2008 Solar Annual Review Meeting

Session: Film Silicon
Organization: National Renewable Energy Laboratory
Funding Opportunity: NREL Core Program (NCPV)

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Budget and Solar America Initiative alignment

NREL - NCPV - 3 Groups			
Project Beginning Date	**FY07 Budget**	**FY08 Budget**	**Total Budget**
10/1/07	*$2.09M*	$3.307M	$5.397M

- This project supports the Solar America Initiative by:
  - R&D that contributes to goal of grid parity by 2015
  - Research to fill the industry R&D pipeline for next-generation low-cost scalable products
  - Development of industry collaborative research
  - Improvement of NREL tools and capabilities for film silicon research

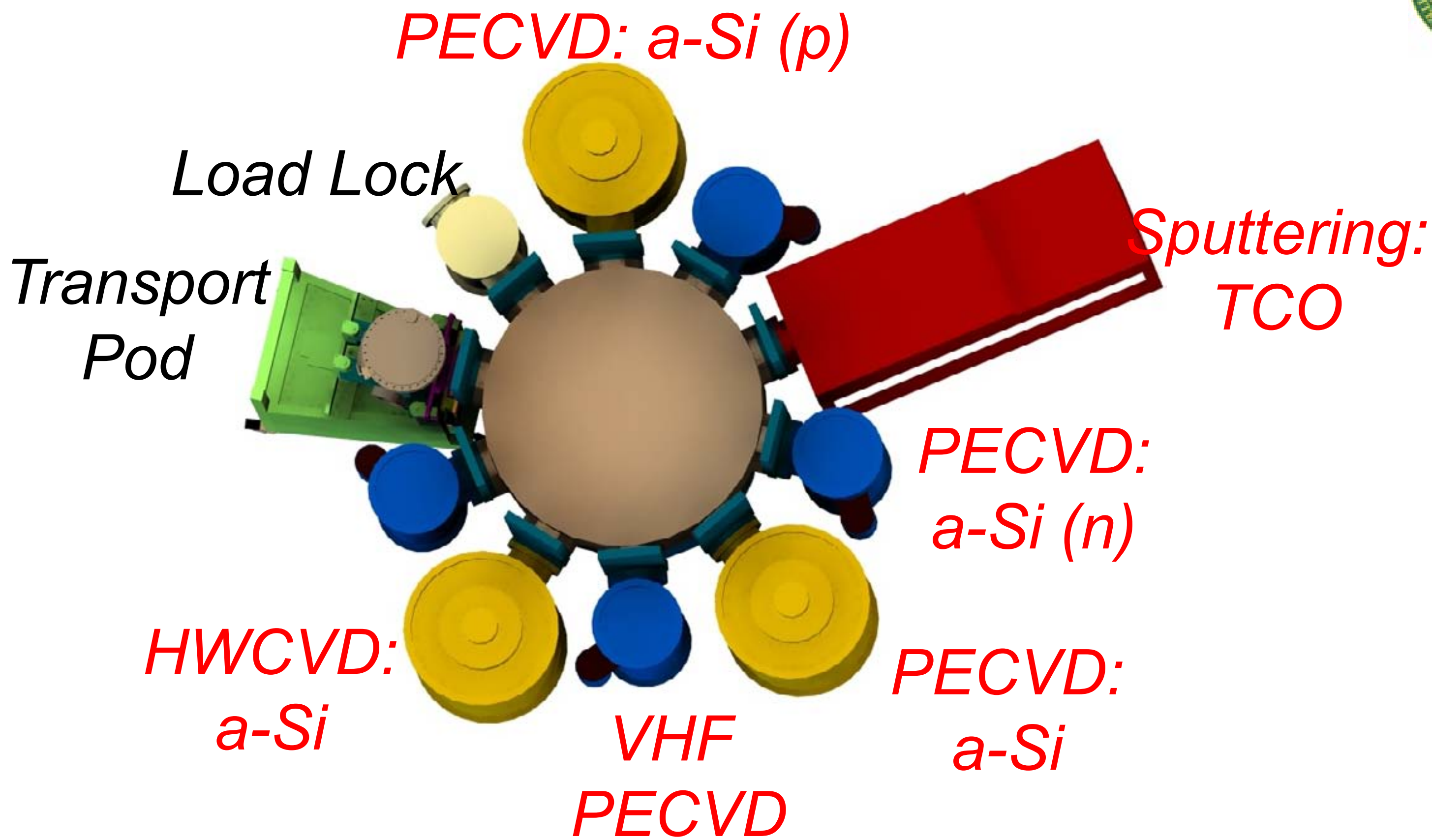
Film Silicon Technology Roadmap has 2 parts

- This Project addresses both parts of Film Silicon Roadmap

- Amorphous-silicon-based thin film PV
  - amorphous and nanocrystalline materials
  - present "2^{nd} Generation" technology
  - 4% of world PV sales in 2007

- Advanced R&D toward film crystal Silicon
  - definition: large-grained or single-crystal silicon <100 μm thick
  - 3-8 year horizon
  - goal of reaching 15% cells at area costs approaching thin films

Project Overview - Thin-Film a-Si and nc-Si



- New PDIL thin-film silicon deposition tool installed - soon operating
- High rate methods available at 6-inch scale, with in-situ diagnostics
  - Plasma-enhanced CVD
  - Hot-wire CVD
  - VHF CVD

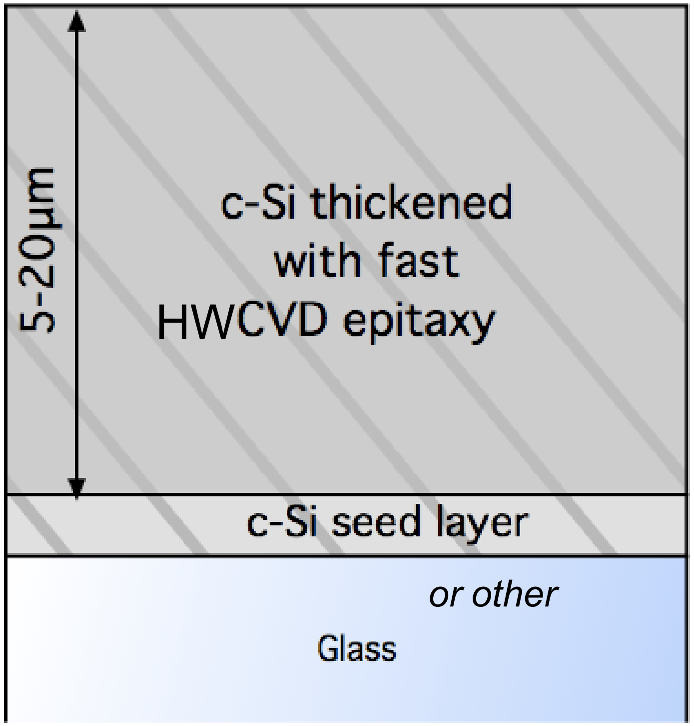
Project alignment with a-Si Technology Roadmap

Roadmap / Approaches

Need	Significance	Approaches
Improve light-stabilized electronic quality of a-Si and low-gap partner for a-Si:H cell	Broader spectrum conversion and increased stable efficiency	Medium-ordered and embedded nanocrystals that stabilize cells
Increase growth rates of all a-Si, a-SiGe layers while maintaining high electronic quality	Increased throughput and reduced capital cost	High-rate (>100 Å/s) , high-efficiency VHF CVD and HWCVD a-Si:H cells
Develop high-growth-rate methods for nanocrystalline silicon while maintaining high electronic quality	Increased efficiency and stability; reduced cost	High efficiency VHF CVD high-rate (>20Å/s) nanocrystalline cells. Understand and model nanocrystallite formation process.
Understand and control light-induced degradation in a-Si:H	Increased efficiency and understanding of intrinsic limits to the efficiency	Study mixed-phase, medium-ordered and high rate light induced degradation
Develop in-situ in-line process monitoring	Increased yield	Correlate cell performance with *in situ* optical reflection and ellipsometry monitoring

Film crystal silicon Project overview: High-quality silicon on inexpensive substrate

- Step 1: Establish good crystal quality with a thin seed layer
- Step 2: Thicken seed layer with rapid HWCVD epitaxy



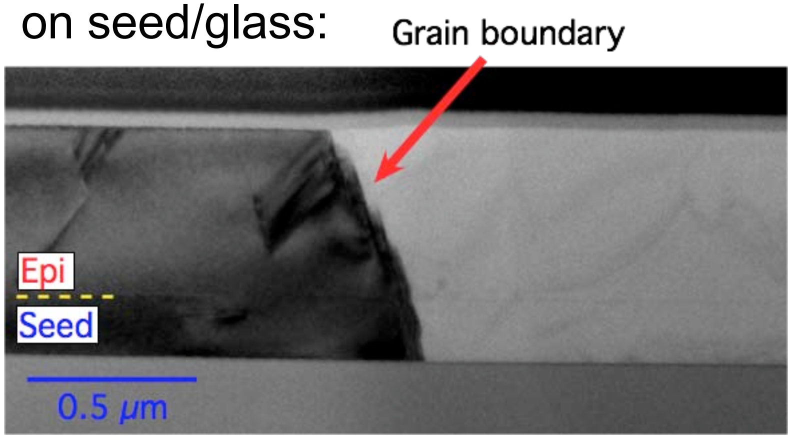
Technology requirements

- High-quality epitaxy at T<700°C
- High-quality, low-cost seed layers
  - good seeds available today
  - better seeds in R&D
- Optimized, manufacturable, device design
  - junction, light-trapping, contacting

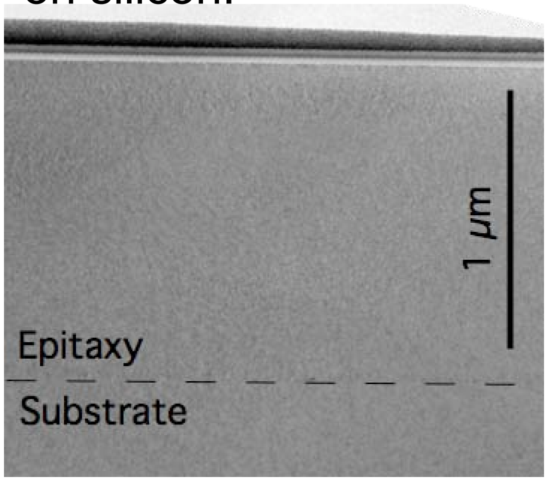
HWCVD epitaxy is key technology enabler

- Compatible with inexpensive substrates
  - T < 700 °C
  - demonstrated on seeds on borosilicate glass
- High rate and scalable
  - 300 nm/min achieved (20 min device)
- Stable and robust
  - growth on (111) demonstrated
  - thicknesses over 10 microns
- High quality
  - upper bound to dislocations $10^6/cm^2$

on seed/glass:



on silicon:



Project Alignment with Film c-Si Technology Roadmap

Roadmap

Approaches

Need	Significance	Approaches
Develop inexpensive large-grain or single-crystal, high-quality c-Si film growth processes and materials for use with low-cost substrates	Higher efficiency than amorphous, but lower cost than wafer-based silicon	Hot-wire (HWCVD) epitaxy on seeds. Working now at glass-compatible 600-700°C, 10 micron films, 300 nm/min, all orientations, dislocations < 10^6 cm^{-2}
Develop seeding techniques for high-quality epitaxial c-Si film formation on low-cost substrates	Increased efficiency	Laser and microwave-induced seeding. Innovative microscopies for Si layers
Develop inexpensive, reduced-temperature processing for c-Si films	Reduced cost	Industrial cooperation for seeds - glass, semiconductor & start-up companies
Develop low-temperature passivation techniques for film-Si surfaces, interfaces, and grain boundaries	Increased efficiency	New tool for inductively coupled plasma and HW hydrogenation and RTP

Project Update - FY07 Tasks

Project Task	Final Status
Improve high-rate a-SiGe:H for tandems with a-Si:H	High-rate (4Å/s) HWCVD a-SiGe:H solar cells with 8.65% efficiency in collaboration with UniSolar. Project terminated. (TSF, JNCS)
Scalable Low-T epitaxy on Silicon	HWCVD growth of 10 micron epitaxial layer on (100) Si at 620°C and epitaxy on (111) Si. (APL)
Measurement and characterization of nanocrystalline Si cells	AFM & Kelvin probe of surface and Raman of xtal fraction vs depth correlated with cell performance. (JAP)
PDIL thin-film silicon deposition tool	Acceptance testing at manufacturer and delivery to PDIL.
Nanocrystalline growth mechanism	Developed new cone kinetics model describing morphologies of protocrystalline and nc-Si. (APL)
Crystallization of a-Si:H on glass	High-rate ((100Å/s) HWCVD a-Si:H can be crystallized 5 times faster than PECVD a-Si:H. (APL)

Project Update - FY08 Tasks

Project Task	Status - April 2008
Scalable Low-T epitaxy on Silicon	HWCVD growth rate increased to 300 nm/min and modeled. Low dislocation density demonstrated. Both n- and p-type doping achieved.
Epitaxy on Seed Layer on Glass	Demonstration on low-quality Al-induced seed layer. High-quality seed acquired.
Microscopy of Recombination	Diffusion length measurement applied to epitaxial Si. Technique development continuing.
Foreign Template seed layer	Al_2O_3 layers grown on MgO. Extensive Si heteroepitaxy testing on Al_2O_3.
Laser nucleation of seed layer	Observed grain growth from incorporated nanoparticles dominating spontaneous nucleation.
Microwave nucleation of seed layer	New microwave optics to flatten profile fabricated. Initial microwave runs in April.
Hydrogen passivation of seed layer	First safety review complete. Final electrical test.
PDIL Wafer Replacement Tool development	New heaters tested. Conceptual design complete.
Baseline thin-film cells in PDIL	First safety review of 156-mm system complete. Leak check underway.

Obstacle Discussion

- Challenging to maintain needed focus in 3 areas
  - NREL Project research goals
  - Interaction with the many companies that call
    - established PV companies
    - startups
    - new-entry companies
    - requests for information
    - requests for collaboration (some in synergy, fortunately)
  - Design and procurement of improved equipment

- Protection of multi-company IP in Cooperative Research (CRADA) and Technical Service Agreements (TSA)