Supply of low-cost and high-efficiency multi-GW mono wafers

Yichun Wang & **Tian Xie**, LONGi Green Energy Technology Co., Ltd., Xi'an City, PR China

ABSTRACT

This paper begins with a brief review of the Chinese PV industry, especially the mono crystalline silicon market. In the situation of a booming mono market, the mono wafer manufacturers are optimizing their capacity in order to guarantee a steady supply and to satisfy increasing customer demand. In addition, these manufacturers strive to drive down the cost of mono wafers and increase wafer performance through continuing technological development, especially in the areas of silicon ingot pulling and wafer slicing. With advanced pulling technology, mono silicon wafers can be produced with a low oxygen concentration and a long minority carrier lifetime, both of which are essential for excellent wafer performance. The development of diamond wire saw technology in recent years, compared with traditional slurry slicing, has dramatically reduced the slicing cost; it is also the perfect solution for thin wafer slicing, which directly reduces the silicon material cost per wafer. Alternatively, in order to facilitate the mono PV industry development, some of the leading companies are promoting various wafer product standards, such as the M2 wafer from LONGi. It is believed that all the above endeavours could boost the mono wafer market and help achieve grid parity.

Introduction

In the Chinese PV market, multicrystalline silicon firmly holds a large market share compared with monocrystalline silicon, entirely as a result of the development of the Chinese PV industry. Dating back to around 2008, silicon casting technology has been successfully developed in China, with multi wafer factory production capacity reaching GW scale. Because multicrystalline silicon casting was extremely productive (five times greater than mono pulling furnace manufacturing), the Chinese PV market began moving to multi and attracted enormous investment. This staggering expansion lasted for several years, which led, as we know, to a tremendous overcapacity and to the Chinese PV industry facing a period of severe disarray. Factories across the industry started to shut down their mono production lines or convert them to multi, since multi was lower in cost and higher in productivity. Thousands of factories were facing a crisis and even closed. The mono proportion of the market, of course, declined dramatically: by 2013 there were only four or five independent mono wafer factories left in the market.

"Low-cost high-performance wafers are becoming increasingly important to solar cell manufacturers and the wafer suppliers upstream."

With the constant efforts by the mono wafer companies to expand mono production and technology R&D, the cost of mono wafers has fallen rapidly over the last few years. In addition, diamond wire saw technology (initially developed for mono wafers) has dramatically brought down the cost of mono wafers even further. Moreover, with the Chinese PV market becoming more mature in terms of understanding both investment and technology perspectives, along with the evolution of related industries, the Chinese PV market focus is shifting to high-efficiency solar cells, which could significantly reduce costs and yield greater financial profit. As a result, low-cost high-performance wafers are becoming increasingly important to solar cell manufacturers and the wafer suppliers upstream.

Growth of the monocrystalline market

After more than ten years of rapid growth, the Chinese PV industry has now entered a period of steady growth. Nevertheless, the technology related to monocrystalline silicon wafer production is still in a period of rapid innovation and development. Emerging solar cell technologies – such as p-type passivated emitter rear cell (PERC), n-type passivated emitter, rear totally diffused (PERT), heterojunction with intrinsic thin layer (HIT) and interdigitated back contact (IBC) – are gradually becoming sufficiently mature for mass production. Compared with multicrystalline solar cells, monocrystalline solar cells are demonstrating increasingly outstanding efficiencies: for example, Kaneka announced that its new HJ-IBC solar cell achieved an efficiency of 26.3%, which is a record-breaking efficiency for a Si solar cell [1].

On another note, the cost of mono solar wafers is being reduced through process technology and material innovations, especially in the areas of ingot growing and wafer slicing. In addition, considering the price decline of auxiliary materials, the non-silicon cost gap between mono wafers and multi wafers is getting smaller and smaller, and is expected to level out, or even reverse, in the next three to five years. Consequently, the latest mono solar cells are outstanding, with the advantages of high efficiency and low cost, and the mono wafer market is exhibiting aggressive growth.

The number of monocrystalline silicon solar module installations in China has steadily increased in recent years, and a market share of over 60% is forecast for 2018. It is expected that the mono cell market in 2017 might be limited by mono wafer supply, and serious mono wafer shortage is becoming an obstacle to mono cell market scaling.

Expansion of mono wafer production capacity

Given the current situation, mono wafer manufacturers are optimizing their production capacity planning in order to guarantee a steady supply and to satisfy growing market demand. Furthermore, it is believed that the increased production and sales volume will help dilute R&D spending and management/administration costs, as well as reducing supply chain and logistics costs.

LONGi is one of the largest mono wafers providers in China; Fig. 1 shows its expansion plan, which is aggressive and anticipates a 5GW year-on-year increase. In 2019 the estimated production capacity will reach 25GW for monocrystalline silicon ingots and wafers.

LONGi's capacity expansion optimization has a number of advantages. First, the increasing production of monocrystalline ingots and wafers could meet the surging market demand and help the development of the mono market. Second, the capacity expansion could reduce the average cost of operation. Third, the wide distribution of LONGi manufacturing sites could spread the business risk, and utilize the low-cost resources in specific locations in order to reduce production costs further. Last, but not least, the production at the Yunnan site, which is currently under construction, will largely use hydroelectric power; thus it will be possible to realize a smaller carbon footprint for wafer production and enhance the environmental performance of the PV industry.

Capacity expansion is one way in which mono wafer manufacturers are coping with the developing mono market; the other important aspect is technology innovation, which could improve mono wafer performance, indirectly bringing down the cost. Besides recharge CZ (RCZ), large-crystal silicon recharging, wafer dimension optimization and so on, some areas of investigation are minority-carrier lifetime, oxygen concentration, diamond wire sawing and thinner wafers.

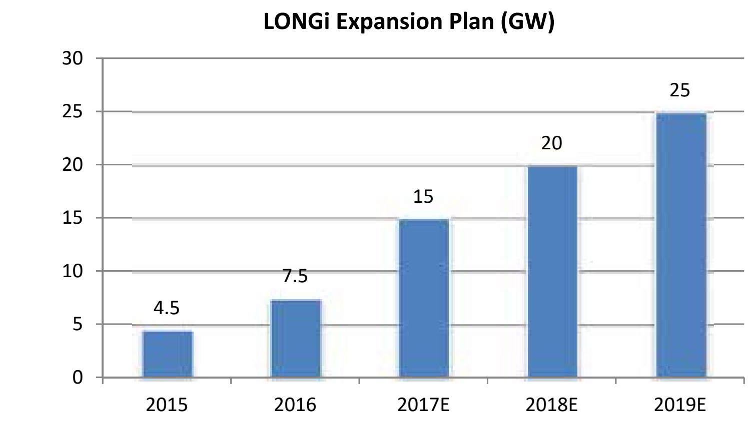


Figure 1. LONGi's plan for wafer production capacity expansion.

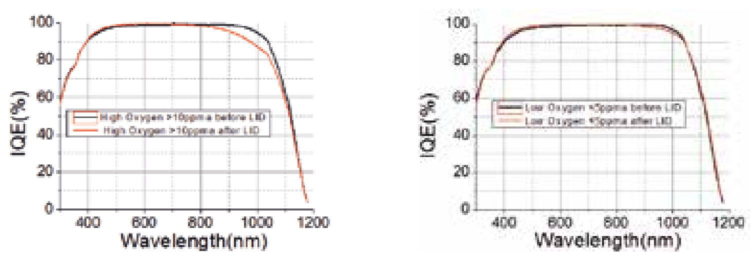


Figure 2. LONGi IQE charts for high-oxygen and low-oxygen wafers.

Pulling technology development – oxygen control and improved minority-carrier lifetime

With the development of the PV industry, the achievement of grid parity requires a higher conversion efficiency for solar cells; this imposes higher intrinsic quality requirements on crystalline silicon material, especially with regard to minority-carrier lifetime, impurity content, density of defects, etc. The minority-carrier lifetime is directly related to the conversion efficiency of solar cells [2]. Impurities and defects are the two main factors affecting minority-carrier lifetime. In monocrystalline silicon wafers, oxygen is the main impurity [3]; therefore, for the future high-efficiency solar cells, one key challenge is decreasing the oxygen content. From experimental investigations, the degradation of mono solar cell efficiency is correlated to oxygen precipitation.

In general, silicon solar cells do not respond to wavelengths of ultraviolet light below around 0.35μm and to wavelengths of infrared light above 1.15μm; the peak value of the spectral response is in the range 0.8~0.9μm. Depending on the solar cell manufacturing process and the resistivity of the material, when the resistivity is low, the spectral response peak value is around 0.9μm. In essence, the spectral response to long wavelengths mainly depends on the minority-carrier lifetime and on the diffusion length in the bulk. In the case of short wavelengths, the response is mainly determined by the minority-carrier lifetime in the diffusion layer and by the recombination velocity at the front surface.

The internal quantum efficiency (IQE) will be reduced in the long-wavelength regions after an extended period of light exposure; an example of such a phenomenon is light-induced degradation (LID). The LID effect is closely related to oxygen concentration. Fig. 2 shows that the decrease in IQE for wafers with low oxygen concentration after 48h LID is smaller than that for wafers with high oxygen concentration.

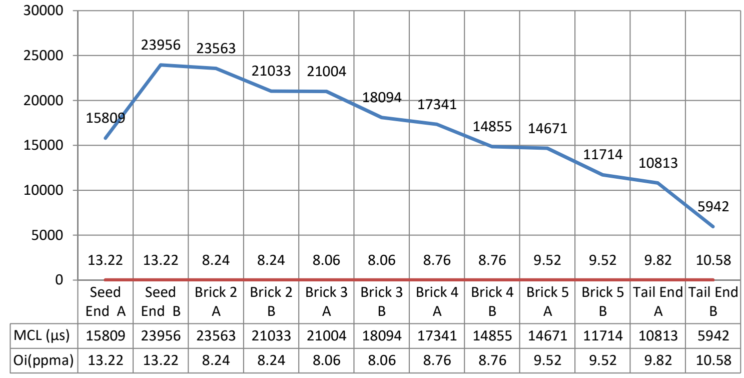
A sensitivity model of the surface recombination and bulk lifetime in a high-efficiency back-contact (IBC) solar cell demonstrates that solar cell performance becomes more sensitive to bulk lifetime as the front-surface diffusion recombination is reduced. This means that, at the same surface current density, the solar cell efficiency increases with higher minority-carrier lifetime, and when the surface current density is low, the increase in efficiency could be much greater [3].

Measurements of external quantum efficiency (EQE) of the solar cells with different oxygen densities after different anneals have revealed that wafers with the highest density of oxygen produce the worst performance [4].

One study of the impact of different improvements on the efficiency of PERCs has indicated that the long-lifetime wafer, i.e. 1ms wafer, is one of the key factors of the high-efficiency solar cell roadmap; other factors include metallization technology, multi-wire, thin fingers and selective emitters [5]. In that study, the impact of rapid thermal annealing (RTA) was investigated; the RTA was performed in a belt-type firing furnace, as used for the metallization of screen-printed silicon solar cells. By varying the peak temperatures and the cooling rates of the RTA treatment, significant differences in the lifetimes after complete degradation, after dark annealing and after permanent recovery were observed. It was possible to improve the permanently recovered lifetime much more dramatically, from 1.1ms to 1.54ms, which means that the long-lifetime wafers undergo a far better permanent recovery on the basis of high bulk minority-carrier lifetime. The LID of long-lifetime wafers is minimized after the RTA process. Long-lifetime wafers are therefore the industry requirement for high-efficiency solar cells.

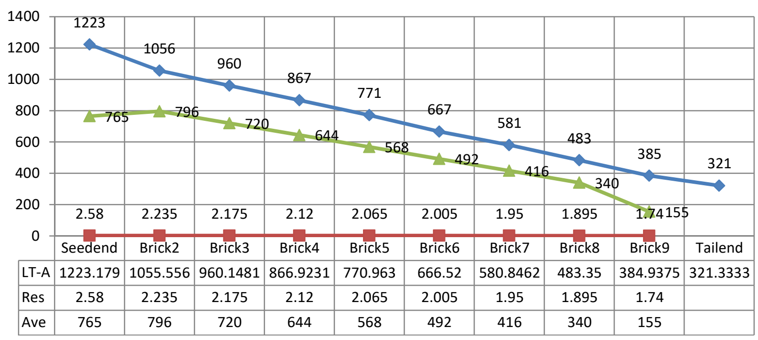
To sum up, a low oxygen concentration and a long minority-carrier lifetime are the two key issues for high-efficiency solar cells at the wafer level; much R&D work and many studies focus on such challenges in the PV industry. The upgraded pulling technology is stable and its implementation is ongoing in order to reduce the oxygen concentration and to improve the lifetime of wafers in mass production.

Today it is possible to produce monocrystalline silicon ingots with a long lifetime, low oxygen concentration and high-quality uniformity across the whole ingot. For example, Fig. 3 shows the performance of LONGi's n-type ingot sample with an advanced controlled crystal pulling process: a minority-carrier lifetime (MCL) of over 10ms (90% of the ingot) is achieved, with a peak value of around 24ms. The wafer resistivity is 1–7Ω·cm.



	Seed End A	Seed End B	Brick 2 A	Brick 2 B	Brick 3 A	Brick 3 B	Brick 4 A	Brick 4 B	Brick 5 A	Brick 5 B	Tail End A	Tail End B
MCL (µs)	15809	23956	23563	21033	21004	18094	17341	14855	14671	11714	10813	5942
Oi(ppma)	13.22	13.22	8.24	8.24	8.06	8.06	8.76	8.76	9.52	9.52	9.82	10.58

Figure 3. Oxygen concentration and MCL for LONGi's n-type ingot sample.



	Seedend	Brick2	Brick3	Brick4	Brick5	Brick6	Brick7	Brick8	Brick9	Tailend
LT-A	1223.179	1055.556	960.1481	866.9231	770.963	666.52	580.8462	483.35	384.9375	321.3333
Res	2.58	2.235	2.175	2.12	2.065	2.005	1.95	1.895	1.74	
Ave	765	796	720	644	568	492	416	340	155	

Figure 4. Oxygen concentration and MCL for LONGi's p-type ingot sample.

In contrast, Fig. 4 shows the performance of LONGi's p-type ingot sample with an advanced controlled crystal pulling process: an MCL of above 300µs (over 100% of the ingot) is achieved, with a peak value of greater than 1ms.

As shown above, mono manufacturers can supply ingot/wafer products that have improved performance. Several technical issues still need to be dealt with, however, and are currently under investigation.

Ring patterns on thin mono wafer surfaces have been observed using photoluminescence (PL) tests, and also ring patterns on the fabricated solar cell using electroluminescence (EL) tests; this raises worries of reduced cell efficiency. Through research and investigation, it has been determined that the ring patterns are formed during the process of ingot pulling, and that they are inherent and inevitable [6].

Slicing technology development – diamond wire slicing

Monocrystalline solar cell development is mainly committed to achieving grid parity, which requires focusing on high efficiency and low cost. Innovations in materials, solar cell structures, manufacturing processes and so on are what drive the PV industry to move forwards. On the other hand, efforts to keep costs down are another key to PV industry scaling.

Wafer cost can be divided into silicon cost and non-silicon cost. Most technology innovations and upgrades today are aimed at reducing the non-silicon cost contribution. Room for further reducing the non-silicon cost, however, is becoming less and less; thus it is beneficial to look at the silicon cost segment.

Diamond wire slicing is the process of using wire of various diameters and lengths, impregnated with diamond particles of various sizes, to cut through materials. This type of sawing produces less kerf and waste material than traditional methods, such as the slurry slicing method. Unlike slurry saws, which use bare wire and contain the cutting material in the cutting fluid, diamond wire saws just use water (or some other fluid) for lubrication, cooling the cut and removing debris. Monocrystalline silicon is composed of silicon atoms in an extended orderly arrangement, with no grain boundaries or hard spots; hence the monocrystalline wafer is suited to the diamond wire sawing technique. Diamond wire saw technology has therefore become a perfectly matched option for mono wafer slicing, and significantly reduces costs.

Compared with the slurry slicing method, diamond wire slicing can cut wafers that have smooth surfaces with shallow regions of damage; moreover, the wafers produced have better strength, thus supporting thinner wafers. The diamond wire slicing method also brings the added benefit of lower metal concentration on the silicon wafer surface.

"The trend for thinner wafers is the future for the solar industry."

Thinner wafers

The industry has up to now been concentrating on aspects other than silicon, and the non-silicon cost has kept on decreasing dramatically in recent years. The trend for thinner wafers, however, is the future for the solar industry. The thinner wafer solution is becoming increasingly important, since it directly addresses the reduction of the silicon cost of wafers. In order to bring down the cost, and facilitate the development of the solar industry, the market has been promoting thinner wafers in recent years, driven by some of the leading companies. LONGi, for example, passes on the benefit of reduced silicon costs of wafers to the customers, i.e. thinner wafers at a lower price.

At the moment, multi-wire cutting is widely used for solar cell wafering: thousands of wafers can be produced in a single-pass cut. In order to produce more wafers from a single ingot, silicon wafer thinning is necessary. Wafer thinning technology could directly bring down the average wafer cost, since less kerf is produced and more wafers are created.

For typical cell technology, however, the performance of thin wafers is inherently inferior in terms of efficiency: thinner wafers yield lower IQEs in the long-wavelength region. To maintain a high efficiency for wafers of thicknesses below 200μm, a lower back-surface recombination is necessary [7]. Screen-printed p-type cells with an Al back-side field (BSF) can scale to a minimum wafer thickness of around 170–180μm. For thicknesses below that, optical and back-surface recombination losses significantly degrade the efficiency; innovations with regard to materials, processes, device structures, etc. (for example, the PERL-type cell) are therefore required in order to continue scaling the wafer thickness.

Compared with the traditional solar cell structure, the new HIT solar cell reaps many more benefits from thinner wafers, notably higher efficiencies. The world-class HIT solar cell has so far demonstrated a laboratory conversion efficiency of 25.6% [8].

For thin wafers, several challenges still exist. Although wafer strength is initially outstanding, the bending strength is reduced with decreasing wafer thickness; further studies have shown that bending strength can be improved after the texturing process. In addition, thin mono wafers with micro-cracks and/or V-shape chips have shown higher probability of breakage. With improved manufacturing processes and inspection tool upgrades, however, the potential for wafer breakage can be minimized.

Besides the wafer quality being improved with pulling technologies, the same is true with slicing technologies upgraded by diamond wire. Wafer thicknesses down to 110μm have been achieved in an R&D setting. Recently, the most technically challenging issues for thin wafers have been resolved, resulting in the creation of extra-thin (down to 100μm) wafers; Fig. 5 shows the first 100μm wafer manufactured by LONGi in 2014. In contrast, a wafer thickness of 150μm is currently possible in mass production,

	Wafer thickness	2013	2015	2017
p-type	200μm	60%	3%	X
	190μm	30%	55%	35%
	180μm	10%	40%	55%
	<180μm	X	2%	10%
n-type	200μm	100%	50%	0%
	180μm	X	30%	90%
	<180μm(110μm)	X	X	10%

Table 1. LONGi wafer shipment statistics.

Dimensions	Diameter [mm]	Length [mm]	Area [cm^2]	Increased area [cm^2]
8 inch	200.00	156.00	238.95	-
M2	210.00	157.75	244.32	5.37 (2.25%)

Table 2. Wafer dimension comparison.

Materials

Figure 5. A flexible solar cell made from a LONGi 100μm wafer.

with all the wafer capacity being easily converted to thinner wafer thicknesses according to a particular customer's request.

As Table 1 shows, the thin wafers manufactured by LONGi have been in increasing demand since 2013; in 2017 it is expected that over 65% of the company's wafer products will be thin wafers, i.e. with thicknesses of 180μm and below. The shipment data of LONGi, a supplier of mono wafers, indicate that the market is moving to thin wafers.

Promotion of an industry standard – the M2 wafer

To help and facilitate the development of the PV industry, planning work has been under way to create a wafer product standard, especially from a wafer manufacturer's perspective. At the end of 2013, LONGi's M2 mono wafer was introduced; on the basis of the product's technology and market performance, it has been widely accepted by customers and is becoming the industry standard. Furthermore, mono wafer companies are actively promoting wafer-thinning technology, so that the cost of the mono wafer can be reduced even further and such wafers can thus be more competitive in the market. In consequence, the PV industry could become a more important player in the field of energy and could achieve grid parity.

The larger-wafer products – M2 mono wafers (Table 2) – have several advantages. First, the unified single crystalline product specifications help to reduce costs in the upstream and downstream industry chains. Second, with virtually no changes necessary to the production line, single-cell power output is increased and the value of a single cell is improved. Third, solar module power is enhanced, and the single-solar-module performance to price ratio is improved.

> "There has been a significant increase in the monocrystalline market share, which clearly indicates that there is a growing demand for high-efficiency wafers."

Conclusion

Innovations in structure technology, manufacturing processes and materials are being introduced, all of which lead to a lower cost for monocrystalline compared with multicrystalline, with a wide scope for even further reductions. Meanwhile, as manufacturing technologies continue to be studied, they are reaching the level of maturity suitable for mass production, especially with regard to oxygen control, improved minority-carrier lifetime, decreased degradation, M2 wafer standardization, etc. As a result, the quality of monocrystalline solar cells will be further improved in terms of conversion efficiency, with a 2% advantage over multicrystalline solar cells.

Looking to the future, there has been a significant increase in the monocrystalline market share, which clearly indicates that there is a growing demand for high-efficiency wafers along with high expectations.

References

[1] Yoshikawaet, K. et al. 2017, "Silicon heterojunction solar cell with interdigitated back contacts for a photoconversion efficiency over 26%", *Nature Energy*, Vol. 2, Article no. 17032.

[2] Steinkemperet, H. et al. 2016, *Prog. Photovolt: Res. Appl.* [DOI: 10.1002/pip.2790].

[3] Cousins, P. et al. 2010, *Proc. 35th IEEE PVSC*, Honolulu, Hawaii, USA, p. 275.

[4] Chen, L. et al. 2011, *Sol. Energy Mater. Sol. Cells*, Vol. 95, pp. 3148–3151.

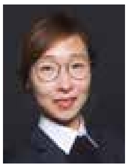
[5] Walter, D.C. et al. 2014, *Appl. Phys. Lett.*, Vol. 104, p. 042111.

[6] Voronkovet, V.V. et al. 2000, "On the properties of the intrinsic point defects in silicon: A perspective from crystal growth and wafer processing", *physica status solidi (b)*, Vol. 222, p. 218.

[7] MEMC workshop, 2010.

[8] Panasonic 2016, PVCellTech, Kuala Lumpur, Malaysia.

About the Authors



Yichun Wang received a B.S. in electrical engineering in 2007 from Northwestern University, China, and an M.S. in electrical engineering in 2010 from the University of Kentucky, USA. She joined LONGi Green Energy Technology Co., Ltd. in 2014, and is currently the application engineering and customer service manager in the silicon wafer business group, where her responsibilities include technical/product quality support and supervising technical collaboration projects with global institutes and corporations.

Tian Xie received his Ph.D. in physics in 2004 from Hiroshima University, Japan. He is the director of the quality management department at LONGi Green Energy Technology Co., Ltd., where his primary responsibility is overseeing the quality management, customer service, product design and sales groups at the company.

Enquiries

Yichun Wang
Tel: +86 186 8185 6911

Email: wangyc@longi-silicon.com