Review of Progress Toward 20% Efficiency Flexible CIGS Solar Cells and Manufacturing Issues of Solar Modules

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***Abstract*—Solar cells based on chalcopyrite Cu(In, Ga)Se_2 (CIGS) absorber layers show the highest potential for low-cost solar electricity by yielding comparable efficiencies to polycrystalline Si wafer-based cells, while also offering inherent advantages of thin-film technology for cost reduction. Highest efficiency of 20.3% was recently achieved on rigid glass substrate. Deposition of CIGS films onto flexible substrates opens new fields of applications and could significantly decrease production costs by employing roll-to-roll manufacturing and monolithic integration of solar cells to develop modules. Whereas, some years back, it seemed difficult to reach performance levels on flexible substrates similar to that obtained on glass, recent results on flexible polyimide prove that the efficiency gap can be significantly reduced. Different materials, i.e., mostly metals or plastics, have been used as flexible substrates, with highest cell efficiency of 18.7% demonstrated on a polyimide film. Improvements in efficiencies of flexible solar cells and modules achieved over the past few decades are discussed in this paper, addressing the main characteristics of substrate materials. The technology transfer from laboratory research to large-scale industrial production of CIGS modules leads to new manufacturing challenges, mainly for CIGS deposition, interconnections of cells, and long-term performance stability.**

***Index Terms*—Cu(In, Ga)Se_2 (CIGS), flexible, manufacturing, module, solar cells.**

I. Introduction

CONVERTING abundant solar energy directly into electricity represents a viable and very attractive option for cost-effective sustainable production of electrical energy. Photovoltaic (PV) technologies based on Si solar cells have been the focus of research since the 1950s and currently they cover 80–85% of the PV market globally [1]. Laboratory-scale conversion efficiency up to 20.4% has been achieved using polycrystalline Si wafer, while modules with a typical efficiency of 15–16% are commercially available nowadays [2], [3].

Interest in alternative materials and device processing technologies has grown over the years due to the weight, rigidity, expensive wafer, and processing limitations of Si wafer-based solar cells. This has led to extensive research and development of thin-film solar cells to overcome some of these limitations. Compound semiconductors with high absorption coefficients such as Cu(In, Ga)Se_2 (CIGS) and CdTe can be utilized as very thin films (2–3 μm) to absorb nearly all incidental solar light. Besides the decrease in required light-absorbing material per solar cell, thin-film solar cells also offer the advantage of low-cost deposition on a large area. One of the most attractive features of flexible thin-film solar cells is the high potential to decrease the production costs, because roll-to-roll manufacturing on flexible substrates enables use of compact size deposition equipment, high throughput, and low thermal budget, especially for CIGS deposition. New application possibilities have emerged with the development of solar modules on flexible substrates.

CIGS-based solar cells are promising for cost-effective solar electricity production. A record efficiency of 20.3% reported in 2011 for a CIGS cell deposited on a rigid glass substrate has closed the gap with the state-of-the-art polycrystalline Si wafer-based technology [4]. Reaching such a high performance level on flexible substrates has proven to be rather challenging, especially due to limitations imposed by the choice of substrate material. Nevertheless, a world record efficiency of 18.7% on polyimide film has been achieved recently [5], revealing that flexible solar cells with performance close to rigid solar cells can be developed. However, several issues still need to be addressed in order to transfer laboratory-scale results on flexible substrates into industrial production of highly efficient flexible CIGS solar modules.

CIGS absorber layers for state-of-the-art high-efficiency solar cells are generally grown by vacuum-based methods such as thermal coevaporation at high substrate temperature of about 600 °C or sputtering of precursor layers followed by selenization in Se vapor or H_2Se gas. Nonvacuum deposition methods are also used, aiming toward further reduction of production costs. These methods are mainly based on printing of precursor layers or on a deposition from a solution (e.g., electrodeposition) followed by the selenization step [6].

In this paper, the development of flexible CIGS solar cells on different substrate materials is reviewed with an emphasis on achieved efficiencies and issues of module manufacturing. Progress toward 20% efficiency devices on flexible substrates is presented based on research carried out in our laboratory.

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TABLE I
SUBSTRATE MATERIALS USED FOR FLEXIBLE CIGS SOLAR CELLS AND THEIR TYPICAL PROPERTIES

	CTE [10^{-6} K^{-1}]	Max. T [°C]	Thickness [μm]	Density [g/cm^3]	Example of groups and selected reference
				Cell material	
$CuInSe_2$	7-11		2-3	5.8	
Mo back contact	4.8-5.9		0.2-1.5	10.2	
ZnO	3-5		0.1-1	5.6	
				Rigid substrate	
SLG	9	600	2000-5000	2.4-2.5	
				Metals	
Stainless Steel	10-11	>>600	25-200	8	Empa [27], FSEC[28], HZB[23], Korea Tech[29], NREL [30], Shanghai[31], ZSW[32]
Mild steel	13	>>600	25-200	7.9	Empa[33], ZSW[34]
Cu	16.6	>>600	50-100	8.9	CIS[35], IST[36]
Ni/Fe alloys	5-11	>>600		8.3	ZSW[37]
Ti	8.6	>>600	25-100	4.5	AGU[38], AIST[19], FSEC[25], HMI [39], ZSW[40]
Mo	4.8-5.9	>>600	100	10.2	AIST[9], CIS[41], ISET[42]
Al	23	600	100	2.7	Empa[33]
				Ceramics	
ZrO_2	5.7	>>600	50-300	5.7	AIST[20]
				Plastics	
PI (Kapton or Upilex)	12-24	<500	12.5-75.0	1.4	AGU[43], AIST[44], Empa[5], HZB[45], IEC[46] , ISET[47], ZSW[37]
PET	60	<500	300-400	1.4	Uni Malaysia[48]

Finally, a brief discussion of industrial manufacturing and the challenges faced by CIGS companies is given. This paper does not concentrate on physical or chemical issues of CIGS absorbers and other layers. It rather gives a historical insight into the development of flexible CIGS solar cells and the main issues that still have to be solved before providing the market with highly competitive flexible solar modules.

II. STANDARD Cu(In, Ga)Se_2 SOLAR CELLS

Chalcopyrite-based solar cells were first developed using $CuInSe_2$ absorber material, but it quickly became clear that the addition of Ga can be used to tune the band gap to values between 1.04 eV for $CuInSe_2$ and 1.68 eV for $CuGaSe_2$ [7]. Best-in-class devices are typically grown with a Ga/(Ga+In) ratio of 0.25 to 0.35, corresponding to a band gap of approximately 1.1–1.24 eV [8]. Several reviews on absorber deposition processes as well as other layers of the CIGS solar cell stack are readily available [9]–[11]. The commonly used standard structure of CIGS solar cells in substrate configuration is presented here.

Sputtered Mo on a substrate is usually used as the electrical back contact. During CIGS deposition, an interfacial $MoSe_2$ layer is formed, which facilitates a quasi-ohmic contact between CIGS and Mo [12]. Adhesion promoting layers, diffusion barriers, and/or insulating layers can also be added on top of the substrate prior to the Mo deposition. CIGS is then deposited using methods mentioned above. As Na was found to improve the electronic quality of the absorber, various methods have also been developed to add Na either prior, during or after CIGS deposition [13]. The CdS buffer layer is then grown via chemical bath deposition. Finally, an n-type ZnO/Al:ZnO transparent conducting window layer is sputtered as front electrical contact to collect the charge carriers. Many variations of this stacking sequence exist, but highest efficiency devices have been developed using such a structure that can be summarized as substrate/Mo/CIGS/CdS/i-ZnO/ZnO:Al [4], [5], [14].

The substrate material has to be chosen in view of its thermomechanical properties, as well as its compatibility with the subsequent deposition steps and integration into a solar module. The following section discusses the relevant characteristics in more detail.

III. FLEXIBLE SUBSTRATE MATERIALS AND DEVICES

To find a suitable flexible substrate for depositing thin CIGS films, different physical and chemical properties have to be taken into account. Stability and compatibility of the substrate material through the whole production process and operational lifetime of solar modules are mandatory requirements. Demands such as vacuum compatibility, thermal stability, suitable coefficient of thermal expansion (CTE), chemical inertness, humidity barrier function, and surface smoothness have to be fulfilled [15]. Availability in large quantities, low cost, and light weight are also necessary for an optimal substrate material.

Table I gives an overview of relevant properties of materials used as flexible substrates for CIGS deposition processes. For comparison, soda-lime glass (SLG) is included as a standard rigid substrate. Typical parameters of the constituent layers of CIGS solar cells are given. Motivated by the need for good adhesion, suitability with the best deposition method, as well as low weight (especially for space applications), material properties such as CTE, maximum suitable temperature, and density are also provided. Optimal CTE of the substrate should be close to that of CIGS and is, therefore, desired between 5×10^{-6} and 12×10^{-6} K^{-1} to avoid adhesion problems and/or crack formation during CIGS deposition at high temperature. SLG meets most of these requirements, which partly explains its widespread use as a substrate. Research groups active in alternative substrate materials and selected references are also shown in Table I.

As flexible substrates, mostly metals and special polymers have been used. Metals have the advantage of being able to withstand very high deposition temperature, but they generally have rather high density, roughness, and CTE (especially Cu and Al). Furthermore, most of them, especially steel, contain metallic impurities (e.g., Fe) that are detrimental for solar cell performance. Reactivity of metals such as Cu or Al with Se is an issue of concern, but it can also be used beneficially, for example, to synthesize $CuInSe_2$ starting from a Cu substrate [16]. On the other hand, polymers as substrates have a much lower density and roughness than metals, but they cannot sustain high temperatures of 550–600 °C, as commonly used to manufacture high-efficiency cells. Therefore, use of a low-temperature process is necessary, but this generally leads to significantly inferior absorber quality [9], [17], [18]. Polyimide films are one of the few polymer films that can sustain temperatures close to or above 450 °C for a short time, but their CTE values are rather high and they can vary widely depending on suppliers, necessitating careful adaptations of the deposition conditions of the stack to avoid cracks formation and/or delamination. Ceramics have also been used as flexible substrates [19], [20]. However, their brittle behavior might be an issue for industrial production on large scale. Typical thickness of metal, polymer, or ceramic substrate materials is generally between 25 and 400 μm, about one or two orders of magnitude lower than standard SLG substrates.

One of the major advantages of polymeric substrates is their electrically insulating property. It allows for direct monolithic integration of solar cells, developing modules through successive patterning of layers in-between the different deposition steps. On the other hand, solar cells deposited on metal substrates have to be stringed and tabbed, as used in Si wafer-based technology, or connected in a shingling-type configuration. Monolithic integration on conductive substrates is still possible by depositing intermediate dielectric barrier layers on metallic substrates. The barrier provides electrical insulation between the substrate and Mo electrical back contact, and it can also serve as a diffusion barrier against impurities from the substrate [21]. Compatibility with further processing steps and good adhesion are necessary, and additionally shunt paths should be avoided. Typical examples of such insulating barrier layer materials are Al_2O_3 and SiO_x [22]–[26].

About a dozen institutions around the world are involved in research and development of flexible solar cells on various substrates. Fig. 1 gives an overview of the highest efficiencies pub-

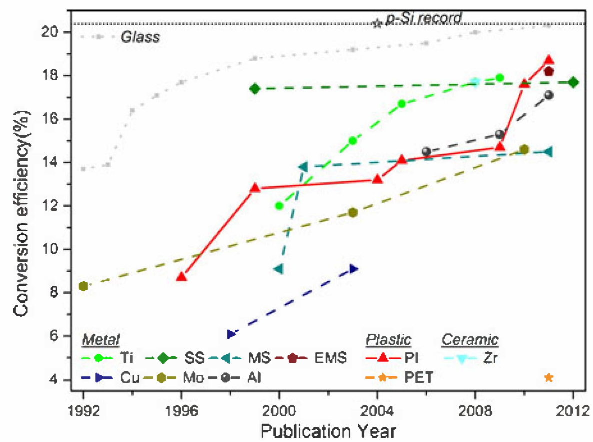

Fig. 1. Evolution of record efficiencies of small (0.4–1 cm^2) CIGS solar cells on various flexible substrates (measured under standard test conditions). The evolution of record values on SLG is shown as a reference for progress of CIGS technology. World record efficiency for polycrystalline Si is also indicated. (SS: Stainless steel. MS: Mild steel. EMS: Enameled mild steel. PI: Polyimide. Zr: Zirconia.)

lished over the past 20 years and covers most of the substrate materials used for CIGS flexible solar cells. Included results are restricted to typical laboratory-scale cells with areas of approximately 0.4–1.0 cm^2. The current polycrystalline Si record efficiency is also given for comparison.

The efficiency of CIGS solar cells on glass substrates progressed significantly during the 1990s. Thereafter, only small incremental improvements have been made toward reaching a level similar to that of polycrystalline Si cells. For flexible solar cells, Mo, Ti, and Al foils were first tested by International Solar Electric Technology (ISET, Chatsworth, CA) in 1992. The absorber was grown using an e-beam evaporation process with subsequent selenization, and only the best efficiency on Mo (8.3%) was reported [42]. In 2003, ISET reported an efficiency of 11.7% on a Mo foil using an ink-based method [49]. In 2010, the Institute for Advanced Industrial Science and Technology (AIST, Tokyo, Japan) was able to achieve 14.6% efficiency on a Mo foil using a three-stage coevaporation process [9]. On Ti foils, Zentrum für Sonnenenergie und Wasserstoffforschung (ZSW, Baden-Württemberg, Germany) published 12% efficiency already in 2000 [37], which was then improved by Hahn-Meitner-Institut, (HMI, Berlin, Germany) [50], [51] before Aoyama Gakuin University (AGU, Tokyo, Japan) reported the highest value of 17.9% in 2009 using a three-stage coevaporation method for CIGS deposition and a Cd-free buffer layer [38]. The Institut für Solar Technologien (IST, Frankfurt, Germany) used Cu-tapes in a galvanic roll-to-roll deposition of In followed by sulfurization, but efficiencies of solar cells remained under 10% [16], [52]. Stainless steel was already used as a substrate by the National Renewable Energy Laboratory (NREL, Golden, CO) in 1999 [53] and their device with an efficiency of 17.4% remained the best until 2012 when our group (Empa, Dübendorf, Switzerland) published a certified efficiency of 17.7% on Ti-coated SS foil [27]. Cells on mild steel yield much more limited efficiencies due to impurity diffusion, and only ZSW and Empa have tried to use it as a flexible substrate [22], [33]. However, enameled mild steel has shown interesting potential,

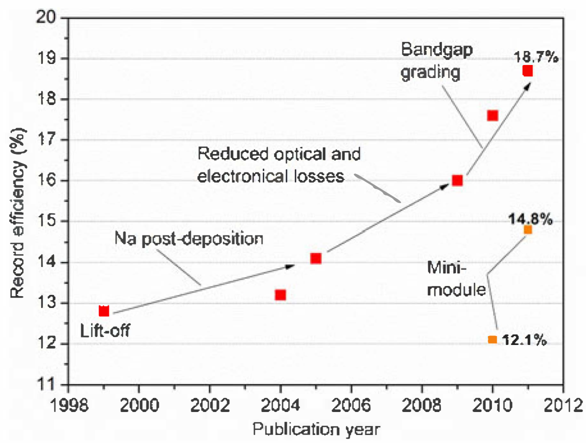

Fig. 2. Efficiency improvements of CIGS solar cells and mini-modules on polyimide substrate developed at Empa (previously at ETH Zürich). Mini-module was developed in collaboration with the company Flisom AG.

as efficiencies of 17.6% [34] (certified but not shown in the plot) and 18.2% [33] (in-house measurement) have been demonstrated recently. Al foils have also been used as flexible substrates, and highest results of 17.1% efficiency have currently been obtained by NanoSolar and Empa. NanoSolar uses a printing method on specially coated Al foil [54], whereas Empa uses a low-temperature coevaporation process [33]. For ceramics, AIST has reported cells on zirconia with highest efficiencies comparable to those on stainless steel, enameled mild steel, or Ti [19].

For polymers, the development of high-efficiency cells seemed difficult because of the requirement of a low CIGS deposition temperature imposed by the thermal sensitivity of polyimide. A first report from ISET in 1996 announced an efficiency of 8.7% obtained by a two-step process of sputtering metal precursors at low temperature followed by a selenization reaction at a higher temperature [47]. Our laboratory, while working at ETH Zürich, reported a record efficiency of 12.8% in 1999 using a coevaporation method, and since then, it has continuously improved setting a new record value of 18.7%, in 2011 [5], [55]. Further optimization and development could allow the fabrication of 20% efficiency flexible solar cells that could close the last efficiency gap between cells fabricated on flexible substrates and cells fabricated on rigid substrates.

Implementation of different processing concepts has allowed our group to achieve efficiency improvements, as shown in Fig. 2. The first breakthrough device was developed in 1999 where the CIGS layer was grown on a spin-coated polyimide film on NaCl/glass and then lifted off after completion of solar cell processing [55]. Modifying the Na addition method from using a NaCl precursor layer to a postdeposition treatment instead led to an increase in efficiency from 13.2% in 2004 to 14.1% in 2005 [56], [57]. Further improvements by reducing optical and electronic losses by optimizing the buffer, window, grid, and antireflection layers led to a 16% efficiency in 2009 (internal measurement). Finally, adjusting the band gap grading was found to be of crucial importance for reducing recombination losses and ensuring highly efficient charge carrier collection, leading to an efficiency of 18.7% which represents the current world-record efficiency for any type of solar cell grown on a flexible substrate [5], [58]. Moreover, a monolithically integrated mini-module with 14.8% efficiency has also been developed on polyimide with an absorber layer grown at Empa and laser patterning done by the company Flisom AG. The mini-module consists of eight interconnected cells. Fig. 3 presents current density–voltage and power–voltage curves of this mini-module, as well as a picture of the finished flexible module.

IV. Module Interconnections and Encapsulation

After processing of solar cells on small scale, development of mini-modules and large-area scale-up are the next logical steps for industrial applications. In order to electrically interconnect the single cells, different approaches are used for flexible substrates [7]. Two schematic examples are shown in Fig. 4.

Monolithic integration is the most desirable way for interconnecting thin-film solar cells and has been successfully implemented on glass, becoming a standard industrial process. The implementation on flexible foils is less mature, and development work is being pursued on different substrates (see, e.g., [20]). Successive scribing/patterning of the different constituent layers allows direct separation of the cells. Deposition of a conducting top layer connects the back contact of one cell with the front contact of the next cell. The patterning can be done either by laser or mechanical scribing techniques. Mini-modules with efficiencies of 15.0% on enameled mild steel [34] and 15.9% on zirconia [20] have been demonstrated using such interconnection methods. Laser scribing on thermally sensitive polymer films is challenging but has been successfully implemented in our group, for example, in the 14.8% efficiency mini-module on polyimide presented in Fig. 3. Monolithic integration on conductive substrates is only feasible by depositing an additional insulating layer between the substrate and the Mo electrical back contact, as discussed in the previous section.

Stringing and tabbing is another method for interconnection comprising connection of individual cells by wiring as applied in Si wafer-based technology. SoloPower is using such an approach for cells grown on stainless steel substrates [59]. A third interconnection method, the so-called shingling, can be used for conductive substrates or in combination with conductive tape for insulating substrates. The front surface of one cell is physically contacted to the substrate of the next cell. Miasolé has chosen such an approach for their cells deposited on stainless steel [60]. The same approach was also used by IST with Cu-tape substrates [36]. Stringing and tabbing, as well as shingling approaches, allow cells to be sorted into their different efficiency (respectively, current) level during production before connecting them to modules, which can improve the overall yield and efficiency level of a production unit.

Transparent conducting oxides (TCO) used as window layers are selected according to their conductivity, transparency, moisture stability, and their compatibility with further processing steps. It has been shown that appropriately designed grid lines deposited onto the TCO can be used to assist the current transport, leading to enhanced performance in spite of optical losses

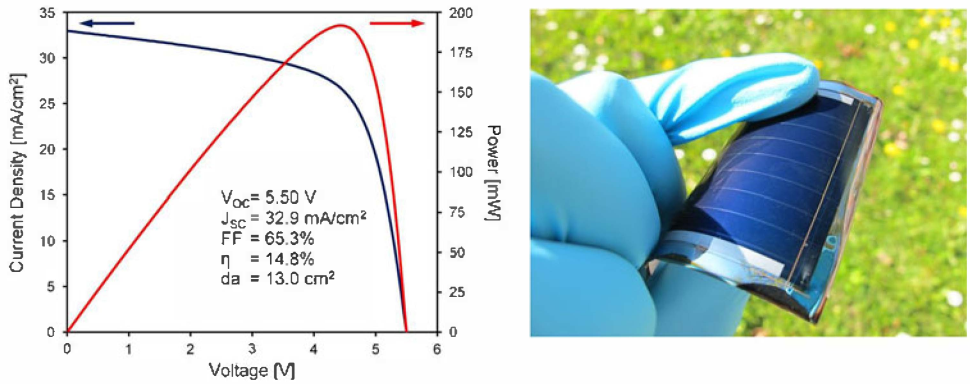

Fig. 3. *J–V* and *P–V* measurement curves of the record efficiency mini-module on polyimide substrate. The module consists of eight cells that are monolithically interconnected by laser patterning in collaboration with the company Flisom AG.

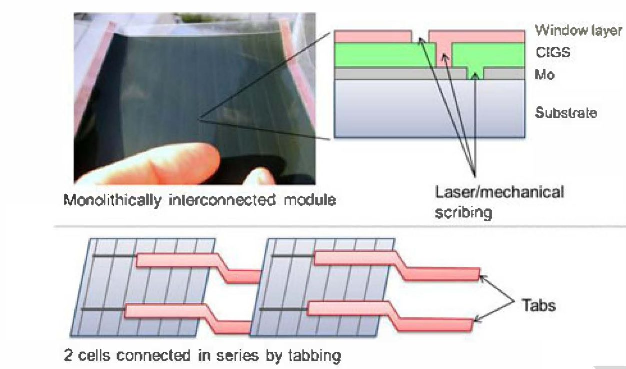

Fig. 4. Different types of interconnections are possible for flexible CIGS cells. Monolithic (top) or stringing and tabbing (bottom) are schematically shown.

due to shading from the typically Ni/Al lines [61], [62]. Use of wider segments (less scribe lines) and thinner TCO are advantages of this type of approach. Monolithic integrated modules in combination with a grid are manufactured by Ascent Solar on a polyimide substrate [63].

High efficiency and large-scale manufacturability of solar modules with high throughput and high average yield are the most important parameters for evaluating the potential of any PV technology for low-cost manufacturing. However, long-term performance durability is also a key issue for commercialization. Field tests on some of the earliest CIGS modules with appropriate encapsulation show that their performance has been stable over a period of 20 years [7]. Nevertheless, not encapsulated or not properly encapsulated CIGS devices tend to degrade under damp heat test conditions. Power loss is mostly assigned to increased series resistance of the window layer. Moisture and thermal cycling are very likely to be destructive, especially due to the sensitivity of window and contact materials to these external factors [64], [65]. However, the CIGS material and cells are known to be stable under different irradiation conditions (photons, protons, and electrons), making lightweight flexible CIGS modules very attractive for space applications [7], [66].

Adequate encapsulation of the flexible modules is necessary for long-term terrestrial applications in order to prevent moisture-induced degradation. This is, at the moment, a challenging problem for the development of low-cost CIGS solar modules with long-term performance stability [7]. A flexible transparent front encapsulation should provide a very effective barrier against moisture. Lifetime prediction studies have shown that the water vapor transport rate (WVTR) through a top sheet should not exceed 10^{-4}–10^{-5} g/(m^2·day) to ensure a 20-year CIGS module lifetime [67]. Transparent polymer such as ethylene vinyl acetate (EVA) [68] is a material available as flexible film which also has good durability under UV irradiation and low price. However, the WVTR of EVA is generally not sufficient for a 20-year lifetime of the current moisture sensitive window layers. Another approach is to use polymers coated with inorganic barriers or polymer multilayers (see, i.e., [69] and [70]). Such materials could meet the WVTR requirements, but up to now they are more expensive than EVAs. Several flexible CIGS modules have obtained UL or IEC certifications (for example, SoloPower [59], [71] and Global Solar [72]). These certifications are not based on real lifetime predictions as done by Coyle *et al.* [67], [73], but they certify that a given CIGS module can withstand a 2000-h damp heat test. Cheap flexible encapsulation materials with sufficiently low WVTR still have to be developed to ensure a 20-year stability. Glass plate encapsulation efficiently protects CIGS modules from the environment [74], but it imposes a loss of flexibility and a higher weight.

V. Industrial Manufacturing

The transition from processing of high-efficiency laboratory-scale devices to industrial manufacturing of CIGS modules is under way, and despite remarkable early progress, many problems still have to be solved. Not just materials-related problems (homogeneity, composition, crack-free deposition, compatibility of processes or encapsulation) but manufacturing issues as well, such as lack of appropriate equipment, tools for roll-to-roll deposition, and monolithic integration, are major issues that prevent the large commercialization of CIGS modules on flexible substrates. Besides high efficiency, yield and throughput are of great importance for low-cost flexible CIGS modules. However, such data on industrially produced modules are not publicly available in general, as companies usually do not disclose them. Nevertheless, some results show that the efficiency of the cells depends on the growth rate of the individual layers [75]. Roll-to-roll production is a clear advantage for

TABLE II
SELECTIVE OVERVIEW OF COMPANIES FROM THE CIGS SOLAR INDUSTRY COMPARING RIGID AND FLEXIBLE SUBSTRATE MANUFACTURERS

	Best cell η [%]	Best (mini) module η [%]	Area [cm^2]	Company	Founded [year]	Cap. [MWp/y]	Method	Notes
Rigid								
SLG		17.4*	16	Q-Cells (Solibro)	2006	135	Coevaporation, monolithic	Light soaking effect
SLG		17.8	900	Solar Frontier	1993 (Showa Shell)	1000	Sputtering, selenization	Cd-free, EVA and glass encapsulation
SLG		15.8*	900	AVANCIS	1981 (ARCO solar)	120	Sputtering of Cu-In-Ga:Na, Se evap., RTP sulphurisation	
SLG		12.6*	7500	Soltecture	2001 (Sulfurcell)	35	CIGS coevap.	EVA encapsulation, glass laminated
SLG		15.1	6500	Manz Automation	1999 (Würth Solar)	6	CIGS coevap.	Innovation production line
Flexible								
PI	14.1	11.7		Ascent Solar (ITN)	2005	30	CIGS coevap.	Monolithic
PI	13.4*			Solarion	2000	20	R2R coevap., ion-beam assisted	Shingling
SS	17.3	15.7*	10000	Miasolé	2003	100	All sputtering	Shingling, glass laminated
SS	15.4	13.2 (string)	3883	Global Solar	1996	75	Coevap.	ETFE front sheet, flexible strings and modules
SS	13.8*	13.4* (ap)		Solopower	2005	20	R2R electrodep.	Serial connection
Al foil	17.1*	11.6*		Nanosolar	2002	100	Non-vacuum printing	Serial connection, glass laminated
Cu tape	<10			Odersun	1994 (IST)	-	Galvanic deposition	n-type CIS, p-type buffer, shingling

Data based on companies' own website. *Externally certified values.

increased manufacturing throughput, and flexible substrates offer this possibility as opposed to glass substrates.

Table II gives selective examples of CIGS solar cells and modules-manufacturing companies in order to discuss different strategies and results achieved to date. Information is taken from the companies' own websites. Even though manufacturing on glass is outside the scope of this paper, a few examples of companies using SLG substrates is given in order to compare the state-of-the-art on flexible substrates with rigid substrates. Table II presents the status of companies at the end of May 2012. For SLG, Solar Frontier is the largest manufacturer with its current capacity of 1 GWp/year CIGS modules produced by deposition and selenization of sputtered metal precursors. Its best module efficiency measured internally is claimed to be 17.8% on a 30 cm × 30 cm glass substrate. AVANCIS has achieved the highest certified efficiency for a module (900 cm^2) with a value of 15.8%. They produce their CIGSSe absorber using rapid thermal processing (RTP) of sputtered precursors. Solibro, Soltecture, and Würth Solar (Manz) are also able to produce high-efficiency modules by coevaporation, with the best reported efficiencies of 17.4% (16 cm^2), 12.6% (7500 cm^2), and 15.1% (6500 cm^2), respectively. Besides Solibro, all of these companies were founded at the end of the last century and it took a few years before first commercialization of their products. The first CIGS modules commercially available in modest volume arrived on the market only over the past few years.

Flexible CIGS solar cell companies are in a rather early phase of industrialization. Most of them—with the exception of Global Solar—were founded after 2000. They are slowly ramping up production, but they still face several manufacturing issues, as mentioned above. Table II does not cover the complete list of flexible CIGS companies. The aim is rather to discuss the various technological approaches used for manufacturing and what results have been obtained thus far. The nominal production capacities are given for comparison with rigid substrate manufacturers, even though actual production might be much lower. Estimates of actual production volumes in 2011 are available for a few CIGS companies in [76]. Miasolé has demonstrated the highest certified efficiency among all flexible substrates (stainless steel), with an efficiency of 15.7% on a 1-m^2 module. This has been achieved by a sputtering-only process, a shingling approach for interconnection, and glass encapsulation. A fully flexible 15.5% commercial-size (1.68 m^2) module has also been reported by Miasolé. Global Solar is the oldest representative of the companies working on flexible substrates, but ISET (not listed here) was the first company to report development of flexible CIGS solar modules. Global Solar, which is a spin-off from ITN Inc. (New York), started in 1996 with the development of CIGS solar cells on stainless steel using a coevaporation method. Solopower also uses stainless steel substrate and employs a roll-to-roll electrodeposition method for CIGS followed by an annealing step. Nanosolar produces glass laminated modules on coated Al foil. They use a printing and subsequent selenization method for CIGS formation. Polyimide is used as a substrate by Solarion and Ascent Solar with the highest recorded efficiencies slightly lower than those on stainless steel. In an alternative technological approach, Odersun has been growing n-type CIS on Cu-tape and depositing a p-type buffer layer on it. Currently, production capacities of CIGS modules deposited on flexible substrates remain small compared with CIGS modules deposited on SLG.

VI. Conclusion and Outlook

Remarkable progress has been made in the development of flexible CIGS solar cells on polyimide films, as well as on different types of metal foils. A cell efficiency of 18.7% has been achieved on polyimide using a coevaporation method, whereas a monolithically integrated mini-module with 14.8% efficiency has been demonstrated. Using metal foil substrates, highest cell efficiency of 18.2% has been obtained on enameled mild steel, 17.8% on titanium, and 17.7% on stainless steel. Commercial-size modules with efficiency above 15% have also been developed on stainless steel substrates. The flexibility and lightweight of the produced modules open new fields of applications. From industrial production point of view, CIGS solar cells on a flexible substrate enable the use of roll-to-roll manufacturing methods. High throughput in production can thus be achieved due to the inherent characteristics of roll-to-roll deposition on thin foils, leading to potential cost reduction of the modules. Based on the substrate material choice, different strategies for interconnection of the cells can be selected for manufacturing of modules. Companies are entering the commercialization phase, and current production volumes of flexible modules are rather modest. Moreover, flexible CIGS module manufacturers still face some problems. Development of better roll-to-roll deposition infrastructure is necessary, while maintaining a high average yield and high throughput. In addition, low-cost flexible encapsulation materials with sufficient moisture blocking properties need to be developed to guarantee long-term stability.

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References

[1] C. A. Wolden, J. Kurtin, J. B. Baxter, I. Repins, S. E. Shaheen, J. T. Torvik *et al.*, "Photovoltaic manufacturing: Present status, future prospects, and research needs," *J. Vac. Sci. Technol. A*, vol. 29, no. 3, pp. 030801-1–030801-16, May 2011.

[2] M. A. Green, K. Emery, D. L. King, S. Igari, and W. Warta, "Solar cell efficiency tables (version 24)," *Progr. Photovoltaics*, vol. 12, pp. 365–372, Aug. 2004.

[3] S. Plaza. (2011, Aug.) Top 10 World's Most Efficient Solar PV Modules (Poly-Crystalline) [Online]. Available: http://www.solarplaza.com/top10-polycrystalline-module-efficiency/

[4] P. Jackson, D. Hariskos, E. Lotter, S. Paetel, R. Wuerz, R. Menner *et al.*, "New world record efficiency for Cu(In,Ga)Se(2) thin-film solar cells beyond 20%," *Progr. Photovoltaics*, vol. 19, pp. 894–897, Nov. 2011.

[5] A. Chirilă, S. Buecheler, F. Pianezzi, P. Bloesch, C. Gretener, A. R. Uhl *et al.*, "Highly efficient Cu(In,Ga)Se_2 solar cells grown on flexible polymer films," *Nat. Mater.*, vol. 10, pp. 857–861, Sep. 2011.

[6] C. J. Hibberd, E. Chassaing, W. Liu, D. B. Mitzi, D. Lincot, and A. N. Tiwari, "Non-vacuum methods for formation of Cu(In,Ga)(Se,S)(2) thin film photovoltaic absorbers," *Progr. Photovoltaics*, vol. 18, pp. 434–452, Sep. 2010.

[7] W. N. Shafarman, S. Siebentritt, and L. Stolt, "Cu(InGa)Se_2 solar cells," in *Handbook of Photovoltaic Science and Engineering*. New York: Wiley, 2011, pp. 546–599.

[8] P. Jackson, R. Wurz, U. Rau, J. Mattheis, M. Kurth, T. Schlotzer *et al.*, "High quality baseline for high efficiency, Cu(In_{1-x},Ga_x)Se_2 solar cells," *Progr. Photovoltaics*, vol. 15, pp. 507–519, Sep. 2007.

[9] S. Niki, M. Contreras, I. Repins, M. Powalla, K. Kushiya, S. Ishizuka *et al.*, "CIGS absorbers and processes," *Progr. Photovoltaics*, vol. 18, pp. 453–466, Sep. 2010.

[10] N. Naghavi, D. Abou-Ras, N. Allsop, N. Barreau, S. Buecheler, A. Ennaoui *et al.*, "Buffer layers and transparent conducting oxides for chalcopyrite Cu(In,Ga)(S,Se)(2) based thin film photovoltaics: Present status and current developments," *Progr. Photovoltaics*, vol. 18, pp. 411–433, Sep. 2010.

[11] U. Rau and H. W. Schock, "Electronic properties of Cu(In,Ga)Se_2 heterojunction solar cells-recent achievements, current understanding, and future challenges," *Appl. Phys. a-Mater. Sci. Process.*, vol. 69, pp. 131–147, Aug. 1999.

[12] M. Bar, S. Nishiwaki, L. Weinhardt, S. Pookpanratana, W. N. Shafarman, and C. Heske, "Electronic level alignment at the deeply buried absorber/Mo interface in chalcopyrite-based thin film solar cells," *Appl. Phys. Lett.*, vol. 93, pp. 042110-1–042110-3, Jul. 2008.

[13] D. Rudmann, D. Bremaud, A. F. da Cunha, G. Bilger, A. Strohm, M. Kaelin *et al.*, "Sodium incorporation strategies for CIGS growth at different temperatures," *Thin Solid Films*, vol. 480, pp. 55–60, Jun. 1, 2005.

[14] I. Repins, M. A. Contreras, B. Egaas, C. DeHart, J. Scharf, C. L. Perkins *et al.*, "19.9%-efficient ZnO/CdS/CuInGaSe_2 solar cell with 81.2% fill factor," *Progr. Photovoltaics*, vol. 16, pp. 235–239, May 2008.

[15] F. Kessler and D. Rudmann, "Technological aspects of flexible CIGS solar cells and modules," *Sol. Energy*, vol. 77, pp. 685–695, 2004.

[16] J. Penndorf, M. Winkler, O. Tober, D. Roser, and K. Jacobs, "CuInS_2 thin film formation on a Cu tape substrate for photovoltaic applications," *Sol. Energy Mater. Sol. Cells*, vol. 53, pp. 285–298, Jun. 1998.

[17] D. Rudmann, D. Bremaud, H. Zogg, and A. N. Tiwari, "Na incorporation into Cu(In,Ga)Se_2 for high-efficiency flexible solar cells on polymer foils," *J. Appl. Phys.*, vol. 97, pp. 084903-1–084903-5, Apr. 2005.

[18] R. Caballero, C. A. Kaufmann, T. Eisenbarth, T. Unold, R. Klenk, and H. W. Schock, "High efficiency low temperature grown Cu(In,Ga)Se(2) thin film solar cells on flexible substrates using NaF precursor layers," *Progr. Photovoltaics*, vol. 19, pp. 547–551, Aug. 2011.

[19] S. Ishizuka, A. Yamada, K. Matsubara, P. Fons, K. Sakurai, and S. Niki, "Alkali incorporation control in Cu(In, Ga)Se(2) thin films using silicate thin layers and applications in enhancing flexible solar cell efficiency," *Appl. Phys. Lett.*, vol. 93, no. 12, pp. 124105-1–124105-3, Sep. 2008.

[20] S. Ishizuka, T. Yoshiyama, K. Mizukoshi, A. Yamada, and S. Niki, "Monolithically integrated flexible Cu(In,Ga)Se(2) solar cell submodules," *Sol. Energy Mater. Sol. Cells*, vol. 94, pp. 2052–2056, Dec. 2010.

[21] K. Herz, E. Kessler, R. Wachter, M. Powalla, J. Schneider, A. Schulz *et al.*, "Dielectric barriers for flexible CIGS solar modules," *Thin Solid Films*, vol. 403, pp. 384–389, Feb. 2002.

[22] F. Kessler, K. Herz, M. Powalla, M. Hartmann, M. Schmidt, A. Jasenek *et al.*, "Flexible and monolithically integrated CIGS-modules," *MRS Online Proc. Lib.*, vol. 668, p. H3.6, 2001.

[23] S. Gledhill, A. Zykov, N. Allsop, T. Rissom, J. Schniebs, C. A. Kaufmann *et al.*, "Spray pyrolysis of barrier layers for flexible thin film solar cells on steel," *Sol. Energy Mater. Sol. Cells*, vol. 95, pp. 504–509, Sep. 2011.

[24] T. Satoh, Y. Hashimoto, S. Shimakawa, S. Hayashi, and T. Negami, "Cu(In,Ga)Se_2 solar cells on stainless steel substrates covered with insulating layers," *Sol. Energy Mater. Sol. Cells*, vol. 75, pp. 65–71, Jan. 2003.

[25] N. G. Dhere, V. S. Gade, and S. S. Kulkarni, "CIGS2 thin films on large area ultralightweight Ti/SiO_2 substrates," in *Proc. 3rd World Conf. Photovoltaic Energy Convers.*, May 2003, vol. a-C, pp. 757–760.

[26] N. Murakami, K. Moriwaki, M. Nangu, T. Ohgoh, S. Yuuya, S. Ishizuka *et al.*, "Monolithically integrated CIGS sub-modules fabricated on new-structured flexible substrates," in *Proc. 37th IEEE Photovoltaic Spec. Conf.*, Jun. 2011, pp. 001310–001313.

[27] F. Pianezzi, A. Chirilă, P. Blösch, S. Seyrling, S. Buecheler, L. Kranz *et al.*, "Electronic properties of Cu(In,Ga)Se_2 solar cells on stainless steel foils without diffusion barrier," *Progr. Photovoltaics: Res. Appl.*, vol. 20, pp. 253–259, Jan. 2012.

[28] N. G. Dhere, S. R. Ghongadi, M. B. Pandit, A. H. Jahagirdar, and D. Scheiman, "CIGS2 thin-film solar cells on flexible foils for space power," *Progr. Photovoltaics*, vol. 10, pp. 407–416, Sep. 2002.

[29] M. S. Kim, J. H. Yun, K. H. Yoon, and B. T. Ahna, "Fabrication of flexible CIGS solar cell on stainless steel substrate by co-evaporation process," *Adv. Nanomaterials Process.*, vol. 124–126, Pts. 1 and 2, pp. 73–76, Jan. 2007.

[30] J. R. Tuttle, A. Szalaj, and J. Keane, "A 15.2% AMO/1433 W/kg thin-film Cu(In,Ga)Se_2 solar cell for space applications," in *Proc. 28th IEEE Photovoltaic Spec. Conf.*, Sep. 2000, pp. 1042–1045.

[31] J. Qin, A. M. Li, Z. Y. Chen, L. Zhao, X. L. Zhang, W. M. Shi *et al.*, "Silicon nitride films as the diffusion barriers for flexible CIGS thin film solar cells," in *Proc. 7th Int. Conf. Thin Film Phys. Appl.*, Feb. 2011, vol. 7995, p. 79952Y.

[32] D. Herrmann, F. Kessler, K. Herz, M. Powalla, A. Schulz, J. Schneider *et al.*, "High-performance barrier layers for flexible CIGS thin-film solar cells on metal foils," *Compd. Semicond. Photovoltaics*, vol. 763, pp. 287–292, Apr. 2003.

[33] A. Chirila, P. Bloesch, F. Pianezzi, S. Seyrling, A. Uhl, S. Buecheler *et al.*, "Development of high efficiency flexible CIGS solar cells on different substrates," in *Proc. 21st Int. Photovoltaic Sci. Eng. Conf.*, Fukuoka, Japan, 4B-3T-02, Dec. 2011.

[34] R. Wuerz, A. Eicke, F. Kessler, S. Paetel, S. Efimenko, and C. Schlegel, "CIGS thin-film solar cells and modules on enamelled steel substrates," *Sol. Energy Mater. Sol. Cells*, vol. 100, pp. 132–137, Jan. 2012.

[35] J. Rechid, R. Thyen, A. Raitzig, S. Wulff, M. Mihhailova, K. Kalberlah *et al.*, "9% efficiency: CIGS on Cu substrate," in *Proc. 3rd World Conf. Photovoltaic Energy Convers.*, May 2003, vol. a-C, pp. 559–561.

[36] M. Winkler, J. Griesche, I. Konovalov, J. Penndorf, J. Wienke, and O. Tober, "CISCuT—Solar cells and modules on the basis of CuInS2 on Cu-tape," *Sol. Energy*, vol. 77, pp. 705–716, Aug. 2004.

[37] M. Hartmann, M. Schmidt, A. Jasenek, H. W. Schock, F. Kessler, K. Herz *et al.*, "Flexible and light weight substrates for Cu(In,Ga)Se_2 solar cells and modules," in *Proc. Conf. Rec. 28th IEEE Photovoltaic Spec. Conf.*, Sep. 2000, pp. 638–641.

[38] T. Yagioka and T. Nakada, "Cd-free flexible Cu(In,Ga)Se(2) thin film solar cells with ZnS(O,OH) buffer layers on Ti foils," *Appl. Phys. Exp.*, vol. 2, pp. 072201 (1–3), Jul. 2009.

[39] A. Neisser, C. A. Kaufmann, R. Klenk, R. Scheer, M. A. Kroon, G. Oomen *et al.*, "Prototype development—Flexible Cu(In,Ga)Se_2 thin film solar cells for space applications," in *Proc. Conf. Rec. 31st IEEE Photovoltaic Spec. Conf.*, Jan. 2005, pp. 227–230.

[40] D. Herrmann, F. Kessler, U. Klemm, R. Kniese, T. M. Friedlmeier, S. Spiering *et al.*, "Flexible, monolithically integrated Cu(In,Ga)Se_2 thin-film solar modules," *MRS Online Proc. Lib.*, vol. 865, p. F15.1, Jan. 2005.

[41] A. Kampmann, J. Rechid, A. Raitzig, S. Wulff, M. Mihhailova, R. Thyen *et al.*, "Electrodeposition of CIGS on metal substrates," *Compd. Semicond. Photovoltaics*, vol. 763, pp. 323–328, Apr. 2003.

[42] B. M. Basol, V. K. Kapur, A. Halani, and C. Leidholm, "Copper indium diselenide thin-film solar-cells fabricated on flexible foil substrates," *Sol. Energy Mater. Sol. Cells*, vol. 29, pp. 163–173, Mar. 1993.

[43] T. Nakada, T. Kuraishi, T. Inoue, and T. Mise, "CIGS thin film solar cells on polyimide foils," in *Proc. 35th IEEE Photovoltaic Spec. Conf.*, Jun. 2010, pp. 330–334.

[44] S. Ishizuka, A. Yamada, and S. Niki, "Efficiency enhancement of flexible CIGS solar cells using alkali-silicate glass thin layers as an alkali source material," in *Proc. 34th IEEE Photovoltaic Spec. Conf.*, Jan. 2009, pp. 002349–002353.

[45] R. Caballero, C. A. Kaufmann, T. Eisenbarth, A. Grimm, I. Lauermann, T. Unold *et al.*, "Influence of Na on Cu(In,Ga)Se(2) solar cells grown on polyimide substrates at low temperature: Impact on the Cu(In,Ga)Se(2)/Mo interface," *Appl. Phys. Lett.*, vol. 96, no. 9, pp. 092104–092104-3, Mar. 2010.

[46] G. M. Hanket, U. P. Singh, E. Eser, W. N. Shafarman, and R. W. Birkmire, "Pilot-scale manufacture of Cu(InGa)Se_2 films-on a flexible polymer substrate," in *Proc. Conf. Rec. 29th IEEE Photovoltaic Spec. Conf.*, May 2002, pp. 567–570.

[47] B. M. Basol, V. K. Kapur, C. R. Leidholm, A. Halani, and K. Gledhill, "Flexible and light weight copper indium diselenide solar cells on polyimide substrates," *Sol. Energy Mater. Sol. Cells*, vol. 43, pp. 93–98, Aug. 1996.

[48] M. G. Faraj, K. Ibrahim, and A. Salhin, "Investigation of CIGS solar cells on polyethylene terephthalate substrates," *Int. J. Polym. Mater.*, vol. 60, pp. 817–824, Jul. 2011.

[49] V. K. Kapur, A. Bansal, P. Le, O. Asensio, and N. Shigeoka, "Non-vacuum processing of CIGS solar cells on flexible polymeric substrates," in *Proc. 3rd World Conf. Photovoltaic Energy Convers.*, May 2003, vol. a-C, pp. 465–468.

[50] A. Neisser, C. A. Kaufmann, M. A. Kroon, R. Klenk, and R. Scheer, "Flexible Cu(In,Ga)Se(2) solar cell for space applications," in *Proc. 3rd World Conf. Photovoltaic Energy Convers.*, May 2003, vol. a-C, pp. 458–460.

[51] C. A. Kaufmann, A. Neisser, R. Klenk, R. Scheer, and H. W. Schock, "Design of a window layer for flexible Cu(In,Ga)Se_2 thin film solar cell devices," *Thin-Film Compd. Semicond. Photovoltaics*, vol. 865, pp. 279–284, Jan. 2005.

[52] O. Tober, J. Wienkel, M. Winkler, J. Penndorf, and J. Griesche, "Current status and future prospects of CISCuT based solar cells and modules," *Compd. Semicond. Photovoltaics*, vol. 763, pp. 371–376, Apr. 2003.

[53] M. A. Contreras, B. Egaas, K. Ramanathan, J. Hiltner, A. Swartzlander, F. Hasoon *et al.*, "Progress toward 20% efficiency in Cu(In,Ca)Se(2) polycrystalline thin-film solar cells," *Progr. Photovoltaics*, vol. 7, pp. 311–316, Jul./Aug. 1999.

[54] Nanosolar, (2011, Aug.). Nanosolar Achieves 17.1% Aperture Efficiency Through Printed CIGS Process [Online]. Available: http://www.nanosolar.com/company/blog

[55] A. N. Tiwari, M. Krejci, F. J. Haug, and H. Zogg, "12.8% efficiency Cu(In, Ga)Se_2 solar cell on a flexible polymer sheet," *Progr. Photovoltaics*, vol. 7, pp. 393–397, Sep./Oct. 1999.

[56] D. Bremaud, D. Rudmann, G. Bilger, H. Zogg, and A. N. Tiwari, "Towards the development of flexible CIGS solar cells on polymer films with efficiency exceeding 15%," in *Proc. Conf. Rec. 31st IEEE Photovoltaic Spec. Conf.*, Jan. 2005, pp. 223–226.

[57] D. Rudmann, D. Brémaud, H. Zogg, and A. N. Tiwari, "Na incorporation for low-temperature Cu(In,Ga)Se_2 growth," in *Proc. 19th Eur. Photovoltaic Sol. Energy Conf.*, Jun. 2004, pp. 1710–1713.

[58] A. Chirila, D. Guettler, P. Bloesch, S. Nishiwaki, S. Seyrling, S. Buecheler *et al.*, "Optimization of composition grading in Cu(In,Ga)Se_2 for flexible solar cells and modules," in *Proc. 35th IEEE Photovoltaic Specialists Conf.*, Jun. 2010, pp. 656–660.

[59] M. Pinarbasi, S. Aksu, J. Freitag, T. Boone, H. Zolla, J. Vasquez *et al.*, "Flexible cells and modules produced using roll-to-roll electroplating approach," in *Proc. 35th IEEE Photovoltaic Spec. Conf.*, Jun. 2010, pp. 169–174.

[60] Miasolé. (2012, Aug.). [Online]. Available: www.miasole.com

[61] J. Kessler, J. Wennerberg, M. Bodegard, and L. Stolt, "Highly efficient Cu(In,Ga)Se_2 mini-modules," *Sol. Energy Mater. Sol. Cells*, vol. 75, pp. 35–46, Jan. 2003.

[62] J. Wennerberg, J. Kessler, and L. Stolt, "Design of grided Cu(In,Ga)Se_2 thin-film PV modules," *Sol. Energy Mater. Sol. Cells*, vol. 67, pp. 59–65, Mar. 2001.

[63] A. Solar. (2012, Aug.). [Online]. Available: www.ascentsolar.com/enerplex/

[64] J. Wennerberg, J. Kessler, and L. Stolt, "Cu(In,Ga)Se_2-based thin-film photovoltaic modules optimized for long-term performance," *Sol. Energy Mater. Sol. Cells*, vol. 75, pp. 47–55, 2003.

[65] F. J. Pern, L. Mansfield, C. DeHart, S. H. Glick, F. Yan, and R. Noufi, "Thickness effect of Al-doped ZnO window layer on damp-heat stability of CuInGaSe_2 solar cells," in *Proc. 37th IEEE Photovoltaic Spec. Conf.*, Jan. 2011, pp. 002798–002803.

[66] A. Jasenek, U. Rau, K. Weinert, I. M. Kotschau, G. Hanna, G. Voorwinden *et al.*, "Radiation resistance of Cu(In,Ga)Se_2 solar cells under 1-MeV electron irradiation," *Thin Solid Films*, vol. 387, pp. 228–230, May 2001.

[67] D. J. Coyle, "Life prediction for CIGS solar modules part 1: Modeling moisture ingress and degradation," *Progr. Photovoltaics: Res. Appl.*, 2011, [Online], DOI:10.1002/pip.1172.

[68] L. Eldada, "Thin film CIGS photovoltaic modules: Monolithic integration and advanced packaging for high performance, high reliability and low cost," *Optoelectron. Integr. Circuits XIII*, vol. 7942 0F (1–24), 2011.

[69] P. F. Carcia, R. S. McLean, and S. Hegedus, "Encapsulation of Cu(InGa)Se-2 solar cell with Al2O3 thin-film moisture barrier grown by atomic layer deposition," *Sol. Energy Mater. Sol. Cells*, vol. 94, pp. 2375–2378, Dec. 2010.

[70] L. C. Olsen, M. E. Gross, G. L. Graff, and S. N. Kundu, "Approaches to encapsulation of flexible CIGS cells," *Reliab. Photovoltaic Cells, Modules, Compon. Syst.*, vol. 7048 (O (1–8)), 2008.

[71] SoloPower. (2012, Aug.). [Online]. Available: www.solopower.com

[72] Global Solar. (2012, Aug.). [Online]. Available: www.globalsolar.com

[73] D. J. Coyle, H. A. Blaydes, R. S. Northey, J. E. Pickett, K. R. Nagarkar, R.-A. Zhao *et al.*, "Life prediction for CIGS solar modules part 2: Degradation kinetics, accelerated testing, and encapsulant effects," *Progr. Photovoltaics: Res. Appl.*, 2011, [Online], DOI:10.1002/pip.1171.

[74] J. S. Britt, E. Kanto, S. Lundberg, and M. E. Beck, "CIGS device stability on flexible substrates," in *Proc. Conf. Rec. IEEE 4th World Conf. Photovoltaic Energy Convers.*, May 2006, vol. 1 and 2, pp. 352–355.

[75] A. Chirilă, S. Seyrling, S. Buecheler, D. Guettler, S. Nishiwaki, Y. E. Romanyuk *et al.*, "Influence of high growth rates on evaporated Cu(In,Ga)Se_2 layers and solar cells," *Progr. Photovoltaics: Res. Appl.*, vol. 20, pp. 209–216, 2012.

[76] E. Wesoff (2012, Aug.). Correction: "Layoffs at CIGS solar hopeful miasolé" [Online]. Available: http://www.greentechmedia.com/articles/read/Layoffs-at-CIGS-Solar-Hopeful-MiaSole/

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