Recent progress in crystalline silicon solar cells

Makoto Tanaka\textsuperscript{a)}

Device Solutions Center, Panasonic Corporation,
3–1–1 Yagumo-naka-machi, Moriguchi City, Osaka 570–8501, Japan
\textsuperscript{a}) tanaka.makoto000@jp.panasonic.com

Abstract: Due to their advantages of high performance, high reliability and low cost, crystalline silicon solar cells have predominated since their invention in 1954. This paper discusses recent progress in crystalline silicon solar cell technologies.

Keywords: solar cell, photovoltaics, crystalline silicon, conversion efficiency

Classification: Optoelectronics, Lasers and quantum electronics, Ultrafast optics, Silicon photonics, Planar lightwave circuits

References

1 Introduction

The first crystalline silicon solar cell was developed in 1954 [1]. Although its conversion efficiency did not exceed 2%, we have, since then, seen dramatically improved performance. The first application of silicon solar cells was in standalone systems such as satellites, lighthouses, and remote communications. In the early 1990s, photovoltaic (PV) systems for residential houses were realized [2], mainly in Japan. Since around 2004, the German market has been expanding rapidly, and photovoltaic systems have since found increasing popularity outside Europe, including in Japan, the US, and China. Crystalline silicon solar cells have predominated so far, due to their advantages of high performance, high reliability and low cost. In this paper, we discuss recent progress in crystalline silicon solar cell technologies.

2 Progress in conversion efficiency

Figure 1 shows improvements in the conversion efficiency of various kinds of solar cells (Ref. [3], with minor revisions by the author). Although crystalline silicon solar cell technologies are relatively mature, their conversion efficiency has steadily increased.

Table I shows the recent highest conversion efficiencies of various crystalline silicon solar cells [4, 5]. Currently, the record is 25.0%, achieved by the University of New South Wales in 1999 [6]. Recent progress in conversion efficiency continues to be made with practical-sized cells and modules. The
Fig. 1. Progress in conversion efficiencies of various solar cells (reprinted with permission by the National Renewable Energy Laboratory [3], with minor revisions by the author). Although progress is a little slower, the conversion efficiency of crystalline silicon solar cells, indicated by blue symbols, has been steadily improving.

Table I. Highest conversion efficiencies for various crystalline silicon solar cells [4, 5]. Highest efficiency is 25.0% in small size cell.

<table>
<thead>
<tr>
<th>small size</th>
<th>conversion efficiency (%)</th>
<th>cell/module size (cm²)</th>
<th>Institute</th>
<th>month/year</th>
</tr>
</thead>
<tbody>
<tr>
<td>single crystalline</td>
<td>25.0</td>
<td>4.00 (da)</td>
<td>UNSW (PERL)</td>
<td>3/99</td>
</tr>
<tr>
<td>multicrystalline</td>
<td>20.4</td>
<td>1.002 (ap)</td>
<td>FhG–ISE</td>
<td>5/04</td>
</tr>
<tr>
<td>cell</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>single crystalline cell</td>
<td>24.7</td>
<td>101.8 (t)</td>
<td>Panasonic (HT)</td>
<td>12/12</td>
</tr>
<tr>
<td>single crystalline cell</td>
<td>24.2</td>
<td>155.1 (t)</td>
<td>SunPower (IBC)</td>
<td>5/10</td>
</tr>
<tr>
<td>thin film transfer</td>
<td>20.1</td>
<td>242.6 (ap)</td>
<td>Solexel</td>
<td>10/12</td>
</tr>
<tr>
<td>multicrystalline cell</td>
<td>19.5</td>
<td>242.7 (t)</td>
<td>Q-Cells</td>
<td>3/11</td>
</tr>
<tr>
<td>module</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>single crystalline module</td>
<td>21.4</td>
<td>15,780 (ap)</td>
<td>SunPower</td>
<td>10/09</td>
</tr>
<tr>
<td>multicrystalline module</td>
<td>18.5</td>
<td>14,661 (ap)</td>
<td>Q-Cells</td>
<td>1/12</td>
</tr>
</tbody>
</table>

(da) designated illumination area
(ap) aperture area
(t) total area

latest highest values are 24.7% at a practical-sized cell [5] and 21.4% for a module [7].

3 Technical issues

Table II shows the recent key technologies in crystalline silicon solar cells. R&D has been carried out aiming to achieve higher performance, lower cost and higher reliability over the entire value chain from ingot/wafer, to cell, to module. Many research institutes have reported on their R&D to achieve higher performance, but there are fewer reports on R&D aiming at lower cost or higher reliability, since this work is chiefly conducted at manufacturers.
Table II. Recent key technologies in crystalline silicon solar cells. R&D has been conducted for higher performance, lower cost and higher reliability.

<table>
<thead>
<tr>
<th>Performance</th>
<th>Ingot/wafer</th>
<th>Cell</th>
<th>Module</th>
</tr>
</thead>
<tbody>
<tr>
<td>thin wafer</td>
<td>MC (multi-crystalline) Si ingot large MC-Si ingot quasi polycrystalline Si mono-like Si</td>
<td>new structure heterojunction back contact selective emitter Perf. metal wrap through emitter wrap through</td>
<td>light weight module flexible module double sided module</td>
</tr>
<tr>
<td>Cost</td>
<td>Cu electrode</td>
<td>low-cost glass sheet frameless</td>
<td></td>
</tr>
<tr>
<td>Reliability</td>
<td>highly reliable electrode</td>
<td>highly reliable AR</td>
<td>highly reliable non-EVA reliable inter-connection</td>
</tr>
</tbody>
</table>

Fig. 2. Energy conversion and losses in crystalline silicon solar cells. These comprise optical loss (A; red), quantum loss (B; yellow) and electrical loss (C; blue).

4 Technologies for higher conversion efficiency

4.1 Energy conversion in solar cells and technologies giving high performance

Active R&D has been conducted at many institutes with the aim of achieving higher conversion efficiency, based on analysis of energy conversion and energy losses in crystalline silicon solar cells, shown in Fig. 2. The basic structure of a crystalline silicon solar cell is a silicon p/n junction with an anti-reflection (AR) coating, silver electrodes on the front surface and aluminum electrodes on the back surface. Figure 2 shows light incident onto solar cell (the red arrow) that is eventually converted into electricity (shown as the blue arrow). In this energy conversion process, there are various losses: optical loss (A; red), quantum loss (B; yellow) and electrical loss (C; blue).
In this report, quantum loss (B) is not discussed, since it can be reduced only if the bandgap of crystalline silicon can be changed, or new materials can be adopted instead of silicon. Higher conversion efficiency can thus be realized by reducing optical loss (A) and electrical loss (C).

Figure 3 shows the key challenges facing the developers of high-performance crystalline silicon solar cells. To reduce optical loss (A in Figs. 2 and 3), the key is reduction of surface reflection and increased absorption of long-wavelength light. Optical confinement structures using anti-reflection (AR) and surface texture technologies have been developed, in addition to enlargement of the effective area by using fine-patterned silver electrodes. Surface texture means the rough surface shown in the photograph on the left of Fig. 3. Incident light is refracted by the rough surface, which results in a longer light path within the cell and higher reflection at the rear.

To reduce electrical loss, which consists of carrier recombination loss (C1 in Figs. 2 and 3) and resistive loss (C2 in Figs. 2 and 3), in recent years the main thrust of research has been passivation technology. A metal layer is fabricated on crystalline silicon in the conventional structure; however, carriers (electrons and holes) readily recombine at the silicon–metal interface. Configuring the interface between silicon and silicon-related thin films such as silicon nitride, the use of silicon oxide or amorphous silicon thin film effectively reduces the interface recombination velocity: this is called passivation technology. Details will be shown in the following section.

Resistive loss originates chiefly from various contact resistances and bulk resistances in the silver electrodes. The use of silver is particularly important to solve trade-offs among resistive loss, optical loss, productivity and reliability. Silver paste and related technologies have been effective in improving these trade-offs.
4.2 PERL solar cells

The highest conversion efficiency of 25.0% has been realized with use of the advanced PERL (Passivated Emitter Rear Locally diffused) structure [6, 8].

Optical confinement has been achieved using an anti-reflection (AR) layer, an inverted pyramid surface fabricated on the front surface, and a silicon oxide layer on the rear surface; surface reflection is reduced by AR and an inverse-pyramid structure. Long-wavelength light is “confined” between the front surface oxide with pyramid shapes and the rear surface oxide.

Carrier recombination at the interface has been reduced by inserting a thin oxide layer at both the front and rear interface, since the Si/Si oxide interface has a low defect density. A minimum contact area between the electrodes and silicon is necessary: oxide has been partially removed and n+ layer and p+ layers have been fabricated (partially diffused) to realize good contact at the front surface and rear surface, respectively.

Although the Perl solar cell has not been industrialized for reasons that include its complicated fabrication process, the basic technologies and concepts used in Perl cells have been utilized in industrialized solar cells.

4.3 Back-contact solar cells

Back-contact solar cells have a high conversion efficiency of 24.2% [9] and 21.4% [7] in practical-sized cells and modules, respectively, as shown in Table I. Solar cells with this structure have been already industrialized.

In this structure, shown in Fig. 5 (a), the electrodes on both the “p-side” and “n-side” (the “metal finger” in Fig. 5 (a)) are located on the rear (back) side of the cell. There is no metal electrode on the front surface, so the effective area can be maximized. In addition, anti-reflection coating and texture structure have been adopted to reduce the optical loss. Interface recombination loss has been reduced by silicon oxide (SiOx) passivation and
Fig. 5. Structure of back-contact solar cells: basic structure (a) and latest structure (b) (© 2013 IEEE. Reprinted, with permission, from [9]). Both p and n are located on the rear surface.

Figure 5 (b) shows SunPower Corporation’s latest-generation technology that adopts several advanced technologies [9]. A dielectric layer has been inserted between the metal and silicon at point contact areas, which has reduced recombination losses at the interface. Passivation at the front surface has also been improved by optimization of diffusion and SiNₓ technology. The rear dielectric has been also optimized.

4.4 Heterojunction solar cells (HIT solar cells)

Another solar cell with a high conversion efficiency is the heterojunction solar cell, also known as the HIT (Heterojunction with Intrinsic Thin-layer) cell [5, 10]. A conversion efficiency of 24.7% at a practical size cell has been achieved; this solar cell is also being manufactured.

The solar cell has a simple structure, with a heterojunction of amorphous silicon (a-Si) and crystalline silicon (c-Si); in which a-Si thin-film has been deposited on both sides of c-Si, followed by deposition of a transparent oxide layer and grid electrode, as shown on the left in Fig. 6. In most cases, n-type c-Si is used as the substrate, and a p/i a-Si layer is deposited on one side and an n/i a-Si layer on the opposite. A thin intrinsic (not intentionally doped) a-Si layer has been inserted between p(n)–type a-Si and c-Si, which has improved the interface properties. As a result, the “heterojunction” simultaneously realizes excellent passivation properties and a “pn” junction or back surface field without any need for patterning.

Thin cells can be easily realized in a heterojunction solar cell in addition
Fig. 6. Structure of HIT (Heterojunction with Intrinsic Thin-layer) solar cell (left) and progress in conversion efficiency of HIT cell in R&D (right). Amorphous silicon (a-Si) layer and transparent electrodes are deposited on both sides of n-type crystalline silicon. A record conversion efficiency of 24.7% for a practical-sized cell has been achieved with a cell thickness of only 98 µm.

to high conversion efficiency, since its symmetrical and “stress-free” structure prevents sagging or bending. A problem with conventional thinner cells is decreased conversion efficiency which originates from low optical absorption. However, a conversion efficiency of 24.7% has been achieved at a cell thickness of less than 100 µm, as shown on the right in Fig. 6. Heterojunction solar cells are thus anticipated to realize high conversion efficiency at low cost.

5 Cost-reducing strategies

To reduce costs, reduction of material costs, such as wafer, silver electrode and module materials, is important in addition to improvement of conversion efficiency.

5.1 High quality and low-cost silicon ingots

Cost reduction of wafers is the most effective, since they account for about half the cost of a crystalline silicon solar cell module. One way of reducing wafer cost has been to use cheaper silicon ingots, such as multi-crystalline silicon, although it is of relatively low quality. R&D is increasingly dependent on higher quality multi-crystalline silicon [11, 12], such as mono-like silicon technology [12]. In this technology, single crystalline silicon seeds are used in to fabricate multi-crystalline silicon.

5.2 Thinner wafers

Another way of reducing wafer cost is to use thinner wafers. New slicing technology, using a diamond wire saw [13], has recently been industrialized: this technology, shown in Fig. 7, has realized thin wafers with a high yield, although more than 100 µm is currently the minimum thickness achieved.

Future technology to create wafers much thinner than 100 µm is also being
developed, including the epitaxial silicon technology [14]. Thin silicon film is deposited on a silicon template by epitaxial growth. In very thin cells, cell and module processing technology is the key to high yield. In this technique, epitaxial Si is peeled off after cell processing and the silicon template is reused. Using this technology, a high conversion efficiency of 20.1% has been achieved [14], as shown in Table I.

This technology also has potential for use in lightweight and flexible solar cell modules.

5.3 Cost reduction of cell and module materials
Reduction in materials costs of silver electrodes, glass, EVA (ethylene vinyl acetate), the back sheet and other items is also important.

As the cost of the silver electrodes is the highest in the overall “cell” cost, utilization of silver has been reduced by using a finer patterned electrode and lower-resistivity silver electrode technologies. Technology is also being developed to allow the use of copper electrodes [15] instead of silver.

Cost reduction of materials for module production such as glass, EVA and back sheets has been conducted, taking into account the trade-off between cost and reliability.

6 Strategies for higher reliability
Figure 8 shows the structure of crystalline silicon solar cell modules and possible threats to reliability. Certain phenomena need to be prevented, such as peeling between cell and tab, de-lamination (peeling between glass/EVA or EVA/cell), and potential-induced degradation (performance degradation under high potential difference between frame and cell). Their origins are
Fig. 8. Structure of crystalline silicon solar cell module and threats to reliability. A cell string (cells connected in series) is sandwiched between the glass and the back sheet, with EVA (ethylene vinyl acetate) used as the “filler”. To ensure long-term stability, peeling, delamination, PID (potential induced degradation), etc., need to be prevented.

also various: water (moisture), ultraviolet light, thermal stress, high voltage, ion migration, cracks and so on.

Although there have been many fewer reports focusing on reliability than on performance, reports on reliability have been increasing recently, such as Ref. [16, 17].

7 The challenge of exceeding the “theoretical limit”

R&D has been also taking place into achieving a higher conversion efficiency than the theoretical limit of a “crystalline silicon” solar cell, which is around 27%, by introducing other materials than crystalline silicon. Figure 9 shows one example: a tandem solar cell that comprises a silicon nano-wire (Si NW)

Fig. 9. Structures of one of the future high-efficiency silicon-based types of solar cells: these are tandem solar cells comprising a silicon nano-wire (Si NW) cell and a crystalline silicon cell [18] ((c) JST 2013).
cell and a crystalline silicon cell [18]. In this project, the aim is a target conversion efficiency of 30% using crystalline silicon and silicon-related materials.

8 Contribution to industry and future prospects

As a result of technological progress, the market for crystalline silicon solar cells has been expanding rapidly, as shown in Fig. 10. At the end of 2012, the accumulated installation of solar cells exceeded 100 GW, most of which are crystalline silicon solar cells. Crystalline silicon solar cells have clearly contributed to the growth of the photovoltaic industry.

Fig. 10. Progress in accumulated installation of photovoltaic solar cells [19] ((c) EPIA 2013). At the end of 2012, installation exceeded 100 GW in the world.

Crystalline silicon solar cell technology is also expected to maintain its market share in the near future, as suggested by Fig. 11. The European Photovoltaic Industry Association reports that production capacity for solar cell modules is expected to increase steadily, and the share of crystalline silicon (c-Si) technology is likely to keep its market share at levels of around 80% (blue line in Fig. 11), principally because of the maturity of the technology [19].

The decreasing price of solar cell modules, especially since around 2008, has led to the market growth shown in Fig. 10. Technological improvements have also contributed to falling prices; however, recent rapid price declines have also originated from a mismatch between supply and demand. To ensure the sustainable growth of photovoltaics, further technological developments are needed to keep driving prices down.

Terawatt-range uptake of photovoltaics, far exceeding the current installation of 100 GW, is needed. From the viewpoint of material resource availability, safety etc., silicon remains the most promising technology.
Fig. 11. Progress in production capacity of solar cell modules [19] ((c) EPIA 2013). Production capacity is anticipated to increase steadily in the next five years, and crystalline silicon (c-Si) share is anticipated to be around 80%.

9 Conclusion

Silicon solar cells have dominated the photovoltaic industry since the first cell was created in 1954. Crystalline silicon solar cell technologies continue to be improved, not only to gain higher performance, but also to reduce costs and enhance reliability. As a result, the cumulative capacity of installed photovoltaic solar cells has exceeded 100 GW worldwide. Further technological advancements are needed, however, to permit national economies to be powered by renewable energy.

Makoto Tanaka

received the M.E. degree from Graduate School of Science, Kyoto University in 1982, and the Ph.D. degree from Graduate School of Engineering Science, Osaka University in 1993. In 1982 he joined Sanyo Electric Co., Ltd. and since then, he has conducted R&D for photovoltaic solar cells. His main work has been concerning silicon solar cells, which includes silicon thin-film solar cells and HIT (Heterojunction with Intrinsic Thin layer) solar cells. Since 2012, he has worked for R&D division, Panasonic Corporation. He won the PVSEC (Photovoltaic Science and Engineering Conference) award in 2011, and best paper awards in two photovoltaic conferences, WCPEC-3 in 2003 and PVSEC-6 in 1992. He is a member of the Japan Society of Applied Physics.