

Towards very low-cost mass production of thin-film silicon photovoltaic (PV) solar modules on glass

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Abstract

Production volume of PV modules increases at >35% per year, but one is yet far from making a global impact on energy supply. One of the obstacles is given by the present high production costs of PV modules. A possibility to reduce costs are thin-film PV modules on glass. The specific option of thin-film silicon is considered. The combination of amorphous and microcrystalline silicon thin films within a tandem solar cell corresponds to a theoretical optimum. In practice, stabilized efficiencies of 10% to 12% have so far been obtained in the laboratory with such tandem solar cells. Silicon being a material with an indirect band gap, its absorption coefficient is relatively low, and therefore light management in the solar cell has to be further optimized. Thin-film silicon can be deposited by plasma-enhanced CVD, as used for AM-LCD displays. The use of modified fabrication equipment from the AM-LCD Display Industry is therefore a promising way to implement low-cost mass production.

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1. Introduction

The quest for cost-effective, sustainable energy sources is one of the major concerns of present-day industrial society. It motivates the broad R & D efforts undertaken in the E.U., Japan, USA and in many emerging countries. Because photovoltaic (PV) solar energy can serve as a decentralized source of electricity, it is a key sector in this quest. Even though the increase in worldwide production of PV solar modules is impressive, so far this source of energy only plays a marginal role (Fig. 1).

The main reason why PV modules have up to now not been used more extensively is related to their manufacturing cost and, thus, to their market price. Present PV modules are, to a large extent, made of silicon wafers, and here the cost of the wafers themselves is the limiting factor. Fig. 1 also

indicates roughly how the price of PV modules has decreased during the last 20 years, (see also [1]), reaching at present average values just between 3 and 4 U.S. \$ per W_p (peak-Watt); for purchase of large quantities of crystalline silicon PV modules, prices as low as 2.60 U.S. \$ per W_p are quoted in certain countries.

For the large-scale application of Photovoltaics, both for Building-Integrated Photovoltaics (BIPV) in Europe and Japan, as well as for rural electrification and irrigation pumps in emerging countries, like India, Brazil, and China, it is imperative to decrease the manufacturing cost of PV modules further, by a factor of at least 2 to 3, even if one thereby has to accept slightly reduced conversion efficiencies.

This has motivated researchers to study, since the early 1980s, different *thin-film* solar module concepts. In all these thin-film concepts the semiconductor can be deposited directly on low-cost large-area substrates. Furthermore, the cells do not have to be self-supporting; therefore, large-area substrates can be used which are already a part of the

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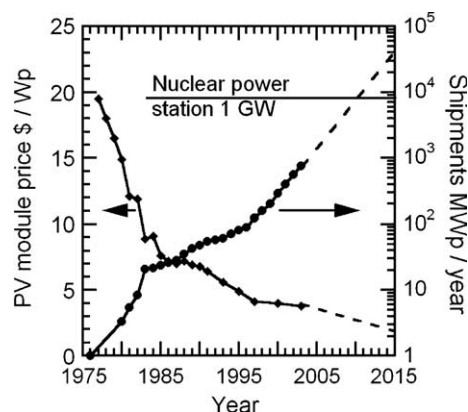


Fig. 1. Worldwide production and average market price evolution of PV modules; also indicated is the PV capacity needed (for average Central European climatic conditions) to replace a single 1 GW nuclear power station.

encapsulation. Various semiconductors have been envisaged for thin-film solar cells: Compound semiconductors, like CdTe and Cu (In, Ga) Se₂ (CIGS), have attracted much attention in the past, and have led to relatively high laboratory efficiencies, but so far their large-scale industrialization has not reached volumes comparable to thin-film silicon based technologies. In this context it must be noted that potential obstacles to the compound semiconductor technologies are justifiably perceived: these obstacles relate to hazards due to the incorporation of Cd, and to an ultimate materials shortage, particularly of In, followed by Te.

The focus of the research group at IMT Neuchâtel has been traditionally on *silicon*, and on the development of low-cost concepts for thin-film silicon solar cell manufacturing. By choosing silicon, we can benefit from the efforts of the Display Industry, where amorphous silicon is widely used for AM-LCD (Active Matrix Liquid Crystal Display) production.

Indeed, as can be seen in Fig. 2, the total estimated worldwide production turnover of the PV module industry is still relatively low (around 5 billion U.S. \$) and, therefore, cannot by itself sustain a large enough engineering effort. It is therefore imperative for the PV Industry to benefit from engineering efforts by other, more lucrative industrial fields, like Flat Panel Displays, where a large enough financial turnover has already been achieved, at the present moment.

The purpose of the present paper is to show some promising current trends in thin-film silicon module design, and in the development of production equipment, based on AM-LCD fabrication tools.

2. Amorphous and microcrystalline silicon in PV solar cells: performance

2.1. Material properties

Thin films are, in general either (a) amorphous, (b) polycrystalline or (c) monocrystalline. The deposition of

monocrystalline silicon thin films is possible by the use of epitaxy and necessitates relatively expensive monocrystalline substrates (wafers); it shall, therefore, not be considered further here. Thin silicon films, with amorphous or polycrystalline structure, can, on the other hand, be deposited on glass, on stainless steel and on plastic substrates, by PECVD (Plasma-Enhanced Chemical Vapor Deposition), from a mixture of silane (SiH₄) and hydrogen (H₂), and, partly depending on the substrate material, at temperatures from 150 to 500 °C. The resulting layers contain hydrogen that passivates the defects (dangling bonds and grain boundaries), yielding, thus, a material that has semiconductor properties and can be doped [2,3]. If amorphous, the layers are subject to light-induced degradation: a reversible increase of defect densities that saturate after some thousand hours of light exposure, yielding, in the stabilized state, layers that have poor mobility \times lifetime ($\mu\tau$) products. In the polycrystalline case, the resulting crystallites are small (dimensions around a few hundred nm), so that one talks of “microcrystalline” silicon. The latter exhibits a wide range of different microstructures [4], and usually does not suffer from light-induced degradation. Here, $\mu\tau$ -products are similar to those of non-degraded amorphous silicon (Table 1).

Of interest for photovoltaic applications is the absorption coefficient in function of photon energy: this is shown in Fig. 3, for various thin-film materials presently studied for solar cell applications.

Because of the relatively low value of the absorption coefficient, solar cells consisting of amorphous and microcrystalline silicon need elaborate light-trapping schemes in order to absorb a sufficient part of the incoming solar spectrum, within a reasonable thickness.

2.2. Single-junction amorphous and microcrystalline silicon solar cells

Solar cells are, generally, diodes, consisting of a p–n structure (p-type doped layer adjacent to a n-type doped layer) and carrier collection/transport takes place mainly by

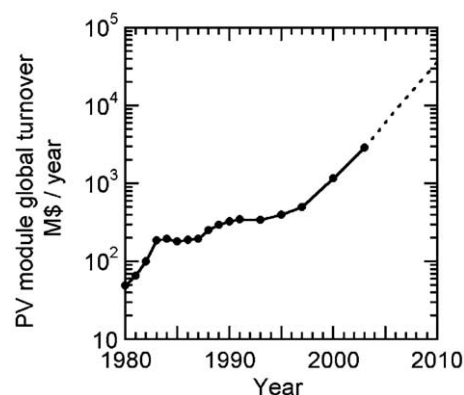


Fig. 2. Estimation of total worldwide financial turnover of PV module Industry, based on data of Fig. 1.

Table 1

Mobility \times lifetime products, diffusion and drift lengths ($L_{\text{diffusion}}$, L_{drift}) of typical Si layers, see [5,6]

	Measured $\mu\tau$ -values	corresponding $L_{\text{diffusion}}^*$	L_{drift} if $E=1 \text{ V}/\mu\text{m}$
Amorphous silicon (initial state)	4×10^{-7}	1.0	40
Amorphous silicon (degraded state)	1×10^{-7}	0.5	10
Microcrystalline Si	4×10^{-7}	1.0	40
Units	cm^2/Vs	μm	μm

*actual, measured diffusion lengths [6] are *ambipolar* diffusion lengths (in the photo-active *intrinsic* layers), and are, therefore, at least a factor 2 lower.

carrier diffusion. Because the mobility \times lifetime products of thin-film silicon layers are relatively low (Table 1), yielding diffusion lengths, that are generally lower than the corresponding penetration depths for the long wavelength part of the solar spectrum (Fig. 3), this type of a diode cannot be employed for the thin-film silicon case. One has, on the contrary, to use *p-i-n diodes*, where the photo-generation takes place in the i-layer and transport and collection are drift-assisted. Fig. 4 shows such a p-i-n diode, as deposited on a glass substrate. Note the Transparent Conductive Oxide (TCO, here ZnO) used as transparent electrode, on the side where the light enters the solar cell¹: this is a feature that is common to all thin-film solar cells. In the case of silicon, the TCO layer has, additionally, to achieve scattering of the incoming light with the help of a surface texture: in this way the TCO layer will ensure, together with an Al or Ag back reflector, efficient light trapping within the solar cell.

This type of solar cells has now reached, in the laboratory, stabilized values of AM 1.5 conversion efficiencies around 9% to 10%, in both amorphous [8,9], and microcrystalline [10–13] single-junction cases.

2.3. Light management issues

As already stated, thin-film silicon solar cells need elaborate methods of light trapping, so as to ensure satisfactory efficiencies [14,15]. To this end, the laboratory at Neuchâtel developed a LP-CVD (Low Pressure Chemical Vapor Deposition) process for the deposition of ZnO layers with as-grown roughness and excellent light scattering properties, especially in the visible range of the spectrum [8,9]. In an alternative approach, light-scattering ZnO layers obtained by sputtering and subsequent texture-etching are similarly successful in enhancing the efficiencies [14].

In order to increase photo-generation and *short-circuit current density* in a solar cell, all reflection and absorption losses have to be minimized. This means here that: (a) an

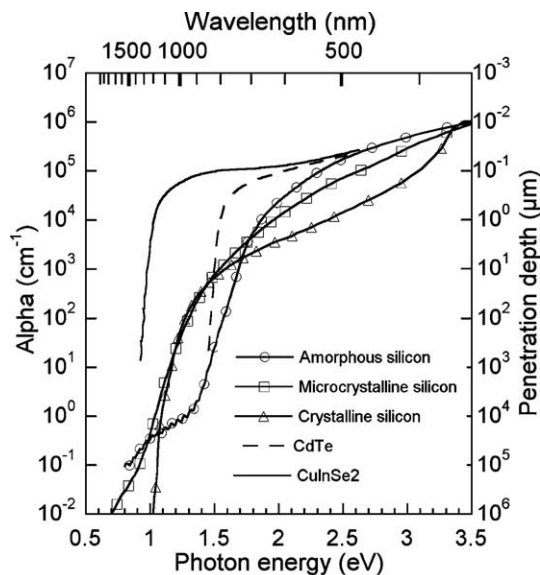


Fig. 3. Absorption coefficient and penetration depths ($1/\alpha$) of various thin-film materials used in solar cells; CIGS has a gap that is higher than that of CuInSe_2 and its absorption curve is therefore slightly shifted to the right, depending on the exact composition of the alloy (i.e. on the gallium content).

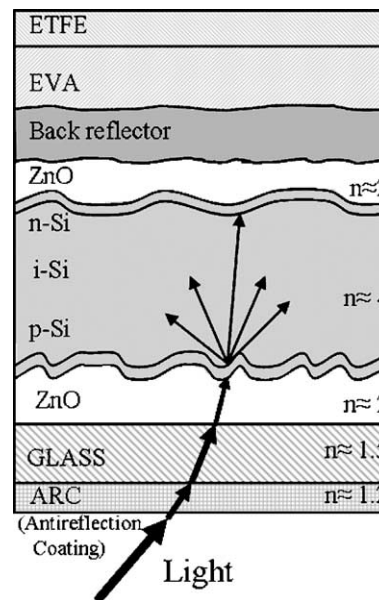


Fig. 4. p-i-n type thin-film silicon solar cell, deposited on a glass substrate. In the case of amorphous silicon, the i-layer thickness is kept very low, i.e. in the range of 150 to 300 nm, because of the light-induced degradation effect, that reduces collection lengths, by adversely affecting both the mobility \times lifetime product (see Table 1), as well as the internal electric field within the photo-active i-layer of the cell. In the microcrystalline case, cell thickness is, in general, not limited by collection, but by the necessity of keeping total deposition time within reasonable limits (see Section 3.1). On the other hand, microcrystalline silicon solar cells are particularly sensitive to oxygen contamination within the i-layer, and it was only through the reduction of such contamination [7], that our laboratory succeeded in producing microcrystalline silicon solar cells with reasonable efficiencies.

¹ A further ZnO or another kind of TCO layer is often also used at the opposite side of the cell, for refractive index matching and back reflector improvement (see also Fig. 4).

antireflection coating might be used on the glass, where the light enters into the PV module; (b) back reflectors must have as little absorption as possible; (c) glass and front TCO must have a high transparency, extending, if possible, from 300 to 1200 nm, i.e. over that part of the spectral range where almost 90% of the incoming solar energy is arriving, (d) TCO layers [and doped silicon layers, which do not contribute to photo-generation and collection], should be kept as thin as possible and have very low absorption coefficients in those spectral ranges, where light trapping is taking place—this is critical for microcrystalline silicon, because the spectral range here falls partly into near-infrared (800 to 1200 nm), where free carrier absorption (FCA) starts to increase, especially for heavily doped TCO layers.

2.4. Choice of substrates, of protective shields and of encapsulation

The choice of a *substrate material* is an essential decision for all thin-film solar cells, but especially for thin-film silicon solar cells:

To date, the majority of thin-film silicon PV module manufacturers use TCO-coated glass as substrate. Commercial TCO producers provide TCO on inexpensive soda-lime glass, which favorably affects the module costs. However, best results are so far achieved with more expensive, low-iron content glass, which, due to its lower absorption in the red spectral range, becomes imperative to fully exploit the extended red response of microcrystalline silicon cells.

Another well-established option for substrates is the use of stainless steel, which lends itself to roll-to-roll processing. So far, however, this does not allow for an integrated electrical series connection of individual cells to form a whole monolithic module, which otherwise is one of the attractive features of thin-film PV technologies.

Various forms of alternative substrate materials have been tried: plastic substrates, such as PET [15], as well as flexible metal substrates clad with an isolating layer (currently under study). For most plastic substrates, cell performance, even for the less sensitive amorphous silicon solar cells, is so far somewhat impaired, because of (1) outgassing from the substrate and (2) the need to even further reduce PECVD deposition temperatures, to around 130 to 170 °C.

In a similar manner, there is a trade-off between quality/performance and material/manufacturing cost for the *protective shield* (on the other side of the PV module, see Fig. 4) and for the *encapsulation material and technique* used in module fabrication: novel solutions are now being developed here, so as to contribute to bring module prices down towards 1 U.S. \$ per W_p .

2.5. “Micromorph” tandem solar cells

A double-junction or “tandem” solar cell consisting of a microcrystalline silicon solar bottom cell and an amorphous

silicon top cell corresponds, with 1.1 eV for the bottom cell and 1.75 eV for the top cell, indeed, almost to the theoretically optimal band gap combination (Fig. 5). Our research group introduced, in 1994, this novel thin-film solar cell concept, called the “micromorph” solar cell [16].

Since then, many university groups and industrial companies have launched research activities in this field. In the laboratory, stabilized efficiencies between 10% and 12% have been reported by several research groups, for laboratory cells of approximately 1 cm² size (or smaller), see e.g. [6,11,17]. In the future, one hopes to achieve stabilized laboratory efficiencies that are near to 15%, by cutting down the optical losses mentioned in Section 2.3 [18]; this should translate into commercial module conversion efficiencies over 10%. If at the same time, total costs per m² can be reduced to 100 U.S. \$, then the generally desired price goal of 1 U.S. \$/ W_p will be finally reached! It may be assumed that this will happen within the next few years.

To increase the current of micromorph tandems, the most promising method is, as of now, to enhance light trapping within the solar cell: an “intermediate mirror layer” between the amorphous top cell and the microcrystalline bottom cell is an interesting scheme that has been tried in this context [19–21]. Such an “intermediate mirror layer” allows one to keep the amorphous top cell thickness low (as low as 0.180 μ m), so as to reduce, or even avoid [8] substantial light-induced degradation, and thereby still obtain sufficient current density J_{sc} from this part of the tandem. Because top and bottom cells of the tandem are electrically in series, it is indeed important to maximize current density J_{sc} of each partial cell. Note, however, that the industrial mass production of micromorph tandem cells with an “intermediate mirror layer” has not yet been addressed and will almost surely involve additional costs.

At the same time, all transparent cover sheets and layers, as well as TCO contacts and reflector layers, have to be

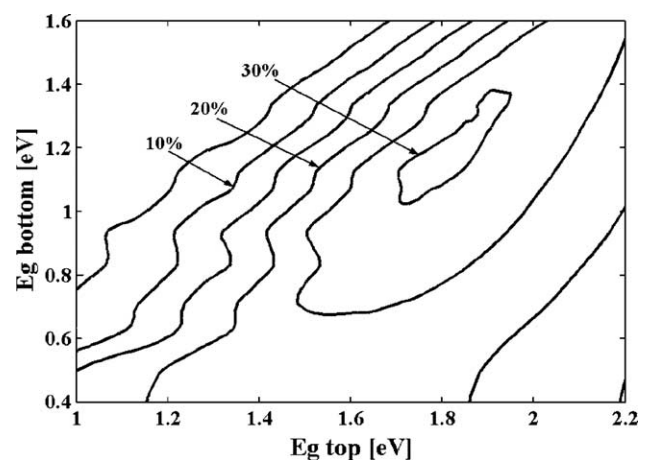


Fig. 5. “Theoretical” limit efficiency for tandem solar cells in function of the band gaps of the bottom and top cells, computed for AM 1.5 illumination (“standard sunlight”), and for a p–i–n diode structure (see also [15]).

optimized with respect to minimizing absorption, especially free carrier absorption (FCA) [18]. This may lead to rather sophisticated tandem cell structures, with a double TCO layer [22,23], such as shown, for example, in Fig. 6. In this figure a high-mobility TCO, like SnO_2 or ITiO or ITO is suggested as a first layer, in order to obtain a high conductivity without increasing the carrier concentration and, thus, the FCA; thereafter, one may deposit a thin layer of ZnO or TiO_2 : this layer should act as a diffusion barrier, because of its more inert behaviour, during the subsequent plasma-assisted deposition of the thin-film silicon layers (see e.g. [22]).

3. Amorphous and microcrystalline silicon in PV solar cells: fabrication issues

3.1. High-rate thin-film silicon deposition by PECVD

Traditionally, the Solar Cell and the Display Industry employ deposition rates for amorphous silicon that are in the order of 0.1 to 0.2 nm/s. By increasing the plasma excitation frequency used for the PECVD process to values in the VHF range (typically to values around 60 to 100 MHz), device-quality amorphous silicon layers can be produced at rates around 0.5 to 1.0 nm/s; this method is called VHF-deposition [24]; it was introduced in 1987 by IMT, and is now being up-scaled to industrial large-area deposition.

Because of standing wave effects that show up at high excitation frequencies, it is, however, basically difficult to obtain uniform deposition on large substrate areas with VHF plasmas. In order to obtain uniformity, special lens-shaped

electrodes have been developed [25]. Ladder-shaped electrodes are also used, in combination with a phase-modulation method for the excitation signal [26].

For microcrystalline silicon solar cells, the deposition rate plays an even greater role, as the cell thickness used is higher. This issue is currently under investigation in many laboratories, see e.g. [6,12,26–28].

3.2. Transparent conductive oxide (TCO) deposition and glass issues

The optical, electrical, and topographical properties of the TCO material crucially influence the photovoltaic data. These properties have been so far optimized independently of each other to yield record efficiencies for small-area cells or modules, but TCO coatings with the same optimized properties are commercially not yet available on large-area substrate glasses.

TCO becomes a typical production issue that implies a trade-off between the method of TCO deposition and its cost, on one hand, and the achievable PV module efficiency, on the other hand. TCO produced on-line directly on a glass float line offers large-area uniformity and reproducibility, as well as the highest potential for low cost [29]. However, its photovoltaically relevant properties cannot concurrently be optimized. On the other hand, optimized TCO is presently only being produced off-line; it may consist of either doped SnO_2 or ZnO , and be prepared by various methods, such as low-pressure CVD or sputtering, but all at a higher cost.

Apart from optimizing the TCO properties, it is also desirable to use glasses with low iron content; these have a higher transmittance compared to typical soda-lime float glass, and, thus, yield higher currents particularly in micromorph cells with their higher response towards the red spectral region. Such on-line TCO-coated low-iron glasses are also float glasses, but they are unfortunately still rather expensive due to the present low demand.

For large-area BIPV applications (facades and roofs), architects often desire to use *tempered* glass, and this fact restricts the deposition temperature for silicon and for off-line deposited TCO layers to relatively low values, such as are currently used at our laboratory (150 to 220 °C). Note that the standard deposition process for SnO_2 as well as many of the processes studied for large-grain thin-film silicon use far higher temperatures. The use of tempered glass is, however, not essential, as other elegant solutions exist [30].

3.3. Single-chamber deposition

To avoid cross-contamination between subsequent layers, amorphous silicon manufacturers have often used multi-chamber PECVD deposition systems. This, however, leads to increased complexity in the deposition equipment. For this reason, several groups, including our own, have studied ways of depositing all thin-film silicon layers within

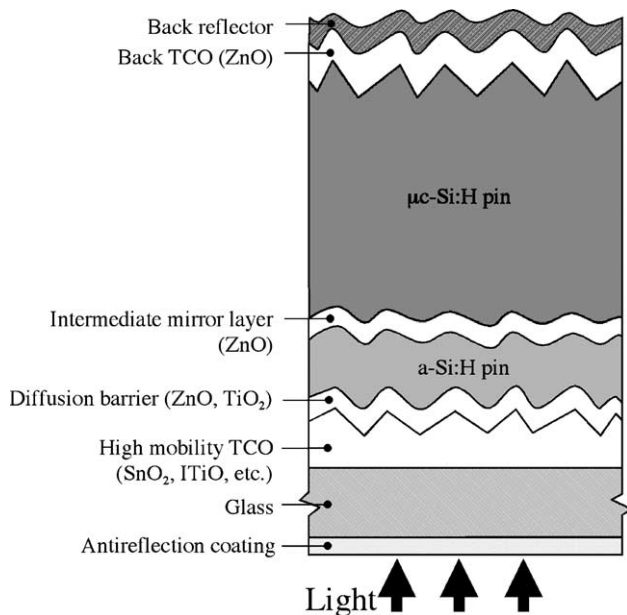


Fig. 6. Micromorph tandem solar cell with an “intermediate mirror layer” between the amorphous top cell (a-Si:H) and the microcrystalline bottom cell ($\mu\text{c-Si:H}$) and with a double layer as front TCO.

the same deposition chamber [27,31–33]. Generally, precautions need to be taken to avoid cross-contamination between the doped and the intrinsic layers, particularly boron tailing from the p- into the i-layer. We have, for amorphous cells, successfully used a flush by water or ammoniac vapor between the deposition of the first doped layer (in our case, the p-layer) and that of the i-layer [33]. For microcrystalline silicon cells, the problem of impurity contamination is presently being intensively investigated.

3.4. Large-area and roll-to-roll deposition

One of the main advantages of thin-film solar modules is the possibility to directly manufacture large-area (1 m^2 and more) PV modules, without having to manually interconnect and assemble individual cells. To this end, large-area PECVD on glass substrates [17,26,34,35], and, also, roll-to-roll deposition of thin-film silicon [36] have been extensively studied. The latter is not possible with glass, but only with flexible substrates, such as stainless steel, aluminum and plastic foils. An interesting variant of the roll-to-roll deposition method is the deposition of the amorphous silicon solar cell on a sacrificial aluminum foil: a foil that is later removed by a chemical wet etching process [37].

One is, on the other hand, at present *well acquainted with glass-based modules*, as glass covers are extensively used for the traditional wafer-based PV modules that today make up over 90% of PV module production. PV modules are mostly used for outdoor applications, and especially for building-integrated installations, and therefore have to last for at least 20 to 30 years, without substantial degradation of their properties. One may therefore expect PV system planners and builders to continue to prefer glass-based modules to the new, unconventional (flexible) PV modules, at least for a further decade or so. Indeed, glass, even though being breakable and relatively heavy, offers, on the other hand, excellent protection against damaging influence of weather (humidity, rain, dust, snow, hailstones and especially high-energy photons from UV light, etc.).

4. Production equipment and cost estimates: example of the KAI deposition system

Cost considerations generally must satisfy two points of view: the module producer must figure his manufacturing costs/ m^2 , whereas the PV module market governs module prices/ W_p (which ought to be the upper limit as manufacturing cost to the producer). For multi-megawatt production facilities the main shares contributing to the cost are materials and consumables with about one half, equipment depreciation with about a quarter, and personnel and infrastructure with about another quarter of the module manufacturing costs. At today's world market module prices of around 3 U.S. $\$/W_p$, the manufacturing cost for present

thin-film silicon modules with between 5% and 7% efficiency should be below 150 to 210 U.S. $\$/\text{m}^2$. Besides the materials costs for the actual cell structure, materials costs include expenses for encapsulation, and possibly framing (about 20 U.S. $\$/\text{m}^2$), cabling and electrical connections (about 10 U.S. $\$/\text{m}^2$).

In view of reaching the highly desirable cost goal of 1 U.S. $\$/W_p$, it, thus, becomes necessary to both reduce area-related costs (in $\$/\text{m}^2$) and, at the same time, to increase stabilized module efficiencies (to around 10%).

4.1. Synergy potential with the Display Industry

The present fabrication cost is for a large part (approximately for one quarter) due to amortization of the PECVD equipment. This part could be definitely cut down, if the mass production techniques developed in the Display Industry were used for PV production. AM-LCD displays are, in fact, at present emerging from niche applications to mainstream markets. They dominate already the desktop monitor market and are expected to replace CRT TVs in the coming years. In 2003, a surface area of roughly 15 km^2 of LCD monitors was manufactured worldwide. In comparison, the surface area for thin-film silicon photovoltaic cells was in the range of 0.5 km^2 in the same year, or roughly 30 times less. Thus, the still relatively small thin-film silicon PV market can certainly benefit from the more mature AM-LCD production technology, especially for the critical PECVD processing steps.

4.2. The KAI concept: AM-LCD technology for thin-film solar cells

A successful and proven PECVD system concept applied in AM-LCD manufacturing is the so-called “KAI” system concept of UNAXIS. Its heart is the Plasma Box[®] PECVD reactor [38], which combines iso-thermal heating with differential pumping, and minimizes process contamination; it is fully compatible with fluorine-based self-cleaning processes, a necessity for high-yield, low-maintenance manufacturing. Large-area deposition up to 5 m^2 has already been demonstrated with this. The parallel processing concept of KAI systems, where up to 20 reactors operate in parallel in two process chambers assures the necessary productivity for economical deposition of thin-film devices. In a KAI 1200 system (Fig. 7), 20 sheets of glass with a size of 1.4 m^2 are processed simultaneously, leading to an annual PV production capacity of 20 MW_p , at minimal foot print requirements.

4.3. Towards large-volume, low-cost manufacturing of thin-film silicon PV modules

A very critical factor in thin-film solar cell manufacturing is *process yield*, because of its big impact on direct cost. Moreover, high yield is important from a logistical point of

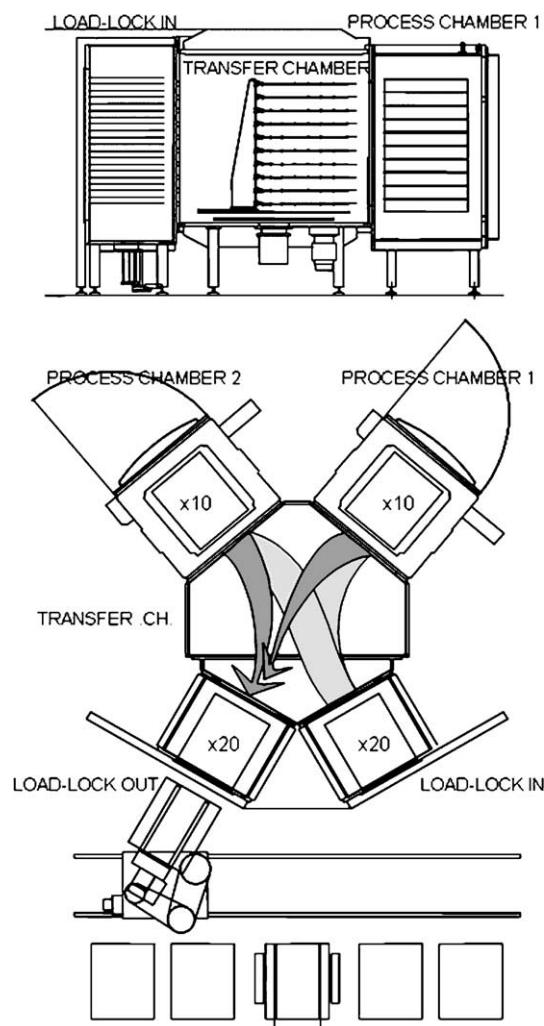


Fig. 7. Schematic representation of KAI-1200 PECVD system.

view in production planning. In AM-LCD manufacturing, yield levels of above 95% are commonly reached and the remaining yield loss is mainly due to process particles, that cause defects of individual thin-film transistors. The impact of this type of yield loss will be less severe in thin-film silicon solar cell production; it can be safely assumed that yield levels of above 95% are attainable for PECVD with KAI production technology.

A further critical factor in thin-film solar cell manufacturing is (as already stated in Section 3.1) process time, especially for the deposition of the relatively thick microcrystalline silicon layers within a micromorph tandem solar cell [5]. Thus, deposition rate is a much more critical parameter for thin-film photovoltaic modules than for AM-LCD displays. To obtain feasible production solutions, the KAI deposition systems to be used for solar cell manufacturing are being modified to incorporate VHF-compatible electrodes [25] and will be run at a plasma excitation frequency of 40 MHz.

Maximizing *module efficiency* in production remains a very important factor in achieving cost reduction. The

biggest impact to module efficiency occurs during thin-film silicon deposition of the actual device. Consistent material quality, layer uniformity, proper means to avoid contamination of intrinsic layers by dopants all play a key role. Therefore, performance optimization of the reactor and of the PECVD process clearly outweigh other considerations. For example, a 5% relative gain in thin-film cell efficiency would justify a 25% higher investment cost for PECVD equipment.

In the past high *investments in* production machinery were considered an obstacle to the growth of thin-film silicon PV. Moreover, typically, prototype systems were built for photovoltaic module production; these systems only reached the targeted uptime performance after an extended ramp-up phase. The high productivity of proven AM-LCD machines such as the KAI PECVD systems reduces both the costs and the risks for a thin-film production line. Using today's generation of KAI machines, one arrives at investments of about 2.4 U.S. \$/W_p of installed production capacity (for the whole production line), resulting in roughly 0.4 U.S. \$/W_p of investment-related cost.

Further reductions are expected here with process improvements and with each new generation of AM-LCD machines. In addition, economies of scale for materials procurement as well as extensive automation for all the other module manufacturing steps will also be needed to arrive at cost levels of 1 U.S. \$/W_p for overall module production.

5. Conclusions

For Photovoltaics (PV) to be widely used, it is necessary to arrive at module manufacturing costs of 1 U.S. \$ per peak-Watt. One of the most promising ways to reach this goal are thin-film silicon PV modules, based on tandem solar cells with an amorphous silicon top cell and a microcrystalline silicon bottom cell. It will be necessary to cut-down optical losses (e.g. absorption losses in the near-infrared, due to transparent conductive oxides used as contacts), so as to attain 15% stabilized laboratory efficiency for small-size cells and 10% stable commercial, large-area module efficiency. At the same time, a major effort has to be made to reduce manufacturing costs. It is mandatory to have stable production equipment with high yield processes, so as to realize the full cost-reduction potential of thin-film solar cells. Thanks to an excellent synergy with the Display Industry, results are expected here well before 2010.

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