

Optimisation of Weak-light Response of Back-Contact Solar Cells

LONGi Product Solution

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From STC to Real-World All-Weather Operation



STC

STC, the baseline for photovoltaic module comparison, defines standardized test conditions: 1000 W/m² irradiance, AM1.5 spectrum, and 25°C cell temperature.

Weak-Light Context

Real PV systems often operate in weak-light scenarios like early mornings, late evenings, cloudy days, or under shading, with irradiance typically ranging from 200-800 W/m².

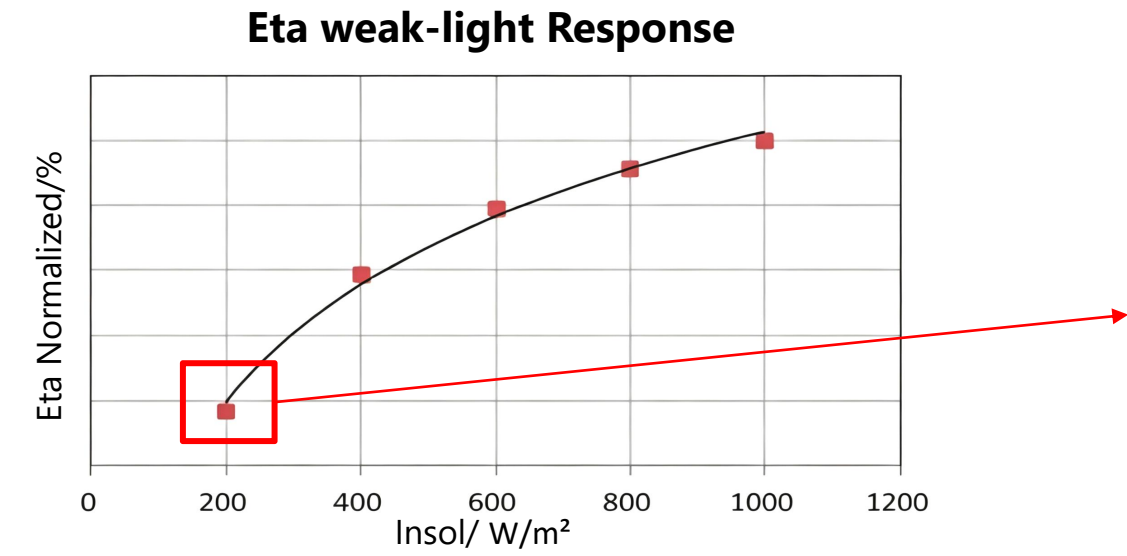
Weak-Light Response

Measured as the normalized performance retention relative to STC, it directly reflects how a module maintains performance in low-irradiance conditions, independent of absolute power output factors.

1. Concept of weak-light Response

➤ **Definition:**

The weak-light response ratio is defined as the ratio of the normalized conversion efficiency of a solar cell under weak-light conditions to its efficiency under the standard test irradiance of 1000 W/m².



Data when Insol=200w/m2

Insol(sun)	Isc	Voc	FF	Eta
1	100%	100%	100%	100%
0.2	19.99%	94.85%	99.51%	94.45%

1. Concept of weak-light Response

Insol(sun)	Isc	Voc	FF	Eta
1	100%	100%	100%	100%
0.2	19.99%	94.85%	99.51%	94.45%

➤ Phenomenon:

The power conversion efficiency of a photovoltaic cell will either degrade or improve as incident irradiance decreases, which is governed by the evolution of core electrical parameters as follows:

- **Short-circuit current (Isc):** Isc varies linearly with irradiance; its normalized value remains nearly constant across all irradiance levels.
- **Open-circuit voltage (Uoc):** Uoc exhibits prominent degradation under low light, following a logarithmic dependence on irradiance.
- **Fill factor (FF):** FF can either rise or fall with decreasing irradiance, determined by series resistance (R_s), saturation current density (J_0), shunt resistance (R_{sh}) and other intrinsic device parameters.
- **Conversion efficiency (Eta):** The overall shift in cell efficiency under low irradiance is predominantly dictated by the variations of (Uoc) and FF.

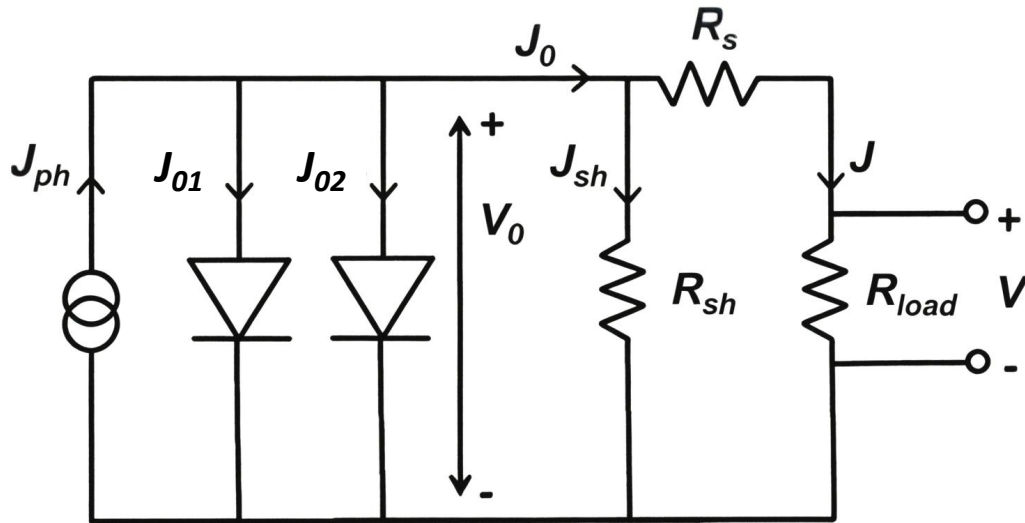
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2. Mechanism of weak-light response



J_{ph} : Photogenerated current density produced by absorbed photons.

J_0 : Saturation dark current density, represents recombination-related loss

R_{sh} : Shunt resistance. It represents leakage paths across the junction.

R_s : Series resistance. It includes resistive losses from wafer, contacts, metallisation and carrier transport paths.

$$J = J_{ph} - \underbrace{J_{01}[\exp(q(V + JR_s)/kT) - 1] - J_{02}[\exp(q(V + JR_s)/2kT) - 1]}_{-J_{dark}} - \underbrace{(V + JR_s)/R_{sh}}_{-J_{sh}}$$

$J = J_{ph}$ $-J_{dark}$ $-J_{sh}$

2. Weak-light Response Mechanism - Short-Circuit Current I_{sc}

The equivalent circuit of the solar cell single-diode model is formulated as follows:

$$J = J_{ph} - J_{0n} \left[\exp \left(\frac{q(V + JR_s)}{nkT} \right) - 1 \right] - \frac{V + JR_s}{R_{sh}}$$

where J_{ph} denotes the photogenerated current density, which exhibits a linear dependence on incident irradiance.

Under the short-circuit condition $V = 0$ the equation is simplified to:

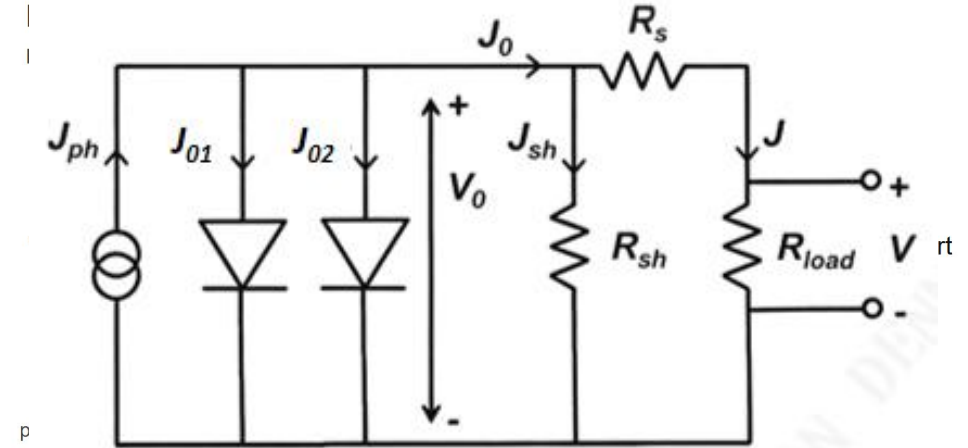
$$J = J_{ph} - J_{0n} \left[\exp \left(\frac{qJR_s}{nkT} \right) - 1 \right] - \frac{JR_s}{R_{sh}}$$

The term $J_{0n} \left[\exp \left(\frac{q(V + JR_s)}{nkT} \right) - 1 \right]$ presents the saturation dark current loss.

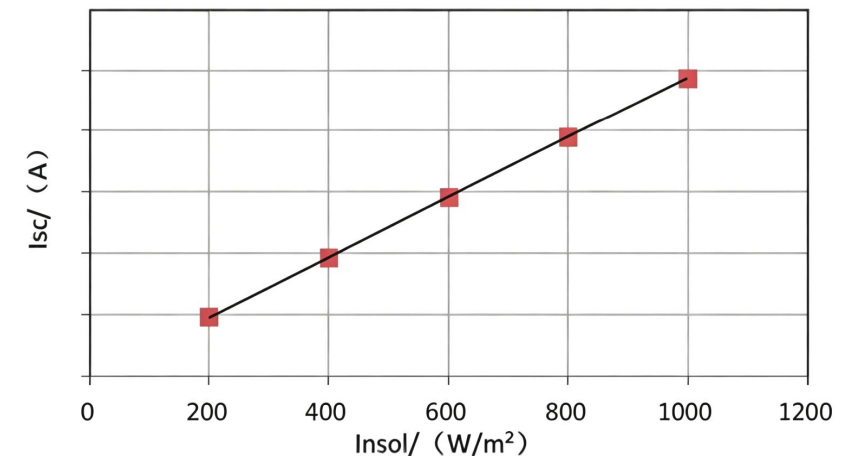
The term $\frac{JR_s}{R_{sh}}$ corresponds to the shunt resistance loss.

Both loss components are negligible in magnitude relative to J_{ph} , which yields the approximation $J_{sc} \approx J_{ph}$

- Accordingly, the short-circuit current density of a solar cell varies linearly with incident irradiance.



Isc weak-light Response



2. Weak-light Response Mechanism - Open-Circuit Voltage U_{oc}

The equivalent circuit of the solar cell single-diode model is given by:

$$J = J_{ph} - J_{0n} \left[\exp \left(\frac{q(V + JR_s)}{nkT} \right) - 1 \right] - \frac{V + JR_s}{R_{sh}}$$

If the effects of series and shunt resistances are omitted, the formula can be simplified to:

$$J = J_{ph} - J_{0n} \left[\exp \left(\frac{qV}{nkT} \right) - 1 \right]$$

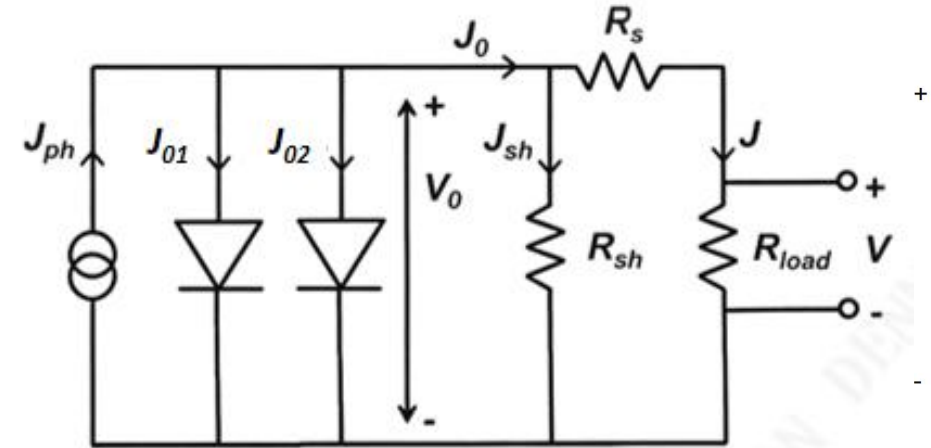
Under open-circuit condition ($J = 0$) open-circuit voltage V_{oc} can be written as:

$$V_{oc} = \frac{nkT}{q} \ln \left(\frac{J_{ph}}{J_0} \right)$$

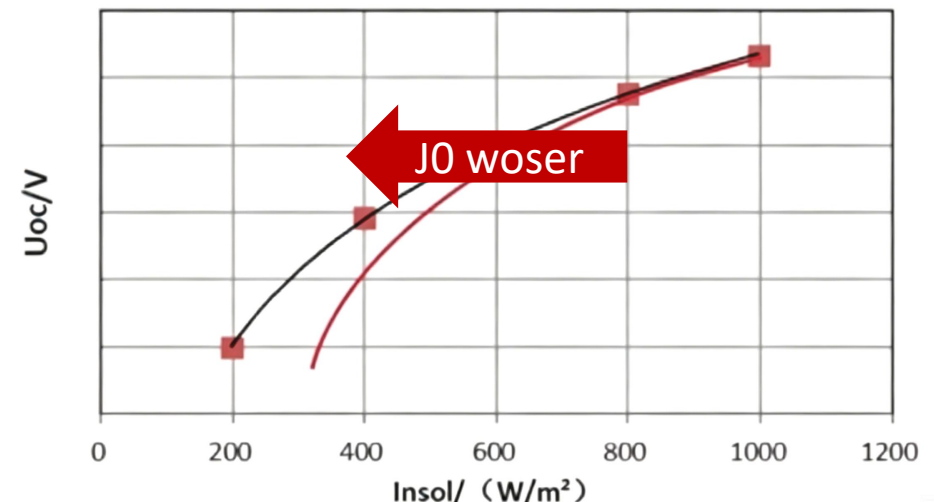
Here n stands for the ideality factor, and J_0 is the saturation dark current density.

At high irradiance levels, n is close to 1 and J_{01} dominates the behaviour; under weak-light conditions, n approaches 2 with J_{02} becoming the dominant.

- Accordingly, the open-circuit voltage of a solar cell varies logarithmically with irradiance (J_{ph}). The worse the V_{oc} is, or the worse it performs under low irradiance, the poorer the weak-light response of J_0 will be.



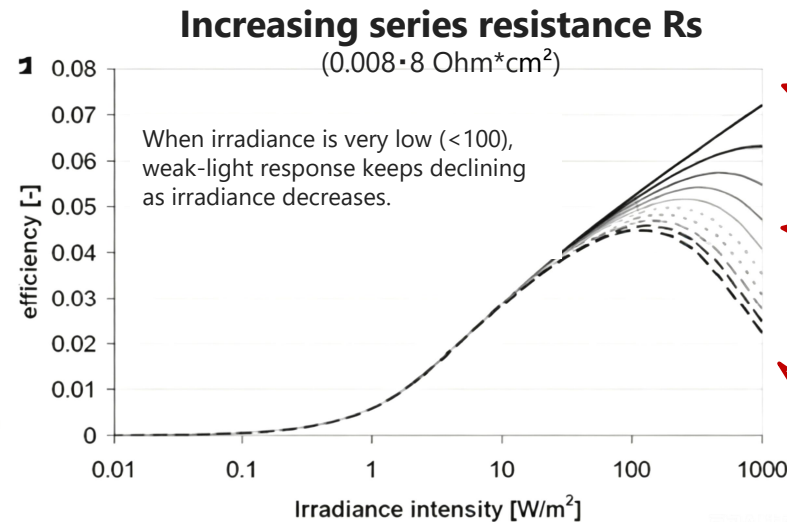
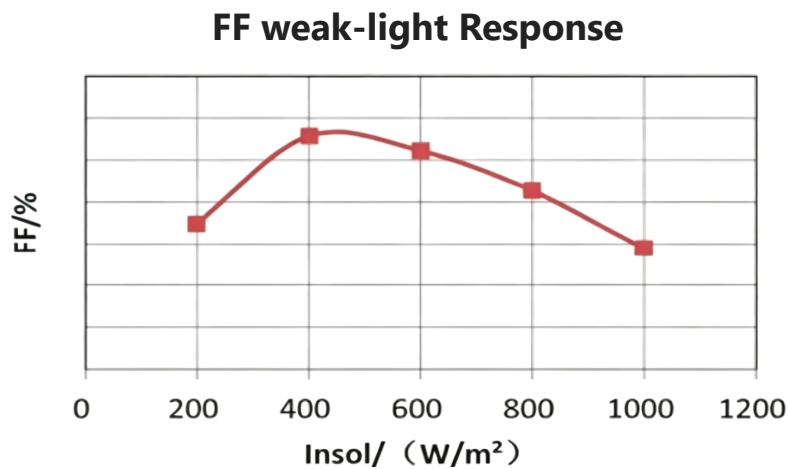
Voc weak-light Response



2. Weak-light Response Mechanism - Fill Factor FF

For the weak-light response of fill factor (**FF**), the typical trend is that **FF** first rises and then falls as irradiance decreases. The position of the turning point and the magnitude of variation depend on device-specific parameters including series resistance R_s and saturation dark current density J_0 . Under high irradiance, **FF** is predominantly governed by series resistance R_s , while J_0 becomes the dominant factor under weak-light conditions.

As illustrated in the following figure, FF rises moderately when irradiance drops from 1000 to 400 W/m². This is mainly attributed to the reduction of current, which drastically cuts down the resistive power loss I^2R induced by R_s and thereby elevates **FF**. When irradiance further declines from 400 to 200 W/m², J_0 dominates device behaviour and results in a reduction of FF.



➤ When R_s is sufficiently small, the weak-light response decreases continuously as irradiance drops from 1000 to 200 W/m².

➤ At an intermediate R_s level, FF first rises and then falls with declining irradiance.

➤ When R_s is sufficiently large, the weak-light response increases continuously as irradiance drops from 1000 to 200 W/m².

2. Weak-light Response Mechanism - Fill Factor FF

$$FF = PFF - \Delta FF_{R_s}$$

High irradiance



$J_0@U_{oc}$

Surface recombination

Low irradiance



$J_0@V_{mp}$

Bulk resistivity ρ

Bulk minority carrier lifetime τ

Low irradiance



High irradiance



Initial R_s

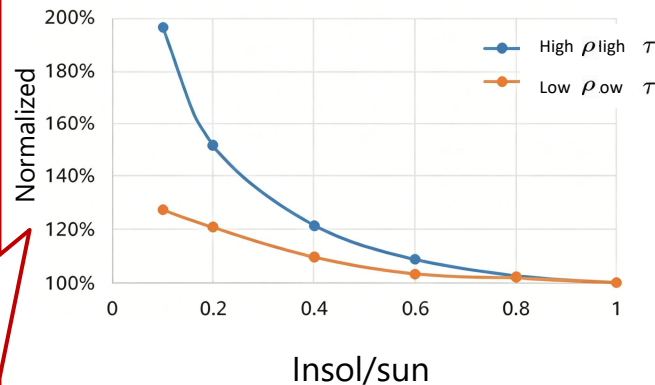
Bulk resistivity ρ

$$R_s = R_{\text{bulk}} + R_{\text{sheet}} + R_{\text{contact}} + R_{\text{line}}$$

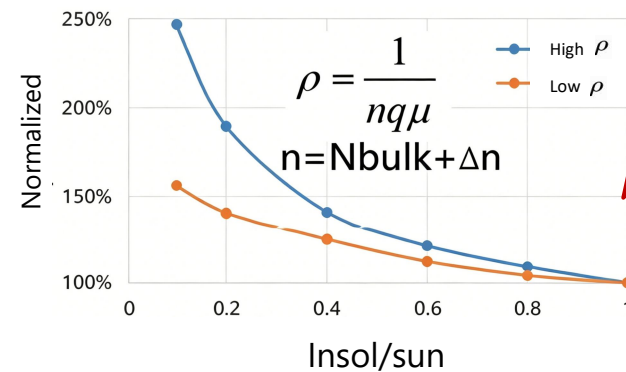
- High bulk resistivity ρ
→ low bulk doping concentration N_{bulk}
- Low irradiance
→ low excess carrier concentration Δn

• The improvement of minority carrier lifetime τ is limited
So J_0 increases sharply under low irradiance, leading to poor weak-light response of PFF

FF weak-light Response



FF weak-light Response



- High bulk resistivity ρ
→ low bulk doping concentration N_{bulk}
- Low irradiance
→ low excess carrier concentration Δn

Accordingly, bulk resistivity ρ es rapidly under weak-light conditions, resulting in severe fill factor loss from series resistance

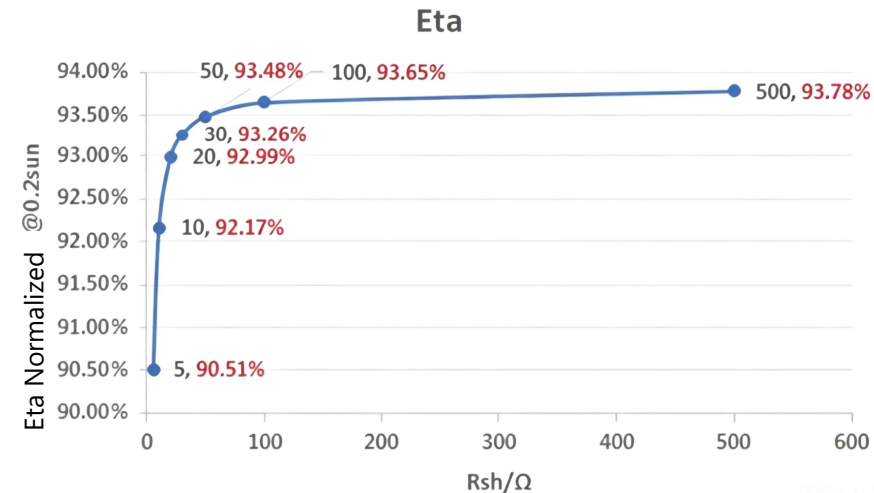
$$\Delta FF_{R_s}$$

2. Weak-light Response Mechanism - Shunt Resistance Rsh

➤ BC cell measured results

	Eta Normalized							
Irradiance (W/m²)	Rsh=2	Rsh=5	Rsh=10	Rsh=18	Rsh=25	Rsh=36	Rsh=46	Rsh=266
1000	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.00%
800	99.5%	99.5%	98.7%	99.5%	99.3%	99.6%	99.7%	99.88%
600	97.4%	98.0%	97.1%	98.3%	98.2%	98.8%	98.8%	98.86%
400	93.1%	94.9%	94.2%	96.2%	96.7%	97.2%	97.6%	97.12%
200	85.2%	89.7%	89.9%	91.9%	93.3%	94.1%	94.5%	93.99%

➤ Quokka simulation results



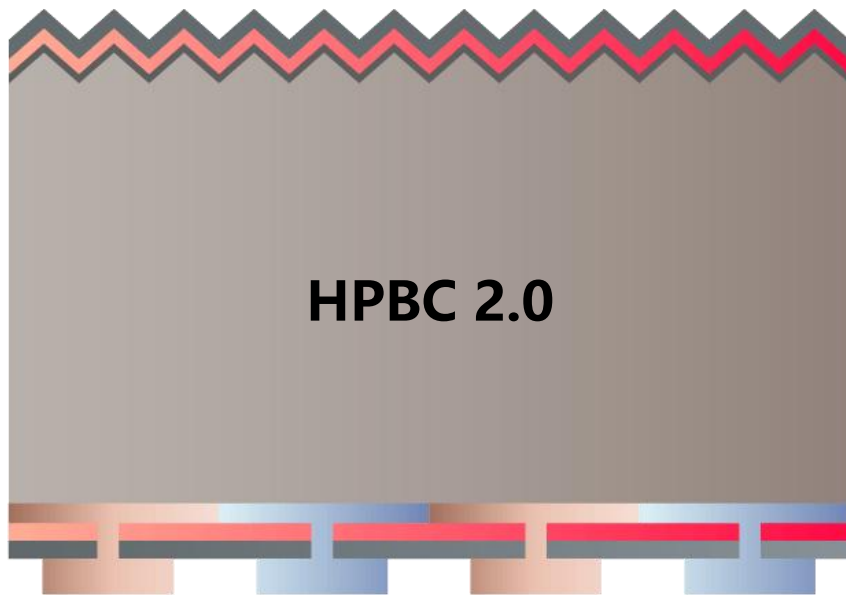
Both experimental measurements and simulation results confirm that shunt resistance $R_{sh} > 30$ virtually no impact on the weak-light response of photovoltaic cells.

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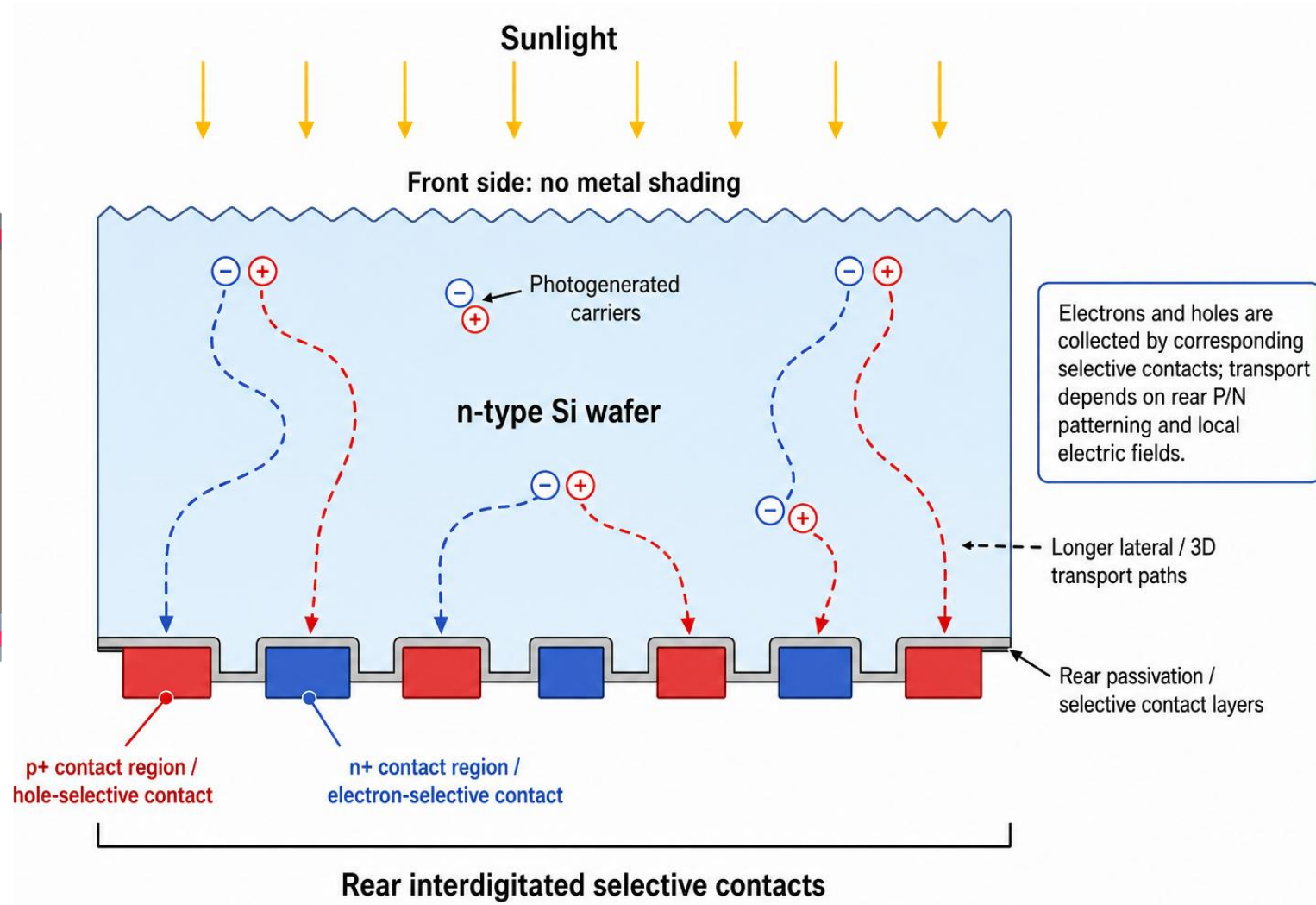
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3. Optimization of BC cell weak-light response

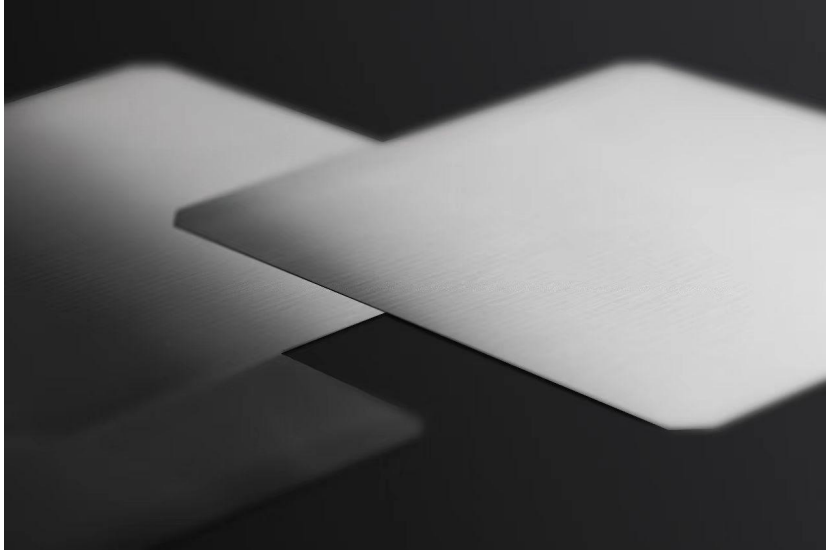
Optimization of BC cell weak-light response : Key Design Levers



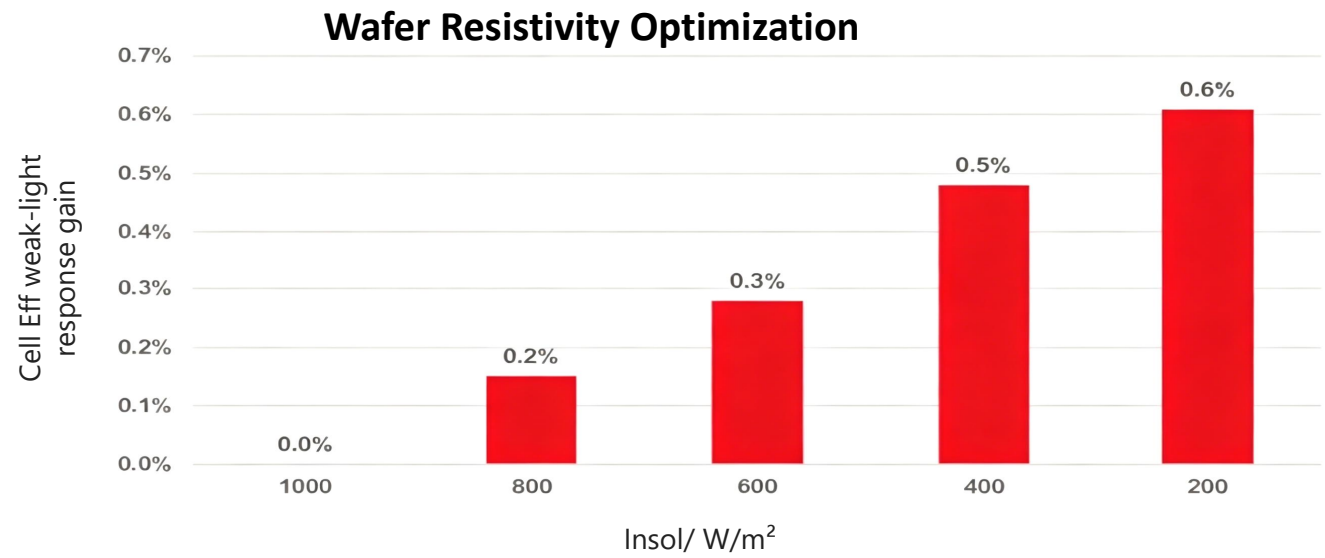
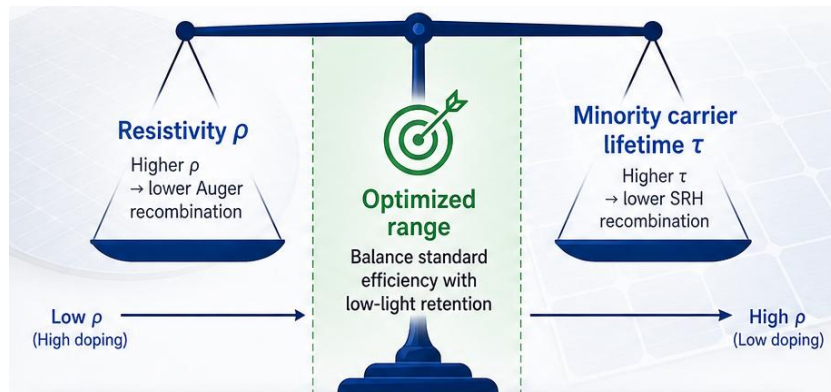
- Material quality
- Recombination behaviour
- Passivation
- Effective resistance distribution



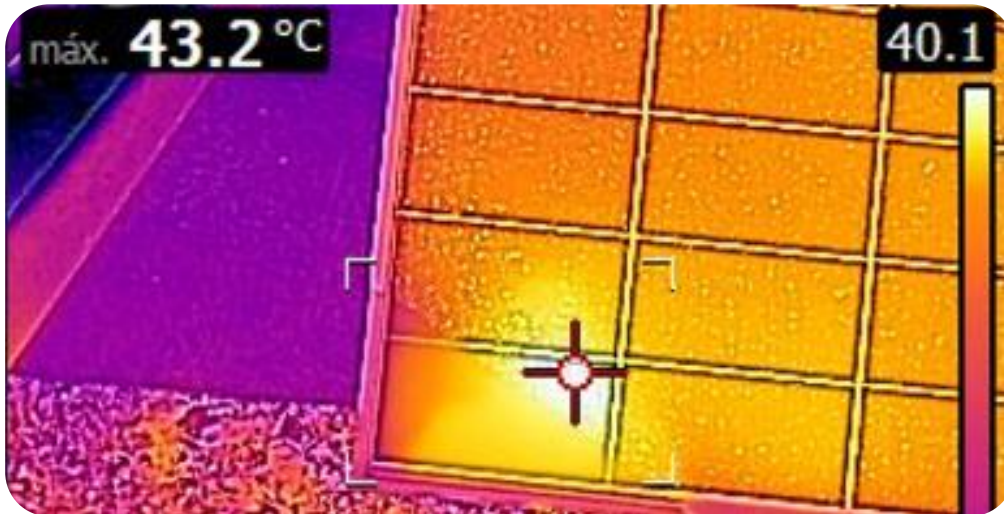
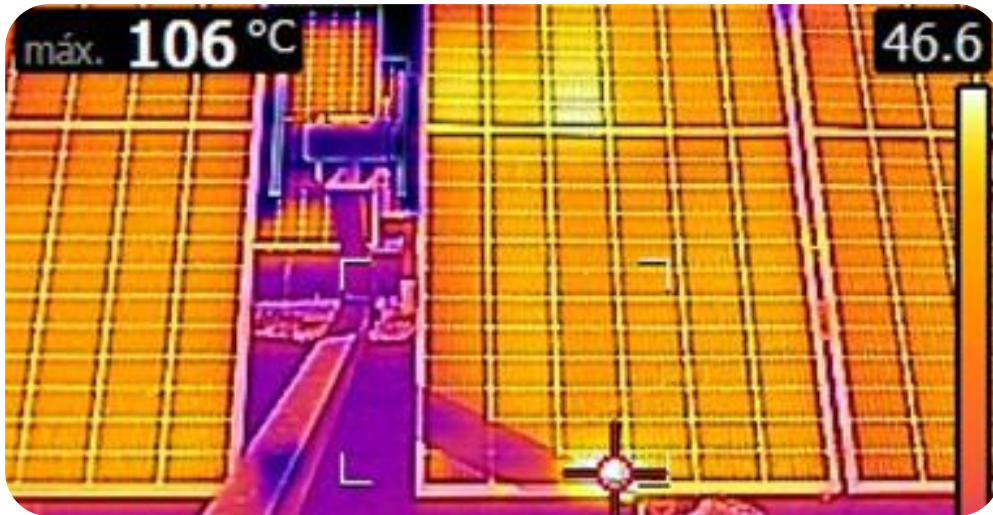
3.1 Wafer Resistivity Optimization



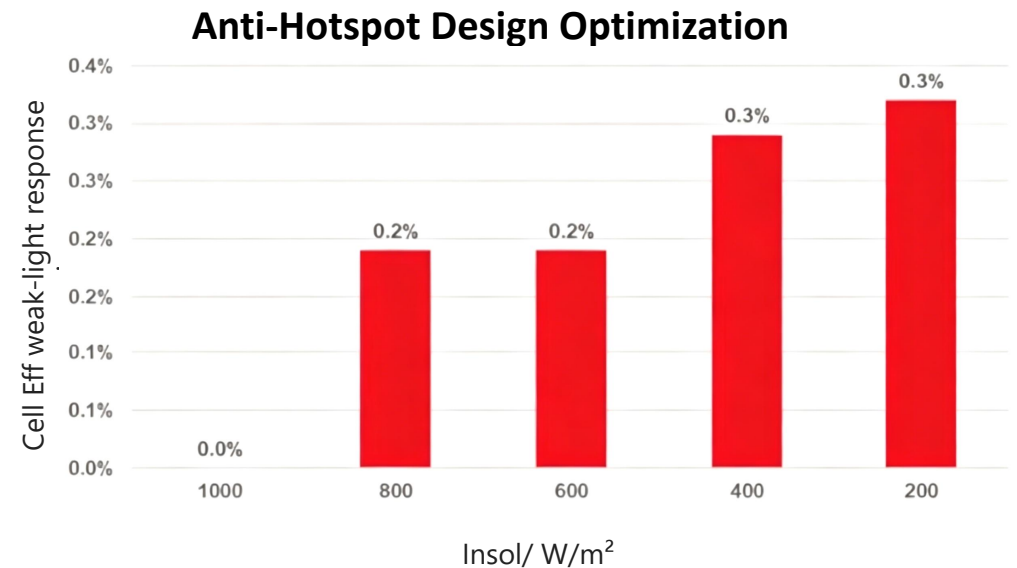
- Select proper silicon wafer resistivity, excluding high-resistance and ultra-high-resistance types;
- Optimize the $J_0@V_{mpp}$ performance under weak light, as well as mitigate efficiency loss triggered by the increase of bulk substrate resistivity in weak light environments;
- The absolute efficiency loss of the cell shall be $\leq 0.03\%$ abs;
- The weak-light response of the cell (under 200W light irradiance) is improved by 0.6% abs;



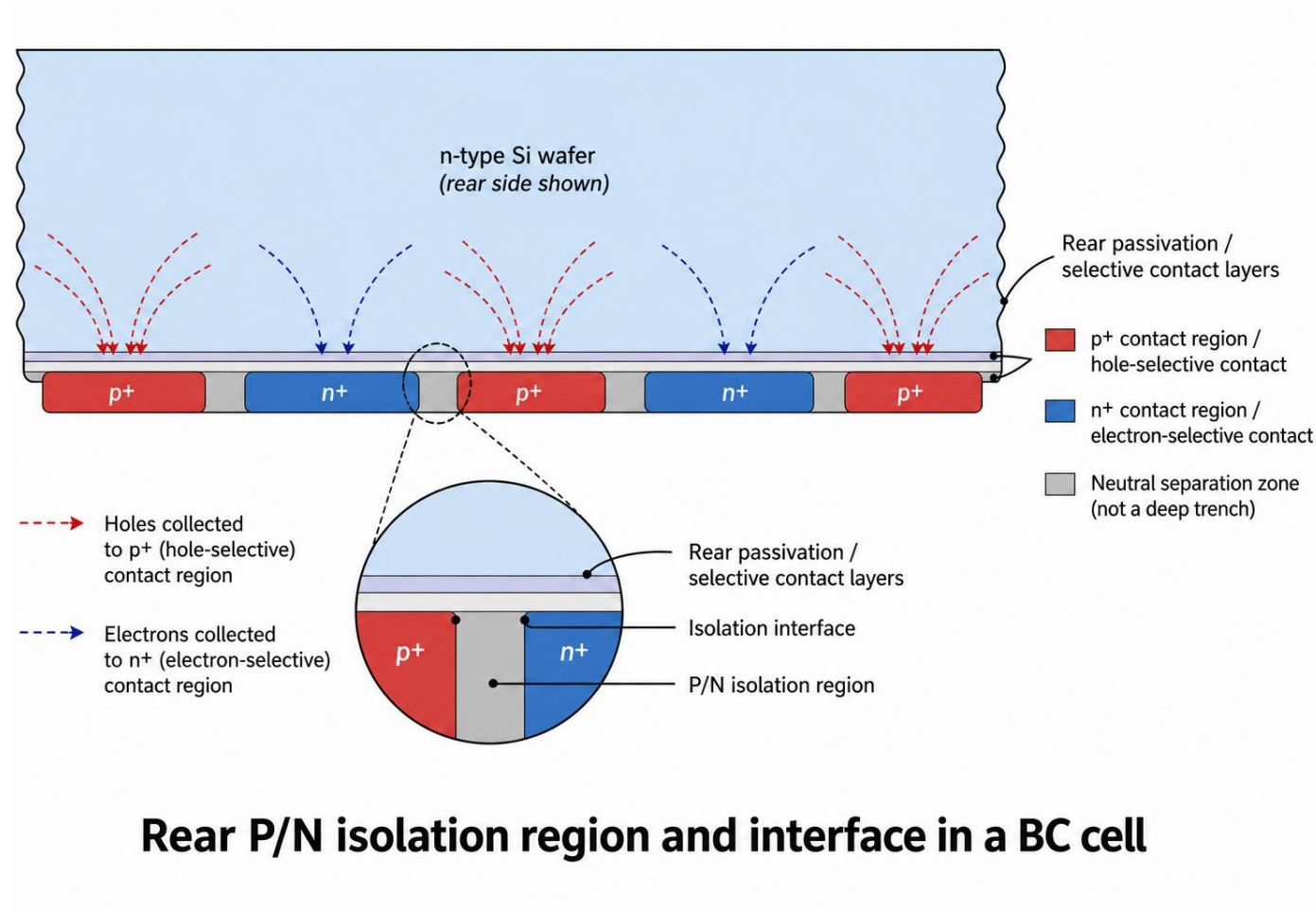
3.2 Anti-Hotspot Design Optimization



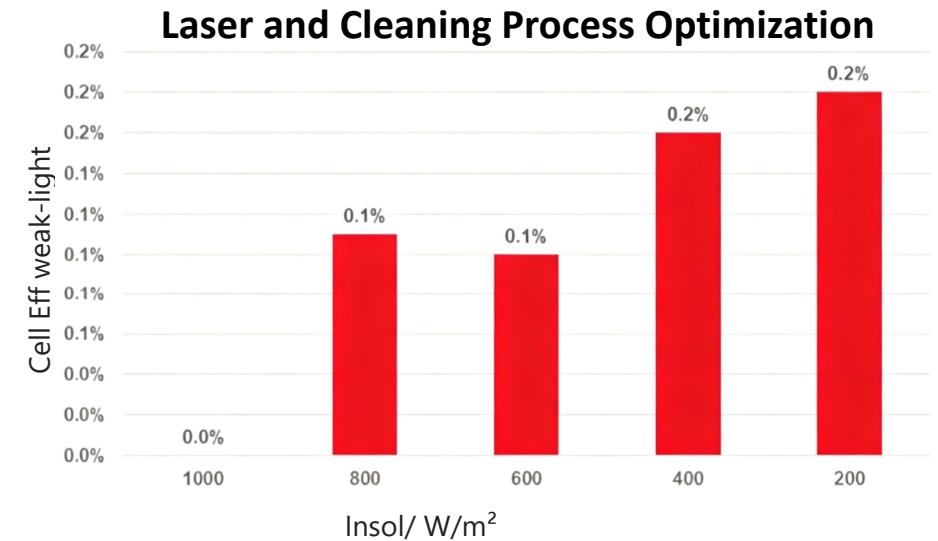
- Optimize hot spot mitigation design on the premise of ensuring hot spot reliability;
- Improve $J_0@V_{mpp}$ performance under weak-light conditions;
- Cell efficiency is improved by approximately 0.05% abs;
- The weak-light response of the cell (at 200W/m² irradiance) is enhanced by 0.3% abs.



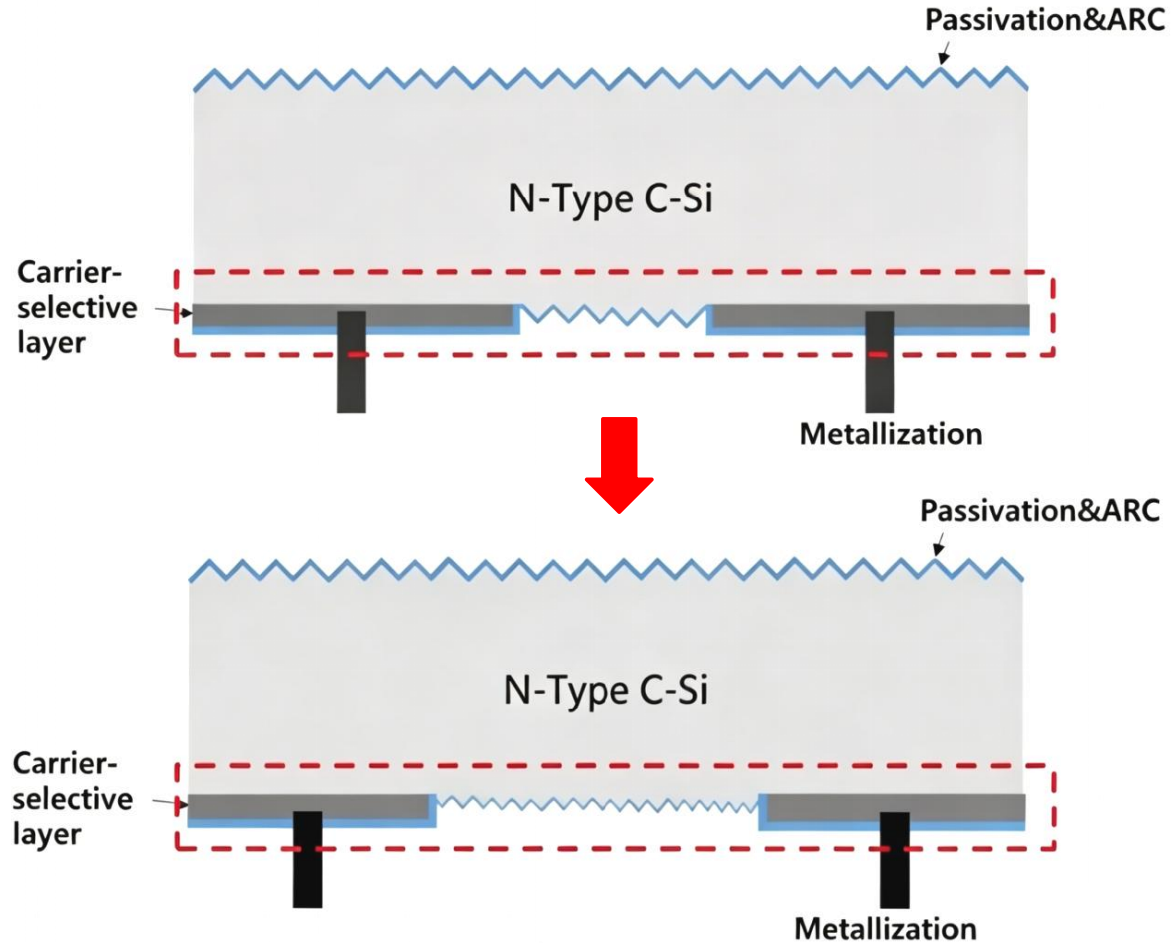
3.3 Laser and Cleaning Process Optimization



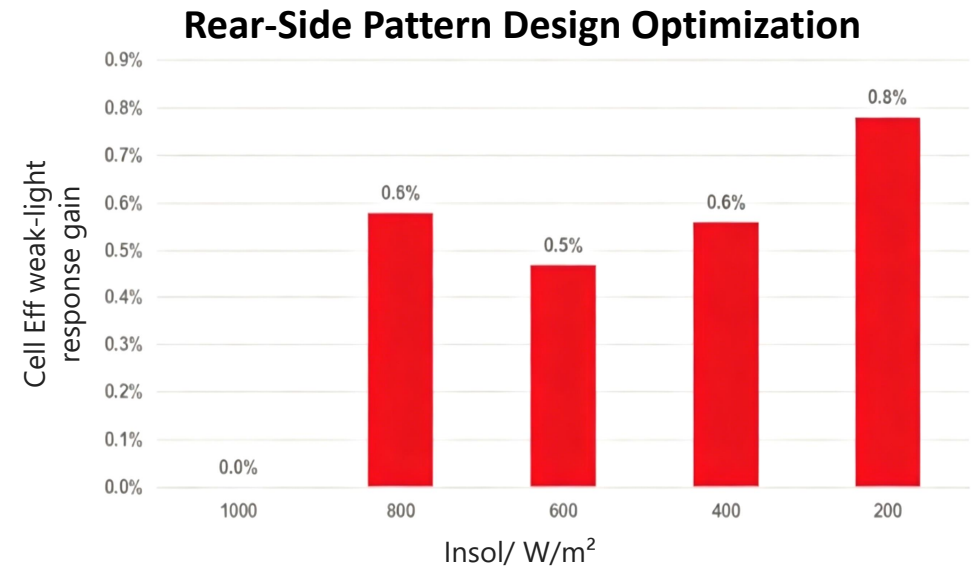
- Improve the quality of the PN isolation region;
- Improve $J_0 @ V_{mpp}$ performance under weak-light conditions;
- Cell efficiency is improved by approximately 0.03% abs;
- The weak-light response of the cell (at 200W/m² irradiance) is enhanced by 0.2% abs.



3.4 Rear-Side Pattern Design Optimization

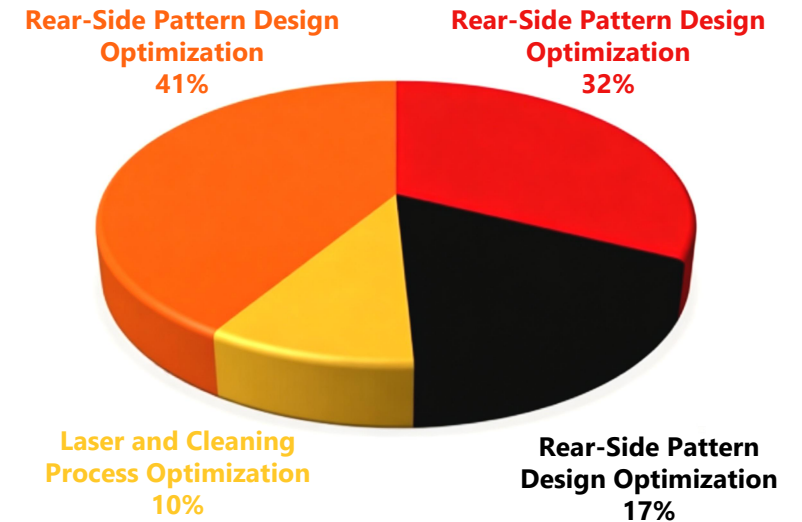


- Increase the initial series resistance R_s to improve weak-light response;
- Cell bifaciality is improved by 4% abs;
- Cell cost is reduced by 1.5 fen per watt (0.015 RMB/W);
- Module power loss $\leq 3W$;
- The weak-light response of the cell (at $200W/m^2$ irradiance) is enhanced by 0.8% abs.



Summary

Optimization Item	weak-light Response Improvement at 200W/m ² Irradiance
Wafer Resistivity Optimization	0.6%
Hot Spot Mitigation Design Optimization	0.3%
Laser and Cleaning Process Optimization	0.2%
Rear Pattern Design Optimization	0.8%
Total	1.9%



- With all optimization measures combined, the weak-light response of the cell (at 200W/m² irradiance) is improved by 1.9% abs.
- Rear pattern design optimization accounts for the highest weight of 41%, indicating that the weak-light response of BC cells is strongly correlated with the initial series resistance R_s .
- Wafer resistivity optimization ranks second with a weight of 32%. It requires a balance between wafer resistivity and minority carrier lifetime, as well as between cell efficiency and weak-light response.
- Hot spot mitigation design optimization and laser & cleaning process optimization follow next. They can enhance weak-light response by improving $J_0 @ V_{mpp}$ and also boost cell efficiency.