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PHOTOVOLTAICS: Short-wave infrared cameras characterize thin-film solar cells

Electroluminescence analysis accelerates development and improves quality of thin-film photovoltaics

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Copper indium gallium diselenide ([CIGS](#)) thin-film cells for solar energy generation offer decisive economic advantages by enabling lightweight and highly flexible photovoltaic (PV) modules. They consume less energy and materials during fabrication and they yield good energy output across a broad spectrum, even in unfavorable weather conditions. Analysis of their inherent near-infrared electroluminescent radiation with sensitive indium gallium arsenide (InGaAs) short-wave infrared ([SWIR](#)) cameras allows a detailed structural examination to shorten the development cycle of new module types and support module manufacturing through components and facilities that meet high reliability, high efficiency, and long-term operability.

The CIGS technology

Thin-film solar cells are made of semiconductor layers of just a few micrometers thick. Because they are so thin, they can be integrated into functional and decorative building elements such as roof shingles and roofing tiles, as well as entire facades of buildings, glass domes, and air wells. As long as solar-enabled roof shingles provide the same degree of weather protection and durability as those made of traditional bitumen, they open up new ways of energy generation, not just on saddle roofs, but also on complex roof shapes (see Fig. 1).



FIGURE 1. Flexible thin-film solar cells can be mounted on curved-shaped roofs and building facades such as the tower shown in the background.

Among the materials currently in use for thin-film cells are crystalline silicon (Si), copper indium gallium diselenide (CIGS)—or gallium-free CIS, as well as cadmium telluride (CdTe). All these already offer interesting market opportunities, although their long-term success will depend on achieving higher efficiency and lower cost.

Compared to cells and modules made of crystalline silicon, which has reached impressive maturity over the last 25 years, not much is known about the behavior of thin-film solar cells under widely varied light and weather conditions, despite their advantages. Nonetheless, some powerful and useful test methods can be used for detailed structural investigation of thin-film modules, which could substantially accelerate their market introduction and improve manufacturing quality.

Electroluminescence: weak but meaningful

One of the most important phenomena occurring in all functional photovoltaic cells is weak electroluminescence (EL) caused by an external bias voltage. A solar cell can be regarded as parallel interconnection of numerous *p-n* junctions, into which the external bias voltage injects electrons that, in part, recombine with the available holes. The surplus energy exits as photons whose wavelength depends on the bandgap of the cell's absorber material (see table). The CIGS thin-film modules have bandgap energies ranging from 0.9 to about 1.7 eV, depending on the ratio of indium and gallium. A higher share of indium will reduce the bandgap energy, more gallium will increase it.

Properties of commercial materials for thin-film solar cell types			
Type	Material	Bandgap (eV)	Wavelength (µm)
CdTe	Cadmium telluride	1.4	0.8
CIGS	Copper indium gallium diselenide	0.9 to 1.7*	1.3 to 0.7*
CIS	Copper indium diselenide	0.9	1.3
Si	Crystalline silicon	1.2	1.2
For comparison: VISNIR camera in InGaAs technology			0.4 to 1.7
* depending on the ratio of indium/gallium			

The wavelength of the resulting EL ranges from 800 to about 1200 nm, which happens to be exactly the spectral area in which SWIR image sensors exhibit the highest sensitivity. To cover even larger band gaps well into the visible realm, and to enable parallel imaging in the visible and the IR areas, image sensors are tending to larger bandwidths. With appropriate fabrication techniques this yields VISWIR sensor arrays with high spectral sensitivity at wavelengths between 0.4 and 1.7 µm.

The intensity of a solar cell's EL emission is determined by the concentration of electrons and holes, which increases exponentially with bias voltage, as expected from the typical I-V characteristic of a diode. Thus, measuring the EL emission intensity of a solar cell

will yield valuable, spatially distributed details of mechanisms that could substantially diminish the power yield of a solar module. Among these mechanisms are locally reduced diffusion lengths, microfissures within the cell, parallel-resistance effects, and contamination of the semiconductor layers.

In a CIGS thin-film solar cell monolithically connected in series to a neighboring cell there are three critical areas that might be affected by humidity penetrating under the transparent and conductive oxide layers (TCO) and thereby diminishing the cell's properties (see Fig. 2). All these effects can at some point cause a significant loss of power.

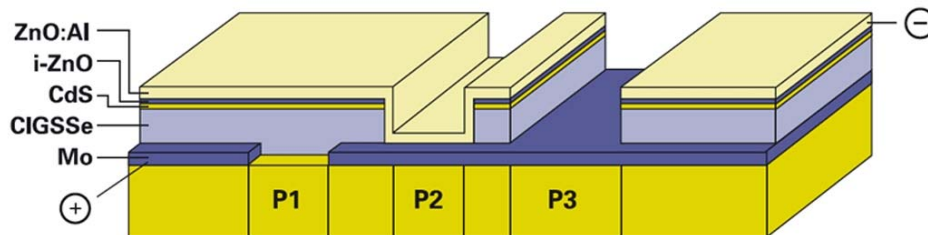


FIGURE 2. In a CIGS thin-film solar/PV cell (shown in cross section as a monolithic series interconnection of two individual cells) there are three areas where humidity can penetrate under the TCO layers. First, in the area marked P1, there is a lowered parallel resistance (shunt R_{sh}). Second, at P2, there is a corroding zinc oxide/molybdenum (ZnO/Mo) contact, and third, at P3, there is a rising series resistance R_s due to corrosion of the molybdenum layer.

The EL image method described here enables a quick and accurate diagnostic of the entire module at one time (see Fig. 3). This can be of utmost value in R&D, as well as in the production of thin-film modules.

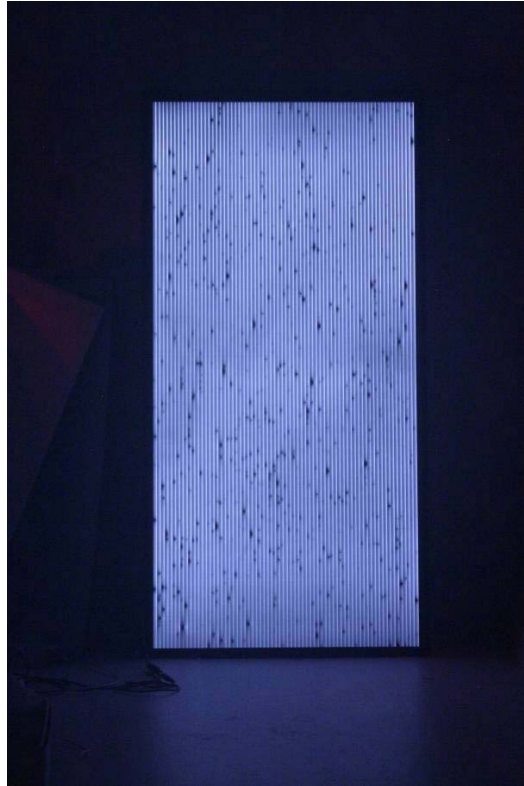


FIGURE 3. A sensitive SWIR camera captures electroluminescent emission of a CIGS panel. Clearly visible is the pinstripe pattern with dark local imperfections indicating possible local short circuits. (Image courtesy Photovoltaik-Institut, Berlin, Germany)

InGaAs SWIR imagers

In a SWIR InGaAs imager for wavelengths between 0.9 and 1.7 μm the IR photodiodes are built on an indium phosphide (InP) epiwafer substrate that is usually more than 125 μm thick (see Fig. 4, left). Because this technology is not particularly well suited for realizing readout circuits, the photodiode array, together with its readout integrated circuit (ROIC), is flip-chip mounted via indium bumping on a CMOS chip. The solar cell's exposure is then from the back, through the substrate. This however absorbs all light from visible wavelengths to 0.9 μm .

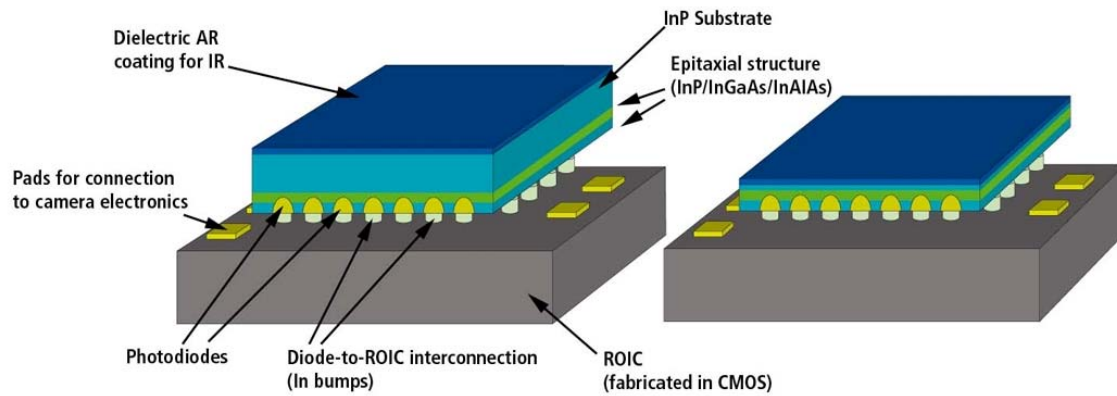


FIGURE 4. Thinning the substrate will turn an InGaAs SWIR imager (left) into a broadband VISWIR sensor (right).

To prevent this loss, the substrate is thinned after flip-chip mounting—as is routine for standard InGaAs sensors to improve response—but here is applied more thoroughly. In order to safely remove the substrate without damaging the InGaAs detector, additional layers of InGaAsP are inserted just below the photodiodes. They function as etch stops within the InP area. A hydrochloric acid (HCL) etch then selectively removes the InP epi-substrate exactly up to the InGaAsP etch stop layer. This effectively thins the sensor chip down from 125 to just 5 μm (see Fig. 4, right), making it transparent to light in the visible realm and opening up the sensor to a broad wavelength coverage from 0.4 to 1.7 μm .

The observed electroluminescent emission is very weak. This places high demands on the measuring technique used. Accurate measurements will necessitate long integration times. In this regard, the dark current of the image sensor sets a limit, which can be detrimental, especially when carrying out more accurate examinations in the design of novel photovoltaic cells and modules. Dark current can be reduced by using low-noise sensors, such as the Xenics XEVA camera, and by one- or multistage thermoelectric cooling of the sensor array (see Fig. 5). This will enable a 100 times longer integration time and prevent weak local imperfections from getting unnoticed in the noise floor.

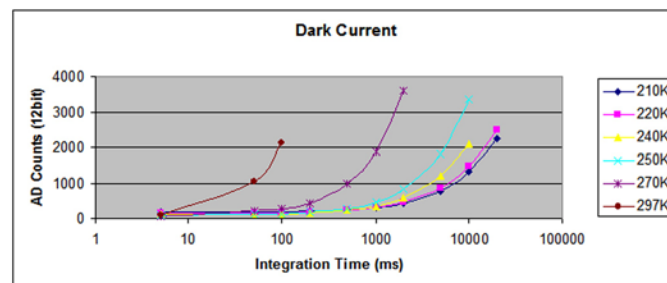


FIGURE 5. One- or multistage thermoelectric cooling substantially increases the sensitivity of InGaAs sensors.

Meaningful measurements

The significance of electroluminescent radiation in the near-IR—as captured by an SWIR camera—is easily demonstrated (see Fig. 6). At the outset of a corrosion test (left) the module still radiated across the entire surface. After an extended 1000-hour hot-steam treatment the sample suffered substantial TCO corrosion along the edges due to its suboptimal mounting (right). The lowering of the shunt resistors R_{sh} , plus rising series resistances R_s practically cut the cell's power yield in half.

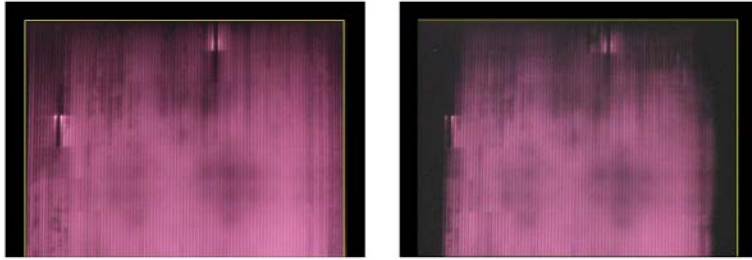


FIGURE 6. An electroluminescence analysis demonstrates the power loss in a solar cell (left) due to TCO corrosion after 1000 hours of hot steam treatment (right). (Courtesy of Photovoltaik-Institut, Berlin, Germany)

An analysis of the weak electroluminescent emission given off by photovoltaic cells and modules using sensitive IR cameras substantially supports development of thin-film solar cells, as well as their integration in functional carrier structures and quality assurance during their manufacture. This will serve the overall goal of reducing the historical lead of traditional solar cells in favor of thin-film cells and developing novel power supply solutions based on freely available solar energy.

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