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APPLICATION OF MICROBEAM ANALYSIS TO PHOTOVOLTAICS

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Verónica Bermudez obtained her Ph.D. in 1998, entitled: “Production and characterisation of periodic structures in $LiNbO_3$ single crystals doped with Er and Yb”. She has more than 12 years experience as Product Manager, in particular on innovation and new technologies in materials for energy.

During the last years she has been involved as project manager and responsible for the characterisation activities, in the creation of NEXCIS. During this period NEXCIS has enabled me to obtain a large expertise on the pre-industrial steps needed to accomplish the scale up and large scale development of a photovoltaic product, based in this case on electrochemical processes. Being associated to a big industrial partner (EDF), NEXCIS is interested, at term, in mass production of low-cost thin film modules. Therefore, during its creation it has been very important that the project developments are accompanied and assessed by the later end-users from the start. NEXCIS gathers and follows the strong experience formerly acquired at the Institute of Research and Development on Photovoltaic Energy (IRDEP), associating the French utility company EDF, the French research organisation CNRS and the university ENSCP, on the technological development of electrodeposition-based processes for CIGS cells, where she was leading the characterisation group and the European Research activities.

At present she is in charge of the research and innovation activities at NEXCIS, in terms of new materials and concepts to increase photovoltaic performances.

"The total solar energy that reaches the Earth's surface could meet existing global energy needs 10,000 times over."

"Solar can and must be a part of the solution to climate change; microbeam analysis helps us shift away from fossil fuel dependence."

1. INTRODUCTION

There is more than enough solar irradiation available to satisfy the world's energy demands. On average, each square meter of land on Earth is exposed to enough sunlight to generate 1,700 kWh of energy every year using currently available technology. The total solar energy that reaches the Earth's surface could meet existing global energy needs 10,000 times over. A large amount of statistical data on solar energy availability is collected globally. For example, the US National Solar Radiation database has 30 years of solar irradiation and meteorological data from 237 sites in the USA. The European Commission's Joint Research Centre (JRC) also collects and publishes European solar irradiation data from 566 sites. Where there is more Sun, more power can be generated. The sub-tropical areas of the world offer some of the best locations for solar power generation.

The average energy received in Europe is about 1,200 kWh/m^2 per year. While only a certain part of solar irradiation can be used to generate electricity, this 'efficiency loss' does not actually waste a finite resource, as it does when burning fossil fuels for power. Efficiency losses do, however, impact on the cost of the photovoltaic (PV) systems.

EPIA has calculated that Europe's entire electricity consumption could be met if just 0.34 % of the European land mass was covered with photovoltaic modules (an area equivalent to the Netherlands). International Energy Agency (IEA) calculations show that if 4 % of the world's very dry desert areas were used for PV installations, the world's total primary energy demand could be met.

There is already enormous untapped potential. Vast areas such as roofs, building surfaces, fallow land and desert could be used to support solar power generation. For example, 40 % of the European Union's total electricity demand in 2020 could be met if all suitable roofs and facades were covered with solar panels.

Photovoltaic systems contain cells that convert sunlight into electricity. Inside each cell there are layers of a semiconductor material. Light falling on the cell creates an electric field across the layers, causing electricity to flow. The intensity of the light determines the amount of electrical power each cell generates.

A photovoltaic system does not need bright sunlight in order to operate. It can also generate electricity on cloudy and rainy days from reflected sunlight.

PV technology exploits the most abundant source of free power from the Sun and has the potential to meet almost all of mankind's energy needs. Unlike other sources of energy, PV has a negligible environmental footprint, can be deployed almost anywhere and utilizes existing technologies and manufacturing processes, making it cheap and efficient to implement.

PV systems can provide clean power for small or large applications. They are already installed and generating energy around the world on individual homes, housing developments, offices and public buildings. Today, fully functioning solar PV installations operate in both built environments and remote areas where it is difficult to connect to the grid or where there is no energy infrastructure.

Modern PV systems are not restricted to square and flat panel arrays. They can be curved, flexible and shaped to the building's design. Innovative architects and engineers are constantly finding new ways to integrate PV into their designs, creating buildings that are dynamic, beautiful and provide free, clean energy throughout their life.

Even if the bottlenecks in total PV deployment are manufacturing and installation costs the cost of PV systems has been constantly decreasing over time especially during the last decade. Grid parity (traditionally defined as the point in time where the generation cost of solar PV electricity equals the cost of conventional electricity sources) is already achieved for some specific applications in some parts of the world. Competitiveness is just around the corner.

2. WHAT ARE FACTORS BEHIND PRICE COMPETITIVENESS OF PHOTOVOLTAICS

2.1. PV module price

Over the past 30 years the PV industry has achieved impressive price decreases. The price of PV modules has reduced by 22 % each time the cumulative installed capacity (in MW) has doubled. The decrease in manufacturing costs and retail prices of PV modules and systems including electronics and safety devices, cabling, mounting structures, and installation) have come as the industry has gained from economies of scale and experience. This has been brought about by extensive innovation, research, development and ongoing political support for the development of the PV market.

In many countries with high electricity prices and high Sun irradiation, the competitiveness of PV for residential systems could already be achieved with low PV system costs and the simplification of administrative procedures.

Conventional electricity prices do not reflect actual production costs. Many governments still subsidize the coal industry and promote the use of locally-produced coal through specific incentives. The European Union invests more in nuclear energy research (~ € 540 million yearly in average over five years through the EURATOM treaty) than in research for all renewable energy sources, smart grids and energy efficiency measures combined (~ € 335 million yearly in average over seven years through the 7th framework programme). Actually today in Europe, fossil fuels and nuclear power are still receiving four times the level of subsidies that all types of renewable energies do. Given the strong financial and political backing for conventional sources of electricity over several decades, it is reasonable to expect continuing financial support for renewable energy sources, such as wind and solar, until they are fully competitive.

As explained above, the price of PV modules has decreased substantially over the past 30 years. The price of inverters has followed a similar price learning curve to that of PV modules. Prices for some balance of systems (BOS) elements have not decreased with the same pace. The price of the raw materials used in these elements (typically copper, steel and stainless steel) has been more volatile. Installation costs have decreased at different rates depending on the maturity of the market and type of application. For example, some mounting structures designed for specific types of installations (such as BIPV) can be installed in half the time it takes to install a more complex version. This of course lowers the total installation costs. Reductions in prices for materials (such as mounting structures), cables, land use and installation account for much of the decrease in BOS costs. Another contributor to the decrease of BOS and installation-related costs is the increase in efficiency at module level. More efficient modules imply lower costs for balance of system equipment, installation-related costs and land use.

The key parts of a solar energy generation system are:

- Photovoltaic modules to collect sunlight;
- An inverter to transform direct current (DC) to alternate current (AC);
- A set of batteries for stand-alone PV systems;
- Support structures to orient the PV modules toward the Sun.

The system components, excluding the PV modules, are referred to as the balance of system (BOS) components.

The solar cell is the basic unit of a PV system. PV cells are generally made either from:

- crystalline silicon, sliced from ingots or castings,
- from grown ribbons, or
- from alternative semiconductor materials deposited in thin layers on a low-cost backing (thin film).

Thin film modules are usually encapsulated between two sheets of glass, so a frame is not needed. Modules can be connected to each other in series (known as an array) to increase the total voltage produced by the system. The arrays are connected in parallel to increase the system current. The power generated by PV modules varies from a few watts (typically 20 to 60 Wp) up to 300 to 350 Wp depending on module size and the technology used. Low wattage modules are typically used for stand-alone applications where power demand is generally low. Standard crystalline silicon modules contain about 60 to 72 solar cells and have a nominal power ranging from 120 to 300 Wp depending on size and efficiency. Standard thin film modules have lower nominal power (60 to 120 Wp) and their size is generally smaller. Modules can be sized according to the site where they will be placed and installed quickly. They are robust, reliable and weatherproof. Module producers usually guarantee a power output of 80 % of the Wp, even after 20 to 25 years of use. Module lifetime is typically considered of 25 years, although it can easily reach over 30 years.

2.2. Factors affecting PV system cost reduction

The solar industry is constantly innovating in order to improve products efficiency and make materials use more environmentally friendly. However, the cost of PV systems also needs to be reduced to make them competitive with conventional sources of electricity. EPIA believes this can be achieved through:

- Technological innovation;
- Production optimisation;
- Economies of scale;
- Increased performance ratio of PV;
- Extended lifetime of PV systems;
- Development of standards and specifications.

2.3. Technological innovation

One of the main ways the industry can reduce manufacturing and electricity generation costs is through efficiency. When PV modules are more efficient, they use less material (such as active layers, aluminium frames, glass and other substrates). This requires less energy for manufacturing and also lowers the balance of system (BOS) costs. With higher-efficiency modules, less surface area is needed. This reduces the need for mounting structures, cables, and other components. All of these savings affect the final generation cost.

However, efficiency even if it is the most important factor it is not the only one that needs to be studied. The PV sector has a primary goal to introduce more environmentally friendly materials to replace scarce resources such as silver, indium and tellurium, and materials such as lead and cadmium.

Another key area of research aims to reduce material usage and energy requirements. The PV sector is working to reduce costs and energy payback times by using thinner wafers, more efficient wafers, and polysilicon substitutes (for example, upgraded metallurgical silicon). In the field of thin film technologies the top priorities are to increase the substrate areas and depositions speeds while keeping material uniformity.

2.4. Production optimisation

As companies scale-up production, they use more automation and larger line capacities. Improved production processes can also reduce wafer breakage and line downtime (periods of time when the production line is stopped for maintenance or optimisation). Production efficiency improvements enable the industry to reduce the costs of solar power modules.

2.5. Economies of scale

As with all manufacturing industries, producing more products lowers the cost per unit. Economies of scale can be achieved at the following supply and production stages:

- Bulk buying of raw materials;
- Obtaining more favourable interest rates for financing;
- Efficient marketing.

Ten years ago, cell and module production plants could remain viable by producing enough solar modules to generate just a few MW of power each year. Today's market leaders have plants with capacity above 1 GW, several hundred times than a decade ago. Capacity increases, combined with technological innovation and manufacturing optimisation, have radically reduced the cost per unit. The decrease is approximately 22 % each time the production output is doubled.

2.6. Increased performance ratio of PV systems

The cost per kWh is linked to PV system quality and reflected in its performance ratio (the amount of electricity generated by the module compared to the electricity measured on the AC side of the meter). The lower the losses between the modules and the point at which the system feeds into the grid, the higher the performance ratio. Typically, system performance ratios are between 80 and 85 %. If losses can be reduced further, the cost per kWh can be lowered. Monitoring of systems enable manufacturers and installers to quickly detect faults and unexpected system behaviour (for example, due to unexpected shadows). This helps to maintain high performance ratios of PV systems.

2.7. Extended life of PV systems

Extending the lifetime of a PV system increases overall electrical output and improves the cost per kWh. Most producers give module performance warranties for 25 years, and this is now considered the minimum lifetime for a PV module.

2.8. Next generation technologies

Next generation photovoltaics present the greatest potential in cost reduction. The main research activities in this field concentrate on increasing stability over the time and increasing the solar cell area. The industry targets for PV technology development of next generation technologies in the period 2010 to 2020.

3. PHOTOVOLTAIC TECHNOLOGIES

PV technologies are classified as first, second or third generation. First generation technology is the basic crystalline silicon (c-Si). Second generation includes thin film technologies, while third generation includes concentrator photovoltaics, organics, and other technologies that have not yet been commercialized at large scale.

3.1. Crystalline silicon technology

Crystalline silicon cells are made from thin slices (wafers) cut from a single crystal or a block of silicon. The type of crystalline cell produced depends on how the wafers are made. The main types of crystalline cells are:

- Mono crystalline (mc-Si);
- Polycrystalline or multi crystalline (pc-Si);
- Ribbon and sheet-defined film growth (ribbon/sheet c-Si).

The single crystal method provides higher efficiency, and therefore higher power generation. Crystalline silicon is the most common and mature technology representing about 80 % of the market today. Cells turn between 14 and 22 % of the sunlight that reaches them into electricity. For c-Si modules, efficiency ranges between 12 and 19 %. Individual solar cells range from 1 to 15 cm across (0.4 to 6 inches). However, the most common cells are 12.7 x 12.7 cm (5 x 5 inches) or 15 x 15 cm (6 x 6 inches) and produce 3 to 4.5 W – a very small amount of power. A standard c-Si module is made up of about 60 to 72 solar cells and has a nominal power ranging from 120 to 300 Wp depending on size and efficiency.

The typical module size is 1.4 to 1.7 m^2 although larger modules are also manufactured (up to 2.5 m^2). These are typically utilized for BIPV applications.

3.2. Thin films

Thin film modules are constructed by depositing extremely thin layers of photosensitive material on to a low-cost backing such as glass, stainless steel or plastic. Once the deposited material is attached to the backing, it is laser-cut into multiple thin cells. Thin film modules are normally enclosed between two layers of glass and are frameless. If the photosensitive material has been deposited on a thin plastic film, the module is flexible. This creates opportunities to integrate solar power generation into the fabric of a building or end-consumer applications.

Four types of thin film modules are commercially available:

a) *Amorphous silicon (a-Si)*

   The semiconductor layer is only about 1 μm thick. Amorphous silicon can absorb more sunlight than c-Si structures. However, a lower flow of electrons is generated which leads to efficiencies that are currently in the range of 4 to 8 %. With this technology the absorption material can be deposited onto very large substrates (up to 5.7 m^2 on glass), reducing manufacturing costs. An increasing number of companies are developing light, flexible a-Si modules perfectly suitable for flat and curved industrial roofs.

b) *Multi-junction thin silicon film (a-Si/μc-Si)*

   This consists of an a-Si cell with additional layers of a-Si and micro-crystalline silicon (μc-Si) applied onto the substrate. The μc-Si layer absorbs more light from the red and near infrared part of the light spectrum. This increases efficiency by up to 10 %. The thickness of the μc-Si layer is in the order of 3 μm, making the cells thicker but also more stable. The current maximum substrate size for this technology is 1.4 m^2 which avoids instability.

c) *Cadmium telluride (CdTe)*

   CdTe thin films cost less to manufacture and have a module efficiency of up to 11 %. This makes it the most economical thin film technology currently available. The two main raw materials are cadmium and tellurium. Cadmium is a by-product of zinc mining. Tellurium is a by-product of copper processing. It is produced in far lower quantities than cadmium. Availability in the long-term may depend on whether the copper industry can optimize extraction, refining and recycling yields.

d) *Copper, indium, gallium, (di)selenide/(di)sulphide (CIGS) and copper, indium, (di)selenide/(di)sulphide (CIS)*

   CIGS and CIS offer the highest efficiencies of all thin film technologies. Efficiencies of 20 % have been achieved in the laboratory, close to the levels achieved with c-Si cells. The manufacturing process is more complex and less standardized than for other types of cells. This tends to increase manufacturing costs. Current module efficiencies are in the range of 7 to 12 %.

   There are no long-term availability issues for selenium and gallium; indium is available in limited quantities but they are no signs of an incoming shortage. While there is a lot of indium in tin and tungsten ores, extracting it could drive the prices higher. A number of industries compete for the indium resources: the liquid crystal display (LCD) industry currently accounts for 85 % of demand. It is highly likely that indium prices will remain high in the coming years. Typical module power ranges from 60 to 350 W depending on the substrate size and efficiency. There is no common industry agreement on optimal module size for thin film technologies. As a result they vary from 0.6 to 1.0 m^2 for CIGS and CdTe, to 1.4 to 5.7 m^2 for silicon-based thin films. Very large modules are of great interest to the building sector as they offer efficiencies in terms of handling and price.

4. THIN FILM MANUFACTURING PROCESSES

Thin films are manufactured in five common steps:

1. A large sheet of substrate is produced. Typically this is made of glass although other materials such as flexible steel, plastic or aluminium are also utilized.
2. The substrate is coated with a transparent conducting layer (TCO).
3. Semiconductor material (absorber) is deposited onto the substrate or superstrate. This layer can be deposited using many different techniques. Chemical and physical vapour depositions are the most common. For some technologies (usually CIGS, CIS and CdTe), a cadmium sulphide (CdS) layer is also applied to the substrate to increase light absorption.
4. The metallic contact strips on the back are applied using laser scribing or traditional screen-printing techniques. The back contact strips enable the modules to be connected.
5. The entire module is enclosed in a glass polymer casing.

For flexible substrates, the manufacturing process uses the roll-to-roll (R2R) technique. R2R enables manufacturers to create solar cells on a roll of flexible plastic or metal foil. Using R2R has the potential to reduce production time, and both manufacturing and transport costs. R2R can be used at much lower temperatures in smaller, non-sterile production facilities.

With the fact that efficiency is the main driver of costs for a PV module it is intended to lead the audience to explore beyond the accepted casual connection between the engineering properties of materials and their microstructural features. The processing route used to manufacture a component (shaping process, thermal treatment, mechanical working, etc.) effectively determines the microstructural features as it is shown in Fig. 1.

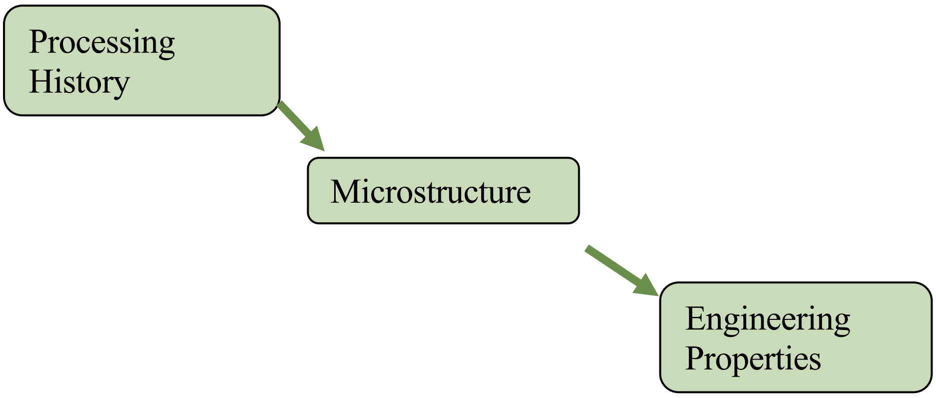

Figure 1.

It is important to note the interrelation between microstructure and the chemical, physical, and/or mechanical properties of materials, developing expressions for the dependence of these properties on such microstructural concepts as grain size, grain boundary, … In particular in this talk apart from the direct relation of performance with microstructure, we will give some details preferred methods used in the PV community to identify microstructural features and how the analysis helps us to convert the microstructural observation into a parameter with some useful engineering significance.

In particular we will analyse the application of microstructural characterisation from three different aspects:

Identification of phases;
Morphology of these phases (size, shape and spatial distribution);
Local chemical composition and variation induced in electronic properties.

We will be concerned not only with the quantitative phase identification, but also with the elementary aspects of applied crystallography used to determine crystal structure, as well as with the quantitative determination of the volume of each phase. Stereological relationships will be included, such as the individual grain seen in a cross-section, into a clearly defined microstructural parameter, the grain size. We will seek to determine the local chemical composition through microanalysis and their impact in optoelectronic properties of the layers and interfaces conforming a solar cell and thus in final cell performance.