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The evolution of solar cells

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Abstract

This paper presents an updated overview of photovoltaic (PV) technologies and materials, with silicon remaining the most significant and widely used. Crystalline silicon continues to dominate the global market, though amorphous silicon also holds importance. The production of crystalline silicon solar cells is closely tied to the semiconductor industry, yet the material still offers significant potential for cost reduction, particularly in its thin-film crystalline form. Thin-film technologies, which require only minimal material usage, are considered highly promising and are expected to play a crucial role in advancing PV systems. Alongside established approaches, numerous innovative materials and concepts remain under research. These developments may enable substantial improvements in efficiency while reducing costs in the future. A mathematical function has been identified that successfully fits past laboratory efficiency records. By applying this function, researchers can estimate the likely trajectory of efficiency improvements across different PV technologies in the coming decades.

Keywords: Crystalline silicon, crystalline thin film cells, thin film materials, new materials and concepts, solar cell efficiency prediction

1. Introduction

1.1 The photovoltaic effect: The photovoltaic effect, first observed by Becquerel [1], is defined as the generation of an electric voltage between two electrodes when light is incident on a solid or liquid medium. Although silicon is not the ideal photovoltaic material for solid-state physics perspective, it has dominating power in the market. For instance, while 1 mm of GaAs can absorb 90% of incident light, crystalline silicon requires nearly 100 mm. High efficiency demands long minority-carrier diffusion lengths, necessitating very pure, defect-free silicon. Despite these limitations, silicon became central to PV technology due to the pre-existing semiconductor industry, which ensured abundant, high-quality material.

The ideal solar cell material should possess: (1) a bandgap of 1.1-1.7 eV, (2) a direct band structure, (3) non-toxic and abundant elements, (4) scalable and reproducible deposition, (5) high conversion efficiency, and (6) long-term stability.

Looking ahead, three pathways are plausible: (i) continued use of single-crystal or polycrystalline silicon, (ii) development of crystalline silicon films on substrates or ribbons, and (iii) breakthroughs in true thin-film technologies such as a-Si, CdTe, or CIS. These approaches may coexist, each serving specific markets, while emerging concepts like organic solar cells may expand the landscape. The diversity of research directions significantly enhances the prospects of achieving low-cost, high-efficiency solar cells.

2. Monocrystalline and multicrystalline silicon

2.1 History

The first silicon solar cell was developed at Bell Laboratories in 1954 by Chapin *et al.* [2]. It already had an efficiency of 6% which was rapidly increased to 10%. The main application for many years was in space vehicle power supplies.

2.1.1 Status today

The current photovoltaic (PV) market exhibits several defining trends. First, conversion efficiencies continue to improve, though at a gradual pace. Second, the cost of modules and complete systems is declining, but only slowly. Third, the supply of polycrystalline silicon as a

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raw material remains uncertain, creating challenges for large-scale production.

Among these factors, conversion efficiency has a critical role. While efficiency is less significant for certain consumer applications, it is essential for most large-scale systems, where area-related costs dominate overall expenses. Consequently, efficiency enhancement remains a top priority for both research laboratories and industrial manufacturers. At present, the highest laboratory-recorded efficiency for single-crystal silicon solar cells is 24.7% [3]. Although such performance is achieved only through highly advanced fabrication techniques, historical trends indicate that laboratory improvements eventually translate into commercial production, albeit with a time lag.

2.1.2 The silicon supply problem

A big question mark for the future is the source of highly purified silicon for solar cells. Fifty percent of the cost of a module is due to the cost of processed silicon wafers. The PV industry has the past used reject material from the semiconductor industry that was available at low cost. This created a dependence that is only viable if both sectors grow at the same rate. Another problem is that the semiconductor market is characterized by violent cycles of boom and depression superimposed on a relatively steep growth curve. In this times the materials supply becomes slow and prices increase. This happened in 1998 when even reject material was in short supply and some solar cell manufacturers had to buy regular semiconductor grade material at relatively high cost. Today silicon supply is again very critical.

2.1.3 Future

Current photovoltaic technology is relatively mature, yet studies indicate significant potential for further cost reduction. Like many industrial products, PV manufacturing costs follow a learning curve, where each doubling of production volume results in an approximate 20% cost decrease. Based on this trajectory, it may take considerable time for conventional technologies to achieve a substantial share of the global energy supply. Nevertheless, crystalline silicon has historically demonstrated resilience and adaptability, remaining the dominant technology despite challenges. In contrast, amorphous silicon has struggled to expand its market presence. The primary technological bottleneck is the availability of solar-grade silicon, as previously discussed. It is expected that once demand grows sufficiently, dedicated large-scale production of this material will emerge, enabling continued cost reductions and broader deployment.

3. The main approaches in ribbon silicon production

In the edge-defined film-fed growth (EFG) method developed by ASE Americas, a self-supporting silicon ribbon is drawn from the melt through a die that shapes the ribbon [4]. Currently, octagonal tubes measuring 5.3 m in length with an average wall thickness of 280 µm are extracted from a graphite crucible containing molten silicon and then separated using a laser. The resulting 10 × 10 cm^2 sheets exhibit slightly lower material quality compared to single crystals and possess a wavy surface. Despite this, production-line efficiencies as high as 14.8% have been achieved, with an overall yield exceeding 90% [5].

Another approach, the string ribbon process, has been under development since 1994 by Evergreen Solar [6]. In this method, silicon ribbons of variable thickness are drawn directly from the melt between two temperature-resistant strings and subsequently cut to length with diamond tools. Growth speeds of up to 25 mm/min yield ribbon thinner than 100 µm, with laboratory cells (1 cm^2) reaching efficiencies of 15.1%. Commercial modules rated at 30 W and 60 W have already been produced, using cells with dimensions of 5.6 × 15 × 0.025 cm^3 [7].

4. Crystalline thin-film silicon

4.1 History

Early investigations into thinner silicon wafers for solar cells were carried out by Wolf [8] and Lofersky [9], who modeled the ideal parameters required to achieve record efficiencies. Their studies demonstrated that reducing cell thickness leads to an increase in open-circuit voltage, primarily due to the reduction in saturation current associated with a lower geometry factor. Subsequent theoretical work on light trapping in silicon layers proposed the use of a Lambertian back reflector as a simple yet highly effective design for enhancing absorption [10].

4.2. The present status of the crystalline silicon thin film solar cell

4.2.1. Si-layers deposited directly onto glass

A fundamental limitation of approaches based on glass substrates is the relatively low softening point of glass, around 600 °C. Consequently, both silicon deposition and subsequent solar cell processing must remain below this temperature for extended durations. Crystallization of the silicon layer can be achieved either through laser crystallization or solid-phase crystallization [11]. Research at the Center for Photovoltaic Devices, University of New South Wales, together with Pacific Solar Corp., is focused on developing multijunction solar cells. This concept involves depositing multiple layers with alternating p- and n-type doping. The advantage of this design is that it can tolerate very short minority-carrier diffusion lengths, thereby allowing the use of relatively impure and low-cost materials [12].

4.2.2. Si-layers on high-temperature resistant substrates

High-temperature approaches exploit high silicon deposition rates (≈5 µm/min) at processing temperatures above 1000 °C, combined with recrystallization techniques through the liquid phase (Si melting point ≈1420 °C). These methods enable high-throughput, continuous in-line processing, the formation of large grains, and consequently, high conversion efficiencies. However, a major challenge remains: identifying a suitable substrate material that combines the required technical properties with low cost.

4.2.3. Transfer technologies of monocrystalline thin Si-films onto glass

Recent progress in transfer technologies for thin monocrystalline silicon films represents one of the most exciting developments in the crystalline Si thin-film field. The core concept involves detaching a semi-processed thin monocrystalline Si layer from a float-zone (FZ) wafer and transferring it onto a glass substrate. This approach offers several advantages: high-quality material enables very high efficiencies even with Si layers thinner than 40 µm, low-cost glass serves as a substrate, and the original FZ wafer can be reused multiple times for subsequent thin-film detachment.

Currently, five major methods are under development [13]: the C process [14]; the epi-lift process by ANU [15]; and Mitsubishi's VEST structure, which employs via-hole etching for thin-film separation [16]. Sony pursues epitaxial growth of monocrystalline Si on a thermally annealed crystalline surface above a buried porous Si layer, enabling detachment due to the mechanically fragile interface [17]. Similarly, the Institute of Physical Electronics develops epitaxial growth on quasi-monocrystalline Si films, where a porous buried layer allows separation and transfer of the processed cell to a foreign superstrate. Using an optimized light-trapping design, this method has achieved efficiencies of up to 14.0%. Moreover, the seeding wafer can be reused multiple times for porous layer formation and subsequent epitaxial growth, further reducing costs [18].

5. Amorphous silicon

5.1. History

Research on amorphous silicon (a-Si) relevant to solar cell applications began in the late 1960s [19, 20], with Carlson reporting the first a-Si solar cell in 1976 [21]. By 1981, the first consumer products reached the market. Initial expectations for this material were tempered by its relatively low efficiencies and by the discovery of light-induced degradation, known as the Staebler-Wronski effect [22]. Despite these challenges, a-Si has established a stable role in consumer applications, particularly for indoor devices. With improved understanding and partial mitigation of light-induced degradation, amorphous silicon has begun to expand into the power market. Cell efficiencies approach 13%, while commercial module efficiencies typically fall in the 6-8% range.

6. a-Si/c-Si heterostructures

A particularly promising development in photovoltaic research is the integration of crystalline and amorphous silicon technologies into heterostructures. In this configuration, sunlight is primarily absorbed by a mono- or polycrystalline silicon wafer, while thin amorphous silicon films are applied as contact layers on both surfaces. This approach effectively combines the advantages of c-Si and a-Si technologies.

Advantages

- High efficiency potential.
- Excellent surface passivation with low surface recombination velocity.
- Low processing temperatures (all steps below 200 °C),
- Reduced thermal budget, leading to shorter energy payback times, and
- Lower overall cell production costs.
- The most significant progress in this area has been achieved by Sanyo, Japan. Their heterostructure solar cells have reached a conversion efficiency of 20.7% for a cell area of 101 cm², using n-type CZ silicon as the light-absorbing base material [23].

7. Tandem cells and materials for concentrating systems

Solar cell efficiency can be greatly enhanced by stacking cells with different band gaps, enabling more effective utilization of the solar spectrum. A key challenge with conventional two-terminal tandem devices, however, is that all subcells must operate at the same current. For terrestrial use, optical concentrator technology offers a promising pathway toward low-cost electricity generation [24]. In these systems, direct sunlight is focused onto small-area solar cells, with concentration factors ranging from 100 to 1000. At such levels, the cost of the cell becomes a minor component of the overall system. Moreover, conversion efficiency increases by 10-20% under concentrated light, provided cell temperature is controlled. Demonstrated results already exceed 30% for concentrator cells and 25% for modules.

Despite this potential, commercial adoption has been slow, constrained by the limited market for medium-scale (≈100 kW) remote PV systems and by uncertainties regarding long-term reliability. A logical development pathway is to advance crystalline silicon-based point-focus concentrator systems to establish technology and markets, followed by a transition to higher-efficiency III-V multijunction cells as they mature.

8. Dye-sensitized cells

Nanocrystalline dye-sensitized solar cells (DSSCs) operate through a fast regenerative photoelectrochemical process [25]. Unlike conventional solar cells, in which light absorption and charge transport occur within the same material, DSSCs separate these functions. In n-type TiO_2 (band gap ≈ 3.2 eV), the working cycle begins when a dye molecule absorbs a photon at the TiO_2/electrolyte interface and injects an electron into the TiO_2. The injected electrons migrate through the nanostructured TiO_2 network to the transparent conducting oxide (TCO) front electrode, where they are collected as external current. Meanwhile, the dye is regenerated by a redox electrolyte, typically consisting of an organic solvent with the iodide/triiodide couple.

The main advantage of this concept is that electron transport proceeds via majority carriers, unlike conventional inorganic cells that rely on minority carrier transport. This allows the use of less pure starting materials and simpler processing without cleanroom conditions, while still achieving conversion efficiencies of 7-11%. These characteristics make DSSCs a promising candidate for low-cost solar energy conversion. However, long-term stability under varying outdoor conditions of temperature and illumination remains the most critical challenge for their commercialization.

9. Organic solar cells

Beyond dye-sensitized solar cells, which can be regarded as organic-inorganic hybrids, purely organic solar cells have attracted growing attention. These devices are generally classified into molecular and polymer-based cells, or alternatively into flat-layer structures and bulk heterojunctions. Organic semiconductors exhibit extremely high optical absorption coefficients, enabling the fabrication of very thin devices (well below 1 µm) with minimal material requirements. The successful development of light-emitting plastic films further supports the possibility of achieving photovoltaic conversion in similar materials.

Early devices showed modest power conversion efficiencies of about 1% until the late 1990s. However, subsequent progress has been rapid. For example, molecular flat-layer systems based on iodine- or bromine-doped pentacene single crystals achieved efficiencies up to 3.3% under AM1.5 illumination at Lucent Technologies. Comparable results have been reported for advanced bulk heterojunction architectures—interpenetrating networks of conjugated polymers and fullerene derivatives [26].Despite these advances, organic solar cells remain far from practical application. Further improvements in efficiency, along with enhanced long-term stability and effective protection against environmental degradation, are essential before large-scale deployment becomes feasible.

10. Future development of solar cell efficiency

We now turn to predicting the future development of solar cell efficiency. Historically, each photovoltaic technology follows a characteristic trajectory: efficiencies rise rapidly during the early stages, and then gradually slow as they approach a limiting value that cannot be exceeded. This trend is most evident in the record laboratory efficiencies, which are the focus here.

If an appropriate mathematical function can be identified to describe past progress, it can be extrapolated with reasonable confidence to forecast future performance. For crystalline silicon, such a function provides a good fit to historical data on best laboratory efficiencies. The model predicts an ultimate efficiency limit of approximately 30%. Similar fitting procedures can be applied to other photovoltaic technologies, though the ultimate efficiency limits will differ depending on the material system and device architecture.

Table 1: Summary of empirical parameters used for modeling the future efficiency trends of various photovoltaic technologies

Technology	ZL	c	a0
Xtal Si	29	30	1948
Thin film Si	30	19	1989
CIS/CIGS	29	30	1969
a-Si	18	20	1968
Organic cells	18	25	1995
New material	42	25	2000

Thin film silicon: very few data points; a-Si: large scatter of data; organic cells: only one data point, undetermined parameters were estimated.

Efficiency for different technologies

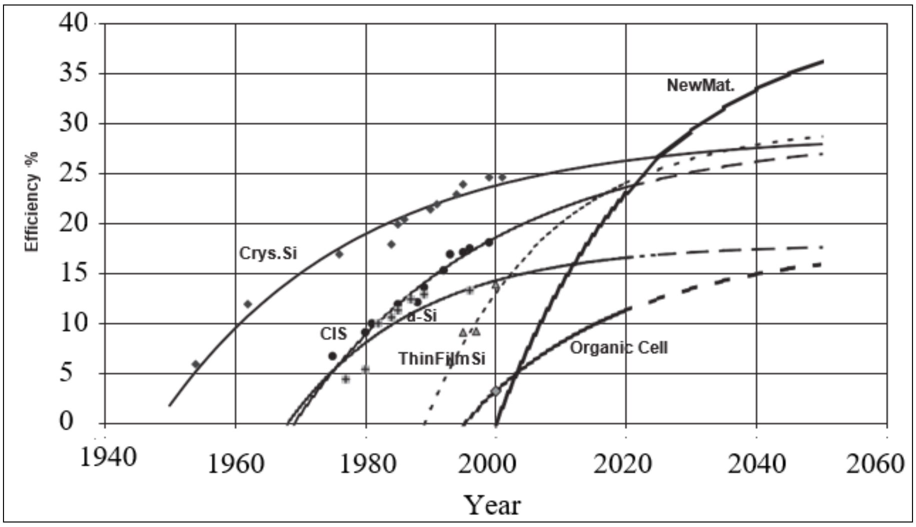

Fig 1: A century of photovoltaic past achievements and future predictions of highest laboratory solar cell efficiencies. Best data are for crystalline silicon.

The rightmost curves are derived from only a limited number of data points, while the curve representing a new material is entirely hypothetical. Curve fitting is carried out using three parameters, listed in Table 1 for silicon and the other key technologies (see Fig. 1). The curve on the far right corresponds to a speculative high-efficiency material or material combination, optimistically assumed to begin development at present. Figure 1 illustrates all curves within a long-term perspective, spanning nearly a century of past progress and projected future advancements. Realizing these trajectories, however, depends on active research efforts. Progress in the asymptotic region of the curves is particularly unlikely, as achieving even marginal efficiency gains there requires disproportionately large efforts.

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