Continuous, Automated Manufacturing of String Ribbon Si PV Modules

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ABSTRACT

A three year PVMaT project which ended in May, 2001 has resulted in major developments in PV module manufacturing technology. The most significant have been in the particular areas of silicon ribbon growth and cell processing. Extensive engineering and process development have been combined and resulted in important steps towards the goal of continuous and automated PV module manufacturing. Evergreen has opened a multi-megawatt factory that has incorporated these advances. A number of papers and patent applications have resulted from this work.

1. Introduction - Evergreen Solar is a fully integrated manufacturer of crystalline silicon PV modules. Beginning with feedstock silicon, ribbon of 8 cm width and 300 microns thickness is grown in a continuous process called String Ribbon. Then, 120 sq. cm. cells are formed on this ribbon and modules are constructed from these cells. In March, 2001, Evergreen moved into a factory with a multi-megawatt capacity and since then, has been selling modules based on these 120 sq. cm. String Ribbon solar cells. All the developments detailed below under this PVMaT subcontract have been incorporated into this new factory production line. The principal areas where the major developments took place were in silicon ribbon growth, cell processing, and plant layout and process flow. In the case of the latter, joint work with the Fraunhofer Center for Manufacturing Innovation at Boston University was employed. To facilitate efficiency improvements, NREL provided characterization work.

2. Ribbon Growth - String Ribbon is a method for the continuous production of silicon ribbon. It is called this because two high temperature string materials are used to stabilize the edges of the ribbon as it is grown. The strings are brought up through small holes in a graphite crucible containing a small amount of molten silicon. The strings are non-conductive and are left in the ribbon when cells are made on the material. There is automatic continuous feed and the machines are run on a 24/7 schedule. The ribbon is grown into 2 m long strips, cut in situ without interrupting growth, and then these strips are cut with a laser into 8 cm. wide x 15 cm long cell blanks. The major effect of leaving the strings in the ribbon is the promotion of high angle grain boundaries for about 3 mm from the ribbon edge. The central portion of the ribbon consists of large grains (in some cases with areas > 50sq. cm^2) and many coherent twin boundaries. The principal lifetime limiting defects are transition metal impurities that decorate dislocations. Starting lifetimes are usually in the 1-5 microsecond range. The as-grown ribbon is p-type, with bulk resistivity at about 3 ohm-cm.

In crystal growth, advances were made which resulted in lower substrate costs, higher yields, and lower capital and labor costs. A new string material was developed and implemented and this resulted in certain reduced consumables' costs of 40% and significant yield gains. Following this development, better control of the edge meniscus was achieved. A completely new furnace design was accomplished with a 20 % reduction in capital costs and the ability to grow wider ribbon and at an increased growth speed over our earlier furnace designs. This became the standard platform in our new factory. Automation included ribbon thickness control and laser cutting of String Ribbon strips. In both the ribbon growth area and in the cell area, bar coding is being used extensively to be able to track as-grown wafers through to module manufacturing.

3.Characterization – This was done with extensive help from NREL. The substitutional carbon level was at about 8×10^{17}, interstitial oxygen was at barely detectable levels on the order of 5×10^{15}. Hydrogen passivation works quite well on reducing recombination at the dislocations. Dislocations are heterogeneously distributed across the ribbon width and tend to follow the grain growth in the vertical direction. Grains which are low in dislocations continue this way and vice versa.

4. Advances in cell manufacturing – The underlying theme here was reducing the number of processing steps and also reducing the number of handling operations. Significant progess was achieved here. This included the development of high-speed printing and drying methods for Evergreen's unique cell making method and the design and building of a completely automated cell line from the beginning of front contact application to the final tabbing of the cells. A so-called no-etch process whereby substrates from crystal growth go directly into p-n junction formation and emerge from this sequence without the requirement of going in and out of plastic carriers for any wet chemical processing was developed and is now deployed on the production floor. Instead a specially designed and bar coded plastic box is used to transport the wafers and cells.

5. Production Cell Efficiencies - The manufacturing process is still undergoing optimization and there is every reason to expect further efficiency gains in the future. At present, the best cells have been just under 14% -as made using our standard production line. Batch averages are lower than this with more typical efficiencies in the 12.3 – 12.6 % range.

6. Plant Layout and Process Flow - Utiliizing state-of-the-art manufacturing science, the Fraunhofer USA Center for Manufacturing Innovation at Boston University facilitated layout and process flow for the operation of our new factory. The new factory has a rectangular shape and about 56,000 ft^2. in area. Using extensive feedback from virtually all the senior technical personnel at Evergreen, the Fraunhofer group helped us to lay out a production line with a very efficient factory flow. At one end of the building incoming feedstock silicon is received, and at the other end of the building, finished modules are shipped out to customers. Evergreen now has two standard products based on the 120 cm^2. cell size, a 50 W and a 100 W module.

7.Papers and Patents

Papers

1. R.E. Janoch, A.P. Anselmo, and J.I. Hanoka, Automation of the String Ribbon Process., 16th NCPV Program Review meeting, March, 2000 ,Denver, CO.

2. J.I. Hanoka, An Overview of Silicon Ribbon Growth Technology, PVSEC meeting, Sapporo, Japan Sept. 1999, to be published in Solar Energy Materials and Solar Cells

3. R.E. Janoch, R.L. Wallace, A.P. Anselmo, and J.I. Hanoka, Advances in String Ribbon Crystal Growth, 9th Workshop on Crystalline Silicon Solar Cell Materials and Processes, August, 1999, Breckenridge, CO

4 .R.E. Janoch, A.P. Anselmo, R.L. Wallace, J. Martz, B.E. Lord, and J. I. Hanoka, PVMaT Funded Manufacturing Advances in String Ribbon Technology, 28th IEEE PVSC, Anchorage, Alaska, Sept 2000

5. A. P. Anselmo, R.L. Wallace, R.E. Janoch, J. Martz, and J.I. Hanoka, Automation of the String Ribbon Process, 10th Workshop on Crystalline Silicon Solar Cell Materials and Processes, August, 2000, Copper Mountain, CO.

Patents

- A patent on edge meniscus control has been filed and two others are under preparation.

8. Summary - Evergreen Solar's new factory began operations in the second quarter of 2001. A good measure of the significant impact of this PVMaT subcontract is that virtually all of the manufacturing developments stemming from this project have been incorporated in this new factory and that we began shipping new products based on the 120 cm^2 cell size soon after the factory start up began.

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