ROLL-TO-ROLL RF PECVD MACHINE FOR a-Si SOLAR CELL MANUFACTURING

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ABSTRACT

Energy Conversion Devices, Inc. (ECD) has designed and constructed a 2 Megawatt (MW) manufacturing line that produces triple-junction spectrum-splitting a-Si alloy solar cells in a continuous roll-to-roll process. The key production machine in this 2MW line is a roll-to-roll RF PECVD machine for depositing a-Si solar cell structures consisting of nine layers of doped and undoped amorphous/microcrystalline silicon. This manufacturing line has reliably and consistently produced high efficiency solar cells. We have demonstrated the production of 4ft^2 triple-junction two band-gap a-Si alloy PV production modules with 8% stable aperture area efficiency. The production line has successfully incorporated: 1) a band-gap profiled a-Si-Ge narrow band-gap solar cell deposited in a continuous roll-to-roll process using a proprietary gas distribution manifold and cathode configuration; and 2) a textured Ag/ZnO back-reflector deposited in a continuous roll-to-roll sputtering machine with production subcell yields greater than 99%.

INTRODUCTION

During the past ten years, ECD has significantly advanced the development of materials, device designs, and manufacturing processes required for the commercial acceptance of photovoltaic technology [1-18]. Among these advancements, ECD pioneered and continues development of two key proprietary technologies having significant potential for achiev-ing the cost goals necessary for widespread growth of the photovoltaic market: 1) a low cost, roll-to-roll continuous substrate solar cell manufacturing process and 2) a high efficiency, multiple-junction, spectrum-splitting amorphous silicon alloy device structure.

Commercial production of multiple-junction amorphous silicon alloy modules has been underway at ECD and its joint venture company since 1985 using ECD's proprietary roll-to-roll process.

ECD has recently designed and constructed a 2MW PV module manufacturing plant for Sovlux, ECD's Russian joint venture company with Kvant. This manufacturing line utilizes a continuous roll-to-roll process to produce triple-junction two band-gap solar cells having a device configuration that previously demonstrated 13.7% initial efficiency. ECD is currently constructing a 5 MW PECVD machine for United Solar Systems Corp (United Solar), ECD's American joint venture company with Canon Corporation, for PV module manufacturing. United Solar will phase in this equipment at its plant in Troy, Michigan to increase production capacity. This new 5 MW plant will provide PV modules with 10% stable efficiency utilizing the most advanced triple-junction, triple-bandgap solar cell structure developed by ECD and United Solar. United Solar recently demonstrated a world record 10.2% stable energy conversion efficiency over a one-square foot area using this advanced technology. The machine will be in operation early in 1996.

In this paper, we report the advances we achieved on the 2MW continuous roll-to-roll amorphous silicon photovoltaic manufacturing line.

ECD'S CONTINUOUS ROLL-TO-ROLL AMORPHOUS SILICON PHOTOVOLTAIC MANUFACTURING TECHNOLOGY

Features and Advantages of ECD's PV Manufacturing Line

1. Spectrum Splitting, Triple-Junction Cell Design

The key feature of our continuous roll-to-roll production line is the use of triple-junction, two band-gap solar cells with high quality, band-gap profiled a-Si alloy as the bottom intrinsic layer, as shown in Figure 1.

ECD has demonstrated 13.7% initial small area photoconversion efficiency in a-Si alloy solar cell devices with a-Si/a-Si/a-Si-Ge triple-junction design.

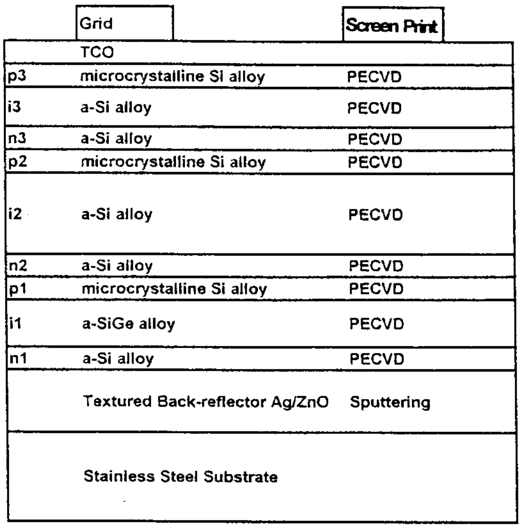

Figure 1: Structure of a triple-junction spectrum-splitting solar cell made in ECD 's continuous roll-to-roll manufacturing process.

The manufacturing line has been designed and engineered to produce solar cells incorporating this most advanced cell design to achieve the goal of high stable efficiency modules.

2. Low cost, large scale continuous roll-to-roll operation.
In the roll-to-roll deposition of a-Si alloy solar cells, nine layers of a-Si alloys are produced in a single pass onto a 2500ft. substrate. This stable steady state process is reliable, and provides uniform cells. The operating cost, which includes maintenance and labor, is low.

3. Flexible thin stainless steel substrate.
The substrate is a 5mil. thick, 14in. wide, 2500ft. long stainless steel roll. It offers many advantages compared to glass substrates. Stainless steel does not shatter during operation and handling. This thin stainless steel substrate can be heated and cooled quickly during deposition, no waiting time is needed for temperature stabilization. During the deposition, the substrate transport mechanism is simple and reliable, and component wear is low. This keeps the maintenance cost low. Also, the substrate is lightweight and flexible.

4. Lightweight polymer encapsulated PV module.
EVA/Tefzel is used for module encapsulation. Modules thus made are flexible, lightweight, and shatter-proof.

ECD's Continuous Roll-to-Roll Manufacturing Line

In the 2MW PV manufacturing line, we deposit triple-junction two band-gap a-Si alloy solar cells in a continuous roll-to-roll process on a 5mil. thick, 14in. wide and 2500ft. long web of stainless steel at a speed of 1 ft./min.

The front end facility of the manufacturing line consists of four continuous roll-to-roll machines:

1. Substrate Washing Machine
2. Back-Reflector Machine
3. Amorphous Silicon Alloy Deposition Machine
4. Transparent Conductor Oxide Deposition Machine

The key process is step 3, the amorphous silicon deposition process, which utilizes a continuous roll-to-roll RF PECVD machine. The amorphous silicon alloy roll-to-roll deposition machine produces, in a single pass, sequentially deposited thin films of doped and undoped amorphous silicon alloy semiconductors. Mixtures of feedstock gases are decomposed at a pressure of approximately 1 Torr in a series of RF CVD plasma chambers to continuously deposit layers of amorphous silicon alloy material onto the coated stainless steel substrate heated to approximately 250°C to 300°C. The multi-section amorphous silicon alloy deposition machine consists of a pay-off chamber section, nine process chamber sections for the triple device structure and a take-up section. The process gas mixtures in each section are dynamically isolated from adjacent sections by proprietary "gas gates." The "gas gates" utilize laminar gas flow through constant geometrical cross section conduits in a direction opposite to the diffusion gradient of the dopant gas concentrations. In this way, migration of dopants between chambers is essentially eliminated and gas mixtures in adjacent chambers are effectively isolated even though no actual physical impediment is present. Substrate transport is accomplished with controlled tension and magnetic rollers for accurate positioning of the substrate in the various process chambers. The web is steered in the take-up chamber to insure that the substrate is properly wound. Substrate passage through the process chambers is such that deposition takes place on the underside, which minimizes film defects due to particulate accumulation. This production equipment has nine RF-plasma deposition chambers to produce a-Si/a-Si-/a-Si-Ge triple-junction two band-gap solar cells. Figure 2 is a picture of the continuous roll-to-roll a-Si alloy deposition machine.

The PV module assembly process consists of the following procedures:

1. Slabbing
2. QA/QC
3. Scribing
4. Short Passivation
5. Screen Print Grid Pattern
6. Final Assembly

Figure 2: Continuous Roll-to-Roll RF PECVD Machine for a-Si Alloy Solar Cell Manufacturing.

The details for the module assembly process have been reported in an earlier paper. [18]

PERFORMANCE OF THE CONTINUOUS ROLL-TO-ROLL AMORPHOUS SILICON PHOTOVOLTAIC MANUFACTURING LINE.

A Typical 2500 Feet (19kW) Production Run
As described previously, ECD's PV production process consists of continuous roll-to-roll machines of; web washing, back-reflector deposition, a-Si alloy deposition, and TCO deposition, followed by module assembly. Ag/ZnO back-reflector, a-Si alloys, and TCO are sequentially deposited onto stainless steel web. A typical 2500 ft. roll is finished within 42 hours. During operation, all of the process parameters are controlled, monitored, and recorded through the use of PC computerized data acquisition and process controlling systems.

Figure 3 shows a three-dimensional plot of subcell efficiency for a 600m production run showing excellent consistency and uniformity.

Module Assembly

Strip cells are produced by processing slabs of solar cell material through TCO scribing, short and shunt passivation and screen printing of Ag paste grid pattern. A strip cell is a single solar cell with an aperture of 12.5" x 5.4". After cutting, trimming and bus bar installing, nine strip cells are connected together in series, as a module. A diode is connected in parallel with every strip to prevent the strip cell from being reverse biased. The module is then vacuum laminated, in a high temperature oven, with Tefzel, EVA and crane glass as the transparent front cover and with layers of EVA, crane glass, nylon, and thin metal backing plate as the back cover. An aluminum frame and junction box are installed to finish the module.

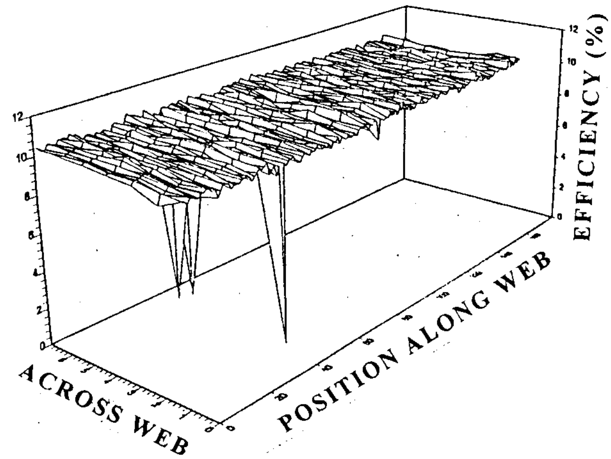

Figure 3: Cell efficiency of a 600m production run.

ECD'S HIGH EFFICIENCY 4FT^2 PRODUCTION MODULE+

4ft^2 modules were assembled using triple-junction two band-gap solar cells produced in a continuous roll-to-roll manufacturing line... The initial aperture module efficiency, measured with a Spire solar simulator, was 9.5% and the total power output was 37.18W for a module of 3923 cm^2 aperture area. This efficiency is higher than any reported efficiency for a-Si alloy production modules.

STABLE EFFICIENCY OF MODULES

To measure the stable efficiency of our modules, light soaking stability tests were conducted. Philip's metal halide 1000/U light bulbs, powered by appropriate ballasts were used. The light intensity is measured with a Silicon detector filtered with a heat filter so that the quantum efficiency of the detector is close to that of an a-Si alloy solar cell. The light intensity inside the module area is within 20% of 100mW/cm^2, with the average at 100 mW/cm^2. Temperature of the module under light soaking was about 50°C to 60°C.

The temperature was slightly higher at the center of the module where the light intensity is about 20% higher than 100mW/cm^2. Each module was degraded with a load such that it was operating at its peak power point. The stable module efficiency after 600 hours of one sun light-soaking at approximately 50°C under load was 8%.

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