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Technological status of plasma-deposited thin-film silicon photovoltaics [☆]

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ABSTRACT

Basic properties of plasma-deposited amorphous and microcrystalline layers are summarized. Limitations for solar cell performance, which are a result of these basic properties are pointed out. Efficiencies and other solar cell parameters obtained for the best laboratory cells are presented and the resulting implications for future research discussed. Large-area Industrial modules and their typical key parameters are then given. Conclusions for the future market position of thin-film silicon PV as very low-cost renewable source of electricity are drawn up.

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1. Introduction: basic properties and facts

Before we report on the status of plasma-deposited thin-film silicon solar cells and modules, we would like to recall some basic facts, which one should always keep in mind, when attempting to evaluate this technology.

1.1. *p-i-n* structure

Plasma-deposited thin-film silicon solar cells always use the *p-i-n* structure, unlike all other solar cells, which use the *p-n* structure. This is because of two reasons: (a) the “quality” of the layers is low (very high density of recombination centers); it is therefore necessary to have drift-assisted transport, because the diffusion lengths are far too low for effective carrier collection; (b) doped layers have, in general, even higher density of recombination centers, and carriers photo-excited in the doped layers can usually not be collected. Thus, the absorber layer in a thin-film silicon solar cell is always an intrinsic layer.

1.2. Possibilities for absorber layer

The *main* possibilities used today for absorber layers are:

(a) (Hydrogenated) amorphous silicon, a-Si:H

(b) (Hydrogenated) amorphous silicon–germanium alloys, a-Si, Ge:H
(c) (Hydrogenated) microcrystalline silicon, $\mu\text{c-Si:H}$

These layers always contain a significant amount of hydrogen; without the hydrogen, the layers would not even have any semiconducting properties at all – the defect densities would be so high that nothing meaningful could be measured.

1.3. Plasma-deposition

This is up to now the main method of producing device-quality a-Si:H, a-Si,Ge:H and $\mu\text{c-Si:H}$ at low deposition temperatures ($< 300\text{ }^\circ\text{C}$); it is the only method industrially used so far. The source gas for the plasma is usually silane diluted in hydrogen-plus, optionally, dopant gases. Controlling plasma deposition over large areas is complex, much more than e.g. sputtering. This is one of the main reasons why progress in thin-film silicon solar cells was at times excruciatingly slow. A particularly interesting technique of plasma deposition, specially suited for the fabrication of thin-film silicon solar cells at higher deposition rates is the so-called “VHF plasma deposition method” (see [1,2]). In the last decades significant improvements have taken place (in synergy with the flat panel display industry) in the understanding of parallel plate PECVD deposition, and large area tools are now routinely available.

1.4. Necessity for light trapping

Amorphous absorber layers {(a) and (b) in the above list} have higher absorption coefficients (within the useful range of the solar spectrum) than microcrystalline absorber layers {(c) in the above

[☆]Please note that this report and the data given herein make no claim on completeness or comprehensive coverage of all the important research and development efforts in the field, authors have used discretion to present selective examples for the status report.

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list). In both cases, however, the possible absorber layer thicknesses are much lower than the penetration depths for most parts of the solar spectrum. Therefore, thin-film silicon solar cells need to use sophisticated light-trapping techniques, in order to obtain “decent” current densities. This point is especially critical for microcrystalline silicon with its indirect band-gap and extended spectral range. Light trapping is generally obtained by the use of rough or “textured” TCO contact layers, but other techniques are beginning to be employed, such as the use of textured or nano-imprinted glasses.

1.5. Band-gaps of thin-film silicon layers

Amorphous silicon (a-Si:H) has a band-gap in the range of 1.7–1.8 eV; the exact value depending on the deposition conditions

- An increase in deposition temperature leads, in general, to a decrease in band-gap.
- An increase in hydrogen dilution leads to an increase in the band-gap, until one reaches the “transition point”, after which the material becomes microcrystalline

Microcrystalline silicon (μ -Si:H) has the same band-gap as a crystalline silicon wafer, i.e. 1.12 eV.

Amorphous silicon-germanium alloys (a-Si,Ge:H) have band-gaps ranging from 1.7 eV (no germanium content) down to 1.0 eV (no silicon content). Layers often used in multi-junction solar cells have a composition of $50\% \pm 20\%$ silicon and $50\% \pm 20\%$ germanium and band-gaps between 1.2 eV and 1.5 eV.

1.6. Staebler–Wronski effect or light-induced degradation (LID)

Amorphous absorber layers suffer from an initial light-induced degradation effect, called the “Staebler–Wronski effect”. The Staebler–Wronski effect saturates after a few hundred hours of light exposure. This means that amorphous silicon solar cells have initial efficiencies, which are significantly higher (10–30% higher) than the “stabilized” equilibrium efficiencies reached typically after 1000 h at 50°. In outdoor conditions, the “stabilized” efficiency can be somewhat higher or lower than the rated efficiency, depending on the temperatures and history of temperature: An example that is frequently encountered, especially in tropical countries, are modules, which operate at average temperatures higher than 50 °C; here, the effective output power will usually be substantially higher than the rated value as measured under Standard Test Conditions (STC), because the Staebler–Wronski effect is reduced by an increase in operating temperature.

1.7. Band-tails and V_{oc} -limitation

Physically speaking, the presence of pronounced band-tails is a characteristic of all amorphous layers; these band-tails are a direct consequence of the disorder in the atomic structure. Doping is impaired by the presence of the band-tails – it becomes impossible to push the Fermi level very near to the band edge. On the other hand, the open-circuit voltage V_{oc} of a solar cell is limited by the relative difference in Fermi-level positions of the n - and p -layers. For this reason V_{oc} -values of amorphous solar cells are always significantly lower than corresponding values of crystalline solar cells with the same band-gap. Thus, the “best” a-Si:H solar cells have V_{oc} -values of around 1 V, instead of 1.4 V, which would be attainable with a crystalline solar cell with the same band-gap of approx. 1.75 eV. Noticeably though, the voltage of amorphous cells, is the highest among all commercial PV technologies (outside of III–V). This translates into a low coefficient of temperature (typically $-0.2\%/^{\circ}\text{C}$), which ensures a high energy yield for a-Si:H modules.

1.8. Tandems and multi-junction cells/modules

To make a more effective use of the solar spectrum, tandem and multi-junction solar cells have been introduced very early in the development of plasma-deposited thin-film silicon solar cells. They constitute now the main line for future work.

1.9. Comparison with Re-crystallized thin-film silicon

There are significant differences between thin-film solar cells based on “direct” plasma-deposition and those which use subsequent (re)-crystallization techniques: the former are characterized by (a) lower processing temperatures; (b) amorphous structure or else: crystalline structure with extremely small (200 nm) grain size and lower carrier mobility but higher lifetime thanks to quasi-perfect hydrogenation; (c) impossibility to use doped layers for photo-absorption; (d) possibility to use underlying TCO (transparent conductive oxide) layers for current collection {possible, because of the low processing temperatures}. A status report on re-crystallized thin-film silicon solar cells is given as a separate paper, within this Special Issue, under the title “Technological status of polycrystalline silicon thin-film solar cells on glass”.

2. Thin-film silicon laboratory cells (approx. 1 cm² area)

2.1. Single-junction amorphous silicon solar cells

Amorphous silicon solar cells were introduced in the mid 70's and were at that time considered to be a very promising option for low-cost photovoltaic modules. The first application was found as power supplies for electronic calculators, where they are still used to date. These solar cells have relatively low efficiencies, in the range of 4–5%. For energy applications higher efficiencies would be needed. This seemed at first to be theoretically possible: If one takes the band-gap of amorphous silicon to be 1.8 V, one should be able to achieve an efficiency over 20%, with the values $V_{oc} \approx 1.4$ V, $J_{sc} \approx 18$ mA/cm², FF $\approx 85\%$ according to the semi-empirical limit given by Martin Green [3].

It became, however, soon quite clear that the efficiency of single-junction amorphous silicon solar cells is limited to much lower values. This is due to two factors:

- The light-induced degradation effect (LID), which limits the fill factor (70% can be considered, based on past experience, to be a limit value for what can be attained in the stabilized state, after LID),
- The V_{oc} -limitation because of the band-tails (to around 1 V in the very best case).

Thus, even if one could achieve “miraculously effective” light trapping, converting thereby all photons with energies above 1.8 eV into electron and hole pairs, and assuming these pairs contribute all to the short-circuit current (without recombining), one would obtain $J_{sc} = 18$ mA/cm²: This now leads to an efficiency of only 12.5%. The best single-junction amorphous silicon solar cell has a stabilized efficiency of 10.1% (see Table 1), which means that there is only a limited increase in efficiency yet to be gained from a single-junction a-Si:H solar cell. (Noticeably however, in the spectral range of 300–700 nm, the efficiency of a-Si:H cells is above 20%, and much higher AM 1.5 efficiencies can hence be reached, when a-Si:H top cells are combined with the right bottom cells within tandem and multi-junction configurations.)

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