



# Flexible solar cells for clothing

Integration of flexible solar cells into clothing can provide power for portable electronic devices. Photovoltaics is the most advanced way of providing electricity far from any mains supply, although it suffers from the limits of ambient light intensity. But the energy demand of portable devices is now low enough that clothing-integrated solar cells are able to power most mobile electronics. We introduce clothing-integrated photovoltaics, their scope and limitations, the status of flexible solar cells, charge controller and system design, as well as prototype solutions for various applications.

Markus B. Schubert\* and Jürgen H. Werner

*Institut für Physikalische Elektronik, Universität Stuttgart, Pfaffenwaldring 47, D-70569 Stuttgart, Germany*

\*E-mail: [markus.schubert@ipe.uni-stuttgart.de](mailto:markus.schubert@ipe.uni-stuttgart.de)

Over the past ten years, photovoltaic power generation has grown rapidly worldwide<sup>1</sup>, and is starting to contribute a noticeable amount of electricity production to public grids, especially in Japan<sup>2</sup> and Germany<sup>1</sup>. Electric energy from solar cells is still too expensive to compete with established power plants, but photovoltaic island systems<sup>3</sup> located far from any grid connection have been economically successful for many years<sup>4</sup>. The size and output power of such island systems varies over a considerable range from several kilowatts to less than one watt. They have a common layout comprising storage batteries and power conditioning electronics, as well as the solar modules themselves.

We discuss here a specific type of island system, namely carry-on photovoltaics integrated with clothing. Jackets, coats, backpacks, accessories, even T-shirts and caps, provide a much larger area for *integrated photovoltaics* (ipv) than the ever-shrinking portable devices themselves. Nowadays, consumers frequently use ubiquitous

entertainment, voice and data communication, health monitoring, emergency, and surveillance functions, all of which rely on wireless protocols and services. Consequently, portable electronic devices like mobile phones, mp3 players, personal digital assistants (PDAs), cameras, global positioning systems (GPS), or notebook computers need a wireless, mobile, and sustainable energy supply in order to overcome the constant problem of batteries running out of power when most urgently needed.

As a result of their steadily decreasing power demand, many portable devices can harvest enough energy from clothing-integrated solar modules<sup>5</sup> with a maximum installed power of 1-5 W. Fig. 1 shows a recent prototype of a winter outdoor jacket with integrated solar modules that deliver a maximum output power of 2.5 W. This clothing-integrated photovoltaic system is designed to power an mp3 player, and after three hours under full sun provides more than 40 hours of music without any additional illumination.



Fig. 1 Prototype of a winter outdoor jacket with ipv. This jacket was developed by Maier Sports<sup>6</sup>, with support from the Institut für Physikalische Elektronik and other partners in the German SOLARTEX project<sup>7</sup>. The jacket was first presented in Munich at the International Trade Fair For Sports Equipment and Fashion (ISPO) in January 2006. It comprises nine amorphous Si solar modules from Akzo Nobel<sup>8</sup> with a maximum power output of 2.5 W under full sun. (Courtesy of Maier Sports.)

Since 2000, design studies on solar cells integrated into clothing have been regularly presented at fairs and exhibitions on 'smart textiles' or 'smart clothes', e.g. the Avantex fairs in Frankfurt, Germany or the Nixdorf Innovation Forum. In 2000, Hartmann *et al.*<sup>9</sup> presented a vision of high-tech fashion including the use of photovoltaic power. A first systematic approach to the layout of complete ipv systems was published by Werner *et al.*<sup>10</sup>. Although consumers and the clothing industry seem to be very interested in clothing-integrated photovoltaics, the advent of real products in the market has been hindered and delayed by the limited availability and performance of flexible solar cells.

From a customer point of view, an ipv system should be easy to use, comfortable and reliable, offer a universal socket for the countless different charging adapters and devices, and, of course, deliver plenty of energy at an affordable price. If parts of the system need to be visible, they should be attractive and integrate well with the particular design of the garments. Connecting wires, charge controllers, and batteries ought to be invisible, lightweight, and maintenance free. As an additional requirement, clothing with integrated electronics and photovoltaics should be as washable as every other textile.

The most decisive and restricting demand, however, is the *conformal flexibility* of solar cells used for clothing integration. Existing cells on plastic or metal foils with protective laminates can only bend in one direction rather than exhibiting full conformal flexibility like a woven textile.

We review various flexible solar cell technologies, with a more detailed focus on amorphous Si (a-Si) and protocrystalline Si (pc-Si), where protocrystalline denotes a film structure right at the edge of crystallinity. Flexible, single-crystalline Si (c-Si) cells are presented, and ipv prototypes are described. The area demand for ipv is examined, as well as issues of optimizing system design and clothing integration.

## Overview of flexible solar cell technologies

The interest in flexible solar cells is steadily increasing, since high-altitude platforms, satellites for telecommunications, and deep-space missions would benefit from rollable or foldable solar generators. Cars, aircraft, and various electric appliances could also cover part of their power demand from ambient illumination of their free-form cases. The integration of photovoltaics with textiles is not only interesting for powering portable devices, which we address here, but also opens a wealth of opportunities for the integration of electronic features with architectural fabrics.

The US company United Solar Ovonic manufactures flexible triple-junction a-Si-based modules on steel foil for building integration<sup>11</sup> with a total power output above 45 MW per year<sup>12</sup>. Since these modules are designed for long-term outdoor stability, the final laminates are comparatively rigid and not suitable for large-area clothing integration.

Current thin-film solar cells consist of a layer stack that is continuous in two dimensions and very thin in the third. Because of their planar substrates, these cells bend but do not crinkle. Solar cells have been formed on Cu wires for fabrics made of photovoltaic fibers<sup>13</sup>. Without a continuous planar substrate, however, the fibers arbitrarily move against each other, which gives rise to many problems like moving interconnects, shadowing, and cancellation of the electric output of single fibers. Considering all the unsolved problems of manufacture and interconnection of such photovoltaics fibers, we do not see 'woven solar modules' to be technically feasible in the foreseeable future.

Finding a compromise between the minimum total thickness and, hence, maximum conformal flexibility of ipv modules on the one hand, and washability, mechanical resilience, and durability on the other, is an important task that has not yet been solved for most of the flexible cell technologies described here.

A lot of hope is focused on organic and dye-sensitized solar cells that could, in principle, be printed on polymer foils. In a major breakthrough in organic solar cell technology, Brabec *et al.*<sup>14</sup> demonstrated bulk heterojunction cells with a conversion efficiency of 5%. The main challenge for all these organic and dye-sensitized cell concepts, however, is in their encapsulation and long-term stability. Organic and dye-sensitized cells work reasonably well in tightly sealed glass-glass packages<sup>15</sup>. For flexible cells, organic-inorganic multilayers can prevent moisture and oxygen permeation into the sensitive

electrode or dye materials<sup>16</sup>. For these solar cells, such barrier films must limit the permeation of water to less than  $10^{-8}$  g m<sup>-2</sup> day<sup>-1</sup>, which is two orders of magnitude less than required for organic light-emitting displays, and has not yet been achieved. Research goals also include enhancing the photochemical stability of the dyes and the absorption of visible light<sup>17</sup>. Further progress in these fields is needed before organic or dye-sensitized cells will be suitable for ipv applications.

Copper indium gallium selenide (CIGS) and copper indium sulfide (CIS) cells demonstrate their best performance on glass substrates, with a record efficiency of 19.5%<sup>18</sup>. Flexible CIGS cells reach efficiencies of up to 17.4% on steel foils<sup>19,20</sup>. A sophisticated barrier layer stack protects the CIGS heterojunction against impurity diffusion from the metal substrate<sup>21</sup>. Since polyimide (PI) substrates limit the deposition temperature to  $T_d < 450^\circ\text{C}$ , the efficiency drops to  $\eta \sim 11\%$ <sup>20,22,23</sup>. Fig. 2 displays some examples of CIGS solar cells and modules on metal and PI foils.

While all these data refer to co-evaporated CIGS, alternative deposition methods try to exploit the potential of low-cost, roll-to-roll deposition<sup>25-27</sup>. Presently, the solar cell efficiency, as well as the maturity of these manufacturing methods, clearly lag behind co-evaporation techniques.

When considering CIGS for ipv, however, the most serious drawback is the poor low-light performance. The material composition and electronic properties of CIGS fluctuate on a micrometer scale<sup>28,29</sup>, introducing local electric shunts into the heterojunctions that result in a high saturation current and deteriorate the low-light efficiency of CIGS solar cells.

Gemmer<sup>30,31</sup> has compared the intensity dependence of realistic models of CIGS, a-Si, and c-Si diodes, and evaluated their possible energy yield in various ipv scenarios. According to the results, CIGS can only compete with Si in outdoor applications. Virtuani<sup>28</sup> and coworkers have shown improved shunt control and low-light efficiency in CIGS cells. Whether this recent development will render flexible CIGS modules competitive for indoor use is still an open question.

The suitability of CdTe cells for ipv has not yet been studied, but Tiwari *et al.*<sup>32</sup> have achieved efficiencies of 8.6% for flexible CdTe cells.

In comparison with the material systems discussed above, flexible thin-film Si is a good choice for ipv, especially because of its good low-light performance. Well-optimized c-Si cells with edge isolation<sup>33</sup> exhibit a value of  $n = 1$  in Shockley's ideal diode equation ( $n$  may also be termed the emission coefficient or diode quality factor). This results in an almost ideal intensity dependence with an open circuit voltage drop of  $\Delta V_{oc} = -70$  mV per decade of the incident radiation, in contrast with  $\Delta V_{oc} = -130$  mV for pc-Si. Consequently, c-Si would be the preferred material for ipv, if it could attain similar flexibility as ultrathin pc-Si cells. At a deposition temperature of  $100^\circ\text{C}$ , our pc-Si cells achieve  $\eta \sim 5\%$  on low-cost polymer foils<sup>34,35</sup>. Flexible, single-crystalline c-Si transfer cells reach  $\eta = 14.6\%$ <sup>10</sup>.

### Flexible a-Si and pc-Si cells

The industrial development of flexible a-Si modules mostly targets the power market and tries to realize the cost advantages of roll-to-roll production. Several players are active in this field with differences in the maturity of their technologies. United Solar Ovonic was mentioned above; Fuji Electric<sup>36</sup> is constructing a large-scale production plant; Akzo Nobel<sup>8</sup> runs a pilot line for manufacturing modules on temporary substrates<sup>37,38</sup>; and XsunX<sup>39</sup> is beginning to develop transparent modules for lamination with architectural glass.

Smaller companies are more interested in small-scale applications like ipv. The Swiss company VHF technologies<sup>40</sup> is developing a-Si modules on  $50 \mu\text{m}$  PI or polyethylene terephthalate (PET) foils in cooperation with the University of Neuchâtel<sup>41</sup>, and delivers modules with a total thickness of only  $150 \mu\text{m}$ . Bailat *et al.*<sup>41</sup> have reported record efficiencies of  $\eta = 7\%$  for single a-Si cells on nanostructured PET, and  $\eta = 8.3\%$  for a double-stacked, so-called micromorph tandem cell. This comprises an a-Si cell on top of a microcrystalline Si cell. Iowa Thin Films Technologies<sup>42</sup> took up former 3M technology<sup>43</sup> in 1988. While the company is now focusing on military applications, it also produces a-Si modules<sup>44</sup> with a specified  $\eta = 3.5\%$  that we use for ipv demonstrators described later and shown in Fig. 12a.

Since research at our institute<sup>45</sup> develops solar cells to comply with the textile feeling of regular clothes like shirts, jackets, etc., we need

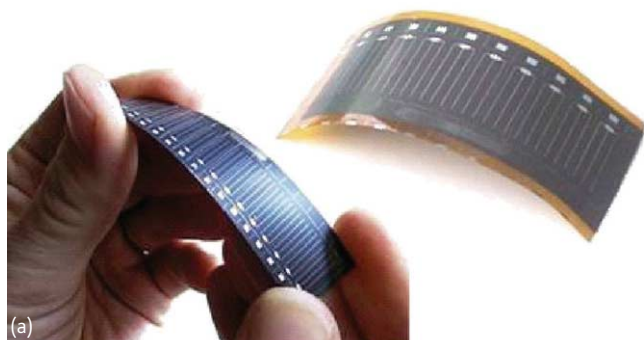


Fig. 2 Examples of flexible (a) CIGS test cells (b) and an integrated module (courtesy of ZSW<sup>24</sup>). Under full-sun illumination, cells on the PI foil reach  $\eta = 11\%$ <sup>21</sup> and those on stainless steel achieve  $\eta = 17.4\%$ <sup>18</sup>. Monolithic series connection of the cells yields a module efficiency of  $\eta = 6.8\%$ <sup>21</sup>.

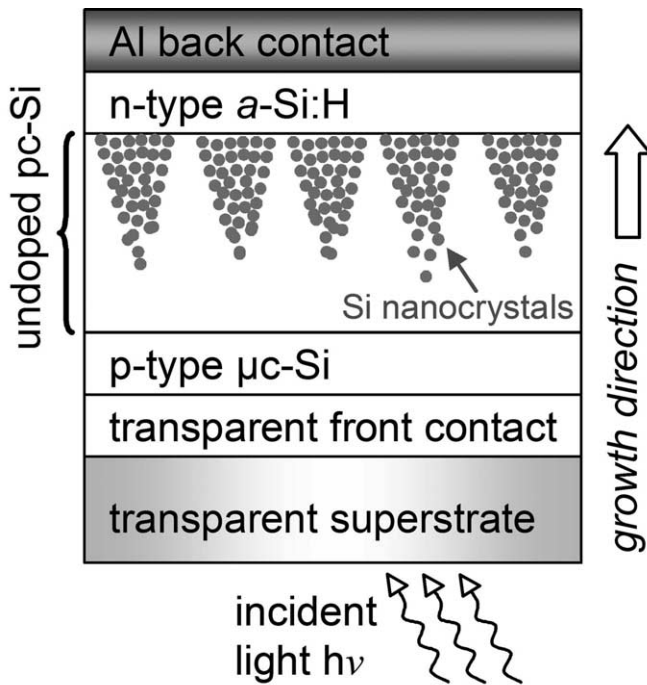


Fig. 3 Schematic of a pc-Si solar cell. Deposition starts with the transparent superstrate and front contact where the incident light will enter the cell. During growth of the undoped pc-Si absorber layer, nanocrystals start to form in an amorphous matrix so that nanocrystalline volume fraction increases with film thickness.

to reduce the substrate thickness further, and also therefore the substrate temperature during deposition. It is only in a deposition temperature range of  $T_d = 100\text{--}130^\circ\text{C}$ , that ultrathin PET or polyethylene naphthalate (PEN) foils with a thickness of  $d = 10\text{--}20\ \mu\text{m}$  retain enough mechanical stability for solar cells and module processing.

The pioneering work of Koch *et al.*<sup>46</sup> has revealed that at  $T_d \sim 100^\circ\text{C}$  protocrystalline absorbers yield better solar cells than amorphous ones. Even at  $T_d = 70^\circ\text{C}$ , an initial conversion efficiency of  $\eta_{\text{ini}} = 3.8\%$  is feasible, while  $T_d = 100^\circ\text{C}$  yields  $\eta_{\text{ini}} = 6\%$  for various configurations of double-stacked cells<sup>34</sup>. Light-induced degradation results in stabilized efficiencies close to 5%, e.g.  $\eta = 4.8\%$  at  $T_d = 110^\circ\text{C}$ <sup>35</sup>. At even lower values, e.g.  $T_d = 40^\circ\text{C}$ , the parameter window for pc-Si growth becomes very narrow<sup>47,48</sup>, hence a range of  $T_d = 70\text{--}130^\circ\text{C}$  proves feasible for solar cell optimization.

All a-Si or pc-Si based solar cells are drift controlled. That is, *p*- and *n*-type doped layers of only 10–20 nm thickness induce an internal electric field  $F$  across a nominally undoped, intrinsic *i*-layer. Photogenerated electron-hole pairs are spatially separated by  $F$  and contribute to the external photocurrent of these *p-i-n* cells. Typical *i*-layer thicknesses  $d_i$  range from 150 nm to 300 nm. With decreasing  $T_d$ , the density of electronic defects in the *i*-layer rises by one to two orders of magnitude. Therefore,  $F$  collapses because of the charge trapped at these additional defects, and consequently  $\eta$  drops.

Moreover, *i*-layer deterioration not only limits the efficiency of low  $T_d$  cells, but also causes a remarkable loss of doping efficiency<sup>5,34</sup>.

Fig. 3 shows the structure of pc-Si solar cells. The optimum absorber material is right at the edge of crystallinity, with dispersed but not yet interconnected nanocrystals in an amorphous matrix. For depositing high-quality pc-Si at  $T_d < 120^\circ\text{C}$ , plasma excitation in the very high frequency (VHF) range is favorable; we routinely use 80 MHz<sup>35</sup>. The transition from amorphous to nanocrystalline growth depends on the  $\text{H}_2$  dilution of the process gases during plasma deposition, but also on the substrate temperature and film thickness. The thicker the films, the greater the nanocrystalline volume fraction.

Fig. 4 demonstrates the clear coincidence of the absorber layer quality and solar cell performance for  $T_d = 110^\circ\text{C}$ . When tuning the  $\text{H}_2$  dilution ratio  $R = [\text{H}_2]/[\text{SiH}_4]$ , our deposition setup produces the best material at  $R_{\text{opt}} = 17$ .

Fig. 5a presents the current density versus voltage ( $J/V$ ) characteristics and key performance parameters of solar cells grown on rigid glass substrates, as well as on 50  $\mu\text{m}$  thick PET foils. Figs. 5b and 5c show arrays of pc-Si test cells deposited on 23  $\mu\text{m}$  thick PET foils at the upper limit of  $T_d = 130^\circ\text{C}$ . These pc-Si cells, optimized for direct lamination with textiles, exhibit a promising  $\eta_{\text{ini}} > 5\%$ . Nevertheless, further challenges arise from the mismatch in thermal

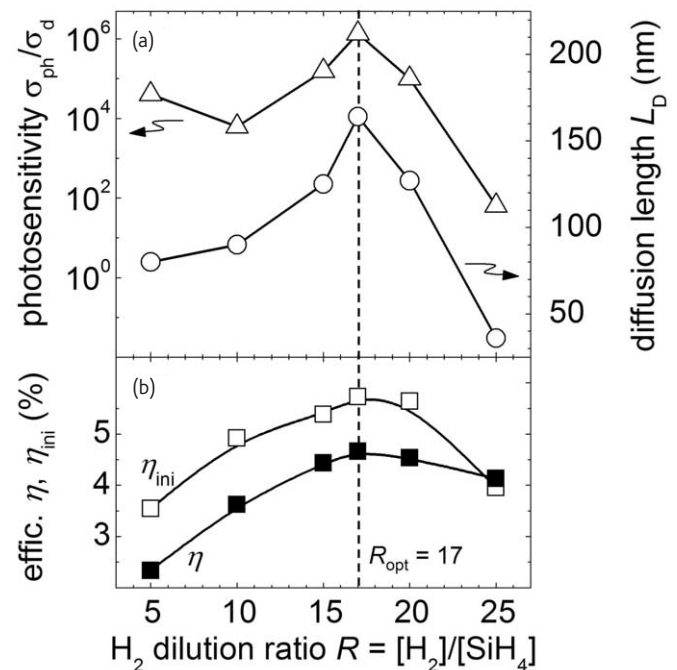


Fig. 4 Optimum  $\text{H}_2$  dilution for pc-Si growth. (a) Two figures of merit, the photo-to-dark conductivity ratio  $\sigma_{\text{ph}}/\sigma_{\text{d}}$  and the ambipolar diffusion length from steady state photocarrier grating (SSPG) measurements, mark the best *i*-layer quality at an  $\text{H}_2$  dilution ratio of  $R_{\text{opt}} = 17$ . (b) Highest *i*-layer quality at  $R_{\text{opt}} = 17$  directly translates into the greatest solar cell efficiency  $\eta$ . Each data point represents an average over 40 test cells of 3 mm  $\times$  3 mm. The efficiency  $\eta_{\text{ini}}$  is measured right after deposition, while  $\eta$  denotes stabilized efficiency after 100 hours of light soaking.

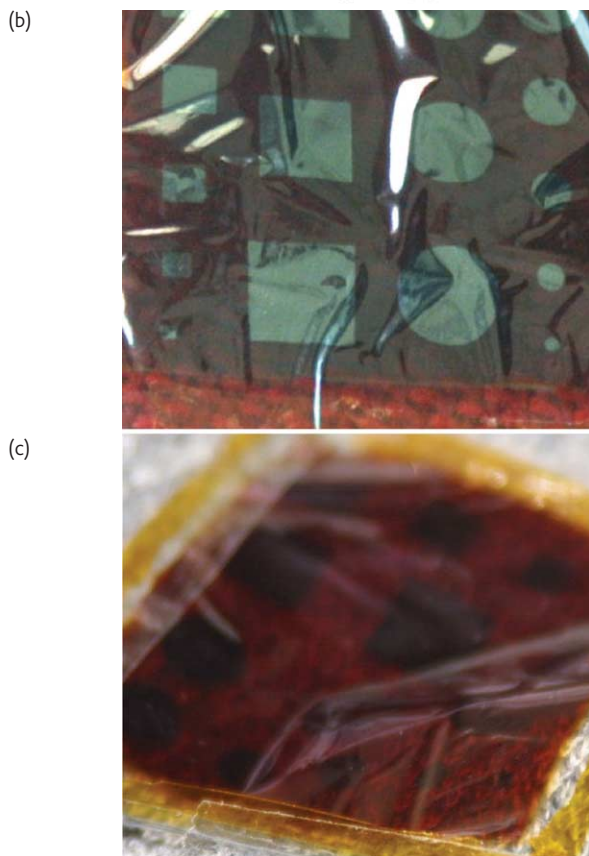
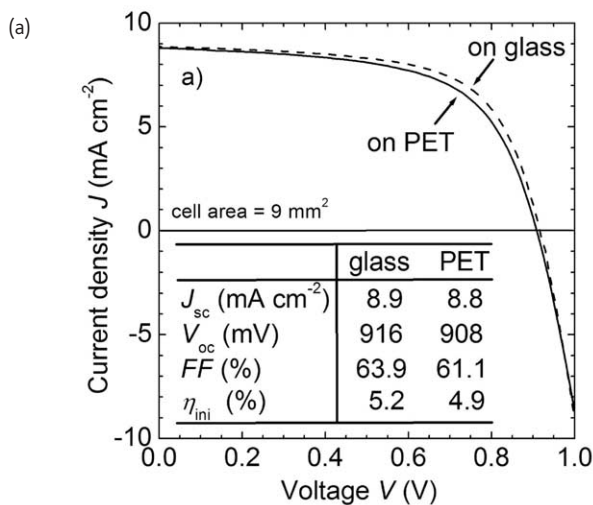


Fig. 5 (a) At  $T_d = 110^\circ\text{C}$ , optimized pc-Si test cells reach very similar efficiencies on nontextured glass and plastic substrates. The  $J/V$  characteristics under full-sun-like illumination yield the cell performance parameters short-circuit current density  $J_{sc}$ , open circuit voltage  $V_{oc}$ , fill factor FF, and initial efficiency  $\eta_{ini}$ . Flexible cells on PET slightly lag behind corresponding cells on glass. This may be the result of a small difference in substrate temperature that cannot be eliminated in our substrate holder setup. (b,c) pc-Si cells on 23  $\mu\text{m}$  thick PET foil, with (b) looking at the Al back contacts, and (c) showing the front view in the direction of the incident light. Since the active cell thickness is less than 1  $\mu\text{m}$ , the PET substrate controls mechanical stability and flexibility. The photographs indicate that the test cells conformally follow textile wrinkles, but it must be kept in mind that additional encapsulation by protecting foils is mandatory for clothing integration.

expansion coefficients of the polymer foils and inorganic solar cell materials, and from moisture permeation into the electronically active layers. Further studies need to explore these limits, especially on long-term stability and washability, for real photovoltaics laminates with textiles.

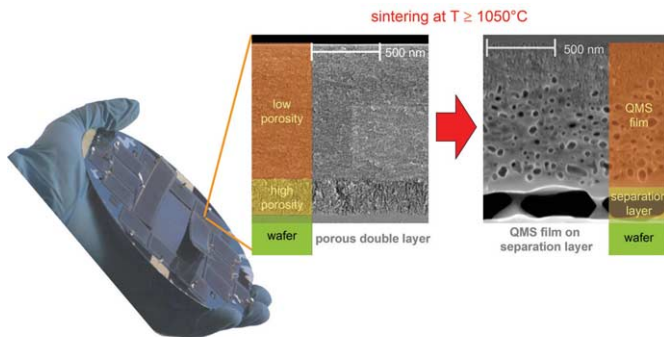
### High efficiency from a single-crystalline Si transfer technique

While the development of low-temperature a-Si cells is aimed at the large-area integration of photovoltaic modules with clothing and other textiles, the single-crystalline Si transfer technique provides high-efficiency cells with a somewhat restricted flexibility, but much smaller area demand. Transfer cells are therefore well suited for implementing eye-catching design highlights in clothing. Fig. 6 shows a BOGNER jacket that demonstrates the potential of small-area photovoltaic add-ons. The small and brittle c-Si cells exceed  $\eta > 20\%$ <sup>33</sup>, but need some care for clothing integration.

The single-crystalline c-Si layer transfer technique developed at our institute<sup>10,50,51</sup> is able to replace the brittle and rigid cells of Fig. 6 with flexible c-Si cells, which have an efficiency  $\eta \sim 15\%$ . In contrast to pc-Si based cells with a total thickness  $d \sim 1 \mu\text{m}$ , such crystalline cells



Fig. 6 BOGNER/MUSTANG denim jacket including a small-area photovoltaic add-on designed for the Avantex fair in 2005. Brittle c-Si cells are fixed onto a rigid metallic backplane that ensures mechanical stability, with their front and back contacts series-connected at the same time like roofing shingles. Two modules, each of 16 cells, power blinking or walking lights along the arms of the jacket where high-brightness white light emitting diodes are incorporated. (Courtesy of MUSTANG<sup>49</sup>.)



**Fig. 7** Flexible *c*-Si solar cells by layer transfer. The left-hand scanning electron micrograph shows the initial porous double-layer structure that extends over a 6" host wafer. This converts into a quasi-monocrystalline Si (QMS) layer on top of a separation layer during a high-temperature anneal. After standard epitaxy and front-side processing, the thin-film *c*-Si cells are transferred to a flexible polymer foil before completing backside passivation and contacts<sup>10</sup>.

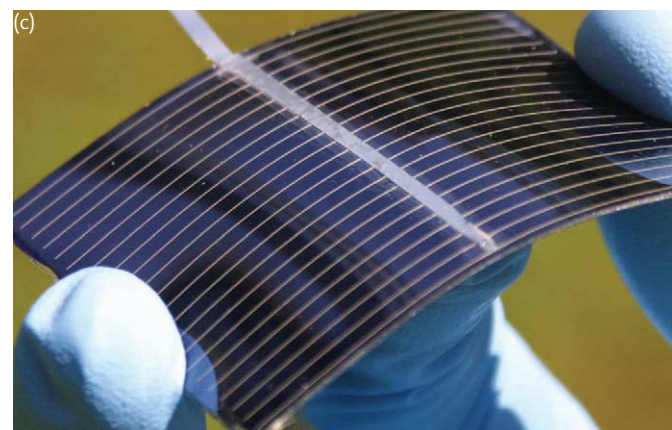
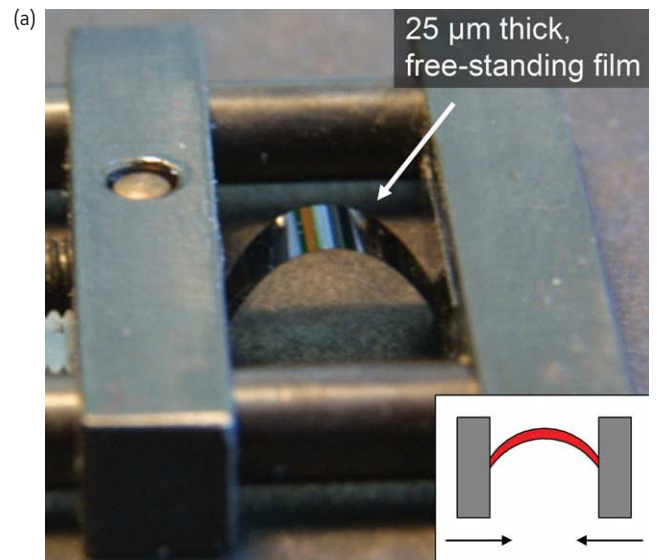
need  $d = 15\text{--}30\ \mu\text{m}$  for sufficient absorption of ambient light. Although they consist of perfect single crystals, the *c*-Si films become flexible at  $d < 50\ \mu\text{m}$ .

A brief description of the steps essential for forming flexible *c*-Si cells starts with the electrochemical formation of a porous double layer over a 6" wafer surface (Fig. 7). A subsequent annealing step restructures the porous layer structure into a separation layer and a so-called 'quasi-monocrystalline Si' (QMS) layer on top<sup>50,52</sup>. This step also closes the top QMS surface to provide a perfect template for high-temperature Si epitaxy.

All solar cell front-side processing then proceeds at high temperature on the device grade epitaxial layer. The separation layer still fixes the half-processed, thin-film solar cell to the original host wafer. By laminating a transparent superstrate like glass or appropriate plastic foils onto the front of the cell, the separation layer finally releases the thin-film cell from the host wafer. Completion of the cell back side must now proceed at low temperature, since either the flexible foil or a transparent adhesive on the front side limit the process temperature to  $T < 200^\circ\text{C}$ <sup>53,54</sup>. For further details of our transfer process, competing approaches, and solar-cell processing, see Werner *et al.*<sup>10</sup> and Bergmann *et al.*<sup>52,55</sup> and references therein.

Bending experiments (Fig. 8a) demonstrate that free-standing 25  $\mu\text{m}$  thick *c*-Si films can be bent to a curvature radius of 2 mm<sup>56</sup>. Fig. 8b shows a monocrystalline, 150 mm diameter sheet of transfer Si laminated between protective foils. Solar cells manufactured into the transfer layers reach conversion efficiencies of up to  $\eta = 16.6\%$  if transferred to glass plates<sup>52,57,58</sup>, or up to  $\eta = 14.6\%$  if transferred to flexible plastic foils<sup>10</sup>.

These record efficiencies require careful optimization and application of photolithographic patterning. However, production technologies mostly apply screen printing for solar cell formation. Without lithographic patterning, Auer and Brendel<sup>59</sup> have demonstrated a small module yielding  $\eta = 9.9\%$ . Fig. 8c demonstrates that our transfer layers are suitable for use in an industrial screen-



**Fig. 8** Flexible *c*-Si films and solar cells made using our layer transfer technique<sup>50-52</sup>. (a) Layer transfer produces *c*-Si films that bend to a 2 mm radius of curvature<sup>56</sup>. Since the crystalline structure favors crack formation and propagation along the crystal axes, the edges of such films and solar cells need to be well protected. (b) A flexible, 150 mm diameter, 25  $\mu\text{m}$  thick *c*-Si sheet laminated between two, 200  $\mu\text{m}$  thick protective foils. (c) Industrial screen printing at the research facilities of Shell Solar<sup>60</sup> forms transfer cells of 5 cm x 5 cm. Some process parameters need to be optimized, therefore the efficiency of these cells has not yet been determined.

printing process. We expect that transfer cells will reach  $\eta > 18\%$  within the next two years.

### Clothing-integrated photovoltaics

Since the idea of a ubiquitous power supply from the photovoltaic conversion of ambient light is very appealing, one needs to investigate how much energy is harvested during a cloudy or rainy day, or during indoor use of ipv. Because of a considerable lack of data in the literature, Gemmer<sup>30,31</sup> performed a detailed study in our laboratory to link empirical, long-term data on the incident solar radiation that reaches the earth's surface under different weather conditions, as well as various indoor illumination scenarios, with the spectral and intensity dependence of different types of solar cells. His modeling of these different conditions enabled, for the first time, a rough estimation of what ipv can accomplish and where its limits are reached.

Based upon typical parameters of real (rigid) solar cells, Gemmer compared the performance of a-Si, c-Si, and CIGS. Fig. 9 shows the intensity dependence under a typical cloudy sky in northern Europe, represented by the D65 spectrum<sup>61</sup>. Because of its higher band gap,  $E_g = 1.8$  eV, a-Si is the best choice for very low illumination intensities and for spectra with a comparatively high blue share, like D65 or fluorescent light. For most real-life situations, c-Si performs best because of its high efficiency and favorably low diode ideality  $n \sim 1$ . Despite a high efficiency under full sun, the output voltage of CIGS cells collapses for light intensities below 1% because of their comparatively low shunt resistances.

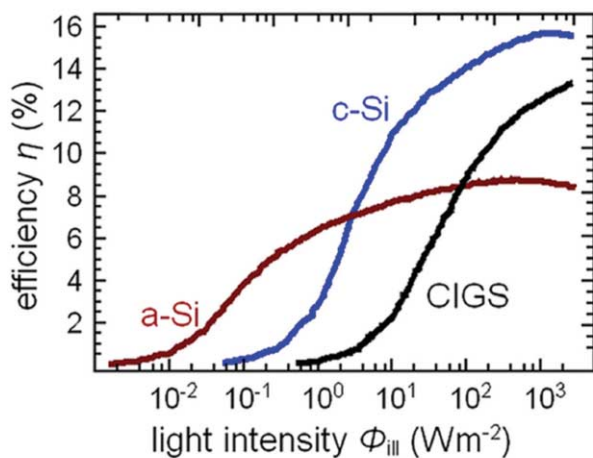


Fig. 9 Photovoltaic conversion efficiency of c-Si, CIGS, and a-Si cells as a function of illumination intensity under a D65 spectrum<sup>61</sup>. The outdoor intensity under these spectral conditions averages only  $80 \text{ Wm}^{-2}$ , whereas a clear sky yields a long-term average of  $560 \text{ Wm}^{-2}$  in Stuttgart, Germany. Because of their high efficiency and low  $\Delta V_{oc}$ , c-Si cells perform best, while a-Si still operates at very low light intensities. CIGS suffers from its low shunt resistance and ceases to function at  $2 \text{ Wm}^{-2}$ . The modeling of conversion efficiencies uses the parameters of real, commercial solar cells, rather than laboratory-scale world record data<sup>31</sup>.

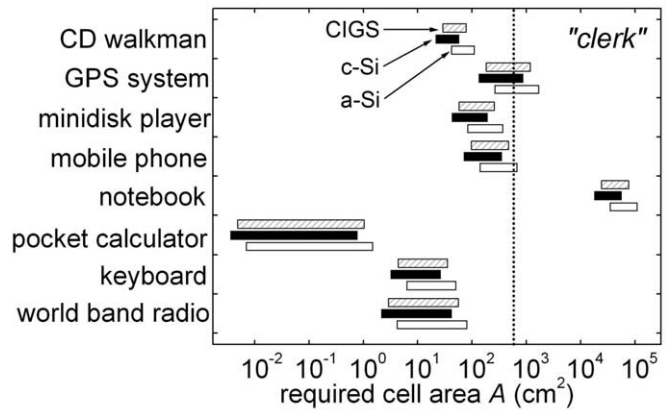


Fig. 10 Solar cell area  $A$  required for clothing-integrated photovoltaics to power the indicated devices sustainably, based on an annual average of the individual illumination conditions experienced by a prototype user 'clerk'<sup>31</sup>. Tentative available areas on jackets range from  $400 \text{ cm}^2$  for children to more than  $1000 \text{ cm}^2$  for adults; the dashed line marks a typical value of  $600 \text{ cm}^2$ . These results indicate that ipv is feasible for powering a wide range of mobile electronic devices.

Taking these intensity and spectral dependencies of the different technologies into account, Gemmer deduced annual energy yields for ipv under real weather conditions in Stuttgart, Germany, and calculated those for a set of prototype user profiles, e.g. a 'regular clerk', an 'outdoor construction worker', and a 'night-shift nurse'. Fig. 10 summarizes the results for a clerk in terms of the demand for clothing-integrated, solar-cell area that is capable of powering the indicated devices. This estimate uses a realistic mix of indoor and outdoor exposure and frequent use of electronic devices. For different user profiles, the area demand varies by a factor of five, with the clerk in Fig. 10 representing a mean value. The performance of different cell technologies is strongly dependent on the spectrum and intensity of the dominant light source. Outdoor conditions at light intensities of  $10\text{-}1000 \text{ Wm}^{-2}$  result in similar areas for CIGS, c-Si, and a-Si, while indoor use down to  $1 \text{ Wm}^{-2}$  favors the Si cells, with a-Si being most efficient below  $0.1 \text{ Wm}^{-2}$ .

In order to make best use of photovoltaic energy, accumulators and power conditioning circuits must be carefully selected and optimized. Rechargeable alkaline manganese (RAM) cells are a good choice for ipv because of their very low self-discharge, robust charging protocol, and extended temperature range for charge and discharge.

Fig. 11 shows some details of charge controller design for ipv. In an ipv garment, not all the solar modules will experience full sun exposure at the same time. Modules subject to a lower illumination level will limit the system performance if all of them are connected to the same charge controller. A better solution is shown in Fig. 11a, where individual charge controllers are attached to each module, i.e. each string of series-connected solar cells and their power outputs are merged at a defined output voltage. Note that compared with the actual price of flexible solar modules (about €40 per peak watt), module-integrated charge controllers, as well as accumulators, are

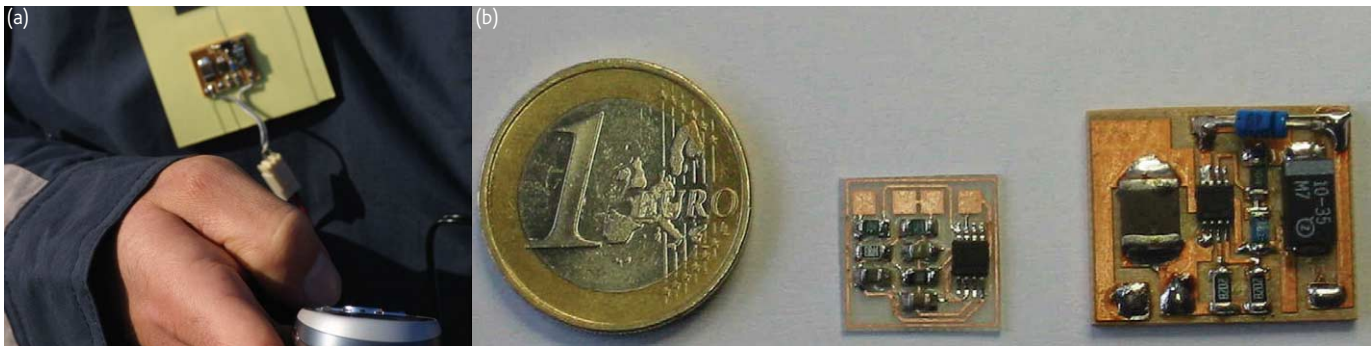


Fig. 11 Optimum ipv performance is achieved through each module delivering its actual photovoltaic power to a common accumulator via a separate control unit. (a) This top-mounted circuit board demonstrates the concept of module-integrated charge controllers. (b) Both charge controllers use a linear regulator that may be complemented with a dc-dc up-converter for improved low-light performance. The drop-out loss of the smaller board in the middle is 40% less than for the larger one. Because of high-volume production for portable phones, the obvious size reduction took less than one year, and actual devices are shrinking further.

almost negligible in their contribution to ipv system cost. Fig. 11b shows specialized low-loss ipv string-controllers developed at our institute.

Fig. 12 shows prototypes realized as part of the German SOLARTEX project<sup>7</sup>. The BOGNER/MUSTANG jacket in Fig. 12a was designed to be a universal, solar-powered source for operating mp3 players or other USB-compliant devices, similar to the Maier Sports jacket shown in Fig. 1. Fig. 12b shows an early example of ipv for driving warning LEDs in TEMPEX protection wear<sup>62</sup> for street construction workers, while Fig. 12c shows ipv warning lights in a KANZ coat<sup>63</sup> that is designed to enhance child safety at dusk and night time.

There is a range of truly interdisciplinary tasks involved in the design and manufacture of ipv products. In the framework of SOLARTEX<sup>7</sup>, the Hohenstein Institutes<sup>64</sup> has developed the first working solutions for the placement and fixing of solar modules into clothing, and the Institut für

Textil- und Verfahrenstechnik<sup>65</sup> in Germany is working on textile wiring and integration procedures fit for garment production. Results of this joint research will be published elsewhere in the near future.

## Conclusion


Clothing-integrated photovoltaics are an interesting option for powering mobile electronic devices. Among various technologies for flexible solar modules, Si thin films currently offer the most promising combination of flexibility and performance, especially under typical low-light conditions. Ultrathin pc-Si cells are ready for direct lamination with textiles, while high-efficiency c-Si transfer cells are suitable for add-on accessories or pocket integration. Low-loss charge controllers, textile wiring, and specialized know-how on integration with garment production will pave the road to the first ipv products. 



Fig. 12 Examples of SOLARTEX<sup>7</sup> prototypes for different applications. (a) The BOGNER/MUSTANG<sup>49</sup> jacket provides a universal socket and energy buffer for operating and charging USB-compliant devices. Iowa Thin Films modules<sup>44</sup> deliver a maximum power of 2.5 W. Three hours of full sun enable 40 hours of mp3 operation. (b) In the TEMPEX jacket<sup>62</sup>, bright photovoltaic-powered warning lights supplement the built-in passive safety features, e.g. for street construction workers. (c) Using photovoltaic power harvested during the day, light-emitting diodes enhance the visibility of children at night in this KANZ coat<sup>63</sup>. (Courtesy of Institut für Textil- und Verfahrenstechnik<sup>65</sup>).

## Acknowledgments

We gratefully acknowledge the indispensable contributions of many coworkers and students at the Institut für Physikalische Elektronik<sup>45</sup> in the development of flexible solar cells and ipv, especially those of A. Al Tarabsheh, C. Berge, R. Bergmann, K. Brenner, C. Gemmer, Y. Ishikawa, C. Koch, J. Krämer, R. Merz, and B. Zinßer. We thank P. Grabitz for careful correction of the manuscript. Funding of the SOLARTEX project comes from the Ministry of Economics of the German Federal State of Baden-Württemberg (from resources of the Landesstiftung Baden-Württemberg). Transfer cell development was partially

supported by the German Federal Ministry for the Environment (BMU) under contract no. 0329818A, and the work on pc-Si by the European Commission under contract no. ENK5-CT-2002-30016. We gratefully acknowledge solar cell fabrication by screen printing at Shell Solar, Munich (A. Münzer). A close cooperation with our SOLARTEX<sup>7</sup> partners resulted in the ipv prototypes presented here. In this respect we owe special thanks to G. Maier and S. Binder (Maier Sports), J. Sefranek (MUSTANG Bekleidungswerke), U. Gerstenmeyer (TEMPEX), U. Gutknecht (KANZ), E. Kirchdörfer, A. Mahr-Erhardt, and M. Rupp (Hohenstein Institutes), and B. Göppinger, H. Horter, and N. Tauber (Institut für Textil- und Verfahrenstechnik).

## REFERENCES

- Barnett, A., and Resch, R., In: *Tech. Dig. 15<sup>th</sup> Int. Photovolt. Sci. Eng. Conf.*, Quinhao, Y. (ed.), Shanghai Scientific & Technical Publishers, Shanghai, China, (2005), 20
- Tomita, T., In: *Conf. Rec. 31<sup>st</sup> IEEE Photovolt. Specialists Conf.*, IEEE, New York, (2005), 7
- Preiser, K., Photovoltaic Systems, In: *Handbook of Photovoltaic Science and Engineering*, Luque, A., and Hegedus, S., (eds.), John Wiley & Sons, Chichester, England, (2003), 753
- Hegedus, S., and Okubo, N., In: *Conf. Rec. 31<sup>st</sup> IEEE Photovolt. Specialists Conf.*, IEEE, New York, (2005), 1651
- Schubert, M. B., et al., in: *Conf. Rec. 31<sup>st</sup> IEEE Photovolt. Specialists Conf.*, IEEE, New York, (2005), 1488
- Maier Sports, Köngen, Germany, [www.maiersports.com](http://www.maiersports.com)
- SOLARTEX is a joint project of the partners<sup>6,45,49,62-67</sup>
- Akzo Nobel, Arnhem, The Netherlands, [www.akzonobel.com](http://www.akzonobel.com)
- Hartmann, W. D., et al., *High-Tech Fashion*, Heimdall, Witten (2000)
- Werner, J. H., et al., In: *Proc. 3<sup>rd</sup> World Conf. Photovolt. Energy Conv.*, Osaka, Japan, IEEE, New York, (2003), **2**, 1272
- Yang, J., et al., *Appl. Phys. Lett.* (1997) **70**, 2975
- Guha, S., In: *Tech. Dig. 15<sup>th</sup> Int. Photovolt. Sci. Eng. Conf.*, Quinhao, Y. (ed.), Shanghai Scientific & Technical Publishers, Shanghai, China, (2005), 35
- Rojahn, M., et al., *Mater. Res. Soc. Symp. Proc.* (2001) **664**, A2.1
- Brabec, C. J., *Sol. Energy Mater. Sol. Cells* (2004) **83**, 273
- Niggemann, M., et al., *Thin Solid Films* (2004) **451-452**, 619
- Chwang, A. B., et al., *Appl. Phys. Lett.* (2003) **83**, 413
- Lagref, J.-J., et al., *Synth. Met.* (2003) **138**, 333
- Contreras, M. A., et al., *Prog. Photovolt.: Res. Appl.* (2005) **13**, 209
- Contreras, M. A., et al., *Prog. Photovolt.: Res. Appl.* (1999) **7**, 311
- Kessler, F., et al., *Thin Solid Films* (2005) **480-481**, 491
- Herrmann, D., et al., In: *Proc. 20<sup>th</sup> Eur. Photovolt. Sol. Energy Conf.*, Palz, W., et al. (eds.), WIP-Renewable Energies, Munich, Germany, (2005), 1875
- Herrmann, D., et al., *Mater. Res. Soc. Symp. Proc.* (2005) **865**, F15.1
- Hartmann, M., et al., In: *Conf. Rec. 28<sup>th</sup> IEEE Photovolt. Specialists Conf.*, IEEE, New York, USA, (2000), 638
- Zentrum für Sonnenenergie- und Wasserstoff-Forschung Baden-Württemberg (ZSW), Stuttgart, Germany, [www.zsw-bw.de/en](http://www.zsw-bw.de/en)
- Lippold, G. et al., *Mater. Res. Soc. Symp. Proc.* (2001) **668**, H3.9
- Tober, O., et al., *Mater. Res. Soc. Symp. Proc.* (2003) **763**, B8.16
- Kampmann, A., et al., *Mater. Res. Soc. Symp. Proc.* (2003) **763**, B8.5
- Virtuani, A., et al., *J. Appl. Phys.* (2006) **99**, 014906
- Grabitz, P. O., et al., *Thin Solid Films* (2005) **487**, 14
- Gemmer, C. E. M., et al., *Mater. Res. Soc. Symp. Proc.* (2001) **664**, A25.9
- Gemmer, C. E. M., *Analytische und Numerische Untersuchungen von Solarzellen unter wechselnden Beleuchtungsbedingungen*, Der Andere Verlag, Osnabrück, Germany, (2003)
- Tiwari, A. N., et al., *Prog. Photovolt.: Res. Appl.* (2001) **9**, 211
- Glunz, S. W., et al., In: *Conf. Rec. 29<sup>th</sup> IEEE Photovolt. Specialists Conf.*, IEEE, New York, USA, (2002), 450
- Koch, C., et al., *Sol. Energy Mater. Sol. Cells* (2001) **68**, 227
- Ishikawa, Y., and Schubert, M. B., In: *Proc. 20<sup>th</sup> Eur. Photovolt. Sol. Energy Conf.*, Palz, W., et al. (eds.), WIP-Renewable Energies, Munich, Germany, (2005), 1525
- Tanda, M., et al., In: *Conf. Rec. 31<sup>st</sup> IEEE Photovolt. Specialists Conf.*, IEEE, New York, USA, (2005), 1560
- Jongerden, G. J., In: *Proc. 3<sup>rd</sup> World Conf. Photovolt. Energy Conv.*, Osaka, Japan, IEEE, New York, (2003), **2**, 2109
- Schropp, R. E. I., et al., *Mater. Res. Soc. Symp. Proc.* (1999) **557**, 713
- XsunX, Aliso Viejo, CA, USA, [www.XsunX.com](http://www.XsunX.com)
- VHF technologies, Yverdon-les-Bains, Switzerland, [www.flexcell.com](http://www.flexcell.com)
- Bailat, J., et al., In: *Proc. 20<sup>th</sup> Eur. Photovolt. Sol. Energy Conf.*, Palz, W., et al. (eds.), WIP-Renewable Energies, Munich, Germany, (2005), 1529
- Iowa Thin Films, [www.iowathinfilm.com](http://www.iowathinfilm.com)
- Jeffrey, F. R., et al., *Mater. Res. Soc. Symp. Proc.* (1985) **49**, 81
- Power Film, [www.powerfilmsolar.com](http://www.powerfilmsolar.com)
- Institut für Physikalische Elektronik, Universität Stuttgart, [www.ipe.uni-stuttgart.de](http://www.ipe.uni-stuttgart.de)
- Koch, C., et al., *Mater. Res. Soc. Symp. Proc.* (1999) **557**, 749
- Ito, M., et al., *Thin Solid Films* (2001) **383**, 129
- Koch, C., et al., In: *Proc. 16<sup>th</sup> Eur. Photovolt. Sol. Energy Conf.*, Scheer, H., et al. (eds.), James & James, London, UK, (2000), 401
- MUSTANG Bekleidungswerke, Künzelsau, Germany, [www.mustang.de](http://www.mustang.de)
- Rinke, T. J., et al., *Appl. Phys. A* (1999) **68**, 705
- Berge, C., et al., In: *Proc. 17<sup>th</sup> Eur. Photovolt. Sol. Energy Conf.*, McNelis, B., et al. (eds.), WIP-Renewable Energies, Munich, Germany, (2002), 1039
- Bergmann, R. B., et al., *Sol. Energy Mater. Sol. Cells* (2002) **74**, 213
- Brendle, W., et al., In: *Proc. 20<sup>th</sup> Eur. Photovolt. Sol. Energy Conf.*, Palz, W., et al. (eds.), WIP-Renewable Energies, Munich, Germany, (2005), 745
- Rostan, P.J., et al., In: *Tech. Dig. 15<sup>th</sup> Int. Photovolt. Sci. Eng. Conf.*, Quinhao, Y. (ed.), Shanghai Scientific & Technical Publishers, Shanghai, China, (2005), 214
- Bergmann, R. B., and Werner, J. H., *Thin Solid Films* (2002) **403-404**, 162
- Berge C., et al., *Mater. Res. Soc. Symp. Proc.* (2003) **769**, H2.7
- Tayanaka, H., et al., In: *Proc. 2<sup>nd</sup> World Conf. Photovolt. Sol. Energy Conversion*, Schmid, J., et al. (eds.), Eur. Commission, Ispra, Italy, (1998), 1272
- Feldrapp, K. et al., *Prog. Photovolt.: Res. Appl.* (2003) **11**, 105
- Auer, R., and Brendel, R., *Mater. Res. Soc. Symp. Proc.* (2001) **681E**, I9.2.1
- Shell Solar Research Facilities, München, Germany, [www.shellsolar.com](http://www.shellsolar.com)
- Colorimetry*, 2<sup>nd</sup> edition, Commission Internationale de l'Eclairage, Vienna, Austria, (1986)
- TEMPEX, Heidenheim, Germany, [www.tempex.com](http://www.tempex.com)
- KANZ, Neufra, Germany, [www.kanz.com](http://www.kanz.com)
- Hohenstein Institutes, Bönnigheim, Germany, [www.hohenstein.de/en](http://www.hohenstein.de/en)
- Institut für Textil- und Verfahrenstechnik (ITV), Denkendorf, Germany, [www.itv-denkendorf.de](http://www.itv-denkendorf.de)
- HighSolar, Ulm, Germany, [www.highsolar.de](http://www.highsolar.de)
- BST Berger Safety Textiles, Maulburg, Germany, [www.berger-safety-textiles.com](http://www.berger-safety-textiles.com)