Crystalline Silicon vs. Amorphous Silicon: the Significance of Structural Differences in Photovoltaic Applications

H Kang

High School Student, Grace Christian Academy, Houston, America
E-mail: gordon24771402@163.com

Abstract. Firstly, the paper briefly introduces the structure of crystalline silicon, amorphous silicon, and hydrogenated amorphous silicon and highlights the structural differences. Then, the paper presents a feature-by-feature based comparison between c-Si solar cells and a-Si solar cells. What roles different structures of silicon play in each PV characteristic are subsequently explored. In the end, based on these previously analyzed features, this paper further discusses circumstances in which the use of either c-Si or a-Si solar cells may be appropriate, the use of c-Si solar cells is more appropriate, and the use of a-Si solar cells is more appropriate. In short, the outstanding conversion efficiency and user-friendly cost of crystalline silicon solar cells prove successful, while the disturbing nature of amorphous silicon solar cells demonstrates several optical and electrical properties, like high absorption coefficient and Staebler-Wronski Effect, never before anticipated.

1. Introduction
With the onset of the world energy crisis, renewable energy sources such as solar, wind, and tides have attracted considerable investments. According to the International Energy Agency (IEA) report, between 2019 and 2024, renewable power capacity will expand by 50%, with solar PV alone accounts for 60% of the projected growth[1]. Therefore, the solar cell, as the core of solar energy, is worth discussing.

In general, two main categories of solar cells, wafer-based and thin-film, have achieved significant progress. Crystalline silicon (c-Si) dominates the wafer-based solar cells. On the other hand, amorphous silicon (a-Si) plays a vital role in thin-film solar cells. Yet, both types of solar cells employ silicon. How does the same element, silicon, differ in optoelectronic properties? The answer lies in the structural differences: one is crystalline while the other is amorphous.

It must be noted that, due to the fundamentally different nature, a direct comparison of crystalline silicon with amorphous silicon is purely theoretical. However, the following paper will be written based on a characteristic-by-characteristic comparison in an attempt to reduce the inconsistencies.

2. Structural difference

2.1. Crystalline silicon
Crystalline silicon consists of two distinct categories: monocrystalline silicon (mono-Si) and polycrystalline silicon (poly-Si). Monocrystalline silicon is homogeneous. It is composed of one continuous crystal without any grain boundary. The orientation of silicon atoms and lattice parameter remain constant throughout the material. In contrast, polycrystalline silicon is composed of multiple small silicon crystals. Either monocrystalline silicon or polycrystalline silicon, the silicon atom is
tetrahedrally bonded to four adjacent atoms, as illustrated by Fig. 1 (a). This tetrahedral structure forms a well-defined or even ideal crystal lattice.

2.2. Amorphous silicon
Amorphous silicon (a-Si), on the contrary, is non-crystalline, as illustrated by Fig. 1 (b). One obvious difference is that the long-range order no longer exists. The resulting dangling bonds, unsatisfied valences on an immobilized silicon atom, exist at the order of $10^{19} \text{ cm}^{-3}$ [2]. It is problematic. First and foremost, dangling bonds serve as the recombination centers, severely reducing the carrier lifetime, which is the exact opposite of the attempt to separate charge carriers in a solar cell. Even worse, the defects pin the Fermi energy level so that the amorphous silicon cannot be doped into either p-type or n-type. It is a semiconductor of little use, losing all other desirable characteristics for the preparation of electronic devices.

![Figure 1](image)

**Figure 1.** Schematic structure diagrams of crystalline silicon (a), amorphous silicon (b), and hydrogenated amorphous silicon (c).

2.3. Hydrogenated amorphous silicon
Fortunately, Chittick, Alexander, and Sterling were the first to come up with an effective solution.[3] Using glow discharge technique (apply a voltage between two electrodes at both ends of a glass tube to form a plasma of the contained gas), Chittick, Alexander, and Sterling dissociated silane gas (SiH4) on heated substrates. It is proven that, with the incorporation of 10% hydrogen during deposition, the defect density greatly reduces to $10^{16} \text{ cm}^{-3}$ [2]. Each hydrogen atom combines with a dangling bond previously present in the amorphous silicon, yielding an exotic material, hydrogenated amorphous silicon (a-Si:H), as illustrated by Fig. 1 (c). The reduction in defect density eventually allows hydrogenated amorphous silicon to be doped and could be widely used in junction devices.

3. Photovoltaic properties comparison
**Table 1** Photovoltaic Properties for a-Si and c-Si solar cells[2] [4]-[6]

| Photovoltaic Properties                  | Hydrogenated Amorphous Silicon | Crystalline Silicon |
|------------------------------------------|--------------------------------|---------------------|
| Optical-Electrical Conversion Efficiency | 14.0% (a-Si:H)                 | 22.3%~26.1%         |
| Bandgap                                  | 1.75 eV                        | 1.1 eV              |
| Sufficient Thickness                     | 1~2 μm                         | 100 μm              |
| Spectral Range (75%~85% QE)             | 550~700 nm                     | 440~650 nm          |
| Temperature Coefficient (Above 25%)      | $-0.2$~$-0.25\%/°C$            | $-0.4$~$-0.5\%/°C$  |
| Area Required/kW (m²)                    | 15                             | 7~8                 |
3.1. Optical-electrical conversion efficiency

One key parameter evaluating the performance of a solar cell is conversion efficiency. The yardstick is the same: at the same incident light power, the more electrical output, the better. As noted in Table 1, amorphous silicon solar cells have a conversion efficiency of 14.0% while crystalline silicon solar cells have a conversion efficiency around 22.3% to 26.1%. Clearly, c-Si solar cells outcompete a-Si solar cells in terms of conversion efficiency.

There is a structural reason behind. A successful operation of a solar cell depends on two fundamental processes: photon absorption to generate charge carriers and subsequent transportation and collection of charge carriers to produce electricity. Although hydrogenation reduces the number of dangling bonds making amorphous silicon accessible, the defect density of $10^{16}/\text{cm}^3$ is still dramatic compared with crystalline silicon. The recombination centers (where positive holes and negative electrons combine) arising from the defects shortens the carrier lifetime and makes the transportation of charge carriers a challenge, resulting in an inferior conversion efficiency.

3.2. Absorption coefficient

Another influential parameter for a solar cell is the ability to absorb light. Concerning the absorption coefficient, amorphous silicon exhibits decisive advantages. As illustrated by Fig. 2, in absorbing photons with energy above 1.8 eV ($h\nu \geq 1.8\text{eV}$), amorphous silicon has an absorption coefficient order of magnitude larger than that of crystalline silicon.

Structure again plays a significant role. The well-defined crystalline structure means well-defined bond lengths and bond angles in crystalline silicon, representing internal homogeneities. The effect of internal scattering of light is trivial. On the contrary, amorphous, or non-crystalline structure means disturbing bond lengths and bond angles in amorphous silicon, representing internal inhomogeneities. These internal inhomogeneities contribute to the internal scattering of light. Therefore, amorphous silicon solar cells absorb light efficiently.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure2.png}
\caption{Absorption coefficient of crystalline silicon (c-Si) and amorphous silicon (a-Si) in the energy band of maximum spectral irradiance[7].}
\end{figure}

In reality, a high absorption coefficient serves at least two purposes. First, if the same amount of light is absorbed, the material requirement is less for amorphous silicon. As noted in Table 1, the absorbing layers' total thickness is around 1 to 2 $\mu\text{m}$ in a-Si solar cells while about 100 $\mu\text{m}$ in c-Si solar cells. In other words, a hundredth of material is used to absorb sunlight compared to conventional cells.

Besides, under low and diffuse light conditions, a higher absorption coefficient means a better capture of light. Therefore, the a-Si solar cell is a better choice for indoor usage than the c-Si solar cell.

3.3. Electrical stability

Electrical stability is another noteworthy parameter. The hydrogenated nature comes with a cost. One type of light-induced degradation, known as the Staebler-Wronski Effect (SWE), is unique to a-Si
solar cells. In general, the beneficial effects of hydrogenation upon amorphous silicon deteriorate under illumination. Within the first 100 hours under exposure to light, a-Si solar cells exhibit a steady drop in efficiency (10%~15%) measured by a decrease of photoconductivity and dark conductivity. What becomes particularly intriguing is the fact that Staebler-Wronski Effect (SWE) is metastable. After the first 100 hours exposure to light, cell performance remains fairly stable[4]. Structure causes the light-induced degradation. So far, it has been discovered that the degradation is associated with “the relatively high diffusion of hydrogen and the changes in local bonding coordination.”[8] Still, the exact cause of the Staebler-Wronski Effect is not fully understood. Historically, the hydrogen bond switching model is favored. It suggests that photogenerated carriers may recombine near a weak Si-Si bond, releasing energy sufficient to break the Si-Si bond. Then, the adjacent H atom forms a new bond with one of the silicon atoms, leaving a dangling bond. These dangling bonds can trap electron-hole pairs, thereby reducing the current passing through[9]. Tested against the latest experimental observations, the explanation becomes complex. The association between hydrogenation and the light-induced degradation is clear, but exactly how or precisely where the light-induced defects occur remains unclear. The absence of a spatial relationship between incorporated hydrogen atoms and dangling bonds is the major challenge in the understanding and further precautions of Staebler-Wronski Effect. Nonetheless, extensive research has suggested several possible measures to reduce the degradation. During film growth, optimized hydrogenated amorphous silicon might be obtained by reducing the H dilution during film growth.[8] Since hydrogenation is introduced to reduce defect density, Staebler-Wronski Effect could hardly be reduced without sacrificing material quality. In addition, reducing the thickness of a-Si:H solar cells or employing emerging multi-junction techniques provides new insights to SWE.

3.4. Temperature stability
Solar cells work under sunlight. Therefore, heat absorption is unavoidable. In most cases, cell temperature can reach around 70℃ under the bright sunlight. As noted in Table 1, above 25℃, the power of crystalline silicon solar cells decreases by 0.4~0.5% with 1℃ increase in temperature. On the contrary, the power of amorphous silicon solar cells decreases by 0.2~0.25% with 1℃ increase in temperature. Overall, amorphous silicon solar cells are temperature insensitive compared with crystalline silicon solar cells.

4. Discussion
In the end, crystalline silicon and amorphous silicon, which one is better? The answer is not straightforward. Based on the previously analyzed characteristics, it is perhaps reasonable to discuss the following conditions.

4.1. The condition in which either c-Si or a-Si may be appropriate:
Area-related factors are not critical. For instance, solar power stations always have vast space (in which other considerations like power density or the overall cost are prior).

4.2. Conditions in which c-Si is more appropriate:
- The installation space is limited. Because c-Si solar cells have higher conversion efficiency, the area required to output 1 kW of power is half of the area required by a-Si solar cells.
- Price is concerned. Currently, compared with a-Si solar cells, the cost per watt of c-Si solar cells is half or less.

4.3. Conditions in which a-Si is more appropriate:
- In artificial (indoor) light conditions. Because the a-Si solar cell has a higher absorption coefficient and a spectral range typical of artificial light sources, it is a better choice.
- Weight-related factors are considered. As mentioned earlier, a-Si solar cells are thinner. Accordingly, the weight density for a-Si solar cells is lower, only one-quarter of the crystalline counterpart. So, a-Si solar cells do not impose excessive additional weight on the buildings.
5. Conclusion

In short, the structural difference of silicon signifies a lot in photovoltaic applications. Despite the low efficiency and stability problems, amorphous silicon solar cells have the advantage of a standardized and simple manufacturing process. However, crystalline silicon solar cells gradually take the ground due to the comparable cost. It is hard to tell which technology dominates the other. Instead, each has its irreplaceable uniqueness.

6. References

[1] IEA (2019), Renewables 2019, IEA, Paris https://www.iea.org/reports/renewables-2019
[2] Chopra, K. L., P. D. Paulson, and V. Dutta. "Thin-film solar cells: an overview." Progress in Photovoltaics: Research and applications 12.2-3 (2004): 69-92.
[3] Chittick, R. C., J. H. Alexander, and H. F. Sterling. "The preparation and properties of amorphous silicon." Journal of the Electrochemical Society 116.1 (1969): 77.
[4] Staebler, D. L., and C. R. Wronski. "Reversible conductivity changes in discharge-produced amorphous Si." Applied physics letters 31.4 (1977): 292-294.
[5] "$File:CellPVeff-rev190416.pdf." Wikimedia Commons, the free media repository. 16 Feb 2020, 11:55 UTC. 15 Aug 2020, 03:55 <https://commons.wikimedia.org/w/index.php?title=File:CellPVeff-rev190416.pdf&oldid=395083457>.
[6] Hart, Paul R. "Crystalline vs. Amorphous Silicon—a Comparison of their Respective Properties and their Significance in Photovoltaic Applications." Seventh EC Photovoltaic Solar Energy Conference. Springer, Dordrecht, 1987.
[7] Design and Simulation of Thin-Film Silicon Quantum Well Photovoltaic Cell - Scientific Figure on ResearchGate. Available from: https://www.researchgate.net/figure/Absorption-coefficient-of-crystalline-silicon-c-Si-and-amorphous-silicon-aSi-in-the_fig5_267940441 [accessed 4 Aug, 2020]
[8] Fritzsche, Hellmut. "Development in understanding and controlling the Staebler-Wronski effect in a-Si: H." Annual Review of Materials Research 31.1 (2001): 47-79.
[9] Stutzmann, M., et al. "Light-induced metastable defects in amorphous silicon: The role of hydrogen." Applied physics letters 48.1 (1986): 62-64.

Acknowledgement

I would like to acknowledge everyone who assisted me on the composition of the paper above. Most importantly, I would like to express my special thanks to Prof. Ya-Hong Xie for his able guidance and support.