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Special Issue

Crystalline Silicon Manufacturing Progress

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The increasing demand for renewable forms of energy is making photovoltaic products an important part of the energy supply future. The costs of producing photovoltaic modules have been significantly reduced during the last 10 years as manufacturing costs per watt have dropped from over \$6 per peak watt to less than half of that value now. This paper summarizes progress in several aspects of photovoltaic manufacturing which have contributed to this reduction. Crystal growth improvements, both in yield and machine design, have reduced the energy consumption by a factor of 3 and improved silicon utilization by 40%. Wafer slicing process changes have resulted in 66% more wafers being produced for a given amount of silicon. Cell production improvements in both automation and improved efficiency have reduced the labor cost contribution by 40% per watt. Larger modules and better materials have added another 10% reduction in the cost to produce photovoltaics. These improvements have contributed to a better energy payback time, reducing it from over 5 years to approximately 3. Reductions in cost and improvements in energy efficiency have made photovoltaic products a commercially viable alternate energy source. Copyright © 2002 John Wiley & Sons, Ltd.

INTRODUCTION

Industrial photovoltaics manufacturing began to grow in the early 1980s, and increased rapidly during the 1990s. During this period significant investments by both private companies and the United States Department of Energy have aimed at lowering the cost of producing and selling photovoltaics. Efforts to reduce materials and energy have been under way for some time, due in large part to the United States Department of Energy's Photovoltaics Manufacturing (PVMat) project, and the need to reduce costs to compete with the established energy supply markets. Much work is being done in the area of thin-film photovoltaic development and production; however, the majority of the market is still dominated by crystalline silicon modules. This paper summarizes the efforts to reduce costs in the four major manufacturing processes for crystalline silicon: crystal growth, wafer slicing, cell processing and module manufacturing, and describes improvements in the processes done in the Siemens Solar Industries factories both in Vancouver, Washington and Camarillo, California.

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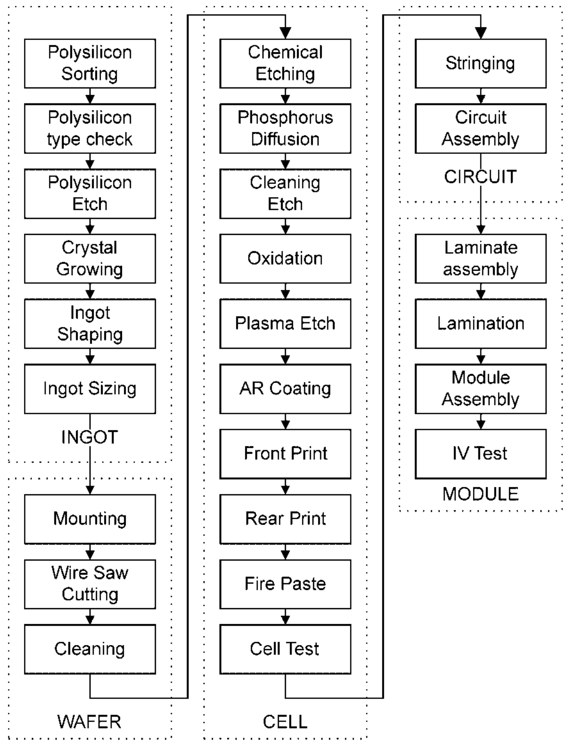

Figure 1. Siemens Solar Industries silicon manufacturing process

MANUFACTURING PROCESSES AT SIEMENS SOLAR INDUSTRIES

The sequence for manufacturing crystalline silicon modules is broken into major process groups, as shown in Figure 1. The processing of silicon solar cells begins with the growth of the silicon ingot, slicing the ingot into wafers, processing wafers into solar cells, and interconnecting the cells into circuits and completing the assembly of a framed and packaged module ready for shipment. The cost breakdown of the major groups is essentially equivalent, as shown in Figure 2, with each major processing area contributing between 20 and 30%.

Crystal growth

Crystalline silicon solar cell processing starts with the preparation of the polysilicon materials used for crystal growth. The sorting of the materials, cleaning and feeding them into the growing machines is an important

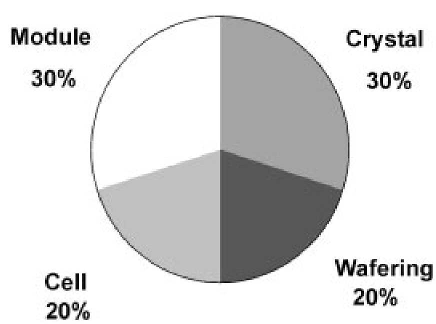

Figure 2. Manufacturing cost by process area

Figure 3. Polysilicon in crucible

process for ensuring high growth yields. The use of both virgin semiconductor stock as well as remelt silicon from semiconductor growing houses is used as feedstock for the Siemens Solar Industries growth technique.

Crystalline silicon ingot growth requires the polysilicon charges be packed in quartz crucibles, as shown in Figure 3. The crucible is used to contain the silicon as it is melted in the grower. A seed of single crystal silicon is dipped into the melted silicon and counter-rotated between the seed and crucible (Figure 4). This results in a single crystal being formed. Ingot formation or growth is followed by a shaping operation, taking the round cross sections and producing square or semi-square ingots.

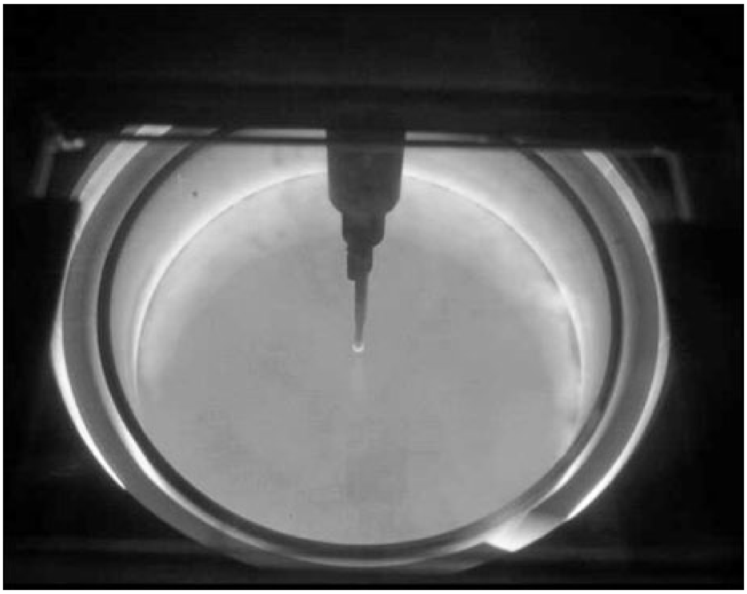

Figure 4. Silicon seed being dipped into molten silicon

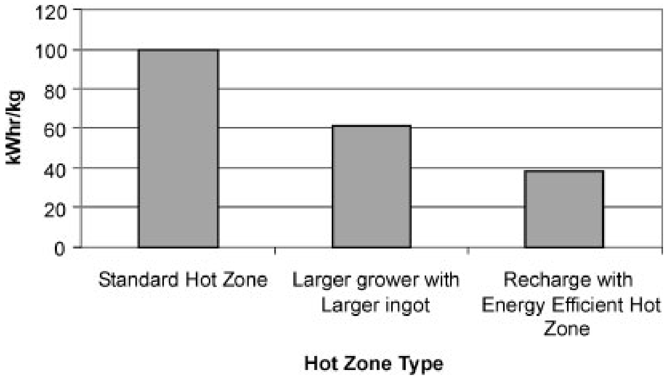

Figure 5. Energy consumption in crystal growth, showing improved hot-zone effects

Crystalline silicon ingot growth requires the melting of raw silicon, an energy-intensive process. A typical Czochralski growth process can require up to 100 kW h consumption per kilogram of silicon ingot produced. Recent developments in improved graphite hot-zone design and gas-flow dynamics,[1,2] coupled with continuous silicon feedstock introduction (recharge), has reduced the energy required for the process to less than 40 kW h per kilogram produced (Figure 5). Larger-size ingots coupled with the improved energy-efficient hot-zone design and recharge feed mechanisms, have added to yield and productivity improvements. The result is an increase of silicon output for a given amount of input of 20%, as shown in Figure 6. These gains in productivity, energy efficiency and materials yield have added significantly to the cost reductions realized during the last 10 years.

Wafer slicing

Silicon solar cells are manufactured from silicon ingots by slicing the ingots into individual wafers. Production of wafers from silicon ingots has been done historically with the use of inner diameter (ID) blade saws in manufacturing. A shift to the use of wire saws (Figure 7) as a cutting tool has dramatically increased the productivity of the slicing operations. This is done by reducing both the cutting losses (kerf losses), and by reducing the amount of damaged silicon left after cutting. The wire slicing leaves a much smoother surface, with less saw damage to the wafers. A typical ID blade cut will consume over 250 μm of silicon which is lost as waste, and require etching of 100 μm of saw damage on the silicon wafer. By contrast, a wire cut will consume less than 180 μm of silicon with less than 25 μm damage to be etched. This has resulted in nearly doubling the amount of wafers produced per length of ingot supplied; Figure 8 shows the increase in yielded wafers per inch (2·54 cm) of ingot. This technology change has dramatically reduced the cost of producing silicon solar cells.

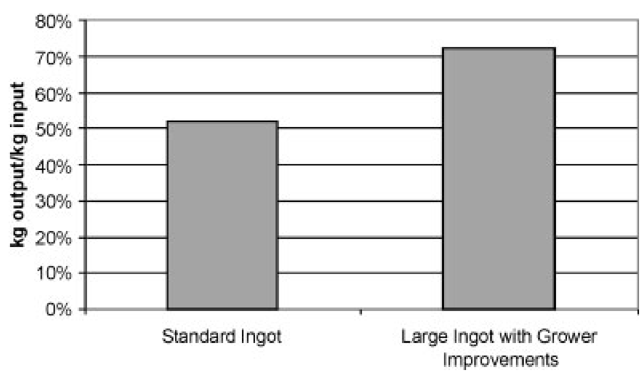

Figure 6. Crystal growth yield, showing effect of cell size and improved growth processing

Figure 7. Typical wire saw

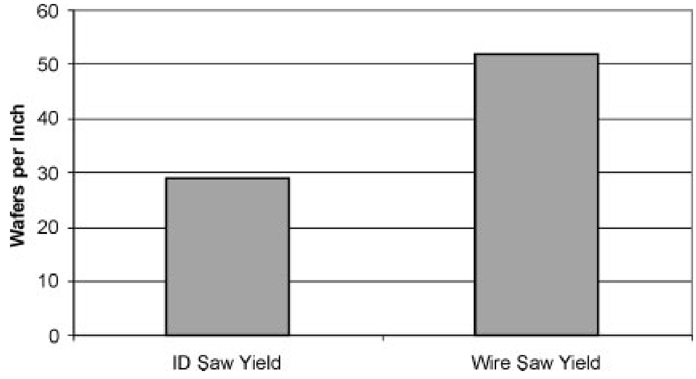

Figure 8. Improved yields with wire saws

Cell processing

Silicon wafers are processed into solar cells by diffusing a dopant material into the surface of the wafer, applying an anti-reflective coating, and printing on contact strips from which to gather the power produced by the cells. The cell production process requires high-speed transfer of cells from one process step to another. Increasing the level of automation in the factory has improved yield and allowed for an increase in the size of cells produced from 100 to 150 cm^2. The automated handling (Figure 9) and the increase of cell size has improved productivity per watt by nearly a factor of two. Figure 10 shows the improved labor contribution for a semi-automated cell factory contrasted with a manual process sequence. Effective labor utilization is an important parameter in well-run manufacturing plants and in optimizing costs.

Figure 9. Automated cell handling

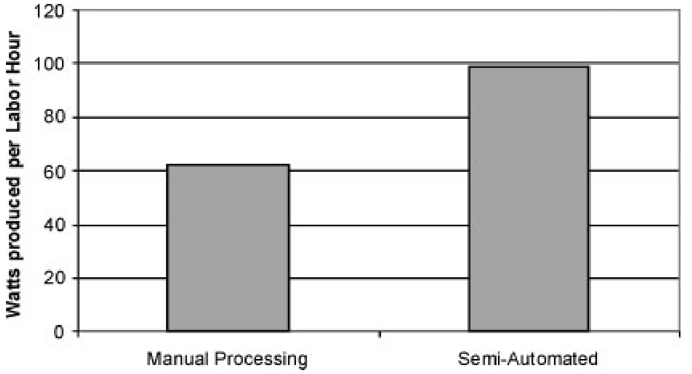

Figure 10. Labor productivity increase with automation

Module assembly

Module assembly is the connection of cells into a circuit, the lamination of this circuit behind a piece of tempered glass, then the finishing of this laminate into a module with external electrical connectors. Larger modules have increased the amount of energy delivered per solar module. Larger units have an increased effect on the efficiency of production. Larger modules producing more watts per unit have lowered labor intensive processing such as module handling and junction box installation. Significant progress is still to be made in these areas with automation equipment, Figure 11 shows two of the major products produced by Siemens Solar Industries, an SM55 with 55 W peak power and an SP150 with 150 W peak power. The larger modules are attractive from a cost and watt density standpoint, as applications drive the specific power level required. Flexible automation in the manufacturing of modules is a requirement for both cost and factory ergonomics. Tooling to build a wide array of module types is yet to be developed and supplied to the photovoltaic industry in large volume, and will be a necessary part of continued cost reduction of the products.

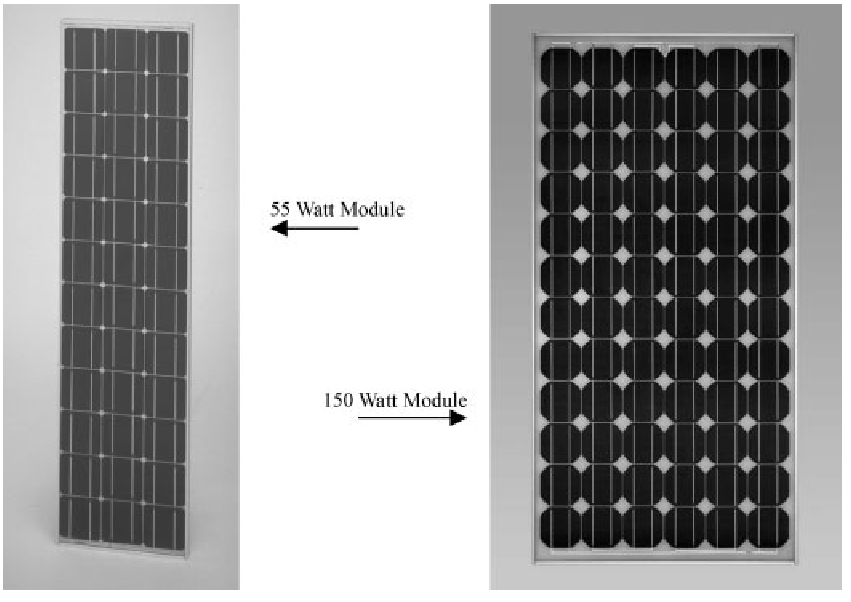

Figure 11. 55 W and 150 W modules

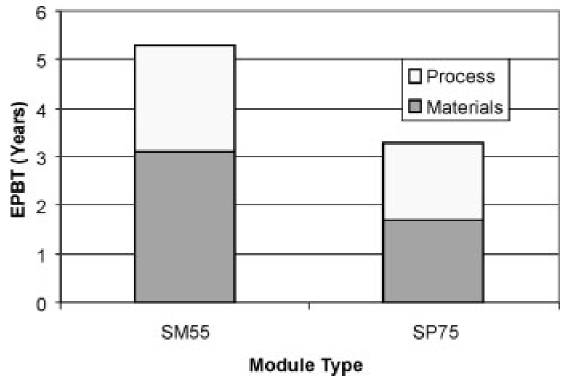

Figure 12. Reduced energy payback times for improved processing and larger modules

Energy payback time

Energy payback time (EPBT) is the analog of financial payback, and is defined as the time necessary for a photovoltaic module to generate the energy equivalent to that used to produce it.[3,4] The gross energy that is required to manufacture a product includes the energy consumed directly by the manufacturer during processing and the energy consumed to produce the raw materials used in the process. The module efficiency determines the rate at which the incoming sunlight is converted to electricity. This ratio of energy consumed to produce the product divided by the energy the solar module produces is the EPBT. For the modules produced by Siemens Solar Industries, this EPBT figure has been steadily decreasing, as shown in Figure 12 where a 55 W module made in 1990 is contrasted with a 75 W module made in the factory in 2000. The larger modules with larger cells, produced using the improvements described, has brought the EPBT down to from over 5 years to approximately 3 years.

SUMMARY

The increasing demand for renewable energy is making photovoltaics a commercially viable energy alternative. Manufacturing volumes have shown a rapid increase to meet market demands. Crystalline silicon still dominates the products commercially available, and cost reductions in the manufacturing processes have cut the product cost by a factor of 2 during the last 10 years. Improved energy efficiency in crystal growth equipment design, coupled with larger ingot growth, has cut the cost of growing crystals significantly. Wafer slicing has moved to wire saws, doubling the effective use of silicon in the process. Cell processing has been automated for both yield and labor efficiency. Larger cells and modules have started to optimize the materials use and energy payback values in producing photovoltaics. Each of these factors is adding to the commercial readiness of solar modules, allowing photovoltaics to compete with established energy supply markets. Progress continues to be made and costs will continue to be reduced.

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