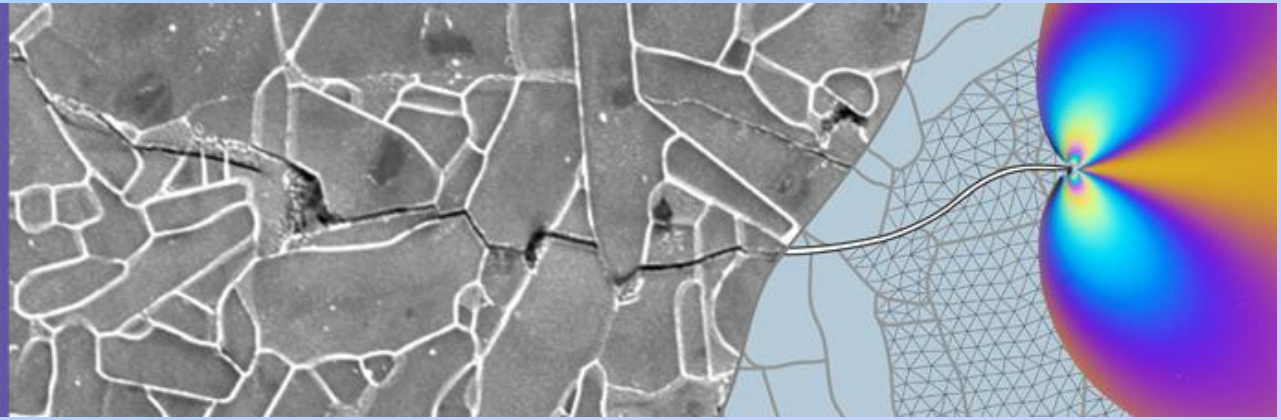
CERMODEL 2013

MODELLING AND SIMULATION MEET INNOVATION IN CERAMICS TECHNOLOGY

July, 10-12, 2013 Trento - Italy



Recent progresses on modelling of cracking in Polycrystalline Silicon for Photovoltaic Applications

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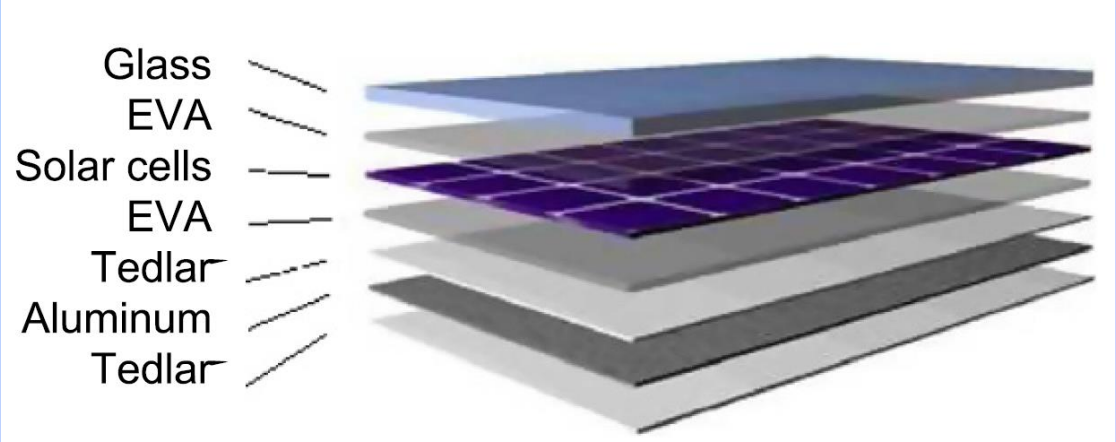
Composite geometry

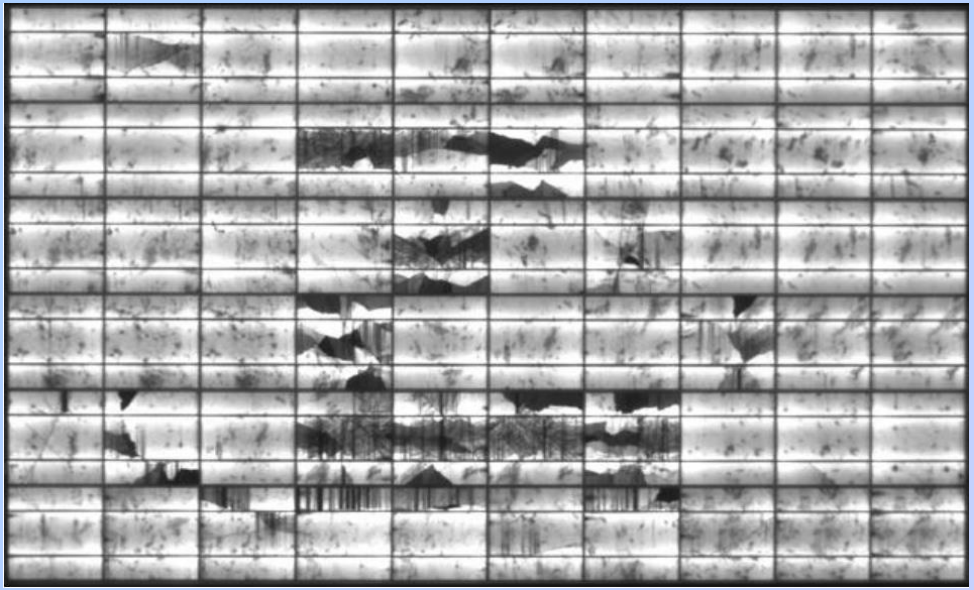
- **A multi-scale and multi-physics computational approach to fracture**
- **Micro-cracking in polycrystalline Silicon cells**



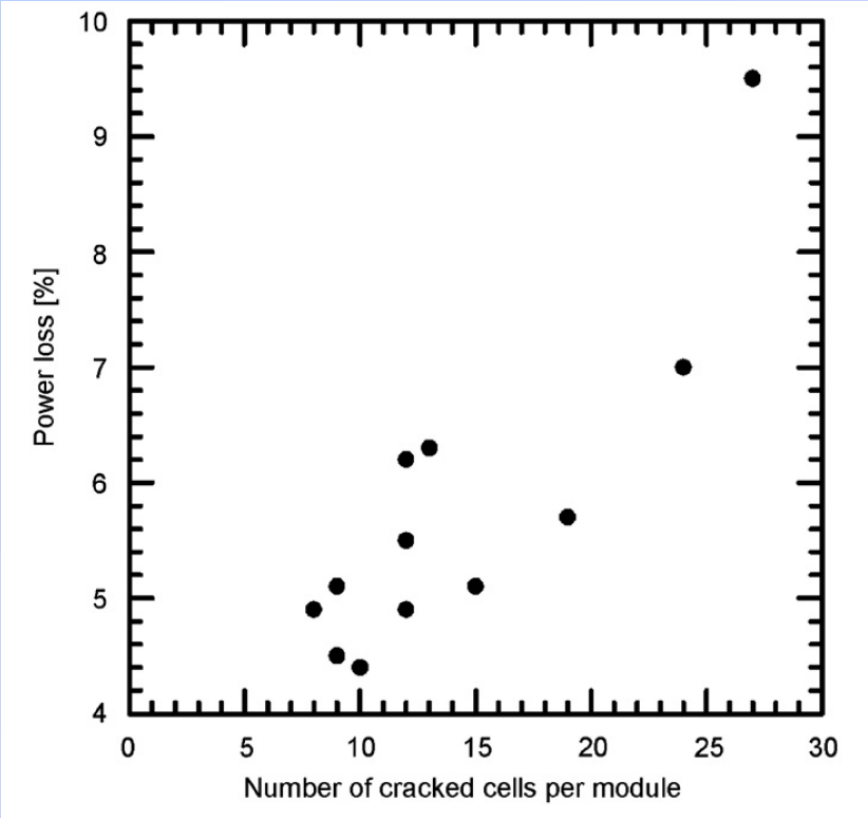
Paggi, Kajari-Schröder, Eitner, 2011

Polycrystalline Silicon cells

Micro-cracking and power-loss

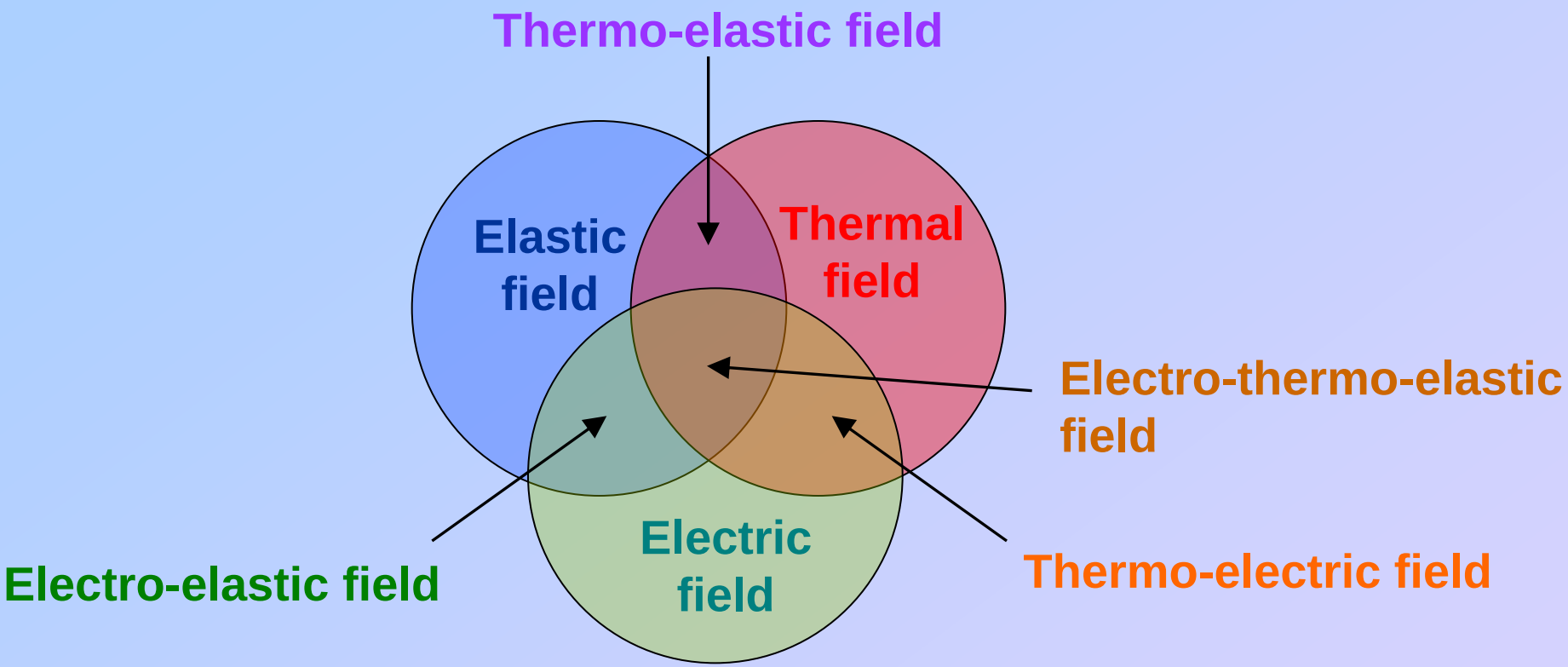


Electroluminescence image of microcracking



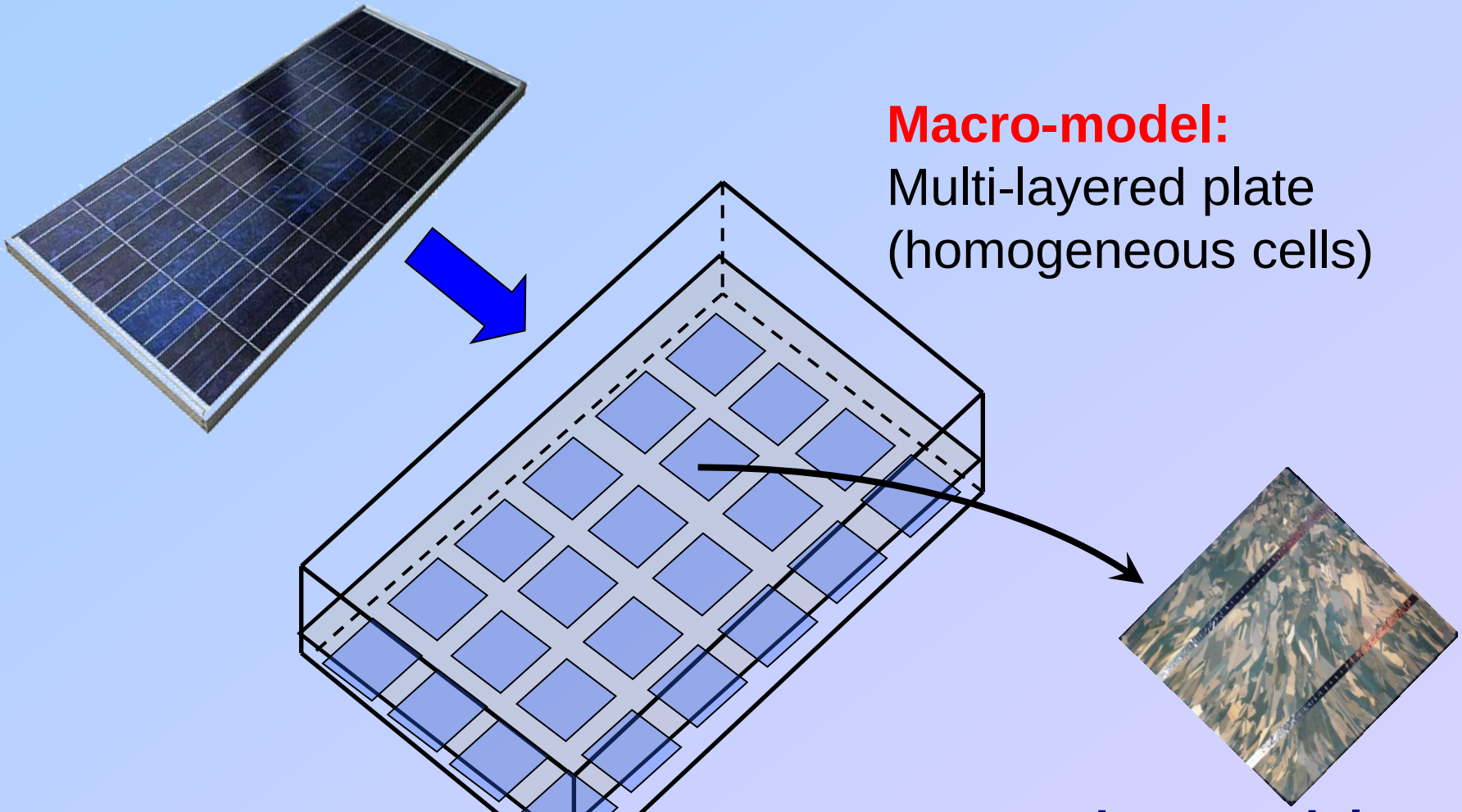
M. Köntges, I. Kunze, S. Kajari-Schröder, X. Breitenmoser, B. Bjørneklett
Solar Energy Materials & Solar Cells 95:1131–1137, 2011

A multi-physics approach



- **Thermo-elastic field: coupling due to thermoelasticity**
- **Thermo-electric field: coupling in the Schrödinger equation**
- **Electro-elastic field: coupling due to microcracks**

A multi-scale solution strategy



Macro-model:
Multi-layered plate
(homogeneous cells)

Micro-model:
Polycrystalline Si cells
with grain boundaries

Paggi et al., Comp. Struct., 2013

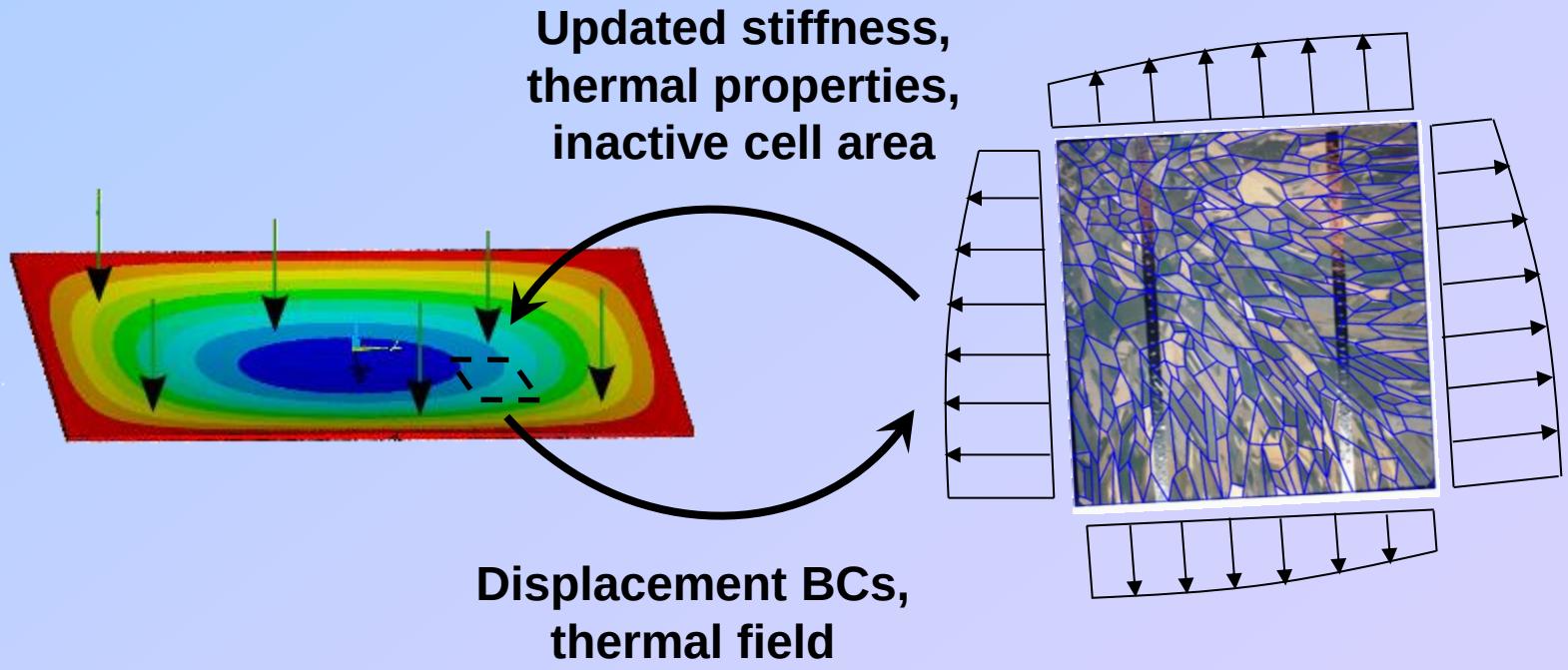
A multiscale-multiphysics FE model

Macro-model of PV panel:

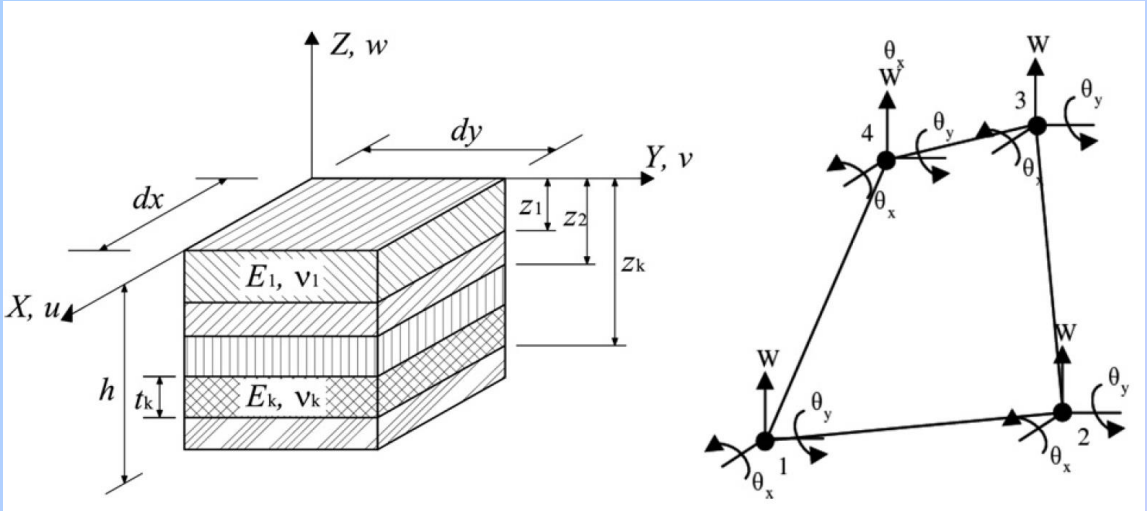
- Multi-layered plate
- Compute displacements
- Compute power-loss

Micro-model of Si cell:

- Heterogeneous with interfaces
- Micro-cracks
- Compute inactive area
- Update cell stiffness



Macro-model computations



$$\boldsymbol{D} = K \begin{bmatrix} 1 & \nu & 0 \\ \nu & 1 & 0 \\ 0 & 0 & \frac{1-\nu}{2} \end{bmatrix}$$

$$\left(\int_{\Omega} (\nabla \boldsymbol{N})^{\mathrm{T}} \boldsymbol{D} \nabla \boldsymbol{N} \, \mathrm{d}\Omega \right) \boldsymbol{\eta} = \int_{\Omega} \boldsymbol{N}^{\mathrm{T}} q \, \mathrm{d}\Omega$$

$where$: $w = N\eta \, , \theta = N_\theta \eta$

where $\boldsymbol{\eta} = [w_1, \theta_{x1}, \theta_{y1}, \ldots, w_4, \theta_{x4}, \theta_{y4}]^{\mathrm{T}}$ and:

$$\boldsymbol{N} = [N_1, 0, 0, \ldots, N_4, 0, 0]$$

$$\boldsymbol{N}_\theta = \begin{bmatrix} 0 & N_1 & 0 & \cdots & 0 & N_4 & 0 \\ 0 & 0 & N_1 & \cdots & 0 & 0 & N_4 \end{bmatrix}$$

In-plane displacements:

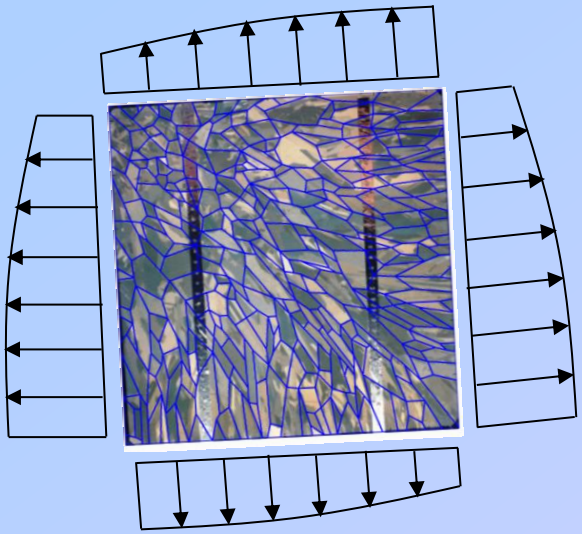
$$u = \theta_y z$$

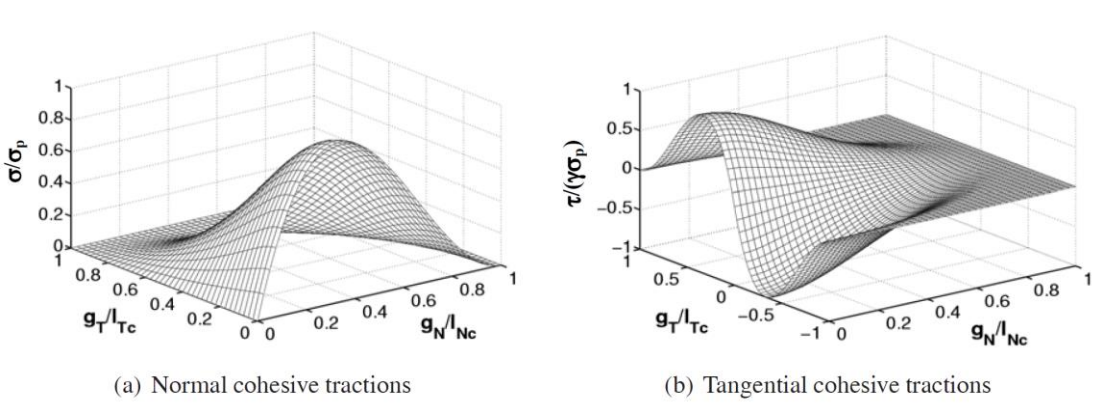
$$v = -\theta_x z$$

Micro-model computations using NLFM

$$\int_V (\nabla \delta \boldsymbol{u})^{\mathrm{T}} \boldsymbol{\sigma} \, \mathrm{d}V - \int_S \delta \boldsymbol{g}^{\mathrm{T}} \boldsymbol{t} \, \mathrm{d}S = \int_{\partial V} \delta \boldsymbol{u}^{\mathrm{T}} \boldsymbol{f} \, \mathrm{d}S$$

CZM contribution





(a) Normal cohesive tractions (b) Tangential cohesive tractions

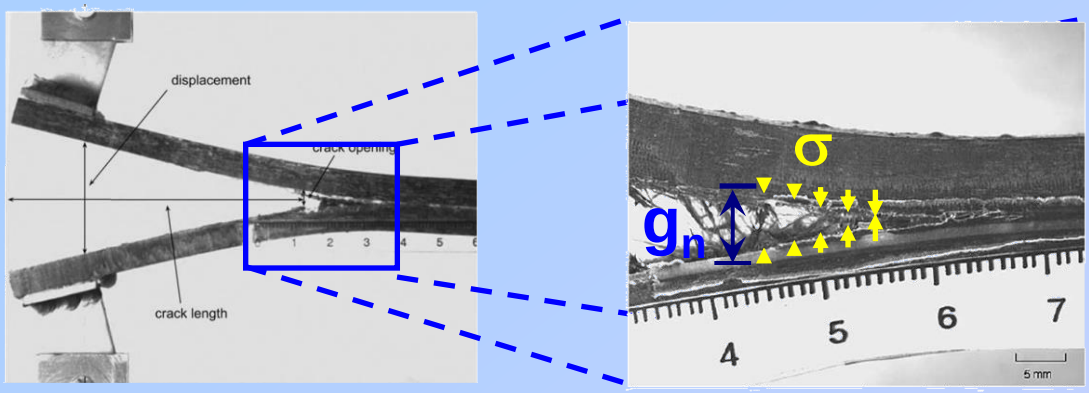
$$\Delta \delta W_{\mathrm{int}} = \delta \boldsymbol{u}^{\mathrm{T}} \boldsymbol{R}^{\mathrm{T}} \int_S \boldsymbol{B}^{\mathrm{T}} \boldsymbol{C} \boldsymbol{B} \boldsymbol{R} \boldsymbol{u} \, \mathrm{d}S$$

Linearization for the Newton-Raphson algorithm (FEAP)

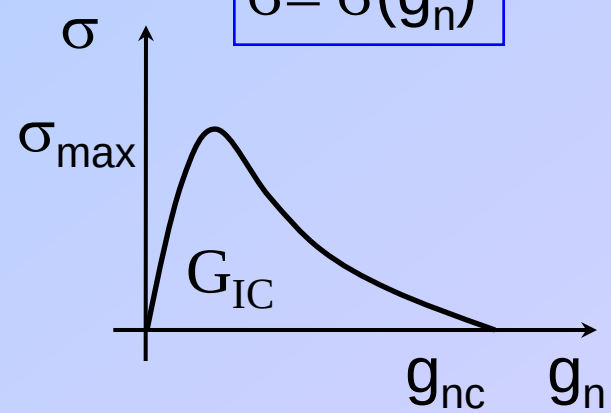
M. Paggi, P. Wriggers (2011) Comp. Mat. Sci., 50:1625-1633.

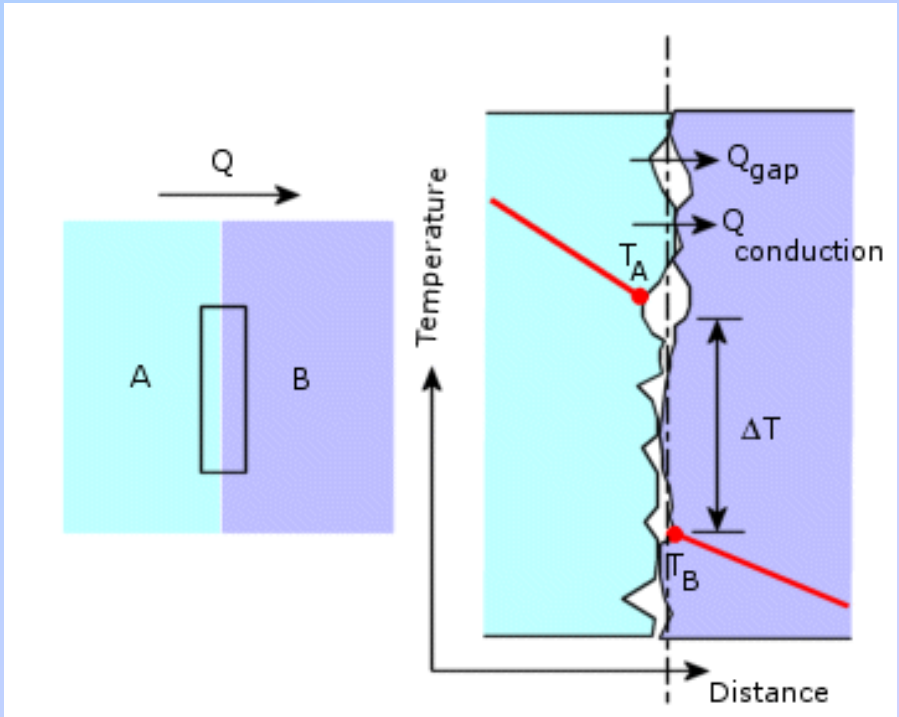
M. Paggi, P. Wriggers (2011) Comp. Mat. Sci., 50:1634-1643.

A thermo-mechanical cohesive zone model

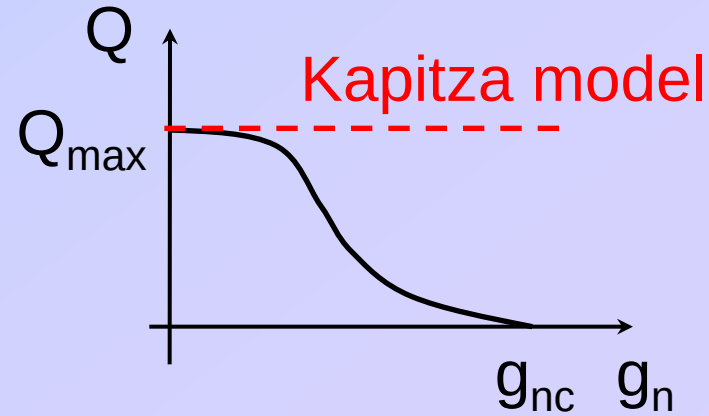


$$\sigma = \sigma(g_n)$$



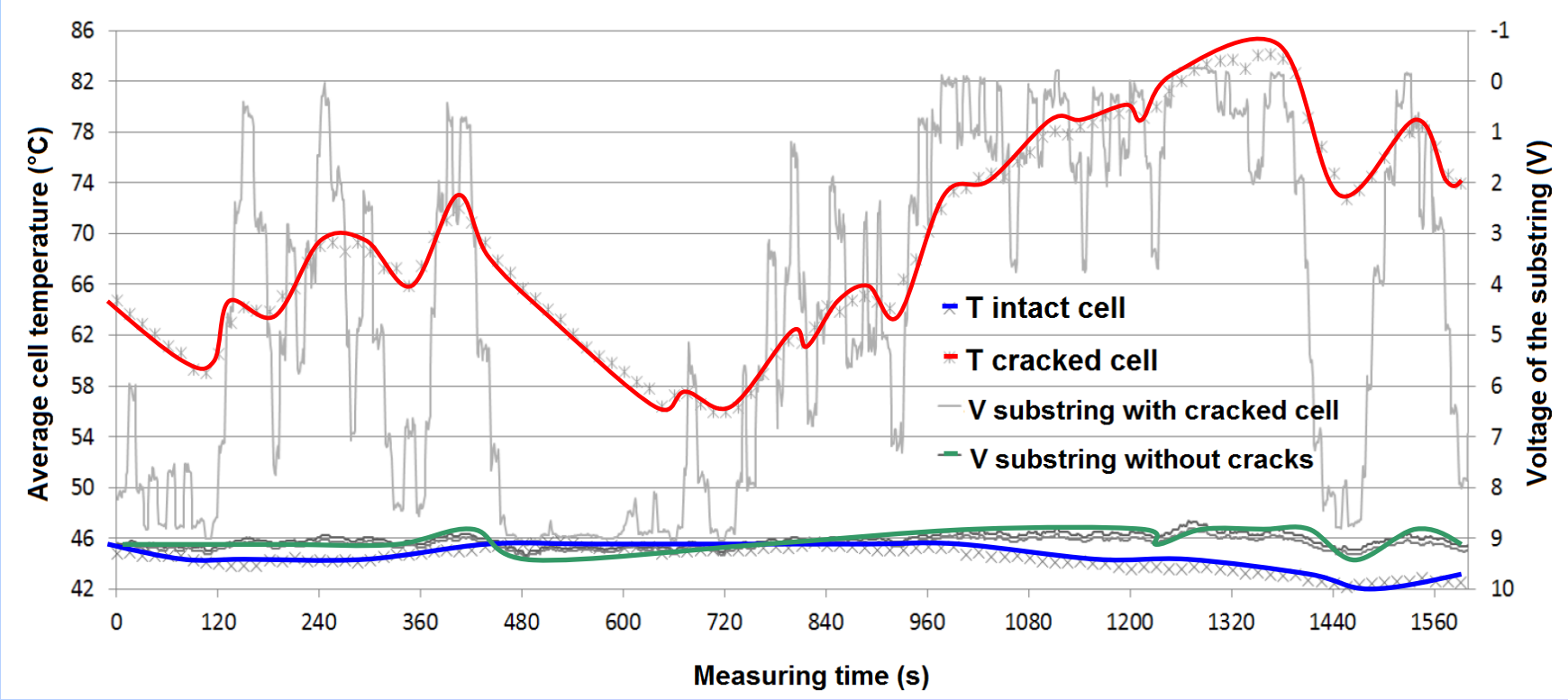


$$Q = -k_{int}(g_n)\,\Delta T$$



Paggi and Sapora, Energy Procedia, 2013.

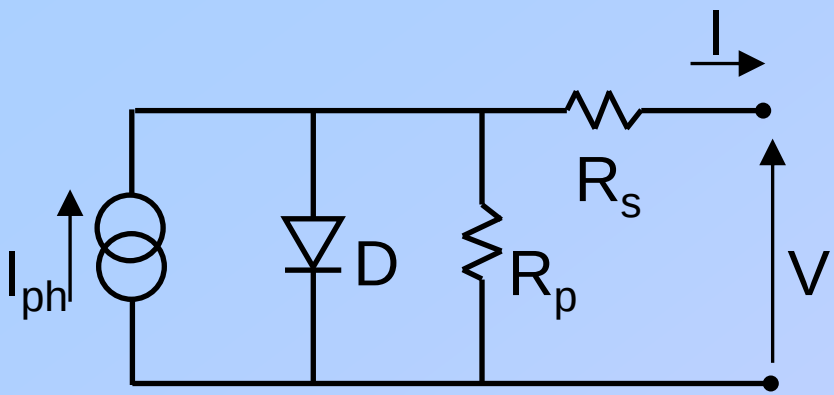
Interaction between thermal and elastic fields



- **High temperature near cracks (additional thermal resistance)**
- **Cracks are source of ricombination effects**

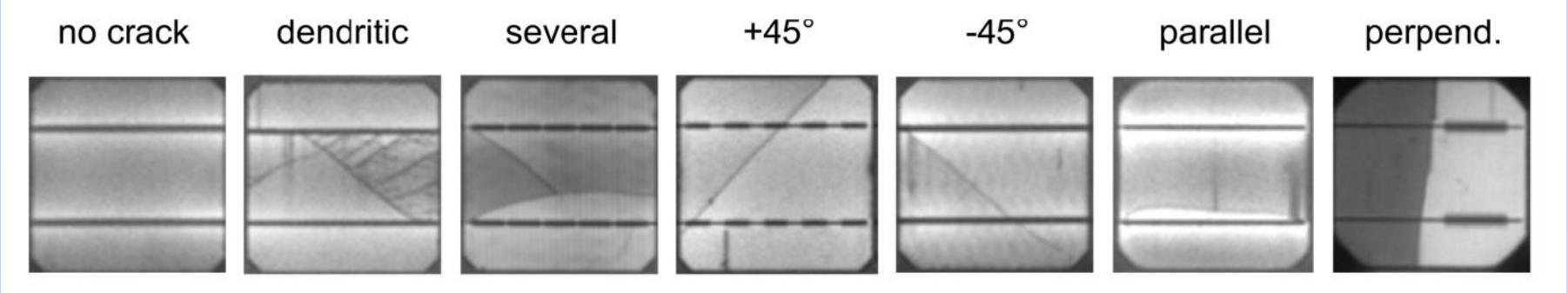
Weinreich et al., 2011

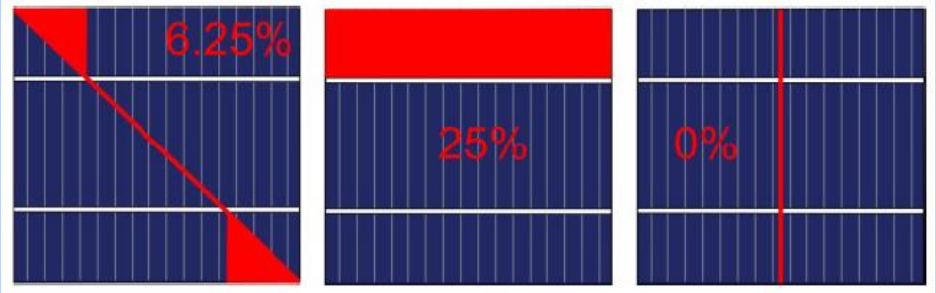
Damage variable and electrically inactive cell area



$$I = I_{ph} - I_s \left[e^{\frac{q(V + IR_s)}{AkT}} - 1 \right] - \frac{V + IR_s}{R_p}$$

$$\left.\begin{aligned} I_s(D) &= I_s^{D=0}(1 - D) \\ I_{ph} &= I_{ph}^{D=0}(1 - D) \end{aligned}\right\} D = \frac{A_{inactive}}{A}$$

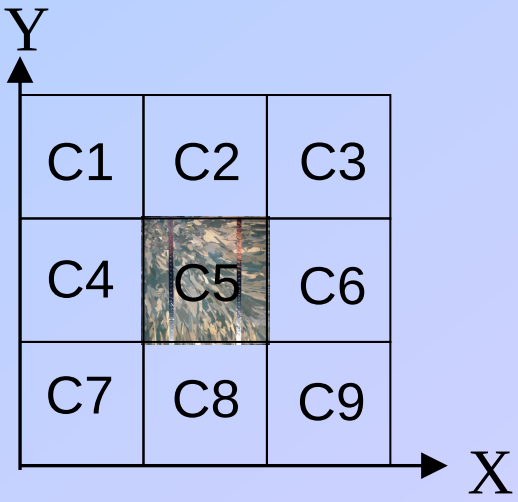




M. Köntges, I. Kunze, S. Kajari-Schröder, X. Breitenmoser, B. Bjørneklett, Solar Energy Materials & Solar Cells 95:1131–1137, 2011

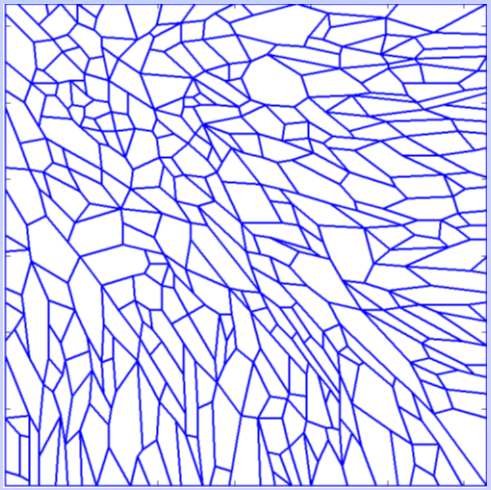
Qualitative numerical example

Simply supported plate subjected to a uniform (snow) pressure of 5400 Pa

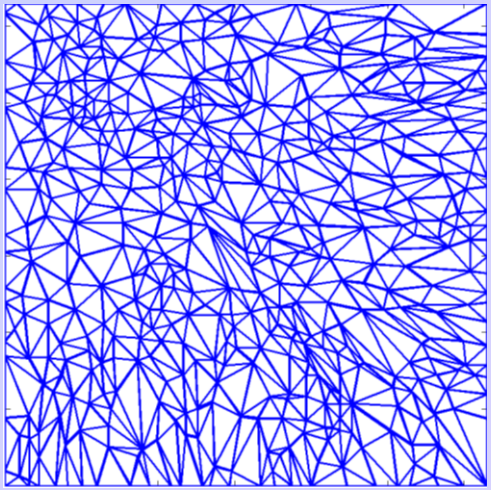


Real microstructure

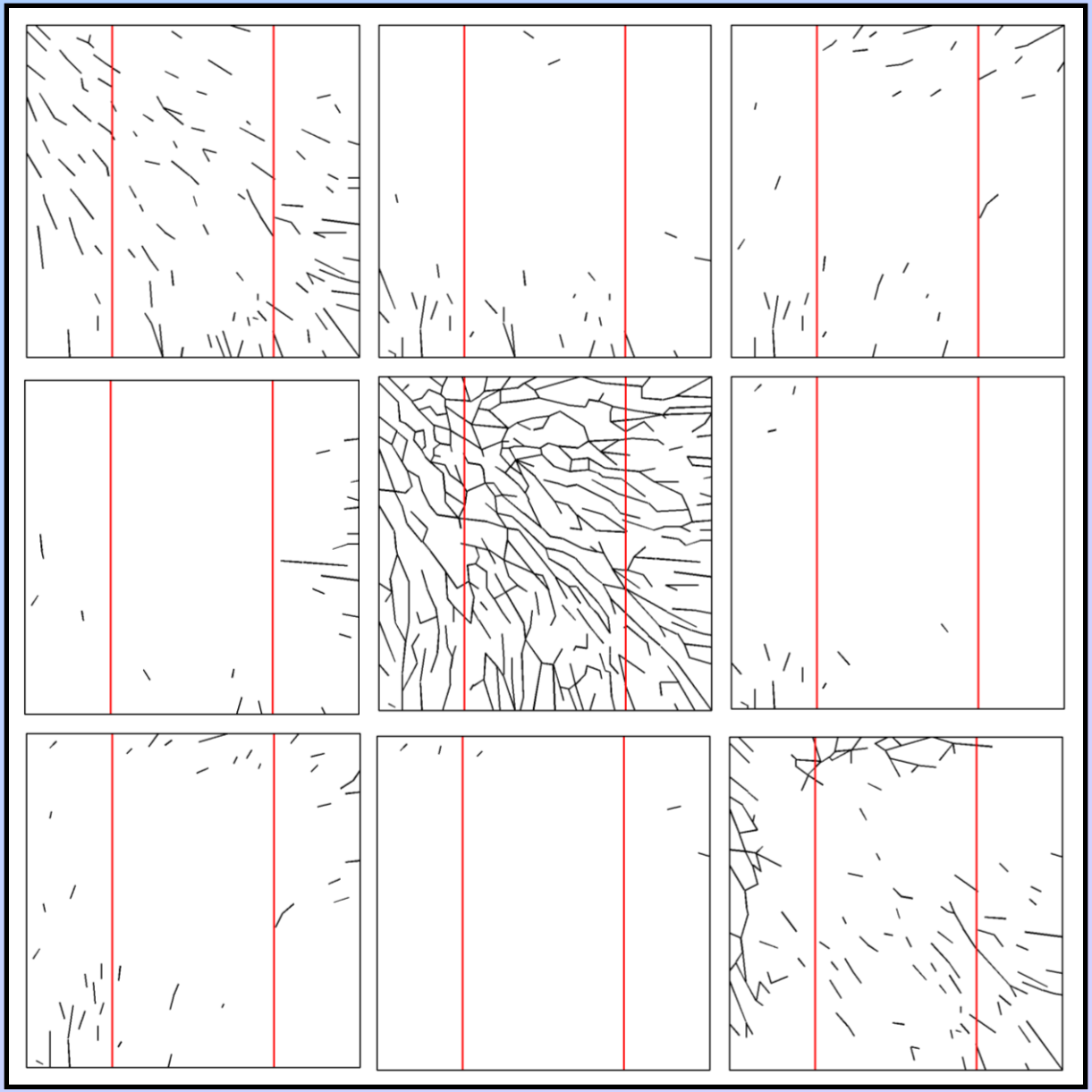
Grains identification



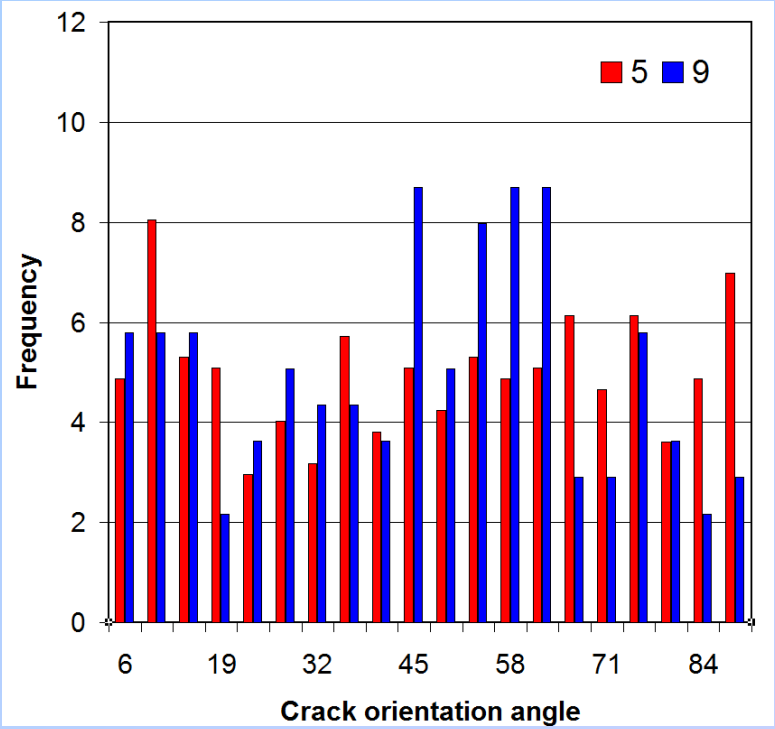
Mesh generation

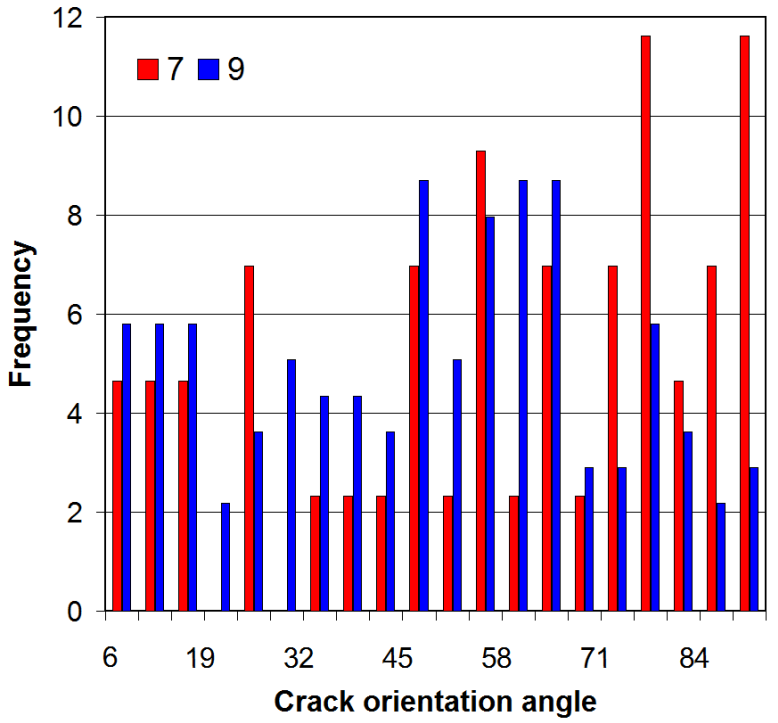


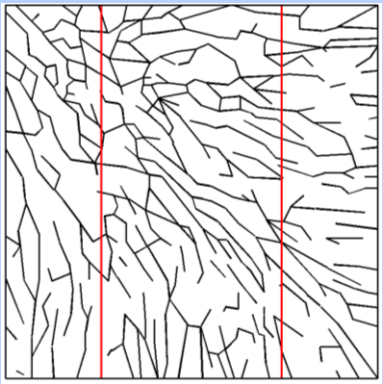
Micro-crack pattern in Silicon cells

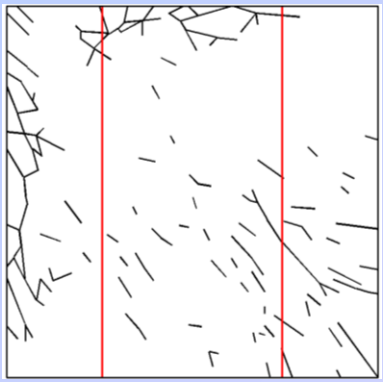


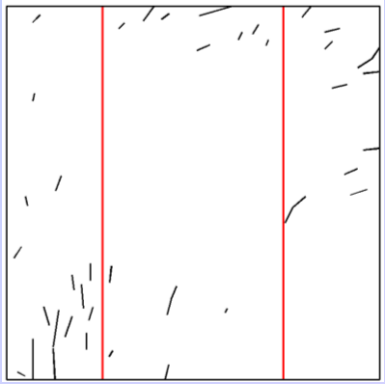
Distribution of crack orientation angles

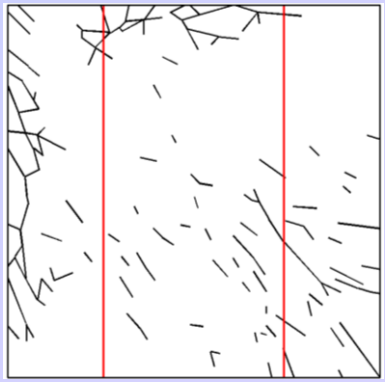






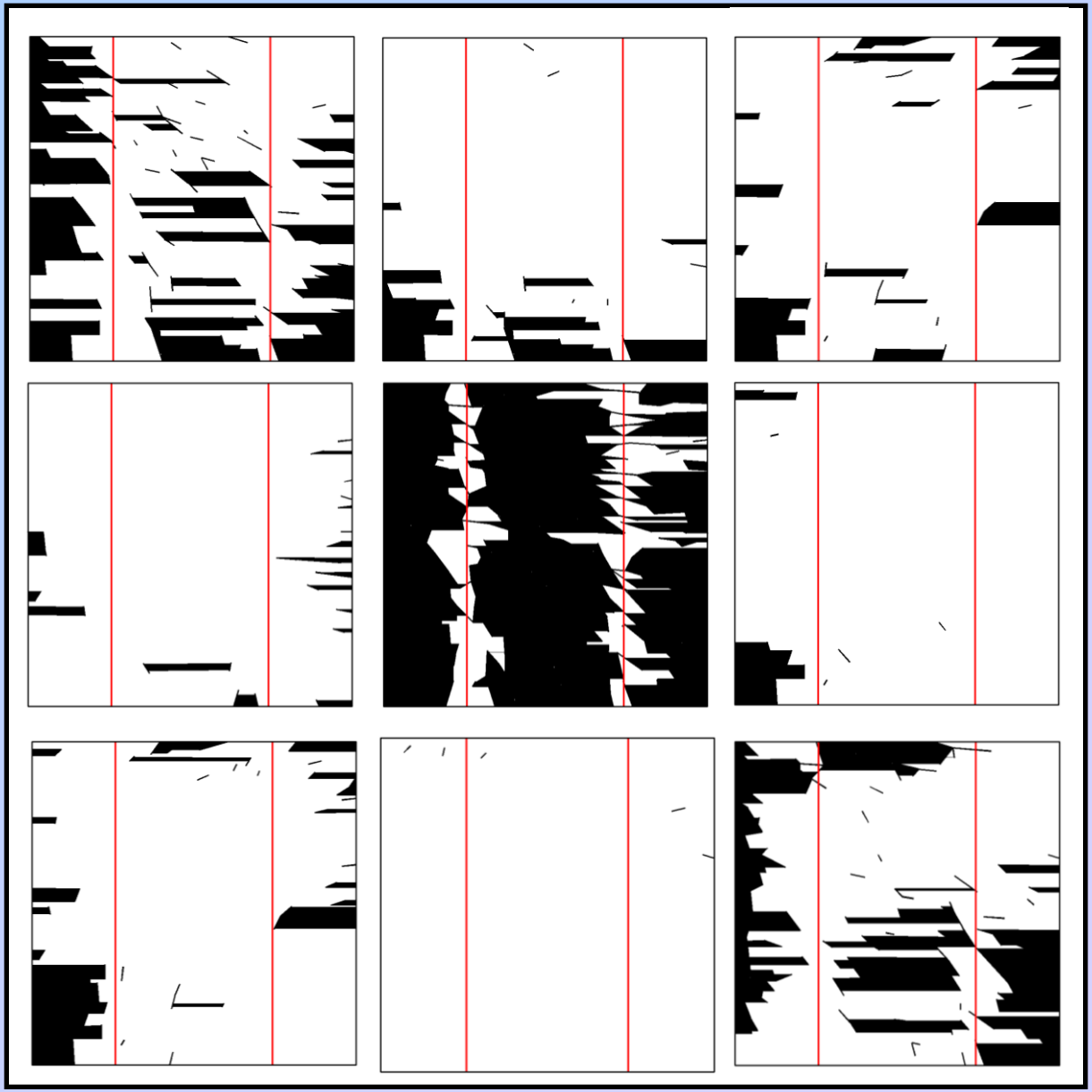




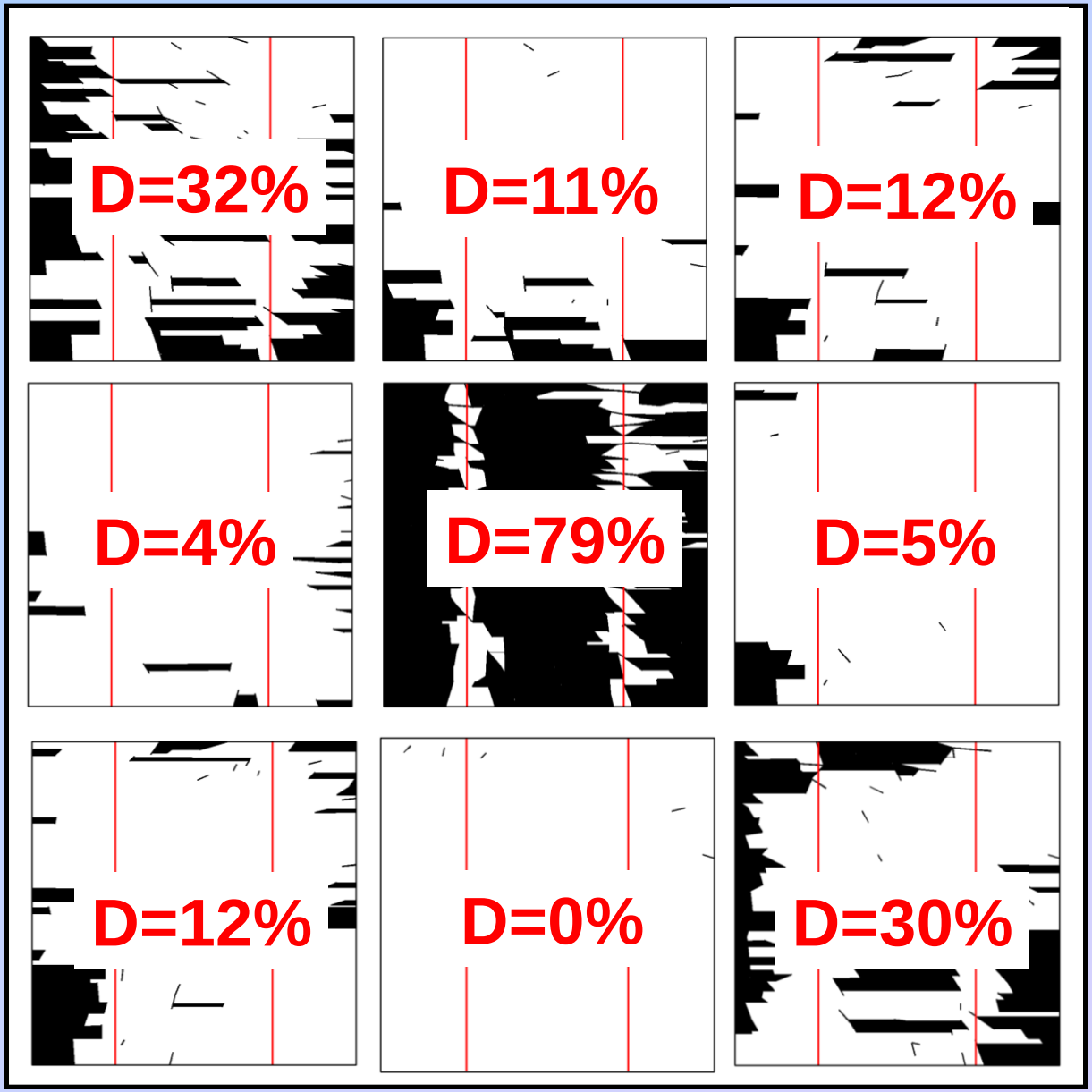


(C5) Central **(C9) Bottom Right corner** **(7) Bottom Left corner** **(9) Bottom Right corner**

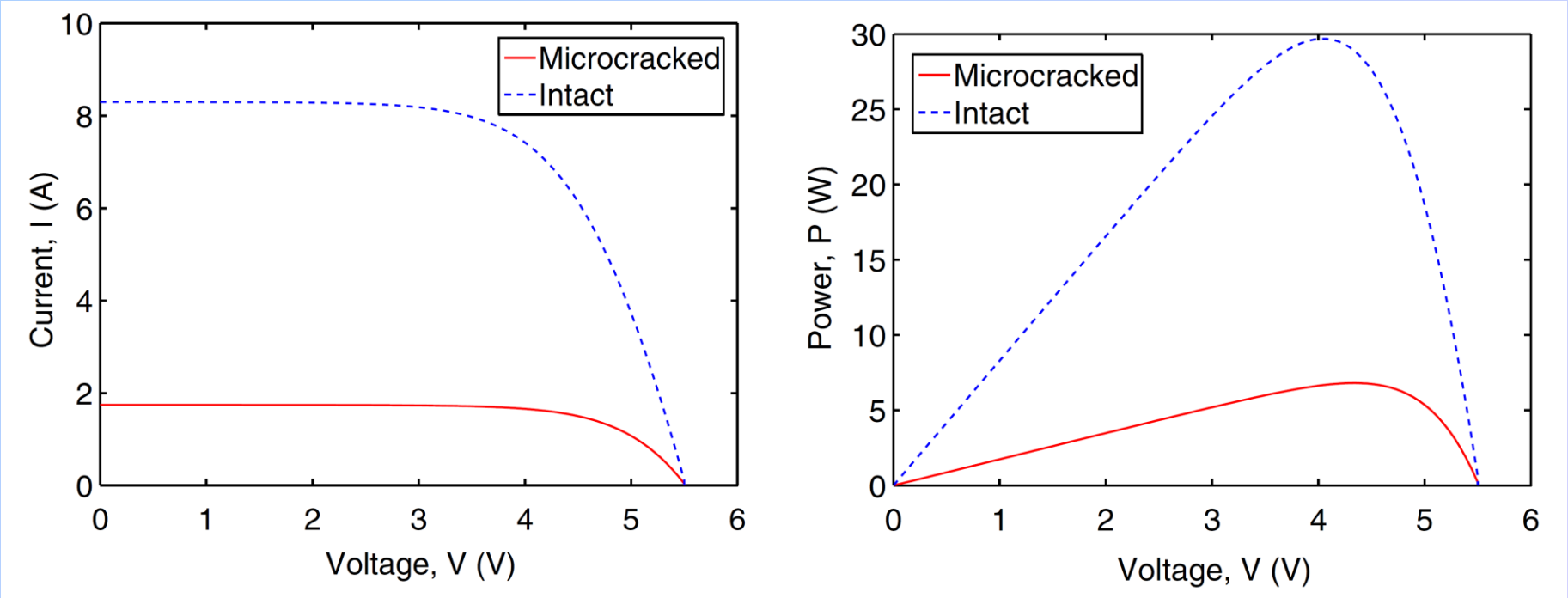
Electrically inactive cell areas: numerical results



Electrically inactive cell areas: electric damage D



Effect of microcracking (worst case scenario)



Electric efficiency of the intact module (fill factor): 65%

Electric efficiency of the microcracked module: 15%

Conclusions

- **The effect of microcracking on the electric performance can only be quantified according to a multi-physics approach**
- **A multiscale solution strategy is effective to reduce the computational cost in case of large panels and to simplify the 3D problem**
- **A thermo-mechanical cohesive zone model for polycrystalline Silicon has been proposed**
- **Due to the analogy with contact mechanics, only 3 model parameters need to be identified by experiments**

Work in progress for future development

- **Partially conductive microcracks (so far, microcracks have been considered as electrically insulated)**
- **Coupling with the electric and the thermal field to predict the degradation rate of PV panels exposed to environmental conditions**
- **Modelling of transgranular cracking**
- **Parameter identification and model validation with experiments**

Acknowledgements

European Research Council
Supporting top researchers from anywhere in the world

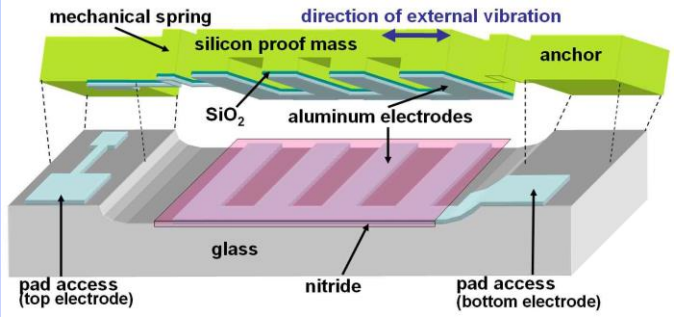
ERC Starting Grant IDEAS 2012

Multi-field and multi-scale Computational Approach to Design and Durability of PhotoVoltaic Modules

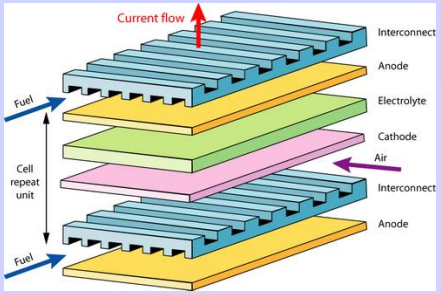
FIRB Future in Research 2010

Structural mechanics models for renewable energy applications

Photovoltaics (POLITO)



MEMS for wind energy harvesting (UNISAL)



Solid oxide fuel cells (UNITN)