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# The role of sodium in photovoltaic devices under high voltage stress: A holistic approach to understand unsolved aspects

Alessandra Colli*

*Brookhaven National Laboratory, Upton, 11973 NY, USA*

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ABSTRACT

The paper reviews the role of sodium in the degradation of PV devices under high voltage stress with the purpose to identify issues still not solved and to introduce a comprehensive method of investigation. If a limited amount of Na diffusion into the CIGS cell structure is beneficial for the cell performance, on the other side when moving in the module structure it could create unpleasant effects, like corrosion and shunts. Soda-lime glass with a concentration of sodium around 13–15% is widely used both as cell substrate and as front layer in PV modules. Glass is not a static material and Na movement is easily activated by different triggering causes (stress, voltage bias, environmental variables). This paper is considered a prelude to further research. For this reason, a methodological approach is outlined, with emphasis on the consideration that PV devices, such as modules, are complex systems of systems. Recalling methodological discussions both in system engineering and in risk analysis, the proposed approach emphasizes the importance to study such complex systems adopting a holistic approach, thus taking into consideration interactions between system components and the surrounding environment. Probabilistic risk analysis (PRA) is suggested as a valid method for representing and understanding the interactions between different system components and environmental factors, while studying system reliability and risks for electricity supply.

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## 1. Introduction

PV cells use different materials, which vary in composition, properties, and structure (crystalline or amorphous). Copper indium gallium (di)selenide (CIGS) and crystalline silicon (c-Si) are two examples. Into PV modules, cells interact with a lot of different components, activating physics-based and chemical reactions. Additional effects originate from the surrounding environment.

Moreover, the use of PV modules within arrays exposes them to a system voltage of 600–1000 Vdc, or even 1500 Vdc. In this case, if not properly protected, modules can undergo a degradation process with corrosive characteristics originating from the high voltage stress.

The aim of this paper is to summarize the present knowledge on the effects of sodium in CIGS and c-Si PV devices. Furthermore, it proposes a method to support and guide the study of reliability of PV devices towards better modeling possibilities (Fig. 1).

Recalling methodological discussions in the area of both system engineering and risk analysis, the proposed approach emphasizes the importance to study such complex systems adopting a holistic approach, which considers interactions between system components as well as between the system and the surrounding environment.

As stated by Haimes [1], "*by their nature, complex systems constitute to modelers, in many respects, black holes that can be penetrated by acknowledging our inability to directly uncover, understand, or predict their behaviors under different scenarios of emergent forced changes. We commonly lack sufficient knowledge to assess the causal relationships among the subsystems, and to compensate for this shortfall we revert to multiperspective experimentation aided by the ingenuity, creativity, and domain knowledge of experts, supported by the availability of databases*".

The scope is to establish the basis for a comprehensive approach to study PV systems that could ultimately lead to a better understanding of the *black hole* PV module. In conclusion, the methodological approach points at the use of probabilistic risk analysis (PRA) as a valuable tool to model the interactions between different system components and identify fault propagation pathways for an enhanced vision on the reliability of PV systems.

* Tel.: +1 631 344 2666.
*E-mail address:* alessandra.colli@gmail.com.

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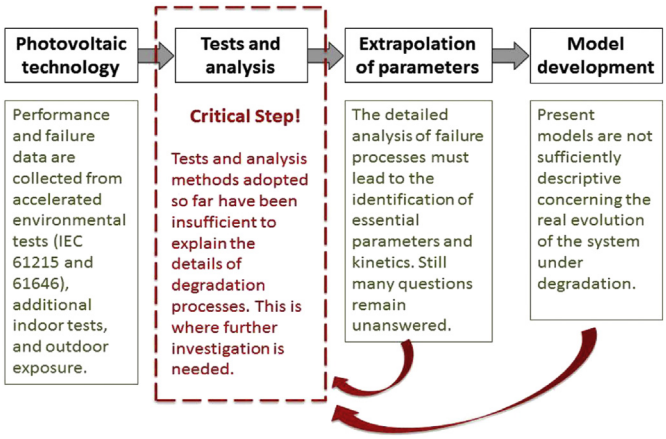


**Fig. 1.** Understanding parameters and kinetics that characterize certain degradation processes is fundamental to reliability of PV devices. Obtaining good reality-matching models will help to answer unsolved issues such as the definition of the limits for an acceptable level of defects for PV cells and modules.

## 2. Sodium movement in glass: soda lime silica glass for PV modules and cell substrates

Soda lime silica glass (SLSG) is used both as substrate to grow CIGS thin-film PV material and as front layer for PV modules (Fig. 2). Normally SLSG is low-iron float glass with thickness $\geq$ 3.2 mm, proved for stress and fatigue [2] and having $SiO_2$ around 70–73%, $Na_2O$ around 13–15% and CaO around 9% as main components, plus other minor elements. Sodium is the component with the highest ion mobility rate under stress at moderate temperature.

### 2.1. Mechanical and compositional stress

The motion of sodium ions is observable in SLSG at moderate temperatures, and under mechanical static stress. This stress condition, which is reversible, generates a current proportional to the stress itself, indicating that carriers of positive charge migrate from regions of compression to regions of dilatation [3]. The same effect originates from stress in the SLSG molecular structure.

The extreme homogeneity of glass, along with the elevated strength of its covalent cohesive bonds, causes a huge stress concentration in a nano-region around small mechanical defects [4].

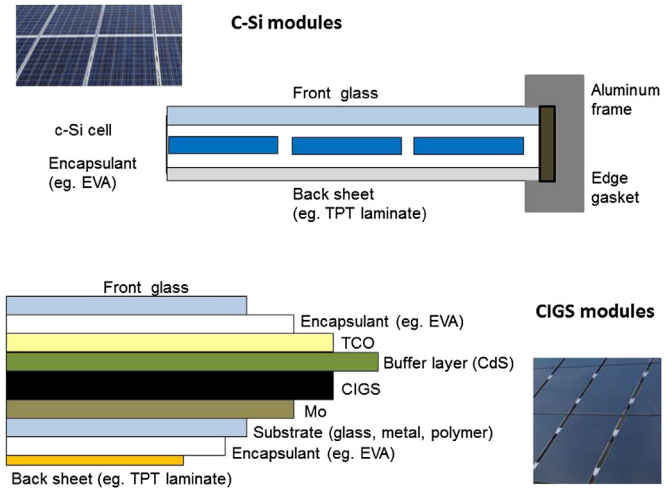


**Fig. 2.** Structure of c-Si and the CIGS modules.

Sodium, as well as potassium, is normally added to glass with the purpose of reducing the melting temperature, while on the other side it increases the predisposition to leaching. Sodium leaching derives from long-term exposure of glass to liquids or vapors, like water. This can cause ion exchange reactions and facilitate $Na^+$ ions migration to the surface of the glass, causing cloudiness or haze on the surface. SLSG water diffusion leads to the formation of alteration layers by selective leaching of alkali ions. Surface hydrated layers on SLSG show the substitution of sodium ions by hydronium $H_3O^+$. This process creates a compressive stress on the glass surface due to the difference in the volume of the exchanged ions [4]. This investigation proved that also a strong stress gradient can induce a very fast Na migration towards the tensile direction of the gradient [5]. The corrosion effect of SLSG in contact with a specific liquid has been extensively studied [4,6] and it is dependent from temperature, pH, and composition of the liquid. It has been verified that laying a silicon dioxide coating on the glass surface can limit the chemically-driven sodium migration created by the reaction with water.

Alkaline earth oxides such as CaO and MgO are usually added to improve alkali leaching resistance and chemical durability of glass [6]. They slow the sodium ion mobility by creating high field strength on their location.

However, the situation is still not well defined in the presence of moisture, when a nano-layer of water is laid down on the glass surface. This specific case requires studying complex patterns and the particular thermodynamics of the system. Additionally, although these reactions are known to be strongly influenced by the local stress state, the accurate study of their behavior at elevated tensile stresses is still missing and is the subject of a strong debate [4].

### 2.2. Electric field and temperature

Thermal effects in glass capable to activate Na movement are associated with electron or proton beam exposure [7,8], voltage bias, photoionization, intense optical radiations from lasers and UV radiation [9]. UV radiation could create a field supporting ion movement into the glass [9]. Quartz glass is usually made from pure silica (mainly fusing $SiO_2$) and its purity minimizes interaction with UV. However, standard glass has additives that can absorb or disperse UV; the optical transmission of SLSG is on average around 90% for wavelengths above 400 nm [10].

It is demonstrated that all alkali ions migrate under an electron beam with the rate of the migration dependent on the current density; this indicates changes of glass composition. The ions migration effect has been considered to depend on the temperature change and the creation of an electric field following the exposure to the electron beam [11]. However, the two effects are normally considered together as their mutual dependence makes it difficult to clearly separate the outcomes. The amount of trapped electrons is linked to the electronic structure of the solid, and in particular to the number of defects in the structure and the energy level of traps.

The mechanism leading to alkali ion migration is explained as belonging to all alkali ions contained in the glass, as they all migrate [8]. The energy that activates the diffusion of the alkali ions consists of two terms: 1) dissociation or vacancy formation, and 2) displacement energy. Once ionized by the electron beam, the alkali atoms can move away from their original location following the pathway of the electric field, till recombination or till encountering a higher energy barrier. In this process, atoms find themselves in a different situation and have their activation energy lowered by weaker bonds or by the alkalis nearby their migration paths. This originates a kind of chain-reaction that activates an always higher number of alkali ions, up to a critical value corresponding to the