The fundamental of standard crystalline silicon solar cells and modules.

The Sun provides more energy every hour than the entire world population consumes in a whole year and the solar power is quickly becoming a clean and affordable alternative to fossil fuels due to advances in technology and high volume manufacturing of the solar cells, the direct converters of sunlight to electricity. There are a large variety of the solar cells but the bulk crystalline silicon cells account for over 90 % world production volume. The first silicon solar cell with a conversion efficiency of 6 % was developed in 1954 at Bell Laboratory in USA and after half of century the highest efficiency verified for the monocrystalline Si cell is 24.7 % [1]. The solar cells in mass production have an average efficiency between 15 – 20 %.

Today, most of solar cells are produced on the base of 6 inch square, 200 μm thick, boron doped, p-type, 1 Ωcm resistivity, monocrystalline (Cz-Si) and multicrystalline (mc-Si) silicon wafers.

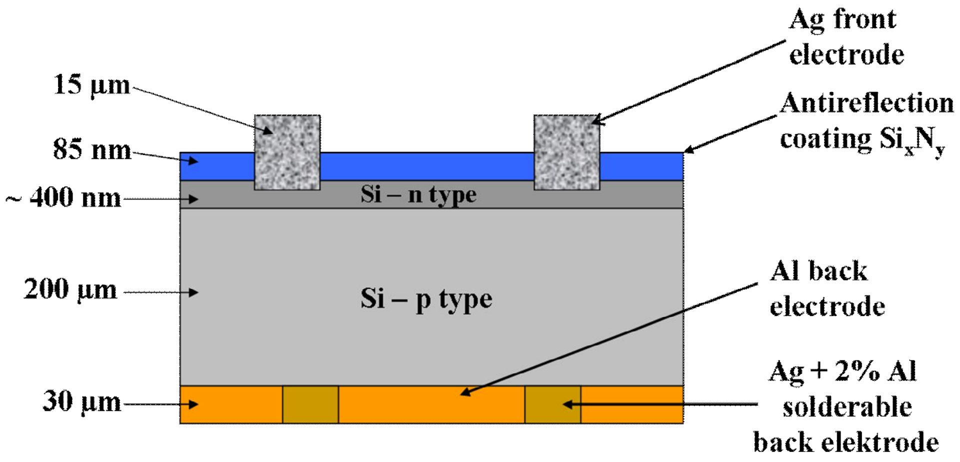

Fig. 1. Schematic diagram illustrating the construction elements of standard crystalline silicon solar cell.

The process uses silica as the starting material. Silica is reduced to metal grade Si of 98 % purity, and than repeated refining is carrier out to obtain polycrystalline Si of purity better than 99.9999 %. The silicon wafers are grown in large ingots carried out either by directional crystallization or the Czochralski growth process. The sawing of Si wafers from an ingot or block is mainly carried out in multi-wire saws with silicon carbide SiC particles in a solution with polyethylene glycol. During separation, the wafer surface is damaged and covered with small cracks. A layer with thickness of 10 μm from both sides of Si wafer is removed during chemical etching in a 20 - 30 wt. % aqueous solution of KOH at temperature 80 ^{o}C. The wafer surface after such alkaline process is flat. Most industrial processes today include a texturing step which has two beneficial effects. Firstly, reduces the reflectance from more than 35 % to less than 10 %, and secondly, ensures that light rays are coupled into the cell under an oblique angle, making it less probable that they will escape from the front surface after reflection from the rear. This effect is especially important when using the substrate under 200 μm thick [2]. Following all chemical processes rinsing with 18 MΩcm deionised water take place as a final stage. The crystalline solar cell on the base of p-type silicon has a planar diode structure, where a 0.4 μm thin n^+ layer of heavily doped silicon, called the emitter, is present at the front of a wafer. In the standard process, the emitter is formed by diffusion using as a phosphorus source the phosphorous oxychloride $POCl_3$. When the wafer is introduced into a process chamber at 850 ^oC, with the small amount of oxygen, the phosphosilicate glass $SiO_2:P_2O_5$ (PSG) is formed at Si surface as a direct source of P elements. After diffusion process the phosphorous total concentration can be higher than the electrically active. That non-active layer is characterized by extremely short of the current curriers lifetime and for this reason is called "dead layer'. Phosphorous not only diffuses into the desired front surface but also the side and the opposite surface to some extend. This gives a shunting path between the cell front and rear. The edge isolation is curried out by laser. In this process, laser scribe an isolation grove on the front surface, usually 15 µm deep into the underlying p-type silicon. In the standard mass manufacturing process, emitter formation and junction isolation is followed by an HF dip to remove PSG after which the passivation layer is applied, usually SiO_2 or Si_xN_y:H. This step reduces surface recombination velocity (SRV), substantially increasing short circuit current and thereby the cell efficiency. In order to capture as many photons from the solar spectrum as possible, it is necessary to coat the silicon substrate with an antireflection layer (ARC). Currently, the silicon nitride Si_xN_y:H is used for all types of silicon solar cells. It has been shown that for a single layer of silicon nitride, the maximum efficiency of light conversion for the Si/SiN/air stack is obtained at refractive index n ~2.05 at a thickness of d ~85 nm. The silicon nitride deposited on the wafer contains approximately 10 – 15 % at. H and is a source of hydrogen to saturate defects on the surface and in the bulk of Si [3]. Industrial systems for Si_xN_y:H deposition can be divided in two main groups: direct or indirect plasma enhanced chemical vapor deposition (PECVD) system, which are based on ionizing the NH_4 and SiH_4 precursor gasses using an electric field. The advantages for an indirect plasma system are the decoupling of the plasma and wafer transportation system which make it possible to use wafer with any size and shape and low ion energies, preventing surface damage and resulting better surface passivation [4]. On single crystalline silicon, Si_xN_y:H provides a surface passivation very similar to that thermally grown SiO_2, which implies SRV < 100 cm/s [5]. Front and back side ohmic contact of crystalline solar cells is currently done by screen-printing a thick film of Ag and Al pastes. Front contact Ag fingers are up to 120 µm wide to obtain sufficient electrical specific resistance below 1 Ωcm. Al is deposited as a paste on the backside contact, which generally covers the entire underside of the cell. Such prepared structure, dried at 180 ^oC for 15 minutes is fired at temperature around 770 ^oC in infrared (IR) belt furnace to form metal electrodes in ohmic contact with the silicon. Since Al is not directly solderable, an Ag + 2 %Al composite paste is also sintered onto back bus bares. The Al forms alloys at eutectic point at 577 ^oC and has a relatively good solubility with concentrations of approximately 10^{19} cm^{-3} in silicon [6]. Metallization based on screen-printed aluminium paste is well proven and is low in investment. It can yield back surface field conditions after alloying and allows easy integration into inline process. The final performance of a solar cell is evaluated by studying the current-voltage (I-V) characteristic measured under standard test conditions, what means AM1.5 spectrum at temperature 25 ^oC. The current is proportional to light intensity whereas the voltage is characteristic of semiconductor and for Si is about 0.6 V. This presented technology process is a compromise between low cost of manufacture and cell efficiency.

Solar cells are interconnected in a series to obtain a configuration which decided of the required output current and voltage. To protect the cells from the environmental effects, the cells are fixed to a module in which the high transmission glass substrate type is the most commonly used design what is presented in Fig. 2. PV modules carry a 25 year warranty. Solar encapsulates are typically made with ethylene vinyl acetate (EVA) and teflon backsheet foil. The completed laminate is than placed into the laminator machine, which is heated to a temperature of 150 ^oC for 15 min. to melt the encapsulant materials. During the lamination step, a membrane presses solar module made of glass, solar cells and foils with the pressure of up to 900 mbar.

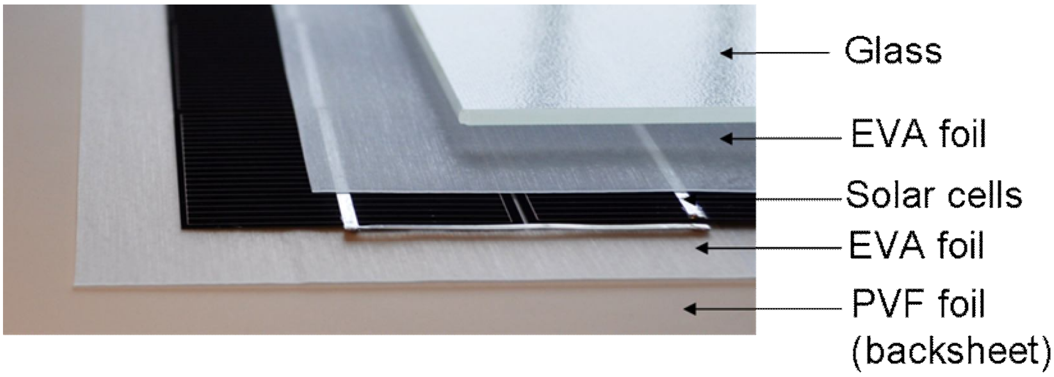

Fig. 2. Cross-sectional view of module layers.

A vacuum is than applied to remove any air bubbles trapped during the process. While the glass provides the required durability and surface transparency, the backsheet provides physical protection, electrical insulation and a barrier to moisture ingress [7]. Gaskets, silicone adhesive and mounting frames are the other materials requires for framing after lamination. Modules are designed to meet rigorous certification tests set by international standards agencies. Standard crystalline Si modules contain 36 to 72 cells and have a nominal power ranging from 50 to 300 Wp. If more power is required for any application, than a PV system is build by linking more modules normally operating at 12 or 24 volts. The small modules for consumer and miscellaneous application have from 1 to 50 Wp.

There are a large variety of crystalline Si solar cells. One is the laser grooved buried contact cell in which the narrow grooves cut by laser through a silicon nitride are filled with plated nickel and copper. Some cell designs use laser drilled holes to form emitter wrap-through (EWT) or metal wrap-through (MWT) construction. In EWT device the metal contacts of both polarities are located on the rear side and is particularly suited for Si with low bulk diffusion lengths and offers the advantages of reduced shading losses and increased emitter area. The MWT cell uses the holes to bring the front contact to the back side, enabling the use of surface-mount methods to provide a high packing density and low resistance losses to increase the efficiency at the module level [8]. Back contact solar cells offer various advantages over conventionally designed cells but their technology process is more complicated.

In recent years developers have also successfully reduced the use of energy and materials in the production, increased the throughput and minimized the error rate. At present, the size of a technologically complete line has an annual capacity of around 50 - 350 MWp. The thickness of crystalline Si wafers has been reduced from 300 µm to currently 200 µm, whereas some manufacturers are able to change up to 150 µm. Cost reduction due to scale effects and technology development bring the direct manufacturing costs of crystalline silicon solar modules down into the range of 0.9 – 1.3 Euro/Wp. This cost corresponds with the level needed to enable “grid parity’, the situation when solar electricity becomes competitive with retail electricity [9]. Despite progress in all aspects of production crystalline Si solar cells and the rapid decrease of production cost for photovoltaic modules, the cost of “solar electricity” is still to high to compete with other sources of electricity generation. In Poland climate, taking into account the PV system costs, one arrives at a cost of 2 zł / 1 kWh, which is definitely to high. Beside the development of new solar cells and modules technologies, large scale manufacturing plants above 500 MWp, are recognized as a part of the second strategy to reduce the overall cost of manufacturing and a bright future for PV.

PV market has never performed so well in its entire history. Once again in 2010 its growth worldwide has been impressive with an estimated installed capacity between 14.3 and 16.5 GWp and the total installed capacity has reached at least the 37 GWp [10].

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