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Status of thin film solar cells in research, production and the market

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Abstract

Photovoltaics is one of the fastest growing industries at present. Over the last five years, the production of photovoltaic solar cells has steadily increased at an annual average of 40%, driven not only by the progress in materials and processing technology, but by market introduction programmes in many countries around the world. This growth is mainly being attained by an increase in manufacturing capacities based on the technology of crystalline, single junction devices. Consistent with the time needed for any major change in energy infrastructure, another 20–30 years of sustained and aggressive growth will be required for photovoltaics to substitute a significant share of conventional energy sources. The question is whether a switch will be possible with the current technologies alone or whether this growth will only be possible with the continuous introduction of new technologies. It leads us to the search for new developments with respect to material use and consumption, device design and production technologies as well as new concepts to increase overall efficiency. This paper analyses the current status of thin film solar cells and their outlook for future developments.

Keywords: Renewable energies; Photovoltaic; Thin film solar cells; Technological development; Policy options; Market development

1. Introduction

Photovoltaics has enjoyed extraordinary growth during the last few years with overall growth rates between 30% and 40% making further increase of production facilities an attractive investment. In 2003, the world-wide photovoltaic industry delivered some 740 MWp (Maycock, 2004) of photovoltaic generators (Fig. 1) and has become a US$ 4.5 b business. However, different solar cell technologies have grown at different rates and over 85% of the current production is based on silicon wafer or silicon ribbon technology. This is a well-established technology, which achieves sufficient efficiency for at least 20 years of lifetime and constitutes a low-risk investment with high demands for return on investments. In addition, the HIT-solar cell of Sanyo (heterojunction with intrinsic thin layer), a heterostructure between a silicon wafer and an amorphous silicon thin film has about 5% market share. In the last 15 years the market share of thin film solar cells has decreased from approx. 30% in 1987 to less than 8% in 2002 whilst no change in the current trend can be observed at present.

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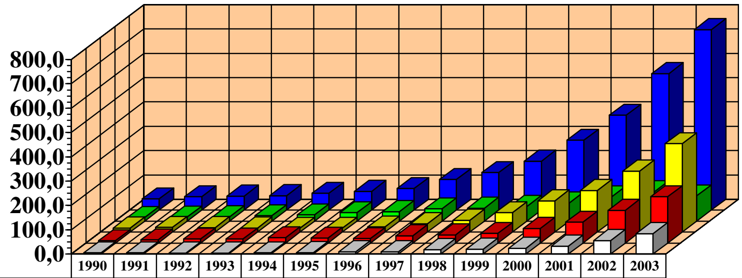

	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003
☐ Rest of World	4,7	5,0	4,6	4,4	5,6	6,4	9,8	9,4	18,7	20,5	23,4	32,6	55,5	83,8
🟥 Europe	10,2	13,4	16,4	16,6	21,7	20,1	18,8	30,4	33,5	40,0	60,7	86,4	135,1	190,4
🟨 Japan	16,8	19,9	18,8	16,7	16,5	16,4	21,2	35,0	49,0	80,0	128,6	171,2	251,1	363,9
🟩 United States	14,8	17,1	18,1	22,4	25,6	34,8	38,9	51,0	53,7	60,8	75,0	100,0	120,6	104,2
🟦 Total	46,5	55,4	57,9	60,1	69,4	77,6	88,6	125,8	154,9	201,3	287,7	390,2	561,8	742,3

Fig. 1. World PV Cell/Module Production from 1990 to 2002 (data from PV News; Maycock, 2004).

What are the reasons for this development? The answer to this question is manifold. Thin film technologies face a wide range of problems, ranging from a lack of knowledge about basic material properties over problems of availability of production technologies to legal issues concerning patent infringements and possible market perspectives. This article will examine the market conditions and research activities for silicon thin films, chalcopyrite (CIGS) and CdTe based thin film solar cells. Dye cell concepts and polymer based solar cells will not be covered.

2. Market situation of thin film solar cells

One of the main driving forces for thin film solar cell development was and still is the potential reduction of manufacturing costs, due to low material consumption in comparison to state of the art silicon wafer technology. An additional issue is the lower energy consumption for the production of thin film solar cells and consequently a shorter energy pay back time for these devices. However, one should bear in mind that the total energy pay back time for a given module does not only depend on the solar cell used, but also on the module design, e.g. framed module, glass/glass, metal foil, EVA, etc.

In 1994, the Multi-Megawatt Upscaling of Silicon and Thin Film Solar Cell and Module Manufacturing study "MUSIC FM" was intended to determine the feasibility to manufacture silicon solar cells with 500 MWp/year in Europe. The final report identified possible cost reductions for different kinds of solar cells in large volume production plants, e.g. silicon wafer 500 MWp/year; CIGS 60 MWp/year (Bruton et al., 1997). The main message was that at such a production volume silicon solar cells could be produced below 1 €/Wp and that thin films even had the potential to reach this price tag at a production volume in the order of 50–60 MWp/year. Calculations made for smaller production capacities lead to similar results (Table 1). However, the possible price advantages for thin film solar cells, to reach lower costs at lower production volumes, have been decreasing over the last couple of

Table 1
Cost estimates for direct production costs and current prices for different solar cell technologies (modules)

Technology		Costs[a] estimated for individual production capacity €/Wp (MW)	Used efficiency (%)	Prices[b] 05/04 excl. VAT €/Wp
Crystalline silicon	min	0.97 (500) (Bruton, 2002)	20	
	max	2.45 (10) (Frantzis et al., 2000)	15	
mc-Si	min	0.71 (500) (Bruton et al., 1997)		2.68 (Price Survey May 2004)
	max	2.10 (10) (Frantzis et al., 2000)	14	
a-Si and LT-f-Si	min	0.69 (60) (Bruton et al., 1997)	9	3.02 (Price Survey May 2004)
	max	2.70 (10) (Frantzis et al., 2000)	6	
HT-f-Si		0.98 (n.a.) (Bossert et al., 2000)	14	
CIGS	min	0.70 (60) (Bruton et al., 1997)	12	
	max	2.25 (10) (Frantzis et al., 2000)	9	
CdTe	min	0.72 (60) (Bruton et al., 1997)	12	
	max	2.30 (10) (Frantzis et al., 2000)	8	

[a] To compare different references from different years the following exchange rate was used: 1 € = 1 $.

[b] Lowest price for one single module, May 2004 exchange rate used: 1 € = 1.19 $; larger purchases can secure prices around 2.50 €/Wp (Price Survey May 2004).

years, due to the improvement in wafer silicon production technology, such as the reduction of wafer thickness or the economy of scale triggered by a rapid growth of wafer silicon production capacities. The largest silicon solar cell factory is operated by Sharp and has now reached an annual capacity of 248 MWp (Sharp Corp., 2003).

Six years following the publication of "MUSIC-FM" global sales of solar cells has increased sixfold and reached 740 MW in 2003 (Maycock, 2004), whereas thin film photovoltaics was not able to profit from this boom. Solid information regarding industrial manufacturing costs of thin film cells remains scarce. As of today only one thin film manufacturer has produced more than 10 MW/year and the thin film industry is far from reaching the anticipated 60 MW "Music-FM" factory size. Thin film solar cells reached an approximate 8% of total PV market share in 2002; excluding indoor applications the technology accounted for a mere 6% (Fig. 2). The three "major" thin film producers BP-Solar (a-Si and CdTe), Sanyo (a-Si) and Kaneka (a-Si and a-Si/μ-Si) produced more than 50% whilst more than 10 manufacturers accounted for the rest (**a-Si**: Dunasolar, Free Energy Europe, Koncar, Intersolar, Iowa Thin Films, Mitsubishi Heavy Industries, RWE-Schott Solar, USSC; **CIGS**: Global Solar Energy, Shell Solar, Würth Solar; **CdTe**: Antec, First Solar, Matsushita).

The above highlights the fact that thin film technology is by no means optimised for low costs. Furthermore, it should be noted that the share of thin films has decreased even further in 2003. One reason is that the growth of Kaneka (a-Si), USSC (a-Si), Global Solar (CIS), Shell-Solar (CIS) and First Solar (CdTe) with approximately 16–18 MW together was close to the lost production capacities caused by the closure of BP-Solar's a-Si (8 MW) and CdTe (2 MW) (BP-Solar, 2002) and Dunasolar's a-Si (3 MW) facilities (Photon International, August 2003) at the end of 2002 and in June 2003. The second reason is that global production grew by over 31% in 2003.

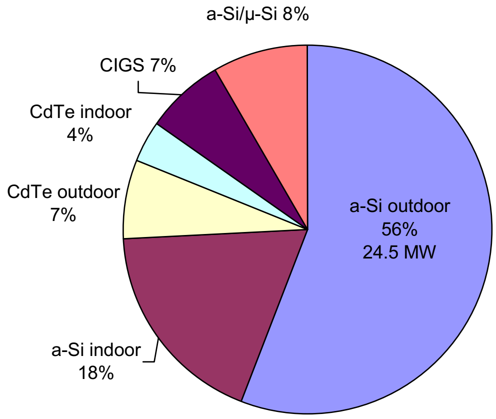

Fig. 2. World-wide sales of thin film solar cells 2002 (43.8 MW) (Maycock, 2003).

With the exception of amorphous silicon thin film technology, manufacturers have failed to reach the 10 MW threshold as depicted in the Arthur D. Little study of 2000 (Frantzis et al., 2000). Details of actual manufacturing costs and possible cost reductions thus depend on estimates and models. An excellent summary of issues concerning cost reductions was compiled by Ken Zweibel, project manager at NREL responsible for the Thin Film Partnership Programme (Zweibel, 2000). He indicated that a number of substantial, cross-technological similarities exist among thin films. Not only does this allow for a simplification of manufacturing cost analysis, it also paves the way for possible synergies—if common specifications for required components were to be achieved.

All thin film technologies share the common issues of relatively high initial investment costs, an aspect that may constitute a considerable barrier to entry for new manufacturers. Capital costs play an important role not only in terms of initial investments for the factory, but also during first years of production. Capital costs are multiplied until production can be run at full capacity, i.e. if production yields are lower than expected and due to downtimes related to maintenance or product development cycles lead to lower production volumes, capital costs could rise to prohibitive levels. Sales and marketing of cells and modules could cause further problems due to disorganised distribution channels or lack of consumer demand, which would then add to negative price pressures of the product in the market.

Realistic cost [1] estimates for the initial investment show values between 0.8–2 mill €/MW for CdTe (First Solar, Press Release 3 June 2003; Bonnet and Harr, 1998), 1–2 mill €/MW for amorphous silicon (Tawada et al., 2003; Photon International, August 2002) and around 2 €/MW for CIGS (Maycock, 2003a; PHOTON, 25 April 2000). For thin film production each new production line is still a unique prototype designed for the respective deposition process, which increases costs considerably. Also, thin films face the above mentioned problems, of time-to-yield and production ramp to full capacity. In comparison, silicon wafer based solar cell production technologies have already attained much higher maturity levels in production and modular scaling of existing production facilities with the installation of readily available equipment at a cost of less than 0.7 mill €/MW (Sharp Corp., 2002). Typically, the commissioning phase of a silicon line merely consists of a few months.

However, there is hope that conditions will improve on the hardware side. Two major hardware manufacturers, Mitsubishi Heavy Industries (Japan) and UNAXIS (Lichtenstein) have decided to establish solar divisions, to produce not only amorphous silicon modules but also

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[1] To compare different references from different years the following exchange rates were used: €1 = US$1; €1 = ¥120.

its production equipment. Though the two concepts are rather different, both companies plan to offer production lines for sale in the future.

Mitsubishi Heavy Industries (MHI) has developed a spider plasma CVD deposition system, which allows for rapid deposition on large sized glass and flexible substrates (roll to roll). MHI has stabilised the a-Si single-junction efficiency at 8%, starting with an initial efficiency of 10%. At present, MHI's strategy is to establish itself as a reputable producer of solar modules, while it plans to offer the spider system for sale to other possible producers in the future. MHI is an equipment manufacturer by tradition and does not see itself as a major player in the appliances market though this might change.

A co-operation of the Institute of Micro Technology (IMT), the University of Neuchâtel (Switzerland) and UNAXIS led to the establishment of UNAXIS Solar. The new company commenced operations on July 1st 2003 with the aim to develop the technology for large-scale production of PV modules that are based on the micromorph solar cell concept developed at IMT and UNAXIS' KAI production systems. The planned milestones are ambitious:

- Mid 2004: a-Si cell on 1.4 m^2
- Mid 2005: μc-Si cell on 1.4 m^2
- 2005: First KAI Production System going into mass production

3. Technology overview

In order to give an overview of the technologies discussed, this chapter will list the different technologies under investigation and in production. The following will focus on general descriptions rather than techno-scientific details, which are better championed by respective specialists.

3.1. Amorphous and thin film silicon

Within thin film silicon the various technologies can be ordered according to the respective grain size: none (amorphous silicon; a-Si), smaller than 0.1 μm (nanocrystalline; n-Si), between 0.1 and 50 μm (polycrystalline; pc-Si), 100–1000 μm (multicrystalline; mc-Si) and single crystals (c-Si). The term TF-Si (thin film silicon) is used here to describe silicon material between 0.7 μm and 200 μm. Another classification often referred to is: (1) amorphous silicon; (2) microcrystalline (μ-Si) and low temperature thin film crystalline silicon (LT-f-Si) with deposition temperatures <600 °C; (3) high temperature crystalline silicon (HT-f-Si) or the deposition temperatures >600 °C. As both categorisations are frequently used I shall quote them according to their use in the literature.

Table 2 summarises the status of the various thin film silicon technologies (Nelson et al., 2003). Green coloured cells indicate favourable aspects of devices made with that particular grain size, Red cells indicate unfavourable aspects. The term "CVD" includes a variety of chemical vapour deposition techniques such as hot-wire, plasma enhanced, very high frequency, etc. Other abbreviations used are: zone-melt re-crystallisation (ZMR), metal-induced crystallisation (MIC) and atmospheric pressure iodine vapour transport (APIVT).

The main scientific and technical issues for all thin film silicon technologies can be summarised as follows:

- For a-Si:H the light induced degradation of the electronic properties or Staebler–Wronski effect (SWE) results in a "stabilised" efficiency of the devices, which is considerably lower than the initial one. If this degradation could be minimised or even eliminated, designs of higher efficiency levels would be possible (20–30% gain possible).
- Due to the wide band gap nature of a-Si:H, the absorption in the red part of the light spectra is rather low. Multi-junction concepts with narrow band gap materials could overcome this problem. Materials under investigation are a-Si:Ge and μ-Si (15–25% gain possible).
- a-Si:H is a highly defective material with a low hole mobility, which requires hydrogen passivation of the intrinsically high concentration of dangling bonds. Although it has the advantage of being relatively easy to deposit from gases which allow easy H-incorporation on large areas, an a-Si:H material with high hole mobility would avoid a number of technical problems.
- TF-Si is a rather complex structure and carriers have to pass through imperfect crystallites of different grain size, grain boundaries as well as amorphous parts. In order to improve device performance, it is necessary to increase basic understanding of the limiting factors for mobility and lifetime as well as the effectiveness of grain boundary passivation or the role of different inter-crystalline defects.

3.2. CdTe

Cadmium telluride has two features that make it appear like an ideal candidate for thin film solar cells. It can be deposited with various deposition methods which all result in reasonable quality and a direct energy gap at $E_g = 1.45$ EV—within the ideal range for solar energy conversion.

When CdTe is deposited onto substrates above 449 °C it condenses stoichiometrically as the stable phase in this regime (Zanio, 1978). These films are in general p-type with carrier concentrations of $p < 10^{15}\,\mathrm{cm}^{-3}$ due to

Table 2
Summary of current amorphous and thin film silicon approaches data taken from Nelson et al. (2003)

	a-Si/Ge–Si	n-Si	pc-Si			mc-Si	c-Si
Grain size (μm)	Amorphous	<0.1	0.1–5	0.1–50	10–50	100–1000	Single crystal
Sub. temp. (°C)	<300	<300	800–1200	<300	900–1000	1000–1400	1000–1400
Typical growth methods	CVD	CVD	CVD	CVD, MIC, low T epitaxy	APIVT	CVD (+ZMR), APIVT, epi	epitaxy + "epilift", "smart-cut"
Rates (μm/m)	0.01–0.1	0.01–0.1	1–3	0.01–0.1	1–10	1–10	1–10
Efficiencies (%)	8–13	3–10	~1	N/A	3–4	~15	~18
Cell thick. (μm)	0.3–0.7	1–2	5–20	10–20	5–50	10–50	5–50
Cell type	Drift, stacked	Diff./drift, stacked	Diffusion	Diffusion	Diffusion	Diffusion	Diffusion
Prospectives	Very high absorption, Eg tailoring	High absorption, no Ge	Existing tech.	Low T	Low system & process costs	Low-cost feedstock	Infrastructure, synergy with IC industry
Constraints	Instable (SWE), poor red collection	Post deposition oxidation	Low H, small grains	Slow, H-limited max. epi thickness	Low H, glass or ceramic substrates	2-step processes, ceramic substrates	3-step processes, large area difficult

The mc-Si and c-Si technologies in this table are for thin films, supported by substrates, not bulk-Si PV (>200 μm).

a slight cadmium deficiency. The most common CdTe solar cell structure is a n-CdS/p-CdTe heterojunction, where the CdS is deposited on a transparent conductive oxide (TCO) coated glass. An important feature of this type of solar cell is, that CdS and CdTe can be deposited with the same deposition technologies.

The standard techniques to deposit p-type CdTe of good crystalline quality and high electron mobility are: sublimation/condensation (S); close spaced sublimation (CSS) a modification of the first process; chemical spraying (CS); screen printing (SP); chemical vapour deposition (CVD); sputtering; and electro-deposition (ED).

The top efficiency achieved at NREL was 16.5 ± 0.5% (Wu et al., 2003) prepared by CSS (CdTe) and chemical bath deposition (CdS). Despite good progress in the understanding of the CdTe solar cell, the following issues require further research efforts:

- CdTe solar cells exhibit strong fluctuations in parameters of nominally identical devices. For example, it is typical to observe noticeable (~10%) experimental differences between cells ~1 cm apart on the same substrate (Shvydka et al., 2003).
- The formation of good ohmic contacts of high stability is still a major issue in the CdTe cell technology. A number of materials are being investigated, but the physical problems are that metals of very high work function are needed and CdTe is difficult to be p-doped due to a strong tendency towards self compensation.
- The heterojunction formation between CdTe/CdS is the critical part of the solar cell. Especially the interdiffusion of CdS and CdTe influences the cell behaviour and is determined by the activation process.

The frequently quoted environmental concerns have been investigated in a number of studies (Bruton et al., 1997; Fthenakis and Zweibel, 2003). It is concluded that the environmental risks from CdTe PV are minimal. Every energy source or product may present some environmental, health and safety hazards, and those of CdTe should by no means be considered barriers to technology scaling.

3.3. Chalcopyrites

Chalcopyrites with $Cu(In,Ga)(S,Se)_2$ are an interesting material system, which offers the possibility to tailor the device's band gap between 1.01 eV for $CuInSe_2$ to 1.68 eV for $CuGaSe_2$ or 2.4 eV for $CuGaS_2$ by substituting indium with gallium or selenium with sulphur. This renders chalcopyrites not only an interesting material for single junction devices, but also opens the route to a possible tandem structure device made from the same class of materials. The use of chalcopyrite solar cells in concentrator applications is being investigated by NREL as a novel development in the NCPV "High Performance PV Programme".

Significant progress has not only been made in the basic understanding of the material properties of these devices, but also in the field of large area production of monolithically interconnected modules. The highest efficiency for small area devices was realised at NREL with 19.2% efficiency (Ramanathan et al., 2003). At the 3rd World Conference on Photovoltaic Energy Conversion in Osaka, very promising results from pilot production lines were reported: 12.2% ($120 \times 60\,\text{cm}^2$) by Würth Solar, 13.1% ($90 \times 60\,\text{cm}^2$) by Shell Solar and 14.2% ($30 \times 30\,\text{cm}^2$) by Showa Shell.

Despite these achievements, the scientific knowledge base for this family of solar cells remains sparse. Amazement for the quality of these devices is still prolific despite the fact that there are more open questions than answers. The following list indicates some of the major research topics:

- Theoretic modelling and understanding of loss mechanisms in chalcopyrite devices.
- Investigation of the different interfaces of chalcopyrite devices and improvement of the understanding of their microstructure and chemical composition.
- Back contact: focus on corrosion stability and transparent back contacts for tandem applications.
- Development of an augmented fundamental science and engineering basis for $Cu(InGa)Se_2$ materials, devices, and processing requirements. There is a particular need for more fundamental understanding of wide band-gap alloys and devices as these should lead to improved module performance and could enable the development of thin film based tandem cells.
- Investigation of the role of the cadmium containing "buffer" layer and elimination or substitution by a cadmium free material.
- Investigation of different transparent conductive oxides.

4. Research situation of thin film solar cells

The following chapter discusses the various research activities for thin film solar cells and attempts to analyse, why funding organisations pay different attention to this technology.

4.1. Thin film activities in the Japanese NEDO PV programme

The research budget excluding demonstration and implementation measures for photovoltaics under the NEDO programme "Projects for New Energies" in 2003 totalled 11.2 billion ¥(93.3 mill €) and the requested budget for 2004 affords a total of (12.0 billion ¥) (Ikki, 2003). As a result of the New Sunshine Project (NSP or NSS) evaluation in 2001, the following priorities have been selected (NEDO, 2002).

- Technology Development for Future Mass Deployment
- Advanced Solar Cell technology
- Advanced Manufacturing Technology
- Innovative PV Technology

All these priorities include thin film topics and one of the dominant priorities, besides the future increase in PV production, is obviously the cost reduction of solar cells and PV systems. In the framework of the last evaluation of the "New Sunshine Project" NEDO, METI, Photovoltaic Power Generation Technology Research Association (PVTEC) and Japan Photovoltaic Energy Association (JPEA) drafted a roadmap for PV research and development as well market implementation measures for the next 30 years. This roadmap reflects the current research activities and their impact on the industrial progress (Fig. 3).

During the evaluation, a number of strategically important connections for the shaping of future R&D programmes were identified between research and development on the one side and market implementation of photovoltaics on the other (Mori, 2001). Their quintessence lies in the realisation that technical R&D of future technologies such as thin films with defined price/cost targets as well as simultaneous market implementation are necessary to realise the mass production scenario of solar cells.

The R&D programme is divided into short to medium-term targets and long-term targets. Short to mid-term targets include cost reduction, mass production, reliability and infrastructure, whilst long-term targets are expressed in prospective research and the transformation of research results concerning innovative PV technologies into the production process. It should be noted that there is a clear R&D focus on those technologies that entail higher risks, e.g. thin film technologies. The justification being that these technologies require additional R&D support, whereas the classic silicon wafer technology should be supported via the industry support programmes as its development needs are centred on the area of short term production technology rather than further research.

4.1.1. Short to medium-term targets (until 2010)

The short to mid-term research is aimed at establishing a technical infrastructure in order to realise mass deployment of PV systems in the future. In addition it is targeted to apply the results of the Sunshine- and New-Sunshine Projects towards mass production to

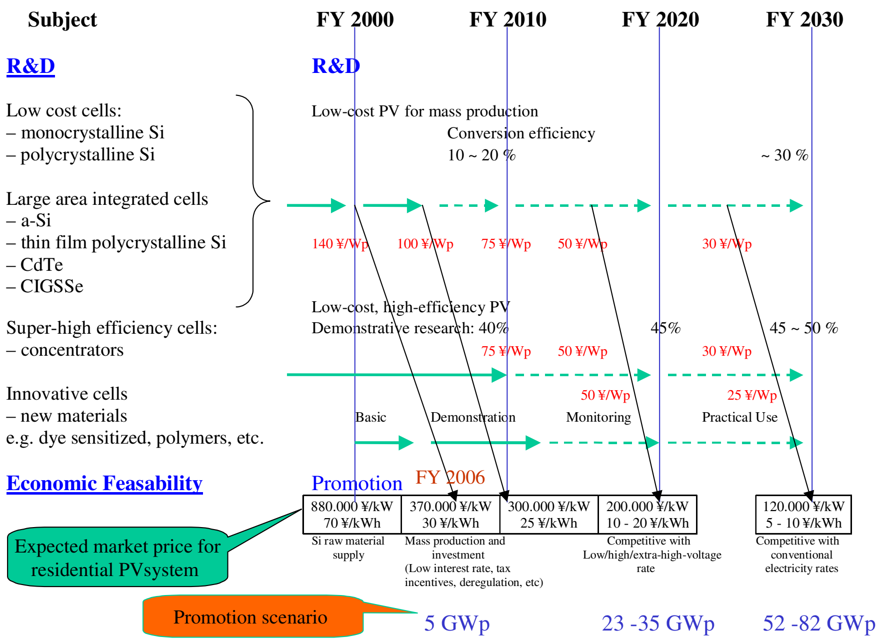

Fig. 3. Japanese roadmap for PV R&D and market implementation.

decrease system costs to 250 ¥/Wp by 2010 (see Roadmap Fig. 3). An urgent technical demand for mass production was diagnosed in order to achieve these goals. The following thin film related projects are running under this heading.

- *Infrastructure* (*Technology Development for Future Mass Deployment*):
  - Technology Development on Measurement of Performance and Reliability of Solar Cells and Modules (National Institute of Advanced Industrial Science and Technologies (AIST), Japan Electrical Safety & Environment Technology Laboratories (JET)).
  - Technology Development on Performance and Durability of Photovoltaic Power Generation Systems (AIST, JET).
  - Research and Development of Recycling Technologies of Photovoltaic Power Generation Systems (Sharp Corp., Showa Shell Sekiyu K.K., Asahi Glass Co. Ltd., PVTEC, AIST).
- *Mass Production*:

  Development of Advanced Manufacturing Technology
  - Development of Mass Production Technology of Amorphous-Silicon Solar Cells on Plastic Films (Fuji Electric Corporate Research and Development, Ltd.)

  Targets for 2005: Active area: 93%; Deposition rate of a-Si: >30 nm/s; Continuous fabrication: 1000 cells/roll; Yield: >90%

  Development of Advanced Solar Cells and Modules
  - Development of High Quality Crystalline Silicon Thin Films (Mitsubishi Heavy Industries, AIST)

  Targets for 2005: Cost: <100 ¥/Wp (calculated for 100 MWp/year production); Module efficiency: $\eta > 12\%$ (3600 cm^2)
  - Development of Hybrid Solar Cells Comprising Amorphous Silicon and Polycrystalline Silicon (Kaneka Corporation)

  Targets for 2005: Cost: <100 ¥/Wp (calculated for 100 MWp/year production); Module efficiency: $\eta > 12\%$ (3600 cm^2)
  - Development of High Quality Thin-Film CIS Solar Cell Modules (Matsushita Electric Industrial Co., Ltd.)

  Roll to roll process

  Targets for 2005: Cost: <100 ¥/Wp (calculated for 100 MWp/year production); Module efficiency: $\eta > 13\%$ (3600 cm^2)
  - Development of High-Speed Production Process for Thin-Film CIS Solar Cell Modules (Showa Shell Sekiyu K.K.)

  Targets for 2005: Cost: <100 ¥/Wp (calculated for 100 MWp/year production); Module efficiency: $\eta > 13\%$ (3600 cm^2).

4.1.2. Long-term targets (beyond 2010)

The goal of the Japanese long-term research programme is to realise a dramatic cost reduction in order to become cost competitive to commercial and conventional power sources (below 15/kWh) by 2020. To achieve this, investigations of novel materials, novel structures and novel manufacturing processes are considered essential to plant the seeds for these developments. The following projects are running under this heading.

- *New Materials*
  - Investigation of Organic Thin Solid Film Solar Cell (AIST, Kanazawa University, Nippon Shokubai Co., Ltd.)

  Target (*end of 2004*): Cell efficiency: $\eta = 5\%$
  - Investigation of Carbon-Based Thin-Film Solar Cell (Chubu University, Nagoya Institute of Technology)

  Target (*end of 2004*): Cell efficiency: $\eta = 8\%$
  - Investigation of High-Efficiency Chalcogenide Solar Cells (AIST, Kagoshima University, Aoyama Gakuin University)

  Target (*end of 2004*): Cell efficiency: $\eta = 18\%$.
- *New Structures*
  - Investigation of Controlled Nanostructure Silicon (a-Si and multi-Si) Solar Cells (AIST; Kyushu University; Toppan Printing Co.; Stanley Electric Co.; Nippon Sheet Glass Co. Ltd)

  Content: Development of a novel a-Si (controlled nanostructure silicon) that is possibly immune to light-soaking and investigation of high efficiency solar cells with this material.

  Target (*end of 2003*): Cell efficiency: $\eta = 12\%$ (after stabilisation)
  - Investigation of Advanced Light-Trapping Silicon Thin-Film Solar Cells (Asahi Glass Co., Ltd)

  Target (*end of 2003*): Cell efficiency: 20% higher than cells with conventional TCO
  - Investigation of Dye-Sensitised Solar Cells (University of Tokyo, Graduate School of Engineering)

  Target (*end of 2003*): Cell efficiency: $\eta > 7\%$ ($100\,\text{cm}^2$ cell, after 500 h of continuous generation)
  - Investigation of Thin-Film Solar Cells with Wide Bandgap Microcrystalline SiC (Tokyo Institute of Technology)

  Target (*end of 2004*): Cell efficiency: $\eta = 9\%$ (single cell)
  - Investigation of High Performance Dye-Sensitised Solar Cells Using Ion Gel (Osaka University, Yokohama National University, Fujikura Ltd.)

  Target (*end of 2004*): Cell efficiency: $\eta = 10\%$; Heat stability: 85 °C × 1000 h.
- *New Processes*
  - Investigation of Solar Cell Manufacturing Technology with Cat-CVD Method (Japan Advanced Institute of Science and Technology; Graduate School of Engineering Science, Osaka University; Institute of Scientific and Industrial Research, Osaka University; Graduate School of Engineering, Gifu University)

  Content: Catalytical Chemical Vapour Deposition of a-Si (Cat-CVD) allows an effective decomposition of the source material by a heated catalyser and a high speed deposition. Solar cell manufacturing technologies using the Cat-CVD process and the stabilisation of the films deposited by vapour and/or liquid CN treatment are investigated.

  Target (*end of 2003*): Cell efficiency: $\eta = 13\%$
  - Investigation of Plating Technology for $CuInS_2$ Thin Film Solar Cells (Shinko Electric Industries Co., Ltd.)

  Target (*end of 2003)*: Cell efficiency: $\eta = 13\%$
  - Investigation of Thin-Film Si Solar Cells Prepared by Lateral-Crystallisation (Hitachi Cable, Ltd.)

  Target (*end of 2004*): Cell efficiency: $\eta = 11\%$.

4.2. Thin film research in the United States

Most research activities are co-ordinated by the National Renewable Energy Laboratory (NREL) and its National Centre for Photovoltaics (NCPV). The current Department of Energy (DOE) "Photovoltaics Technology Plan" runs from 2003 to 2007 (DOE, 2003). The technology plan is divided into tree main areas with 10 sub chapters.

• Fundamental Research:	Basic University Research High Performance and Concentrator Research Crystalline Silicon
• Advanced Materials and Devices:	Crystalline Silicon Thin Films Manufacturing research and development Module Performance and Reliability
• Technology Development:	Module Performance and Reliability System Engineering and Reliability Partnerships for Technology Introduction Programme Integration and Facilities.

Thin film research is a main focus in "Basic University Research", "High Performance and Concentrator Research", "Thin Films", "Module Performance and

Reliability" and "System Engineering and Reliability". Within the other topics thin film research is touched upon, but not with the same focus. The two main research programmes focused on thin films are described in more detail below. In these programmes NCPV directs in-house research and subcontracts to research centres and industry after an open call for proposals.

4.2.1. High performance PV initiative

This project is exploring the ultimate limits of the performance of existing PV technologies with the aim to approximately double sunlight-to-electricity conversion efficiencies. The project was initiated by the U.S. Department of Energy in FY 2001 and is intended to run for 10–12 years. The aim is to substantially increase the viability of PV for cost-competitive applications. Two specific objectives of this research include:

- Increasing efficiency levels for thin-film cells toward 25%, and for modules toward 20%.
- Creating 33%-efficient multi-junction concentrators, that is, devices that convert more than a third of the sun's energy to electricity.

The project is designed in three phases to steer high-efficiency technologies toward commercial, prototype products. Each phase of the project focuses on a specific approach to solving problems associated with high efficiencies.

- Phase I—Identifying Critical Paths (2000–2003).
- Phase IB—Exploring and Accelerating Ultimate Pathways (2003–2006).
- Phase II—Implementation.
- Phase III—Prototype Finalization.

Phase I: "Identifying Critical Paths" was designed to identify problems, approaches, and alliances. This phase was critical in providing a means to accelerate toward the most promising paths for implementation followed by commercial, prototype products. This phase delivered promising results, but revealed the need for prolongation into Phase IB "Exploring and Accelerating Ultimate Pathways" in order to have a solid foundation for the implementation phase.

The NCPV in-house portion of the HiPerf PV research is co-ordinated through three teams:

- High-Performance Thin-Film Team: It leads the investigation of tandem structures and low-flux concentrators.
- High-Efficiency Concepts and Concentrators Team: This is an expansion of an existing team that leads the development of high-flux concentrators.
- Thin-Film Process Integration Team: It performs fundamental process and characterisation research, to resolve the complex issues of making thin-film multi-junction devices.

In Phase I, the following sub-contracts were granted:
Polycrystalline Thin Films

- AstroPower, Inc.: InGaP/GaAs-on-Ceramic Thin-Film Monolithically Interconnected, Large Area, Tandem Solar Cell Array.
- Global Solar Energy, LLC: Progress Toward 20% Efficient CuInxGa1-xSe2 Photovoltaic Devices on Foil Substrates.
- The University of Toledo: Polycrystalline Thin-Film Tandem Photovoltaic Cells.
- University of Delaware: Thin Film Multi-junction Solar Cells Development of a High Bandgap Cell.
- University of Florida: Identification of Critical Paths in the Manufacturing of Low-Cost High-Efficiency CGS/CIS Two-Junction Tandem Cells.
- University of South Florida: Development of a II–VI-Based High Performance, High Band Gap Device for Thin-Film Tandem Solar Cells.

Multi-junction Concentrators

- EMCORE Photovoltaics: A Three-Junction Solar Cell for High Concentration Applications.
- ENTECH, Inc.: Near-Term Integration of III–V Cells Operating at 440X, into ENTECH's Field-Proven Concentrator Module.
- Spectrolab, Inc.: High Efficiency, Low Cost, III–V Concentrator PV Cell and Receiver Module.
- SunPower Corporation: Lens-Based Concentrator Modules: Exploring Critical Optical and System Integration Issues.
- University of Illinois: Cu(In,Ga)Se_2 Heterojunction Solar Cells for Extreme High-Efficiency Photovoltaic Concentrators.

In Phase IB, the call for proposals has been completed, but no projects have been announced yet.

4.2.2. Thin film partnership programme

The funding focus of this programme is on cost-shared contracts with companies that are leading the way to bring thin-film technology to pilot production ("Technology Partners"). The programme also funds the NCPV in-house R&D as well as that of other organisations ("R&D Partners") contributing to the successful development of thin-film technologies. The programme is divided into four teams to address issues in the following areas:

- amorphous silicon (a-Si),
- copper indium diselenide ($CuInSe_2$ or CIS) and related materials,
- cadmium telluride (CdTe),
- environment, safety, and health (ES&H).

The team concept is considered crucial because it brings together people involved in research and industry to discuss issues common to a certain technology. For example, when a manufacturer is having trouble with encapsulating cadmium telluride, a research scientist is at hand to diagnose the problem and offer solutions. This easy bilateral exchange of information produces solutions to problems in a fraction of the time it would take without such a collaboration.

4.3. Thin film research in the European Union and Candidate Countries

The European research activities in photovoltaics are funded from a variety of different sources. Activities are often carried out at Universities by small groups making it difficult to determine the level of funding for such projects. To determine the level of regional or state funding would clearly be beyond the scope of this article and I will therefore concentrate on funding on the European Union level. The European Union has been funding research (DG RTD) and demonstration projects (DG TREN) with the Research Framework Programmes since 1980. Compared to the combined national budgets the EU budget is rather small, but it plays an important role in creating a European Photovoltaic Research Area.

The European Commission's R&D activities are organised in Framework Programmes (FP), with a duration of 4 years. In the FP5 (1998–2002) around 120 million € were spent for research (66 million €) and demonstration (54 million €). Descriptions of EC funded projects can be found at the CORDIS web site (http://www.cordis.lu/guidance/services.htm).

Fourteen research projects with a focus on thin films were funded within FP5. 10 (total 33) of these projects dealt with cell and material development, two (total 7) with BIPV, one with Life Cycle Analysis and one with outdoor performance testing. EU funding for these projects totalled 16.95 million € or 27% of the photovoltaic research budget.

The current Framework Programme FP6 (2002–2006) foresees 810 million € for the topic "Sustainable energy systems" split into two equal parts for short-to-medium and medium-to-long term research, which include PV. However, no specific budget has been earmarked for PV. The first call was published on December, 17th 2002 and most of the successful projects have already started. The European Commission introduced new funding instruments for FP6.

The first, called Integrated Projects (IPs), is designed to create the knowledge required to implement the prioritised thematic areas of FP6 by integrating a critical mass of activities (research, demonstration, training, innovation, management) and resources (staff, skills, competence, finances, infrastructure, equipment etc.). The second, called Networks of Excellence (NoE) is an instrument for directly tackling the fragmentation of research activities in Europe in a given thematic area.

In addition, a third instrument known as 'Article 169', a reference to the treaty that established the Framework Programmes, is new in the sense that it will be used for the first time. This Article 169 instrument allows the Commission to support the opening and joining of national research programmes of Member States.

The 'shared-cost research projects' of earlier Framework Programmes are now represented by 'Specific Targeted Research Projects', improving existing or developing new products, processes or services or contributing to meet the needs of society or Community policies. These STREPs will have some differences in areas such as contractual and IPR rules.

Concerted actions and thematic networks have been replaced by 'Co-ordination actions' which are essentially additional actions intended to promote and support networking and co-ordination of research and innovation activities.

The 'Accompanying Measures' of FP5 have been replaced by 'Specific Support Actions', which are actions the Commission may wish to take in support of the Framework Programme. They can comprise needs studies, input to policy, showcasing research results, seminars, groups etc.

Thirty-four million € or 16.6% of the "Sustainable energy systems" budget is to be spent on 6 photovoltaic research projects, 2 IPs (CrystalClear and Full-Spectrum), 3 STREPs (BIPV-CIS, HICONPV, MOLICELL) and 1CA (PV-Catapult). Despite the fact that the validation of thin film PV technologies with higher efficiency/cost ratio was identified as a key issue, the respective IP could not be funded due to insufficient overall funding. Therefore, new thin film research on the European Union level is currently only supported by two STREPs (BIPV-CIS and MOLICELL), one of them dealing with BIPV of CIS modules. This creates the following setback for thin film R&D:

In member states where PV is not on the top priority list of research funding bodies it is very difficult to continue with thin film research, particularly for smaller institutions. The reason being, that national funding is often only granted on the condition that additional EU funding is acquired. This situation will not ease for some time, as the next call for proposals is scheduled for the second half of 2004 with estimated project starting dates anticipated for the autumn of 2005.

5. Conclusions

Thin film solar cells still offer the possibility of reducing the manufacturing costs considerably, however, considering the increasing maturity of wafer based production technologies and observed learning curves, this advantage is rapidly shrinking. In addition, the entry ticket for thin film manufacturers into the market is becoming more and more expensive the more the market grows.

Thin film technologies still face a wide range of problems, ranging from a lack of knowledge of basic material properties over availability issues of production technologies to legal concerns regarding patent infringements and the possible market perspectives. To tackle these problems, a long term vision for photovoltaics and long term research is needed. Compared with Japan or the US, Europe still has not formulated this long term research vision for photovoltaics. Therefore, public R&D funding is more directed towards industry support.

However, there is no ‘‘winning technology’’ and a viable variety of technology options has to be ensured. To focus on any single technology option now could be a road block in the future. Funding structures should take into account that different technologies are at different development stages and need different support measures.

In order to realise high production volumes for PV we must now look towards already available high throughput, high yield production technologies analysing if and how they can be utilised for PV in the future. This is especially important for thin film solar cell materials which lack industry backing, such as that provided by the microelectronic industry, in the development of production technologies. In addition, there are a number of research issues common to all thin film technologies which have to be solved. No single solar cell technology can neither satisfy the world-wide demand nor satisfy all the different wishes consumers have for the appearance or performance of PV systems.

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