Finite Element Evaluation of the Strength of Silicide-Based Thermoelectric Modules

A. Miozzo[1], S. Boldrini[1], A. Ferrario[1] and M. Fabrizio[1]
1. CNR - National Research Council of Italy, ICMATE, Corso Stati Uniti 4, Padua, 35127 Italy

Introduction: Silicide-based thermoelectric modules (TEMs) for power generation operate at mid-high temperature range. In the operating conditions, thermal stresses in materials with different coefficient of thermal expansion may reduce the mechanical strength of the modules. In this work, a finite element (FE) evaluation of the mechanical strength of a 16 legs thermoelectric module prototype (Figure 1) operating with 300 K temperature difference is presented.

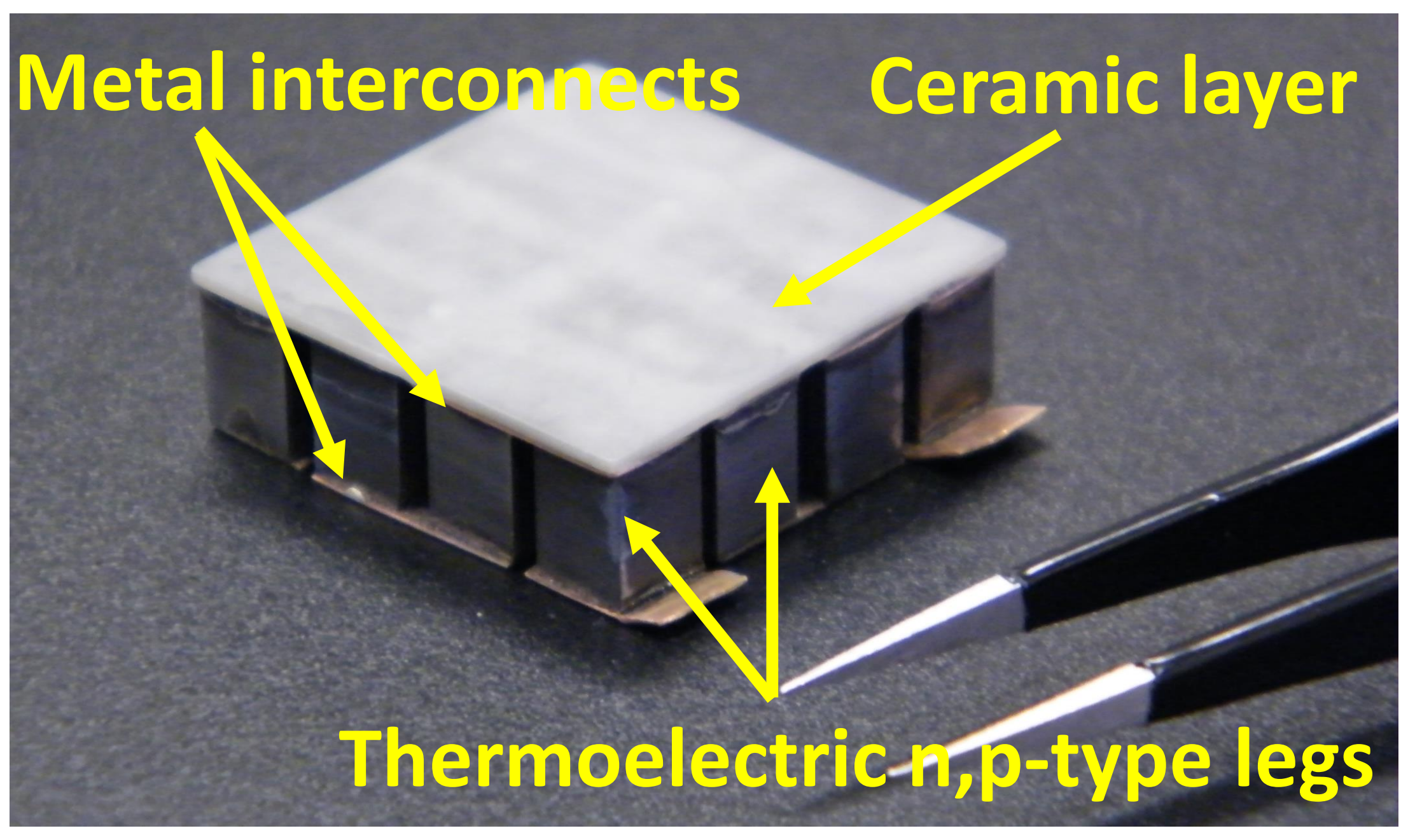

Figure 1. Prototype of the 16 legs silicide-based TEM. Heat flows from the top (*Th*) to the bottom (*Tc*) side.

Computational Methods: In the simulation, the thermoelectric module has been evaluated in open-circuit conditions, i.e. only conduction contribution was considered for heat flux (no Peltier or Joule effect taken into account).

$$\nabla\cdot(-k\nabla T)=0$$
$$\nabla\cdot S+F_v=0$$
$$S=C:(\epsilon-\epsilon_{th})$$
$$\epsilon=\frac{1}{2}(\nabla\boldsymbol{u}+(\nabla\boldsymbol{u})^T)$$
$$\epsilon_{in}=\epsilon_0+\epsilon_{th}$$

COMSOL® Heat transfer in solids and Solid mechanics interfaces have been coupled considering:

$$\epsilon_{th}=\alpha_{th}(T-T_c)$$

being α_{th} the thermal expansion coefficients of components and Tc the cold side temperature.

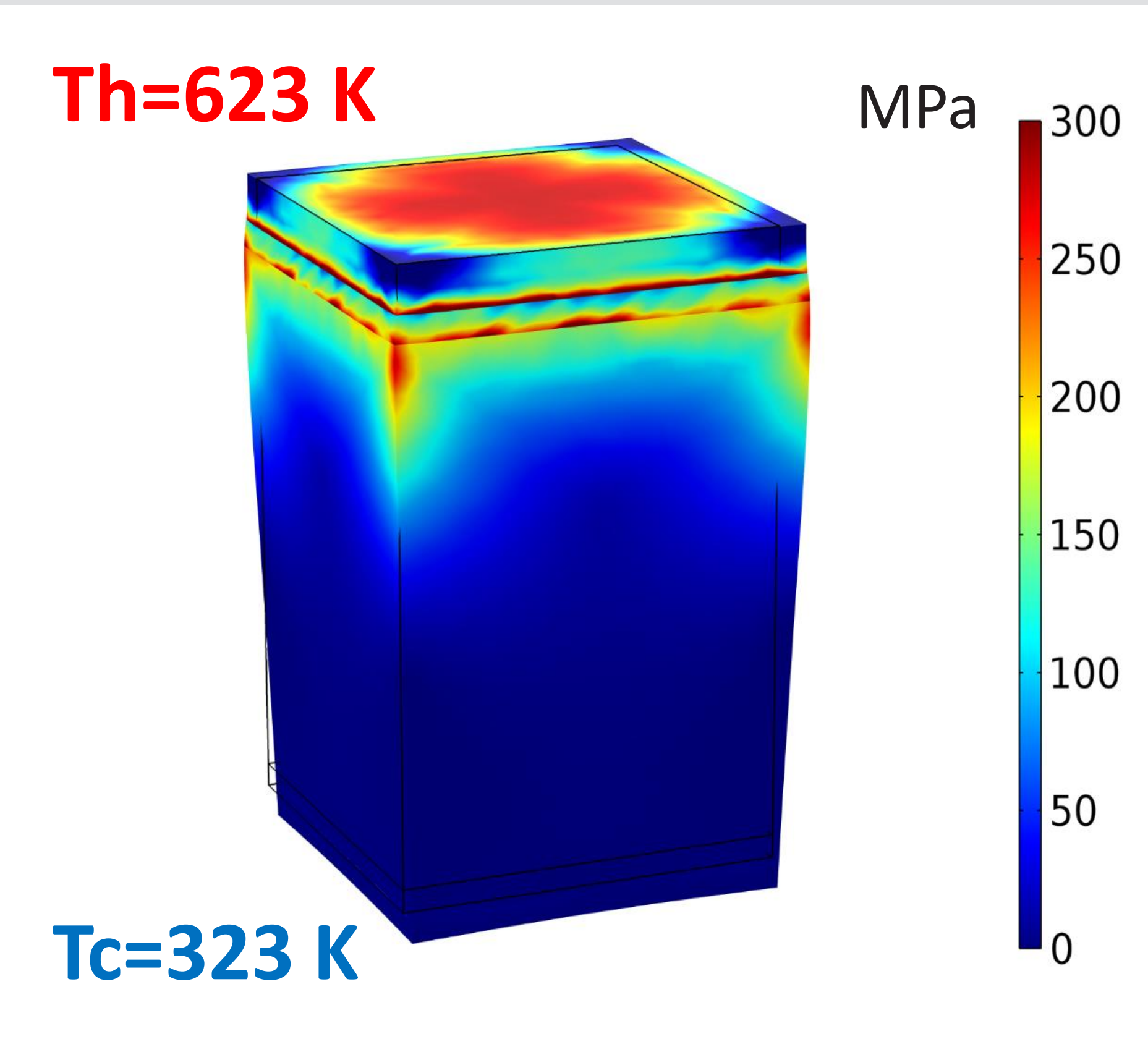

Figure 2. Evaluation of maximum tensile stress on a single n-type leg ($\Delta T=300$ K) with top/bottom metal connections and top ceramic layer. Thermal expansion leads to high stress on the hot side.

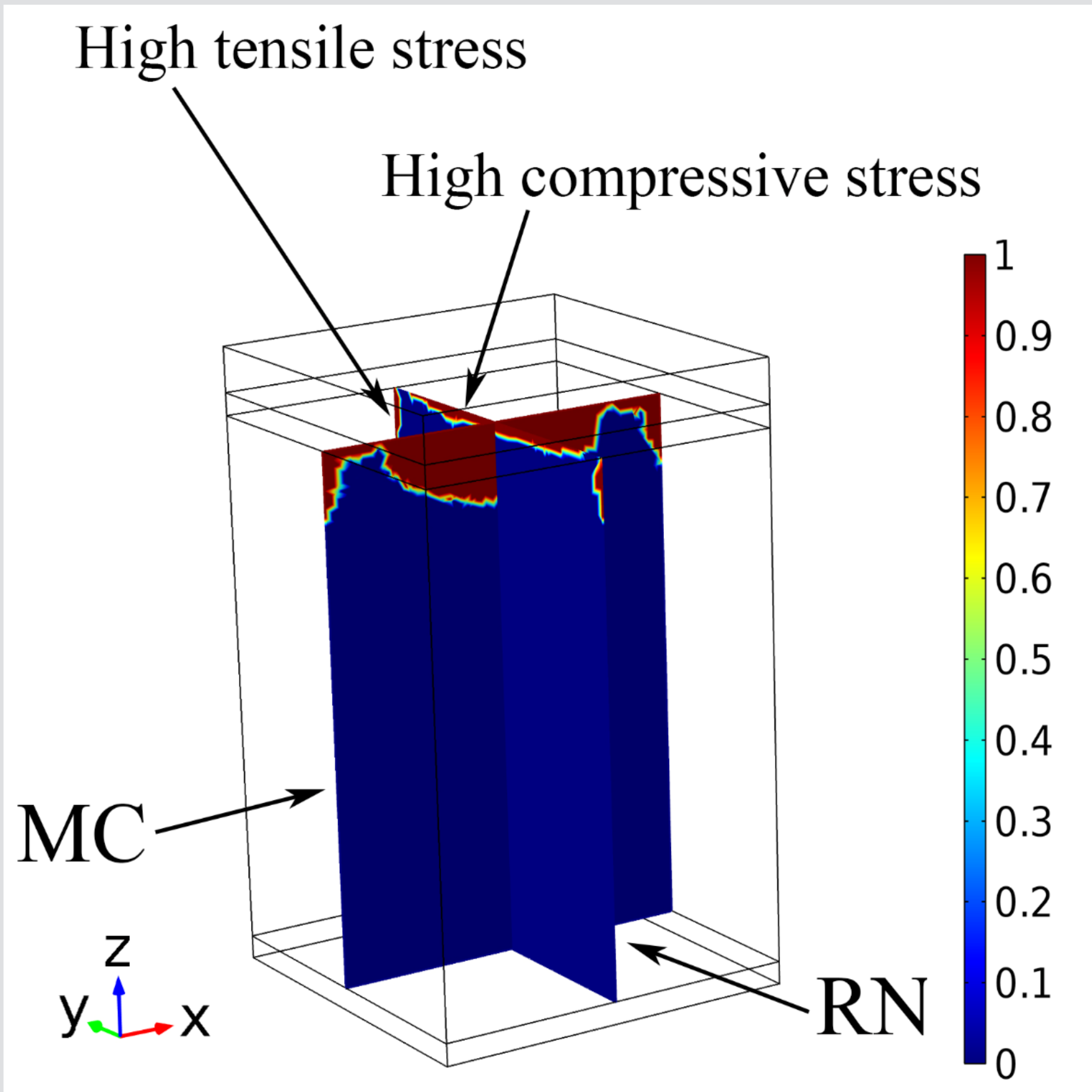

Figure 3. Evaluation of failure of a single n-type leg with Mohr-Coulomb (MC, *xz*-plot) and Rankine (RN, *yz*-plot) criteria. Blue (0) depicts the elastic region, dark red (1) depicts plastic/failure region. Mohr-Coulomb criterion leads to wider failure region, since it sets a more strict condition on stress.

Results: In the simulation, mechanical properties of materials have been taken as follows:

	Young's Modulus *E*[GPa]	Poisson's ratio ν	CTE (α_{th}) [1/K]
Sb-doped Mg_2Si (*n*-type legs)	116	0.18	$15.0\text{x}10^{-6}$
HMS (*p*-type legs)	245	0.2	$11.1\text{x}10^{-6}$
Cu connections	110	0.35	$17.0\text{x}10^{-6}$
Alumina (top ceramic layer)	300	0.22	$8.0\text{x}10^{-6}$

Table 3. Elastic properties and CTE values of materials.

Mohr-Coulomb (*failure*) and Von Mises (*yield*) criteria have been considered for thermoelectric legs and metal interconnects respectively. Failure on thermoelectric legs was found to occur on the top (hot side).

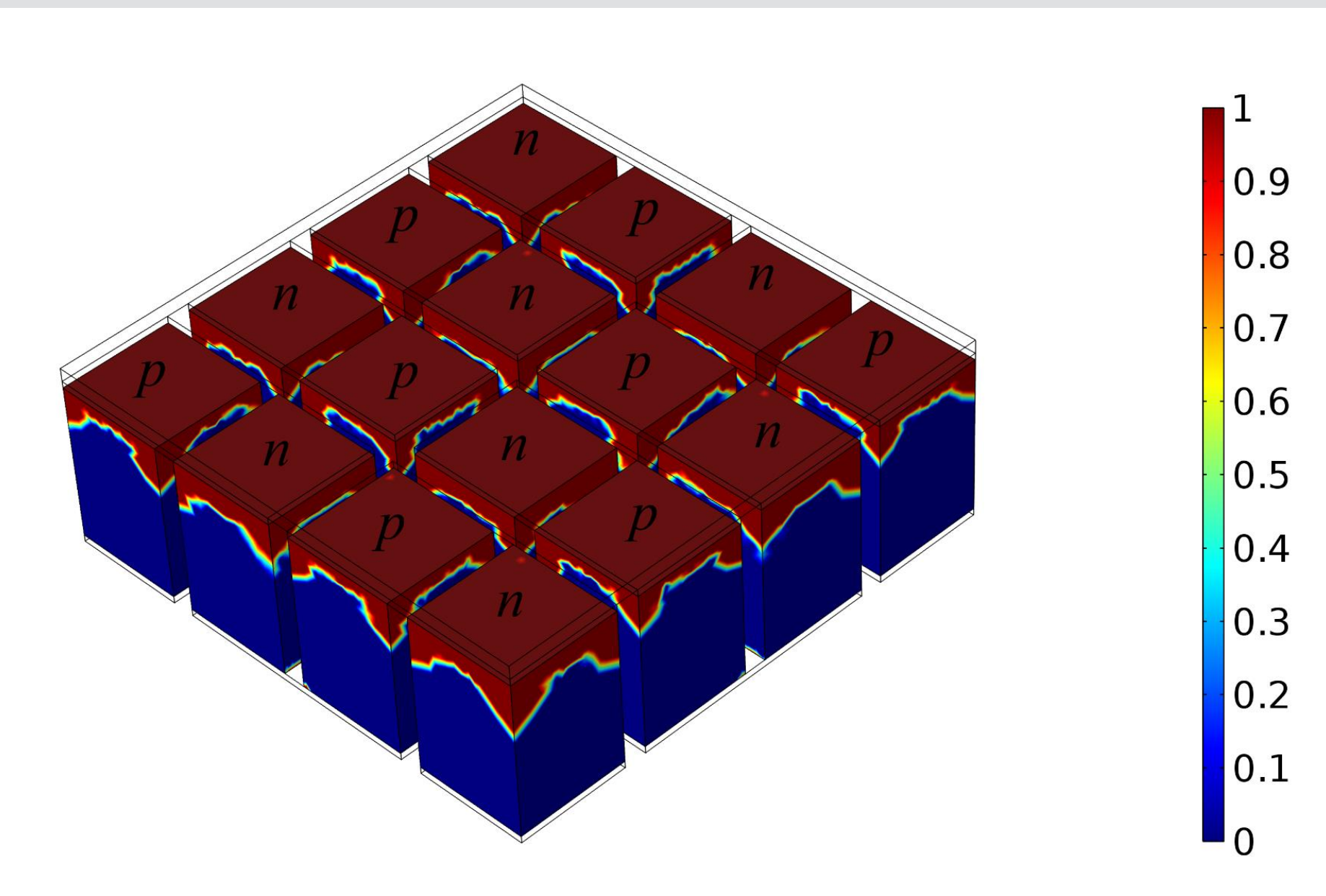

Figure 4. MC evaluation of potential failure in TE elements, taking 80 MPa and 140 MPa tensile and compressive strength for TE legs. Potential failure occur because of less dilating alumina layer.

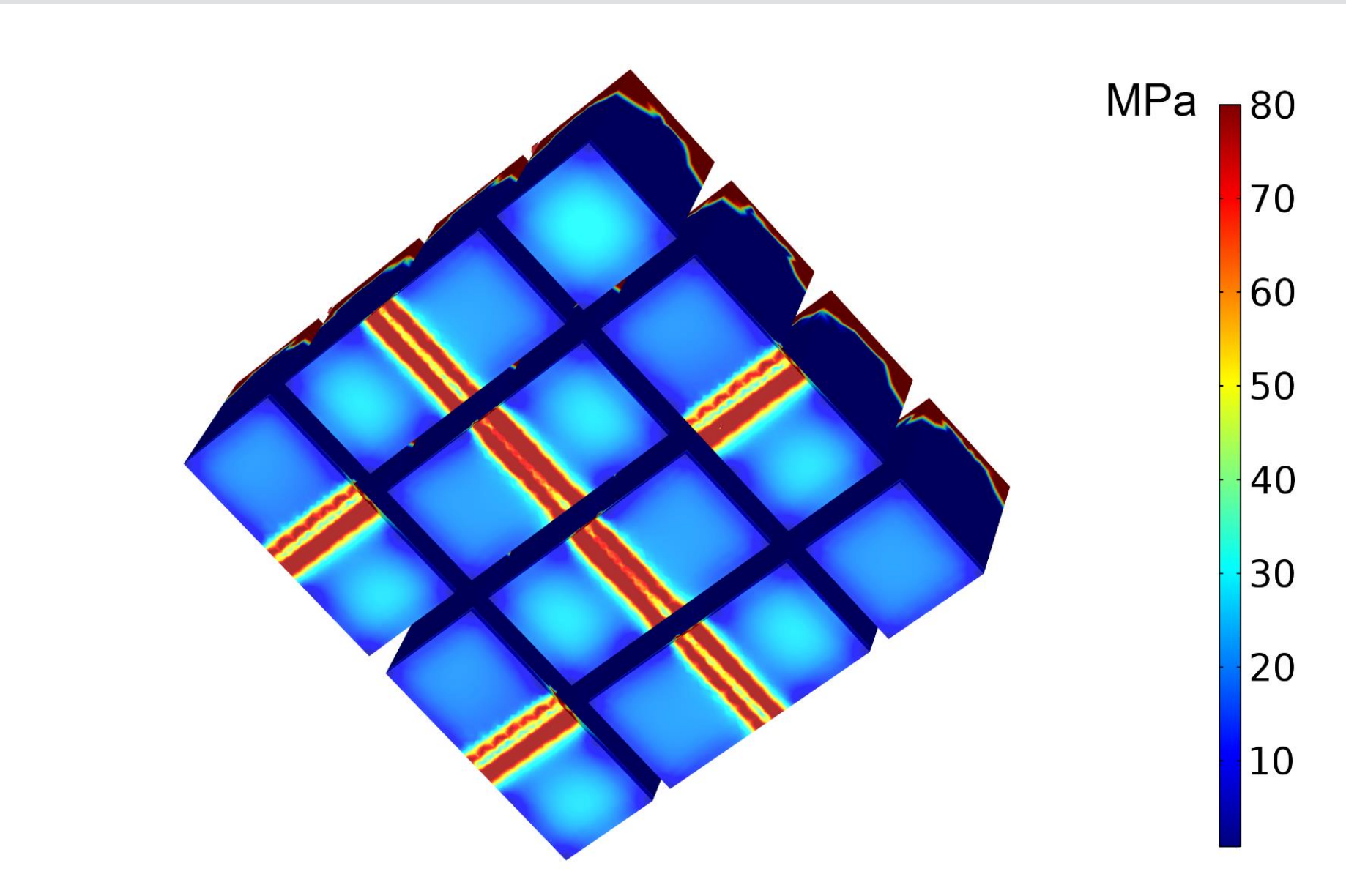

Figure 5. Yielding of bottom Cu connections is due to different longitudinal expansion of n,p-type legs.

Comparison with module testing results

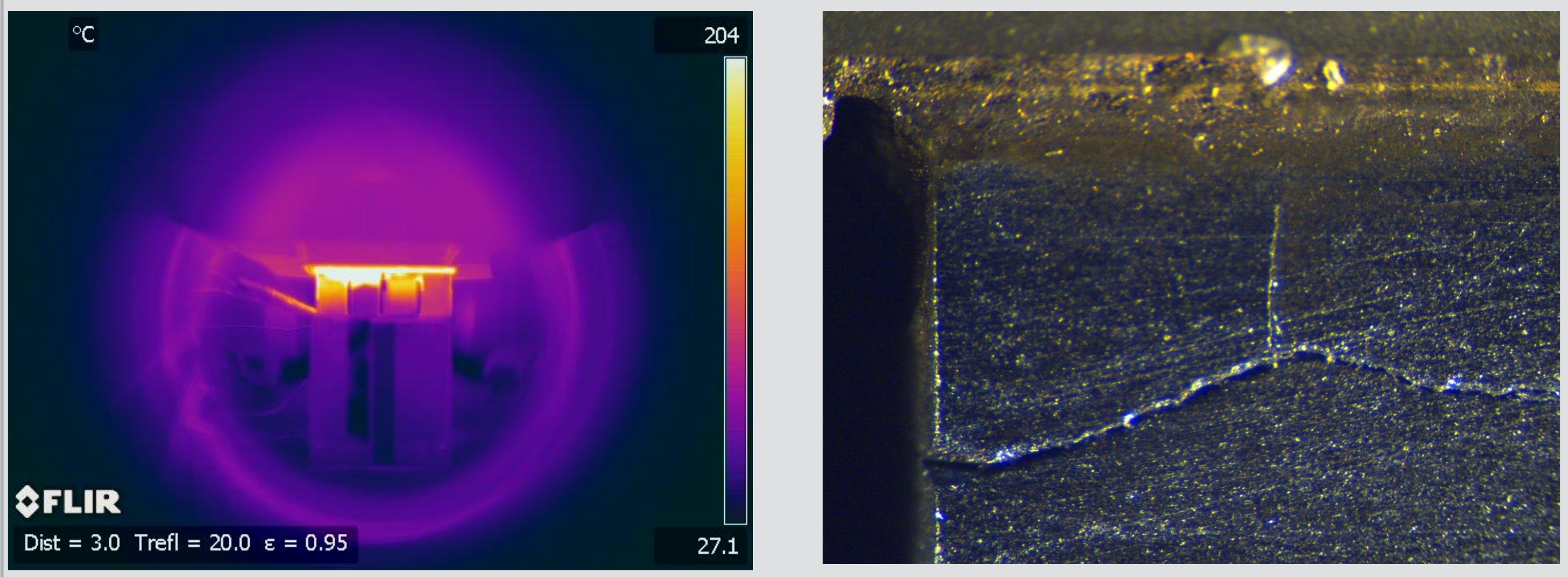

Figure 6. Cracks occurring on the top of n-type legs was observed also through IR Thermography on the tested prototype (a). Detail of crack (b).

Conclusions: FE analysis highlighted critical issues led by coupling elements with different values of α_{th} . Some results have been confirmed by module testing. However, contact nonlinearities should be further investigated and considered in the model.

References:

1. Zienkiewicz O. C and Taylor R. L., *The Finite Element Method (vol. 2): Solid Mechanics*, 5th ed., Butterworth-Heinemann, Oxford (2000)
2. A. Miozzo et al. Finite Element Approach for the Evaluation and Optimization of Silicide-Based TEG, *Proceedings of 11th ECT*, Noordwjik (2013)
3. S. Boldrini et al., IR Thermography for the Assessment of the Thermal Conductivity of Thermoelectric Modules at Intermediate Temperature, *Proceedings of SPIE 9861* (2016)

Excerpt from the Proceedings of the 2016 COMSOL Conference in Munich