A computational method to simulate thermo-oxidative degradation phenomena of poly(ethylene-*co*-vinyl acetate) used in photovoltaics

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Poly(ethylene-*co*-vinyl acetate) (EVA) is usually used as encapsulant material of solar cells in photovoltaic (PV) modules. EVA layers act not only as a physical barrier against environmental agents, but also provide mechanical support, electrical insulation and serve as a glue for the other layers composing the module. EVA is an organic copolymer that undergoes degradation under UV exposure and absorption of moisture and oxygen from the external environment. Moreover, the high working temperature of modules (up to 85°C) accelerates the degradation process of the encapsulant.

The repeating units of EVA are ethylene and vinyl acetate. The degradation of the first unit produces unsaturations (double bonds between carbon atoms –C=C–) and carbonyl bonds (>C=O) after reaction with oxygen, while vinyl acetate decomposes giving, in addition to carbonyl bonds and unsaturations, free acetic acid. The encapsulant degradation is related to the loss of performances in PV modules and appears through the discoloration of the area exposed to sunlight, the damaging of electrical connections between silicon cells and the breaking down of the layered module structure. A general overview of degradation phenomena in a PV module is summarized in Figure 1.

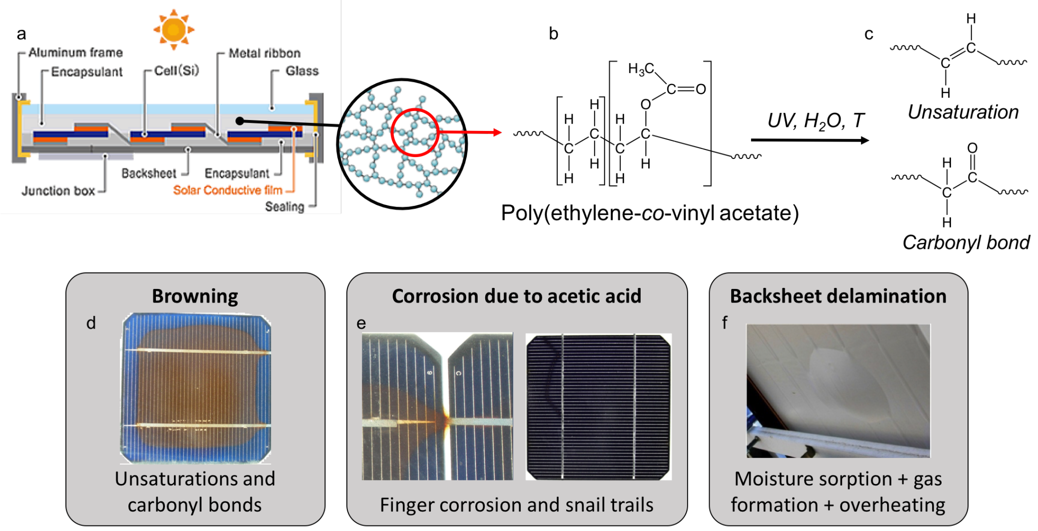

Figure 1: **a** Schematic representation of the layered structure of a PV module; **b** chemical structure of EVA copolymer; **c** degradation products; examples of: **d** browning, **e** corrosion due to HAc (rust and snail trail), **f** backsheet delamination.

Unsaturations and carbonyl bonds are chromophore groups, or chemical bonds that absorb certain wavelengths of the visible light, and are related to one of the most common ageing phenomena in PV modules, i.e., *browning* [1]. Browning of the EVA layer appears as a darkening of the exposed surfaces and it limits the transmission of the sunlight, that is partially absorbed by the encapsulant layer, causing a decrease of PV cell performances.

Vinyl acetate units suffer deacetylation, or the loss of small molecules of acetic acid (HAc). HAc molecules can dissolve in the moisture absorbed from the external environment causing an acidic and aerobic environment that promotes debonding of EVA and the corrosion of the metallic grids present in the PV module, generally composed of aluminum or silver [2]. Rust-colored areas are typical outputs of corrosion, causing debonding of electrical connections. Silver shows, in addition, the characteristic phenomenon of *snail trails*, or the formation of dark strips above fingers, due to the presence of silver nanoparticles [3].

Finally, the absorbed moisture diffusing within the EVA layer, and the small molecules produced after degradation, in combination with the PV module overheating cause a blistering that leads to the backsheet delamination [4], facilitating the moisture ingress and then enhancing the deterioration of the module.

In this study, a finite element model is proposed for the comprehensive simulation of all the encapsulant degradation phenomena listed above. In particular, the complete set of partial differential equations describing the reaction-diffusion phenomena taking place in the polymer are considered. In this framework, two exogenous species, moisture and oxygen absorbed from the external environment, also considered.

The proposed numerical scheme provides a quantitative evaluation of the chemical specie concentrations in time and in space involved in the thermo-oxidative degradation of EVA and its related effects. Numerical predictions are compared with experimental data resulting from environmentally-aged PV modules and a remarkable good agreement is noticed. These encouraging results pave the way to the development of more predictive numerical schemes for the evaluation of durability and performances of PV modules.

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