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Solar Energy Technologies Program

National Solar Technology Roadmap:

Film-Silicon PV

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National Solar Technology Roadmap: Film-Silicon PV

Scope

Silicon photovoltaic (PV) technologies are addressed in two different technology roadmaps: Film-Silicon PV and Wafer-Silicon PV. This *Film-Silicon PV roadmap* applies to all silicon-film technologies that rely on a supporting substrate such as glass, polymer, aluminum, stainless steel, or metallurgical-grade silicon. Such devices typically use amorphous, nanocrystalline, fine-grained polycrystalline, or epitaxial silicon layers that are 1–20 µm thick.

The *Wafer-Silicon PV roadmap* applies to bulk-silicon-based PV technologies, including those based on Czochralski, multicrystalline, float-zone wafers, and melt-grown crystals that are about 100 µm or thicker, such as ribbons, sheet, or spheral silicon. There may be some overlap between this roadmap and the Wafer-Silicon PV roadmap.

Technology development stage: Commercial production for amorphous silicon; early-stage commercial production for amorphous/nanocrystalline tandem cells and crystallized film silicon on glass; concept stage for most implementations of crystallized and epitaxial crystal-silicon film approaches.

Target applications: Residential, commercial, and utility; primarily on-grid, but including off-grid, with unique advantages well-suited for building-integrated PV (BIPV) applications.

Background

We further categorize within this Film-Silicon PV roadmap to distinguish two distinct types of supported silicon-film technologies: amorphous-silicon-based (a-Si:H) thin-film technologies and crystal-silicon (c-Si) film technologies.

Amorphous-silicon-based thin-film technologies typically use chemical vapor deposition (CVD) at below 300°C to deposit relatively thin (<2 µm) layers of a-Si:H alloys and/or nanocrystalline Si material with 100-nm crystal grain size. All-amorphous thin-film modules are manufactured inexpensively, with high yield, over large areas, with conversion efficiencies of 5%–8%. Monolithic, large-area module integration is in commercial production. For a-Si/nanocrystalline Si tandem thin-film modules, the production is limited but growing. The thin-film industry benefits from synergies with the thin-film a-Si:H used by the display industry. Production growth has increased at the same rate as c-Si; thus, it remains at about 5% of the total market.

Crystal-silicon film technologies rely on a wider variety of film-fabrication techniques aimed at creating an entirely crystalline-silicon film (2–20-µm-thick) absorber on a supporting substrate. Creation or deposition of c-Si requires processing temperatures well above 500°C. The c-Si film technologies have the potential to approach the capability of wafer Si at significantly lower cost than wafers by avoiding the costs of feedstock production, bulk crystal growth, wafer sawing, kerf loss, polishing, and the currently high cost and limited supply of feedstock. However, efficiencies are still lower than wafer-based Si. Current manufacturing is limited to a pilot capability that produces 7%–8%-efficient modules from crystallized amorphous silicon.

Roadmap Overview

In 2006, film-silicon production was about 100 MW worldwide, mainly of amorphous-silicon thin-film modules. A doubling of the annual amorphous-silicon production rate to 200 MW is likely by 2008. The efficiencies will be about 7% (aperture-area efficiencies of 8%–9%) at prices competitive with wafer Si.

There are at least two developing technological paths within the film-Si technologies defined above and which we describe below.

The first technology pathway is an amorphous-silicon-based cell at dramatically reduced area-costs and moderately increased efficiency. If the production volume of amorphous silicon continues to increase at its current rate, it will reach ~2 GW/yr by 2020. At this production volume, great economies of scale are possible due to the simplicity and high yields: for example, a float-glass production line can be dedicated to a production facility, reducing the cost of the transparent-conducting-oxide (TCO)-coated glass. Higher deposition rates for improved low-gap material partners to the amorphous silicon cells (e.g., a-SiGe:H or nanocrystalline Si), reduced light-induced instability, and lower interconnection and encapsulation costs could raise module efficiencies to 15% and their cost could be reduced to below $0.50–0.75/W for large-capacity (1–2 GW) plants.

A second higher-risk, high-payoff technology path uses c-Si films fabricated on one of several candidate inexpensive substrates such as glass, glass-ceramics, metallurgical-grade Si, or stainless steel. This wafer-replacement approach has the potential to raise efficiencies to levels competitive with polysilicon-wafer technology while maintaining the low-cost structure of amorphous-silicon-based thin-film manufacturing. When the silicon film is crystalline in nature, the material quality and cell efficiency can increase, approaching the values of bulk, large-grain polycrystalline Si. However, the absorption coefficient decreases, requiring thicker films and exceptional light-trapping. A high-deposition-rate process of the active materials and a mechanism to produce single crystals, large grains, biaxially textured grains, and/or well-passivated grain boundaries is needed.

Metrics

a-Si-Based Thin-Film Technologies

Parameter	Present Status (2007) (costs are estimated)	Future Goal (2015)
Production volume	100 MW/yr	>5 GW/yr
Capital equipment cost	$1–2/W @ plant capacity	$0.7/W @ plant capacity
Substrate cost	$12–20/m^2	$4/m^2
Module manufacturing cost for a-Si	$125–200/m^2	$0.45–0.70/W or $70/m^2 @10%–15% efficiency

Stabilized efficiency, best a-Si lab cells	13%	15%
Stabilized efficiency, commercial a-Si modules	5%–8%	10%–13%
Reliability of a-Si panels	~1%/yr degradation	1%/yr degradation

c-Si Film Technologies

Parameter	Present Status (2007) (costs are estimated)	Future Goal (2020)
Production volume	<1 MW/yr	1 GW/yr
Capital equipment cost	\$2–3/W @ plant capacity	\$0.7/W @ plant capacity
Substrate cost	\$26/m^2	\$10/m^2
Module manufacturing cost for waferless silicon	Not available \$/m^2	\$0.50/W or \$65/m^2 @ 13% efficiency
Efficiency, best supported-film c-Si lab cells	10%	16%–18%
Efficiency, best supported-film c-Si pilot modules	5%–6%	13%–16%
Reliability of Si-film panels	??%/yr degradation	1%/yr degradation

Identified Needs

a-Si-Based Thin-Film Technologies

			Nat'l Lab			Industry		
Need	Significance	University	NREL	Sandia	Other	TPP	Incubator	Other
Improve light-stabilized electronic quality of a-Si and low-gap partner for a-Si:H cell	Broader spectrum conversion and increased stable efficiency	x	x			x	x	
Increase growth rates of all a-Si, a-SiGe layers while maintaining high electronic quality	Increased throughput and reduced capital cost	x	x			x	x	
Develop high-growth-rate methods for nanocrystalline silicon while maintaining high electronic quality	Increased efficiency and stability; reduced cost	x	x			x		
Understand and control light-induced degradation in a-Si:H	Increased efficiency and understanding of intrinsic limits to the efficiency	x	x			x	x	
Develop in-situ in-line process monitoring	Increased yield	x	x			x	x	
Improve light-management	Increased efficiency	x	x			x	x	

strategies								
Improved transparent conducting oxides	Increased efficiency	x	x			x		
Develop low-cost packaging	Reduced cost. Currently represents a significant portion of the total cost.	x	x	x		x	x	
Understand and improve reliability of low-cost packaging options	Reduced cost increased long-term performance	x	x	x		x	x	
Automate and scale up large-format amorphous silicon fabrication and enlarge module size	Reduced cost					x	x	

c-Si Film Technologies

			Nat'l Lab			Industry		
Need	Significance	University	NREL	Sandia	Other	TPP	Incubator	Other
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	x	x				x	
Develop seeding techniques for high-quality epitaxial c-Si film formation on low-cost substrates	Increased efficiency	x	x					
Develop light-management strategies for weakly absorbing c-Si films	Increased efficiency	x	x				x	
Develop inexpensive, high-temperature (>600˚C) substrates for c-Si films	Reduced cost						x	
Develop inexpensive, reduced-temperature processing for c-Si films	Reduced cost						x	
Develop low-temperature passivation techniques for film-Si surfaces, interfaces, and grain boundaries	Increased efficiency	x	x					
Develop, automate, and scale up deposition equipment for c-Si film fabrication	Reduced cost and increased yield		x			x	x	

Develop in-situ in-line process monitoring	Increased yield	x	x			x	x	
Develop improved characterization of c-Si films and establish key measures of quality	Accelerate the development of this technology.	x	x				x	
Develop low-cost packaging	Reduced cost. Currently represents a significant portion of the total cost.	x	x	x	x	x	x	
Understand and improve reliability of low-cost packaging options	Reduced cost, increased long-term performance	x	x	x	x	x	x	
Design manufacturable device structures and module designs	Allow for deployment	x	x	x	x	x	x	