1 Introduction

The potential of solar energy is now well established, yet photovoltaic technologies struggle to prevail in the energy landscape. There are problems with both the enhancement of the performances of the cells and the costs. In this context, thinning the different device layers is being envisaged in order to reduce the total costs of solar cells while maintaining their good performance. As the thicknesses of the different layers in a solar cell can be less than 100 nm in some cases, the importance of an optical design becomes critical for achieving competitive performances. Since photovoltaic solar cells are optoelectronic devices, mastering the interaction of light and matter is of utmost importance. Indeed, the behavior of the light in very thin-film layers is completely different than in bulk materials. Furthermore, even if the semiconductor materials used currently in the different technologies are quite good absorbers, the need for improved performances means that integrating photonic structures in the devices are increasingly envisaged. Thus, the photonic concepts must be considered as potential solutions to improve the photonic absorption of thin-film devices.[1]

The development of thin-film solar cells requires controlling the light inside the cell. Such control is not only useful to increase the efficiency but also for designing new kinds of solar cells such as "transparent and colored solar cells," which is interesting for building integrated photovoltaics. In these thin-film solar cells, the apparent color and the transparency are given by their reflected and transmitted spectra, taking into account human eye sensitivity. One can also use the light-management concept, i.e., using Bragg mirrors,[2] diffraction gratings,[3] surface plasmonic effects,[4] or photonic crystals[5] to optimize the cell performances.

The investigations into the improvement of solar cell efficiencies have also led researchers to look for new materials with optimized bandgaps that can absorb a large part of the solar spectrum. The mechanical flexibility, the low specific weight, and the color properties of these emerging materials open wide fields of applications. The optimization of the morphological and/or optical and/or electrical properties of these materials is thus a crucial issue today, along with the environmental and geopolitical issues (scarcity of elements, toxicity of elements, imported materials). It is obvious that all of the studies and progress have been and will be made keeping in view the final application. The applications are numerous—ground or building integration, mobile applications, and so on—and suggest that each technology can meet a given problem i.e., cost, efficiency, flexibility, color, and so on.

The new solar cell architecture is thus relatively complex and requires a thorough understanding of the materials' behavior, involving accurate knowledge of the electrical, optical, and structural properties of these materials. This Spotlight focuses on optical tools, both experimental and simulation, to improve the optical design of the thin-film solar cells. This approach provides a correct prediction and validation of device performance. Obviously, this work, directly related to the fields of optics and photonics, also involves the use of a more

comprehensive set of tools that includes structural (e.g., electronic microscopy, x-ray scattering, x-ray photoelectron spectroscopy, ultraviolet photoelectron spectroscopy, and atomic force microscopy) or electrical techniques (e.g., conductance measurements, Hall effect, and deep-level transient spectroscopy), which also contribute to the improved elaboration of the solar cells. Some of these techniques, although not described in this book, will be mentioned as related to our studies on solar cells.

2 Materials and Solar Cells

2.1 Generations of solar cells

Today, there are many types of solar cell technologies that use either organic or inorganic materials, or both. Research of photovoltaic solar cells is booming, not only on hybrid solar cells and thin-layer cells, but also on the new perovskite solar cells. Figure 1 illustrates the conversion efficiency of the best research solar cells worldwide, published by National Renewable Energy Laboratory (NREL; see Fig. 1), which can be compared with today's performance ranking chart. In this context, new materials for photovoltaics have emerged in recent years (inorganic nanostructures, organic materials, kesterites, perovskites, transparent conducting oxides, and so on) to increase cell performance while reducing technological costs.

Classical photovoltaic technology relies on the p-n semiconductor junction; the silicon solar cell is the example of what has been called first-generation photovoltaics. This technology, based on the preeminent silicon microelectronics technology, is at present the most industrialized and the most commonly used photovoltaic technology in the world. Nevertheless, a number of limitations prevent it from reaching the status of a really low-cost technology, such as the large amount of Si material needed for complete absorption of the incident light, the indirect bandgap, and the competition over this material with the more successful microelectronics market.

To overcome these problems, the second generation of photovoltaics proposed using materials with high absorption coefficients, allowing thin-film configurations and thus reduced use of materials. Mention may be made first of CdTe, CIGS (copper-indium-gallium-sulfide), kesterites (CZTS or copper-zinc-tin-sulfide), and GaAs, which are all direct bandgap materials, and second of amorphous silicon and microcrystalline silicon (indirect bandgap). CdTe, CIGS, and CZTS photovoltaic materials are deposited in the form of polycrystalline thin films. CdTe, CIGS, and CZTS photovoltaic devices are deposited as a polycrystalline thin film, offering very competitive manufacturing costs but limited efficiencies due to a high defect density. Silicon thin films are based on hydrogenated amorphous and hydrogenated microcrystalline silicon (a-Si:H, μc-Si:H), which are usually deposited by plasma-enhanced chemical vapor deposition. The best efficiency for this technology is obtained with a triple junction.[6] Epitaxial GaAs solar cells, on the other hand, can have very high efficiencies,