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Innovation highway: Breakthrough milestones and key developments in chalcopyrite photovoltaics from a retrospective viewpoint



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ABSTRACT

The present contribution is a summary of an event that was organized as a special evening session in Symposium V “Chalcogenide Thin-Film Solar Cells” at the E-MRS 2016 Spring Meeting, Lille, France. The presentations in this session were given by the coauthors of this paper. These authors present retrospectives of key developments in the field of Cu(In,Ga)(S,Se)₂ solar cells as they themselves had witnessed in their laboratories or companies. Also, anecdotes are brought up, which captured interesting circumstances in that evolutionary phase of the field. Because the focus was on historical perspectives rather than a comprehensive review of the field, recent developments intentionally were not addressed.

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1. Introduction

Research and development of solar-cell devices based on chalcopyrite-type absorber layers has been conducted for more than 40 years. Since often in science, past findings and knowledge fall into oblivion if reported too long ago, it was the motivation of a special session organized at the recent 2016 E-MRS Spring Meeting (Symposium V on “Chalcogenide Thin-Film Solar Cells”) to have a retrospective view of some important milestones and key developments in chalcopyrite-type solar cell absorber layers and corresponding devices. The presentations by the coauthors of this paper during the special session, which included also video recordings of colleagues absent at the session, were

focused describing the circumstances and issues relevant at that time, while looking back to the evolution of the field. Unfortunately, the circumstances allowed for only limited contributions in terms of number and time.

The presentations started with the invention of CdS/CuInSe₂ photo-detectors and solar cells in 1974, via thin-film solar cells with the same structure, to CdS/Cu₂S and CdS/Cu(In,Ga)(S,Se)₂ cells on the laboratory scale and early phase of industrial efforts. Other presentations on different topics included unintentional incorporation of Na in Cu(In,Ga)Se₂ introduced from soda-lime glass substrates, native point defects in the absorber materials, transition from evaporated CdS to chemical-bath-deposited buffer layers, insight into industrial developments, and the challenges of CuInS₂ solar cells. The intent was not to give a comprehensive review of the field, but only a selection, limited mostly to the activities of the presenting authors. Therefore, various important

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contributions were omitted. The present summary is restricted to this limited selection of retrospective factual views.

2. Invention of the first photodetectors and solar cells based on CdS/CuInSe₂ heterojunctions

In the beginning of the 1970s, the development of light-emitting diodes was a hot topic in semiconductor device research. At that time, S. Wagner and colleagues at Bell Telephone Laboratories developed green light-emitting diodes based on heterojunctions made of *n*-type CdS and *p*-type CuGaS₂ [1], which exhibits a band-gap energy of 2.5 eV. Since GaAs lasers (photon energy of 1.4 eV) were also studied at that time as light sources for fiber optics, S. Wagner and colleagues were looking for semiconductor materials with band-gap energies of about 1 eV, to fabricate photodetectors for the GaAs lasers. This is how CuInSe₂ came into focus. Based on the CdS/CuGaS₂ heterojunctions, which they had already fabricated, S. Wagner and colleagues invented the CdS/CuInSe₂ heterojunction photodetector [2].

After measuring the quantum-efficiency spectrum over the entire wavelength window, S. Wagner and colleagues realized that what they had produced performed well as a solar cell [3]. Thus, they started paying attention to raising the open-circuit voltage (V_{oc}), reducing the series resistance, and evaluating complete photocurrent-voltage characteristics. With just a few experiments, they demonstrated a conversion efficiency of 12% [4].

The CdS/CuInSe₂ heterojunctions were based on what appeared under the optical microscope to be CuInSe₂ single crystals. They were ultra-precious, since their growth in sealed quartz ampoules by horizontal directional solidification of stoichiometric melts took several weeks. The melt crystallized by random nucleation on the quartz wall, with the largest crystallites forming at the top of the boule, with (112) Se surfaces. The largest crystals were selected by visual inspection and then cut out in ~1-mm-thick pieces, with ~1 mm² surface areas of the single crystals. The crystals were polished, etched, annealed in Se vapor to raise the *p*-type conductivity, polished and again etched. The diode was completed by coevaporation of Cd and S to form a 5–10- μ m-thick CdS layer. After electroless deposition of Au for the CuInSe₂ back contact and soldering indium as a front contact to the CdS layer, the device was evaluated.

First, current-voltage, capacitance-voltage, and quantum efficiency measurements were conducted at zero-to-low bias voltages. Then, the applied voltage was increased to see how far it was possible to go into forward and reverse bias, until the device shorted. Since the CuInSe₂ single crystal was so precious, it was recycled by stripping the In contact and the CdS layer, and by etching the CuInSe₂ crystal to obtain a fresh surface for fabricating a new diode. The device was the result of a typical Bell Labs interdisciplinary collaboration: Horst Kasper grew the CuInSe₂ crystals, Joe Shay and Piero Migliorato were solid-state physicists who learned device physics on the fly, and Sigurd Wagner fabricated the solar cells.

In 1974, the CdS/CuInSe₂ heterodiode was one of four solar-cell concepts that realized power-conversion efficiencies of >10%. Further research on solar cells with chalcopyrite-type semiconductors included Cu₂CdSnS₄, a forerunner of earth-abundant semiconductors, in the CdS/Cu₂CdSnS₄ heterojunction [5].

3. First thin-film solar cells based on CdS/CuInSe₂ heterojunctions

Soon after the success of S. Wagner and colleagues, in 1976, L.L. Kazmerski, then at University of Maine, demonstrated 4–5% conversion efficiency for CdS/CuInSe₂ solar cells based on CuInSe₂ thin films deposited by evaporation from CuInSe₂ and Se sources [6]. In 1980, R.A. Mickelsen and W.S. Chen from Boeing Aerospace Company won a proposal with the Solar Energy Research Institute (which became later the National Renewable Energy Laboratory) in Golden, CO, U.S.A. These researchers based the proposed development of CdS/CuInSe₂

thin-film solar cells on earlier work that they had performed on Cu₂S/CdS solar cells (see Section 4 below) under NASA contract. Like other researchers at that time, they found that CdS/Cu₂S devices would decompose under bias. One of the ideas Mickelsen and Chen had to stabilize these devices was introducing impurities into the crystal, of which one option was In. Combining this approach with the earlier work by L.L. Kazmerski described above (who used evaporation of CuInSe₂ from the compound), they proposed coevaporation from the elements as a technique to obtain better control of the process. Thus, Mickelsen and Chen demonstrated the first 10% efficient CuInSe₂ thin-film solar cell in 1982 [7].

Until 1985, the conversion efficiencies of CuInSe₂/CdS solar cells were improved to almost 12%, mainly by using (Cd,Zn)S instead of CdS as *n*-type counterpart to the *p*-type CuInSe₂ [8]. Soon thereafter, Mickelsen, Chen, and colleagues demonstrated the first Cu(In,Ga)Se₂ thin film solar cells with conversion efficiencies of >10%, using a [Ga]/([Ga] + [In]) ratio of 0.25 [9]. Adding Ga to CuInSe₂ provided flexibility to either fabricate absorber layers with band-gap energies matching the solar spectrum (low Ga concentrations) or to produce high-gap partners for CuInSe₂ in a tandem solar-cell device (high Ga concentrations). The conversion efficiencies for CuInSe₂ and Cu(In,Ga)Se₂ thin-film solar cells were improved to 14.1% and 12.9% by Mitchell et al. at ARCO Solar [10], mainly by reducing the thickness of the evaporated CdS buffer layer from few μ m to about 50 nm, and by using a 1.5–3- μ m-thick ZnO window layer.

As an interesting incident during the initial development period of Cu(In,Ga)Se₂ thin film solar cells at Boeing Aerospace Company, the power packs for the substrate heaters on the Cu(In,Ga)Se₂ evaporation system failed. The power thyristors shorted, and a thermal run-away in the system occurred. At that time, the solar-cell stacks were deposited on borosilicate glass. The substrate temperature went very high, much higher than normal. When the Cu(In,Ga)Se₂ thin films were imaged by electron microscopy in cross-section, the researchers found that the grain sizes were much larger than normal. This incident gave rise to growth recipes for Cu(In,Ga)Se₂ thin films with much higher temperatures than commonly used for CuInSe₂ at that time.

4. Development of CdS/Cu₂S and CdS/CuInSe₂ thin-film solar cells

It is noteworthy that in the two decades before the first CdS/CuInSe₂ photodiodes were produced, a related technology had already been developed and studied intensively by several research groups. In 1954, the photovoltaic effect was found in rectifiers composed of Cu contacts and CdS single crystals [11], at about the same time that Si homojunction solar cells were first reported [12]. Initially, CdS-based photovoltaic thin-film devices relied on a heterojunction of Cu₂O and CdS, with illumination through the rather thick (up to 100 μ m) CdS layer (the backwall configuration). During the subsequent years, the design of CdS thin-film solar cells was modified by the deposition of thin (few

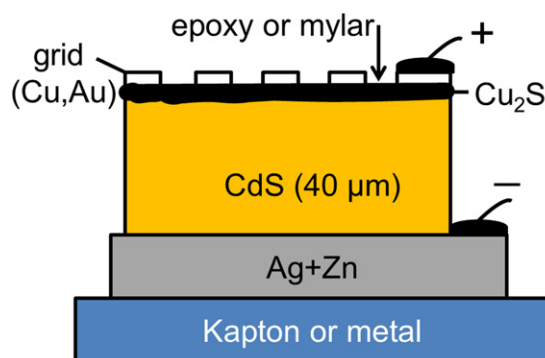


Fig. 1. Stacking sequence of CdS/Cu₂S solar cell with a front-wall design (adapted from Ref. [14]).

μm $p\text{-Cu}_2\text{S}$ layers on the $n\text{-CdS}$ layers (see stacking sequence given in Fig. 1) and by switching to a frontwall configuration (illumination through the Cu_2S layer). Most of the incident light is absorbed in the Cu_2S layer (band-gap energy of about 1.2 eV [13]).

Both the Si and CdS/ Cu_2S technologies were considered equally important owing to the demonstrated conversion efficiencies of 5–8% (for CdS/ Cu_2S in the 1960s [15,16]). While the Si devices soon showed progress towards 10% and higher efficiencies, they were also found to be vulnerable to radiation damage, which was a substantial problem for application of these devices in space, e.g., on satellites. Similar to other thin-film technologies developed during that time, such as CdTe solar cells [17], CdS/ Cu_2S heterojunction devices were demonstrated to be inherently far more stable to the whole spectrum of proton and electron radiation in space environment (see Ref. [18] and references therein).

Until the 1980s, conversion efficiencies of up to >9% were achieved with CdS/ Cu_2S solar cells [19], and >10% by the addition to Zn to the CdS layer [20]. However, as heterojunction devices, CdS solar cells exhibit substantial limitations on their device performances via trapped charge densities near the CdS/ Cu_2S interface, which causes a persistent increase in junction capacitance (photocapacitance) and plays a significant role in determining carrier transport properties [21]. Also, the Cu_2S layer was found to decompose into other, Cu-poorer Cu-S phases for bias voltages of larger than about 0.3 V [22], leading to an intermediate Cu-S layer between Cu_2S and CdS with a larger band-gap energy (1.8 eV) than that of chalcocite Cu_2S (1.2 eV), hence substantially deteriorating the $p\text{-}n$ junction performance [23].

As mentioned above in Section 3, one solution to this problem was to introduce indium to the Cu-S compound, in order to stabilize the structure. This approach led to the development of CdS/ CuInS_2 heterojunctions, which were considered as promising alternatives to CdS/ CuInSe_2 heterojunctions (Section 3) and will be discussed in the following.

A first report on this topic was published by L.L. Kazmerski et al. in 1975 [24], encouraged by their work on CuInSe_2 (see Section 3). Apart from solving the problem of stabilizing the structure of $\text{Cu}_2\text{S}/\text{CdS}$ $p\text{-}n$ junctions, their motivation was also to replace costly Se and to obtain devices with larger band-gap energies in the absorbing layers. Achieving a conversion efficiency of 10% was considered a challenging milestone. However, first devices were far below this performance level [25]. In 1988, solar cells based on mm-sized CuInS_2 crystals in contact with a redox electrolyte came close to this milestone (conversion efficiency of 9.7% [26]), while a patent on this device concept was issued already in 1979 [27]. However, it was not possible to grow crystals reproducibly by this specific technique.

In 1993, the milestone of 10% conversion efficiency was reached eventually by a joint effort of scientists at the Hahn-Meitner Institute, Berlin (now Helmholtz-Zentrum Berlin) and at the Institute for Physical Electronics, University of Stuttgart, Germany. A Cu-rich ($[\text{Cu}]/[\text{In}] > 1$), coevaporated CuInS_2 film with standard CdS/ZnO emitter exhibited a conversion efficiency of 10.2% [28], but at the same time also a large V_{oc} deficit (i.e., difference with respect to the corresponding value at the Shockley-Queisser limit [29]) of about 0.8 V. Secondary phases of Cu-S due to Cu-excess were etched away by cyanide treatment prior to emitter deposition [30]. Soon it became clear that ZnO/CdS/ CuInS_2 photovoltaic devices were limited by enhanced recombination at the CdS/ CuInS_2 interface – unlike the $\text{Cu}(\text{In,Ga})\text{Se}_2$ devices, which, at that time, exhibited conversion efficiencies of around 15% with a V_{oc} deficit of only about 0.5 V (see also the further sections below). Attempts to copy the concept of Cu-poor ($[\text{Cu}]/[\text{In}] < 1$) growth applied for CuInSe_2 thin films failed because of the very low resulting conductivity [31] and Cu-Au defect ordering [32], leading to enhanced recombination [33] in the CuInS_2 layers.

Further progress with CuInS_2 grown under Cu-rich conditions was achieved by the application of sequential phase formation [34] and by the addition of Ga [35]. The company Sulfurcell (later Solteecture) in Berlin, Germany, was able to commercialize the CuInS_2 technology in full-

size modules with conversion efficiencies of around 10% [36]. In the meantime, the Asahi Kasei group revised the Cu-poor $\text{Cu}(\text{In,Ga})\text{S}_2$ formation with the aim of avoiding the cyanide treatment prior to emitter deposition [37,38]. These colleagues achieved around 10% conversion efficiency, for which an increase in conductivity by Na doping and Ga addition appeared to be the key. It was not until 2015 that this effort was resumed by scientists from Solar Frontier, Japan, who reached the next milestone of 15% by detailed growth optimization and a novel ZnMgO buffer layer [39]. The V_{oc} deficit was reduced to 0.6 V. This result may now lead to revived interest in $\text{Cu}(\text{In,Ga})\text{S}_2$ solar cells.

5. A short history of point defects in $\text{Cu}(\text{In,Ga})\text{Se}_2$

In the previous sections, research and development of $\text{Cu}(\text{In,Ga})(\text{S,Se})_2$ solar cells has been described as driven by the goal to improve the conversion efficiency. Fundamental studies on the electronic structure of $\text{Cu}(\text{In,Ga})(\text{S,Se})_2$ absorber layers themselves had been rare and not very systematic until the late 1990s. One evident reason for this fact is that understanding the electronic defects may lead to substantial improvement of the device performance only very indirectly and with a long delay. However, the $\text{Cu}(\text{In,Ga})(\text{S,Se})_2$ material used in solar cells – a solid solution of CuInSe_2 , CuGaSe_2 , CuInS_2 , and CuGaS_2 , which is Cu-poor (i.e., substoichiometric with $[\text{Cu}]/([\text{In}] + [\text{Ga}]) < 1$) and highly compensated – is not really suitable for (optical) defect spectroscopy.

Nevertheless, there is a growing insight into the importance of shallow defects, which govern the doping levels of the $\text{Cu}(\text{In,Ga})(\text{S,Se})_2$ absorber and thus the $p\text{-}n$ junction formation, as well as deep defects which are responsible for recombination of photogenerated carriers as well as for metastable behavior of the solar cells. Comprehensive reviews on this topic can be found in Refs. [40] and [41]. In the present overview, we will concentrate on shallow (doping) defects in $\text{Cu}(\text{In,Ga})\text{Se}_2$.

In contrast to Si, the doping behaviors of CuInSe_2 and CuGaSe_2 are dominated by intrinsic defects, i.e., cation antisite defects, vacancies, and interstitials. A specific property of CuInSe_2 and CuGaSe_2 compounds is that their ternary characters give rise to extremely low defect formation energies [42]. Shallow (doping) defects are usually investigated by photoluminescence (PL) spectroscopy or by the activation energies determined from Hall measurements. The interpretation of corresponding measurement results is easier when obtained on ternary compounds (i.e., CuInSe_2 and CuGaSe_2), because the alloy disorder present in $\text{Cu}(\text{In,Ga})\text{Se}_2$ can be avoided [43].

Unfortunately, energy values for defect levels in CuInSe_2 and CuGaSe_2 single crystals or thin films reported in the literature [40] almost fill the whole energy ranges of the corresponding band gaps. One problem in the interpretation of PL measurements is that the Cu-poor ($[\text{Cu}]/[\text{In}] < 1$) $\text{Cu}(\text{In,Ga})\text{Se}_2$ layers used in high-efficiency solar cells do not exhibit narrow transitions in the PL spectra, which may be interpreted in terms of defect levels, but rather a broad, red-shifted luminescence peak, even at low temperatures. Already in early 1976 [44], it was discussed that this broad luminescence peak in CuInSe_2 is due to potential fluctuations, and rediscovered in 1998 during PL investigations in Meyer's lab at the University of Giessen, Germany, when analyzing $\text{Cu}(\text{In,Ga})\text{Se}_2$ absorbers fabricated at the company Siemens Solar (now Avancis) [45]. Defect spectroscopy on CuInSe_2 with narrow PL lines is only possible on layers grown under Cu-rich ($[\text{Cu}]/[\text{In}] > 1$) conditions [46]. The same behavior was found in Cu-poor and Cu-rich CuGaSe_2 [47].

Still, on the Cu-rich side of both materials, several different transitions were detected in different samples, which made the interpretation difficult in terms of defect energies. Clarification of this dependence of defect levels on the process conditions was possible by using epitaxial films grown in the Siebentritt group (in M.C. Lux-Steiner's department at Hahn-Meitner Institute, Berlin) by metal organic vapor epitaxy, by which the composition can be well controlled. It was shown that both,

CuInSe₂ and CuGaSe₂, are dominated by three shallow acceptors and one shallow donor [40,48,49]. For both materials, the shallowest acceptor dominates near stoichiometry ($[\text{Cu}]/([\text{In}] + [\text{Ga}]) = 1$) and disappears with increasing [Cu], whereas the second acceptor increases with increasing [Cu]. The third acceptor is rather composition independent and has been related to structurally damaged material [50]. All defects exhibit energy levels which are slightly deeper in the band gap for CuGaSe₂ than for CuInSe₂.

Although a corresponding analysis is difficult for Cu(In,Ga)Se₂ since alloy disorder broadens the emission peaks in the PL spectra, it seems that a continuous transition exists between defect energies (see Fig. 2) [43]. For the interpretation of the chemical nature of these defects, comparison with calculations based on ab-initio density functional theory is necessary [42]. Here, the discussion is still ongoing, with substantial improvements concerning the applied functionals in the recent years [51, 52,53,54]. Structural, experimental evidence is available for the Cu vacancy V_{Cu} as well as for the In_{Cu} antisite defect and the Ga interstitial Ga_i [55,56], and also for a $V_{\text{Se}}-V_{\text{Cu}}$ double vacancy [57], which has been reported to be the origin for various metastabilities in Cu(In,Ga)Se₂ [58,59].

In addition to intrinsic defects, doping in Cu(In,Ga)Se₂ thin films can be influenced by defects related to impurities. These may be intentionally introduced [60] or diffuse into the layers from the substrates of the solar-cell stacks (e.g., Na, O, and K from soda-lime glass; Fe from steel foils); see also Section 6 below. Charged point defects play an important role on surfaces of CuInSe₂ and CuGaSe₂ thin films, where they stabilize polar configurations by atomic reconstructions [61]. Similar reconstructions have also been identified to occur at planar defects (i.e., stacking faults, randomly-oriented grain boundaries) in polycrystalline Cu(In,Ga)Se₂ thin films (see Ref. [62] for a recent review on this matter).

6. The role of alkali metals in Cu(In,Ga)Se₂ solar cells: from the old Boeing days to the present

Apart from native point defects in Cu(In,Ga)Se₂ treated in the previous section, defects related to impurities may also affect the photovoltaic performance of Cu(In,Ga)Se₂ solar cells. A particular role is played by Na, which can diffuse into the growing Cu(In,Ga)Se₂ layer when using substrate materials such as (e.g.) soda-lime glass, from a precursor layer (e.g., NaF) deposited between the substrate and the Mo back contact, or via a post-deposition treatment (for an overview, the reader is referred to the very good work by D. Rudmann [63]).

Experiences with the effects of Na on the growth of CuInSe₂ thin films were already obtained at Boeing Aerospace Company in the 1980s. At that time, B.J. Stanbery and coworkers implemented monolithic integration in the solar-cell stack for module production [64],

and they used borosilicate glass substrates (not containing Na). In order to selectively etch the molybdenum to form the P1 base metal contact isolation pattern, these colleagues used, among other etchants, a hot aqueous solution of NaOH. They observed that this etching solution lifted the photoresist off at the end of the Mo etching process, without requiring a separate photoresist stripping process, which was a very attractive process simplification. The conversion efficiency of the completed device was not extraordinary. However, the grain size in the CuInSe₂ thin films was much larger than in processes for which no NaOH was applied as an etchant. In spite of this astonishing result, this matter was not followed up any further since a contract milestone-deliverable had to be reached in due time, and NaOH was no longer used as the Mo etchant for monolithic integration.

It was indeed many years later when work of L. Stolt and colleagues at the University of Uppsala, Sweden, showed that Na from soda-lime glass indeed is a very important impurity for growing large-grain CuInSe₂ layers [65]. At this institution, CuInSe₂ solar-cell stacks were deposited on sintered alumina substrates in the 1980s. This substrate material is tough, temperature resistant, inert, and exhibits a thermal expansion coefficient similar to that of CuInSe₂ (and Cu(In,Ga)Se₂). However, the supply of alumina substrates was limited, and therefore, substrate materials with enhanced availability were required. This is why, among other materials, soda-lime glass was tested, which is less tough, less temperature resistant, less inert, but cheap, accessible, and has a thermal expansion coefficient which is similar to CuInSe₂ (and Cu(In,Ga)Se₂).

At about the same time, H.-W. Schock and colleagues at the Institute of Physical Electronics, University of Stuttgart, Germany, ran out of Na-free Corning 7059 glass substrates and used, accidentally, “dirty” soda-lime glass. These scientists found increased oxygen concentrations at the CuInSe₂ surface using photoelectron spectroscopy, which is (as we know today) related to the Na diffusion from the soda-lime glass into the CuInSe₂ layers, and allowed fabrication of devices with conversion efficiencies of 12.4% using this glass type in 1991 [66] (collaborative work within the EUROCIS project). By 1992, conversion efficiencies of almost 15% were achieved using CuInSe₂ absorber layers and soda-lime glass as substrates [67], which improved to 16.9% in 1993 with Cu(In,Ga)Se₂ absorbers [68] (both results also obtained within the EUROCIS project).

The influence of Na on the grain growth of Cu(In,Ga)Se₂ thin films has been related to the formation of Na polyselenides during the growth process [69], which act as a source of Se. In addition, Cu(In,Ga)Se₂ phase formation via Cu₂Se binaries is favored in the presence of Na, which was suggested to lead to larger grains owing to the templating function of the large Cu₂Se crystallites (formed during the Cu-rich stage of the growth process) [70]. The main effect of Na in Cu(In,Ga)Se₂ thin films on the device performance has been attributed to the effective annihilation of In_{Cu} point defects (donors) [71,72], which results in an overall higher net doping concentration [73], thus, leading to higher open-circuit voltages [74].

7. Early years of chemical bath deposition of buffer layers

While in the previous sections, the focus was on the technological development and the properties of the Cu(In,Ga)(S,Se)₂ absorber layer, the main issue of the solar-cell device was the optimization of the *p-n* junction. For this purpose, the use of various materials systems as *n*-type counterparts to the *p*-type Cu(In,Ga)(S,Se)₂ have been elucidated. Moreover, these materials have been also deposited using a variety of methods, ranging from (co)evaporation, sputtering, chemical vapor deposition, and atomic layer deposition, to deposition from a chemical bath. From all these research efforts during the past decades, it was found that chemical bath deposition (CBD) is particularly suitable for a controlled and well-adapted junction formation of various *n*-type materials with the *p*-type Cu(In,Ga)(S,Se)₂. Therefore, a specific section is dedicated to this topic.

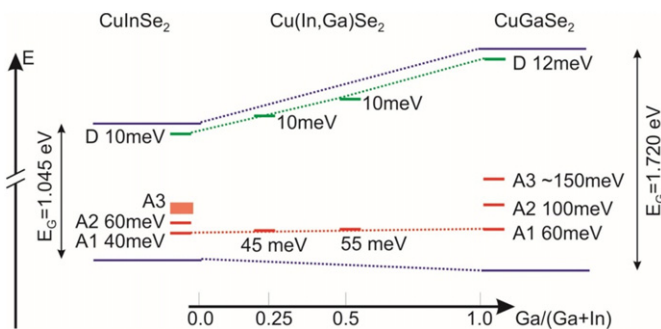


Fig. 2. Shallow acceptor (A1, A2, A3) and donor (D) levels, with energy differences given with respect to the valence and conduction band edges, determined by means of photoluminescence spectroscopy on Cu(In,Ga)Se₂ layers grown at four $[\text{Ga}]/([\text{In}] + [\text{Ga}])$ ratios. (Adapted from Ref. [43].)

7.1. Historical overview

The CBD of semiconducting sulfide, selenide, and oxide thin films was introduced a long time ago, already in 1884, when J. Emerson-Reynolds reported the deposition of lead sulfide by a reaction between lead tartrate and thiourea under basic conditions [75]. In addition, lead sulfide and lead selenide devices prepared by CBD were even used at the industrial level as infrared detectors during the Second World War. Thereafter, this deposition method for semiconducting films has then been mostly ignored for decades also owing to the rapid development of deposition methods from the gas phase (physical and chemical vapor deposition).

A revival of research efforts into CBD-CdS thin films in the beginning of the 1980s originated from the work of Prof. Chopra's group in New Delhi, India, who provided a detailed review and an in-depth study on the CBD of CdS thin films [76], first reported in 1961 [77]. In 1989, when working on CuInSe₂ solar cells within the European EUROCIS project, interest arose at the Ecole Nationale Supérieure de Chimie Paris in trying the CBD method developed by Prof. Chopra's work to prepare CdS films for CuInSe₂ solar cells, as an alternative to the evaporation methods applied up to that date. D. Lincot and coworkers repeated the experiments described by Prof. Chopra's publication and eventually found appropriate conditions for optimal CBD of CdS, after having broken several tens of glass tubes. This allowed for rapidly testing a broad range of experimental parameters and to select those leading to heterogeneous instead of homogeneous deposition of CdS films on the inner glass-tube surface [78]. At about the same time, R. Birkmire and coworkers at the Institute of Energy Conversion at the University of Delaware, U.S.A., reported first experiments on the use of CdS buffer layers synthesized by CBD for solar cells [79].

The key finding by D. Lincot and coworkers was that the deposition proceeded according to a well-defined, surface-controlled mechanism, independent of the hydrodynamic regime. These researchers also found that CBD solutions with an excess of thiourea resulted in good coverage properties of the CdS thin films at low thicknesses (20 nm). Joint studies immediately started within the EUROCIS project, in particular in collaboration with the group of H.-W. Schock at IPE, Stuttgart, Germany, using such recipes with high thiourea concentrations. These efforts resulted in a considerable breakthrough with solar-cell efficiencies exceeding those of devices with sputtered or evaporated buffer layers. Not only increased current densities, but also higher open-circuit

voltages were achieved [80,81] (see Fig. 3), which indicated a better interface quality between the CuInSe₂ absorber and the CdS buffer layers. This work on the improvement of CBD-CdS buffer layers contributed substantially to the record conversion efficiency published by the EUROCIS group in 1993 (see Section 6 above).

Soon thereafter, it was found by analyzing the surface chemistry of Cu(In,Ga)Se₂ thin films after the CBD process that the CBD solution cleans selectively and changes the composition of the Cu(In,Ga)Se₂ surface, involving in-diffusion of Cd by surface-exchange reactions [82]. In the following, CBD became the standard technology for CdS buffer layers [83]. Fundamental mechanistic studies demonstrated in parallel that the growth mechanism relies on well-defined and successive reaction steps at the atomic level at the Cu(In,Ga)Se₂ surface, as also occurring when depositing thin films by means of chemical-vapor deposition methods [84]. This fact was confirmed by the occurrence of epitaxial growth of CBD-CdS on various substrates, including CuInSe₂ [85].

In 1994, another challenge was met within the follow-up of the European network project EUROCIS (EUROCIS-M), which was devoted to the large-scale manufacturability of solar-cell devices. One of the problems with CBD processes performed in beakers was the enormous loss of material by homogeneous precipitation, which was why CBD was initially not considered as a possible method for large-area deposition. This obstacle was solved by using large substrates oriented face-to-face with each other, with rubber rings, having a thickness of 1–2 mm, as separators. The reacting solution was poured into the spacing provided by the rubber rings. The walls of the beaker were covered by the substrates. In the first successful attempt, on substrate areas of 30 × 30 cm², due to the lack of larger rubber rings, the window glasses were separated by soft telephone cables.

Modifications of this configuration, termed “two-plates configuration” or “closed-space” CBD, were developed also for CdS deposition in CdTe solar modules by the companies BP Solar and Shell Solar (using multiplates in back-to-back pairs of substrates). However, mechanical breaking problems arose in the EUROCIS project when upscaling the plate area, owing to a bending effect induced by thermal stress during the deposition of the Cu(In,Ga)Se₂ layer at high temperature. In 1993, a flat reactor concept with the substrate at the bottom and an oscillating wave to insure the renewal of the solution at the surface was presented by D. Lincot [86], which was called the “photographic” process and which was further developed within the EUROCIS M project. It was successfully transferred to the industry and is sold nowadays as standard equipment for solar-module manufacturers. This success was unpredictable in 1989 during the “test tube breaking” period.

In the early 1990s, the CBD method was developed also for other buffer-layer materials, especially for Zn-based semiconductors (see the excellent review by D. Hariskos [83]). In 1992, a recipe for a ZnS buffer layer based on thioacetamide was presented, which resulted in solar-cell efficiencies of 9%. However, the devices exhibited a considerable light-soaking effect [87]. In a subsequent publication, the formation of zinc hydroxyl sulfide in an ammonia thiourea bath was reported [88]. However, the real breakthrough for Zn-based buffer layers was achieved by using Zn(OH)₂/Zn(O,S,OH)_x by K. Kushiya and coworkers at Showa Shell Sekiyu in Japan (today: Solar Frontier) (Ref. [89]; for more details, see Section 7.2 below).

Apart from CBD, atomic layer deposition (ALD) has also been used successfully as a deposition method for buffer layers in Cu(In,Ga)(S,Se)₂ solar cells, particularly successful for In₂S₃ buffers [90]. Although ALD is nowadays also considered scalable and thus suitable for industrial module production, CBD as buffer-deposition method still remains in a strong leadership position with conversion efficiencies of up to >22% reached by Zn-based CBD buffers, for devices with both, coevaporated Cu(In,Ga)Se₂ [91] and sequentially processed Cu(In,Ga)(S,Se)₂ [92] absorber layers. The success story that started in the late 1980s, followed by ten years of golden pioneering period [93,94] is still continuing.

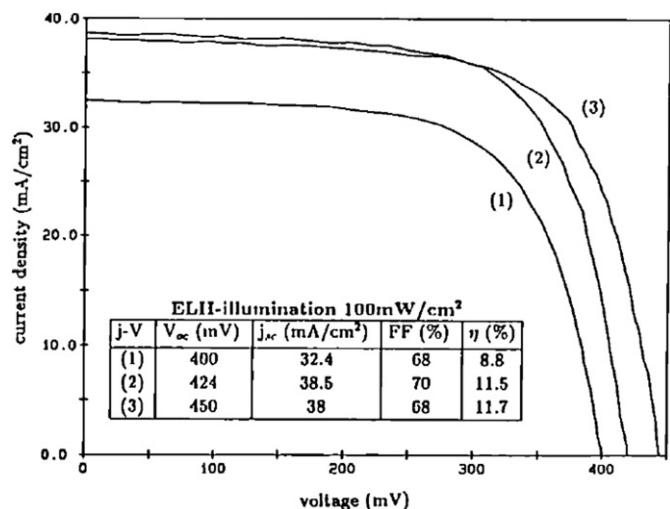


Fig. 3. Key results of the EUROCIS consortium concerning the use of CBD-CdS buffer layers from 1991. Current-voltage characteristics of a Cd_{0.85}Zn_{0.15}S-CuInSe₂ standard device (1) and corresponding ZnO-CdS-CuInSe₂ devices with sulfide-based and iodide-based CBD-CdS buffer layers.

Reproduced with permission from Ref. [80].

7.2. Motivations for the development of a Cd-free Zn(O,S,OH)_x buffer layers

Showa Shell Sekiyu K.K. joined the Japanese New Energy and Industrial Technology Development (NEDO) Solar Research and Development project in 1993. Within this project, it was not planned to use a CdS buffer layer for the solar modules, although CdS had, up to then, been the main material for this application. In the following, the circumstances for the development of a Cd-free Zn(O,S,OH)_x buffer are described in detail.

CdS exhibits a rather small band-gap energy of 2.42 eV. First, ZnO was selected owing to its wider band gap (>3.3 eV). Also, it is of the same material as the window layer applied (i.e., doped ZnO), but with high resistivity being undoped. However, Zn is well known as an amphoteric element, i.e., it was very difficult to annihilate the Zn(OH)₂ content completely by dehydration of Zn(OH)₂ → ZnO + H₂O in a strong, caustic (pH > 10) solution of a CBD process. The chemical stability of the Cu(In,Ga)(S,Se)₂ based absorber layer allowed for the usage of a strong caustic condition given by an ammonia solution. However, it led to the formation of a complex with a Zn ion. Due to the larger molecular size of Zn(OH)₂, the colloid formation reaction was accelerated. Therefore, a higher bath temperature of 85 °C, compared with 65 °C, for CdS was employed to increase the growth rate [89,95].

To reduce the Zn(OH)₂ content further and to enhance the resistivity of the buffer layer, thiourea dissolved in a deionized water was added to the CBD solution. As a result, a mixture of ZnO, ZnS and Zn(OH)₂ (termed Zn(O,S,OH)_x) as a high-resistivity buffer layer was deposited on the Cu(In,Ga)(S,Se)₂ absorber. Owing to the Zn(O,S,OH)_x band-gap energy of >3.3 eV, the short-circuit current densities j_{sc} were enhanced by at least 2 mA/cm², without any loss in absorption, within the wavelength range from 300 to 520 nm [95].

As one of the disadvantages of a wet CBD process for CdS deposition, in which the Cu(In,Ga)(S,Se)₂ surface layer/Cu(In,Ga)Se₂ absorber/Mo/glass stack is immersed completely into the solution, it was recognized that it required an extra step to wipe off the CdS-deposited edge and rear sides of the substrate by ethanol. This extra work was understood as a substantial disadvantage for commercialization. In contrast, ZnO was employed as a buffer layer because it was an essentially high-resistivity material, and the additional cleaning step was not necessary.

The resistivity of Zn(O,S,OH)_x is about ten times larger than that of CdS. Therefore, CBD techniques have been employed in order to not only deposit Zn(O,S,OH)_x films with good coverage on the Cu(In,Ga)(S,Se)₂ absorber layers, but also to realize substantially smaller thicknesses (around 5 nm) than normally applied for CdS buffer layers (50 to 100 nm). Such small thicknesses were expected to enhance the tunneling of charge carriers through the barrier.

When depositing CBD-CdS buffer layers, large amounts of Cd-containing, liquid waste have to be dealt with in commercialization, and the corresponding waste disposal of the CBD solution is rather expensive, substantially increasing the manufacturing costs. In contrast, for baseline processes with Zn(O,S,OH)_x buffer layers, the same CBD solution can be used at least six times, resulting in equally good solar modules, although the colloid formation reaction proceeds continuously. At Showa Shell Sekiyu K.K., a waste-disposal process was developed for the caustic CBD solution containing ZnO, ZnS and Zn(OH)₂. In this process, ammonia was at first removed from the heated solution by decomposing with a catalyst, in order to neutralize the waste CBD solution, and then, dry-solid powders of ZnO and ZnS were collected, which were treated as industrial waste.

Maintenance of the CBD equipment used for CdS deposition always requires full protection clothing, as well as other safety goods because of the use of a dilute acidic (e.g., HCl) solution. In order to avoid such extra expenses, and for enhanced safety conditions in the workplace, Cd-free materials for the buffer layer were selected, even in the early stage of research and development.

The hardness of ZnO-based buffer layers is larger than that of CdS. As a result, CdS did not work well as a suitable shock absorber against the

sputtering process applied for the doped ZnO window layer. Thus, owing to damage on the surface of the Cu(In,Ga)Se₂ absorber, it was not possible to control the junction quality, although researchers tried to reduce the impact of the sputter bombardment. Therefore, deposition techniques based on metal-organic chemical vapor deposition (MOCVD) were applied for a ZnO:B (BZO) transparent conductive oxide window [96]. One of the advantages of the MOCVD-BZO window was that an insufficiently doped, high-resistivity ZnO thin layer was deposited at the initial stage of its hetero-growth on a Zn(O,S,OH)_x buffer layer [97]. The thickness of this initial layer was controlled by adjusting the timing of the doping. This technique had been, for the first time, developed by ARCO Solar, Inc. (ASI) [98], where a MOCVD-BZO window was deposited on a CdS buffer layer. Then, based on this growth model, the window design was modified by depositing a high-resistivity ZnO layer between the Cu(In,Ga)Se₂ absorber and the conductive ZnO:Al (AZO) window layer.

The finding of a light-soaking effect of the baseline Zn(O,S,OH)_x buffer layers was key to achieve enhanced conversion efficiencies. The sensitivity to light soaking is believed to correlate strongly with the concentration of hydroxide in the CBD buffer layer. CBD-CdS, in contrast, does not exhibit a strong light-soaking effect, probably since the hydroxide concentration is substantially smaller (less than a few mol%, as measured by means of X-ray photoelectron spectroscopy) [99].

8. Production processes for Cu(In,Ga)(S,Se)₂ photovoltaic industries: from ARCO Solar to the present day

Eventually, research efforts performed at the laboratory scale are supposed to be transferred to industrial production of Cu(In,Ga)(S,Se)₂ solar modules. Therefore, it is essential to look into the development of industrial production during the past decades in this final section of the present contribution.

8.1. Development of stacking sequences during the past three decades

Fig. 4 gives an overview of this development. For a recent review on industrial Cu(In,Ga)Se₂ processes and stacking sequences of the corresponding solar modules, the reader is referred to Ref. [100]. The first 10% efficient solar-cell produced at Boeing Aerospace Company in 1982 consisted of a CdS:In(2–4 μm)/CdS(0.5–1.5 μm)/CuInSe₂(2–6 μm)/Mo thin-film stack on a borosilicate glass substrate, where CuInSe₂ was deposited as a high-resistive/low-resistive bilayer [7]. Back then, SiO_x was used as antireflection coating, instead of MgF₂ as applied nowadays. During the following years, the CdS:In/CdS window was replaced first by evaporated CdZnS [8], then by a thin (50 nm) CdS layer, grown by CBD, which was introduced by ARCO Solar Inc. [10] (see also Sections 3 and 7 above). Further improvements in the window layers of the solar-cell stack were achieved by using a high-resistivity/low-resistivity ZnO:Al bilayer, which was sputtered on the CdZnS buffer layer. The high resistivity part was realized by an undoped, intrinsic (i-)ZnO layer of few tens of nanometers in thickness [101]. Using this approach, a 13.7% efficiency record was reached at Boeing Aerospace Company, applying a bilayer process for Cu(In,Ga)Se₂ deposition, during which first a Cu-rich, and then a Cu-poor Cu-In-Ga-Se layer was coevaporated, resulting in an overall Cu-poor composition. In contrast, 13% solar cells were produced at ARCO Solar Inc. using a sequential Cu(In,Ga)Se₂ process, i.e., first sputtering of Cu, In, Ga, and then selenization of these precursors in H₂Se gas [10].

In 1994, researchers at NREL developed a three-stage process for Cu(In,Ga)Se₂ layer deposition. It comprises the deposition of an In-Ga-Se precursor, then coevaporation of Cu-Se until excess Cu-Se forms on top of the Cu(In,Ga)Se₂ layer, and finally In-Ga-Se in order to consume the excess Cu-Se again, resulting in a Cu(In,Ga)Se₂ layer with overall Cu-poor composition [102]. The beneficial role of the Cu-Se phase was discussed by Klenk et al. [103].

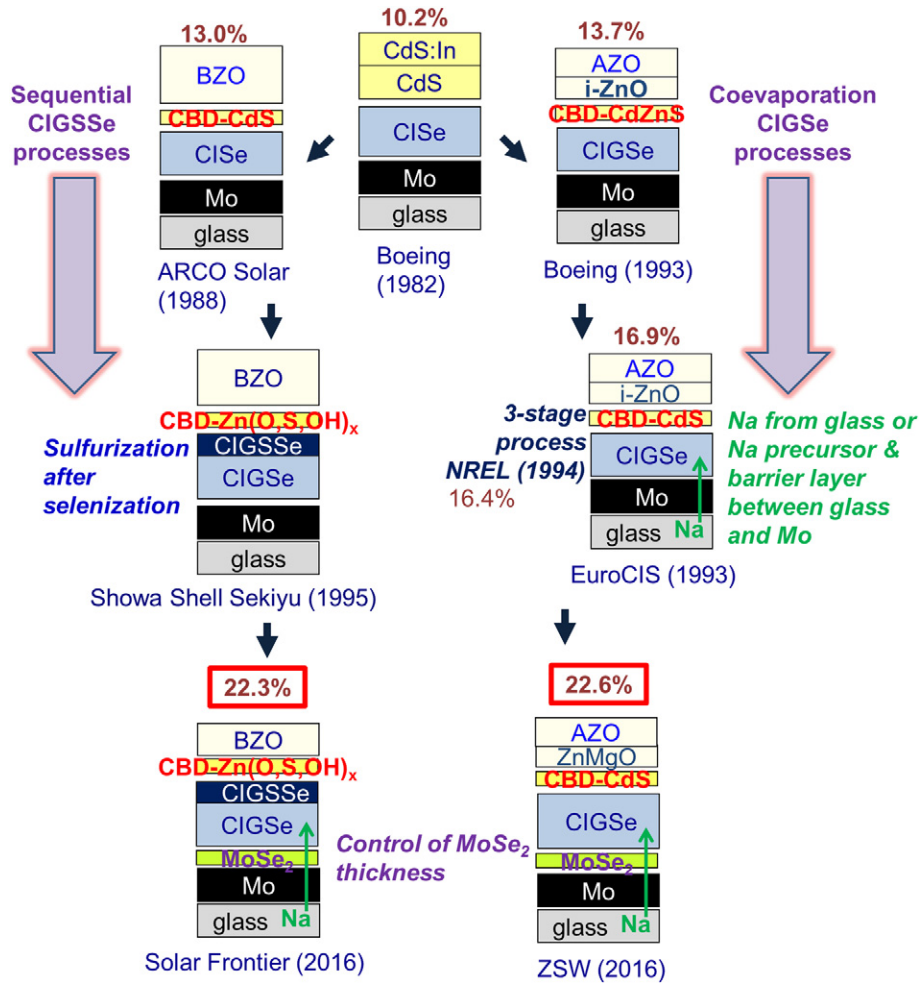


Fig. 4. Development of stacking sequence in Cu(In,Ga)(S,Se)₂ solar cells for industrial application through the past four decades.

Introducing Na during or after Cu(In,Ga)(S,Se)₂ layer deposition improved the Cu(In,Ga)(S,Se)₂ solar-cell performance even further (see Section 6 above). One option is that Na diffuses from the Na-containing glass substrate. Alternatively, a diffusion-barrier layer (e.g., Si-N, Si-O) prevents Na diffusion from the glass, and a Na precursor (e.g., a thin NaF layer) is deposited on top of the Mo/barrier/substrate stack (or Na is already incorporated in the Mo layer), prior to the Cu(In,Ga)(S,Se)₂ layer deposition. By the end of the 1990s, MoSe₂ formation between Mo and Cu(In,Ga)(S,Se)₂ has attracted substantial attention [104], and efforts have been made in order to control its thickness and other properties in order to optimize the electrical properties at the back contact.

8.2. ARCO Solar

ARCO Solar Inc. (ASI) was founded as Solar Technology International in 1975, and by 1980, it was the world's largest photovoltaic manufacturer with a crystalline silicon capacity of about 1 MW/yr. ASI began work on CuInSe₂ photovoltaic devices in late 1981, soon after Boeing Aerospace Company had reported a 10% thin-film CuInSe₂ solar cell (see Section 3 above). Early ASI work on CuInSe₂ focused on elemental coevaporation, but the company also explored sputtered binary selenides and electroplated elemental metal stacks with subsequent H₂Se selenization as pathways to lower-cost commercialization. The challenges of uniform precision electroplating on large areas at high rates motivated a shift to sputtering of Cu and In precursor stacks, from which world record cells (13% in 1988 [10]) were produced. A key enabling advance was a first-order Cu-In hydride-selenization model, based on an adaptation of Si-oxidation models [105].

Early two-step CuInSe₂ films often featured poor adhesion at both the Mo/substrate and the CuInSe₂/Mo interfaces. Overall, the adhesion improved substantially by upgrades in substrate cleaning, implementation of adhesion layers (e.g., Cr), adjustments to the Mo properties (via the sputter conditions), and tuning of the selenization parameters, which probably also affected the properties of the intermediate MoSe₂ layer (as discovered only later, see Section 8.1). Ga was added by using Cu-Ga sputter targets with the aim of producing Cu(In,Ga)Se₂ films exhibiting larger band-gap energies; however, the selenization processes of that time yielded strong Ga concentration gradients, i.e., the effective band-gap energy of the Cu(In,Ga)Se₂ absorber layer was largely unchanged. However, the presence of a high Ga concentration near the Mo further improved the adhesion at the Cu(In,Ga)Se₂/Mo interface and broadened the selenization processing ranges, which in turn led to larger average grain sizes in Cu(In,Ga)Se₂ films.

Cu(In,Ga)Se₂ solar cells at ASI initially comprised evaporated CdS/CdS:In transparent electrode stacks, similar to contemporaneous solar cells at other manufacturers. The photocurrent densities of these devices were increased by decreasing the optical absorption in the CdS layer, first by replacing CdS:In with metal oxides exhibiting larger band-gap energies, and second by replacing evaporated CdS with thin, dense, and conformal chemical-bath-deposited buffer layers. A low-temperature, chemical vapor deposition process was developed to deposit ZnO:B as a low-cost, controllably-textured transparent conductor.

Improvements in Cu(In,Ga)Se₂/Mo adhesion and Cu(In,Ga)Se₂ film quality increased the stable cell efficiency and sparked a shift to work on larger, commercially-relevant substrate sizes as well as the development of manufacturing tools, processes and infrastructure, including

large-area selenization systems. A mishap with a selenization tool interrupted this progression; the focus shifted to vapor-phase and solid-state selenization. Eventually hybrid chalcogenization processes incorporating solid-state Se and hydride gases were developed, e.g., H_2Se to improve the optoelectronic properties of $\text{Cu}(\text{In,Ga})\text{Se}_2$, and H_2S to produce $\text{Cu}(\text{In,Ga})(\text{S,Se})_2$ films. Sulfurization of the surface of the synthesized $\text{Cu}(\text{In,Ga})\text{Se}_2$ layer resulted in an increased band-gap energy at the $\text{Cu}(\text{In,Ga})(\text{S,Se})_2/\text{CdS}$ interface, which improved the open-circuit voltage of the device substantially.

In 1990, ASI was taken over by the European joint-venture partner Siemens Solar, and in 1998, the first worldwide commercial series production of $\text{Cu}(\text{In,Ga})(\text{S,Se})_2$ solar modules (with 40 W_p of nominal power) was started in Camarillo, California. The Siemens Solar $\text{Cu}(\text{In,Ga})\text{Se}_2$ research team in Germany realized various additional advances, including, most notably, rapid thermal processes, which were subsequently commercialized at Avancis, Germany. Also at ASI's Asian joint venture partner Showa Shell Sekiyu, progress in module manufacturing was achieved, mainly by a "sulfurization after selenization" $\text{Cu}(\text{In,Ga})(\text{S,Se})_2$ process as well as by a $\text{Zn}(\text{O,S,OH})_x$ buffer layer, commercialized later by Solar Frontier (see Section 7.2 above and Section 8.3 below).

ASI's 1980s work on electroplating and atmospheric-pressure selenization, on chemical bath deposition of buffer layers and on chemical vapor deposition of transparent conductors indicated that non-vacuum processes may yield $\text{Cu}(\text{In,Ga})\text{Se}_2$ solar-cell devices with good qualities. Various groups further explored non-vacuum $\text{Cu}(\text{In,Ga})\text{Se}_2$ processing with the aim of reducing the capital cost of production tools and facilities as well as the materials costs of manufacturing. These groups included Unisun and International Solar Electric Technologies, which independently developed non-vacuum processes based on nanoparticulate materials. Unisun focused on core-shell, mixed-metal oxide nanoparticles formed by aerosol pyrolysis, on precursor layer deposition by spraying, dipping, spinning, or printing, and on $\text{Cu}(\text{In,Ga})\text{Se}_2$ film formation by reactive annealing and on-demand, in-situ hydride generation. Unisun technology was licensed to Nanosolar, which in turn went on to develop low-cost mechanical milling of mixed-metal nanoparticles, high-speed roll-to-roll slot-die printing of precursor layers on metal foil, and non-hydride selenization to form large-area cells. SoloPower developed roll-to-roll Cu-In-Ga electroplating, solid-state chalcogenization, and light-weight flexible modules. In France, an electroplating route for $\text{Cu}(\text{In,Ga})\text{Se}_2$ was initiated in the beginning

of the 1990s within the EUROClS and EUROClS-M projects, which was then further developed at IRDEP at the beginning of the 2000s and led to the founding of the start-up company Nexcis. These non-vacuum strategies provide a high-return-on-capital alternative to vacuum-based $\text{Cu}(\text{In,Ga})\text{Se}_2$ technologies.

8.3. Solar Frontier, Japan

The baseline process for production of $\text{Cu}(\text{In,Ga})\text{Se}_2$ absorber layers with a very thin surface layer of $\text{Cu}(\text{In,Ga})(\text{S,Se})_2$ at Solar Frontier is depicted in Fig. 5. The absorber synthesis by "sulfurization after selenization" (SAS) is described in detail further below. A $\text{Zn}(\text{O,S,OH})_x$ buffer layer instead of CdS, and a ZnO:B window layer (BZO, originally developed by ARCO Solar Inc.), instead of a ZnO:Al (AZO, introduced by Boeing Aerospace Company), are used in order to reduce absorption losses in the short-wavelength and plasma regions.

The "sulfurization after selenization" process (Fig. 6) comprises sputtering of a Cu-Ga-In precursor layer using Cu-Ga alloy and In targets, selenization using dilute H_2Se gas and finally a sulfurization step using dilute H_2S gas in the reaction furnace, which results in a $\text{Cu}(\text{In,Ga})(\text{S,Se})_2$ surface layer on top of a $\text{Cu}(\text{In,Ga})\text{Se}_2$ absorber [106, 107]. Goushi et al. showed that Ga diffusion towards the $\text{Cu}(\text{In,Ga})(\text{S,Se})_2$ surface is enhanced when using higher substrate temperatures and longer holding durations for the sulfurization step [108]. It was also revealed that it is possible to increase the sulfur content incorporated into the Ga-graded $\text{Cu}(\text{In,Ga})\text{Se}_2$ absorber by properly selecting the growth parameters [108,109].

The use of dilute instead of pure reactive gases has the advantage of reduced gas consumption; thus, reduced production costs. The thicknesses of the complete $\text{Cu}(\text{In,Ga})\text{Se}_2/\text{Cu}(\text{In,Ga})(\text{S,Se})_2$ layers are about 1.2–1.5 μm . Used sputtering targets can be recycled, because they are not contaminated considerably in the baseline process.

9. Conclusions

The present work provides a historical retrospective on several milestones and key innovations in the research and development of $\text{Cu}(\text{In,Ga})(\text{S,Se})_2$ solar cells, as witnessed and presented by the coauthors working in their laboratories or companies at that time. It becomes apparent that one is well advised to remain open minded, even when concentrating on very specific issues in daily research work.

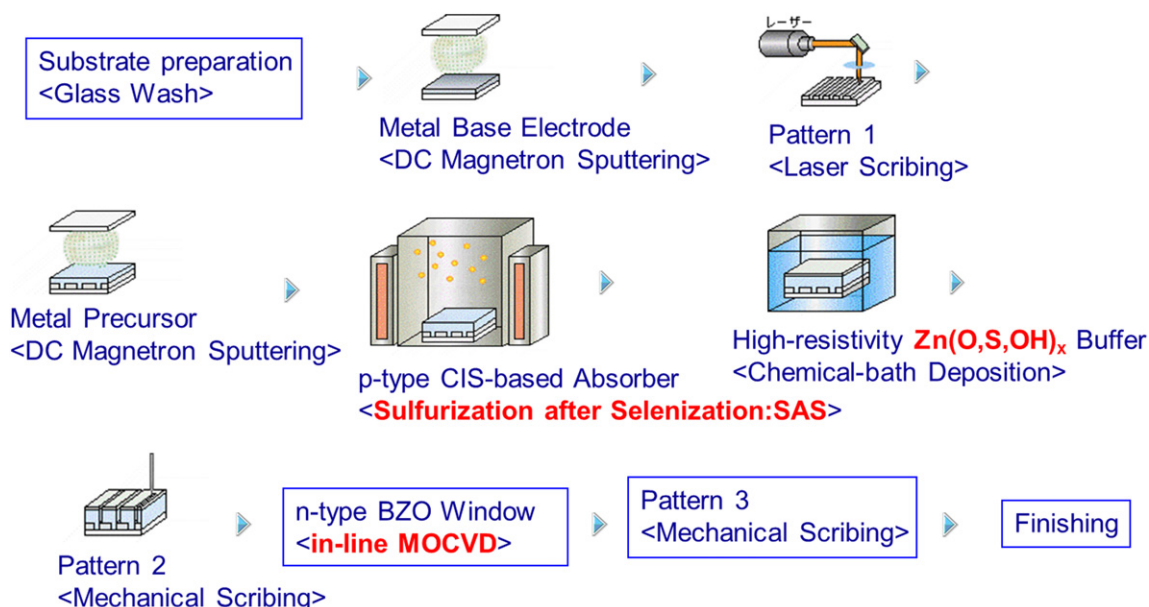


Fig. 5. Baseline process of $\text{Cu}(\text{In,Ga})(\text{S,Se})_2$ solar modules transferred to commercial production at Solar Frontier.

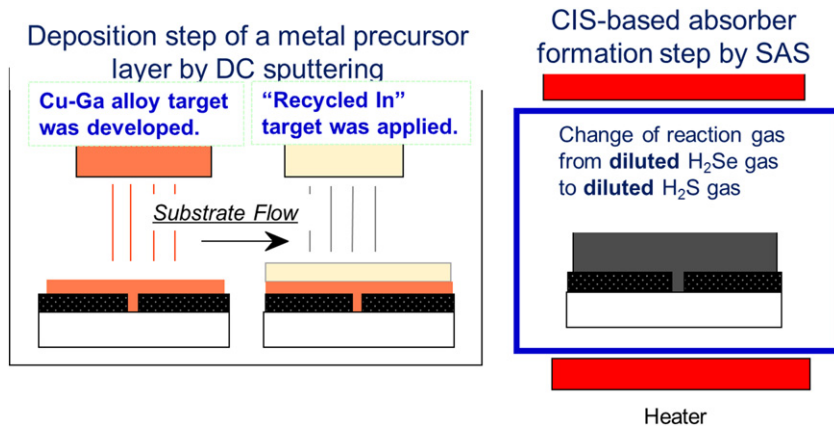


Fig. 6. Schematics of the “sulfurization after selenization” (SAS) process at Solar Frontier K.K.

Taking the example of the first CuInSe_2 solar cells, which were produced by chance when actually aiming at developing broad-band photodetectors for optical communication, it was shown that innovative technologies for a specific application may arise from developments in a different field. Other insights simply resulted from accidents or by chance in the experimental work, as, e.g., the issue of Na from the soda-lime glass substrate. Moreover, very often, the observation of an unexpected result or effect gets overlooked and receives no further attention for investigation or analyses, owing to restricting boundary conditions, such as project milestones. Here, it is recommended to always pay attention to things one does not understand, study them and analyze them, because this is where breakthroughs come from.

$\text{Cu}(\text{In,Ga})(\text{S,Se})_2$ solar-cell efficiencies have improved to remarkably high values of $>22\%$. There are good prospects for further improvement as progress continues. However, industrial production of correspondingly high-efficiency solar modules with low production cost requires overcoming additional challenges. In this context, further work is necessary, especially for the development of simple and robust deposition methods along with device structures requiring less complexity for processing and less stringent conditions of large-area uniformities, without sacrificing the efficiencies. New directions of research, such as flexible solar cells on low-cost substrates, cells with thinner absorber layers, device concepts based on passivated surfaces and point contacts or tandem solar cells, microcells among others, offer interesting options for further developments. The historical developments described in the present summary may provide motivation for finding innovative and unconventional solutions.

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