Assessment of the Micromorph Tandem Solar Cell

by

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ABSTRACT

The bringing of high efficiency photovoltaics from extraterrestrial applications to terrestrial ones has begun to be realized. The micromorph tandem solar cell shows great promise as it boasts both high efficiency and low cost. The device consists of an amorphous top cell and a microcrystalline bottom cell. Optimization through high-rate silicon deposition, light trapping, and film growth make efficiencies of 15% possible. Current micromorph cells in the market are competitive in performance and cost to other similar technologies. This paper reviews the research progress and market penetration of this young but promising technology.

Thesis Supervisor: Lionel C. Kimerling
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# Table of Contents

Acknowledgements..................................................................................................................3  
List of Figures..........................................................................................................................6  
List of Tables.............................................................................................................................9  

Chapter 1 – Introduction.............................................................................................................10  
  1.1 History.................................................................................................................................10  
  1.2 The Case for Thin Film Solar Cells....................................................................................11  
  1.3 Technology Descriptions.....................................................................................................13  
    1.3.1 Amorphous Silicon........................................................................................................14  
    1.3.2 Cadmium Telluride.........................................................................................................15  
    1.3.3 Tandem Solar Cells........................................................................................................15  

Chapter 2 – The Case for Micromorph.....................................................................................20  
  2.1 The Micromorph Solar Cell.................................................................................................20  

Chapter 3 – Optimizing the Micromorph Solar Cell...............................................................23  
  3.1 Manufacturing....................................................................................................................23  
  3.2 Substrates...........................................................................................................................24  
  3.3 Light Management..............................................................................................................25  
    3.3.1. Amorphous....................................................................................................................25  
    3.3.2 Microcrystalline............................................................................................................27  
  3.4 Light Management Solutions.............................................................................................28  
    3.4.1 Transparent Conductive Oxide (TCO)........................................................................28  
    3.4.2 Intermediate Mirror Layer..........................................................................................29  
    3.4.4 Microcrystalline Anti-Reflection Layer........................................................................34
3.5 Microcrystalline Structure and Defects .............................................. 35
3.6 Deposition via Plasma Enhanced Chemical Vapor Deposition (PECVD) ... 37
  3.6.1 High-rate Thin Film ............................................................. 37
  3.6.2 Single Chamber Deposition .................................................. 40
  3.6.3 The KAI-concept: AM-LCD technology for thin-film solar cells ... 41

Chapter 4 – Patents/Intellectual Property ................................................. 44
  4.1 Amorphous Silicon Solar Cells .................................................... 44
  4.2 Microcrystalline Silicon Solar Cells ............................................. 47
  4.3 Micromorph Cluster Tools ........................................................ 50

Chapter 5 – Market Overview ................................................................. 53
  5.1 Micromorph Solar Cells ............................................................. 53
    5.1.1 Uni-Solar ................................................................. 53
    5.1.2 Kaneka ................................................................. 54
    5.1.3 Oerlikon Solar ......................................................... 54
      5.1.3.1 Auria Solar .................................................... 55
    5.2 CdTe .................................................................................. 56
      5.2.1 First Solar ............................................................. 56

Chapter 6 – Cost Considerations ............................................................. 58
Chapter 7 – Cost Model .......................................................................... 60
Chapter 8 – Conclusions ........................................................................ 67

References ............................................................................................. 68
Appendix 1: Cost Model ......................................................................... 73
List of Figures

Figure 1 Past and estimated future evolution of PV world production volume and of PV module prices (at current $/W_p) [4].

Figure 2 Actual and planned PV production capacities of Thin-Film and Crystalline Silicon based solar modules [5].

Figure 3 Regional and technology distribution of thin-films [5].

Figure 4. The approximate shape of the solar spectrum and arrangement of three different p-i-n diodes to utilize photons in three regions [8].

Figure 5 Schematic diagram of a tandem solar cell fabricated by connecting three p-i-n diodes in series through two tunnel junctions [8].

Figure 6 Energy band diagram of a tandem solar cell connected in series [8].

Figure 7 Schematic diagram of a tandem solar cell fabricated by connecting a large number of cells in parallel [8].

Figure 8 Energy band diagram of a tandem solar cell connected in parallel [8].

Figure 9 (a) Schematic of the micromorph tandem cell. (b) Separately measured external quantum efficiencies of the a-Si:H and μSi:H cells of one tandem cell [10].

Figure 10 I-V characteristic curve of a micromorph module with 9.1% stabilized efficiency [13].

Figure 11 Initial (squares) and stable (circles) parameters for various thicknesses of a-Si:H absorber layer. Triangles show the relative degradation on the right axis [22].

Figure 12 Micromorph tandem cell with an “intermediate mirror layer” between the amorphous top cell (a-Si:H) and the microcrystalline bottom cell (μc-Si:H) [17].

Figure 13 SEM micrographs of LPCVD zinc oxide surface (a) as grown and (b) with plasma treatment for 40 min [20].

Figure 14 Schematic diagram of a homogeneous ZnO film functioning as an IR in a micromorph tandem cell [28].

Figure 15 Schematic diagram of a Bragg-reflector comprising alternative layers of μc-Si:H and ZnO functioning as an IR in a micromorph tandem cell [28].

Figure 16 Schematic diagram of an inverted ZnO opal functioning as an IR in a micromorph tandem cell [28].
Figure 17 Schematic structure of a single-junction p-i-n μc-Si:H solar cell with LPCVD ZnO as front and back contact, and implantation of a TiO₂/ZnO bi-layer as an anti-reflection layer [20].

Figure 18 Defect-related absorption in initial and light-soaked state (1000h under standard conditions) as a function of the intrinsic layer crystalline volume for a dilution series of n-i-p μc-Si:H single junction solar cells [20].

Figure 19 Bright field TEM cross-section micrographs of μc-Si:H p-i-n on (a) V-shaped and (b) U-shaped substrates, corresponding to the same TCO without (a) and with (b) surface treatment [36]. The crack is shown by the arrow [20].

Figure 20 Deposition rate of amorphous silicon layers versus plasma excitation frequency, as obtained by various research groups [37-40].

Figure 21 Schematic representation of KAI-1200 PECVD system [17].

Figure 22 A sectional view showing a conventional amorphous silicon solar cell [43].

Figure 23 Sectional view showing an amorphous silicon with n-i-p configuration [43].

Figure 24 Sectional view showing an amorphous silicon with p-i-n configuration [43].

Figure 25 View explaining the main components of a plasma CVD apparatus according to the present invention [43].

Figure 26 Cross-sectional view illustrating a microcrystalline silicon formed along a texture portion of a zinc oxide thin film according to a prior art [44].

Figure 27 Cross-sectional view illustrating a microcrystalline silicon formed along a texture of a zinc oxide thin film in accordance with an embodiment of the present invention [44].

Figure 28 Flow chart illustrating a method for manufacturing a microcrystalline silicon solar cell in accordance with an embodiment of the present invention [44].

Figure 29 Uni-Solar’s Roadmap to 20+% Micromorph Cells [47].

Figure 30 Schematic of micromorph cell produced by Auria Solar using Oerlikon micromorph technology [50].

Figure 31 Relative maximal power versus product of relative area and relative cost of the modules [54, 55].
Figure 32 Relative maximal power versus product of relative area and relative cost using weighted market data for each technology.

Figure 33 Relative maximal power versus product of relative area and relative cost of micromorph modules
List of Tables

Table 1 Mobility x lifetime products, diffusion, and drift lengths, $(L_{\text{diffusion}}, L_{\text{drift}})$ of typical Si layers. [18, 19]

Table 2 The current generated in the a-Si:H and μSi:H cells within micromorph cells with different IRs and the corresponding current losses due to reflection and parasitic absorption occurring in the IR [28].

Table 3 Cost-effectiveness and power generating factor $G$ of different types of solar modules calculated with Equation 3.

Table 4 Cost-effectiveness and power generating factor $G$ of different types of micromorph solar modules calculated with Equation 3.

Table 5 Comparison between the calculated price $C_{\text{mod,cal}}$ and the actual price $C_{\text{mod,list}}$ of micromorph modules.
Chapter 1 – Introduction

1.1 History

Even in the 20th century, people realized that fossil fuel was a finite resource and a reliance on it would be unrealistic. The sun was looked toward as a promising source of energy. It is readily available globally and non-exhaustible. Semiconductor devices that utilize solar energy create no pollution, noise and emit no carbon.

The first silicon solar cell was made in 1954 by Daryl Chapin at Bell Laboratories. This solar cell had an efficiency of 6%. Solar cell research continued but due to its high cost, its primary use was for extraterrestrial applications such as satellites. With the 1973 oil supply crisis came a boost in renewable energy research. Solar cells were improved for terrestrial use, but the price was still high. After the oil prices settled again, solar cells became only a small fraction of the energy market sector. Recent investments into solar energy have again propelled the mission to create solar cells which are efficient enough to match and overtake current non-renewable energy sources [1].

Currently, there are three defined generations of solar cells. First generation cells are characterized by high-efficiency and high-price. Very pure silicon and a single-junction are used for extracting energy. Current first-generation solar cells are capable of reaching the theoretical maximum efficiency of 33%. However, because they are so expensive, it takes years for the energy savings to make up for the purchasing. Second generation solar cells are characterized by low-efficiency and low-price. This generation is made up of different types of thin film solar cells such as copper indium gallium selenide (CIGS), cadmium tellurides (CdTe), amorphous silicon (a-Si), and micromorphous silicon. These cells have efficiencies that are only 10-15%, but the low
cost makes up for this deficit. The market shows this to be a good trade-off. Thin film solar cells in the market are growing at a much faster rate than first generation bulk-Si solar cells. It is estimated that thin film solar cells may soon occupy a significant share of the market equal to that of bulk-Si solar cells. Third generation solar cells are characterized by high efficiency, low cost. These technologies include tandem/multijunctioned solar cells and nanostructured solar cells. These areas are still under high research and may not be marketable until later in the future [2].

1.2 The Case for Thin Film Solar Cells

From the EIA Renewable Energy Consumption and Electricity 2008 statistics, solar energy only accounts for less than 1% of the energy consumed in the US [3]. Currently, solar modules produce 300 MWp/year. In order for photovoltaic energy to be substantial and competitive with fossil fuels, an annual production level on the order of 100-1000 GWp/year needs to be produced. From Figure 1, it can be seen that even taking into account the rapid growth rate of +40%/year, it would be take 2-3 decades before this goal can be accomplished. First generation silicon wafer cells have already been optimized to cost US $4/Wp. Therefore, in order to push forward, attention must then be drawn to thin film solar cells and tandem solar cells [4].
Figure 1 Past and estimated future evolution of PV world production volume and of PV module prices (at current $/W_p) [4].

There are currently more than 150 companies involved in thin-film solar cell production, ranging from R&D activities to major manufacturing plants. The first 100MW thin-film factories opened in 2007 and announcements of expansions plans with high production capacities are announced each year. Figure 2 shows the estimated growth of the thin-film solar cell market in comparison with the crystalline bulk silicon solar cell market to the year 2015. It is estimated that that the thin film capacity could be 11.9 GW or 30% of the total 39GW in 2010 and 20.4GW in 2012 of the total 54.3 GW [5].
1.3 Technology Descriptions

The biggest cost to a solar cell is the silicon. Thin film solar cells have an active layer thickness that is only on the order of several microns or thinner. They also have simpler device processing and manufacturing technology, as well as a shorter pay-back time. Although less efficient, they will be attractive if it is more cost effective than conventional bulk silicon solar cells.

The distribution of thin film companies and technologies varies significantly from region to region. Figure 3 shows the regional and distribution of the thin-film production capacity increases. Currently the distribution of thin film technology companies worldwide is as follows: 48 in Europe, 41 in China, 25 in the US, 17 in Taiwan, 9 in
Japan, and 16 elsewhere. The majority of the 117 companies are silicon based. The reason for this is that there are already existing companies which offer complete production lines for amorphous or micromorph silicon [5].

![Regional and technology distribution of thin-films](image)

**Figure 3** Regional and technology distribution of thin-films [5].

### 1.3.1 Amorphous Silicon

Amorphous silicon solar cells are attractive because they are relatively cheap (approximately $3/W_p$). They account for 10-15% of the world PV solar cell market and are used exclusively in devices such as calculators and watches. The current commercial module efficiencies are 6-8%, which are low for many energy-relevant applications. Amorphous silicon has the advantage of having low substrate temperatures (180 -300°C). This allows for the use of very low-cost substrates such as glass, stainless steel, aluminum, and polymers. Depositions times have also been reduced using new techniques such as VHF-PECVD [6].
1.3.2 Cadmium Telluride

Cadmium telluride thin film solar cells has given rise to considerable interest because of its corresponding performance of small size (1 cm² surface area) and its remarkable improvement in efficiency levels which are currently in the 15-20% range. This is due to the fact that CdTe has a bag gap of 1.46 which is optimal for the photoelectric conversion of solar radiation under terrestrial conditions. Long term mass production of CdTe cells is controversial for many reasons. Some believe it is not viable for the following reasons: lack of adequate industrial/technological experience, low production yields, production hazards, necessity for production processes at relatively high temperatures (400-500 °C), problems with substrates and contacts, and difficulties in passing the “damp heat test” required of PV modules [4].

However, not all sources agree that CdTe cells should be ruled out completely based off the reasons previously stated. In fact, some sources argue the opposite. CdTe cells are estimated to have a maximum theoretical efficiency of above 29%. Though CdTe cells cannot be scaled to overtake a market equivalent to that of fossil fuels, there is still sufficient natural reserves of Cd and Te for large-scale industrial production. Also, the health and environmental hazards of CdTe are questioned as well. Medical and chemical studies show that in contrast with Cd, CdTe is not toxic and highly resistant to decomposition [7].

1.3.3 Tandem Solar Cells

A tandem solar cell consists of different bandgap semiconductors which are connected to enhance PV conversion. By using different bandgap semiconductors, a
bigger part of the solar spectrum is absorbed; this increases the electric current and cell efficiency. An example is shown in Figure 4. Cell 1 at the front is fabricated with a wide bandgap material to convert high-energy photons form the blue-end whilst cell-3 at the back is fabricated with a narrow bandgap material to convert low-energy photons from the infra-red end [8].

Figure 4. The approximate shape of the solar spectrum and arrangement of three different p-i-n diodes to utilize photons in three regions [8].

There are two different ways of connecting a tandem solar cell: connection in and connection in parallel. Series connection is the more widely used connection. The schematic and energy band diagram for a series connection are shown in Figure 5 and 6.
In a series connection, the n-type material is connected to the adjacent p-type material of the adjacent device. The idea is to convert photons with different energy ranges in 3 different devices and collect the charge carriers efficiently to generate high power in the external circuit. The schematic and energy band diagram for a parallel connection are shown in Figure 7 and 8. In a parallel connection, the structure is sliced into a large number of different cells such as n'-n-n'. This denotes heavily n-doped, moderately n-doped, low n-doped, and intrinsic semiconducting materials respectively. An analogous definition holds for p-type materials. Full absorption of the solar spectrum can be achieved by gradually reducing the bandgap from the front to the back of the solar cell. However, the lowest bandgap material used is a compromise since the open-circuit voltage produced by the device depends on the minimum bandgap material used in the structure.

![Schematic diagram of a tandem solar cell](image)

**Figure 5** Schematic diagram of a tandem solar cell fabricated by connecting three p-i-n diodes in series through two tunnel junctions [8].
Figure 6 Energy band diagram of a tandem solar cell connected in series [8].

Figure 7 Schematic diagram of a tandem solar cell fabricated by connecting a large number of cells in parallel [8].
Figure 8 Energy band diagram of a tandem solar cell connected in parallel [8].
Chapter 2 – The Case for Micromorph

Photovoltaics are increasing at a rate of 35% per year. However, this still has not made a sufficient and significant impact on the growing demand for energy. Two of the main obstacles that must be overcome are the low efficiency and high costs. Despite First Solar’s success in the PV market, there exists controversy on whether they are viable for large-scale industrialization and whether that can produce on the same level as silicon based solar cells. Skeptics of CdTe solar cells worry about the hazards due to the incorporation of Cd and to the possible material shortage of Te. No matter the position taken, it is imperative nonetheless to have another option in addition to CdTe for mass thin-film production.

2.1 The Micromorph Solar Cell

A micromorph tandem solar cell provides a possible optimal solution. Micromorph tandem solar cells were first introduced by IMT Nechatel [9]. The schematic and external quantum efficiencies for the micromorph are shown in Figures 9. A micromorph tandem solar cell consists of a microcrystalline silicon solar bottom cell and an amorphous silicon top cell. This corresponds to a low bandgap of 1.1 eV for the bottom cell and a high bandgap of 1.75 eV for the top cell. This has been deemed as “optimal” matching. Stabilized efficiencies between 10% and 12% for 1 cm² size cells have been realized in the laboratory [11, 12, 13]. An I-V characteristic curve for a 9.1% stabilized efficiency micromorph module is shown in Figure 10. In the industry, Kaneka Corp. has announced an initial efficiency up to 14.7% [14] and a best confirmed stable value of 11.7% [15].
Figure 9 (a) Schematic of the micromorph tandem cell (b) Separately measured external quantum efficiencies of the a-Si:H and μSi:H cells of one tandem cell [10].
A push for even higher efficiencies is undergoing intense research. Higher deposition rates and optimized light-trapping are also sought to be achieved as well. High deposition rates allow for high throughput, and efficient light trapping allows for the reduction of the thickness of the μc-Si bottom cell. These factors account for the economical manufacturing of micromorph tandem cells. Aims at reducing optical losses and other factors make it possible to achieve 15% efficiencies, total costs per m$^2$ at 100 US$, and 1US$/W_p$ [16]. These individual factors are looked into detail in the following chapter.
Chapter 3 – Optimizing the Micromorph Cell

3.1 Manufacturing

Thin amorphous or polycrystalline structured silicon thin films can be deposited on glass, plastic, or stainless steel by PECVD (Plasma-Enhanced Chemical Vapor Deposition). This is done in a silane (SiH₄) and hydrogen (H₂) environments on temperatures from 150 to 500°C, depending on the substrate material [17].

The silane concentration (SC) is defined as the ratio of silane gas flow over silane and hydrogen flows as shown in Equation 1:

\[
SC = \frac{\text{SiH}_{4}}{\text{SiH}_{4} + \text{H}_{2}}
\]  

At low silane concentrations (SC ~5-10%), microcrystalline material is formed. Whereas at high silane concentrations, amorphous silicon is formed. The exact cutoff threshold between the two different material formations vary for each system [20].

The layers deposited have different properties depending if they are amorphous or polycrystalline. Amorphous layers are prone to light-induced degradation which causes increase in defect densities and poor mobility x lifetime (μτ). Polycrystalline layers consist of small crystallites with varying microstructures and sizes on the hundreds of nanometer scale. These layers are not prone to light-induced degradation. The mobility x lifetime (μτ) for initial-state amorphous layers, degraded amorphous layers, and polycrystalline layers are presented in Table 1.
Measured corresponding $L_{\text{diffusion}}$ if $E = 1 \text{ V} / \mu\text{m}$

<table>
<thead>
<tr>
<th>Material</th>
<th>$\mu\tau$-values</th>
<th>$L_{\text{diffusion}}$</th>
<th>$L_{\text{drift}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amorphous silicon</td>
<td>$4 \times 10^{-7}$</td>
<td>1.0</td>
<td>40</td>
</tr>
<tr>
<td>(initial state)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Amorphous silicon</td>
<td>$1 \times 10^{-7}$</td>
<td>0.5</td>
<td>10</td>
</tr>
<tr>
<td>(degraded state)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Microcrystalline Si</td>
<td>$4 \times 10^{-7}$</td>
<td>1.0</td>
<td>40</td>
</tr>
<tr>
<td>Units</td>
<td>cm$^2$/Vs</td>
<td>$\mu$m</td>
<td>$\mu$m</td>
</tr>
</tbody>
</table>

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

Table 1 Mobility x lifetime products, diffusion, and drift lengths, ($L_{\text{diffusion}}, L_{\text{drift}}$) of typical Si layers. [18, 19]

3.2 Substrates

Different substrates such as glass, stainless steel, and plastics can be used for thin-film solar cells. In the p-i-n configuration, glass coated with transparent conductive oxide is the most common substrate. In the n-i-p configuration, flexible substrates such as plastic foils are used. The decision of which to use is balancing a trade-off between quality/performance and material/manufacturing.

TCO-coated glass substrates are the most common and inexpensive in the market. TCO is presently produced offline and prepared with low-pressure CVD or sputtering. This preparation process incurs more cost but is necessary to optimize photovoltaically relevant properties. In the future, TCO can be produced on-line directly on a glass float line which offers large-area uniformity, reproducibility, and lower costs. TCO on soda-lime glass is the currently the most cost effective option. However, more expensive low-iron content glass has achieved better results, due to its lower absorption in the red spectral range. They yield higher transmittance and higher currents particularly in the
micromorph cell. Until demand grows higher to lower its cost, soda-lime glass will continue to be the preferred glass type to use.

Stainless steel glass substrates are attractive because they can be easily produced via roll-to-roll processing. However, it is limited with the fact that these cells cannot be individually connected in an electrical series to form a whole monolithic module [17].

Plastic substrates such as PET have been researched into, but the performance has been limited by outgassing from the substrate and the need to deposit at reduced PECVD operating temperatures [21].

3.3 Light Management

3.3.1 Amorphous Solar Cells

The efficiency of amorphous silicon solar cells decreases at initial stages of operation due to the Staebler-Wronski effect [22]. Efficiency stabilizes at 75-80% of the initial value for a single-junction cell after 1000 hours under light soaking condition. The decrease in efficiency is due to creation of additional dangling bonds which act as recombination centers.

Microcrystalline silicon cells have shown stability under light soaking. In micromorph cells, they are exposed to a lower illumination and hence lower recombination rate. However for cells with i layers of medium crystallinity (40-60%), single-junction cells suffer from a mild form of light-induced degradation when exposed to blue. Yan et al. observed that degradation is due to larger absorptions in the amorphous phase and at the p-i interface [23].

The thickness of the top a-Si:H cell has to be kept sufficiently thin to minimize the impact of light-induced degradations and its current. A thinner cell has a higher
electric field in the absorber layer. This correlates to a higher collection efficiency of the photogenerated charged carriers and the recombination process within the absorber is reduced. This therefore limits the current of the overall cell. The effect of layer absorber thickness is shown in Figure 11 [22]. $J_{sc}$ and FF are the parameters that degrade the most significantly.

Figure 11 Initial (squares) and stable (circles) parameters for various thicknesses of a-Si:H absorber layer. Triangles show the relative degradation on the right axis [22].

To solve this problem, an intermediate reflective layer (IRL) can be introduced between the top and bottom cell as shown in Figure 12 [17]. An IRL must have a refractive index lower than that of silicon to ensure light reflection at the interface, be
conductive to avoid electrical losses, and also be transparent to minimize the absorption of light outside the active PV layers.

![Diagram of a micromorph tandem cell with an "intermediate mirror layer" between the amorphous top cell (a-Si:H) and the microcrystalline bottom cell (μc-Si:H) [17].]

ZnO was the first material used for intermediate reflectors. However, its necessity for ex-situ deposition and additional laser scribing for monolithic series interconnection impedes it for further industrialization.

### 3.3.2 Microcrystalline cells

The two limiting factors of microcrystalline cells are: (i) lower open circuit voltage values due to a bandgap of ~1.1 eV and (ii) an absorption coefficient that is larger in the near infrared but lower in the visible range. This had led to a requirement for a thicker intrinsic layer to obtain sufficient absorption and longer deposition times. This
had made production of microcrystalline cells costly. More efficient light-trapping together with high material quality, and how higher deposition speeds are needed.

3.4 Light Management Solutions

To increase photo-generation and short-circuit density, reflection and absorption losses must be reduced via the following methods:

a. antireflection coated glass
b. low absorption back reflectors
c. high transparency glass and front TCO
d. thin TCO layers

3.4.1 Transparent Conductive Oxide (TCO)

The front TCO fulfills two requirements: (i) it provides high transparency to minimize optical losses due to absorption and reflection and (ii) it provides high conductivity to limit the series resistance of the solar cell. A front TCO with a surface roughness RMS value between 50 and 200nm reduces reflection due to refractive index grading and increases the optical path of incoming light due to increase optical diffusion. This leads to higher absorption and short circuit density values. However, TCO layers that are too rough with steep slopes will lead to reduced values of $V_{oc}$ and FF.

The surface morphology differs for sputtered ZnO and ZnO via LPCVD. Sputtered ZnO is flat and treated subsequently by wet etching. ZnO via LPCVD is rough as grown. Figure 13 [20] are SEM micrographs of LPCVD zinc oxide surfaces as grown and with plasma treatment for 40 minutes.
The LPCVD technique is relatively simple and has been upscaled to deposition areas larger than 1 m$^2$ with deposition rates greater than 2 nm/s [24].

ZnO layers have drawbacks of optical transmissions that are limited in the short wavelength region and in the near-infrared region. This is due to ZnO’s bandgap of 3.3 eV and free carrier absorption. The chosen thickness for a ZnO layer is a compromise between the sheet resistance and the optical transmission. Increased thickness reduces sheet resistance but increases optical absorption, and vice versa. Other TCO materials encounter the same problem. Novel ways to solve this problem have been presented by J. Anna Selvan et al. [25] with combining different TCO materials and by J. Steinhauser et al. [26] with growing films with lowly doped large grains and high mobility.

3.4.2 Intermediate Mirror Layer

An intermediate mirror layer has been proposed as a possible option to enhance light trapping within the solar cell. This would be placed in between the amorphous top cell and the microcrystalline bottom cell. Adding this layer would allow keeping the
amorphous top cell thickness low (as low 0.180 μm). This would reduce or prevent substantial light-induced degradation and maintain good current density J_{sc}.

The ZnO layer ideally returns incident photons of energy greater than ~1.7 eV to boost current in the top cell while transmitting photons of lesser energy to the underlying μc-Si:H cell.

Doped silicon oxide IRs (SOIRs) have the advantage of being deposited in-situ. It is produced in the same forming gases and reactor as the thin-film silicon-based cells. Micromorph cells with efficiencies of 12.2% have been fabricated [27].

Three-dimensional photonic crystals (PCs), in the form of inverted ZnO opals have also been researched as intermediate layers. Photonic crystals can also be engineered to possess a photonic band-gap over a specific spectral range within which light cannot propagate and incident light undergoes 100% reflection.

Opaline PCs possess a one-dimensional band-gap known as stop-gap. The narrow stop-gap in the [111] direction is aligned with the normal of the surface which the PC is grown. Opaline PC can be used as a reflector for normally incident light over its stop-gap frequencies.

Schematics of micromorph cells with ZnO, Bragg-reflectors, and ZnO opal PC functioning as IRs are shown in Figure 14, 15, and 16 [28] respectively.
Figure 14 Schematic diagram of a homogeneous ZnO film functioning as an IR in a micromorph tandem cell [28].

Figure 15 Schematic diagram of a Bragg-reflector comprising alternative layers of μc-Si:H and ZnO functioning as an IR in a micromorph tandem cell [28].
Bragg-reflectors functioning as the IR are comprised of alternating layers of μSi:H and ZnO. The large contrast in their indices of refraction provide a broad and intense stop-gap. The absorption enhancements and reflection in the upper a-Si:H are the highest in these stop-gap frequencies. The amount of parasitic absorption in the IR however is also increased. Doping and increasing the conductivity of the μSi:H films has been proposed to make this drawback obsolete. O'Brien et al. [28] determined the optimal case occurs when the IR is three and half bi-layers thick with ZnO film serving as both the top and bottom layers.

Inverted ZnO opal PC functioning as the IR share similar properties with the Bragg reflector. The absorption enhancement is also maximum over the stop-gap frequencies. The maximum amount of current generated corresponds to inverted ZnO
opal IR that is 13 layers thick with 264nm diameter long air-holes. The parasitic absorption is greatest for the inverted ZnO opal PC IR as compared to the others.

The current generated in the a-Si:H and µSi:H cells within micromorph cells with different IRs and the corresponding current losses due to reflection and parasitic absorption is shown in Table 2.

<table>
<thead>
<tr>
<th>Intermediate Reflector</th>
<th>Generated Current [mA/cm²]</th>
<th>Integrated Losses [mA/cm²]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>a-Si:H cell</td>
<td>µ-Si:H cell</td>
</tr>
<tr>
<td>No IR</td>
<td>11.5</td>
<td>26.5</td>
</tr>
<tr>
<td>Single ZnO film</td>
<td>12.5</td>
<td>21.4</td>
</tr>
<tr>
<td>µ-Si:H/ZnO BR 1.5 layers</td>
<td>13.5</td>
<td>17.3</td>
</tr>
<tr>
<td>µ-Si:H/ZnO BR 3.5 layers</td>
<td>13.8</td>
<td>14.9</td>
</tr>
<tr>
<td>i-ZnO-o</td>
<td>13.0</td>
<td>14.6</td>
</tr>
</tbody>
</table>

*The thickness of the upper a-Si:H cell within the micromorph is 100nm and the direct solar irradiance is normally incident

Table 2. The current generated in the a-Si:H and µSi:H cells within micromorph cells with different IRs and the corresponding current losses due to reflection and parasitic absorption occurring in the IR [28].

The Bragg-reflector outperforms the ZnO inverted opal because it has a larger stop-gap (stop-gap of the ZnO inverted opal is ~14%, whereas the Bragg-reflector is ~45.2%), is optically thin, and suffers less from parasitic absorption. It is attractive because its fabrication is the least challenging and the thickness of the a-Si:H cell is within the acceptable range for the optimal mitigation of the Staebler-Wronski effect. However, Bielawny et al. [29] showed that material choice and the amount of parasitic absorption can prove the opposite, with ZnO inverted opals outperforming the Bragg-reflector. Therefore, the optimal IR is yet to be definitively determined.
3.4.3 Microcrystalline anti-reflection layers

In a p-i-n solar cell, incident light is reflected at the following interfaces: 4% at the air/glass interface, 2% at the glass/ZnO interface, and 11% at the ZnO/silicon interface. The first two reflections can be minimized with standard industrial anti-reflection coatings (ARC) on glass [30]. As proposed by Matsui et al. [31] and investigated at IMT Neuchatel [32], a TiO$_2$/ZnO stack as an ARC layer can be put between the TCO and silicon layers. Figure 17 shows a schematic structure of a single-junction p-i-n µSi:H solar cell with the implantation of a TiO$_2$/ZnO bi-layer as an anti-reflection layer. A short-circuit density can be increased by up to 4%, corresponding to a total reflectance reduction from 10.2 to 6.4% at 550nm.

Figure 17 Schematic structure of a single-junction p-i-n µc-Si:H solar cell with LPCVD ZnO as front and back contact, and implantation of a TiO$_2$/ZnO bi-layer as an anti-reflection layer. Refractive index is indicated. [20].
3.5 Microcrystalline Structure and Defects

Microcrystalline silicon is composed of silicon nanocrystals embedded in an amorphous phase. The 10-20nm diameter long nanocrystals are packed into >0.5μm diameter conglomerates. The growth depends sensitively on the substrate material and underlying layers.

The evolution of layer crystallinity with increasing hydrogen dilution can be observed microscopically by transmission electron microscopy (TEM) [33], X-ray diffraction [34], and Raman spectroscopy [35].

Figure 18 [20] shows that the optimum in μSi:H intrinsic quality is observed for medium crystalline volume fractions \( \varphi_c \). This is approximately 40-60% as determined by Raman spectroscopy with a HeNe laser. The defects can be due to surface dangling bonds at the amorphous/crystalline interface.
Figure 18 Defect-related absorption in initial and light-soaked state (1000h under standard conditions) as a function of the intrinsic layer crystalline volume for a dilution series of n-i-p μc-Si:H single junction solar cells [20].

In addition cracks may be observed as a defect for challenging substrates such as V-shaped substrates. In this highly rough surface with large and steep pyramids, cracks appear at the bottom of the valleys. However, by using U-shaped substrates which have smoother morphologies, cracks density can be dramatically decreased. Figure 19 [20] shows bright-field TEM cross-section micrographs of μSi:H p-i-n on V-shaped and U-shaped substrates. The crack is indicated by the arrow.
Figure 19 Bright field TEM cross-section micrographs of $\mu$-Si:H p-i-n on (a) V-shaped and (b) U-shaped substrates, corresponding to the same TCO without (a) and with (b) surface treatment [36]. The crack is shown by the arrow [20].

3.6 Deposition via Plasma Enhanced Chemical Vapor Deposition (PECVD)

Large area-PECVD on glass substrates is an attractive method because it is what the industry is well acquainted with. Glass covers are used for the traditional wafer-based module, which currently make up 90% of module production. PV on glass is heavy and fragile, but they meet the demands of outdoor PV applications. They have a long lifetime of 20 to 30 years and are not subject to severe degradation or influences of weather.

3.6.1 High-rate thin-film silicon deposition by PECVD

The silicon deposition rate for microcrystalline is critical as it directly related to the cell thickness. Currently, deposition rates for amorphous silicon are in the order of
0.1 to 0.2 nm/s. VHF deposition can deposit at rates of 0.5 to 1.0 nm/s and is now being up-scaled to industrial large-area deposition.

As shown in Figure 20, the deposition rate of amorphous silicon layers can be dramatically increased when the plasma excitation frequency is increased from radio frequency (RF) to very high frequency (VHF). This corresponds to 13.56 and ~ 70 MHz respectively. At this frequency, the flux of lower energy ions is increased. This leads to higher density of vacant sites and deposition rates. At even higher frequencies, a decrease in deposition rate is observed. This is attributed to a less efficient power coupling within the reactor, a decrease in electron density, or a depletion of SiH4 in the feed gas. A parallel can also be drawn for microcrystalline silicon under high deposition pressures.
Figure 20 Deposition rate of amorphous silicon layers versus plasma excitation frequency, as obtained by various research groups [37-40].

The use of higher frequencies also affects other factors. The powder level (the maximum power level or maximum deposition rate above which a significant amount of powder is formed in the plasma) is increased. The maximum energy of ions reaching the growing surface is reduced, and the optical emission line of SiH* radicals is increased. This corresponds to more effective silane dissociation within the plasma as well as better film uniformity.

VHF deposition operates at increased plasma excitation frequencies from 60 to 100 mHZ. Operating at higher frequencies induces standing wave effects and compromises the uniformity of the films deposited on the substrates. To correct this,
ladder-shaped electrodes are used in combination with a phase-modulation method for the excitation signal.

Deposition time can be reduced with suitable light trapping schemes or by increasing deposition rates to over 10 Angstroms/second. This was investigated at IMT Neuchatel. It was observed that by increasing the pressure and silane depletion, microcrystalline material could be improved. Under these conditions, plasma potential decreases and ion energy are reduced.

3.6.2 Single-chamber deposition

Amorphous silicon manufacturers use multi-chamber PECVD deposition systems in order to avoid cross-contamination between different layers. This however creates for higher complexity and higher equipment costs. Developers are now looking into single chamber PECVD deposition chambers.

Care for contamination must be taken especially between the doped layer and the intrinsic layer. Kroll et. al [41] has successfully controlled contamination between the p-layer and i-layer be using a flush by water or ammoniac vapor. Impurities in the microcrystalline are being investigated further.

The level of certain contaminants such as oxygen and nitrogen within the intrinsic layer must be kept low in order to obtain a high value of external quantum efficiency. These may be incorporated into the layers through contamination of feedstock gases and from the reactors. They become positively ionized and act as unintentional dopants. Boron, which is used for the p-layer may contaminate the initial intrinsic layer if care is not used. It affects the carrier collection efficiency at the p-i interface and leads to a
reduction in quantum efficiency in short wavelength range and a loss in open-circuit voltage and fill factor.

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

PECVD equipment makes up a quarter of the present fabrication costs. To offset this cost, it has been recommended to use a successful and proven PECVD system concept applied in the AM-LCD manufacturing called the “KAI” system concept of UNAXIS. Its heart is the Plasma Box PECVD Reactor [42], which combines iso-thermal heating with differential pumping, and minimizes process contamination. In a KAI 1200 system (Figure 21), 20 sheets of glass with a size of 1.4m² are processed simultaneously, leading to an annual PV production capacity of 20 MWp.
Using this system has the benefits of high yield and low processing time, two factors necessary for large-volume, low-cost manufacturing. Yield levels of above 95% are anticipated to be attained. KAI deposition systems are also being modified to incorporate VHF-compatible electrons capable or running at a plasma excitation frequency of 40 MHz.

The KAI PECVD system reduces both the costs and the risks for a thin-film production life. Typical machinery for thin-film silicon PV required high investment and prototyping. The system itself can be continually modified and adjusted to maximize module efficiency in the final PV product. Factors to control include consistent material
quality, layer uniformity, and proper means to avoid contamination of intrinsic layers by dopants. With the improvements of future generations of the AM-LCD machine and increased demand, cost levels of 1 U.S. $/W_p for overall module production can be realized.
Chapter 4 – Patents/ Intellectual Property

The basic technology for the micromorph solar cell has been around for a decade or more. Companies however make modifications in the manufacturing and processing. These are proprietary and not readily available to the public. The basic patents are however presented in this chapter.

4.1 Amorphous Silicon Solar Cells

A conventional solar cell is shown in Figure 22. It consists of a transparent electrode (2), a power-generating film (3), and a metal electrode (4) on a glass substrate (1). The power generating film (3) is made up of a p-type a-SiX\textsubscript{1-x}C\textsubscript{1-y}:H layer (5), an i-type a-SiH layer (6) and a n-type a-Si:H layer (7). Light enters the glass substrate and passes through the transparent electrode and p-layer. Upon reaching the i-layer, the optical energy in the light is converted into electrical energy. The i-layer thus has direct influence on the overall characteristic of the solar cell.

Figure 22 A sectional view showing a conventional amorphous silicon solar cell [43].
Takeuchi et al. present two examples of their solar cell invention as shown in Figure 23 and 24 [43]. The defect density of i-type hydrogenated amorphous silicon is less than $10^{15}$ defects/cc. This enables the raising of the initial efficiency without lowering the productivity and achieving high stabilization efficiency compared to conventional solar cells. The thickness of the i-type hydrogenated amorphous silicon layer is 300 nm or less. This improves the productivity compared to conventional solar cells.

Figure 23 Sectional view showing an amorphous silicon with n-i-p configuration [43].

Figure 24 Sectional view showing an amorphous silicon with p-i-n configuration [43].
Figure 23 and 24 are amorphous silicon solar cells comprising of a transparent substrate, a transparent electrode, a power generating film, and back-side electrode. The power generating film in Figure 23 consists of sequentially stacked p-type/i-type/n-type hydrogenated amorphous silicon layers. Whereas the power generating film in Figure 24 consists of sequentially stacked n-type/i-type/p-type hydrogenated amorphous silicon layers.

Figure 25 shows a sectional view showing the major parts of a plasma CVD apparatus used to form the power-generating films in the aforementioned inventions. It consists a plasma chamber (31), substrate (32), substrate holder (33), substrate heater (34), thermocouple (35), second heater (36), RF electrode (37), gas supply pipe (38), gas supply hole (39), and plasma (40). The plasma CVD was operated with the use of monosilane (SiH₄) as a gas at a flow rate of 20 to 100 sccm, a pressure of 50 to 200 mTorr, a RF power of 5 to 60W, and a substrate temperature of 160 to 200°C.
4.2 Microcrystalline Silicon Solar Cell

Microcrystalline silicon solar cells have the benefits of lower light-induced degradation and the ability to absorb near infrared light as well as visible light. However, due to its low absorption coefficient, a thickness of 50 μm is necessary. In order to increase efficiency and make high volume manufacturing viable, light trapping must be maximized. This is done via light scattering on a surface textured transparent front electrode.

Zinc oxide (ZnO) is widely used as the transparent conductive oxide (TCO). It is deposited by chemical vapor deposition (CVD). The deposition rate and uniformity are high and the manufacturing costs are low. A natural surface is formed having V-shaped pyramidal shapes of 100 nm- 500 nm size. This is show in Figure 26 [44]. The V-shaped valley shape however acts like cracks to inhibit formation of microcrystals, and the incubation layers and grain boundaries induce more recombination which lowers efficiency.

Myong presents a microcrystalline solar cell whereby the pyramidal textured surface (20) of Figure 26 [44] are transformed into a gentle crator-like surface with U-shaped valley shape in a short time via chemical etching. This is shown in Figure 27 [44] and the flow chart of this process is shown in Figure 28 [44].
Figure 26 Cross-sectional view illustrating a microcrystalline silicon formed along a texture portion of a zinc oxide thin film according to a prior art [44].

Figure 27 Cross-sectional view illustrating a microcrystalline silicon formed along a texture of a zinc oxide thin film in accordance with an embodiment of the present invention [44].
Figure 28 Flow chart illustrating a method for manufacturing a microcrystalline silicon solar cell in accordance with an embodiment of the present invention [44].

Etching is controllable with an acid water solution ranging from 0.5% to 5%. The etching time ranges from 5 second to 20 seconds. The gentle texture surface is formed in a short enough time which doesn’t inhibit the light trapping effect, short-circuit current, and conversion efficiency. The shape transformation also gives an enhancement to the open voltage and fill factor.
There have also been proposals to accomplish the same means via plasma processing. However, such a process takes longer than 120 minutes and is not suitable for mass production [45].

4.3 Micromorph Cluster Tool

Shinichi Kurita, Takako Takehara, and Suhail Anwar invented a method for forming solar panels from n-doped silicon, p-doped silicon, intrinsic amorphous silicon, and intrinsic microcrystalline silicon using a cluster tool. It consists of multiple load lock chambers, transfer chambers, and buffer chambers. As few as five and as many as thirteen processing chambers can be present. This cluster tool meets the challenge of high substrate throughput for large area deposition.

Depending on the embodiment of the cluster tool, different cells can be made. This includes amorphous silicon single PIN junction, amorphous silicon PINPIN double junction, and amorphous silicon/microcrystalline silicon tandem cells. An example of a cluster is show in Figure 29 [46].
Figure 29 Triple cluster tool of current invention [46].

Two embodiments can be used to form amorphous silicon/microcrystalline silicon tandem cell for cluster tool 300 shown above. In one embodiment, each process chambers 304, 308, and 310 can be used to deposit p-doped silicon, intrinsic amorphous silicon, intrinsic microcrystalline silicon, and n-doped silicon. In another embodiment, one process chamber 304 can deposit the p-doped silicon layer, one process chamber 304 can deposit the n-doped silicon layer, two process chambers 304 can deposit the intrinsic amorphous silicon layer, and eight or nine process chambers 308, 3010 can deposit the intrinsic microcrystalline silicon layer. However, it is probably best to have all the chambers deposit the same type of layer. This will avoid the issue of potential leakage and can allow for more efficient cleaning.

The cluster tool can process 14 substrates per hour. Each substrate is 1960mm x 2500mm. Between each deposition of p-doped silicon and intrinsic silicon deposition, the chambers are purged for 300 seconds. The p-doped and n-doped silicon layers deposit
2 times faster than the intrinsic amorphous silicon layer and 8 times faster than the microcrystalline layer. The difference in deposition time is because the intrinsic layers need to be thicker than the doped layers. The amorphous silicon layer can be deposited at 50 nm per minute and the microcrystalline silicon layer can be deposited at 100 nm per minute. The p-doped, n-doped, amorphous, and microcrystalline silicon layers can be deposited to thicknesses of 20 nm, 20 nm, 150 nm – 300 nm, and 300 nm respectively.

The cluster tool has the benefits of a flexible configurations, high throughput, high mechanical reliability, high particle performance, high mean time between failure (MTBF), low material and cost of operation, and low process risk.
Chapter 5 – Market Overview

5.1 Micromorph Solar Cells

Micromorph solar cells are slowly becoming mainstream in the market. Literature reports have demonstrated prototypes which can be scaled to industrial levels. At the time this thesis was written, companies had just recently published press releases for micromorph production and sale. Therefore, details on manufacturing and cost were very limited. Some of the companies are described below.

5.1.1 Uni-solar

Uni-solar published a press release on June 1, 2010 stating that it aims to push conversion efficiencies to 12% and cost-per-watt of 95 cents by 2012. [47]

This is coming more from material improvements and process optimizations, rather than fundamental cell changes. This includes using an improved back-reflector layer for enhanced light trapping, an a-Si/germanium alloy which captures red light more effectively, and proprietary plasma CVD which doubles throughout and offers deposition uniformity over a large area. The upgraded CVD equipments have an estimated cost between US$15 to US$20 million, along with capacity boosts of 30MW.

Unisolar roadmap toward achieving 20% efficiency is based on optimizing three factors: light trapping, high rate deposition and HybridNano technology. The roadmap is show in Figure 23. Although First Solar has already achieved its goal of reducing cost-per-watt below $1US, Unisolar claims its competitive edge over its reduced installation prices, especially in its core commercial rooftop market.
5.1.2 Kaneka

Kaneka Corp has adopted the Institut de Microtechnique (IMT) original concept of a superstrate micromorph tandem configuration deposited on glass. Kaneka has renamed this structure as “hybrid” solar cells. They have fabricated large-area PV “hybrid” modules of 0.4m² size with initial efficiencies of close to 10% [48].

5.1.3 Oerlikon Solar

Oerlikon Solar is a company based in Switzerland. They offer field proven equipment and end-to-end manufacturing lines for the mass production of thin film silicon modules. They use different processes to deposit transparent conductive oxide (TCO) layers for front and back contacts, plasma enhanced chemical vapor deposition
(PECVD) to build the photosensitive layers and laser patterning to generate the serially connected cells.

Oerlikon Solar use two technologies for the photosensitive layer: amorphous solar modules and micromorph solar modules. The first module is made by depositing amorphous silicon (a-Si) on a TCO layer. The second module is a tandem structure with an additional microcrystalline absorber. This layer converts the energy of the red and near infrared spectrum. This allows for an efficiency increase of approximately 30% [49].

5.1.3.1 Auria Solar

Auria Solar is a solar cell manufacturing company based in Taiwan. They are the first to have an end-to-end manufacturing line using Oerlikon’s micromorph technology. Auria Solar can already produce modules with 120 W stabilized power output and 9% conversion efficiency.

Oerlikon solar’s micromorph process significantly boosts solar cell efficiency by adding a second microcrystalline absorber to the amorphous silicon (a-Si) layer. This layer converts the energy of the red- and near-infrared spectrum, yielding efficiency and module power gains of up to 50 percent. The schematic of the product is shown in Figure 30 [50]. Its goal is to produce 500 Wp by 2010 at $1 per watt.
5.2 CdTe

The main competitor in the market to thin film Si solar cells would be CdTe solar cells. These solar cells are very attractive due to their high efficiency, long lifetime, short payback periods, and low cost.

5.2.1 First Solar

First Solar is the largest manufacturer of thin film solar modules, having expanded manufacturing capacity to an annualized run rate of 53.4MW per line in the 4th quarter of 2009. It has had over 1 gigawatt (GW) of working installations worldwide. The current PV module is called the FS Series 2 and it is the first module to break the $1/watt production barrier.
Unique to First Solar is its operating life cycle which takes care of the PV cells from manufacturing to sales and installation to disposal and recycling. This had made the buying of PV modules from First Solar an all encompassing, convenient, and cheap option as compared with its competitors. The life cycle steps are: product design, material sourcing, manufacturing, product use, product collection, and recycling technology. [51]
Chapter 6 – Cost Considerations

The purpose of this cost model is to see qualitatively with very crude estimates how efficiency and process improvements can affect the overall cost of solar PV and if it can be scaled to meet future energy demands on the MW to GW level. It is unrealistic and impossible to create a cost model that is quantitatively sound. Company and technology specific information in regards to thin film manufacturing is highly proprietary, and actual prices fluctuate depending on volume and demand. However, it is possible to see if the claims that different papers and company make about the future of micromorph tandem cells are sound.

Cost is determined by two factors: the manufacturing cost/m², and the price/Wp. The module manufacturing costs can be broken down by approximate percentages as: materials and consumables (25%), equipment depreciation (25%), and personnel and infrastructure (25%). Thin film modules currently have efficiencies ranging between 5-7% and their equivalent market module price is around 3 U.S. $/Wp. In order to reach the cost goal of 1 U.S. $/Wp, area-related costs should be below 150-210 U.S $/m² and efficiencies need to reach 10%.

In addition to just cost estimates in relationship to the PV cell/module, other factors such as material availability, land area needs, and energy payback are just as important. Cadmium and tellurium remain to be controversial with respect to their toxicity and supply. Silicon and glass substrates on the other hand have shown in other industries that material supply is not an issue. Land area needs for residential PV application are not significant as they can be installed on building rooftops. Payback periods have been reduced significantly to about 1-2 years. The financing of solar cells,
government incentives, and full services offered from point of sale to installation to disposal has made PV’s even more attractive to the average consumer. [52]

Another thing that is overlooked in cost models are the reduced costs of transmissions and distribution infrastructure. This is due to the fact that solar PV within an electrical grid is produced on-site at the location of the end user. However, Borenstein’s [53] analysis of installations of solar PV in California showed no cost reduction.

The paradigm shift from an oil-based society to renewable one will depend on whether one thinks that the net social return on installing renewable devices such as solar PV is positive. All the factors as mentioned must be considered together because they all play a role.
Chapter 7 – Cost Model

Yatsuto Marouka has proposed a method for determining cost-effectiveness and price of solar modules [54]. An empirical equation clarifies the relationship between the maximal power of standard modules as well as module cost in the German, US, and Japanese market. Using published list prices for different modules in the market, Marouka proposes a method for determining cost-effectiveness and setting new market prices for new modules.

The empirical equation is given as:

\[
\frac{P_{\text{max,mod}}}{P_{\text{max,sys}}} = G \left( \frac{A_{\text{mod}}}{A_{\text{sys}}} \cdot \frac{C_{\text{mod}}}{C_{\text{sys}}} \right)^{\frac{2}{3}}
\]  

(2)

where \( P_{\text{max,mod}} \) is the maximal power of a standard module at Standard Test Conditions (STC), \( P_{\text{max,sys}} \) is the maximal power of an assumed reference system (3000 W), \( G \) is the power generating factor, \( A_{\text{mod}} \) is the front surface area of the module, \( A_{\text{sys}} \) is the area needed for the reference photovoltaic system (30m²), \( C_{\text{mod}} \) denotes the list price or suggested retail price of the module; and \( C_{\text{system}} \) denotes the average price for the PV system (21000USD, 16000EUR, 2000000JPY).

Equation 2 can be simplified to:

\[
P^* = G \left( A^* \cdot C^* \right)^2
\]

(3)

where \( P^* \) is the relative maximal power, \( A^* \) is the relative area, \( C^* \) is the relative price. The product of the relative area and the relative price may be interpreted as the investment required for deriving power output.

The application ranges for equation 3 are:
The G-factor was derived from a previous analysis from Maruoka using a sample base in excess of 120 modules produced by 26 different manufacturers in the German, US, and Japanese markets [55]. The G-factor was found to be 3.3 for seven cell materials: poly-Si, c-Si, a-Si, a-Si/c-Si, a-Si/µSi, CIS, and CIGS. For CIGs-module data, the G-factor is 3.8.

The module price per watt ($/W), price per module area ($/m²), and watt per module area (W/m²) are published by individual companies, however they in themselves do not always directly tell which module is best in terms of cost and performance. By collecting tabulating the data from the different companies, one can graph relative max power $P^*$ versus the product of relative area $A^*$ and relative cost $C^*$. These points can be graphed with equation 3 as the reference line. The modules above the line are more cost-effective than the modules which lie below the line. Points in the upper left of the graph are most cost-effective; they correspond to high power and low investment.

The data used in Marouka’s previous analysis is updated and combined with current market data for micromorph technologies. This is shown in Figure 31.
Figure 31 Relative maximal power versus product of relative area and relative cost of the modules [54, 55] for various thin film technologies.

The product data for the various thin film technologies in Figure 31 was further condensed. The data was separated into its respective technology and the average cost, area, and power output were calculated. The calculated data is tabulated in Table 3 and the individual market data is given in Appendix 1. To get an even rougher idea of where the different technologies stand holistically relative to one another, Figure 32 re-graphs Figure 31 with only one point representing one technology. Equation 3 is used as a reference line. The difference between the calculated values and the line is minimal. Thus all the different thin film technologies are cost-effective relative to one another and the micromorph cell is determined to be a formidable contender in the market.
Figure 32 Relative maximal power versus product of relative area and relative cost using weighted market data for each technology.

Table 3 Cost-effectiveness and power generating factor G of different types of solar modules calculated with Equation 3.

<table>
<thead>
<tr>
<th>Type</th>
<th>Pmax(W)</th>
<th>Cost (US$)</th>
<th>Area (m2)</th>
<th>P*</th>
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<th></th>
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<th>C*</th>
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<td>0.025939</td>
<td>0.001307</td>
<td>0.01184</td>
<td>3.540554191</td>
</tr>
</tbody>
</table>

63
To compare how cost-effective the individual micromorph cells in the market are relative to each, Figure 33 graphs the relative maximal power versus product of relative area and relative cost for micromorph modules from different companies. With the exception of Sharp, all other companies are near or above the reference line. Sharp was one of first companies which introduced the micromorph into the market. This accounts for the lower performance and higher cost as compared with more recent releases. The market has not equilibrated for this technology. It can only be concluded that this technology is cost-effective. Performance, cost, and market players can and will change dramatically over the next few years.

Using Figure 33 and Equation 4, one can also calculate what should be the cost of future micromorph cells in respect to their improved power and area. To test the accuracy and reliability of this method, the deviation between the calculated and actual price are compared using equation 5. Again, cost deviation is more pronounced for older releases of the micromorph cell than newer ones. Also, at the time this thesis was written, micromorph cells were just beginning to be introduced in the market. Thus competition was not strong, and higher prices were advertised in response to generated hype from new technology releases. As more companies invest in this technology, the market will drive competition up and prices down both nationally and internationally. As micromorph cells become more streamlined in the market, the cost can be accurately modeled with this method. The pattern and trend of micromorph cells are thus following in suit with its other thin film technology counterparts.
Figure 33 Relative maximal power versus product of relative area and relative cost of micromorph modules

Table 4 Cost-effectiveness and power generating factor G of different types of micromorph solar modules calculated with Equation 3.

<table>
<thead>
<tr>
<th>Company</th>
<th>Model</th>
<th>Pmax,mod (W)</th>
<th>Cmod (USD)</th>
<th>Amod (m2)</th>
</tr>
</thead>
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<td>M140000</td>
<td>140</td>
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\[
C_{mod, \text{cal}} = \left( \frac{P_{max, \text{mod}}}{G \cdot P_{max, \text{sys}}} \right)^{3/2} \cdot \left( \frac{A_{sys}}{A_{mod}} \right) \cdot C_{sys} \quad (4)
\]

\[
\text{rel.dev.} = \frac{C_{mod, \text{list}} - C_{mod, \text{cal}}}{C_{mod, \text{cal}}} \quad (5)
\]

Table 5: Comparison between the calculated price \( C_{mod, \text{cal}} \) and the actual price \( C_{mod, \text{list}} \) of micromorph modules.
Chapter 8 – Conclusions

First and second generation solar cells are limited in how cost effective and efficient they can be. It is very unlikely that these technologies could be a prime solution to meet the terawatt challenge of this century. Third generation solar cells such as tandems show more promise as higher efficiencies have been achieved time and time again. The costs for the materials and equipment for these technologies are very high because the demand is not high. As cells like the micromorph become more mainstream, this is likely to change.

The micromorph tandem cell serves as a good bridge between second generation thin film solar cells and novel high-efficiency third generation solar cells. It promises higher efficiency at a competitive price. As cells like the micromorph and other similar technologies become more readily available in the market, there are good possibilities that they will slowly replace prior ones. The bringing of high efficiency photovoltaics from extraterrestrial applications to terrestrial ones has thus begun to be realized.
References


## Appendix 1 Cost Model

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