

Review

Fabrication of Photovoltaic Textiles

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Abstract: Solar photovoltaic (PV) arrays are providing an increasing fraction of global electrical demand, with an accelerating rate of new installations. Most of these employ conventional glass-fronted panels, but this type of PV array does not satisfy applications that require a light-weight, flexible PV generator. An option discussed in this article is to consider textiles for such solar cell substrates. As explained in this review, combining the choice of PV cell type with the choice of textile offers alternative structures for flexible PV cells. In particular, the relative advantages and disadvantages are contrasted, either forming PV-coated fibres into a fabric, or coating an already formed fabric with the PV materials. It is shown that combining thin-film amorphous silicon PV technology and woven polyester fabric offers one solution to realizing flexible fabric PV cells, using well-understood coating methods from the textile and semiconductor industries. Finally a few applications are presented that are addressed by this approach.

Keywords: photovoltaics; solar cells; textiles; thin-film semiconductors

1. Introduction

Textile fabrics nowadays possess a multitude of applications. In addition to their obvious use as materials for clothing, they have a wide variety of highly technical uses, ranging from conventional bulk bags to sophisticated medical implants. Moreover, the miniaturisation of electronic devices over the past twenty years or so has expanded textile applications still further. In particular, there is extensive interest in the incorporation of sensors into wearable fabrics: for example, for medical, military, sports and leisure applications [1]. In this paper, we explore the innovative use of textiles as supports for electricity-generating photovoltaic (PV) solar cells, contrasting the different approaches that seek to use the performance of a fabric without compromising the operation of the solar cells. The simplest approach, of bonding solar cells to a fabric, is less effective in retaining the textile properties than it is in maintaining the solar cell performance. The other two approaches use contrasting architectures for integrating solar cells with fabrics: Either the cells are constructed on fibres that are subsequently fashioned into a fabric or the cells are formed on a finished fabric. Each of these techniques has its advantages and disadvantages, with rather more effort reported on making coated fibres.

Solar PV is one of the alternative sustainable energy sources that make up increasing amounts of electrical demand in many countries. In 2015, PV provided 1.2% of global electricity demand [2]. The renewable sources available include hydroelectric schemes, wind turbines, wave power and tidal power. However, the most compelling direct source of energy, and one that will provide an “endless” supply, is the sun. The sun provides the whole Earth with more energy in one hour than the world’s population uses in one year. Despite its variability, in harnessing solar power, particular success has come from its direct conversion to electricity, using solar cells.

Solar panels are perhaps most commonly recognised on the roofs of offices and houses, and as large arrays set in the countryside. These panels consist of interconnected solar cells applied to glass or polycarbonate plates. Despite the success that such solar panels have achieved, they nevertheless possess a number of drawbacks. They can be attached only to flat surfaces. In addition, the plates are heavy, and so the structures to which the panels are to be attached must be strong enough to withstand their weight. In addition, glass plates are fragile: care has to be taken with their storage and transport. To overcome these drawbacks, attention has increasingly been turned to the construction of lighter, flexible cells, which can withstand harsh environments, maintain durability and involve lower materials use and reduced cost in their construction. An extensive commercial range of photovoltaic cells now exists that has been applied to thin plastic or metal films. These films are much lighter and generally cost less to produce. However, the thinness of the films may still render them liable to fracture during both construction and application, so care has to be taken when they are attached to underlying structures.

Textile fabrics offer a solution to this difficulty, not least because they are the most widespread flexible materials in everyday use. There is a huge range of textile constructions that can be produced from woven, knitted, embroidered and nonwoven fabrics, comprising a wide choice of natural and synthetic fibres that have been in use not just for centuries but for millennia [3]. Although used primarily for the provision of clothing, they have also in this time enjoyed extensive technical use, for example in sailcloth, tents and sacks. It is considered that the ancient Egyptians began to use cloth sails as long ago as around 3000 BC. The role of textile fabrics as substrates for solar cells increases still further their range of applications.

The fabrics can be either ones that have been specially constructed for particular PV applications or, on the other hand, conventional fabrics adapted to be photovoltaic. Textile fabrics possess a very broad range of markets and applications, and can be produced by a wide variety of fabrication processes, all of which provide enormous versatility for tailoring fabric shape and properties. In addition, there is now extensive interest in the integration of sensors into textile fabrics, such as in wearable technologies and healthcare, an objective made attainable by the miniaturisation of electronic devices. These sensors have to be powered, either directly from external sources or via small battery intermediates. Either way, it would be highly desirable that the energy harvester is also integrated into the textile, and a PV approach can offer a means of achieving this goal. The combined use of solar cells, batteries and sensors is an obvious extension.

An additional advantage of textile substrates is their lower embedded energy ($53 \text{ MJ}\cdot\text{m}^{-2}$) compared with traditional glass ($150\text{--}200 \text{ MJ}\cdot\text{m}^{-2}$) plates. This impacts on the energy pay-back period, which should be shorter than the panel lifetime if photovoltaics are to be real renewable energy sources: we have calculated a pay-back period for textile-based PV, in a modest solar climate, of 1–2 years which is 2.5 times less than that of similar rigid panels [4].

Nevertheless, in adopting textiles as substrates, several criteria have to be met. For example, will the textile substrate be able to withstand the processing conditions required to render it photovoltaic, and will the finished solar textile be able to withstand wear and tear in use, and also washing and drying cycles? Will any important physical and aesthetic features be compromised by the presence of solar cells? These considerations are taken into account in this article. The following sections introduce the photovoltaic effect itself and the variety of device types that have been developed since the first practical Si PV cell; then, the variety of textile constructions is described together with options for rendering them electrically conducting. The central portion of the paper contrasts the alternatives of either using PV fibres that are then woven together, or of coating a finished fabric with the PV materials, with the simple expedient of attaching pre-formed PV cells to a fabric. The final sections describe remaining challenges that are mainly technological and potential applications.

2. Photovoltaic Cells and Fabrics

In order to understand the restrictions of adding solar cells to a fabric, it is necessary to appreciate how solar cells convert solar radiation into electrical energy by a planar architecture of semiconducting

and conducting materials. Variations of this basic device have been developed to enhance PV performance whilst reducing production costs, and to enable thinner semiconducting layers to perform the same function as more conventional crystalline wafers. The following section describes these solar cell types and is followed by a section on the options for textile constructions. There is then an account of how textiles may be made electrically conducting so as to form the base layer of a solar cell.

2.1. The Photovoltaic Effect and Its Realization

The PV effect was first observed over a century and a half ago, which was in a very different form to the present-day devices that are installed on buildings around the world or used to power mobile electronics from clocks to satellites. Becquerel's 1839 discovery came from an electrochemical arrangement of metal electrodes immersed in a liquid, but most existing cells are solid-state, which awaited the understanding of semiconducting materials, beginning with selenium and then copper oxide. The ubiquitous silicon P-N junction PV cell was developed in the early 1950s by three researchers at Bell Laboratories in Murray Hill, New Jersey, USA [5] into a usable but rather inefficient energy source, from which point many others contributed to achieving its present efficiency of over 20% (i.e., producing $200 \text{ W}\cdot\text{m}^{-2}$ from standard sunlight conditions of $1000 \text{ W}\cdot\text{m}^{-2}$). In addition, a variety of PV materials have competed for the varied markets that have emerged.

In all of these types of cells, the basic principle is the same: Generation of electrical energy from radiant energy by two dissimilar materials in electrical contact, without chemical reaction, mechanical motion, or requiring thermal energy. Illumination falling on a PN junction cell produces pairs of positive and negative charges which are then separated by the in-built electrical field that arises at the junction between P-type and N-type semiconductors. This junction field is a consequence of adding minute amounts of selected impurities into each side of the junction, which then causes a potential energy barrier to be set up across the junction: negative electrons will tend to move from P-type to N-type, and positive "holes" will tend to move in the other direction. The combination of this flow of charges (an electrical current) and the potential barrier ("voltage") provides electrical energy that may be fed into a connected load. Figure 1 illustrates schematically the layered sandwich construction of a typical solar cell.

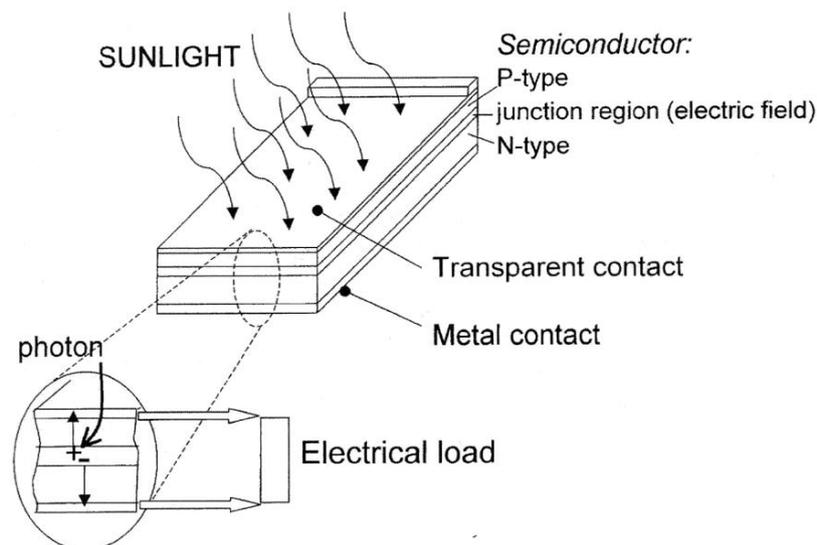


Figure 1. The layered sandwich structure of a simple PN junction solar cell using a transparent conducting oxide upper contact.

In order to improve the early conversion efficiency from sunlight into electricity, it was essential to optimize the absorption of light to generate many charge pairs, and also to enhance the collection of these charges. There is a threshold energy for any semiconductor, such as silicon, to absorb light and

produce the freely moving charges: if this is too high, then the semiconductor is transparent to much of the sun's spectrum and if it is too low then the potential barrier is small. Fortunately, silicon is close to optimum for these competing trade-offs, as it is a well-known material with mature technology and is an abundant element. In contrast, it has been developed as a precision material for microelectronics rather than a low cost energy converter, so to reduce the cost of PV power, a thin-film version has been sought that would use less material. Such a choice generally comes with a reduction of performance.

A variety of thin-film semiconductors have been proposed for low cost PV power, from inorganic compounds of several elements to organic molecules and polymers. These mostly lie at the opposite end of the performance spectrum from single crystalline inorganic materials like Si or GaAs, but thin-film CdTe and copper indium gallium selenide (CIGS) are each capable of similar conversion efficiencies to commercial Si cells. One of the earliest thin-film PV options was "amorphous silicon", which its abbreviated name, a-Si:H, indicates is actually a combination of silicon and hydrogen. Its strong optical absorption is an advantage for thin solar cells, but its poorer electrical properties counter this to some extent: photo-generated charge pairs can only diffuse a short distance before recombining again, but carrier separation is improved by introducing an electrical field region with a double-junction (P-I-N) structure that is wider than a simple P-N junction. Nonetheless, a-SiH cells can only achieve ~10% efficiency but use relatively low temperature synthesis (~200 °C) in contrast to most other inorganic semiconductors.

Organic polymer PV materials challenge this with similar efficiency but simpler and lower temperature processing. The photoactive material may be a large organic molecule, such as a fullerene, or a polymer, or a combination, although polymer types have dominated developments [6]. These have required advanced polymer chemistry and highly dependable hermetic encapsulation to avoid rapid degradation in air or sunlight [7]. Hybrid organic/inorganic cells should be able to combine the optical and electrical advantages of both types of material, but have sometimes shown poor carrier collection unless the built-in electric field was well designed (e.g., [8,9]) Organic cells differ from all inorganic cells in producing electrical charge pairs that remain tied together (as excitons or polarons) as they move through the material, for instance by hopping along the conjugated bonds in polymer chains. This limitation is generally solved by a larger area, non-planar junction to reduce the distance travelled and so separate the photogenerated charges more effectively. The liquid-based coating techniques used for many organic materials are obviously well-suited to application on fibres or textiles.

For over 25 years, an alternative type of PV cell has been researched, the dye sensitized solar cell (DSSC), which is strictly an electrochemical device [10]. By using a dye to absorb the sunlight, these cells should be better able to match the spectrum of the light source than a single semiconductor type of cell does, and placing the dye on the nano-structured surface of a transparent insulating material, such as TiO₂, separates the functions of optical absorption and electrical charge injection. Insulators have a much larger threshold energy than semiconductors for optical absorption, and so can support a larger potential barrier, giving greater output voltage in a suitably constructed PV cell. However, instead of a PN junction, the charge separation is facilitated by an electrolyte comprising a redox couple in a solvent—for instance, iodine ions in an organic liquid or gel, in contact with the TiO₂. A counter electrode of corrosion-resistant metal such as platinum completes the electrical circuit and regenerates the electrolyte. Although these cells mimic photosynthesis, the process on which most life depends, degradation issues and the non-solid electrolyte have hampered widespread commercial uptake.

Significant progress towards ameliorating these problems has come from innovative perovskite compounds. These are organic-inorganic halides in a dye-sensitized device, initially methylammonium lead iodide with a liquid iodine-based electrolyte and around 3% efficiency, but now attaining 20% for all-solid-state versions (and around 15% for flexible versions). As they use a liquid coating technique, they are suitable for low cost, large area fabrication, but require a lead-free composition and improved stability before commercial acceptance [11,12]. Already low temperature liquid processed, stable, cells have been produced that might be appropriate for application to textiles [13]. A recent review discusses the different architectures and electrode materials that have been assessed for hybrid versions

of these cells [14]. There is a regular six-monthly review of photovoltaic efficiencies that only includes accepted, corroborated performances and this has yet to include any textile-based cells, but hybrid perovskite/Si cells are amongst the most efficient devices included [15].

An alternative strategy of aiming for much higher conversion efficiency whilst using expensive materials involves the design of small area, multilayer semiconducting structures that are illuminated through optical concentrators (either mirrors or lenses). These are capable of the highest performance, attaining >40% efficiency in sunlight concentrated up to 500 \times , by using a stack of group III/group V semiconducting compounds. However, this approach is not yet relevant for PV cells to be produced on textile bases, although fibre configuration cells have been constructed, usually with fine metal wire substrates, that are placed within a microreflector to enhance optical collection area and angle (e.g., [16]).

The range of PV devices offers variety in materials and construction, albeit with a similar underlying mechanism for the conversion of light to electricity and broadly similar performances.

2.2. Textile Fabric Constructions

Textile fabrics are unique amongst materials in their variety of constructions and the hierarchical nature of these constructions. The basic building block is the textile fibre. Most natural textile fibres exist as staple fibres of 10–40 μm cross-section, and these are twisted together in a spinning process to form yarn. Synthetic fibres and silk are produced by extrusion as continuous filament yarns, although, in some processes, these yarns are cut to convert them to staple fibres of a desired length, which are then spun into bulkier yarns. Yarns are then converted to fabrics by weaving or knitting or maybe embroidery, or by a so-called nonwoven process to form felts or webs. As will become apparent, some constructions are intrinsically better suited than others for adaptation to PV fabrics, depending to some extent on the method by which they are rendered photovoltaic. The degrees of yarn bending and interlacing are important in this respect. A brief description of each type of fabric construction now follows, but a fuller account may be found in [3].

There are three basic types of woven structure: plain, twill and satin, shown schematically in Figure 2. In all cases, the yarns are interlaced and are subject to bending. They also undergo compression, at the points where warp (longitudinal) yarns and weft (transverse) yarns interlace. In plain weaves, the warp and weft yarns interlace at every single crossing, but in twill weaves, the yarns interlace after two or more crossings. In satin weaves, each warp yarn interlaces over and under a weft yarn, and then crosses two or more weft yarns before the next interlacing: In Figure 2, six yarns are crossed between consecutive interlacings. Figure 3 illustrates cross-sectional views of the weave constructions in Figure 2. It can be noted that the yarns of twill weaves are subjected to the least bending. The lower degree of interlacing in satin fabrics can more severely impair electrical conductivity in a PV fabric.

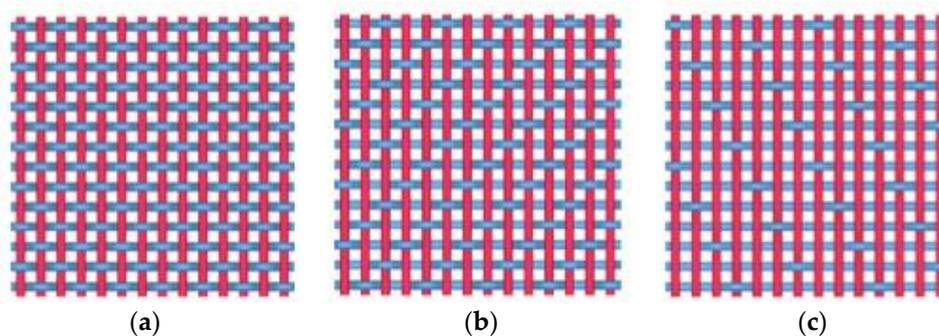


Figure 2. Woven textile constructions: Plain weave (a); twill (b) and satin (c).

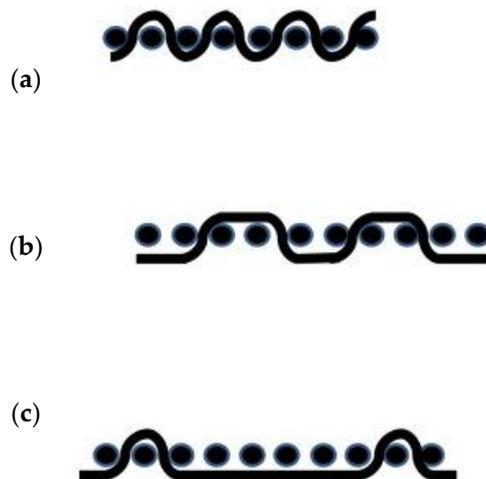


Figure 3. Cross-sectional schematics of the three different weave constructions shown in Figure 2; Plain weave (a); twill weave (b) and satin weave (c).

Knitted structures are either weft knitted or warp knitted, and examples are shown schematically in Figure 4. The more familiar type is weft knitting (which is used for example in hand knitting), in which a continuous yarn feeds through consecutive loops in a transverse direction. Although they have many desirable functional and aesthetic qualities, especially drape, they are not all dimensionally stable and they ladder easily. Warp knitted structures are more dimensionally stable but lack drape. They are produced using multiple yarns and the loops intermesh diagonally with adjacent columns. In both types of knitted fabric, the yarns are subjected to tight bends with small radii of curvature.

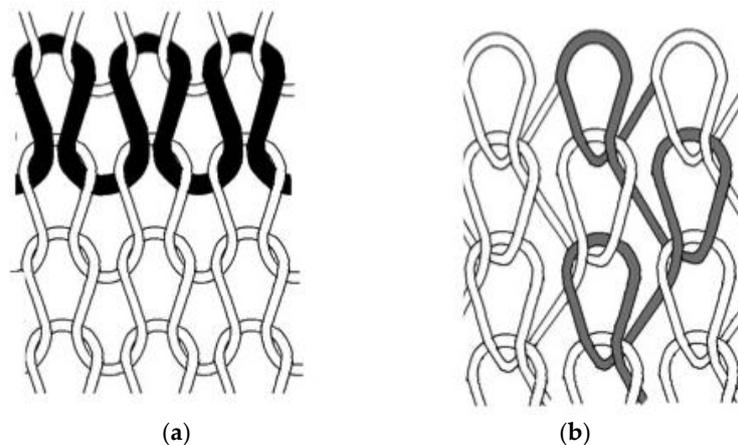


Figure 4. Knitted textile constructions: Plain weft knit stitch (a) and warp knit tricot stitch (b).

Nonwovens are different from other types of fabric in that their constituent yarns are not regularly oriented. The yarns are bonded to form webs by mechanical, chemical or thermal means, depending on the nature of the yarn and the nature of the desired web. There are numerous applications for nonwoven fabrics, including absorbent products such as nappies, caps and masks used by hospital staff, automotive upholstery and insulation products. Rendering nonwoven fabrics photovoltaic has received less attention than for woven and knitted fabrics, perhaps because nonwovens are less prominent in the general perception of textiles.

Embroidered structures may seem an odd choice to include in this article because they are traditionally perceived in terms of domestic craftwork. At their most prosaic, they can be considered as a collection of yarns applied to a base fabric that achieves a desired pattern or design.

Embroidery therefore provides a contrast to weaving, in which yarns are constrained to just a few—usually two—directions. However, during the past twenty years or so, embroidered structures have become increasingly used for high-tech applications, including those applications requiring conductive textiles, such as intelligent sensors. Three kinds of embroidery methods are available: Chain-stitch, standard embroidery and tailored fibre replacement (TFP). Chain-stitch, which is a one-thread system, produces a pattern with a moss-like surface. Standard embroidery is a two-thread system, and the base fabric, on which the embroidered pattern is to be created, is held under tension on a frame. The frame is programmed to move in x - and y -directions, as required for the desired patterned to be obtained. The TFP method extends standard embroidery by utilising a three-thread system, and is the most versatile and precise method, as it allows for placement of the textile material using a highly controlled geometry. Three-dimensional structures can be created. Details of each method can be found elsewhere [17,18].

2.3. Making Fabrics Electrically Conducting

It is evident that the top and bottom of any PV cell must be able to conduct electricity, as illustrated in Figure 1. Moreover, the bottom layer of a textile PV cell has to be rendered conductive in a way that affects the textile's flexibility as little as possible.

There are in broad terms two ways in which fabrics can be made electrically conducting. One method is to first make the constituent fibres conducting before the fabric is constructed from them. The other method is to render an already constructed fabric conducting: either by (a) interlacing conducting yarns into the fabric or by (b) depositing a thin conducting coating onto the fabric. The first method results in the production of customised fabrics, whereas the latter method can involve the adaptation of an everyday, "off-the-shelf" fabric. We can consider the two approaches in turn.

2.3.1. Conductive Fibres

From the point of view of fibre conductivity, perhaps the most straightforward approach is to produce metal wires, or, perhaps better, metal fibres and to construct fabric from them. Metal wires have been classified as possessing diameters of 30–1400 μm , and metal fibres as possessing diameters of 2–40 μm [19]. Whether the fabric produced can be considered a textile or not is a matter of opinion! Suffice to say, though, a metal fabric possesses very few of the physical properties normally associated with a textile. An alternative is to incorporate metal wires or fibres into yarns during construction of the fabric. The metal fibres must be thin if the stiffness of the resulting fabric is not significantly increased. They are then, however, liable to break under the rigorous conditions of practical fabric construction, and also even in application, depending how demanding the application is. Moreover, there is the risk that contacts between the metal wires or fibres may only be intermittent.

A number of polymers possess some electrical conductivity, though 2–3 orders of magnitude lower than metals. Several of these intrinsically conducting polymers, such as polyaniline, polypyrrole and polythiophene, can be converted into fibres. Their mechanical performance is, however, generally inadequate [20], and their flexibility is quite limited [21]. Fibrous blends of these conducting polymers with conventional polymers have been tested with some measure of success [21], but it is crucial that the conducting polymer can survive the conditions for producing yarn and afterwards for constructing the fabric.

Yet another approach to rendering a fibre conducting is through deposition of metal or conductive polymer onto the fibre surface. Good conductivity is then achievable, without compromising bulk fibre properties. Indeed, the art of winding precious metal strips around silk yarns to produce so-called filé yarns has been practised for at least 2000 years and maybe even earlier. Fabrics consisting of these yarns were considered luxury items. Nowadays, metal coatings are commonly achieved by vacuum deposition or sputter coating [22]. Conducting polymer may be deposited from a suspension or solution by means of bulk polymerisation with the fibres present [23], but better control is achieved if the polymerisation occurs on the fibre surface. After the adsorption of a layer of monomer, it is then

polymerised by exposure to a suitable initiator [20,23]. The success of this method depends on the extent and uniformity of adsorption of the monomer and on the resistance of the fibres to the initiator, invariably an oxidising agent.

The success of deposition methods depends too on how strongly the deposited metal or polymer adheres to the fibres. For example, the metal layer, being much stiffer than the underlying fibre, is liable to crack when the fibre is flexed. The continuity of the layer is hence broken and conductivity is lost. Moreover, the metallic or polymeric coating has to withstand all the subsequent processes undergone by the fibre. These processes include both fabric construction and the subsequent conversion of fabric into product. The conditions for the deposition of PV cells also have to be taken into account: For example, polymeric coatings must be stable at the elevated temperatures that may be required.

The incorporation of carbon black or carbon nanotubes prior to fibre extrusion can impart conductivity to the fibres produced, though the proportion of carbon required has to be at least 10%: Graphene is another highly conductive option for which a smaller concentration should be sufficient. At the 10% level, however, the fibres stiffen, with the result that subsequent fabric construction is rendered more difficult [23]. Moreover, the black or grey appearance of the fabric may be aesthetically undesirable. The incorporation of metal particles in a similar way has also been used to impart conductivity, but metal particles can in time abrade the holes in the spinneret used in the extrusion process.

2.3.2. Conductive Fabrics

Of the two broad approaches to rendering fabrics electrically conducting, the integration of conductive yarns into a fabric structure is the more complex and less uniform process. It has to be taken into account that the yarns comprising a fabric are interlaced, and that, at the points where they interlace, they are subjected to bending and compression. Therefore, those structures where bending and compression are the least are liable to be the ones that are most desirable for conducting yarns [24].

For woven fabrics, the best integration of conducting yarns is in some types of twill weave structures [24]. Knitted structures pose a greater problem: The yarns in both warp and weft structures are subjected to severe bending in the loops, as shown in Figure 3. Indeed, the bends are so tight that mechanical failure of the incorporated conducting yarn would very likely result. It is therefore risky to interlace conducting yarns in the same way as the component fabric yarns. Instead, the yarns are often integrated in straight lines that interlace with the loops of the fabric. Whilst this approach may render the fabric conducting, there is a danger of impairment to its physical and aesthetic character.

In the case of nonwoven fabrics, imparting conductivity depends very much on the structure of the fabric. In a nonwoven fabric that possesses clear layers, conductive yarns can be placed in straight lines between the layers. Where layers are not readily identifiable, the ease of incorporation is governed to an appreciable extent by the nature of the fabric's porous structure.

Embroidery seems a way forward in producing conductive textile fabrics, in that a pre-programmed arrangement of conductive yarns can be created [25]. There has been interest, for example, in embroidered textile antennae for communication systems [26]. However, whilst embroidery could well prove to be a valuable way to impart conductivity to a fabric, it does render it more textured, a feature that could make deposition of PV layers more demanding. To the authors' knowledge, little has so far been attempted on rendering embroidered structures photovoltaic, but this approach may provide an avenue in the future.

A textile fabric can also be rendered electrically conducting through the addition of a conductive layer over one of its surfaces. Conductivity can, for example, be conferred by printing a conductive ink or paste onto the fabric. Conductive inks can be applied by ink-jet printing, a method that is now well established as a decorative technique. The ink consists of nanoparticles of a highly conducting metal, such as silver or copper, dispersed in a suitable liquid, normally an aqueous one. It is essential that there is a high level of dispersion stability, coupled with suitable viscosity and surface tension, and so

additives to promote these properties are also present in the ink. Aggregation of the metal particles would lead to poorer print quality and also risk clogging in the ink-jet nozzles.

The ink is deposited on the fabric as separate droplets, which, after drying, give rise to tiny independent zones of metal particles. These particles may then have to be sintered on the fabric to provide continuous connectivity between them, but the elevated temperatures usually required for sintering may degrade the underlying fabric. Silver nanoparticles can be sintered at 180 °C [19], so commodity fabrics made from polyester or nylon, for example, whose melt temperatures are well above 180 °C, are likely to be suitable. It is also important that the metal adheres well to the fabric, as, for bending and folding, the fabric can induce cracking in the metal layer, with consequent loss of conductivity. Spray deposition of silver nanowires has shown great promise as a technique to produce semitransparent electrodes [27] despite the tendency for unprotected silver to tarnish.

Screen printing, a historic process for the decorative printing of textile fabrics, can also be adapted for conferring conductivity. The process requires the use of a metal paste, usually a silver paste. The thickness of the paste on the fabric must be sufficient to impart high enough conductivity, and several passes are often required. As with ink-jet printing, once the paste has dried, it may crack on bending or folding of the fabric. Screen printed silver grids have been applied to the PEDOT (poly(3,4-ethylenedioxythiophene) anode contact of organic solar cells on polymer foil, to eliminate ITO and give increased cell efficiency [28].

An alternative method that we are pioneering in our work on the direct integration of silicon PV cells onto fabric is the direct deposition of a thin metal film onto textile fabric. Indeed, the incorporation of metal, and notably gold, goes back to the era of the ancient Egyptians and has been practised in India too for some millennia. Such decorative effects are still fashion features today, both in clothing and in interior design. Whilst this method can undoubtedly produce electrical conductivity at the fabric surface, care has to be taken that the complete surface is covered. This aspect is especially important for a rougher, textured surface like a textile fabric surface. In addition, as highlighted above, the deposited metal film is susceptible to cracking, when the fabric is bent or folded. Conductivity is then lost. To obviate this difficulty, we deposit first a thin layer of conducting polymer before depositing an aluminium film on top of it. Since the polymer is more flexible and more compatible with the fabric surface, sufficient conductivity is still maintained across any cracks that appear in the metal film [29].

Metal coatings on textile fabrics can be achieved by a variety of techniques [22,30]. These techniques include vacuum deposition, ion plating and sputter coating. Electroless plating is another technique that has begun to attract interest in the textile sector and is widely used in a number of other industries. It depends on the presence of a reducing agent, generally sodium hypophosphite, which reduces metal ions to metal atoms that are then deposited on the fabric surface. Nickel is often the metal used in this process.

3. Photovoltaic Textiles

With this introduction to photovoltaic cells and textile materials, it is feasible to consider how the two may be combined to produce an active solar electricity generator. As we have just explained, there is a big difference between smooth continuous surfaces, such as presented by glass or plastic sheets, and the rough discontinuous surface presented by textiles, for carrying the layers of a PV cell array. There are at least three alternative strategies:

- attachment of individual cells or photovoltaic films to a fabric;
- weaving or knitting fibres that have been rendered photovoltaic;
- direct deposition of photovoltaic cells on a fabric.

The first of these will not be considered in detail in this article, as it compromises the handle and integrity of a textile fabric and does not produce a true photovoltaic fabric. The other two each have different advantages and disadvantages as will be explained now, but both require the deposition of electrical contacts and semiconducting layers on to a substrate having different characteristics from

those used in conventional electronic technology. For instance, woven fabrics offer a wide range of constructions that may be used to advantage, such as capturing more light than a smooth reflective backing sheet.

3.1. Photovoltaic Attachment

Textile fabrics rendered PV through attachment of a PV cell or PV film are not strictly solar textiles, in that they are merely a combination of a textile fabric and PV panels [31,32]. Nevertheless, it is perhaps instructive to briefly highlight approaches that have been applied adopting this strategy. One of these is simply the attachment to a textile fabric of a PV panel, though one that is not fragile. Such combinations are present, for example, in some bags and backpacks. In other examples, an array of small individual cells, like sequins, is attached to the fabric. A more intimately single product unit is obtained, using a combination of known technologies. No special adaptation of PV cells or fabric is required, so a wide range of both can be chosen. However, the physical, mechanical and aesthetic properties of the fabric are very likely to be compromised. Moreover, the attachment of the cells and the electrical connections between them would be difficult to achieve on a commercial scale.

Textile fabrics can be rendered photovoltaic by attaching PV films to them, and many current solar textile products use this strategy. Thus, the technologies already developed for producing PV films can be extended to solar textiles. In addition, the methods of attaching a thin film to a fabric, e.g., sewing, welding and lamination, are all well established. However, we have already alluded to the problems with PV films in the Introduction, and indeed it is also important that the PV film is not ruptured during the attachment process. As with the addition of PV cells, the properties of the fabric may well be compromised.

Krebs et al. [33] adopted the strategy of incorporating polymer PVs on fabric. One adaptation of their strategy was the incorporation directly onto a fabric of a polymer PV on a polyester substrate. Another adaptation was notably more complex. It initially comprised the lamination of a thin layer of polyethylene onto a fabric and then, after plasma treatments of the layer, the application of a PEDOT electrode. The next stage was screen printing of the polymer PV and finally deposition of a further electrode. Krebs et al. [33] reported that the resultant fabrics performed well, though they were susceptible to degradation resulting from exposure to oxygen and water vapour, as is common with polymeric PV devices generally.

3.2. Photovoltaic Fibres

For direct deposition of PV cells, the fibre material must be chosen to withstand the processing conditions of the various layers required. For thin film semiconducting compounds, this generally needs a high temperature material, but most organic cells and some inorganic cells may be produced at close to room temperature or at least below 200 °C. If this restriction is not acceptable, then high temperature fibres are required, such as metal, carbon, glass or polyimide, whereas up to 200 °C, it is possible to use polyester or some nylons.

Perhaps the main drawback of using a photovoltaic-coated fibre is its subsequent ability to be formed into a fabric by weaving or knitting, with the attendant friction of the process placing big demands on the coating durability. Even if this is not a problem, the fabric topology must allow access to both electrical contacts of the coating on each fibre. This cannot be at the ends of long fibres because it would make the series resistance too high, limiting the current, so a scheme is needed to allow connections between separate smaller fibre cells on each longer woven or knitted fibre (It is usual to connect photovoltaic cells in series strings to sum the small voltages from each cell.). Figure 5 shows small cells connected in series along a PV fibre (i.e., upper contact to lower contact at each joining) which may then be interleaved with other similar fibres: There should be a contacting arrangement for connecting the fibres together to enable power take-off to a load. Consideration must also be given to the overlaps so that no unintended electrical connection is made at these points (i.e., top contact to top contact of adjacent cells, or other linking variations).

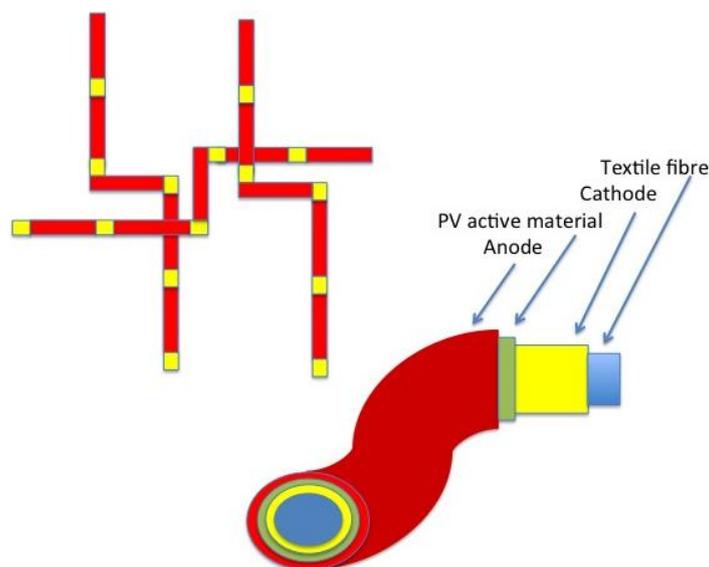


Figure 5. Generic photovoltaic cells on fibres showing the series connection of cells on a single fibre (upper contact to lower contact and so on) and crossovers where cells may make unintended electrical contact with each other.

The approach taken by Konarka Technologies, Inc. (Lowell, Massachusetts, USA) for organic PV wires used two wires to reduce the series resistance posed by thin PV active layers of organic compounds: A thin (100 μm diameter) stainless steel wire supported the photoactive layer (comprising a conducting polymer and a fullerene derivative sandwiched between electron transport and hole transport layers) and a second (50 μm) silver-paste-coated stainless steel wire spiral-wound around the first coated wire formed the counter electrode [34], the whole ensemble being clad in a polymer coating. In these organic PV cells, excitons are generated in the polymer and separate into electrons moving into the fullerene phase and then into the underlying metal, whilst holes move slightly further along the polymer chains to the secondary spiral electrode. These wires were liquid-coated at up to 15 m/min with only mild heating stages, and lengths of 5–30 cm had PV outputs of around 3% efficiency in standard test conditions. The optical performance is enhanced by light capture in the cladding.

A similar two-wire geometry was also used for DSSCs coated onto a titanium wire with an upper electrode formed of carbon nanotube (CNT) fibres or sheets spiralled on top [35,36]. These materials, depending on the CNT shape and the redox couple used in the DSSC, gave efficiencies of over 4% and good performance when tested for bending-induced degradation. Exchanging the top electrode wire for a CNT sheet provided greater contact area between the photoactive layer and the electrode and was less prone to separation when bent. The same research group demonstrated that polymer solar cell wires (based on Ti wires coated with titania nanoparticles and then with a photoactive polymer pair P3HT:PCBM and PEDOT:PSS, completed by an aligned CNT fibre electrode) could be interlaced into a simple open structure having cells connected in series to boost the voltage [37]. A variation of these two PV types by the same group was tested for operation when stretched, including a simple interwoven structure of five DSSC cells in each direction, which continued to generate power after 50 stretch cycles: a central elastic conducting fibre wound with multi-walled CNTs was placed within a Ti wire holding the DSSC material [38].

Miniature sensors on optical fibres may be powered by PV coatings, as they only require low power, for which it is less important for the contacting geometry to meet the requirement of low series resistance. [39] This avoids the limitations imposed by metallic wire substrates, not the least being the common lower electrical contact for all cells fabricated upon such supports, making it difficult to connect cells in series. These Finnish researchers used glass and PMMA (poly(methyl

methacrylate)) optical fibres with a conducting transparent metal oxide (TCO), atomic layer deposition (ALD), coating of ZnO:Al as a base for DSSC layers of TiO₂ plus dye and an iodine gel electrolyte, completed by a gel counter electrode and metal contacts. ALD was used for the TiO₂ on plastic fibre, in order to avoid the usual 450–500 °C high temperature sintering step that could be used for the TiO₂ on glass fibre; low temperature dip-coating was used for the dye and electrolyte and counter electrode additions to both fibres. The limitations of the special coating methods reduced the adhesion of the porous TiO₂ on glass and limited the porosity of the ALD TiO₂ on plastic, so PV performance was modest whether the light came from the side of the fibre or was coupled into the end.

Polyimide-coated glass fibre was the substrate for miniature organic PV cells fabricated by thermal vacuum evaporation. The plastic coated fibre was covered, whilst rotating, with a thin multilayer metal anode, organic photoactive layers of copper phthalocyanine and C₆₀ with an overlayer of an organic aluminium compound, and completed with a thin multilayer metal cathode. PV efficiency was less than 1%, partly due to the intermittent deposition of the organic layers as the fibre was rotated, although it was less affected by shading than similar planar cells [40].

The variety of coating methods employed in efforts to deal with fibre substrate material restrictions is displayed in a review by Peng and Zou [41], which lists several examples of inorganic, organic, and DSSC PV fibres with mostly rather short length. Methods include high pressure CVD, electrodeposition, chemical bath deposition, aerosol spray pyrolysis, and RF magnetron sputtering for inorganic components, and evaporation, solution, and dip coating for organic components. Although DSSC fibre shaped PVs can perform almost as well as conventional planar DSSCs, they are complicated to fabricate. However, the improved performance and solid-state structure of perovskite PV cells has been tested in a fibre configuration (e.g., [42]), albeit on a stainless steel wire, using a single step solution process for the active layer. Both types of electrochemical PV cell have similar concerns for stability.

There is yet a big step between PV fibres and a PV fabric: The assembly of fibres into a two- or three-dimensional structure requires the fibres to withstand twisting, stretching, and abrasion, all of which have yet to be greatly tested. In particular, the easily coated organic PV materials tend to be sensitive to moisture, oxygen, UV and abrasion, so that effective hermetic sealing is a necessity. Bedeloglu et al. [43] made organic PV cells on polypropylene fibre with conducting PEDOT:PSS as the lower electrode and a thin metal top electrode, between which two alternative photoactive polymer blends were tried: P₃HT/PCBM and MDMO-PPV)/PCBM. Dip coating and mild drying temperatures were used for all of the organic layers, but vacuum thermal evaporation was used for the metal layers. The efficiencies of these small area PV cells were below 1%, with low photocurrents and high resistance losses arising from the rather thin photoactive layers. Optimising the thicknesses should improve performance, and so the authors' suggestions on how such PV fibres could be manufactured using liquid coating and drying treatments are pertinent. They note the need to protect the fibre surface when spinning or weaving textiles from PV fibres. Assembling these into a fabric is still a challenge!

Examples of a PV textile made from PV fibres that look more like a fabric have employed two mesh-like electrodes on each side of the PV material to avoid transparent conducting oxide (TCO) contacts, but it is difficult to encapsulate and retain a textile feel. (e.g., [44]). However, a further paper from these researchers explains further how to include DSSC cells in a woven glass yarn textile: the cells used perforated, dye-loaded, TiO₂-coated stainless steel ribbon photoanodes (weft) and Pt-coated carbon yarn counterelectrodes (warp), with an acetonitrile electrolyte injected into a laminating plastic pouch after the cells had been inserted into the glass textile [45]. Alternatively, the two conducting parts of a PV cell may be woven in an interlaced arrangement, one set holding the PV materials over one electrode, and the other set providing the counter electrode. In the textile woven by Zhang et al. [46,47], a metallised polymer fibre (made by chemical plating and electroplating) was coated with dye-sensitized ZnO nanowhiskers and then overcoated with CuI (all by liquid coatings); the counter-electrodes were copper coated polymer fibres. During weaving, the tension of the counterelectrodes (the warp fibres) was controlled so as not to apply too much pressure to the CuI

surface on the weft photoactive fibre, which reduced the output voltage and current. Different weaves and different combinations of fibre diameter and spacing were tested, although simple plain-weave was the best performer at a little over 1% efficiency. Moreover, cells could be connected in series and parallel arrangements to step-up voltage or current according to requirements.

The cylindrical shape of fibre PV cells may offer less sensitivity to the illumination direction than conventional planar cells, but fibres will be non-uniformly illuminated across their diameter, and may be shadowed in a woven construction. A more easily handled shape between planar and fibre is presented by Krebs et al. [32] as PV tape. The Danish group's sustained development of organic PV cells by printing and roll-to-roll coating has shown that cells may be rapidly produced on long webs, with the ability to build-in series connections for strings of cells, and are suitable for cutting into tapes for further assembly. They have woven 10 mm wide organic PV tapes as weft with woven polyester tapes having embedded silver wires as warp, producing $25 \times 25 \text{ cm}^2$ sample textiles. Each strip of PV tape had 16 cells in a series string, several tapes being aligned in parallel and connected together along each side of the web to provide a positive terminal at one side and a negative terminal at the other: The output was 7.9 V open circuit or 114 mA short circuit, with an efficiency of about 1%. As the tapes could be hermetically sealed before weaving, and as the cells are readily connected or separated at the gaps between them, this scheme offers an effective way of producing a true designer PV fabric.

3.3. Photovoltaic Fabrics

Coating an already fashioned fabric avoids the restrictions of processing coated fibres and of designing fibre-level interconnections between small cells, although with the same temperature restrictions. It does, however, present a rough texture for the multilayer coatings to be added, and will usually offer a complex surface that shifts as the individual yarns move over each other. This suggests that a big aim of any PV fabric design will be to ensure electrical continuity across the fabric as it flexes. A simple first step has been to coat the fabric with a filler that levels the rough texture and fills in the spaces between fibres. This approach was taken by Plentz et al. [48] who produced low efficiency amorphous silicon PV cells on glass fibre fabrics having a dip-coating of polymer before the usual PV layers were applied, although cracking was mentioned as a potential problem. Higher efficiencies were achieved with CIGS cells deposited on to glass fibre fabric pre-coated with particle-filled resin that withstood the high processing temperatures of this type of cell [49]. Both of these inorganic PV cells use vacuum processes to apply the semiconductor: thermal evaporation of elements for CIGS and plasma enhanced chemical vapour deposition for a-Si:H. The electrical contacts are commonly applied by sputtering in a partial vacuum, whether they are metallic or a conducting transparent oxide.

The more usual fabric materials demand low temperatures, which suggests organics or DSSC-types of PV rather than inorganic semiconductors. However, as mentioned in Section 2.1 above, amorphous silicon is still an option, as it may be formed at $200 \text{ }^\circ\text{C}$ by plasma enhanced chemical vapour deposition (PECVD) from gaseous sources of Si and the dopants for the other two layers, enabling several commodity textiles to be used. We chose woven polyester for our flexible PV devices [50] because it is stable to over $200 \text{ }^\circ\text{C}$ in vacuum, is UV resistant, and is available in large amounts, with a choice of weaves and fibre sizes. PV cell fabrication uses a mix of techniques known to the semiconductor and textile industries. First, the fabric is cleaned and then lightly calendered to render the surface continuous without melting the whole thickness. The lower PV contact is formed of two layers: A liquid coated conducting polymer, PEDOT:PSS, and a vacuum evaporated metal, aluminium. The polymer coating is insufficiently conducting to form an effective PV electrode, but its flexibility enables it to bridge any microcracks that develop in the more brittle aluminium as the device is twisted or stretched [29]. This is followed by the photoactive, triple amorphous silicon layers (N-type, undoped, and P-type) laid down by low pressure, RF PECVD from silane with phosphine or diborane, at $200 \text{ }^\circ\text{C}$ or slightly less. The upper contact is a conventional sputtered TCO that also acts as a first encapsulating coat. Figures 6 and 7 give a schematic diagram of the several layers (offset vertically) and their visual appearance as they are successively added to a plain weave polyester fabric.

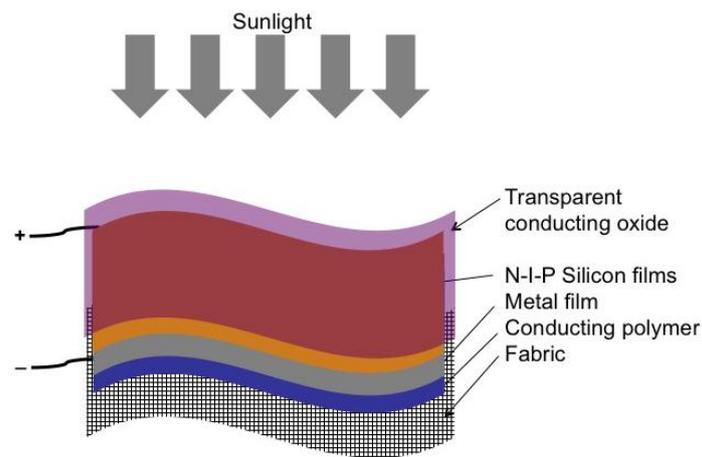


Figure 6. Schematic diagram of the successive layers in an amorphous silicon flexible PV cell on textile (the layers are offset vertically).

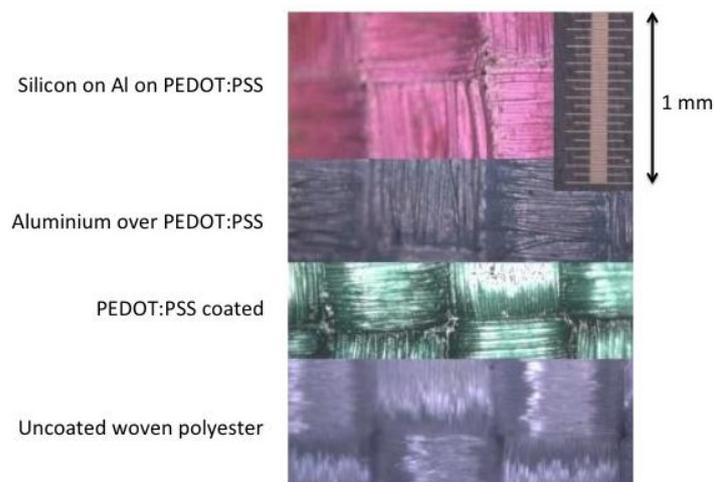


Figure 7. Optical micrograph of plain weave polyester successively coated with the layers of an amorphous silicon PV cell, showing conformal coverage.

Each of these layers is defined by depositing it through a thin mask, thus enabling any shape or size of cell to be made. Interconnections are made by connecting the selected upper and lower contacts of each cell with metal tracks on the fabric, and wires may be taken to an external load by connection to metal studs pressed through the tracks. Present performance is limited by shunt paths through the thin semiconductor at places where there are protruberances from the textile fibres that are not conformally coated by the various layers. These are largely eliminated by calendaring and the first liquid coat, but the problem may be further alleviated by selecting a yarn that has fewer fine fibres. Note that the active PV cells lie on the bundles of fibres in each warp and weft yarn, rather than between them, but the interspaces of the open weave may be reduced by selection of another weave pattern. Thus, the advantage of a non-planar surface for scattering incident illumination deeper into the cells rather than reflecting it away may be retained although there is still the disadvantage of requiring exact conformal coating of each successive layer. In addition, a silicon-based cell has a relatively narrow spectral response compared with DSSCs or stacked cells that can tailor their response by using more than one photoactive material: In particular, the a-Si:H cells have the same spectral response on textiles as they do on smooth glass substrates.

The non-planar surface of a textile offers the opportunity to increase the optical absorption over that of a smooth reflective surface, but it has not been realized yet. The advantage of a textured back

contact has been recognized for some years, as this can scatter light back into a solar cell for a further chance of absorption, either because longer wavelengths are weakly absorbed or because a cell is too thin to be optically opaque. The effect for thin N-I-P thin-film silicon cells has been investigated for glass substrates with random-textured TCO layers overcoated with silver: Angular reflection measurements were made for different laser wavelengths [51]. Although the more complicated behavior of the multi-layers in complete solar cells includes the effects of refractive index changes at the interfaces as well as layer thicknesses, this textured back surface did have a dominant effect on light trapping within the cell. For smooth layers, the planar structure of thin cells can also trap light as guided waves, according to the angle of incidence, although the angular dependence may be reduced by employing a periodic pattern along the layer thickness [52]. Absorption with the randomly rough surfaces found in practice may be enhanced by adding photonic structures, even with modest spatial features which do not detract from the desired electrical properties of the layers [53]. Full photonic light trapping generally requires periodic structural elements with nanosized features (e.g., [54–56]) that are difficult to fabricate on a textile surface, but some degree of light trapping is still feasible even with disordered nanostructures and these do have less sensitivity than coherent light trapping structures to the acceptance angle of the light (e.g., [57,58]).

4. Technological Specifications

It will now be apparent that specifying a textile-based PV power source offers a wide range of options for the basic construction, as well as for the PV cell shapes, sizes, and their interconnection into a PV array. The starting point has to be consideration of the application and its power demand: is it possible to supply this by PV alone, or will batteries also be required? Integrating thin batteries into a PV textile has been proposed, with some loss of fabric handle and drape, and is possible for low power demands, such as for sensors or portable electronics items. Further attention should be given to the choice of materials (both environmental and economic issues) and to the thermal limitations of the fabric (process energy cost and processing stability). In addition, the application will have its own requirements for operating conditions and perhaps for washing or cleaning if the fabric is to form part of clothing or furnishings.

We should also take into account the effects of incorporating PV cells on the properties of the fabric itself. It is evident that the surface character of the fabric will necessarily be altered by the incorporation of PV cells, and indeed the deposited PV cells are liable to be highly susceptible to external conditions. For this reason, the PV fabric surface has to be suitably protected, depending on the application for which it is destined. For an outside use such as tents, the robust resin coating that is used on tent fabrics will also have to protect the PV cells on it. For an indoor application, such as curtains, where conditions are expected to be more clement, the protective layer can be thin, so that drape in particular is not compromised.

Although surface character will be altered, the factors comprising the bulk properties of the fabric should be affected as little as possible. These factors include fibre composition, yarn construction, fabric construction and, particularly in the case of nonwovens, porous nature. It is clear too that the construction and properties of the products made from PV fabrics should also be unaffected. For some particular applications, there will be further specifications. An obvious example is that clothing should retain its comfort and aesthetic appeal.

From the PV point of view, the specification will have to work with the presently low conversion efficiencies of many flexible PV materials: Although any required voltage may be met by coupling cells in series, regardless of their size, current is proportional to cell area and many small cells would be needed in parallel to meet more than low demands. It should also be remembered that the performance of conventional PV cells and panels is specified at “standard operating conditions” (STD): $1 \text{ kW}\cdot\text{m}^{-2}$, AM1.5 spectrum, $25 \text{ }^\circ\text{C}$. For novel applications, the light intensity may be much lower and from an artificial source instead of the sun. There may be extensive and changeable shadowing for flexible PV whose shape is continuously changing with movement. All of these factors will reduce the available

irradiance for conversion to electricity, despite some photoactive semiconductors, such as amorphous silicon, responding better to low light levels than does crystalline silicon. For example, a crystalline Si PV panel may have a maximum efficiency of 18% at STD but indoors could be only 5% efficient, depending on the irradiance [59].

5. Manufacture of PV Fabrics

We have seen that many coating techniques have been employed for laboratory development of flexible PV cells, including both chemical and physical processes: they include electroless and electro-plating, liquid printing, dip-coating, vacuum evaporation, atomic layer deposition, sputtering, chemical vapour deposition and polymerisation. In order to manufacture these devices on fabrics, it would be helpful if the methods were familiar to the textile industry, or alternatively, if there was expertise within the electronics industries of handling rolls of flexible materials. Neither of these circumstances is common. However, the textile industry is accustomed to liquid coating of rolls of material and has been looking to gas-based processes, including plasma treatments, to reduce the need to handle large quantities of liquid waste (e.g., [60]). Roll-to-roll coating is also used for plastic packaging, and for some solar cells on polymer film. Researchers in Germany proposed a scheme with moveable-wire masking to fabricate PECVD amorphous silicon solar cells on plastic sheets [61] that could be used with a roll-to-roll system (Figure 8). Uni Solar Inc. (Auburn Hills, MI, USA) has for some years manufactured triple-junction amorphous silicon solar cells on a flexible laminate, with a self-adhesive backing for fixing to structures, by a roll-to-roll process. Around the same time, Krebs showed how organic solar cells may be fabricated on a polymer film without vacuum processes, using all solution-based layers, that would be suitable for roll-to-roll production [62]. However, more development is needed for handling the very flexible textile materials in a controlled manner for precise coating with solar cell over-layers. Recently “activated” cotton has been used together with graphene and a polymer gel electrolyte as the base for flexible supercapacitor energy storage, manufactured mainly by wet processing. This was combined with a flexible solar cell by roll-to-roll assembly to form a complete power pack [63]. Another use of graphene on a fabric describes its active performance as a strain sensor when formed from reduced graphene oxide on cotton, demonstrating the repeated flexibility of the combination [64].

In contrast, manufacturing the connections and electrical leads for PV textiles may build on experience with heated textiles, from electric blankets to racing car tyre heaters, where they have been used for over a hundred years. Conducting wires are readily incorporated into a woven or knitted textile and may be used as the main conductors to the electrical load (e.g., [65]).

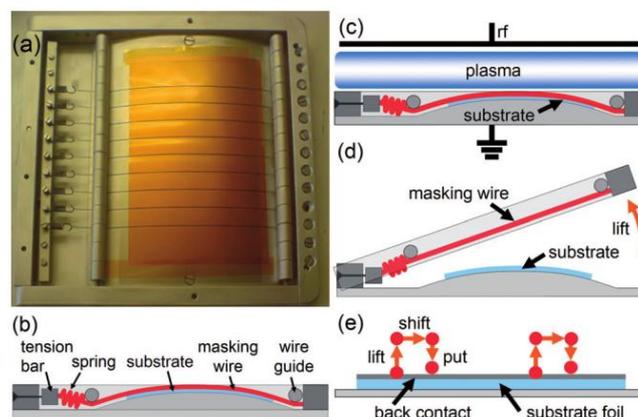


Figure 8. Cont.

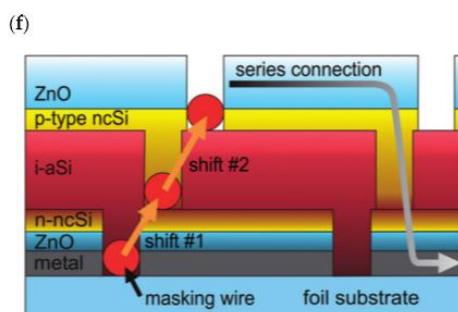


Figure 8. In situ series connection of PECVD silicon solar cells on polymer film: Masking wires are shifted laterally between the deposition steps for silicon and contacts (evaporated metal and sputtered ZnO). Insulating intrinsic amorphous silicon isolates the back contacts of adjacent cells from each other. (Reproduced from [61] with permission from Taylor & Francis Ltd., Abingdon, Oxford, UK) (a,b) photograph and diagrammatic cross-section of the substrate holder used for static substrate tests; (c,d) show how tensioned masking wires hold the substrate in position within the deposition chamber, but can be lifted for repositioning between coating layers; (e) shows the sequence of wire lifting, shifting, and replacement; and (f) diagrammatic cross-section of three series connected cells indicating the successive mask shifts used in the deposition sequence.

6. Applications

There is no doubt that over the past few years, much wider commercial interest has developed in PV textile fabrics, an interest principally promoted by the drive for wearable technologies (e.g., [66]). For example, well-known brand names have been moving into PV fabric technology, such as Ralph Lauren (New York City, NY, USA (solar backpack) and Tommy Hilfiger (Amsterdam, Netherlands) (solar powered jacket). In the Netherlands, Pauline van Dongen (<http://www.paulinevandongen.nl/philosophy/>) has designed a number of dresses featuring PV cells. However, these designs for the most part utilise the attachment of PV cells to fabric, as outlined in Section 3.1. Indeed, in extreme cases, dresses have been designed that are in effect a collection of small interconnected PV panels. One of the chief problems with producing PV fabrics through genuine integration of PV cells stems from the contrasting properties of traditional fabrics and electrically conducting materials. As already noted above, metals have high conductivities but poorer flexibility and extensibility, whereas the opposite is true for conducting polymers. It has been speculated that carbon nanomaterials may provide a solution to this paradox, but optimisation of preparation and structure is still needed [67]. Nonetheless, our own work does indicate that applying both conducting polymer and metal can provide an effective solution to the problem.

In addition, the area of clothing on the body that would be exposed to light is only around 0.1–0.3 m². For an array of cells possessing 5% efficiency, as might be expected with amorphous silicon cells for example, the power generated would be 50 W·m⁻², when the cells are exposed to standard solar irradiation of 1 kW·m⁻², the value when the sun is directly overhead. Thus, there will be a maximum power output of 5–15 W. This is enough for devices such as mobile phones and tablets to be powered. Importantly, tiny sensors can also be powered. For example, sensors embedded in clothing to monitor a subject's condition are increasingly being used in sportswear and healthcare. These sensors are small enough not to impair fabric properties to a significant extent.

In a number of instances, an additional benefit would be given to textile fabric products of a large area from the integration of PV cells. Not only could awnings, canopies, tents and so on provide protection but they could also fulfil the additional function of generating electricity. This aspect could be very helpful for disaster relief in remote locations. Several PV fabric products have been commercially developed: Examples include Power Film Solar (Ames, IA, USA), and ShadePlex (Ann Arbor, MI, USA). Many have used amorphous silicon, on the basis that it is particularly effective early and late in

the day compared to crystalline cells, when sunlight impinges on the fabric surface at a lower angle. These products, however, consist of a thin PV film attached to a textile fabric.

There is also scope for laying PV fabric over other surfaces, especially those that are curved or irregular. Roofs on buildings are a good example, and indeed putting PV fabrics on roofs is starting to gain traction in remote areas of the world, away from a mains electricity supply. There has also been growing interest from the military in PV fabrics. There would be benefits for tents and field hospitals, particularly in remote areas. Logistic chains would be simplified through the reduction of heavy, cumbersome batteries employed in theatres of operation and transported between charging stations. In horticulture, interest is developing in the use of PV fabrics for controlling airflow, humidity and irrigation in greenhouses. Solar sails are being devised to power electronic devices in sailing boats.

Ideally, a PV generator needs to be functionally integrated with a device for storing electricity, such as a battery or supercapacitor, which, in turn, is linked to the device to be powered. The miniaturisation of electronic devices has sparked real interest in their incorporation into textiles. However, although tiny sensors have been successfully used in textiles and energy storage devices are now also becoming capable of being used in textiles, the challenge of energy supply devices is still regarded as tricky. The direct integration of amorphous silicon PV cells, however, such as we are attempting, represents one realistic response to this challenge.

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