

# Enhancing industrial c-Si cell efficiency by chemical treatment of the SiN layer

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## ABSTRACT

The need for higher efficiency solar cells is becoming more and more urgent nowadays in the photovoltaic industry. In this paper, a new method of increasing efficiency is described whereby SiN is coated by a special commercial chemical after the final step of manufacturing, which is screen printing. No mask is required for this method, but a drying temperature of 200–400°C is mandatory to activate the SiN layer. It is shown that the efficiency of a crystalline solar cell can be increased by at least 0.16% (absolute value) on average. At the same time, modules made from these solar cells do not degrade after sun exposure, and have the potential to pass the stringent standards of a potential-induced degradation (PID) test. The total cost for all the equipment and the chemical is around US\$300,000 for retrofitting two (30MW each) production lines.

## Introduction

The traditional processes for manufacturing crystalline silicon solar cells are: texturing, diffusion, edge and back-side isolation, surface passivation and screen-printing metallization. The average conversion efficiency achieved is 16.4–16.8% for industrial multicrystalline solar cells. Various technologies have been used to optimize each step, but the manufacturing process is still not perfect. For industrial solar cells, there are a number of ways to reduce the optical losses [1]:

- Minimize the top contact coverage of the cell surface (although this may result in increased series resistance).
- Apply anti-reflection coatings (ARC) to the top surface of the cell.
- Use surface texturing to reduce reflection.
- Make the solar cell thicker to increase absorption (although any light which is absorbed more than a diffusion length away from the junction will not typically contribute to short-circuit current, since

the carriers recombine).

- Increase the optical path length in the solar cell by a combination of surface texturing and light trapping.

In this paper, the ARC layer is the main focus and the other factors mentioned above will not be considered. The ARC method developed at Chinalight Solar involves coating the cell with a special chemical and activating the SiN layer. By doing this, all the optical and electrical properties of the cell are enhanced. This technique can be easily

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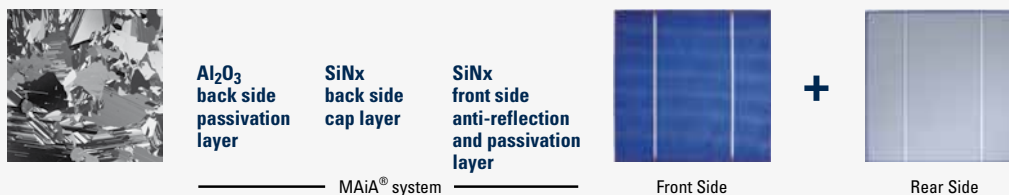
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## UPGRADE CELL PERFORMANCE BY BACK SIDE PASSIVATION WITH Al<sub>2</sub>O<sub>3</sub>

Aluminium oxide (Al<sub>2</sub>O<sub>3</sub>) has been found as an excellent means for the passivation of the wafer backside. Thus, the passivation of the wafer backside leads to a considerable improvement of the cell efficiency – up to 19% and more. Basing on the industrially proven anti-reflection coating equipment SiNA®, the MAiA® system has been developed to provide a double side coating tool for solar cells, in which all coating steps for back side passivation plus the anti-reflection coating of the front side can be carried out in one run.

### 3 PROCESS STEPS – 2 SIDES – 1 SYSTEM ONLY

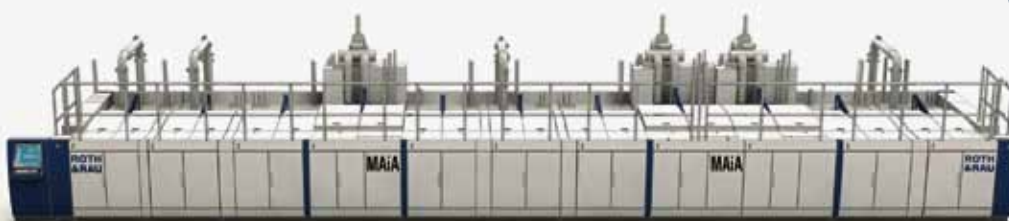


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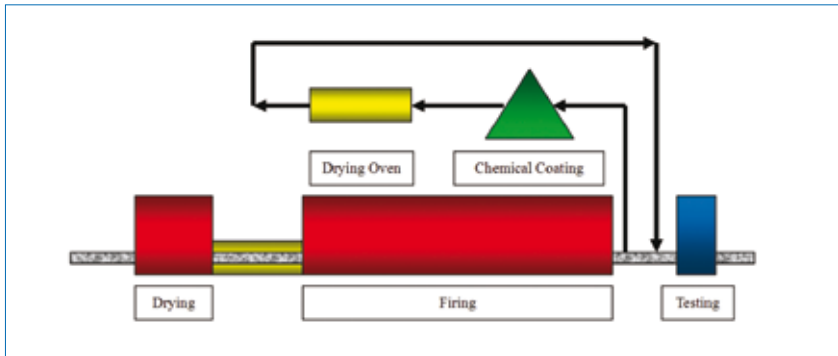


Figure 1. Formation of the coating in the ARC-layer manufacturing process.

incorporated into existing metallization process lines, as well as being beneficial for already manufactured cells.

### State of the art of ARC

The most common method of forming the ARC layer in the solar industry is plasma-enhanced chemical vapour deposition (PECVD). Roth & Rau and Centrotherm are the two main manufacturers of PECVD machines, which are remote and direct in terms of plasma generation. At the same time, other competitors, for example Applied Materials, use sputtering to deposit the ARC layer. Although this method yields a high SiN density, the equipment costs are too high.

The thickness of the ARC is chosen so that the wavelength in the dielectric material is one quarter of the wavelength of the incoming wave. For a quarter-wavelength ARC of a transparent material with a refractive index  $n$ , and light incident on the coating having a free-space wavelength  $\lambda$ , the thickness  $d$  that causes minimum reflection is calculated by:  $d = \lambda/4n$ . Reflection is further minimized if the refractive index of the ARC ( $n_1$ ) is the geometric mean of that of the materials on either side; that is, glass or air ( $n_0$ ) and the semiconductor ( $n_2$ ). This is expressed by:  $n_1 = (n_0 n_2)^{1/2}$ .

The thickness and refractive index of the ARC layer are dependent on the wavelength, so zero reflection occurs only at a single

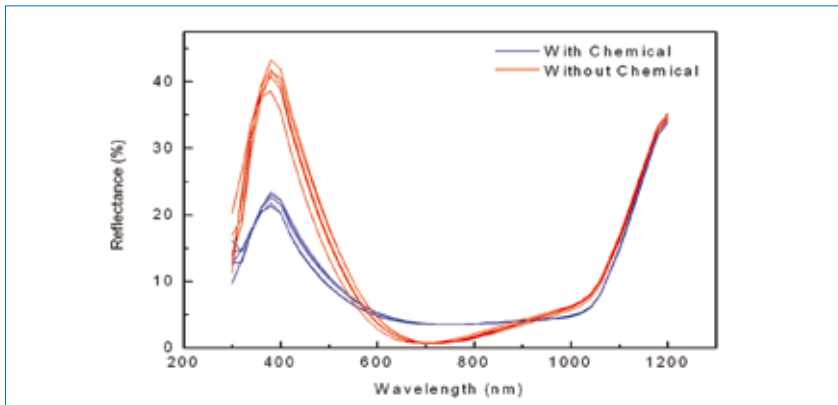


Figure 2. Reflectance of incident light with chemical treatment (blue lines) and without (red lines).

wavelength. For photovoltaic applications, the refractive index and thickness are chosen in order to minimize reflection for a wavelength of 600nm. This wavelength is chosen since it is close to the peak power of the solar spectrum [1]. However, for the real application of a solar cell, the significant reflectance below 600nm is still too high (as evidenced by the graph of reflectance vs. wavelength discussed in the next section). Dielectric stack layers – such as SiO<sub>2</sub>/SiN/Si, SiN/SiO<sub>2</sub>/Si and SiN(N rich)/SiN(Si rich)/Si – have been used to further reduce the surface reflectance, but this process is still complicated and expensive, and sometimes has no effect at all.

### An additional ARC-layer manufacturing step – chemical coating

#### Formation of the coating

Only two machines and one chemical are required in this process. Commercial spin-coating, dip-coating or spray equipment can be used to disperse the chemical; a spray machine is chosen here, for speed considerations. After the chemical spraying, a drying oven at a temperature of 200–400°C is used to activate the SiN layer, requiring no special environment apart from air. These two processes are illustrated in Fig. 1, between the firing furnace and the tester. At Chinalight Solar, we use a Despatch firing furnace and a Berger efficiency tester.

#### Function of the coating

The chemical applied in this technique can activate the SiN layer surface and change its refractive index and thickness, thereby causing a solar cell to absorb more light. Fig. 2 shows the surface reflectance of five industrial solar cells (without back-side metal), with chemical treatment (blue lines) and without (red lines). It can be clearly seen that light reflectance for wavelengths below 600nm is dramatically reduced (by half) after chemical coating and activation. For a band gap of silicon of 1.1eV, the maximum

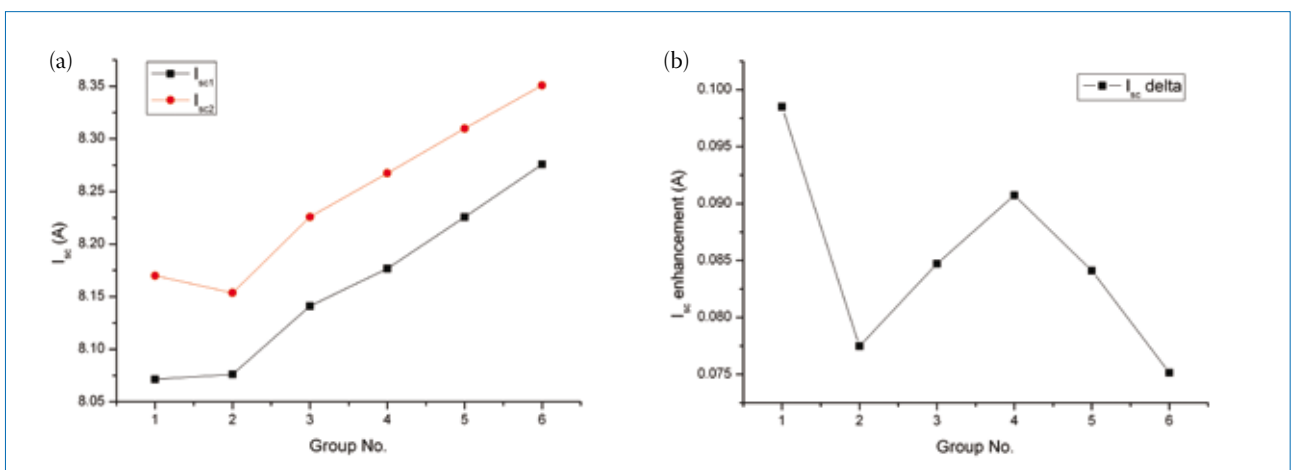


Figure 3. (a)  $I_{sc}$  before and after chemical treatment; (b)  $I_{sc}$  enhancement after treatment.

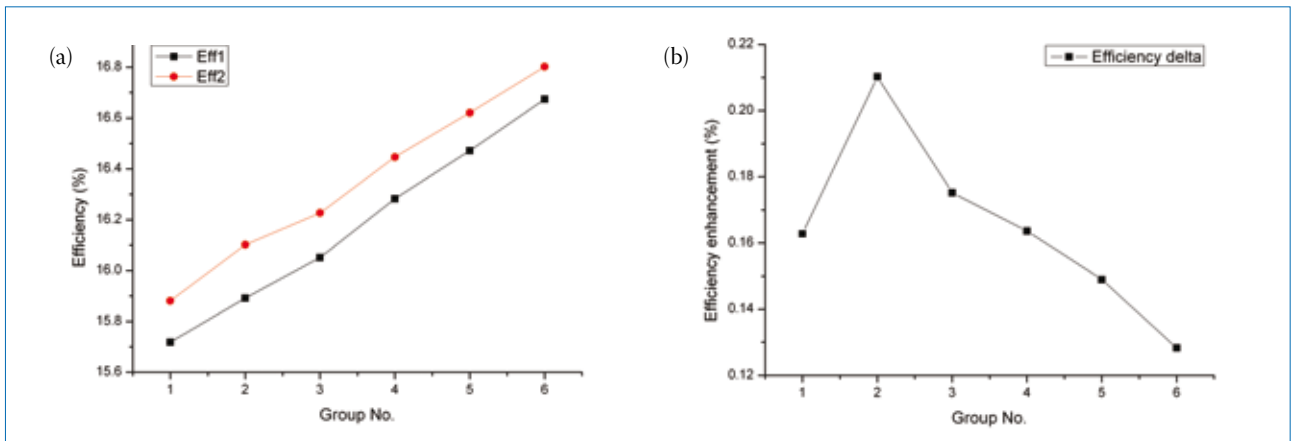


Figure 4. (a) Efficiency before and after chemical treatment; (b) efficiency enhancement after treatment.

wavelength is 1128nm, where photons can be used to generate electron-hole pairs. Short-wavelength photons are very useful; they will contribute to the whole cell performance. This phenomenon is indicated by short-circuit current ( $I_{sc}$ ) enhancement.

### Cell experimental results

Six groups of cells (each group containing 50 screen-printed cells from Chinalight Solar’s multicrystalline silicon production line) were measured before and after the chemical treatment. Fig. 3 shows that the value of  $I_{sc}$  after treatment ( $I_{sc2}$ ) is up to ~0.1A higher, no matter what the previous cell efficiency. Fig. 4 shows that the efficiency is at least 0.12% (absolute value) higher than before, with a maximum value of 0.21% for group 2. The efficiency of all the cells is boosted by 0.16% on average by the chemical treatment, but the best results are obtained when the cells’ efficiency is close to 16%. Another factor to note is that this treatment can be used throughout the whole cell efficiency range, from below 16% to ~17%. This is especially important for solar cell manufacturing.

There is almost no change in the open-circuit voltage ( $V_{oc}$ ), series resistance ( $R_s$ ) and shunt resistance ( $R_{sh}$ ). The only problem is that there is a small fill factor (FF) loss during the chemical coating and further heating. The reason for fill factor deterioration is still unknown, but the trend is that the stronger the chemical treatment is, the lower the fill factor will be. The relationship between fill factor loss ( $\Delta FF$ ) and efficiency change ( $\Delta Eff$ ) is illustrated in Fig. 5.  $\Delta Eff$  and  $\Delta FF$  exhibit a near-linear relationship. When fill factor loss can be controlled to less than 1 (absolute value), the efficiency of all the cells will increase. When there is no fill factor loss, the efficiency will increase by ~0.2% (absolute value).

### Module experimental results

Sixty cells constructed with a chemical coating (with an average cell efficiency increase from 16.16% to 16.30%) were integrated into a module. Soldering on the busbar was not a problem and therefore

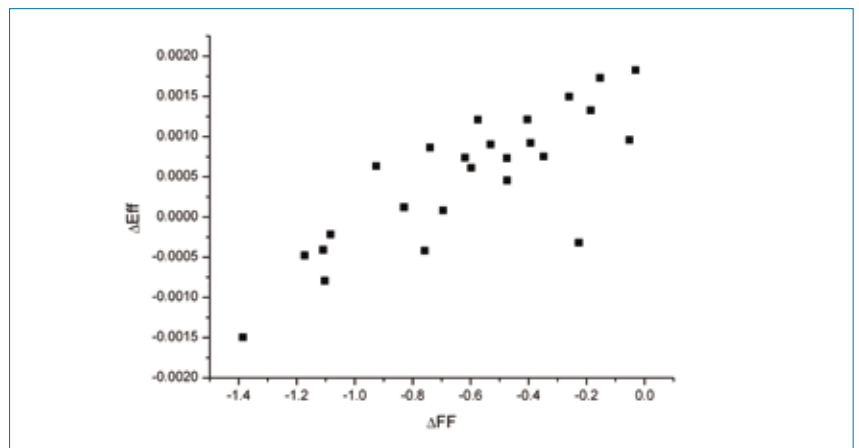


Figure 5. Relationship between fill factor loss ( $\Delta FF$ ) and efficiency change ( $\Delta Eff$ ).

no mask during coating was needed. The module colour was identical to the one made by traditional screen-printed cells.

The module was tested at an ambient temperature of 25–26°C. Detailed information about the module is shown in Table 1. The maximum power output is 231W and the theoretical power is 238W, giving an assembling power loss of 2.94%.

The module was put outdoors and exposed to the sun for two weeks prior to the experiments. Compared to traditional modules, where a 1–2% degradation is quite normal, there was no degradation for this special module. As shown in Table 1,  $I_{sc}$  and  $R_s$  became worse, but  $V_{oc}$ ,  $R_{sh}$ ,  $P_{max}$ , FF and Eff were better after exposure. We can assume there was no hot spot on

the infrared image, where the EVA would turn yellow and deteriorate very fast, leading to early damage of the module. The deterioration of  $I_{sc}$  and  $R_s$  may be due to partially broken soldering on the busbars (after two weeks’ exposure); in any case, the silver front contacts are coated by some of the chemical, leading to non-perfect soldering. Therefore, as little as possible of the chemical must be used, so that there is no significant loss of efficiency.

Normally the light-induced degradation of monocrystalline solar cells and modules is stronger than in the case of multicrystalline cells. Because Chinalight Solar only has multicrystalline production lines, the mono tests will need to be carried out in the future as well, to prove the quality

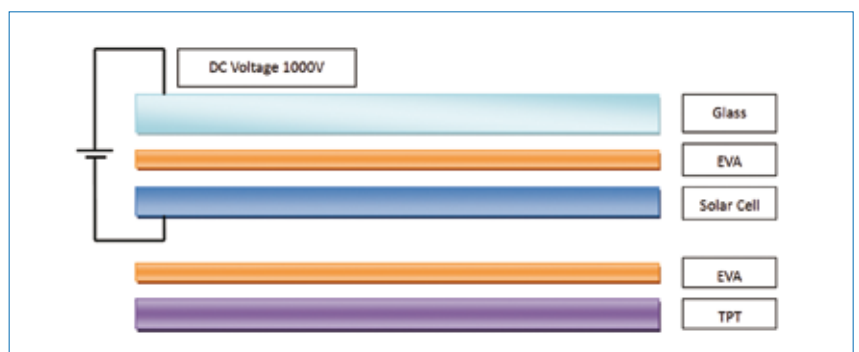


Figure 6. PID test setup showing the structure of the module [3].

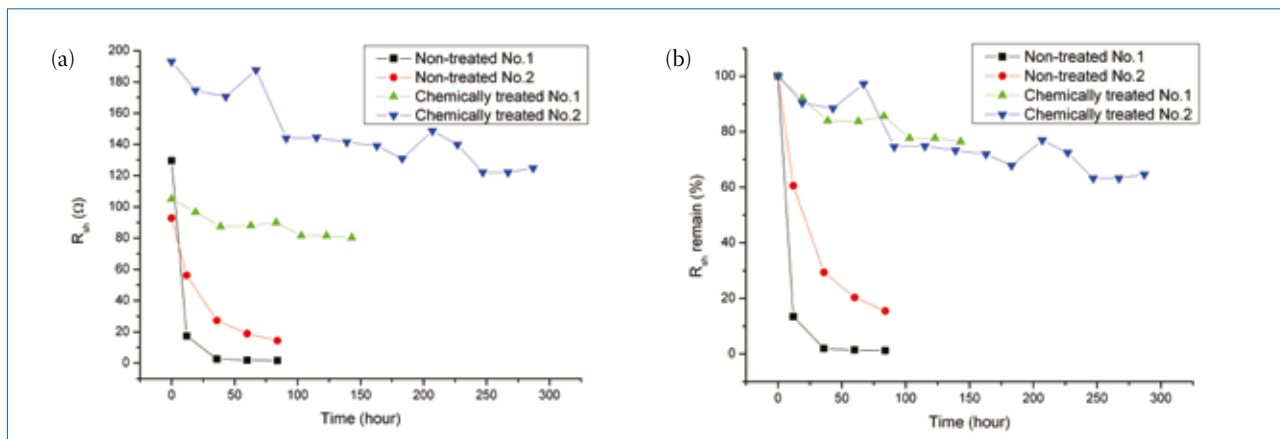


Figure 7. PID test results for normal and chemically treated modules: (a) change in  $R_{sh}$ , and (b) percentage  $R_{sh}$  remaining.

of the chemical treatment. Light-induced degradation is usually caused by boron-oxygen recombination pairs, which leads to a decrease in minority carrier lifetime. The reason for the non-degradation of this module is still under investigation.

### Potential-induced degradation (PID) test results

Recently, module degradation and power loss have started to become more and more common in solar plants. When solar cells are interconnected in series, high system voltages can lead to unwanted leakage currents between the solar cells, bedding materials, glass and grounded module frame. This allows a positive charge to build up on the ARC at the surface of the cells [2]. There are two main ways to solve the PID problem. First, at the cell level, a better ARC layer having better dielectric ability can be applied. Second, at the module level, a better encapsulation foil can be used.

To perform the PID test [3], at Chinalight Solar we encapsulate each cell in a 156mm-square glass frame to make a one-cell module. The detailed structure of the module is shown in Fig. 6.

In Fig. 7 it is seen that the  $R_{sh}$  of normal modules degrades dramatically over the first 50 hours, but chemical-treated modules retain most of the  $R_{sh}$ , even after 300 hours. A possible explanation is that an insulation layer is formed on top of the solar cell during the chemical treatment, making up for the drawbacks of low density of SiN and pin holes inside the ARC layer. This

phenomenon is still under investigation.

### Alternative coating techniques

Other coating methods, such as coating before drying and coating between drying and firing, were also used to test the chemical. At one stage the cells' efficiency soared from 16.29% (mass production average) to 16.64% (continuous average of ten cells) – an increase of  $\sim 0.35\%$ . A possible explanation for this big jump is that the chemical not only changes the optical property of SiN, but also functions as a cap layer during the firing process. Hydrogen is used to passivate the dangling bonds on the wafer surface and inside the bulk material, for example the grain boundaries. When cells that have not undergone the chemical treatment go through the firing furnace (maximum temperature of  $920^{\circ}\text{C}$ ), hydrogen diffuses from the bulk material and the SiN layer to the ambient air, and the passivation quality deteriorates to a greater or lesser degree. When a capping layer is formed, the hydrogen is prevented from leaving the solar cell, and the passivation quality is maintained. This phenomenon is indicated by an increase in the open-circuit voltage ( $V_{oc}$ ), from 620mV to 621mV. When there is no protection on the SiN surface, any high-temperature process will reduce the value of  $V_{oc}$ .

Because the cells are taken out for the chemical treatment before entering the drying furnace, the silver busbars and fingers are still wet and no efficiency data is available at this stage. The possibility

of existing high-quality wafers inside the 10 cells cannot be excluded. The earlier example of an increase in efficiency to 16.64% could therefore be just a coincidence. Repeat experiments have been conducted, but all the cells show a poor sheet resistance ( $R_{sh}$ ) below  $20\Omega/\text{sq}$ , which indicates that the p-n junction has been contaminated during the high-temperature firing. Further tests in this area are ongoing.

### Potential for mass production

A specially designed accurate coating machine can accommodate six rows of 125mm wafers or five rows of 156mm wafers. The normal transport speed is 120 inch/min. A Despatch drying and firing machine can operate at 240 inch/min, yielding a production capacity of solar cells of  $\sim 700\text{--}900$  pcs/hour in one screen-printing line, which equates to 30MW. The capacity of the coating machine is 2.5 times that of a screen-printing line. Therefore, based on this figure, one coating machine has a production capacity of 75MW. Taking into account the machine downtime, the coating machine can support at least two production lines, which would be 60MW.

A drying oven can produce 1500 pcs/hour, equivalent to two screen-printing lines, which are 60MW. To avoid the manual insertion of cells into the boat, a continuous conveyer-driven oven (like a Despatch) is the best option. To put this innovation into practice, manual handling or a Robert arm is

	$I_{sc}$ [A]	$V_{oc}$ [V]	$R_s$ [ $\Omega$ ]	$R_{sh}$ [ $\Omega$ ]	$P_{max}$ [W]	$V_{pm}$ [V]	$I_{pm}$ [A]	FF	Eff [%]
<b>Original</b>									
With junction box	8.4643	36.8557	0.5299	102.0390	231.3204	29.2055	7.9204	0.7415	14.1610
Without junction box	8.4665	36.8368	0.5176	98.2200	232.6565	29.3572	7.9250	0.7460	14.2428
<b>After exposure</b>									
With junction box	8.4531	36.9104	0.5603	113.4711	231.6265	29.2404	7.9214	0.7424	14.1798
Without junction box	8.4562	36.8714	0.5308	106.1162	233.0796	29.3744	7.9348	0.7476	14.2687

Table 1. Module CLS-SP110611RD001 made from chemically treated cells.

required between the stages 1) firing and chemical coating, 2) chemical coating and drying oven, and 3) drying oven and Berger tester.

### Cost of ownership (COO) evaluation

As mentioned previously, a specially designed accurate coating machine costs in the region of US\$300,000 for an industrial application. The total annual cost for the chemical is only US\$1500 and the price of the drying oven is only US\$1000. Including machine maintenance, workforce salaries and power usage (electricity, water, vacuum and compressed air), this technology innovation is a relatively cheap option for the solar industry, but detailed calculations would need to be performed to estimate the cost of a fully automated process.

### Summary

Solar cells with an efficiency below 16.4% are becoming increasingly unacceptable to industrial manufacturers, so ways of improving their efficiency are currently being sought. At Chinalight Solar, a method involving chemical treatment of the SiN layer has been developed, resulting in the efficiency of all the cells being boosted by 0.16% on average. This technology can meet the requirements for mass production in terms of practicality and cost. The installation cost for this method is acceptable and the annual running costs are relatively low. Moreover, experiments have shown that the integrated module does not degrade after two weeks' exposure to the sun and also withstands high voltage for longer in the PID test. This innovation has a potential for becoming an additional stage of the current manufacturing line of crystalline silicon solar cells. However, the scope for adaptability still needs to be proven.

### Acknowledgements

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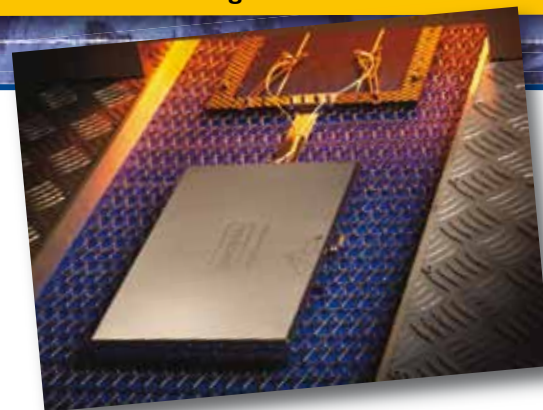
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