CALIFORNIA
ENERGY
COMMISSION

ENERGY INNOVATIONS SMALL GRANT PROGRAM
Renewable Energy Technologies

Non-Vacuum Thin-Film Photovoltaics Processes

FEASIBILITY ANALYSIS

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LEGAL NOTICE

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 $2 million/year is allocated to the Energy Innovation Small Grant (EISG) Program for grants. The EISG Program is administered by the San Diego State University Foundation under contract to the California State University which is under contract to the Commission.

The EISG Program conducts four solicitations a year and awards grants up to $75,000 for promising proof-of-concept energy research.

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

- Residential and Commercial Building End-Use Energy Efficiency
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Environmentally-Preferred Advanced Generation
- Energy-Related Environmental Research
- Strategic Energy Research

The EISG Program Administrator is required by contract to generate and deliver to the Commission a Feasibility Analysis Report (FAR) on all completed grant projects. The purpose of the FAR is to provide a concise summary and independent assessment of the grant project using the Stages and Gates methodology in order to provide the Commission and the general public with information that would assist in making follow-on funding decisions (as presented in the Independent Assessment section).

The FAR is organized into the following sections:

- Executive Summary
- Stages and Gates Methodology
- Independent 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 FAR, 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 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.

Executive Summary

Introduction

Photovoltaics (PV) is a small but rapidly growing sector of California's electrical power generation capacity. For PV to significantly impact the State's economy and quality of life, the cost of PV-generated power must decrease. One of the most promising strategies for lowering PV costs is the use of technologies in which thin films of materials are deposited on inexpensive substrates like window glass. One of the most promising thin-film materials is copper indium gallium selenide ($CuIn_{1-x}Ga_xSe_2$ or CIGS).

Vacuum deposition processes have difficulty depositing CIGS films on large areas with the precision and control necessary to achieve low manufacturing costs. Non-vacuum deposition techniques provide a simple, low-cost alternative. Preparing fine powders of precursor materials, depositing thin layers of the particulate precursor materials, and sintering the layers into high-quality dense films can form high quality thin films.

Simple, non-vacuum techniques such as spraying and printing can deposit layers of particles on large-area substrates. Exploratory materials research using simple pneumatic spraying yielded cells with 11.7% efficiencies and monolithic multi-cell modules with 5% efficiencies. However, the sprayed layers were not very planar (i.e. flat) and were not very well packed (i.e. dense), and deposition rates and materials use efficiency were low. The aim of this EISG project was to deposit uniform, planar, well-packed layers with high materials use efficiency (MUE).

Objectives

The goal of this project was to determine the feasibility of depositing planar, well-packed particulate layers at high rates with high materials use efficiency (MUE) using non-vacuum techniques. The researcher established the following project objectives:

1. Identify high-MUE, non-vacuum deposition techniques and obtain suitable equipment for experimental evaluation
2. Develop high-MUE spraying techniques using CIGS precursor materials
3. Fabricate efficient thin-film PV devices using high-MUE techniques.

Outcomes

1. The researcher identified high-MUE, non-vacuum deposition techniques and procured suitable equipment for experimental evaluation.
   - Pneumatic spraying resulted in good atomization and excellent spray directionality, but materials use efficiency was low.
   - Without gas assistance, ultrasonic spraying resulted in good atomization, but the lack of carrier gas resulted in poor spray directionality.
   - Gas-assisted ultrasonic spraying yielded good atomization and good spray directionality.
   - Electrostatic spraying at 30 kV yielded relative materials use efficiency gains of 50-65%, but the deposition pattern was erratic and irreproducible.

- Casting and spray casting yielded high materials use efficiencies and well-packed, planar layers.

2. The researcher developed high-MUE deposition techniques for depositing layers of CIGS precursor particulate materials.
    - The morphology of particle layers deposited by pneumatic spraying varied with spraying conditions.
    - Layers sprayed in a manner that facilitated rapid local solvent evaporation exhibited microscopically planar surfaces.
    - Layers sprayed using slow solvent evaporation conditions exhibited non-planar surfaces characterized by a network of ridges and valleys.
    - Droplet drying mechanisms resulted in observed morphological variations.
    - Individual droplets of well-dispersed, well-suspended slurry dried to form rings of particles.
    - Networks of ridges and valleys evolved as particles were differentially collected into ridges by the interplay of ring overlap, particle bounce-back, high-angle over spray, and particle/gas lateral flow.
    - Spray conditions that facilitate rapid solvent drying mitigated local drying effects that cause non-planar layer morphologies; but such conditions reduced materials use efficiency.
    - Ultrasonic spraying minimized particle loss mechanisms and yielded higher materials use efficiencies; however, ultrasonic spray deposition resulted in non-planar layers characterized by ridges, valleys, and small agglomerates.
    - Spraying under conditions that mitigate in-flight droplet drying sharply reduced the density of small agglomerates; but slow-evaporation conditions aggravated the tendency to form a ridges and valleys topology.
    - Casting techniques, which use a continuous "wet film" of slurry rather than isolated droplets, circumvented the non-planar morphologies that result from cycles of wetting and drying.
    - The substrate-wide drying front inherent to solvent evaporation from continuous wet films minimized the formation of ridges and valleys.
3. The researcher fabricated thin-film PV devices using particulate precursor materials deposited using high-MUE techniques, achieving cell efficiencies of 9.4%.

Conclusions

1. The results demonstrate high-MUE deposition processes can yield PV devices with the efficiencies needed to fabricate commercially viable products.
2. Cost-effective formation of high-quality PV films using particle-based, non-vacuum processes requires the deposition of reasonably planar, well-packed layers of particulate precursor materials with high materials use efficiencies.

3. Non-vacuum spraying techniques provide the necessary combination of planar, well-packed layers and efficient materials use provided one mitigates nozzle-related agglomeration, avoids repeated wetting/drying that can cause non-planar morphologies, and facilitates particle rearrangement that can increase packing densities. The demonstration of efficient spray deposition of planar, well-packed layers lays the foundation for the fabrication of efficient, large-area, thin-film PV modules using non-vacuum processes.
4. Since the techniques developed in this project can yield higher particle packing densities in particulate precursor layers, improvements to final film quality can accrue from adjustments to the reactive sintering processes used to convert porous precursor layers into dense final films.

Benefits to California

If this line of research reaches a successful conclusion, California will benefit in several ways. Rooftops equipped with solar power systems provide customers the option of generating their own clean, quiet, reliable electricity. Solar power, with its ability to provide electricity at home or at a business site, can help offset the need to purchase electricity and increase consumer autonomy. PV technologies based on thin films can potentially deliver the end-user price reductions necessary to expand the use of PV significantly and aid California ratepayers in realizing a pollution-free, renewable energy option.

Recommendations

The techniques developed in this project yield efficient small-area solar cells. Further research is needed to test these techniques in the fabrication of larger-area, monolithically integrated, multi-cell modules suitable for commercial production. The next steps are:

- Investigate synergies that might arise from combining improved particle layer deposition techniques with improvements to the layer-to-film sintering processes
- Apply the high-MUE particulate layer deposition techniques to the fabrication of large-area, multi-cell modules.

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Stages and Gates Methodology

The California Energy Commission utilizes a stages and gates methodology for assessing a project's level of development and for making project management decisions. For research and development projects to be successful they need to address several key activities in a coordinated fashion as they progress through the various stages of development. The activities of the stages and gates process are typically tailored to fit a specific industry and in the case of PIER the activities were tailored to be appropriate for a publicly funded energy research and development program. In total there are seven types of activities that are tracked across eight stages of development as represented in the matrix below.

Development Stage/Activity Matrix

	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6	Stage 7	Stage 8
Activity 1								
Activity 2								
Activity 3								
Activity 4								
Activity 5								
Activity 6								
Activity 7								

A description the PIER Stages and Gates approach may be found under "Active Award Document Resources" at: http://www.energy.ca.gov/research/innovations and are summarized here.

As the matrix implies, as a project progresses through the stages of development, the work activities associated with each stage needs to be advanced in a coordinated fashion. The EISG program primarily targets projects that seek to complete Stage 3 activities with the highest priority given to establishing technical feasibility. Shaded cells in the matrix above require no activity, assuming prior stage activity has been completed. The development stages and development activities are identified below.

Development Stages:	Development Activities:
Stage 1: Idea Generation & Work Statement Development	Activity 1: Marketing / Connection to Market
Stage 2: Technical and Market Analysis	Activity 2: Engineering / Technical
Stage 3: Research & Bench Scale Testing	Activity 3: Legal / Contractual
Stage 4: Technology Development and Field Experiments	Activity 4: Environmental, Safety, and Other Risk Assessments / Quality Plans
Stage 5: Product Development and Field Testing	Activity 5: Strategic Planning / PIER Fit - Critical Path Analysis
Stage 6: Demonstration and Full-Scale Testing	Activity 6: Production Readiness / Commercialization
Stage 7: Market Transformation	Activity 7: Public Benefits / Cost
Stage 8: Commercialization	

Independent Assessment

For the research under evaluation, the Program Administrator assessed the level of development for each activity tracked by the Stages and Gates methodology. This assessment is summarized in the Development Assessment Matrix below. Shaded bars are used to represent the assessed level of development for each activity as related to the development stages. Our assessment is based entirely on the information provided in the course of this project, and the final report. Hence it is only accurate to the extent that all current and past work related to the development activities are reported.

Development Assessment Matrix

Stages / Activity	1 Idea Generation	2 Technical & Market Analysis	3 Research	4 Technology Develop-ment	5 Product Develop-ment	6 Demon-stration	7 Market Transfor-mation	8 Commer-cialization
Marketing								
Engineering / Technical								
Legal/ Contractual								
Risk Assess/ Quality Plans								
Strategic								
Production. Readiness/								
Public Benefits/ Cost								

The Program Administrator's assessment was based on the following supporting details:

Marketing/Connection to the Market.

The researcher has not submitted a preliminary business plan at this time. Potential commercializers should be contacted and interviewed to provide feedback from currently identified potential customers as well as to identify additional customers and stakeholders.

Engineering/Technical.

Each method that was tested was unable to achieve all goals. Future work will involve incorporating two or more processes to achieve the stated goals.

Legal/Contractual.

Prior to this project, the researcher defined intellectual property, reviewed prior art, submitted patent applications, and assessed technology-licensing requirements. During this EISG project he received notice of allowance for the first patent. No contractual agreements have been made.

Environmental, Safety, Risk Assessments/ Quality Plans.

Initial drafts of the following Quality Plans are needed prior to initiation of Stage 4 development activity: Reliability Analysis, Failure Mode Analysis, Manufacturability, Cost and Maintainability Analyses, Hazard Analysis, Coordinated Test Plan, and Product Safety.

Strategic.

This product has no known critical dependencies on other projects under development by PIER or elsewhere.

Production Readiness/Commercialization.

No commercialization partner has been selected.

Public Benefits/Costs.

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

Photovoltaic systems reduce environmental impacts of the California electricity supply or transmission or distribution system. This project potentially reduces the cost to manufacture PV cells and modules. Lower cost modules will lead to lower cost PV generation systems. Cost effective PV systems will increase the application of this technology and thus reduce the environmental impact of electric generation in California.

Appendix A: Final Report (under separate cover)

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