Plant epidermal structures for enhanced sunlight harvesting in solar cells

Ruben Hünig, Adrian Mertens, Michael Hetterich, Michael Powalla, Uli Lemmer, Alexander Colsmann, and Guillaume Gomard

A broadband, omnidirectional light-harvesting layer replicated from plant surfaces improves light management in thin-film solar cells.

Achieving efficient sunlight collection over an entire day is a demanding task for stationary devices. The problem becomes even more complex when the harvested photons have to be absorbed within layers limited to a few hundreds of nanometers (or less) in thickness. This optical challenge can be addressed by a light in-coupling element that operates over a broad angular and spectral range, and that is also capable of trapping the collected light to maximize photon-to-electron conversion efficiency.

Solutions developed in the silicon photovoltaic (PV) industry that rely on microscale pyramidal texturization of the absorber for light trapping are not suited to systems made of thin layers. In contrast, experimental nanophotonic approaches employing, for example, planar photonic crystals and diffraction gratings or plasmonic structures have been successfully implemented within or next to the active layer of thin-film solar cells.1,2 An alternative route consists of integrating a light-harvesting, polymer-based coating onto the planar thin-film stack that does not affect charge-collection properties and could enable fully flexible devices.3 In this context, biomimetic structures—mostly subwavelength and inspired by moth eyes—exhibit broadband omnidirectional anti-reflection (AR) but lack the light-trapping contribution.4

For this reason, we have replicated structures that decorate plant surfaces to produce a light-harvesting layer that combines all the previously mentioned attributes.5 More specifically, we have focused on rose petal epidermal cells, which are densely packed and convexly shaped, and display a height and width of few tens of microns (see Figure 1).

Figure 1. Schematic illustration of the replica approach based on plant epidermal cells. Yellow arrows show light in-coupling, which is enhanced in the solar cell as a result of its bioinspired microstructured coating. KIT: Karlsruhe Institute of Technology.

The structures that we have replicated improve light management in two ways. First, the high packing factor and aspect ratio (i.e., the ratio of the length of the vertical axis to the base diameter) of the cells confer excellent AR properties, regardless of the wavelength or the angle of incidence (AOI). The main light-collection effect of the conical microstructures is fully described by the principles of ray optics and originates from the ability of the reflected light to bounce back onto a neighboring epidermal cell. Shallow nanocorrugation on the surface of the epidermal cells assists the light in-coupling mechanism to a lesser extent. Second, each epidermal cell acts as a microlens that broadens the distribution of the light-propagation angle. Thus, the optical path length is enhanced in the underlying solar cell, which results in a higher photon absorption probability and device efficiency.

Continued on next page
Before testing our method in operating PV devices, we first analyzed the optical properties of replicas obtained from different plant species. We realized this step by pouring transparent polymer directly onto the biosurfaces, resulting in an exact copy of the micro/nanostructures over a few square centimeters. We determined that the aspect ratio of the epidermal cells was the essential parameter for achieving low reflection at high AOI (see Figure 2). In fact, the integrated front-side reflection could be kept as low as 7% for an AOI of 80° by using an aspect ratio of 0.6, as found in rose petals.

Owing to its remarkable AR properties, we selected the rose petal replica and imprinted it into a transparent polymer layer positioned atop a substrate comprising state-of-the-art organic solar cells. The latter were based either on PTB7-Th:PC$_{71}$BM-type or on PDTP-DFBT:PC$_{61}$BM-type polymer active layers absorbing up to 800 and 900 nm, respectively. Notably, we measured a relative efficiency enhancement (with respect to an unpatterned device) of up to 13% under normal incidence, which we attribute solely to the optical effects. The most important benefits were captured for high AOI (see Figure 3). Indeed, we demonstrated a short-circuit current density enhancement of 44% at AOI $= 80\degree$, that is, more than 3× higher than that obtained at AOI $= 0\degree$.

In summary, we have shown that plant epidermal cell replicas can be used as efficient light-harvesting elements that

Continued on next page
satisfy both the spectral and angular requirements imposed by PV. As these structures can be imprinted via a one-step process in a variety of materials and subsequent to solar cell fabrication, our approach is cost-effective, versatile, and can easily be applied to any PV technology. The plant replica structures can also be exploited for improving light management in other technologies. For example, they can be applied to organic LED substrates to enhance their light-extraction efficiency. Recent reports have shown that structural disorder can strongly impact the optical properties of photonic biostructures as well as artificial and complex light-harvesting designs.\textsuperscript{6,7} Consequently, we are now conducting a numerical analysis of the various types of disorders encountered in rose epidermal cells, which will enable us to fine-tune our plant selection criteria.

R.H. and A.M. acknowledge financial support from the Karlsruhe School of Optics and Photonics. A.M., A.S., and A.C. thank the Federal Ministry of Education and Research for funding under contract 03EK3504 (Project TAILKUS), and G.G. acknowledges the support of the Helmholtz Postdoctoral Program (FE.5370.0169.0008). The authors thank Martin Theuring (NEXT ENERGY – EWE Research Centre for Energy Technology), Raphael Schnager and Benjamin Fritz (Light Technology Institute, Karlsruhe Institute of Technology, KIT), Hendrik Hölscher (Institute for Microstructure Technology, KIT), and Joachim Daumann (Botanischer Garten Karlsruhe). The experiments were performed using facilities at the Light Technology Institute, the Institute for Microstructure Technology, and the Zoological Institute at KIT.

Author Information

Ruben Hünig, Adrian Mertens, Michael Hetterich, Uli Lemmer, Alexander Colsmann, and Guillaume Gomard
Karlsruhe Institute of Technology (KIT)
Karlsruhe, Germany
http://www.lti.kit.edu

Ruben Hünig is pursuing his PhD at the Light Technology Institute (LTI) at KIT on light-management structures for thin-film solar cells. His work currently focuses on plant surfaces as light-harvesting elements.

Adrian Mertens studied physics at KIT and is now doing his PhD at the LTI and the Material Research Centre for Energy Systems at KIT. The main focus of his work is the investigation of angle-dependent absorption in organic single and tandem solar cells as well as the impact of scattering layers on the performance of such devices.

Michael Hetterich is coordinator of the Thin-Film Photovoltaics Group at the LTI and the Institute of Applied Physics at KIT. His current research activities focus on the development and investigation of novel solar cell absorber materials as well as device modeling and optimization.

Uli Lemmer received a diploma degree from the RWTH Aachen University, Germany, in 1990 and his PhD from the University of Marburg, Germany, in 1995. In 2002, he was appointed a full professor and director of the LTI.

Alexander Colsmann heads the Organic Photovoltaics Group at the LTI and the Material Research Centre for Energy Systems at KIT. His further research interests include solar cells for building integration, perovskite solar cells, organic LEDs, printed electronics, printable electrodes, charge carrier transport, and electrical doping of organic semiconductors.

Guillaume Gomard is the group leader for the ‘Nanophotonics’ activities at the LTI. His current research encompasses the analysis of disordered photonic crystals, scattering stochastic ensembles, and hierarchical bio-inspired photonic structures and their implementation within optoelectronic devices for enhanced efficiencies.

Michael Powalla
ZSW
Stuttgart, Germany

References


© 2016 SPIE