Thin Film CdTe Module Manufacturing

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Abstract

This paper reports on high-throughput and high-volume manufacturing of thin-film, CdS/CdTe-based photovoltaic modules at First Solar enabling clean, affordable solar electricity. These sustainable and cost-effective energy solutions are provided by using abundant solar resources in concert with comprehensive, pre-funded end-of-life collection and recycling programs.

INTRODUCTION

First Solar was created in 1999 to commercialize low-cost, high-quality, high-volume CdTe-based solar module thin-film technology. . A pilot facility was formed in 1991 and in 1998 the high-speed deposition technology, to form the CdS and CdTe semiconductor layers, was developed. The construction of the 1st generation pilot production plant began in 1999 and in 2001 the product was validated and production ramp began. Since then First Solar has constructed manufacturing facilities in Frankfurt An Der Oder and in Kulim, Malaysia.

First Solar's mission is to create enduring value by enabling a world powered by clean, affordable solar electricity. The overarching strategic objective is to reduce the cost of solar electricity to a level competitive with conventional energy, enabling solar to become a sustainable mainstream source of energy. The business model focuses on driving continuous cost reduction through strong economies of scale and leveraging subsidized markets to enable future participation in non-subsidized markets. First Solar has achieved total, cumulative solar module manufacturing volumes in excess of 1 GW in the 1st quarter of 2009 and has secured a multi-gigawatt U.S. pipeline through the acquisition of OptiSolar's project pipeline. This acquisition enhances First Solar position for leadership in U.S. utility markets.

First Solar is targeting cost-parity with fossil-fuel electricity in the 2010–2012 timeframe assuming levelized cost of electricity (LCOE) between \$0.08-\$0.10/kWh for conventional electricity. This translates into turnkey system cost of approximately \$2.00-\$2.50/Watt as shown in Figure 1. As the system cost comes down so does the LCOE. Power purchase agreements (PPA) with Federal investment tax credit (ITC) and optimized capital bring the costs down further enabling grid parity to be reached sooner at a higher system cost point.

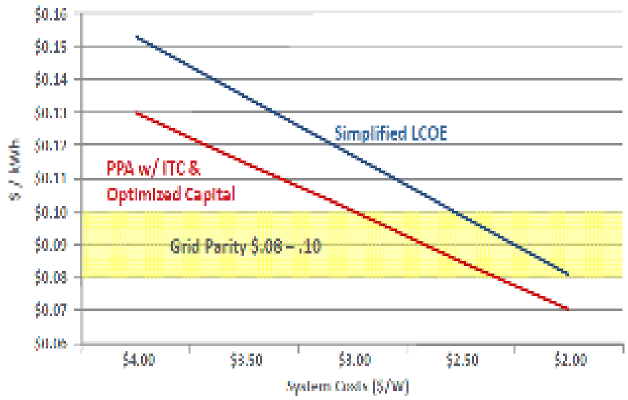

Fig 1: Levelized cost of electricity (LCOE) as a function of First Solar system cost [1].

A historic goal was reached in the 4th quarter of 2008, for the solar industry, as First Solar was able to lower the cost per module below the \$1.00/Watt price barrier for the quarter to \$0.98/Watt. Mass market adoption is expected for an average selling price (ASP) between \$1.00-1.25/Watt as shown in Figure 2.

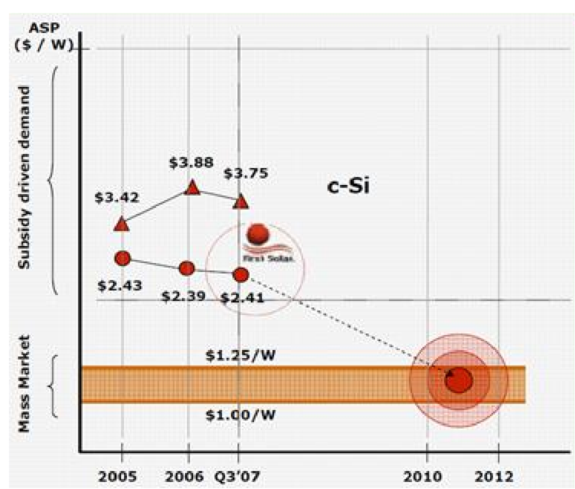

Fig 2: Average selling price per Watt for crystalline Silicon and First Solar's thin film CdTe modules [2].

First Solar's engineering, procurement and construction (EPC) division functions as a contractor for developing utility power plants. This division works on reducing the balance of system (BOS) costs, which excludes the module costs, and can be broken down into inverter components, mechanical installation, electrical installation, project costs, and overhead. First Solar's BOS target is $1.00/Watt and coupled with continued reduction in module costs through increased module efficiency, increased throughput, reduced spending, increased plant scale, and low cost locations enables the system cost to be below the target of $2.00/Watt in 2012 [1].

MANUFACTURING

First Solar employs a fully-integrated, automated and continuous manufacturing line as opposed to using batch processing approaches. The company combines manufacturing leadership and operational excellence from experienced individuals from outside the solar industry with technically talented and experienced individuals from inside the solar industry. Continuous improvement tools that are proven in other successful high technology manufacturing sectors including robust engineering, design of experiments (Taguchi Methods), statistical process control, and theory of constraints (TOC) manufacturing flow optimization are utilized extensively to improve throughput, improve quality, and lower cost. Comprehensive process change management and 6-sigma methodologies such as Define-Measure-Analyze-Improve-Control (DMAIC) are used for process and device improvement. A policy of "Copy Smart" for rapid expansion of existing manufacturing is used extensively throughout the corporation. A core competency for the organization's growth through economies of scale is manifest through the use of theory of constraints methodologies.

First Solar produces a single-product, a 60 x 120 cm (2' x 4') thin-film CdTe/CdS solar cell module on a soda-lime glass substrate module with a laminated cover glass. The company has over 90 U.S. and foreign patents granted and pending plus substantial trade secrets. These intellectual property filings encompass process, equipment, device design and product packaging. There exist many proprietary equipment designs and exclusive relationships with key vendors as equipment and process standardization does not exist to a full degree across the thin-film solar industry.

The First Solar process is robust and employs a simple manufacturing flow with low raw material costs. It is highly automated and can be replicated in new factories quickly. The First Solar module is manufactured on standard soda-lime float-glass. The glass is produced on a float line where a continuous stream of molten glass is deposited onto a bath of molten tin. The molten glass spreads onto the surface of the metal and produces a high quality, consistently level sheet of glass. Molten glass poured onto a bath of clean molten tin will spread out in the same way that oil will spread out if poured onto a body of water. Gravity and surface tension enables the formation of flat and parallel top and bottom surfaces. The float glass process was developed by Sir Alastair Pilkington. He patented the process in 1959 and presented a detailed history of the development of the process in a review lecture to the Royal Society of London in 1969 [3].

The First Solar module is manufactured in a "super-substrate" orientation, where the substrate glass will ultimately become the top of the module. The glass is initially coated with a TCO (transparent conducting oxide) prior to deposition of the semiconductor absorber. The semiconductor film is adsorbed on the glass substrates at temperatures between 500 and 600ºC. Growth rates upwards of 1 μm/s can be achieved in this system enabling thick semiconductor films to be deposited in under 1 minute.

An annealing treatment is performed after the glass quench and the semiconductor coating is complete. Post-deposition heat treatments of CdTe treated with Cl-containing species enables passivation of grain boundaries, reduces defect density, causes grain growth, decreases the density of stack faults and dislocations in the CdS and CdTe, and increases minority carrier lifetime [4].

A series of scribes is done in the Sub-Module line to isolate adjacent solar cells that are connected in a parallel manor, to make contact to the underlying TCO material and to disrupt the continuous back metal film. The First Solar series II module contains 116 solar cells connected in series and separated by a pitch of ~1 cm. No reverse diode electrostatic discharge protection is required.

Final assembly begins with connecting the bus-bars to the ground and the bias lines. Encapsulation of the device is followed by cover glass, lamination, and cord plate for electrical connection to external circuitry. Final test is performed to complete the processing. The time from "glass in" to "glass out" through the entire manufacturing line is under 2.5 hours. This incredibly fast cycle time enables First Solar to dramatically lower the cost of modules and to support very high volume manufacturing.

DEVICE AND MATERIALS

First Solar uses CdTe and CdS to form the p-n junction semiconductor diode. Cadmium sulfide is a direct band gap semiconductor, a gap of 2.42 eV at 300 K, and CdTe is a direct band gap semiconductor, a gap of 1.56 eV at 300 K. The thickness of the CdS layer limits short wavelength cell response and also, obviously has an impact on manufacturing cycle time. CdS has, like zinc sulfide, two crystal forms; the more stable hexagonal wurtzite structure, found in the mineral Greenockite, and the cubic zinc blende structure found in the mineral Hawleyite. CdS has a melting point of

1750 °C at 10 MPa. CdTe forms in a zinc blende crystal lattice and has a melting point of 1092 ^{o}C.

Cadmium is produced mainly as a byproduct from mining, smelting, and refining sulfide ores of zinc, and, to a lesser degree, lead and copper. Its abundance in the Earth's crust is 1 to 5 parts per billion, Tellurium is sometimes found in its native, elemental form, but is more often found as the tellurides of gold which include calaverite, krennerite, petzite, sylvanite, and others. Tellurium is also found combined with elements other than gold, in salts of other metals.

The integration and optimization of the glass super-substrate with the CdS/CdTe semiconductor and with the contact metals is a very challenging task. Some aspects of these issues are discussed next.

Typical soda-lime glass, used for flat glass, is composed of 73% SiO_2, 14% Na_2O, 9% CaO, 4% MgO, 0.15% Al_2O_3, 0.03% K_2O, 0.02% TiO_2, and 0.1% Fe_2O_3. The Iron content in glass greatly affects the transmission characteristics of the glass and the resultant solar cell performance. The high Sodium content in glass can greatly influence the solar cell performance. Sodium can propagate through the glass super-substrate and enter into the semiconductor layers. The strain point of soda-lime glass is stated as 514 ^{o}C and great care needs to be taken during heating and cooling of the glass to ensure the glass sheet does not warp appreciably.

The growth of CdS on the glass super-substrate is dependent on the surface chemistry of the glass and therefore pre-treatments prior to semiconductor growth can be very important. Differences in thermal expansion co-efficient within the glass super-substrate as well as between the glass super-substrate and the semiconductor layers can result in the formation of stress within the deposited thin films. Intermixing of the CdS and CdTe materials at the main p-n junction also occurs to some degree and can have a direct impact on cell performance.

RELIABILITY, QUALITY AND RECYCLING

The First Solar Series II thin film module is architecturally aesthetic and can be integrated into a variety of applications – both on and off the grid. The 60 x 120 cm module weighs 27 lbs. Power increments of 2.5 W with power per module of up to 72 W are available. The modules have a low temperature co-efficient of -0.25%/^{o}C. The product is certified for reliability and safety according to IEC 61646 and SK II @ 1000V. First Solar's manufacturing is certified to ISO9001:2000 quality and ISO14001:2004 environmental standards. The product comes with a 25 year warranty maintaining a power output of greater than 80%.

First Solar has a pre-financed collection and recycling program. For each module sold, the company sets aside funds to meet the estimated future cost of collecting and recycling modules at the end of their life. Anyone in possession of a First Solar module can participate in the program and request that modules be taken back at any time. Modules are labeled with the web site and the telephone contact information. First Solar manages the logistics of taking back modules and provides the packaging and transportation of modules to the recycling center. Modules undergo treatment through schemes that comply with local regulations regarding health, safety, and waste management.

First Solar performs quantitative, cradle-to-grave assessment of environmental impacts of their product taking into account the transfer of environmental impacts from one medium to another and from one life-cycle stage to another. This quantitative life-cycle assessment allows the comparison of the environmental attributes of competing alternatives with a systematic, quantitative, and comprehensive methodology. At least 89% of the green house gas emissions associated with electricity generation circa 2008 could be prevented if electricity from photovoltaics displaces the present electricity sources being fed into the grid [5].

Cadmium emissions can be categorized as direct and indirect. The estimated total direct emissions of Cadmium during the mining, smelting, plus purification processing and during the synthesis of CdTe is 0.015 g/GWh. The total direct emissions of Cadmium during module manufacturing at First Solar is approximately 0.004 g/GWh. Indirect Cadmium emissions due to electricity and fuel use, accounting for emission due to the generation of electricity, are greater by more than an order of magnitude relative to direct emissions during First Solar module manufacturing. The total Cadmium emissions for First Solar's thin-film technology are approximately 0.3 g/GWh compared to 43.3 g/GWh for electricity generation from oil [5]. Electricity generation by fossil fuels creates such a large quantity of heavy metal emissions.

CdTe is a highly stable compound sealed between two glass plates. There are no emissions during operation and in case of fire CdTe melts into the glass with 99.95% of the Cadmium retained within the glass [6]. CdTe is insoluble in water and will not chemically decompose unless directly contacted with an oxidizing agent.

CONCLUSIONS

First Solar recovers and converts mining byproducts into clean, renewable energy. The high-throughput and high-volume manufacturing technology that First Solar has developed over the years is enabling clean and affordable solar electricity. A comprehensive program to bear the financial and environment responsibility of the solar modules is at the core of First Solar's business enabling the safe use of solar-generated electricity using CdTe thin film modules.

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ACRONYMS

ASP: average selling price
BOS: balance of systems
DMAIC: define, measure, analyze, improve, control
DoE: Department of Energy
EPC: engineering, procurement and construction
EVA: ethylene vinyl acetate
ITC: Federal investment tax credit
LCOE: levelized cost of electricity
NREL: National Renewable Energy Laboratory
PPA: power purchase agreements
TOC: theory of constraints
TCO: transparent conducting oxide