Arnold Schwarzenegger
Governor

HIGH-VOLUME MANUFACTURING FOR LOW-COST, FLEXIBLE SOLAR CELL

INDEPENDENT ASSESSMENT AND FINAL EISG REPORT

Prepared For:
California Energy Commission
Public Interest Energy Research Program

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ENERGY INNOVATIONS SMALL GRANT (EISG) PROGRAM

INDEPENDENT ASSESSMENT REPORT (IAR)

HIGH-VOLUME MANUFACTURING FOR

LOW-COST, FLEXIBLE SOLAR CELL

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PREFACE

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable and reliable energy services and products to the marketplace. The PIER Program, managed by the California Energy Commission (Commission), annually awards up to $62 million of which 5% is allocated to the Energy Innovation Small Grant (EISG) Program. The EISG Program is administered by the San Diego State University Foundation through the California State University, which is under contract to the Commission.

The EISG Program conducts up to four solicitations a year and awards grants for promising proof-of-concept energy research.

PIER funding efforts are focused on the following seven RD&D program areas:

- Residential and Commercial Building End-Use Energy Efficiency
- Energy Innovations Small Grant Program
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally-Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies

The EISG Program Administrator is required by contract to generate and deliver to the Commission an Independent Assessment Report (IAR) on all completed grant projects. The purpose of the IAR is to provide a concise summary and independent assessment of the grant project in order to provide the Commission and the general public with information that would assist in making follow-on funding decisions. The IAR is organized into the following sections:

- Introduction
- Objectives
- Outcomes (relative to objectives)
- Conclusions
- Recommendations
- Benefits to California
- Overall Technology Assessment
- Appendices
  - Appendix A: Final Report (under separate cover)
  - Appendix B: Awardee Rebuttal to Independent Assessment (awardee option)

For more information on the EISG Program or to download a copy of the IAR, please visit the EISG program page on the Commission's Web site at:
http://www.energy.ca.gov/research/innovations

or contact the EISG Program Administrator at (619) 594-1049, or email at:
eisgp@energy.state.ca.us.

For more information on the overall PIER Program, please visit the Commission's Web site at http://www.energy.ca.gov/research/index.html.

High-Volume Manufacturing For Low-Cost, Flexible Solar Cell

EISG Grant # 01-18

Awardee:	InterPhases Research
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Introduction

Photovoltaic (PV) systems supply secure, reliable, and clean electric power by converting solar energy directly into electricity. However, the installed costs for photovoltaic systems are as high as $10,000/kW, which is too expensive to compete successfully in the current electricity market. This project proposed to develop a new, thin-film PV technology that could effectively push costs low enough to be competitive at current electricity prices. This technology is based on an innovative, flexible-cell configuration on flexible foil and a new high-volume fabrication process that can simplify processing, reduce number of cell components, and lower manufacturing costs.

The project offers special benefits to California, where solar energy is abundant and environmental concerns and the price of electricity are higher than the national average. Its success could propel PV into California's energy market by reducing costs from the current on-grid PV price of 25¢/kWh to ~5¢/kWh within a 4-year span. By reducing CO_2 emissions and contributing to clean air and ground water, PV energy will improve health, safety, and the quality of life.

This project undertook the development of an innovative, lightweight, flexible photovoltaic technology based on a 3-layer *n*-CIS film deposit on a compatible substrate. The eventual success of this technology requires several scientific advances:

- An electrodeposition method for the new absorber layer on a compatible substrate.
- An electrodeposition method for a new window layer.
- A sequence of electrodeposition and annealing steps for the *n*-CIS device.

Figure 1 illustrates the new photovoltaic cell configuration.

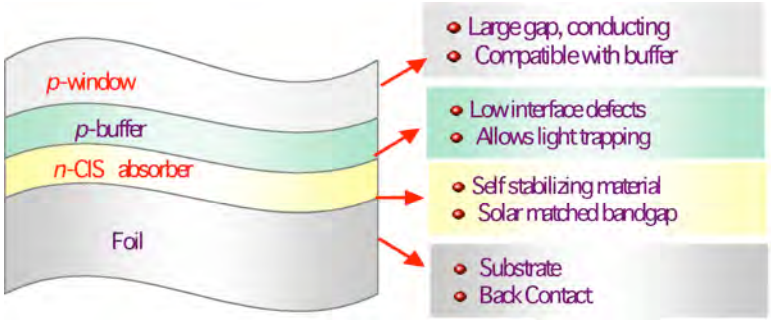

Figure 1 - *n*-CIS PV Cell Configuration

Objectives

The goal of this project was to determine the feasibility of an innovative, lightweight flexible photovoltaic technology based on n-copper indium diselenide (n-CIS) film, with only 3 layers on a metal foil and a new 4-step manufacturing approach, using roll-to-roll electroplating. The researcher established the following project objectives:

1. Develop an electrodeposition method for the new absorber layer on a compatible substrate.
2. Develop an electrodeposition method for a new window layer.
3. Construct an n/p device.
4. Validate PV response of the device.
5. Demonstrate the potential reductions in cost.

Outcomes

1. The researcher determined that, under specific conditions, high-quality n-CIS films could be electrodeposited on two types of flexible, compatible substrates. Non-vacuum, low-temperature heat treatment was able to transform the CIS films into electronic-grade absorbers.
2. The project developed new methods for creating n/p heterojunction and depositing a wide-gap p-window layer.
3. The first photoactive *n*-CIS solid-state device was constructed.
4. The researcher measured photovoltages between 170 and 200 mV with low intensity, white-light illumination.
5. The researcher's cost estimate for manufacturing *n*-CIS flexible cells of 23-35¢/Wp is nearly 10 times lower than the current costs of $3/Wp ("Wp" is the photovoltaic cell peak power output at Standard Test Conditions).

Conclusions

The data provide evidence of initial steps achieved to reduce the cost of photovoltaic cells. While suggestive, the feasibility of the concept remains unproven, particularly in relation to cell performance and any resulting economies.

1. The results from this project, as reported, are very encouraging in demonstrating successfully the feasibility of a low-cost manufacturing process based on scalable electrodeposition methods for producing n/p or n/p/p junction and device structures.
2. The development of copper iodide-based, high bandgap, p-type window layers is particularly important to complement the n-copper indium diselenide absorber.
3. The ability to deposit *n*-CIS thin film on flexible foil substrates is significant, not only for high-volume manufacturing, but also for building-integrated photovoltaics (BIPV). However, the results lack analytical and quantitative characterizations of the claimed success.

4. The researcher did not report current-voltage curves or cell-efficiency data to illustrate performance of their devices. The commercial utility of "photoactive" films will depend on their conversion into good cell efficiency.
5. It is unclear why the researcher assumed 10% to 15% efficiency to calculate the levelized electric production cost of 3-5¢/kWh. Cell devices made from the electrodeposited n-CIS polycrystalline thin films do not easily produce 10% efficiency because of impurities, defects, grain size, and boundary effects.

Recommendations

Performance and physical evaluation of the *n*-CIS cells produced in this project must be completed to improve the manufacturing processes and maximize the commercial viability of the technology.

The following questions should be considered when determining additional work in this area:

1. What are the physical and photoelectric characteristics of the cells produced with this process? The answer to this question should include results from comparative testing of the substrate and the back contact materials to determine effects of temperature cycling, mechanical stress, adhesion, and electrical properties of the substrate/contact and substrate/n-CIS interfaces.
2. How can the cell structure be changed to raise its conversion efficiency? The answer should consider improvement of the junction quality by optimization of the CIS surface conversion step. Optimize device efficiency by improving morphology, increasing conductivity, and reducing thickness of the window layer.
3. How can the manufacturing process be modified to achieve improved device structure? Some example answers include fine-tuning the process parameters for CIS film deposition and the heat-treatment step to improve electro-optical properties. In addition, verify process repeatability for construction of high-efficiency devices.
4. What should further experimentation produce to accurately forecast levelized electric production cost? To answer this, the PI must reasonably predict both cell efficiency and cell life to calculate electric production cost.

Benefits to California

Public benefits derived from PIER research and development are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system.
- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary benefit to the ratepayer of this research would be reduced environmental impacts of the California electricity supply and transmission and distribution system. If the technology evaluated in this project were proven and developed into a commercial product, it would make solar power generation cost competitive with today's grid power. This would reduce the consumption of fossil fuels in conventional power plants and their environmental impact. Since

the technology is still far from commercialization, it is difficult to estimate when California ratepayers would realize these benefits.

Overall Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researcher's overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

Marketing/Connection to the Market

No paper has been published, but the PI has indicated that a paper may be published after the patent has been received. Currently the PI is discussing the results of this project with photovoltaic cell manufacturers.

Engineering/Technical

This project successfully produced a photoactive n-CIS cell that was manufactured using relatively inexpensive deposition methods. The simple phase conversion procedure for producing n/p or n/p/p junction and device structure is very attractive for achieving low-cost high volume production. The development of copper iodide-based, high bandgap, p-type window layers is particularly important to complement the n-copper indium diselenide absorber. This technology, indeed, does have potential to significantly impact the photovoltaics market, if it can achieve cell conversion efficiencies of 7% to 10%. Further research should aim to maximize cell-conversion efficiency.

Legal/Contractual

The researcher has filed for a US patent, as well as a provisional European patent.

Environmental, Safety, Risk Assessments/ Quality Plans

Formal quality planning would be premature for a project in this early stage of research. Quality Plans include Reliability Analysis, Failure Mode Analysis, Manufacturability, Cost and Maintainability Analyses, Hazard Analysis, Coordinated Test Plan, and Product Safety and Environmental**.**

Production Readiness/Commercialization

This project is in the early stages of research and is not yet ready for commercialization.

Appendix A: Research Final Report (under separate cover)

Appendix B: Awardee Rebuttal to Independent Assessment (none submitted).

ENERGY INNOVATIONS SMALL GRANT (EISG) PROGRAM

EISG FINAL REPORT

HIGH-VOLUME MANUFACTURING FOR LOW-COST, FLEXIBLE SOLAR CELL

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Inquires related to this final report should be directed to the Awardee (see contact information on cover page) or the EISG Program Administrator at (619) 594-1049 or email eisgp@energy.state.ca.us.

Acknowledgement Page

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Abstract

The project develops a new solar cell configuration that could potentially compete with conventional fuels. It features an innovative lightweight flexible photovoltaic technology based on *n*-copper indium diselenide (*n*-CIS) film, with only 3 layers on a metal foil and an ingenious 4-step manufacturing approach, using roll-to-roll electroplating. Cost reduction is achieved with inexpensive, stable, non-toxic cell components and simple, high-throughput, low-temperature electrodeposition. The research identified and synthesized compatible materials for the absorber, buffer and window layers. It demonstrated process feasibility and proof-of-concept with a functional *n*-CIS thin-film device. Breakthroughs in device design, characterization and fabrication provide a valid measure of the project success and lay a strong foundation for the next steps, prototype and process development. The distinctly different *n*-CIS solar cell offers the same potential for 20% efficiency, radiation hardness and high reliability as the state-of-the-art *p*-$CuInGaSe_2$ cell, but avoids its complex, hazardous and expensive fabrication. Fewer processing steps and materials lead to an ultra-simple, low-cost *n*-CIS solar cell that can be readily scaled for mass production. The same laboratory-scale fabrication equipment can be used for a large manufacturing plant. Compelling cost and scalability benefits have sparked interest from potential manufacturers. Technology commercialization can deliver the promise of photovoltaic energy to California and its electricity consumer. It can avert future power crises, reduce global warming and make a tangible contribution to the California's energy supply, environment and social welfare.

Key Words:

Electrosynthesis, $CuInSe_2$, photovoltaic, flexible solar cell, roll-to-roll electrodeposition, *p*-type window, $CuInGaSe_2$, solar electricity, electroplating, non-energy benefits.

Executive Summary

1. Introduction

Affordable photovoltaic (PV) electricity generation promises multiple benefits for California. Electricity consumers could readily tap into a free, unlimited, non-polluting solar energy if PV modules could be manufactured in high volume at a low cost. At 30-40 ¢/ KWh, PV electricity is too expensive to compete with the current 6¢/KWh electricity market. This project aims to provide a new flexible PV technology based on *n*-copper indium selenide (*n*-CIS) thin-film that could effectively compete with the electricity price, without a need for state subsidies.

InterPhases conceived a new *n*-CIS device configuration, comprising efficient, stable and compatible components. It uses fewer materials and a simpler, safer, cheaper manufacturing approach than the leading thin-film PV technology that is based on positively doped copper indium gallium sulfide selenide (*p*-CIGS). Its structure is much more adaptable to a flexible configuration and roll-to-roll electrodeposition than the *p*-CIGS device. The *n*-CIS device is designed for easy mass-production and for integration into existing buildings. It can provide non-energy benefits in addition to its energy value. It is also totally cadmium free. These special aspects of *n*-CIS and InterPhases' core processing technologies are aimed at attaining a 5¢/KWh price goal for PV electricity. Under best circumstances, this technology could be implemented within 4 years. It could meet California's electricity needs cost-effectively without damage to the environment.

2. Project Objectives

The goal of this project was to prove the feasibility of a new flexible solar cell configuration and a new electrochemical manufacturing method that can be inexpensively scaled for high volume production. This new PV cell design aims to reduce PV module manufacturing cost by 75% from the current $3/Wp [1]. Primary technical goals for EISG Stage III were to identify compatible components for the new PV cell and develop processing technology that includes:

- Electrodeposition method for the new absorber layer on a compatible substrate.
- Electrodeposition method for a new window layer.
- n/p device construction.
- Performance validation via PV response of the device.
- Demonstration of the cost reduction potential.

3. Project Outcomes include:

- Under specific conditions, high quality *n*-CIS films may be electrodeposited on 2 alternate flexible compatible substrates. Non-vacuum, low temperature heat treatment transforms the CIS films into electronic grade absorbers.
- New methods for creating *n/p* heterojunction and depositing a wide-gap *p*-window layer.
- First functional *n*-CIS solid-state device, which provides proof-of-concept for the new device and a valid measure of the project success.

- Cost estimate for manufacturing *n*-CIS flexible cells of 23-35¢/Wp is nearly10 times lower than the current costs ($3/Wp). Translated to 3-5¢/KWh, it shows that PV could compete with conventional electricity and still rake up over 56% profit for the manufacturer.
- This project has attracted commercial interest from large corporations in the mining, energy and electronic industries.

4. Conclusions

- *n*-CIS PV cell can be made of a variety of inexpensive substrates without additional barrier layers, unlike the *p*-CIGS. This feature will lower manufacturing cost and module weight.
- Producing device quality *n*-CIS films via electrodeposition and anneal steps is a major milestone towards attaining a PV technology that can realistically compete with fossil fuel prices.
- Two easy electrochemical steps convert the n-CIS layer into an efficient n/p device. Successful deposition of *n*-CIS absorber, buffer and window layer on a metal foil validates a totally new flexible PV cell configuration. Its PV output confirms the viability of the *n*-CIS PV technology.
- Project results lead to a simple roll-to-roll electrodeposition method with only 4 simple steps, on continuous metal tape: (1) CIS electrodeposition, (2) thermal anneal, (3) surface conversion, and (4) window layer electrodeposition.
- The method offers high-throughput, low-cost and environmental safety and practicality for mass production of PV modules. The same laboratory-scale fabrication equipment can be used for a megawatt-scale manufacturing plant.
- Fewer components and fewer processing steps than the *p*-CIGS can lead to an ultra-simple *n*-CIS PV technology with optimum PV properties and lowest fabrication cost.
- Compelling cost benefits can make PV accessible to the electricity consumer, open up new commercial markets and eliminate the need for government subsidies.
- The *n*-CIS PV technology affords a lucrative business opportunity for its investors, with a profit margin of 48-59 ¢/W.

5. Recommendations

This EISG project generated new breakthroughs in device design, characterization and fabrication that laid a strong foundation for the next steps, which should include:

Recommendation 1: Absorber layer optimization

- Comparative testing of the substrate/contact and substrate/*n*-CIS interfaces to determine effects of temperature cycling, mechanical stress, adhesion and electrical properties.
- Fine-tuning the process parameters for CIS film deposition and annealing to improve electro-optical properties.

Recommendation 2: Prototype development.

- Improve the junction quality by optimization buffer and window layer properties.
- Optimize front current collection with higher doping, transparent contact or grid.
- Verify process repeatability for construction of high efficiency devices.
- Demonstrate an efficient prototype and initiate licensing negotiations with industrial partners

Recommendation 3: Pilot development.

- Design a pilot-scale roll-to-roll deposition system using commercial plating equipment for inexpensive, high throughput manufacturing of continuous CIS device rolls.
- Derive cost projection, financial plans for pilot and commercial production scale. Compare costs of competing technologies, e.g., *p*-CIGS.
- Link with potential manufacturers to commercialize the PV technology.

6. Public Benefits to California

The EISG research results will lead to an affordable, non-polluting, renewable n-CIS PV technology to meet the growing energy demand in California. The new *n*-CIS PV technology will be suitable for high volume production of cadmium-free flexible lightweight PV devices. Combining the new cell configuration and the new fabrication methods will drive down PV costs. The dual impact of flexible foil based PV modules will boost the market competitiveness of PV energy. By integrating into an existing structure or environment, the PV modules can provide energy and non-energy benefits, thus addressing new niche markets.

The project offers special benefits to California where solar energy availability, environmental concern and the electricity price are higher than national average. Its success can lead to cost reduction from the current on-grid PV price of 25¢/kWh to ~5¢/kWh within a 4 year span. These features could propel PV into California's energy market. PV energy in turn, will reduce CO_2 emissions, contribute to clean air and ground water and hence impact health, safety and quality of life.

The *n*-CIS PV technology meets cost, volume, weight, fragility and flexibility requirements for a wide spectrum of commercial markets:

- Off-grid and grid-tied residential and commercial electricity
- Power generation systems, central power plants
- Non-utility – building integration, electric vehicles recreational power
- Satellite, spacecraft.

Its commercialization will make a tangible contribution to California's energy supply, environment and social welfare. It will create new revenues and new jobs. It will deliver the promise of PV power and also boost the state's 'green' image. Its implementation will provide a timely, expedient solution of PV electricity to the California ratepayer, avert future power crises, reduce global warming and generate profits for the manufacturer.

1. Introduction

This project addresses California's needs for an affordable, non-polluting, secure energy resource. Photovoltaic (PV) electricity generation could meet California's rising need for the next decades if PV modules can be manufactured on megawatt scale at a low cost. At 30-40¢/KWh, the PV generated electricity is too expensive to compete with the current electricity market. This project presents a cutting edge thin-film PV technology that could effectively compete with current electricity prices, without the need for state subsidies. This technology is based on an innovative flexible cell configuration with a *n*-copper indium diselenide (*n*-CIS) absorber on flexible foil and a new high volume fabrication process that can

- Simplify processing
- Reduce number of cell components
- Lower manufacturing costs.

The project addresses the 'Renewable Generation' area of the PIER program. The research specifically targets the PIER research Issues 3 and 5 in the Renewables area. It focuses on providing an economically competitive PV technology with energy and non-energy benefits, by:

- Drastically lowering today's capital and O&M costs for PV module manufacturing by nearly an order of magnitude and
- Opening up new niche markets for building integrated PV (BIPV) to boost the marketability of PV energy.

Manufacturing flexible cells on continuous rolls presents many advantages, e.g., lower packaging costs [2]. Flexible cell strips can be used directly into building systems without requiring module fabrication. Uni-Solar has been producing amorphous silicon based flexible cells for several years, mainly intended for roofing systems or building facades. But amorphous silicon cannot match the performance of CIS PV.

In 1999, *Shell Solar* introduced commercial CIS modules, based on *p*-copper indium gallium sulfide selenide (*p*-CIGS) absorbers on rigid glass module. Nearly every CIS company is now trying to make flexible CIGS cells due to their lower cost/W and cost/area potential. Unfortunately, the fabrication of flexible *p*-CIGS is much more complicated, hazardous and expensive, costing ~ $\$26/m^2$ for absorber layer deposition alone [3]. *p*-CIGS needs special expensive substrates, e.g. Mo foil or sputtered Mo with several diffusion barriers, all too expensive for terrestrial use.

The *n*-CIS innovation is designed to eliminate many *p*-CIGS issues, such as:

- Complex graded deposition
- Expensive or toxic materials, Ga, Mo, Na, S, Cd
- Hazardous cyanide etch, CdS deposition and waste disposal.

The PV performance potential of the *n*-CIS solar cell was demonstrated by our early results of 12% efficiency & stability on crystalline substrates, similar to the *p*-CIS crystalline cell [4,5]. When optimized, the *n*-CIS thin-film cell is projected to match the optimum properties of *p*-CIGS at ~10 times lower-cost. It could potentially provide high (20%) efficiency, long-term reliability, radiation hardness and >1000 w/kg specific power rating.

However, there is no existing *n*-CIS device technology, nor is there methodology for depositing the *n*-CIS or compatible window layers. This EISG grant provided the first opportunity to develop the *n*-CIS cell, an InterPhases' invention. Realizing that developing a new PV technology is a major undertaking, we are seeking assistance of large corporations and National Laboratories. With their assistance and adequate funding, we can transition this exciting new PV technology into a useful and affordable energy commodity for California.

This report summarizes the advances made with the EISG grant. It is organized to:

- Present the objectives of our research.
- Outline the project approach and the principle tasks.
- Summarize the outcomes.
- List the conclusions.
- Present recommendations for future work.

2. Project Objectives

The goal of this project was to prove the feasibility of an innovative flexible PV cell configuration and a new electrochemical method for high volume manufacturing. The project aims to provide a simpler PV technology with non-energy benefits in order to facilitate the PV energy market competitiveness. The following technical objectives were planned, to investigate the feasibility of the thin-film flexible PV technology:

Objective 1. Identify components and processing steps for a cost effective *n*-CIS PV cell including:

- A flexible substrate/ohmic contact suitable for an *n*-CIS absorber.
- Optimal process parameters/steps for *n*-CIS layer electrodeposition.
- An annealing step to effectively improve the CIS layer properties.

Objective 2. Determine the viability of a new cadmium-free thin-film solar cell configuration for inexpensive mass production, via:

- Construction of photoactive n/p heterojunctions.
- Fabrication and analysis of *n*-CIS PV output for solid-state devices.

Objective 3. Determine the market potential of the new PV technology:

- Demonstrate potential for 75% cost reduction for module manufacturing from the current $3/Wp [1].
- Identify industrial partners and/or an investor to develop and commercialize the *n*-CIS technology.

Demonstration of photovoltaic response for this entirely new device configuration will provide proof-of-concept and a valid measure of the project success. Project results will provide the groundwork for Stage IV to optimize performance and develop the technology for niche markets, e.g. BIPV.

3. Project Approach

The *n*-CIS cell comprises a new device structure with efficient, stable, compatible components, as illustrated in Fig. 1. The project focused on developing inexpensive electrochemical methods for depositing of the device layers, in order to reach the proposed cost and volume goals. Project Tasks performed were:

Task Ia: Identify a suitable flexible substrate for the electrodeposition of *n*-CIS absorber

A variety of flexible substrates including steel, Mo and Cu foils, as well as SnO_2 or Mo coated rigid glass substrates were investigated for depositing the *n*-CIS layer and fabricating the cell. The films were analyzed for adhesion, uniformity, composition and morphology.

Task 1b. Devising an electrodeposition method for the *n*-CIS absorber layer

This task was the major focus of this project. New procedures were investigated for the synthesis of *n*-type CIS. *n*-type conductivity was induced by increasing the In concentration in the films. The research focused on identifying the optimum parameters for electrodeposition of CIS absorber with desirable composition electronic quality and *n*-type conductivity. This task investigated various electrolyte compositions, pH, systems, deposition sequences and other conditions to produce smooth photoactive *n*-CIS films. Electrolyte systems are listed in Appendix I. Salts of Cu, In and SeO_2 were added to the electrolytes in various ratios. Other experimental conditions for CIS electrodeposition included:

Pulsed potentials: to eliminate the unwanted secondary phases such as Se, Cu_xSe and thus improve the electronic properties.

Sequential Deposition using different combinations of materials to produce CIS films, as listed in Appendix I.

The electrodeposited CIS films were characterized with:

- Photoelectrochemical techniques during deposition to optimize their electronic and material properties and also to monitor n/p junction formation. Monitoring the photocurrent *in-situ*

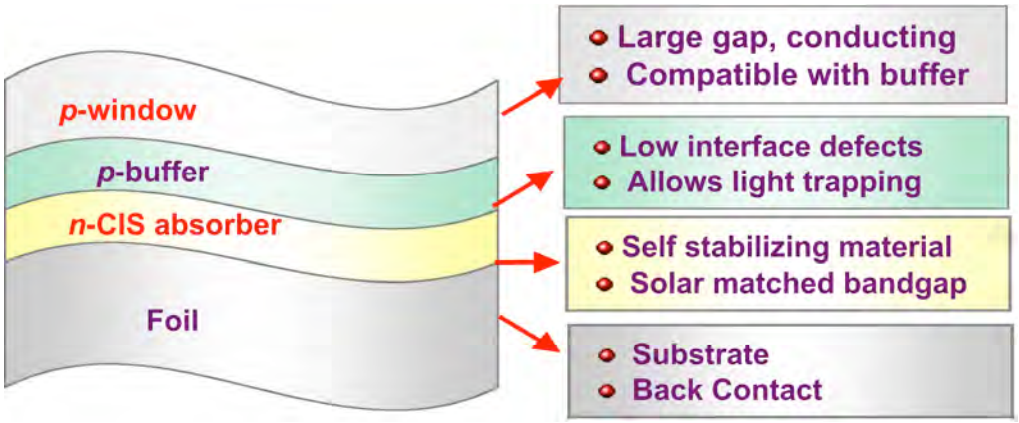

Figure 1. *n*-CIS PV cell configuration and components

during the deposition assured the formation of photoactive *n*-type CIS films.

- Anodic stripping voltammetry for composition analysis.
- Electron microprobe analysis (EPMA), X-ray fluorescence (XRF), X-ray diffraction (XRD) and scanning electron microscopy (SEM) for thickness and atomic % composition and microstructure.

Task 1c: Selecting and optimizing an annealing step

Annealing steps were used during different stages of film formation. The electrodeposited films were usually annealed at temperatures from 100- 500°C under Se vapor pressure to improve crystallinity and the electronic properties. Different annealing steps were used for one-step and sequential deposited films, see Appendix I.

Task 2a. Constructing *n*-CIS/*p*-type heterojunction partner

Two types junctions were investigated: *n*-CIS/*p*-window or *n*-CIS/*p*-buffer/*p*-window. The *p*-buffer and window layers were constructed using Interphases' proprietary electrochemical technologies. The photocurrent was monitored during the *p*-layer deposition to assess the quality of the junction and the absorber layer.

Task 2b. Fabricating *n*-CIS based devices

Devices were assembled in several different configurations comprising: a substrate/ohmic contact, *n*-CIS absorber, p-buffer/window and TCO layers [Appendix I]. The solid-state devices were tested under illumination using a probe wire or grid, in contact with the outer window layer.

Task 2c. Estimating Manufacturing Cost

This task was not included in the original proposal. Cost estimation is based upon published data for electrodeposition [3].

4. Project Outcomes

Key Outcomes of tasks 1 and 2 are summarized below:

Outcome 1:

a. Two flexible substrates, steel and Mo foils, were suitable for the electrodeposition of *n*-CIS absorber.

b. Prefered sequences of electrodeposition steps and effective deposition parameters were identified for electrochemically making dense, stoichiometric, In rich, photoactive *n*-CIS absorber films on metal foil.

c. Optimum temperature and other annealing conditions were identified to improve the properties of electrodeposited CIS films.

Outcome 2:

a. A new method was developed for electrodeposition of a wide gap *p*-type window layer. *n*/*p*/*p* heterojunctions were constructed and characterized.

b. A functional photoactive solid-state *n*-CIS/*p*-buffer/*p*-window device was fabricated and evaluated.

Outcome 3:

a. Manufacturing cost for flexible *n*-CIS cells is estimated at 21-31¢/Wp. These costs, translated to 3-5¢/KWh, allow PV to compete with conventional electricity.

b. Potential manufacturing partners from large corporations in the energy, mining and electronic industries were identified.

4.1 Results in Support of Outcome 1-3

Outcome 1 was achieved through detailed investigations of

a. Reaction mechanisms for Cu_xSe, In_2Se_3 and CIS formation and

b. Relationships between the deposition conditions and the film properties. The CIS film properties vary with the solution composition, pH, temperature, deposition potential, and deposition sequences as outlined in Appendix I.

Outcome 2 was based on comparing the photocurrent and photovoltage characteristics of the heterojunctions and devices. Electrochemically constructed buffer layer led to higher PV output. *In-situ* photocurrent measurements during the construction of the n/p heterostructure allowed optimizing the *p*-layer thickness and ascertaining device properties. Photovoltages between 170-200mV were measured with low intensity white light illumination. Device performance assessment with calibrated solar simulator is underway for various device configurations.

Outcome 3 is based on the cost estimate in Table I, which assumes a deposition rate of 0.1

Table I. Module manufacturing cost estimate

#	Component	$/m^2
1	Capital cost	2.0
2	Maintenance cost	0.6
3	Material cost	15.0
4	Utilities	2.0
5	Labor	8.0
6	R&D	1.0
7	Warranty	1.0
8	Rent & overhead	5.0
9	Total	34.6

#1. Capital cost of $10M for 100 MW per year production plant

#2. Maintenance cost, assumed at 4% of capital cost, depreciated over 7 year period,

#3. Material costs of $3/m^2 for substrate, ~$2/m^2 for 2 micron thick film of Cu-In-Se, ~$10/m^2 for encapsulation and modularization.

Table II. PV electricity cost projections

#	PV module efficiency	10%	15%
9	Module manufacturing cost	35¢/W	23¢/W
10	Module selling price	80¢/W	80¢/W
11	Profit margin	56%	71%
12	On-grid installed system cost	1.3 $/W	1.3 $/W
13	Electricity cost	5¢/kWh	5¢/kWh

Cost projections are derived from

#9. Total manufacturing costs based on 10% and 15% efficient *n*-CIS modules.

#10. Arbitrary value that can generate profit and compete with electricity price.

#11. Higher efficiencies can either increase profits or further reduce electricity cost.

#12. System cost = 40% module cost [6].

#13. Electricity generation of 1600 kWh/year per installed kW (~4.38 pk hrs/day) [7] and 20 years depreciation of PV system investment.

micron/min and CIS layer thickness for 2 microns. Other assumptions listed below for the values in Table II are based on the cost estimates for BP Solar's electrodeposition pilot line [3].

Item # 11 in Table II shows that InterPhases' *n*-CIS PV technology can offer a lucrative business opportunity for an investor or manufacturer. This technology has attracted commercial interest from large corporations in the mining, energy and electronic industries and from investment companies. The key players see a 'fitting business opportunity" for their organization with a markedly different PV technology, with obvious profit potential and free from patent infringement and other encumbrances associated with the current *p*-CIGS PV.

5. Conclusions

Conclusion 1:

a. The *n*-CIS absorber may be electrodeposited on a variety of substrates unlike the *p*-CIGS, which is restricted to a Mo contact. This result has serious implications regarding the manufacturing cost, compatibility with temperature-sensitive polymer and thermal stress issues. The latter two issues are important for space use.

b. Deposition of smooth, dense, stoichiometric, photoactive *n*-CIS films by electrodeposition is a major milestone leading to a PV technology that can realistically compete with fossil prices in the near term.

c. A simple, low temperature anneal to transform the CIS films into high performance absorbers obviates the need for any high temperature vacuum steps.

Conclusion 2:

a. An all electrochemically created n/p/p heterojunction under equilibrium conditions with similar materials produces an effective PV device that avoids future stability problems due to inter-diffusion (Appendix I).

b. The successful deposition of *n*-CIS, its surface conversion to a buffer layer and electrodeposition of a compatible window layer validates a totally new foil/*n*-CIS/*p*-buffer/*p*-window cell configuration. PV properties of the solid-state PV device confirm the viability of the *n*-CIS technology for low cost mass production of PV modules.

c. Compelling cost benefits can ultimately make PV accessible to the electricity consumer, generate huge profits for the investor, open up new commercial markets and eliminate the need for government subsidies.

Conclusion 3:

Figure 2. Sequential steps for roll-to-roll fabrication of *n*-CIS PV cell

Project results confirm the viability of a new thin-film PV cell configuration. Further, they lead to a simple manufacturing method with only 4 simple steps, on continuous metal tape:

1. Co-electrodeposit 2 micron thick CIS layer on metal foil.
2. Brief anneal under Se atmosphere.
3. Convert the surface layer to *p*-type buffer.
4. Electrodeposit a *p*-type window layer to complete the cell.

This approach combines the InterPhases core technologies with roll-to-roll electrochemical processes. The method is inherently high-throughput, low-cost and environmentally benign. The same laboratory-scale fabrication equipment can be used for a MW-scale manufacturing plant. The *n*-CIS technology is much more suitable to a flexible configuration than the *p*-CIGS. It is also totally cadmium free.

Fewer components and fewer processing steps could lead to an ultra-simple *n*-CIS PV technology with optimum PV properties and lowest fabrication cost.

Recommendations

This EISG project generated new breakthroughs in device design, characterization and fabrication that laid a strong foundation for the next steps. The recommendations for the next stage of this project are as follows:

Recommendation 1: Absorber layer optimization

- Comparative testing of the substrate and the back contact materials to determine effects of temperature cycling, mechanical stress, adhesion and electrical properties of the substrate/contact and substrate/*n*-CIS interfaces.
- Fine-tuning the process parameters for CIS film deposition and the heat treatment step to improve electro-optical properties.

Recommendation 2: Prototype development.

- Improve the junction quality by optimization of the CIS surface conversion step. Optimize device efficiency by improving morphology, increasing conductivity and reducing thickness of the widow layer.
- Improve conductivity of window layer by doping, transparent conducting oxide deposition or using a metallization grid.
- Verify process repeatability for construction of high efficiency devices.
- Demonstrate an efficient prototype device to potential manufacturer; initiate the licensing negotiations with industrial partners.

Recommendation 3: Pilot development.

- Design a pilot-scale roll-to-roll system for manufacturing continuous strips of PV devices. Adapt commercial roll-to-roll electroplating system for inexpensive, user-friendly, environmentally benign, high throughput CIS cell fabrication process.
- Derive cost projection and financial plans for pilot and commercial production on 100KW–100MW scale. Compare costs of competing technologies particularly the *p*-CIGS PV technology.
- Partner with a California based manufacturer to develop a pilot line production. Access their manufacturing facilities, technical expertise and marketing infrastructure to market the *n*-CIS PV products.

7. Public Benefits to California

The EISG research results will lead to an affordable, non-polluting, renewable *n*-CIS PV technology to meet the growing energy demand in California. The new *n*-CIS PV technology will be suitable for high volume production of cadmium-free, flexible lightweight PV devices. It will have dual impact on the market competitiveness of PV energy. The new flexible PV cell configuration can be integrated into an existing structure or environment. It will provide energy and non-energy benefits, thus addressing new niche markets. The new low-cost deposition method allows high volume production of Cd-free *n*-CIS PV devices. The cost benefits afforded by combining the new cell configuration and new fabrication methods will drive down PV costs.

The project offers special benefits to California where solar availability, environmental concern and the electricity price are higher than national average. Its success can lead to cost reduction from the current grid-connected PV price of 25¢/kWh to ~5¢/kWh (= conventional electricity price) within a 4 year span. These features could propel PV into California's energy market. PV energy in turn, will reduce CO_2 emissions, contribute to clean air and ground water and hence impact health, safety and quality of life.

The *n*-CIS PV technology meets low cost, high volume, flexibility portability, low weight and robustness requirements for a wide spectrum of commercial markets:

- Off-grid and grid-tied residential and commercial electricity
- Power generation systems, central power plants
- Non-utility – building integration, electric vehicles recreational power
- Satellite, spacecraft.

Its commercialization will make a tangible contribution to California's energy supply, environment and social welfare. It will create new revenues and new jobs. It will deliver the promise of PV power and also boost the state's 'green' image. Its implementation will provide a timely, expedient solution to:

- Provide PV electricity to consumer
- Generate profits for manufacturer
- Compete with fossil fuels
- Avert future power crises
- Reduce global warming.

References

1. R.L. Mitchell, C. Edwin Witt, R. King and D. Ruby, 29th IEEE PVSC proceedings, New Orleans, 2002
2. J. Penndorf, M. Winkler, O. Tober, D. Roser and K. Jacob*s, Solar Energy Materials and Cells,* 285, 1998.
3. K. Zweibel, "Issues in Thin Film Solar Cells Cost Reduction" www.nrel.gov/ncpv/documents/25249.html
4. S. Menezes, H.J. Lewerenz and K.J. Bachmann, *Natur*e, **305**, 316, 1983.
5. S. Menezes, *Appl. Phys. Lett,* **54**, 148, 1984.
6. Industry developed PV Roadmap, NREL www.nrel.gov/ncpv/documents/27061.html
7. R. Haas, "Market Deployment Strategies for PV Systems in the Built Environments", International Energy Agency, Report IEA PVPS T7-06: 2002, September, 2002
8. S. Menezes, *Appl. Phys. Lett,* **61,** 1564, 1992
9. B. Rever, *Renewable Energy World*, July-August, 177-189, 2001
10. P. Maycock, *Renewable Energy World*, July-August, 2002.
11. K. Zweibel, "Thin Films: Past Present and Future", Progress in Photovoltaics, Special Issue on Thin Films (1995).