Improvements in Polycrystalline Silicon PV Module Manufacturing Technology

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ABSTRACT

This paper reports on the work performed by BP Solar under NREL Subcontract #ZAX-8-17647-05. The objective of this three year PVMaT program is to continue the advancement of PV manufacturing technologies in order to design and implement a process which produces polycrystalline silicon PV modules that can be sold profitably for $2.00 per peak watt or less and which increases the production capacity of the Frederick, Maryland plant to at least 25 megawatts per year. Progress has been achieved in the areas of silicon feedstock development, casting, wire sawing, cell processing, faster cure encapsulation, handling and measurement and control.

1. Introduction

Achieving the overall objectives of the program is based on the following components:

- Developing a solar-grade silicon feedstock.
- Improving process control in casting.
- Reducing wire diameter and wafer thickness.
- Reducing wire saw operating costs.
- Developing a faster cure encapsulant.
- Increasing cell efficiency and process robustness.
- Improving handling and eliminating non-value added handling steps.
- Improving measurement and control throughout the production line.

2. Silicon Feedstock

In this task, BP Solar worked with subcontractor, SiNaF Products, Inc. to develop a process to produce silicon feedstock from H_2SiF_6. The overall process for Si production includes generation of the high purity SiF_6 gas and then its reduction with Na to form Si.

SiNaF successfully developed and demonstrated the gas production process, verifying that high purity SiF_6 can be obtained from both fluosilicic acid, a byproduct of the phosphate fertilizer industry, and from chemical interaction with spent catalysts from the petroleum industry.

Several silicon reduction experiments were completed during the program. These proved that the reaction of SiF_6 gas and Na did produce silicon, although the resultant material was contaminated with nitrogen, oxygen and carbon, (due to leakage of air into the reaction chamber), and with NaF. The production unit must allow the NaF to be poured off before it freezes, and for the silicon to agglomerate into larger pieces for subsequent use in the casting process.

3. Casting

In this effort, BP Solar is improving control of and optimizing the casting process. This will increase the process yield (kilograms of silicon out divided by kilograms of silicon in) by 3% and improve material quality to result in a 1% increase in average cell efficiency.

We first implemented replacement control systems for the existing casting stations, which produce 66 kg cast ingots. The new systems provide a much higher level of automated control and data acquisition. The operator interface, alarm and troubleshooting functions were all improved. Actual yields in this area increased by 4% because of these changes.

In 2000, we worked with an equipment manufacturer to establish the ability to cast 240 kg silicon charges with better run-to-run control and with silicon quality at least equivalent to the 66 kg runs. In tests at the manufacturer's site, overall yields improved by 6.2%. Subsequent expansion of the Frederick casting operation has begun using these stations.

4. Wire Sawing

BP Solar has reduced the wire "pitch" (center-to-center spacing) from 500 microns to 450 microns with no loss of downstream yield. A planned further reduction to 440-micron pitch was halted after tests showed significant losses in downstream yield due to wafer bowing in the cell metallization steps.

We have increased the throughput of several older-generation saws by 40% after modifying the brick mounting structure.

We also introduced prototype slurry and silicon carbide recycling systems to significantly reduce the operating cost of the saws. Second-generation production recycling systems are now under consideration. These systems will use a non-oil based slurry.

Prototype work with diamond-coated wire lead to the purchase of a diamond-wire sizing saw for installation in 2001.

5. Cell Processing

In this task, BP Solar is developing, demonstrating and implementing a cost-effective, robust cell process that produces a minimum average cell efficiency of 15% and improves the cell line electrical yield.

An aluminum paste Back Surface Field (BSF) process was successfully implemented in each of the company's screen-print production lines, resulting in a 5% increase in average power.

A PECVD silicon nitride process was developed in Frederick and implemented in the Tata BP facility in Bangalore, India. PECVD silicon nitride produces cell efficiency improvement through the passivating effect of the plasma-enhanced process on both surface and bulk defects. Production efficiencies have averaged above 14%. All BP Solar screen print plants will be converted to PECVD silicon nitride in 2002.

Building on the PECVD silicon nitride process now in production in India, we have demonstrated advanced process variations capable of producing up to 15.7% average efficiency on polycrystalline screen-printed cells.

6. Faster Cure Encapsulation System

BP Solar subcontracted to Specialized Technology Resources, Inc. (STR) to develop an encapsulation system that meets all technical and reliability requirements and can be laminated and cured in less than 6 minutes in the present BP Solar laminators.

STR developed an EVA formulation that cures in 6 minutes in BP Solar's production laminators. Sample modules produced with this material were adequately cured and have successfully passed all of the requirements of IEC 61215 "Crystalline silicon terrestrial photovoltaic (PV) modules - Design qualification and type approval".

The major issue remaining with implementation of this material is its manufacturability. Because it cures so quickly, STR had trouble extruding it into films. While STR will investigate the production process, this will likely result in a significant delay in implementation. Meanwhile, BP Solar is evaluating a shorter-term solution using a material from STR that will cure in 9 minutes. Samples of that material are now undergoing testing to IEC 61215.

7. Handling

In this effort, BP Solar is developing improved product and materials handling techniques (including efforts in at least three separate areas) to increase line yields by 3% and reduce handling labor to save $0.05/watt. BP Solar is supported in this effort through a lower-tier subcontract with ARRI, the Automation and Robotics Research Institute of the University of Texas at Arlington.

A completely new, U-shaped assembly line was designed, purchased and installed in the BP Solar plant in Frederick. The new line provides automated handling of large modules, starting with tabbed cells and producing a fully assembled, tested and packaged product for shipment. Labor productivity improved by over 50% relative to the existing manual lines, and labor cost was reduced by more than the goal of $0.05 per Watt.

An automated load unload system was implemented on the last expansion using the 66 kg casting stations. The system uses pneumatic cylinders to move the lift table out from under the station, makes it easier to service the station, and with other improvements reduces the cost by approximately $3000 per station. The system also increases operator safety by eliminating any need for the operator to reach under the station.

A self-drying back silver paste was developed in cooperation with one of our paste vendors. This eliminates the need to dry the partially completed cell between the two back printing steps. A rotary printer was then developed in which both back print steps are done on a single rotary table, without any cell handling in between the prints. This process eliminated five manual handling steps and a furnace in the Frederick manual line. The new process will be included in all future line automation and expansion plans.

8. Measurement and Control

BP Solar is developing process measurement and control procedures for use on the production line (including efforts in at least three separate areas) to improve yield by 3% and reduce rework by 50%. ARRI also provides support in this area.

A Manufacturing Execution System (MES) was installed. The system provides a wide range of operational and process data on local-area web pages. For example: wafer thickness; process coefficient of variation (COV); solder joint pull strength; output; and many other parameters are tracked in real-time and available through the local network. The system has been used to drive process improvement in the wire saw and cell areas. It is being expanded to link each of the manufacturing sites worldwide.

ARRI, working with a sensor vendor, has developed a prototype wafer crack detection system. The system can successfully identify damaged wafers at any stage in the manufacturing process. Measurement time is well less than two seconds, making this design compatible with high-speed automation. Production units are planned as part of the automated handling systems being designed for deployment in 2002.

Ascor supported BP Solar in the development of improved in line monitoring and control of the solder bond process. We will use a high-speed IR sensor along with the appropriate data collection hardware to provide a "benchmark" measurement of the process.

We have also developed and are implementing a physical re-design of the solder head in which the solder tips are rotated 90° with respect to their traditional alignment. This reduces process sensitivity and increases solder joint footprint.