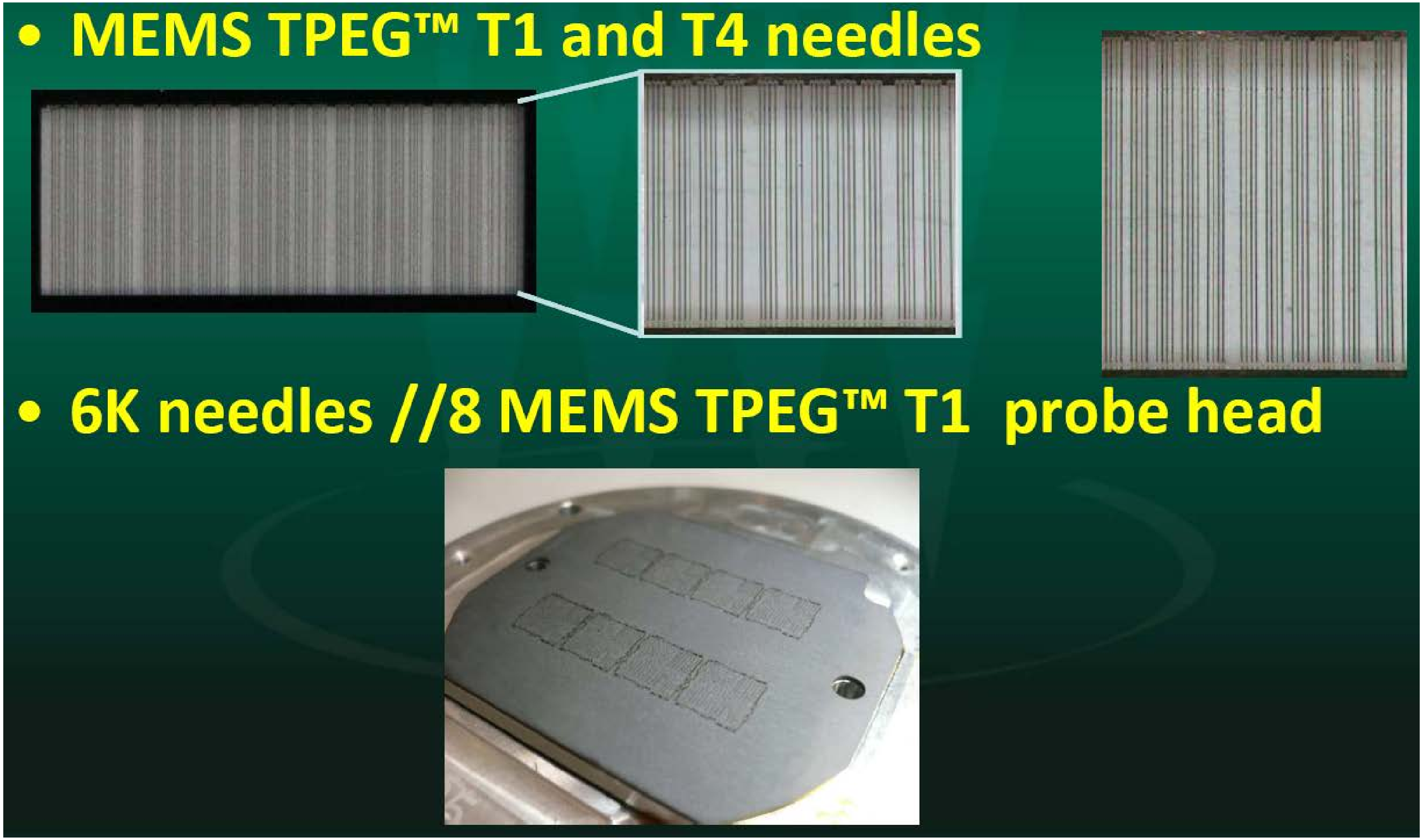
Tip etching

PR removal/ substrate etching

Needle strips removal from substrate

Needles ready for assy

Micro-needles produced with MEMS process



- MEMS TPEG™ T1 and T4 needles
- 6K needles //8 MEMS TPEG™ T1 probe head

Development steps

Material characterization
- Mechanical
  - Young Modulus
  - Tensile Yield Strength
  - Ultimate Tensile strength
  - Elongation %
- Electrical
  - Resistivity
- Thermal
  - CTE
  - Resistivity (T)
  - Young Modulus (T)

Market trend & Customer roadmap
- Min pitch
- Parallelism
- Testing Temp
- Current per probe
- Probe force

Simplified FE models
- Mechanical PH model
- Electro - thermal model

Full FE models
- Mechanical model
- Electro-thermal model
- El. – Thermo – Mech. model

PH design
- Alloy definition
- Needle design
- PH mechanical design

External MEMS process:
> 13 WKs learning cycle

Continuous fine tuning and optimization

In-house MEMS process:
< 4 WKs learning cycle

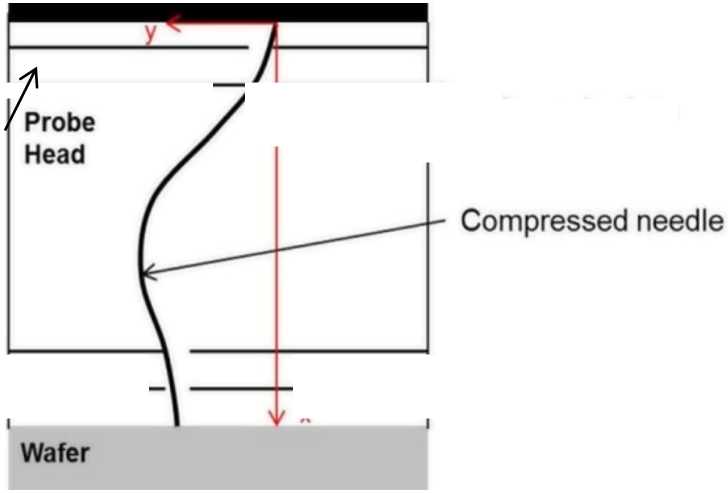
PH testing – lifetest
- Mechanical cycling
- Interference test
- Scrub mark analysis

PH testing
- Probe force
- CCC and C_RES
- Mechanical cycles

Improved PH design and process

Micro-needles as flexible beams

During wafer testing of electronic and other microsystems, contact between probe-head and pads, and the closing of the electric circuit are assured by micro-needles that can be considered as beams under buckling regime.



Probe-head micro-needle

Micro-needles must be **flexible, with high electric conductivity and high resistance to electro-thermo-mechanical fatigue**.

The correct design of micro-needles can be performed only on the basis of accurate multi-physics simulations in which thermal, electrical and mechanical responses are correctly simulated in a fully coupled environment.

FE electro-thermal model

A fully coupled electro-thermo-mechanical model was created by combining two numerical tools.

- An electro-thermal model created with COMSOL MP
- An in-house thermo-mechanical beam FE model programmed in Matlab

Electro-thermal simulations results are used as inputs in the thermo-mechanical model.

FE electro-thermal model

- Joule heating interface
- Stationary analysis
- Electrical resistivity ρ is assumed to be a linear function of the temperature

$$\rho(T) = \rho_0\left[1 + \alpha_{res}\left(T - T_{ref}\right)\right]$$

where

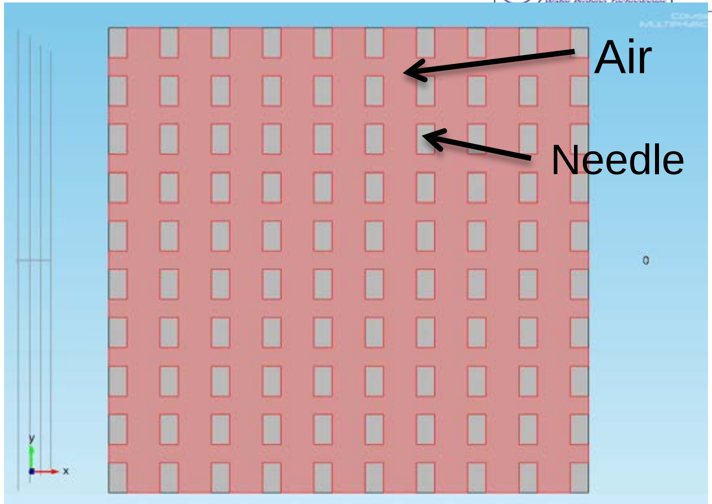
- T_{ref}: reference temperature (K)
- ρ_0: electrical resistivity at T_{ref} (Ω m)
- α_{res}: temperature coefficient of resistivity (1/K)

FE electro-thermal model

Various simulations were done to put in evidence the influence of the presence of other needles on the temperature distribution .

Three configurations were studied:

- Single needle
- Grid of 3*3 needles
- Grid of 10*10 needles



In the cases where a grid of needles was studied, the Rayleigh number was computed, which allows to compare the free convection with the conduction regimes. For a Rayleigh number less than 2000, the convection can be neglected with respect to the conduction.

Inside the grid, the Rayleigh number is less than 0.02 due to the small distances between needles.

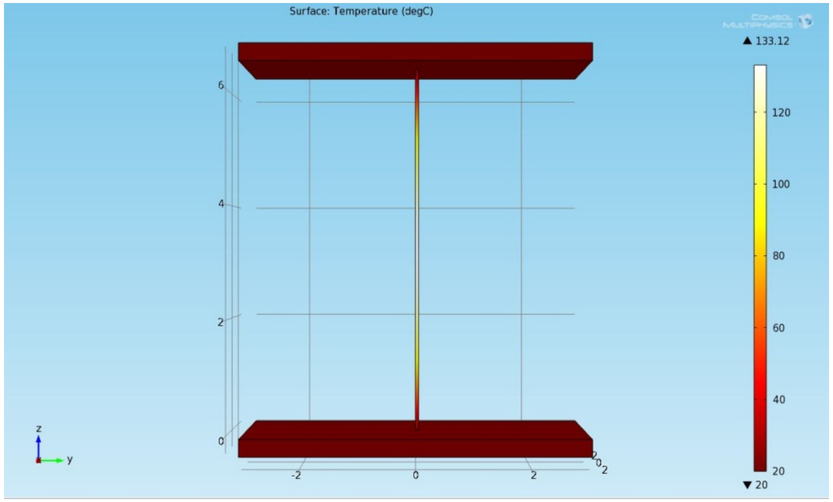
→ convection taken into account for the external needles only

Rayleigh number:

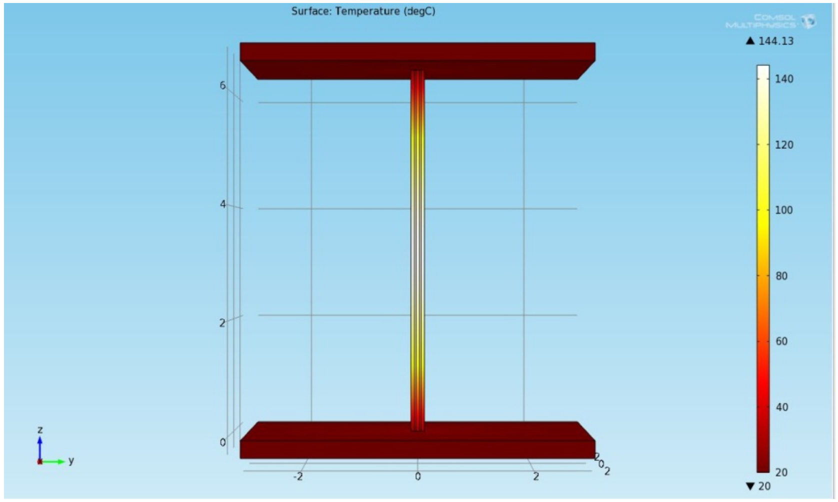
$$Ra = \frac{g\beta}{\nu\alpha_{th}}(T_s - T_\infty)\delta^3$$

g: acceleration due to gravity (m.s^{-2})
β: thermal expansion coefficient (K^{-1})
ν: kinematic viscosity (m^2.s^{-1})
α_{th}: thermal diffusivity (m^2.s^{-1})
T_s: temperature on the surface of the needle (K)
T_∞: fluid temperature far from the surface of the needle (K)
δ: needle length (m)

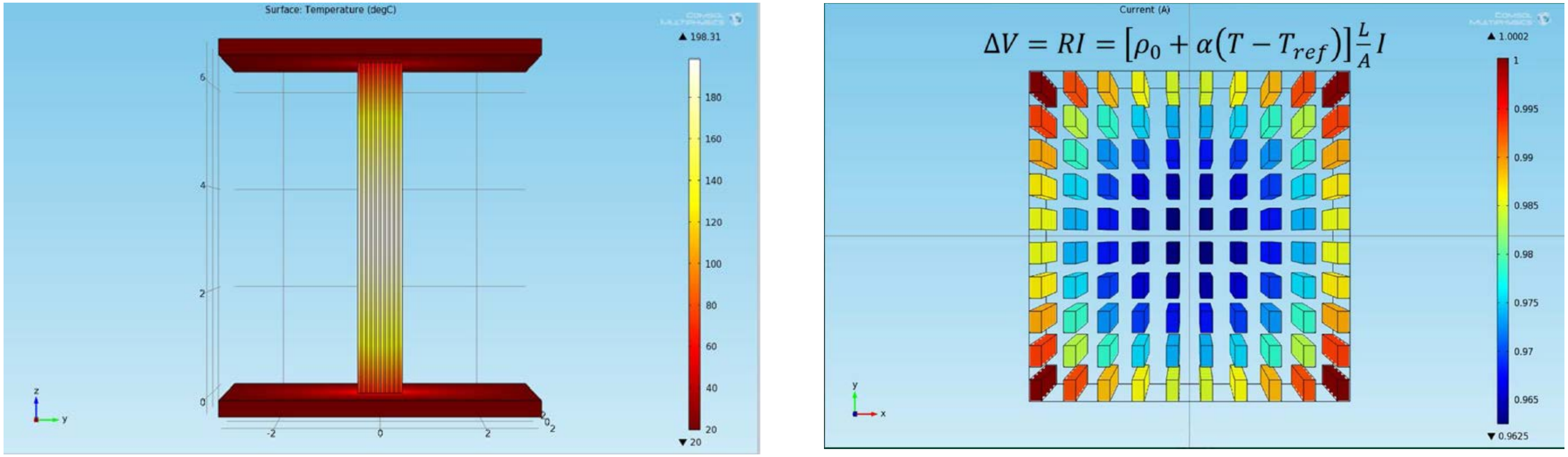
FE electro-thermal model



Single micro-needle



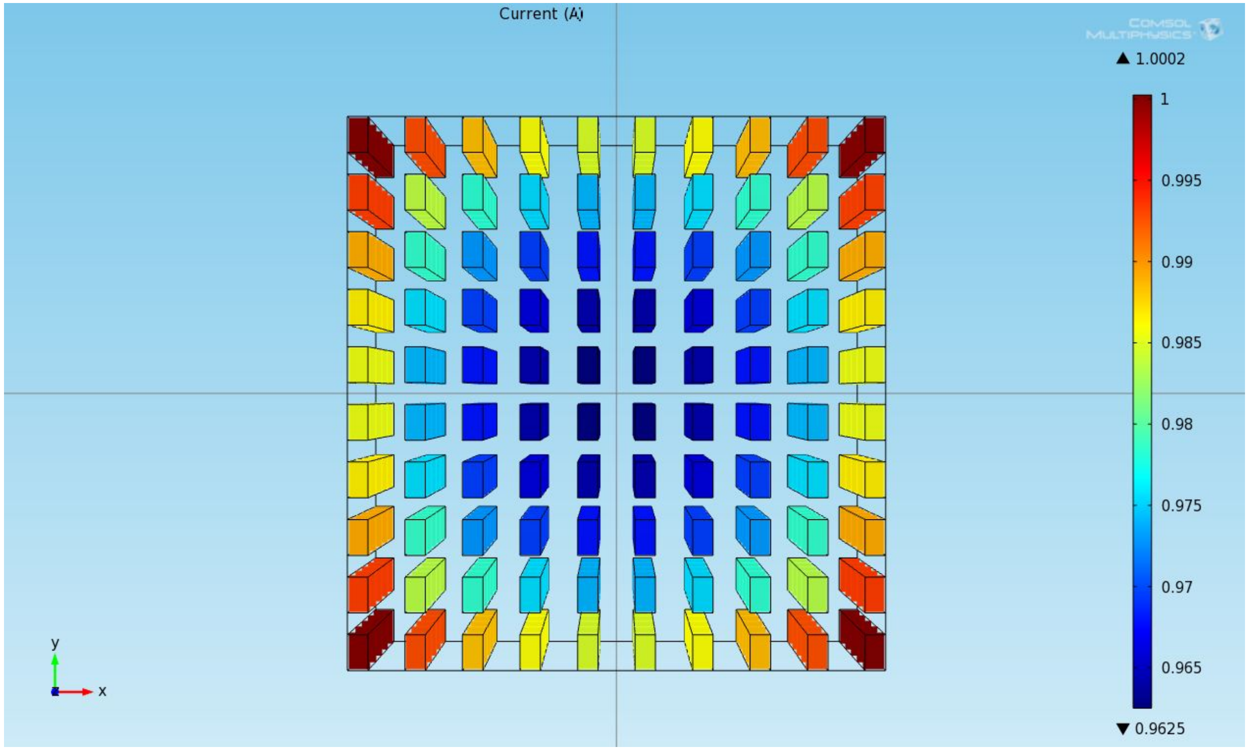
Grid of 3*3 micro-needles



$$\Delta V = RI = \left[\rho_0 + \alpha\left(T - T_{ref}\right)\right]\frac{L}{A}I$$

Grid of 10*10 micro-needles

FE electro-thermal model



Current distribution for an array of 10*10 micro-needles

Electric resistance

$$R = \rho \frac{L}{A} = \left[\rho_0 + \alpha\left(T - T_{ref}\right)\right] \frac{L}{A}$$

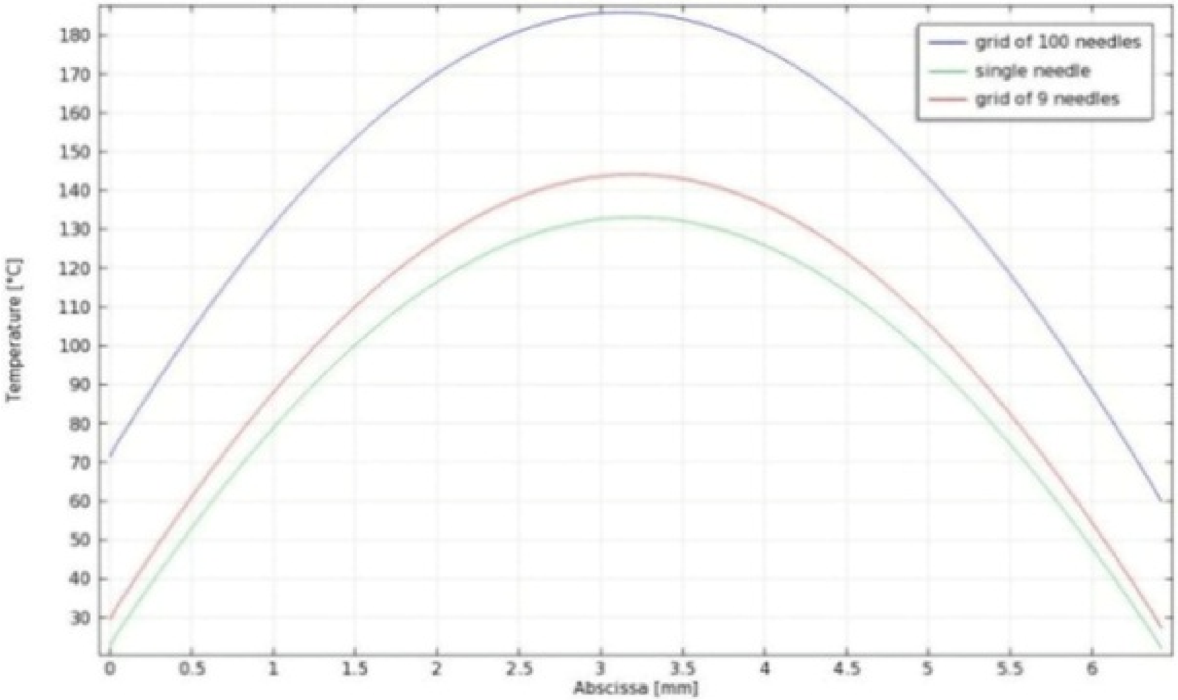
Ohm's law

$$\Delta V = RI = \left[\rho_0 + \alpha\left(T - T_{ref}\right)\right] \frac{L}{A} I$$

When T increases, I reduces for fixed ΔV;

The current intensity is lower at the centre of the array.

FE electro-thermal model



Temperature along the central micro-needle for a 1 A current

Simulations evidenced higher temperature values in the presence of several needles with respect to the case with a single needle.

The hot needles reduce the surrounding air cooling thus decreasing the heat dissipation by conduction in the air.

Consequently, the maximum current that a micro-needle can sustain will be reduced.

Thermo-mechanical beam model

The influence of the temperature on the mechanical properties (Young's modulus, yield stress) was taken into account. The Young's modulus and yield stress were supposed to follow a linear function of the temperature.

Due to large deflections of the needle, the Von Kármán hypothesis on the strain was used in the beam model.

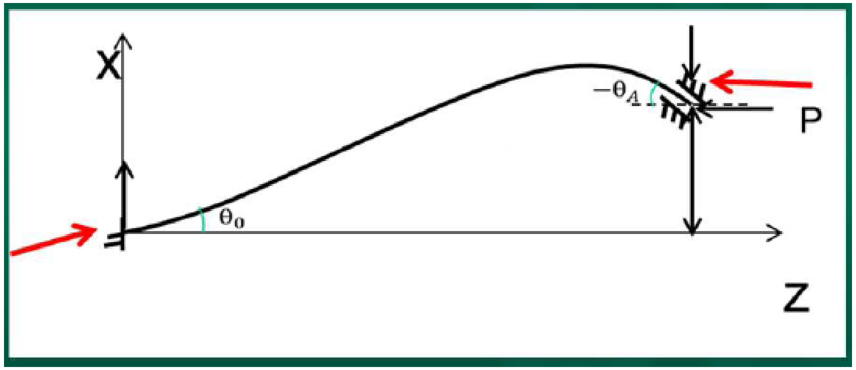
Strain:

Non-linear term due to Van Kàrmàn hypothesis

$$\varepsilon_x = \frac{du}{dx} + \frac{1}{2}\left(\frac{dw}{dx}\right)^2 - y\frac{d^2w}{dx^2}$$

where

- u: horizontal displacement (m)
- w: vertical displacement (m)



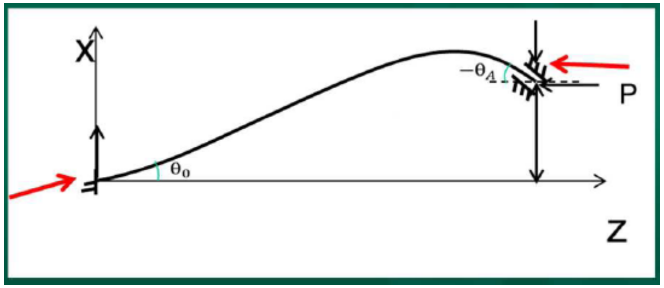
Thermo-mechanical beam model

the thermo-mechanical behavior of the micro-needle is governed by the following system:

$$\begin{cases} E(T)A\left(\dfrac{du}{dx}+\dfrac{1}{2}\left(\dfrac{dw}{dx}\right)^2-\alpha\Delta T\right)+P=0 \\ \dfrac{d^2}{dx^2}\left(E(T)J\dfrac{d^2w}{dx^2}\right)-\dfrac{d}{dx}\left[E(T)A\dfrac{dw}{dx}\left(\dfrac{du}{dx}+\dfrac{1}{2}\left(\dfrac{dw}{dx}\right)^2-\alpha\Delta T\right)\right]=0 \end{cases}$$

where:

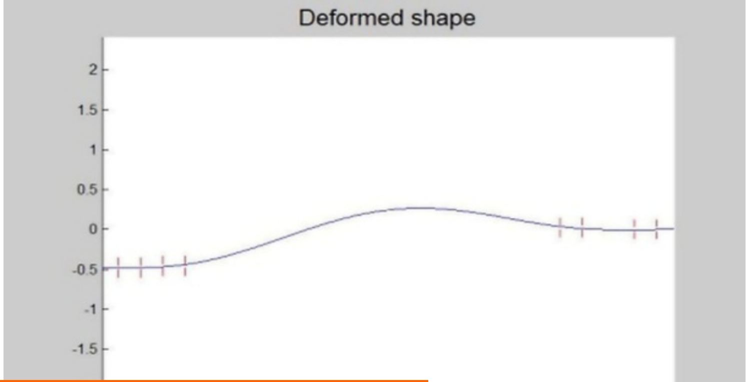
- $E(T)$: Young’s modulus (Pa)
- A: cross-section area (m^2)
- ΔT. temperature gradient (K)
- J: moment of inertia (m^4)
- P: force applied at the micro-needle extremity (N)

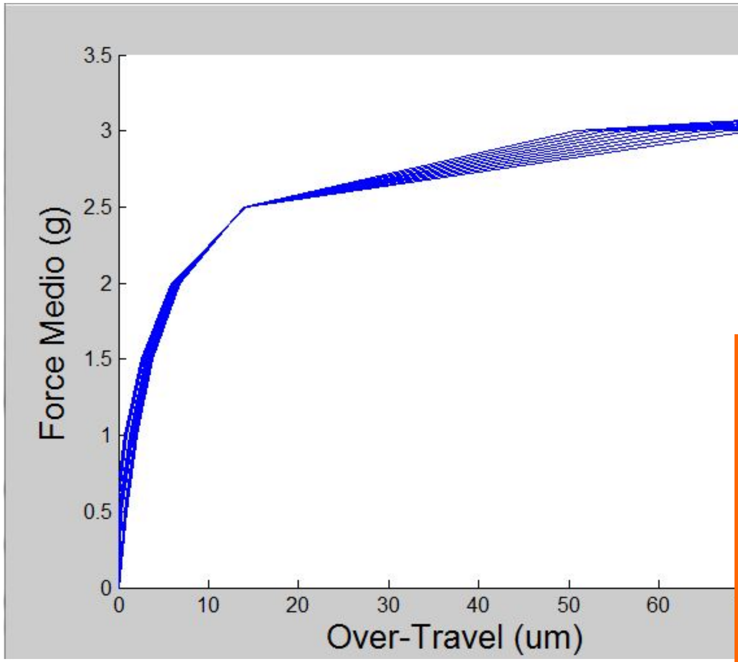


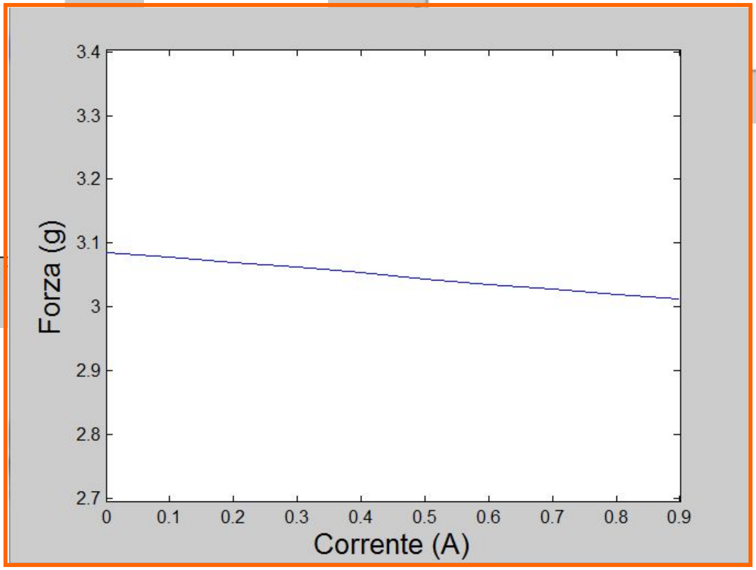
We used ad-hoc formulated beam elements to solve the system above.

Thermo-mechanical beam model

As the temperature varies along the micro-needle (the ends are colder than the center), so do the Young’s modulus and the yield stress.







Results of the thermal-mechanical simulation

Current Carrying Capability test simulation

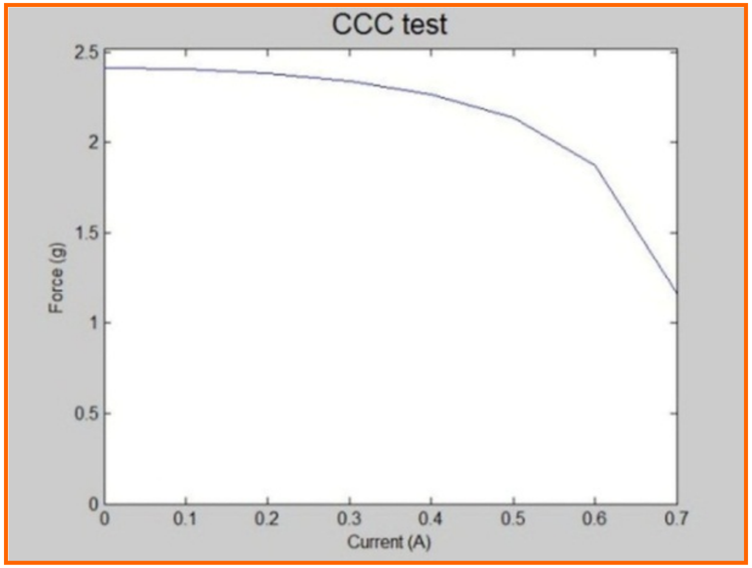
The two FE models combined were used to numerically reproduce the so-called Current Carrying Capability (CCC) test, which consists in the measurement of the reaction force of a single compressed needle subject to an increasing direct current.

The CCC test is the standard used by the industry to characterize needles performance.

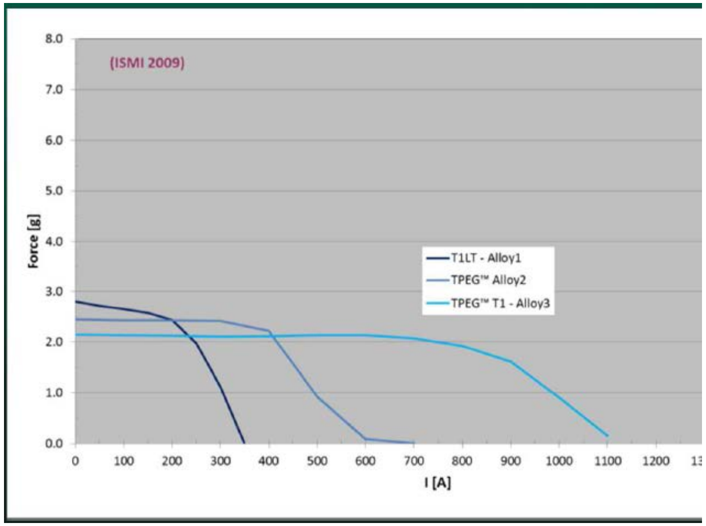
The CCC is defined as the current associated to a decreasing of 20% of the reaction force. For higher currents, the micro-needle is irreversibly deformed.

At the end of the test, the micro-needle is plastically deformed due to the reduction of the yield stress with temperature.

The elastic-plastic behavior of the material was modeled introducing plastic hinges, which are activated when the stress reaches the yield stress.



CCC test of a micro-needle



Closing remarks

The combined use of multi-physics simulations obtained with COMSOL Multi-Physics and with a research oriented FE code allowed to numerically simulate the CCC test.

It was possible to show that the CCC can be reduced by an important amount in the case of a grid of micro-needles with respect to the single needle configuration.

The developed simulation tool could be useful for future needles design.

Thank you for your attention

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