

# PROGRESS IN AMORPHOUS SILICON BASED SOLAR CELL TECHNOLOGY

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## *Abstract*

*As the negative environmental effects of the current use of non-renewable energy sources have become apparent, hydrogenated amorphous silicon (a-Si:H) solar cell technology has advanced to provide a means of powering a future sustainable society. Over the last 25 years, a-Si:H solar cell technology has matured to a stage where there is currently a production of 30 MW<sub>peak</sub>/year; and this production capacity continues to increase. The progress is due to the continuous advances made in new materials, cell designs, and large area deposition techniques for mass production. The absence of long-range order result in not only characteristics which make a-Si:H excellent for thin film solar cells, but also provide great flexibility in the design of different solar cell structures and in the manufacturing of large area monolithic modules. A review is presented here of the progress in the development of a-Si:H based materials as well as the evolution of solar cell structures which led to the continuous improvement in their performance and stability.*

## 1. INTRODUCTION

The negative social, health, and environmental impacts of our current unsustainable patterns of energy use are apparent (Minger, 1990; Keeling *et al*, 1997). If current trends continue, future society will require the use of even more energy. Thus, large-scale alternative methods of providing this energy are needed to permit sustainable development (WCED, 1987; Flavin, 1992). Definitions of sustainable development generally encapsulate some version of that found in the World Commission on Environment and Development, where sustainable development is “development that meets the needs and aspirations of the present without compromising the ability of future generations to meet their own needs” (WECD, 1987:43). Fortunately, advances in science and technology have provided us with several alternative means of producing energy on a sustainable level, such as wind, geothermal, biomass, and solar (Turner, 1999). Of these means, solar (photovoltaic technology) provides the most widely adaptable applications of converting sunlight directly into electrical energy (Rose, 1979; Shah *et al*, 1999). Cost, remaining the leading factor in the adoption of solar cells, is being greatly reduced for all types of photovoltaic materials. Of the photovoltaic materials, we will consider a-Si:H here, because of its comparative economic viability as a source of renewable energy. This economic advantage exists for a-Si:H because the disordered nature of the material gives it greater flexibility in tailoring improved photovoltaic properties and solar cell structures. It also allows for conformal, large area deposition at relatively low temperatures on a variety of substrates that facilitates the mass production of a wide range of photovoltaic modules. Mass production lowers production costs, thereby opening market opportunities for commercial residential applications and building facades, as well as the established off-grid applications.

The first report of amorphous silicon solar cells in 1976 (Carlson and Wronski, 1976) sparked worldwide interest because of their promise as an economically viable source of renewable energy. The discovery of the importance of hydrogen in these materials (Brodsky *et al*, 1977), led to a wide range of deposition techniques and conditions which attempted to improve the properties of hydrogenated amorphous silicon (a-Si:H). The early discovery of light induced changes (Staebler and Wronski, 1977) had a major impact on the design of the a-Si:H solar cells – as *stabilized* cell

efficiencies became the figure of merit. Advances made in improving materials, device structures, and manufacturing processes sustained progress (as seen in Figure 1) in a-Si:H based technologies. Currently there is a 30MW annual production capacity for a-Si:H solar cells, which includes the manufacture of 2ft x 4ft monolithic panels. The immense potential for growth in the photovoltaic industry assures that the progress of a-Si:H technology is far from complete.

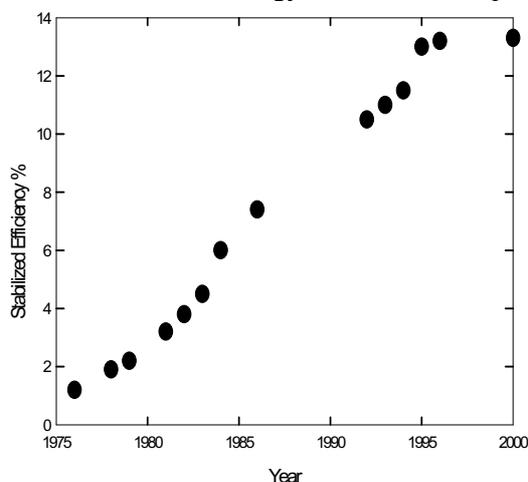


Figure 1. Advances in Stabilized efficiency of a-Si:H solar cells.

## 2. PROGRESS OF A-SI:H MATERIALS

The materials used in the a-Si:H based solar cells are deposited by plasma enhanced chemical vapor deposition. This relies on the decomposition of gases containing silane ( $\text{SiH}_4$ ) in plasmas created with DC, r.f., VHF and microwave power sources. These materials are in fact silicon hydrogen alloys which typically contain about 5 to 20 at.% of hydrogen. The intrinsic disorder of the material creates broken bonds which negatively impact the electronic properties of a-Si:H materials. Passivation of the broken bonds by hydrogen reduces their electrical density from  $\sim 10^{19} \text{ cm}^{-3}$  present in unhydrogenated a-Si to as low as  $10^{15} \text{ cm}^{-3}$  in a-Si:H. The incorporation of hydrogen and disorder also have a profound effect on the bandgap and optical absorption. a-Si:H does not behave like an indirect bandgap semiconductor so that even though its bandgap increases to  $\sim 1.7 \text{ eV}$  it has the very high optical absorption typically associated with direct bandgap semiconductors. Because of the low densities of defects in intrinsic materials the incorporation of dopants during deposition allows the formation of n and p-type materials making a-Si:H unique amongst amorphous materials.

Another property which greatly enhances the flexibility of a-Si based materials is the ability to form a-Si:Ge:H and a-Si:C:H alloys by concurrent decomposition of  $\text{GeH}_4$  or  $\text{CH}_4$ . This has allowed a variety of multijunction cells to be developed which have been a key element in improving the performance (efficiency) of a-Si solar cells. The bandgaps of these alloys are as low as 1.3 eV for the a-SiGe:H and as high as about 2.0 eV for a-SiC:H materials. By appropriately changing the deposition conditions, it has also been possible to deposit high quality nano- and micro- crystalline ( $\mu\text{c}$ ) Si materials that can be used as an intrinsic as well as n and p doped contact materials. By optimizing the growth conditions, it is possible to obtain outstanding properties for an amorphous semiconductor.

The light induced degradation of a-Si:H materials electronic properties was first observed as the large changes due to sunlight in the carrier transport of thin films which were found to be completely reversible after annealing the materials for several hours at temperatures  $\geq 150^\circ\text{C}$  (Staebler and Wronski, 1977). These changes, result from the introduction of meta-stable defects whose rate of creation and density depend on both the illumination intensity and temperature. The reversible changes that occur between an “annealed” state and a “light soaked” state have become one of the most investigated phenomena in a-Si:H-based materials and solar cells (Wronski, 1984). However, advances have been made in the understanding of SWE, but as of yet there is still no *general*

*agreement* on the *exact nature* of the light induced defects or the mechanism responsible for their creation. There is general consensus, however, that hydrogen, which plays a key role in eliminating the defects in the a-Si:H alloys, also plays a key role in their creation by light (Fritzche, 1997; Stutzmann, 1997; Wronski, 1997). Continuous, progress has been made over the years not only in improving the initial properties of a-Si based materials but also in reducing their light induced degradation. This has been achieved by optimizing the growth conditions of the materials that improved the incorporation of hydrogen into the network and the corresponding microstructure.

The quality of the a-Si based materials is determined by deposition parameters such as: substrate temperature, pressure, flow rate of the source gases, plasma frequency, power, electrode spacing, and dilution of the feedstock gases with hydrogen. Although it was shown in 1986 that light induced degradation in a-Si:H films was improved by diluting SiH<sub>4</sub> with hydrogen (Ganguly et al, 1986), it was not until several years later that the first results of a similar effect on solar cells were reported (Bennett *et al*, 1993). At about the same time the beneficial effects on a-Si:H alloys were also reported (Collins and Vedam, 1995). In depth understanding of the effects of hydrogen dilution on the growth and microstructure of a-Si has been obtained from real time spectroscopic ellipsometry studies (Lu *et al*, 1994; Koh et al, 1998). This work has developed evolutionary phase diagrams that describe how the different hydrogen dilution ratios lead to different thickness regimes of bulk layers in which predominantly a-Si:H and  $\mu$ c-Si:H films are obtained. Such phase diagrams identify four separate growth regimes: 1) a-Si:H with a smooth surface and a stable roughness layer thickness, 2) a-Si:H with a rougher surface and an unstable roughness layer thickness, 3) mixed phase (a+ $\mu$ c)-Si:H, and 4) fully coalesced (single phase)  $\mu$ c-Si:H. This is illustrated in Figure 2 for a-Si deposited onto c-Si substrates at 200°C under standard r.f. power conditions where the dependence is shown of the thickness at which the phase boundaries occur as a function of hydrogen dilution. Results of detailed studies, which also established how the location of these boundaries depends on the substrate, have enabled the optimum i-layers for p-i-n solar cells to be identified (Koval *et al*, 1999), and, controlled improvements in p/i interfaces to be carried out (Pearce *et al*, 2000). Results on p-i-n solar cells have shown that optimum material is deposited under conditions that produce a stable surface throughout the i layer growth (shaded area), a characteristic associated with the concept of a more ordered "protocrystalline" material (Koh *et al*, 1998). The large improvement in the stability of cells whose a-Si:H i layers are grown in this regime, over those grown with an amorphous unstable surface, is illustrated in Figure 3 which shows the changes in Fill Factor (FF) under 1 sun illumination at 25°C for p-i-n solar cells with 400nm i layers deposited with R=0 and R=10 (where R=H<sub>2</sub>/SiH<sub>4</sub>).

### 3. PROGRESS IN A-SI:H SOLAR CELLS

Protocrystalline solar cells have superior performance to standard a-Si:H solar cells. Not only does the protocrystalline cell retain a high FF and efficiency but it also reaches a degraded steady state (DSS) at 25°C in less than 100 hours of illumination whereas the R=0 cell attains a much worse DSS only after several hundreds of hours. The materials obtained with high hydrogen dilution, which are microcrystalline throughout their entire thickness, do not exhibit any light induced changes. These materials have the same bandgaps as c-Si and offer an alternative to the unstable a-Si:Ge:H alloys and have been incorporated into solar cells (Meier *et al*, 1998; Vetterl *et al*, 2000).

From the beginning, the developers of a-Si based solar cells sought improvements in the performance not only of the initial but also the degraded solar cell efficiencies. At first the effort focused on single junction a-Si:H cells but quickly expanded to include optimization of tandem and multi-junction cells with particular emphasis being given to the 1 sun DSS efficiencies. The development proceeded along several tracks that included improvements in materials and solar cell structures as well as *engineering* approaches for minimizing the effects of light induced degradation. It also relied heavily on the flexibility that a-Si alloys offer in terms of bandgaps and their ability to generate high open circuit voltages (Guha *et al*, 1986).

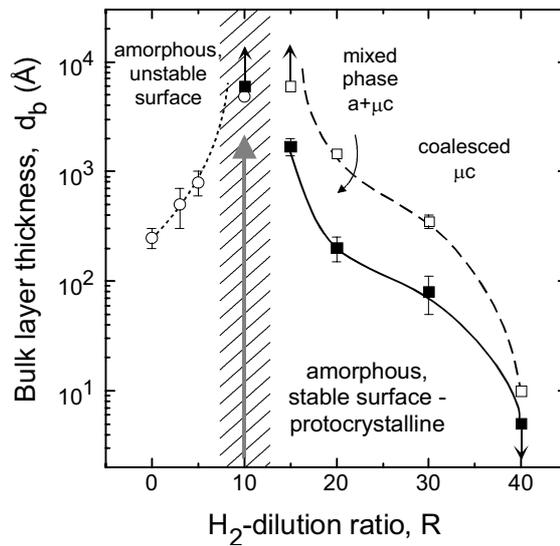


Figure 2. Film thickness,  $d_B$ , for the different phase transitions during growth as a function of hydrogen dilution ratio  $R$ .

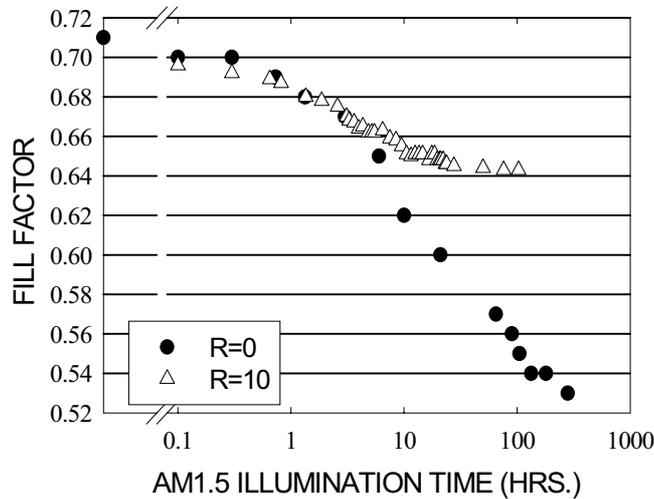


Figure 3. Degradation of an  $R=0$  and an  $R=10$  protocry stalline p-i-n solar cells

The challenge was to maximize the thickness of the *i*-layers for absorption of sunlight without loss in the ability to efficiently collect carriers so as to obtain fill factors. The acceptable thicknesses of such high performance cells were further limited by the SWE because of the decrease in carrier collection caused by light induced defects which leads to degradation of the FF.

A major breakthrough in achieving thin, high efficiency cells was obtained with the application of optical enhancement achieved with textured substrates and reflectors (Yablonovitch and Cody , 1982). The large optical enhancement obtained by texturing which results in multiple internal reflections allows weakly absorbed light to undergo many passes through the *i*-layer. This in effect greatly increases optical absorption at longer wavelengths so that significantly higher quantum efficiencies can be obtained at these wavelengths without any increase in the cell thickness.

By taking advantage of optical enhancement, as well as the continuous improvements in materials such as obtained with “protocry stalline” com ponents, has led to significant improvement in performance and stability of single junction cells. However, the large interest in further improving not only the initial, but in particular the DSS efficiencies, initiated the early development of multijunction cells which more efficiently generate power from the different parts of the solar spectrum. Continuous progress has been made on such multijunction a-Si:H/a-SiGe:H (tandem) cells, but their performance is still seriously limited by the quality of the narrow bandgap a-SiGe:H materials which are markedly inferior to that of a-Si:H. To overcome this limitation, special cell designs have been developed for maximizing the cell performance and at the same time minimizing its light induced degradation. This

includes bandgap profiling and constructing cells whose initial performance is not necessarily optimized, but rather individual degradation is taken into account so as to achieve a maximum stabilized overall performance (Yang *et al*, 1994).

Triple junction (a-Si:H/a-SiGe:H/a-SiGe:H) stacked cells offer an even more efficient utilization of the solar spectrum with thin component cells where the i layer materials have appropriate bandgaps for successful absorption and collection of blue, green, and red light (Yang *et al*, 1998). The highest efficiencies have been obtained with cell combinations where: the top cell, which captures the blue photons, has an a-Si:H i-layer with a gap of  $\sim 1.8$  eV; the middle cell, ideally suited for absorbing the green photons, is a a-Si:Ge:H with a gap of  $\sim 1.6$  eV; and the bottom a-Si:Ge:H cell, capturing the red and the infrared photons, has a gap of  $\sim 1.4$  eV. The introduction of a third cell increases the open circuit voltage but lowers the short circuit current relative to the tandem structures since now each component cell absorbs a smaller fraction of the solar spectrum. It is important to note here also that currents are generated in triple junction cells that are thinner than those of the other cell structures. This lowers the requirements on carrier transport for efficient collection of carriers and high fill factors thus reducing the deleterious effects of light induced defects.

In order to avoid light induced degradation effect completely p-i-n and n-i-p solar cells are being developed with microcrystalline Si intrinsic layers. Progress has been made in increasing their performance both as single junction cells as well as the narrow bandgap component of a-Si:H/ $\mu$ c-Si:H tandem cells (Meier *et al*, 1998; Vetterl *et al*, 2000). However, because of the low optical absorption in  $\mu$ c-Si:H such cells have to be much thicker than their a-Si:H based counterparts, even when advantage is taken of optical enhancement. There is thus an extensive effort to increase the deposition rates of both  $\mu$ c-Si:H and a-Si:H.

#### 4. CONCLUSION

Amorphous silicon based solar cells and their technologies have progressed rapidly in the last twenty-five years. It appears that the disadvantages associated with the disordered structure of the material have been offset by the corresponding advantages due to its flexibility so it is now a serious contender in the expanding field of terrestrial solar energy. a-Si:H solar cell technology will undoubtedly continue to advance to provide a means of powering a sustainable society. As the world population of over 6 billion aspires to a standard of living which is based on the current energy consumption in the west, the large-scale use of terrestrial solar energy has become inevitable, as eloquently predicted by Albert Rose in 1979.

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