Development of HJT technology in China

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Abstract

In this paper, three generations of silicon heterojunction (HJT) solar cell technical routes in China are reviewed. We define the structure of HJT cells with an amorphous silicon thin film on two surfaces of a monocrystalline-silicon (c-Si) wafer as HJT 1.0, which is the first generation of HJT. HJT cells with silicon-oxygen thin film on the front side of a c-Si wafer are defined as HJT 2.0, and HJT cells with a silicon-oxygen structure on the front side and a microcrystalline silicon structure on the back side are defined as HJT 3.0. HJT 1.0 and 2.0 have been mass produced in China since 2021. Generation 3.0 will be going into mass production in the next two years. Several other advanced technologies also support the continuous cost reduction and efficiency improvement of HJT cells, such as new metallization technologies based on high mesh count screen plates and silver-coated copper paste, thin wafer technology, and new module technologies based on novel encapsulation materials. Huasun established a 500MW HJT 1.0 cell and module production line in 2021, with a 2GW HJT 2.0 cell and module production line following in 2022. Huasun set up an R&D laboratory in 2021 to conduct in-depth research on HJT 2.0 and HJT 3.0 technologies in order to promote the industrialization of HJT 2.0 and HJT 3.0 through collaboration with other companies, such as Maxwell.

Introduction

Photovoltaic technologies are in a stage of rapid development. On the one hand, the majority of market share has been taken up by conventional passivated emitter rear contact (PERC) cells with a superior economic performance. New cells, on the other hand, based on advanced technological routes, are progressively making their way into mass production. Among them, silicon heterojunction (HJT) cells, as a novel technology, have attracted the attention of the market for their high efficiency.[1]

Currently, n-type silicon wafers are mainly used for mass-produced HJT cells. Cleaning and texturing, silicon-based film deposition, transparent conductive oxide (TCO) film deposition and metallization are the four steps in producing HJT. During the cleaning and texturing stage, wafers are placed in an alkaline solution containing organic additives to remove surface dirt, etch saw damage and form a pyramid structure that reduces reflection. Deposition of silicon-based thin films is generally accomplished via chemical vapour deposition (CVD). Intrinsic amorphous silicon layers are deposited on both surfaces of the substrate to passivate the silicon surface. Doped silicon-based thin films are then deposited to create a built-in electric field.[2] Physical vapour deposition (PVD) is commonly applied for the deposition of TCO films, which protect silicon-based films and laterally conduct the electrical current as a transparent conductive electrode. Metallization is typically carried out by screen printing. The paste is printed on TCO films and then annealed in a furnace to dry the paste and solidify the grid lines. The efficiency is further improved after light soaking.[3]

World records for the efficiency of HJT cells have been set in recent years by numerous companies. In November 2022, the efficiency of LONGi HJT cells was verified by the Institute for Solar Energy Research in Hamelin (ISFH) to be 26.81%, setting a new record for HJT, which was the first time that a Chinese solar technology company had broken the record for silicon solar cells. This further demonstrates the technical superiority and market potential of HJT.

In this paper, we concentrate on the evolution of the internal structure of HJT and the current status and application of new materials and technologies, taking the large-scale manufacturing process of HJT at Huasun as an example to introduce the development of the product in China. Anhui Huasun Energy Technology Co., Ltd. was established in July 2020 and is located in Xuancheng City, Anhui Province. The company is dedicated to the production of and research into HJT, and has become one of the leading suppliers of HJT products in China with the world's largest HJT production capacity.

The evolution of the HJT structure

The structure of HJT determines the maximum possible absorption of sunlight and the effective collection of photogenerated carriers in the whole solar cell, which are key elements in determining photoelectric conversion efficiency. The technical route of the HJT cell is divided into three main generations, as shown in Fig. 1.

First generation: HJT 1.0

Fig. 1(a) illustrates the structure of mainstream HJT in the market up to 2019. The overall structure is Ag/TCO/n-a-Si:H/i-a-Si:H/n-c-Si/i-a-Si:H/p-a-Si:H/TCO/Ag, where n-a-Si:H is on the front side, and the p-n junction is located on the back of the cell to reduce light absorption of the p-a-Si:H. In this paper, an HJT cell with this amorphous silicon structure on both surfaces

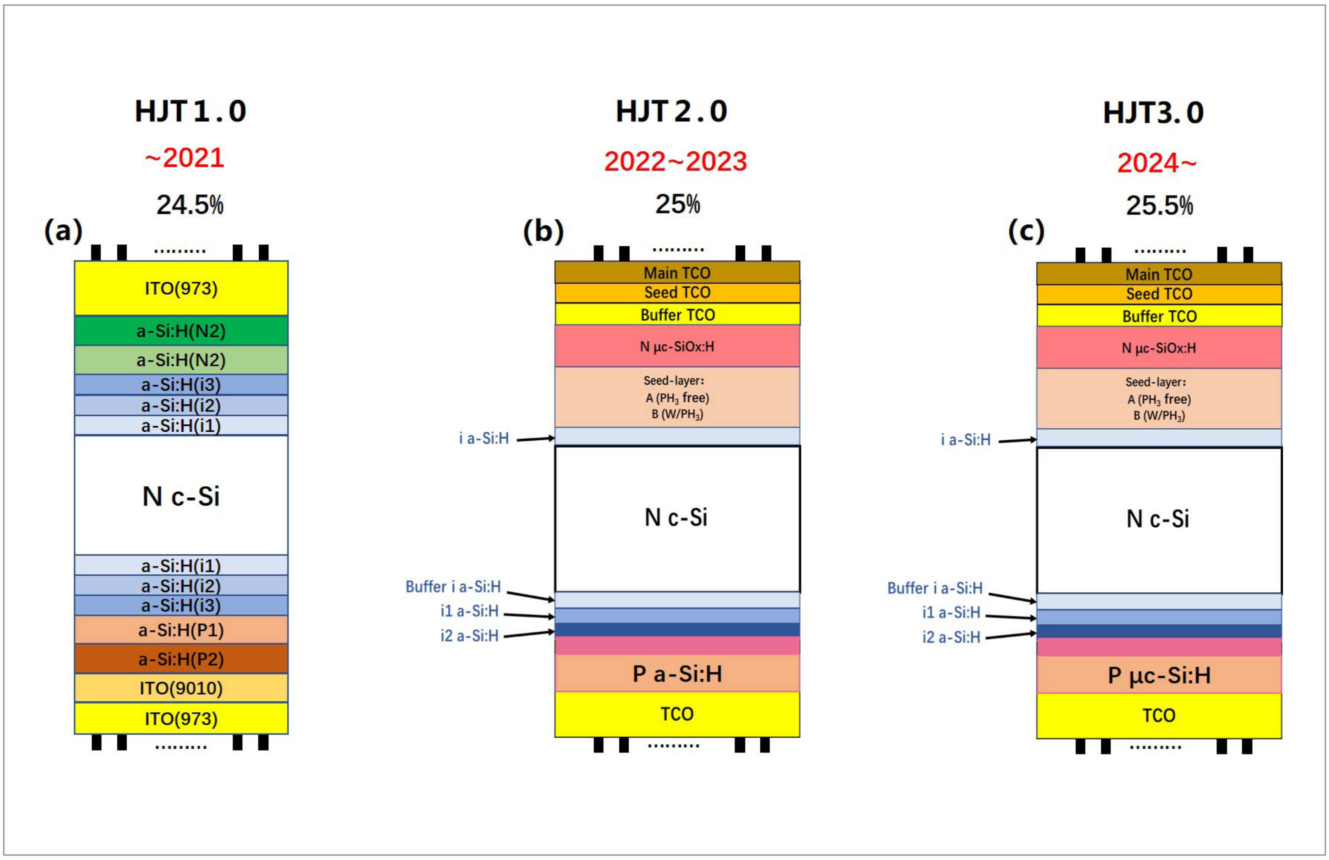

Fig. 1. Three generations of HJT technical routes

is referred to as HJT 1.0. The individual layers of these films can also be further separated and optimised in accordance with equipment conditions or production requirements. In Fig. 1(a), the i-a-Si:H films on the front and back surfaces are divided into three layers. The i1 + i2 stack is a thin composite buffer layer with a high percentage of dihydride (Si-H2) bonds.[4,5] It effectively inhibits epitaxial growth[6] and passivates the substrate surface. In addition, the i3 layer is a dense passivation layer[7,8] in which monohydride (Si-H) bonds dominate.[4,5] n-a-Si:H and p-a-Si:H films are also divided to form a gradient-doped structure. This improves contact between intrinsic and doped silicon-based film, as well as between the doped silicon-based film and TCO. Composite films are used in TCO to achieve high efficiency and low cost,[9] such as the bilayer of ITO-90/10 (In_2O_3:SnO_2 = 90 wt.%:10 wt.%) and ITO-97/3 (In_2O_3:SnO_2 = 97 wt.%:3 wt.%) in Fig. 1(a). ITO-90/10 and a-Si:H have strong electrical compatibility, and ITO-97/3 has a higher deposition rate and a lower material price than ITO-90/10. The bilayer is a good balance between electrical properties and the cost of manufacture. After optimisation, the efficiency of mass-produced HJT 1.0 can reach 24.5%.

Second generation: HJT 2.0

At present, companies have successively entered the HJT 2.0 mass-production technology route to increase short-circuit current density. From the equipment side, very-high-frequency (VHF) excitation generally replaces radio-frequency (RF) excitation in plasma-enhanced chemical vapour deposition (PECVD) for amorphous silicon film microcrystallization. The structure of HJT transforms from n-a-Si:H on the front side into n-μc-SiOx:H. The optical band gap of n-type silicon-based film becomes wider and the light parasitic absorption is reduced as a result. [10] Additionally, the effective doping ratio of phosphorus is increased, so the built-in electrical field is strengthened via microcrystallization. TCO is also split into layers that contain the buffer layer, seed layer and the main function layer, to enhance contact with n-μc-SiOx:H and with grid lines. Combined with the matching and optimisation of other films, mass-production efficiency has been increased to more than 25%.

Third generation: HJT 3.0

Over the next one or two years, it is anticipated that the mass-production technical route for HJT will enter HJT 3.0. In contrast to HJT 2.0, the p-a-Si:H layer on the back side of HJT is also microcrystallized to form p-μc-Si:H.[11] The effective doping rate of boron is also greatly increased in microcrystalline silicon, similar to phosphorus. Therefore, microcrystallizing the p-type silicon-based film can improve the conductivity of layers, as well as enhance the built-in electrical field. With further optimisation, the cell efficiency of HJT 3.0 can surpass 25.5%.

No.	Item/test data	Power loss	I_{sc}	U_{oc}	*FF*
1	Original data	/	/	/	/
2	DH 1000h with 6A	−0.18%	−0.43%	0.30%	−0.05%
3	DH 2000h with 6A	−0.76%	−1.26%	0.29%	0.21%
4	DH 3000h with 6A	−1.28%	−1.82%	0.33%	0.22%
5	Place 50 day	−2.02%	−1.82%	0.05%	−0.26%
6	DH 6400h	−2.85%	−0.45%	−0.39%	−2.00%

Table 1. Damp-heat (DH) testing of modules based on Ag-coated Cu paste at Huasun (U_{oc} = open-circuit voltage, I_{sc} = short-circuit current, *FF* = fill factor)

In addition, cleaning and texturing and metallization processes should also be tailored to each technical route. For instance, different CVD technologies may require altering the size of the pyramids. In order to match the requirements, the texturing time and alkali and additive concentrations should be adjusted. The furnace temperature needs to be regulated since cells with different film structures have varied temperature tolerances. Different light-soaking parameters result in varying degrees of improvement for cells with different structures, necessitating appropriate modification.[12]

Advanced HJT technologies to achieve efficiency improvement and cost reduction

Designing and enhancing the HJT internal structure is key to increasing efficiency. In addition, numerous other advanced technologies are capable of further increasing the efficiency and stability of HJT, or reducing manufacturing costs.

New metallization technologies

The two major components of new metallization technologies are the screen plate and paste. In general, to a limited extent, increasing the mesh count in the rapid printing of high-viscosity silver paste can dramatically reduce silver paste consumption without compromising cell efficiency. At present, screen manufacturers promote 480 mesh count screen plates as their primary high mesh screen products. By appropriately adjusting printing parameters, improved grid line characteristics can be acquired while maintaining the same silver paste consumption, thus increasing efficiency. Besides silicon, silver paste has always been one of the most expensive components in HJT manufacturing costs. Reducing the quantity of silver will effectively reduce the cost of HJT. The application of silver-coated copper paste can replace silver with copper, which has become a specific cost-reduction strategy for HJT. It is specific to HJT since silver-coated copper paste can only be used in the region for low-temperature paste to prevent the silver coating from being damaged. Huasun has conducted trials on silver-coated copper paste from several manufacturers. The efficiency of printed cells is close to that of silver paste printed cells, and the grid line tensile strength and electrical performance stability (as shown in Table 1) are also excellent. It is expected that, in 2023, some companies will begin to fully use silver-coated copper paste instead of silver paste, reducing the silver consumption of a cell to 80 mg, which is consistent with PERC cells and completely solves the problem of high silver consumption.

Thin wafer technology

At the moment, the high cost of silicon wafers poses challenges for cell and module manufacturers. As a result, thin wafer technology is a method to considerably reduce costs. Fig. 2 depicts the electrical performance of cells that are made from wafers with different thicknesses using the same process. Clearly, the open-circuit voltage (U_{oc}) increases as wafer thickness decreases. This stems from the reduction of bulk recombination[13] with the thinning of the silicon wafer. However, the short-circuit current (Isc) and fill factor (FF) both decrease in line with decreasing wafer thickness due to the reduction in light absorption. There is no significant change in the efficiency of cells with thicknesses of 100–150 μm, it being evident that appropriately thinning the wafer does not lead to a decrease in cell efficiency. For the sorted cells with the same efficiency level, the power of a module composed of cells with a thickness of 130 μm is 0.16% greater than that of cells with a thickness of 150 μm, meaning that the module has a better cell-to-module (CTM) ratio. The cell efficiency is still 24.9% when the thickness is 70~80 μm and the cell can be bent properly, thus providing conditions for the future production of flexible HJT modules. Some HJT manufacturers now have their own silicon wafer department, providing thin silicon wafers for cell manufacturing. During the next one or two years, the silicon wafers used to produce HJT cells will be thinned to 130 μm. Of course, thin wafer technology will face a challenge in the case of automated systems.

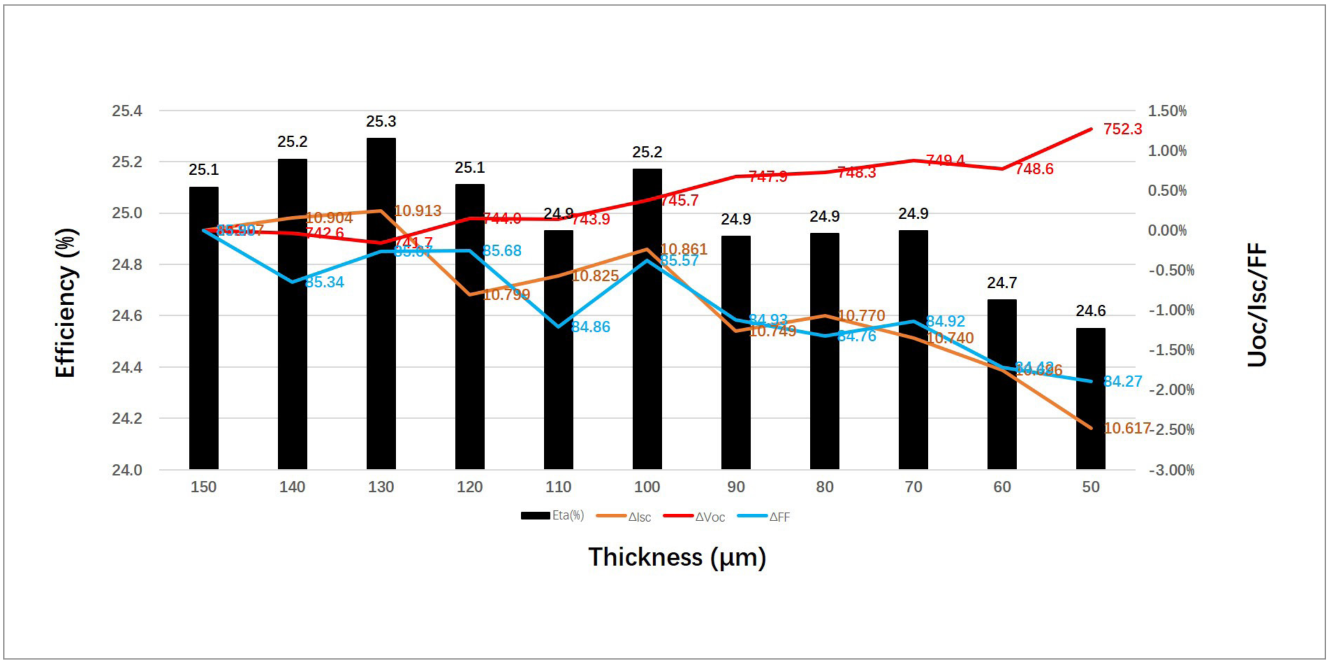

Fig. 2. Electrical characteristics of HJT 2.0 with different thicknesses

New module technologies

Module technology plays an essential role in the power generation and stability of the final product. In recent years, more and more advanced materials have been utilised for module encapsulation, resulting in high efficiency and high stability of HJT modules, water resistance having long been one of the most significant qualities of encapsulants. As an adhesive, transparent butyl adhesive guarantees not only superb light transmission but also excellent air and water tightness. It can greatly improve the weatherability of the module and effectively extend the product's life. Ultraviolet (UV) degradation has been a significant cause of crystalline silicon solar cell and module degradation.[14] UV light can be transmitted effectively over highly transparent film because it transmits light of different wavelengths well. This causes UV damage to the cells. Typically, the UV cut-off encapsulant film is used to restrict the irradiation of short-wavelength light and thus inhibit UV degradation.[15] Nevertheless, in the technology routes of HJT 2.0 and HJT 3.0, the n-μc-SiOx:H film on the front side is more favourable for short-wave light transmission than the n-a-Si:H film in HJT 1.0. So, the utilisation of UV cut-off film significantly reduces the short-wave response benefits of HJT 2.0 and HJT 3.0. To address this issue, UV conversion encapsulant film can be used as an encapsulant. UV conversion encapsulant film converts the short-wave light (about 300~400 nm) to a slightly longer wavelength band (about 400~500 nm), so that the near-UV light can be absorbed without inhibition, thereby maximising the benefits of n-μc-SiOx:H film. The quantum efficiency (QE) curves demonstrate that the module's response to short-wave light can be effectively improved by employing UV conversion encapsulant film, as shown in Fig. 3.

The UV results (as shown in Fig. 4) indicate that UV conversion encapsulant film provides the HJT 2.0-based modules with excellent resistance to UV degradation.

The development level of HJT in China

HJT 1.0 is now being produced at a mature level in China, with consistent efficiency and yield. The current capacity of the major HJT producers is shown in Table 2. Other companies also have their own pilot test lines in addition to these. Among these production lines, the HJT 1.0 lines were all constructed early on with limited capacity. HJT 1.0 can be updated to HJT 2.0 with a small modification. The majority of HJT producers started HJT 2.0 mass production during 2022, with the result that HJT 2.0 now makes up a greater percentage of total HJT production capacity than HJT 1.0. The primary technologies in the future are HJT 2.0 and HJT 3.0, and large-size and thin wafer technologies will be gradually implemented. New technologies, including high mesh count screen plates, silver-coated copper paste and UV conversion encapsulant film, will be implemented one at a time to further cut costs after confirmation of stability.

To demonstrate the production status in further detail, the following takes Huasun as an example. Huasun completed a 500 MW HJT production line in 2021 with the technical route of HJT 1.0. The products consisted of cells and modules. The cell size was 166*166 mm and the average efficiency in mass production was 24.5%. In 2021, the company carried out its plans for increasing production capacity. As shown in Fig. 5, the daily production capacity of cells reached 187,900 units in June 2021 and full production capacity was achieved by mid-June. The stability of production

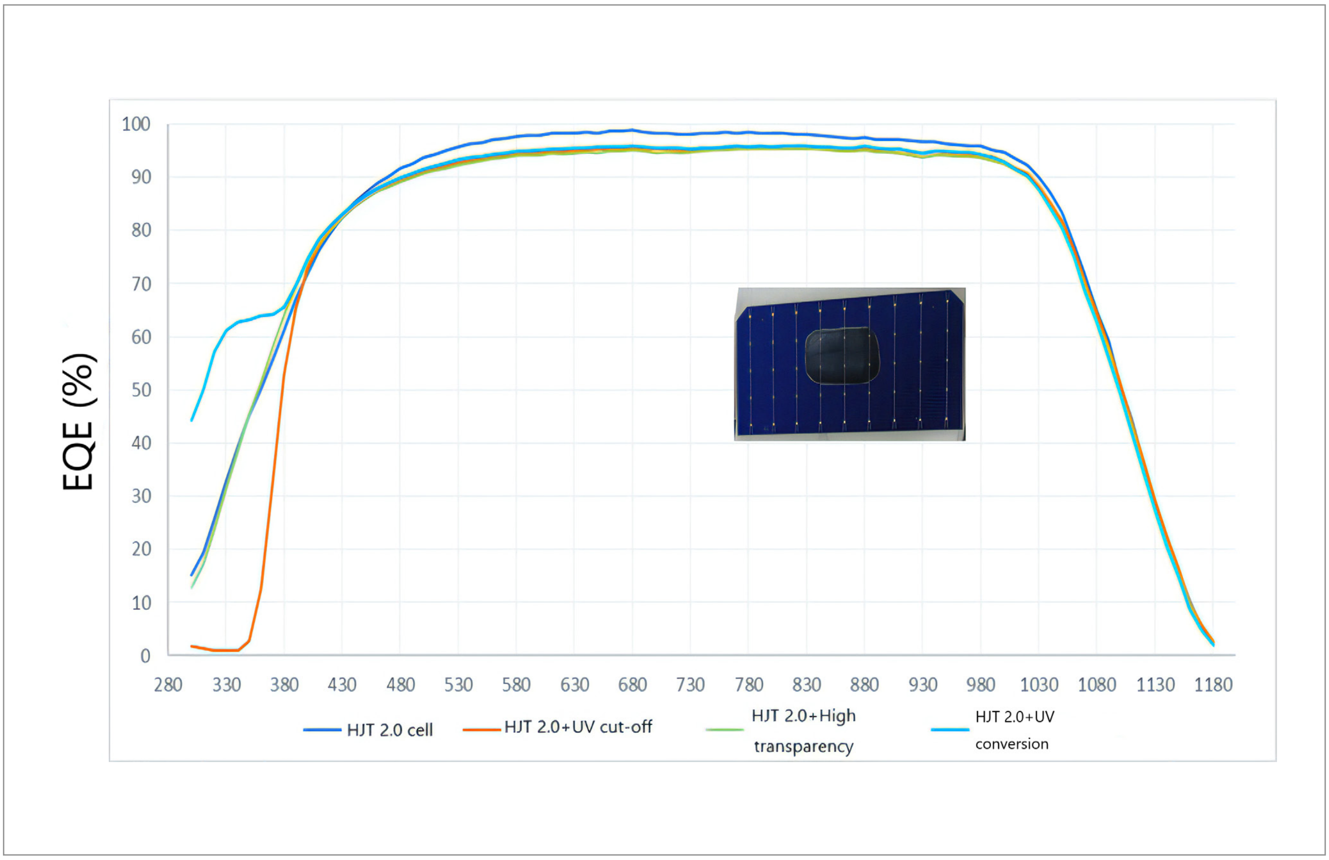

Fig. 3. QE curves of different package films based on HJT 2.0

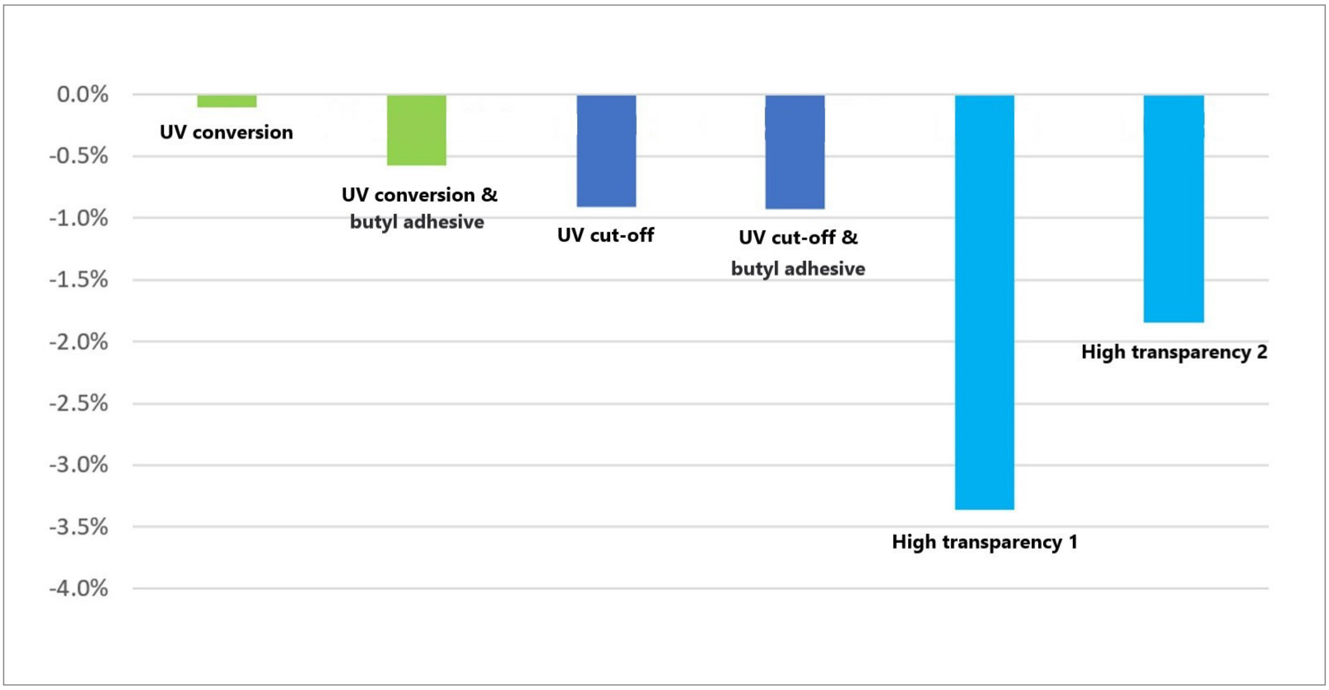

Fig. 4. Outdoor UV experiment for different encapsulant films with HJT 2.0 modules

line equipment continued to improve, the yield for A0 grade reaching 98% and that for A0+A1+A2 reaching 99.5%, equivalent to PERC. After process improvements, a daily output of 245,000 pieces was achieved on 4 July 2021, surpassing 125% of the designed capacity. The production capacity reached the same level of 660 MW in the fourth quarter of 2021.

In 2022, Huasun completed an HJT production line for cells and modules with a capacity of 2GW. The technical route was HJT 2.0 and capacity is currently climbing. Unlike the 500MW production line, this line produces 210*210 mm half-cells. In addition, this production line involves a phosphorous diffusion gettering process to remove impurities from the n-type silicon wafers, to further improve the

Company	Established HJT 1.0 (MW)	Established HJT 2.0 (MW)	Planning (MW)
Huasun	500	2,200	17,500
Company T	1,000	250 (upgrading from 1.0 to 2.0)	
Company J		1,200	4,800

Table 2. The capacity of major HJT production companies

efficiency of the cell. The average efficiency in mass production has now reached 24.7%, with maximum efficiency at 25.21%, as shown in Fig. 6. However, there is still room for further improvement.

With the completion of the 500 MW production line in 2021, the Huasun R&D Centre began building a laboratory to conduct in-depth research on HJT 2.0 and HJT 3.0 technologies. In May 2021, Huasun collaborated with Maxwell to set a world-record HJT efficiency of 25.26%. Self-developed HJT 2.0 technology was launched after completion of the 2GW production line in April 2022, and will be upgraded to increase capacity and efficiency. Simultaneously, the R&D Centre is also actively researching into HJT 3.0 technology. Under the same equipment conditions as the production line, a maximum efficiency of 25.6% was achieved in August 2022 (validated by the Chinese Institute of Metrology) while, at the same time, many of the stability issues that could affect the final efficiency were resolved. As a consequence, the foundation was laid for the industrialization of HJT 3.0.

Summary and expectation

HJT technology has progressed as expected. By combining a variety of modern photovoltaic technologies, it has increased efficiency and decreased cost.

In the future, HJT 3.0 will become the mainstream, achieving a levelised cost of electricity (LCOE) comparable to products of other technology lines, like PERC. Huasun has been at the forefront of this technology since its inception, pioneering the development of HJT, and will continue to expand its production capacity to achieve mass production of HJT 3.0. Combined with thin wafer technology, new metallization technologies and new module technologies with different encapsulant materials, Huasun will further reduce costs and improve the efficiency of mass-produced cells and modules, making HJT the most cost-effective photovoltaic technology. The Huasun R&D Centre will carry out additional research into new HJT structures, focusing on heterojunction back contact (HBC) and tandem cells, while the company gradually implements R&D outcomes into its production lines.

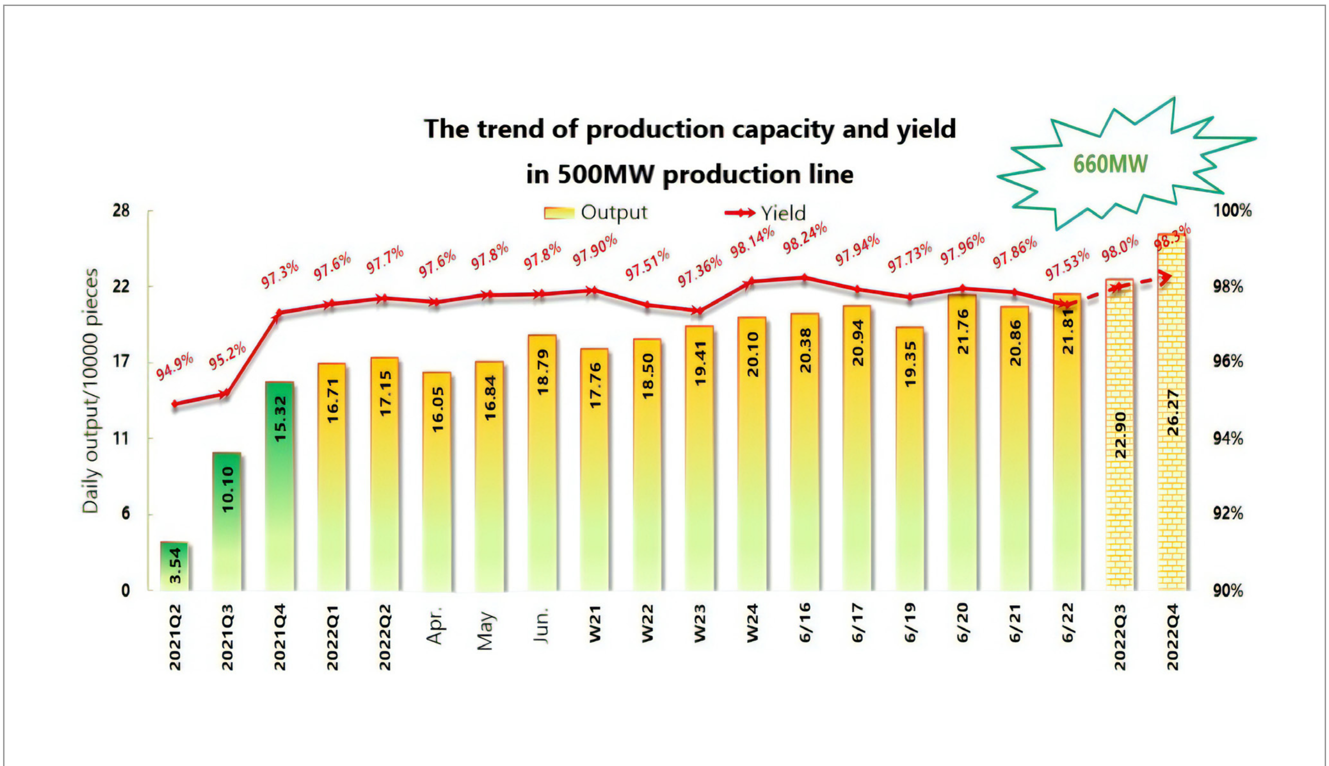

Fig. 5. Production status at Huasun in 2021

Qua	Eta_Ave	Eta_Max	Uoc	Jsc	FF	Pmpp	Rser	Rshunt
5467	24.92	25.21	0.746	39.19	85.24	5.49	0.0047	1458.69

Fig. 6. Maximum efficiency trend of 2 GW production line at Huasun (Qua = quantity, Eta_Ave = average efficiency, Eta_Max = maximum efficiency, J_{sc} = short-circuit current density, P_{mpp} = power at maximum power point, R_{ser} = serial resistance, R_{shunt} = shunt resistance)

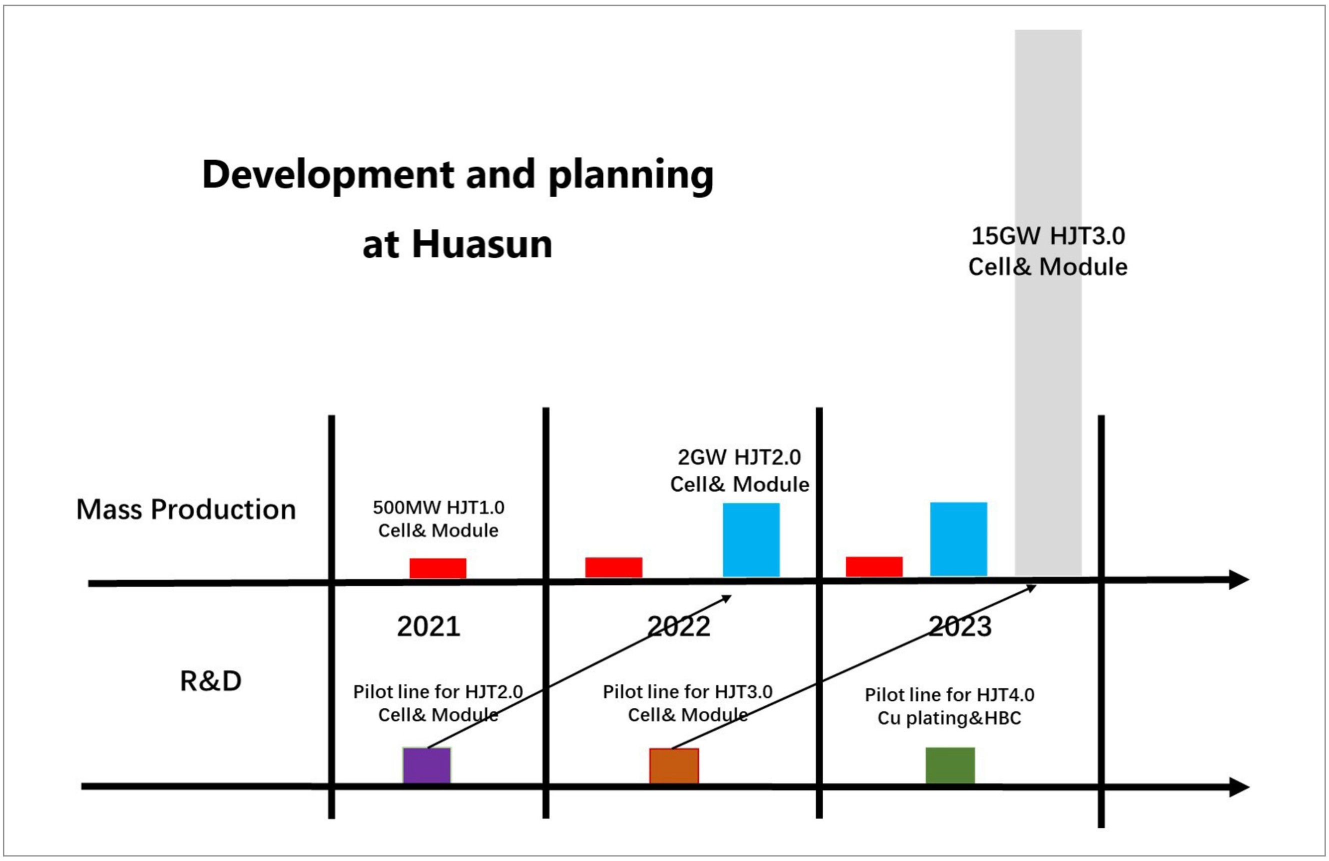

Fig. 7. Development and planning for HJT at Huasun

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