# Quantitative EL image analysis towards thermo-electro-mechanical simulations in solar cells

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## Outline

Damage, micro-cracks, and other defects introduced in PV modules are important features impacting on their electrical power-loss, their actual solar conversion efficiency and also their lifetime. The aim of this work is to perform quantitative analysis of electroluminescence (EL) images of solar cells through two models: a distributed two-dimensional model and a one-dimensional one. The proposed improvement, with respect to the approaches available in the literature, represents a fundamental step towards the development of an innovative fully coupled thermo-electro-mechanical numerical method.

## Distributed circuit for series resistance and current identification

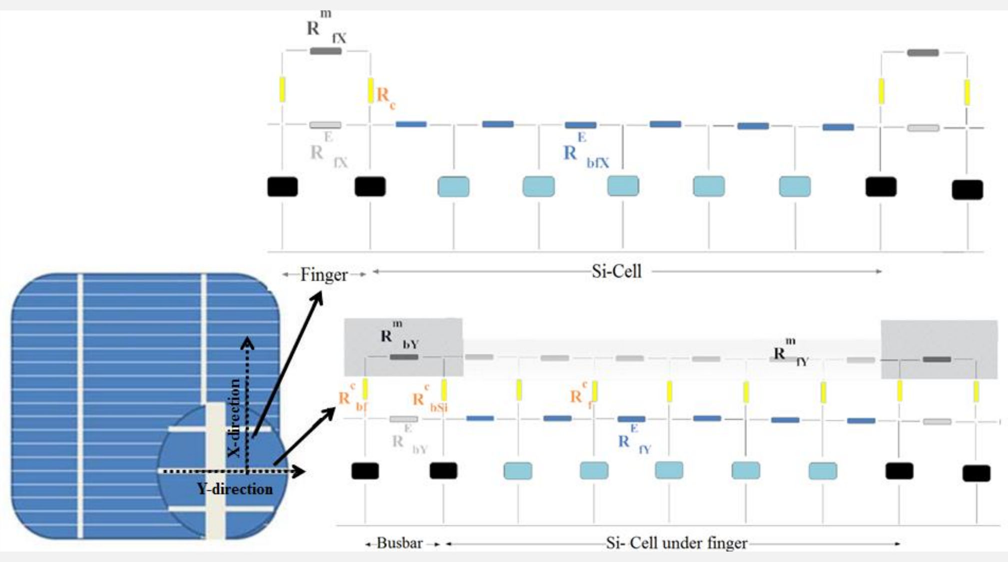
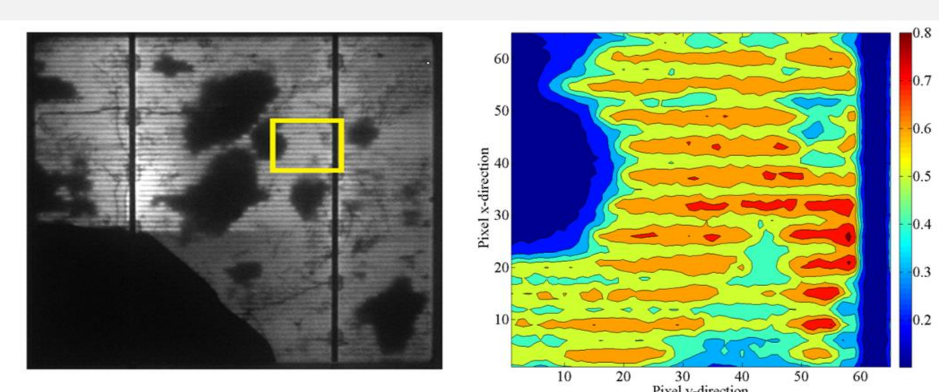


FIG. 1 Schematic representation of the discrete distributed circuit.

Simulation of a cell operating during an EL test: each series resistance is an equivalent one and takes into account all different resistances (emitter, contact, metallization)[1]. Using Kirchhoff's law, the I-V equation for each discretized node is given by:

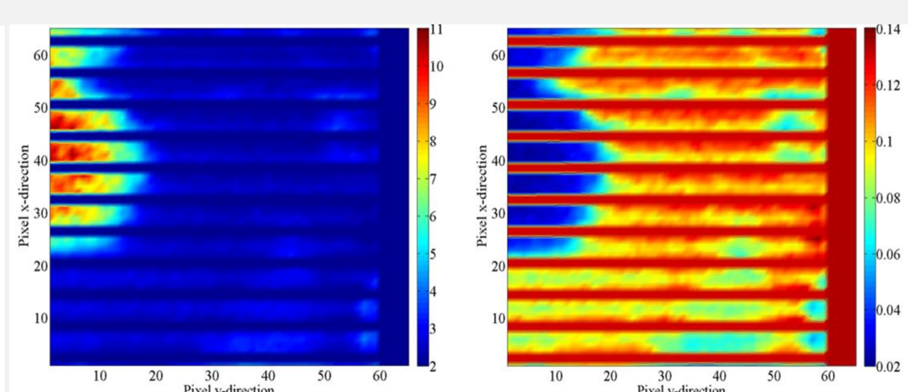
$$I = I_{01}\left(exp\frac{V-R_S\times I}{n_1\times V_T}-1\right)+\frac{V-R_S\times I}{R_P} \quad (1)$$

The simulation aims at computing average values for $I$ with discrete homogeneous resistance. The series resistance value to be identified is determined from Eq. (1) according to a Netwon-Raphson method[2] due to the nonlinearity of the equation. Performing this procedure for different EL images, a lookup table relating the type of defects and the spatial distribution of resistances can be build up.



(a) EL image (b) Contour plot of EL intensity

FIG. 2. (a) EL image of a damaged polycrystalline Silicon cell and (b) EL intensity (a.u.) of the examined area identified in Fig. 2(a) by a yellow rectangle.



(a) Contour plot of resistances (b) Contour plot of current

FIG. 3. (a) Identified resistances (Ω) and (b) predicted current (A) from the nonlinear identification procedure.

## One-dimensional model for current distribution

The model proposed in Ref. 3 aims at simulation current and voltage as a function of the series resistance:

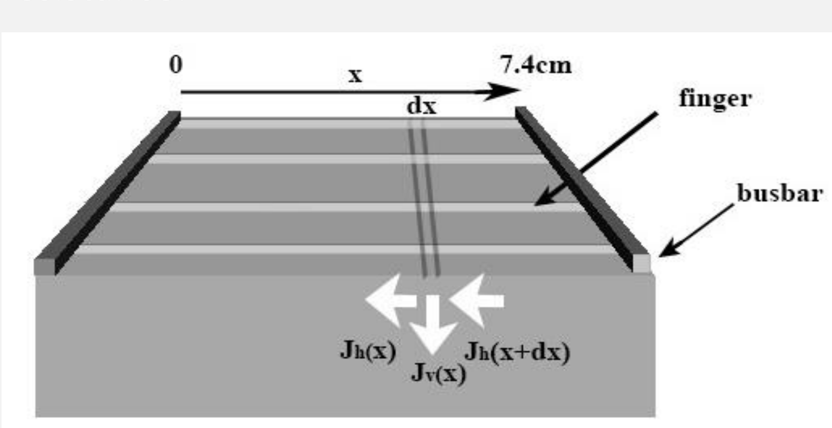


FIG.4. Schematic representation of investigated area with $I_v$ and $I_h$vertical and horizontal current density, respectively.

$$I_v(x) = I_{01}exp\frac{V(x)-R_{loc}\times I_v(x)}{n_1\times V_T}-I_{sc}$$

$$\frac{\partial V(x)}{\partial x} = V'(x) = -\rho_S I_h(x)$$

$$\frac{\partial I_h(x)}{\partial x} = I_v(x)$$

$$\frac{\partial^2 V(x)}{\partial^2 x} = V''(x) = \rho_S I_v(x)$$

The integration path from $x=0$ to $x=d$ is divided into fractions of length $dx$. Between $x$ and $x+dx$, $I_v$ is constant and, therefore, the voltage assumes a quadratic trend governed by the following ordinary differential equations:

$$I_h(x+dx) = I_h(x) + I_v(x)dx$$
$$V'(x+dx) = V'(x) + V''(x)dx$$
$$V(x+dx) = V(x) + V'(x)dx + \frac{V''}{2}dx^2$$

## Generalization of the model in case of cracks

The previous electric model is modified by including localized resistances due to the presence of cracks crossing Si cells and/or fingers. This allows the coupling between the thermo-mechanical field and the electric one. The electric model presented is modified including a voltage discontinuity, dependent on the relative crack opening displecement at crack faces. This discontinuity, proportional to the crack resistance $R_{cr}$ and to the horizontal current $J_h(x)$, may be written as:

$$V(x) = V(x) + R_{cr}J_h(x).$$

➢ **Monocrystalline Si cells**

The connection between discontinuity $R_{cr}$ and relative crack opening displacement at crack faces has been analysed in monocrystalline-Si using bending tests on a semi-flexible rectangular PV module[4] (made of two rows of 5 monocrystalline cells). Tests have been performed in the laboratory by monitoring cracking at different deformation levels by EL imaging. In the model, $R_{cr}$ depends on crack opening. Therefore, it changes from loading to unloading case. For monocrystalline cells $R_{loc}$ is equal to 0.2 Ωcm².

➢ **Polycrystalline Si cells**

EL tests have been performed in the laboratory on undamaged and damaged modules after a sequence of environmental cycle tests. For polycristalline–Si, $R_{loc}$ is dishomogeneous and depends on grain boundaries and defects. In order to quantify its variability from its average value, $R_{loc}$ has been replaced with $\bar{R}+dR$, where $\bar{R}$ is the average value and $dR$ takes into account the fluctuations using pseudo-random values taken from a gaussian distribution with a prescribed variance.

## Results for monocrystalline Si cells

The parameters used for the simulations are: $I_{sc}=0$, $R_{loc}=0.2\ \Omega\text{cm}^2$, $V_T=25$ mV, $\rho_S=0.13\ \Omega/\text{cm}$, $I_{01}=1.48\times10^{-12}$ mA/cm².

$V_0$ and $R_{cr}$ are free parameters used to fit the EL experimental data and to obtain the same voltage in correspondence of the two busbars, at $x=0$ and $x=d$.

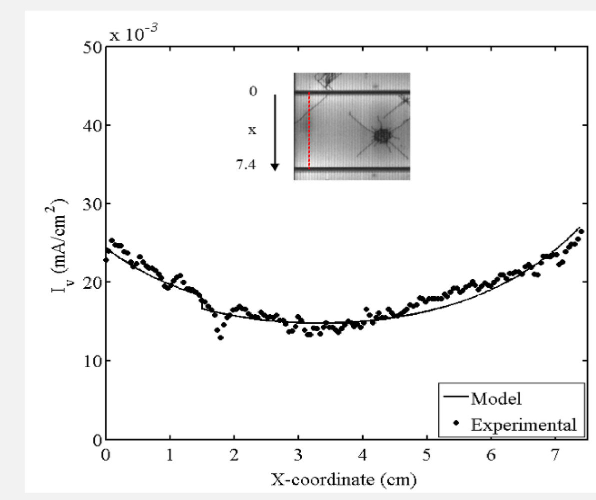


FIG. 5. Vertical current for a cell with a crack, across the section, unloaded condition. $R_{cr}$=0.096 Ωcm², $V_0$=0.579 V.

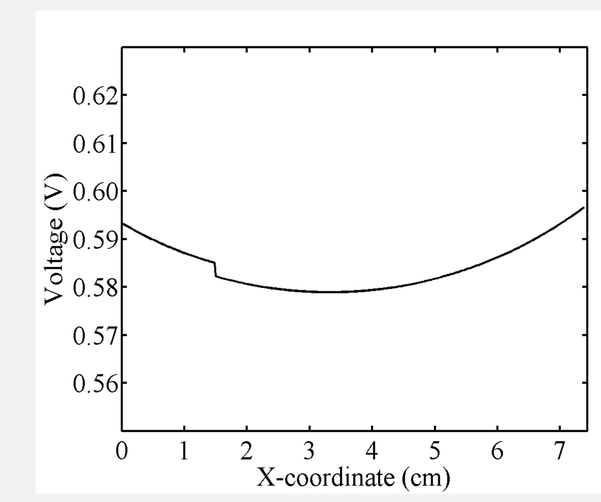


FIG. 6. Voltage for the cell shown in Fig. 5, unloaded condition.

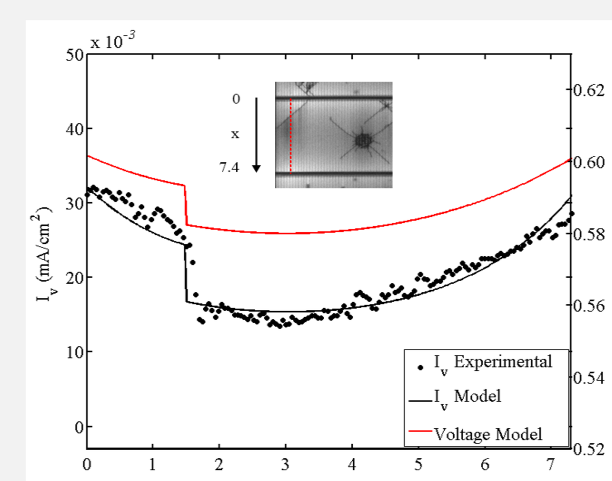


FIG. 7. Vertical current and voltage corresponding to Fig. 5, in loaded condition $R_{cr}$=0.22 Ωcm², $V_0$=0.580 V.

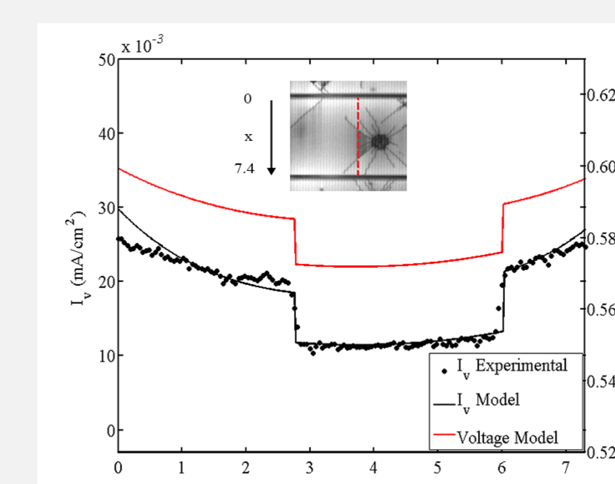


FIG. 8. Vertical current and voltage for a cell with two cracks, loaded condition. $R_{cr1}$=1.13 Ωcm² $R_{cr2}$=0.48 Ωcm² $V_0$=0.572 V.

## Results for polycrystalline Si cells

The parameters are: $I_{sc}=0$, $V_T=25$ mV, $\rho_S=0.13\ \Omega/\text{cm}$, $I_{01}=1.48\times10^{-12}$ mA/cm². To obtain $R_{loc}$, the pseudo-random value $dR$ has been chosen as a percentage of $\bar{R}$, which is set equal to 0.5 Ωcm². $V_0$ and $R_{cr}$ have been varied to obtain an appropriate fit of experimental data and to have the same voltage in correspondence of the two busbars.

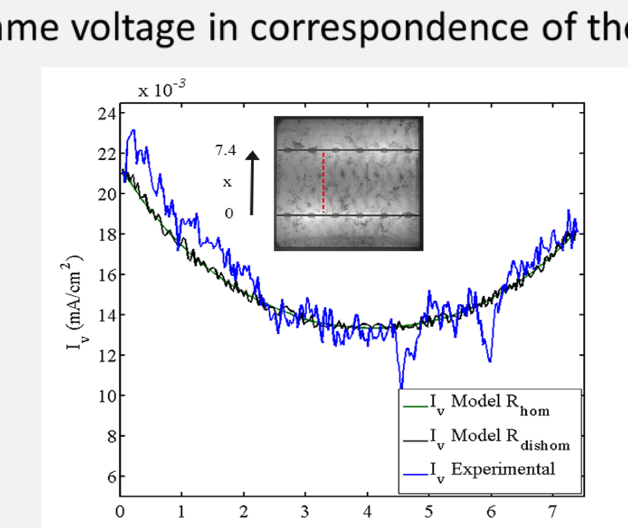


FIG. 9. Vertical current for an intact cell. $V_0$=0.58 V, $R$=0.5 Ωcm², $dR$=10%.

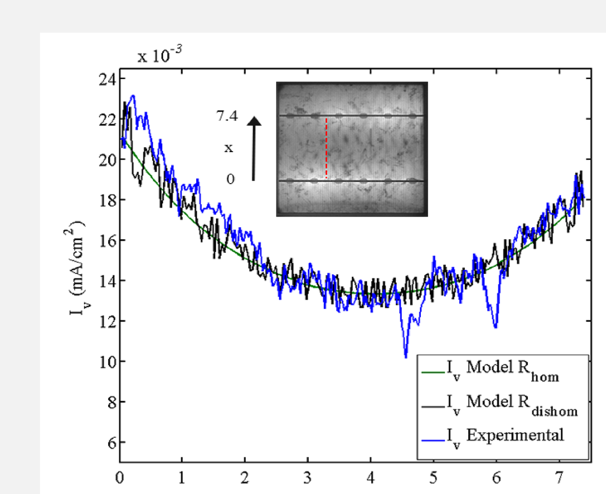


FIG. 10. Vertical current for an intact cell. $V_0$=0.58 V, $R$=0.5 Ωcm², $dR$=30%.

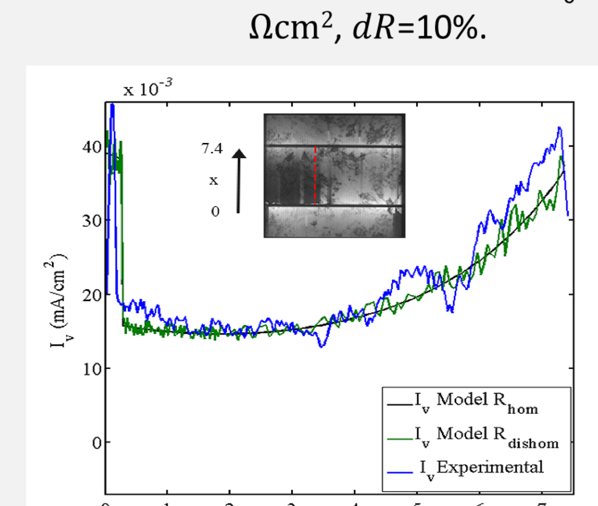


FIG. 11. Vertical current for a cracked cell. $R_{cr}$=1.4 Ωcm², $dR$=30%.

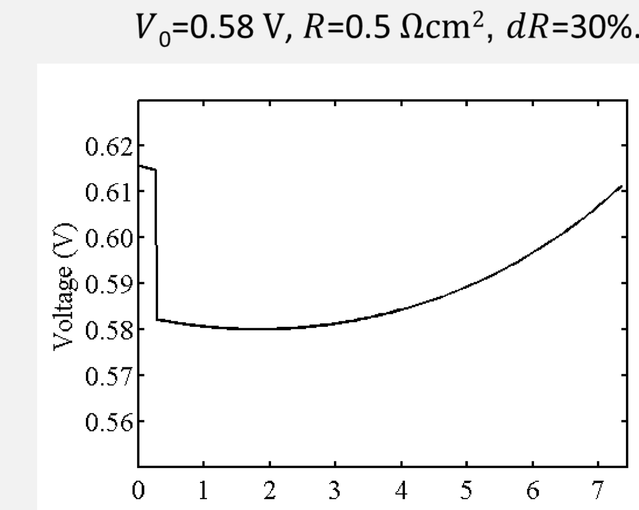


FIG. 12. Voltage for the cracked cell considered in Fig. 11.

## Conclusions

- The extension of the one-dimensional model for current distribution to the presence of cracks allows considering the coupling between thermo-mechanical field and electric one.
- The proposed method can be used to interpret the relation between voltage discontinuity and crack opening displacement at crack faces.
- In monocrystalline Si cells the influence of crack opening on the electric response is evident. In loaded conditions the value of $R_{cr}$ significantly increases (Figs. 7, 8).
- The polycristalline case is more complex due to a voltage fluctuation caused by the contemporary presence of defects and dishomogeneity of Si grains.
- The amplitude of the variation term, $dR$, is about 30% of $\bar{R}$ to match experimental tests.

**References:**

[1] D. Grote. Analyses of silicon solar cells and their measurement methods by distributed, circuit simulations and by experiment PhD thesis, University of Konstanz, Germany, 2010.

[2] M. Paggi, M. Corrado and M.A. Rodriguez. A multi-physics and multi-scale numerical approach to microcracking and power-loss in photovoltaic modules. Composite Structure, 95: 630-638, 2013.

[3] O. Breitenstein and S. Rißland. A two diode model regarding the distributed series resistance. Solar Energy Materials and Solar Cell, 110: 77-86, 2013

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