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Dislocation and Saturation Current Density Analysis by Rear-Side Al Amount Variation for n -Type Al- p^+ Emitter Crystalline Silicon Solar Cell

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ABSTRACT

This paper presents a dislocation and saturation of current density analysis by varying the amount of rear-side Al. The fabrication process optimizes an aluminum-alloyed emitter using a screen printing number and varying the co-firing on n -type crystalline silicon (c-Si) wafers using a suitable industry method. N -type silicon materials have high diffusion-lengths due to the reduced recombination activities of metal impurities and other nonmetallic defects compared with p -type silicon and this fulfills the requirement for innovative solar cells. To utilize the advantage of the n -type silicon wafers for manufacturing simple and industrially feasible high-efficiency solar cells, we adopted screen-printing and co-firing of aluminum (Al) alloyed $n^+n p^+$ solar cells featuring a rear Al- p^+ emitter easily fabricated through the screen-printing process. We achieved a back surface field (BSF) that was 7 μm in thickness by applying 13.14 mg/cm^2 of Al paste in by printing on both sides and heating the material in an high temperature infra-red (IR) furnace at a peak temperature of 756.5 $^\circ\text{C}$. In the furnace, the temperature increased at a rate of 70.82 $^\circ\text{C}/\text{sec}$ with an efficiency of 17.36%, saturation current density J_{01} of $7.16 \times 10^{-9} \text{ mA}/\text{cm}^2$ and J_{02} of $3.55 \times 10^{-5} \text{ mA}/\text{cm}^2$, respectively.

KEYWORDS: Al- p^+ Emitter, N -Type Silicon Solar Cell, Dislocation, Saturation Current Density.

1. INTRODUCTION

Most of the commercial silicon solar cells are fabricated on p -type c-Si wafers because of the simplicity of the phosphorous diffusion process for the n^+ emitter formation. Due to a decline in the availability of p -type silicon; the photovoltaic (PV) market requires new sources of silicon to meet the demand for solar cell production in the future. The n -type wafer is a potential candidate and it possess better properties than p -type wafers. The key advantage of n -type silicon is its higher carrier lifetime and better lifetime stability under illumination compared to p -type silicon. In addition to its superior bulk lifetime, its tolerance towards of iron (Fe), oxygen (O) impurities, as well as its higher diffusion lengths and reduced degradation, make n -type wafers desirable as a rear emitter.^{1,3} SunPower and Sanyo are the only manufacturers that have succeeded in mass producing solar cells with n -type wafers. Sanyo forms a hetero-junction with very thin films to create. The Heterojunction with Intrinsic

Thin-layer (HIT).² Controlling the emitter thickness, impurity, interface, and uniformity is difficult in the case of the HIT cell. The process that SunPower uses when manufacturing the Interdigitated Back Contact (IBC) cell results in increased manufacturing cost.³ The mass production of these cells is unlikely since they either use float zone (FZ) wafers, which are too expensive, or the process time is too long.⁴ The prolonged process time was the result of fabricating the emitters by Spin on Doping (SOD) or producing the contacts through photolithography and evaporation.

The highest efficiency of an FZ grade n -type solar cell with an Al- p^+ rear-side emitter is 16.4%, and that of a Czochralski (CZ) grade is 15.8%.⁵ In the former, the front side of FZ grade wafer is doped with phosphorus oxychloride (POCl_3), while the back side is printed with Al. The emitter is then formed through a firing process. Since the electrodes of the latter are formed using screen printing, it is considered suitable for industry. However, its efficiency is relatively low despite the high cost of the FZ grade wafer, and this further increases its production costs.

Later on, photolithography was used for front contacts and the back contacts were formed using chemical vapor deposition. The drawback of this cell is that it is difficult to commercialize it. Even though they used cheap CZ wafers,

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the fabrication process took up too much time. In addition, ECN Solar Energy and the University Center of Excellence for Photovoltaic Research and Education achieved 14.86% and 15.4%, respectively by using the Spin on Doping process just for research.⁶

This paper suggests a simple structure for an n -type solar cell with an Al- p^+ rear-side (Aluminum-doped p -type) emitter. The emitter is formed at the back side through screen printing and co-firing the aluminum. This process is cost effective, because it is less complicated than the p -type wafer process.

2. EXPERIMENTAL DETAILS

The substrates used in this experiment were CZ (100) n -type silicon wafers that have a resistivity of 1–3 Ω -cm and a thickness of about 200 μ m. Saw damage removal (SDR) and texturing were carried out. The pyramidal texturing was done by dipping the wafers for 25 minutes in the 2% NaOH etching solution maintained at 84–86 $^{\circ}$ C. The reflectance was measured for n -type textured. The wafers were doped with phosphorous in a furnace using a conventional POCl_3 diffusion source at 800 $^{\circ}$ C resulting in a sheet resistivity of 55 ohms/square. The phosphorus-silicate-glass (PSG) layer was removed by dipping the wafer in a 10% HF solution for 30 seconds, followed by DI-water rinsing and drying. A SiNx antireflection coating layer that was 75 nm thick was then deposited onto the substrate using the plasma enhanced chemical vapor deposition (PECVD) technique. During deposition, the RF power, plasma frequency, pressure, and substrate temperature were maintained at 300 mW/cm^2 , 13.56 MHz, 1 Torr, and 450 $^{\circ}$ C respectively. The reflectance was measured for the n -type bare wafer, after texturing and anti-reflectance coating respectively. The results show that the average reflectance decreased from 22.72% to 9.91% and 2.78% after texturing and SiNx anti-reflectance coating respectively. Rear side metallization was carried out with standard aluminum paste using the screen-printing process. After electrode printing, the sample was dried at 150 $^{\circ}$ C. To minimize the shading loss, metal fingers with a finger thickness of 80 μ m and spacing of 2.4 mm were made. The front and back contacts were formed using silver paste and aluminum paste screen printing followed by a firing step for the metallization in a belt furnace as normally used in industrial processes. The co-firing of the electrodes at the front and the back was done in a 4-zone infrared (IR) belt furnace at peak temperatures ranging from 725 to 850 $^{\circ}$ C. The Al- p^+ rear-side emitter was formed from co-firing. The edges of the cells were mechanically ground before undergoing the measurement. The fabricated cells were characterized by using illuminated current–voltage (LIV) measurements under a global spectrum of AM 1.5 condition and dark current–voltage (DIV) measurements for analyze saturation current density on the rear-side due to a loss factor during the Al–Si alloying process.

3. RESULTS AND DISCUSSION

The fabrication process of the proposed Al- p^+ rear-side emitter crystalline solar cell with n -type silicon is less complicated than the process that uses p -type silicon. The process sequences for both proposed n -type Al- p^+ rear-side emitter solar cells and conventional p -type c-Si solar cells, just changed in the electrode formation processes. As a result, there is no increase in the manufacturing cost and time compare to the conventional p -type c-Si solar cell fabrication process.

Figures 1(a) and (b) show the furnace temperature profile and dependence of open-circuit voltage (V_{OC}) on the peak temperature of the furnace respectively. The different co-firing conditions are shown in Table I. In Al- p^+ rear-side emitter solar cells, the p – n junction is formed at the back of the wafer by co-firing the aluminum. Therefore, it is important to assure thickness and uniformity between alloying Al–Si. In general, a thicker and uniform BSF is formed as the slope of the co-firing profile increases. From Figure 1(b), it is seen that higher V_{OC} is obtained with a rapid slope in the co-firing temperature profile. This is because Al is fired in a very short time and the p^+ emitter is uniformly formed at the back.⁷ To find the optimum thickness of the back surface field, TCAD simulations were carried out using PC1D.⁸ The results show

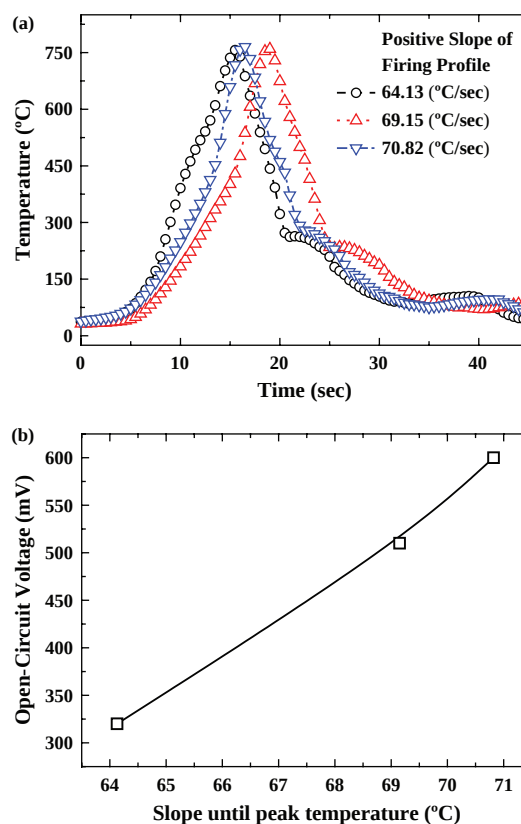


Fig. 1. (a). Temperature shape and positive slope values of the firing process using firing profile variation. (b). The relationship between the open-circuit voltage trend and increases in the peak temperature.

Table I. The furnace temperature profile with firing temperature, positive slope, and peak temperature.

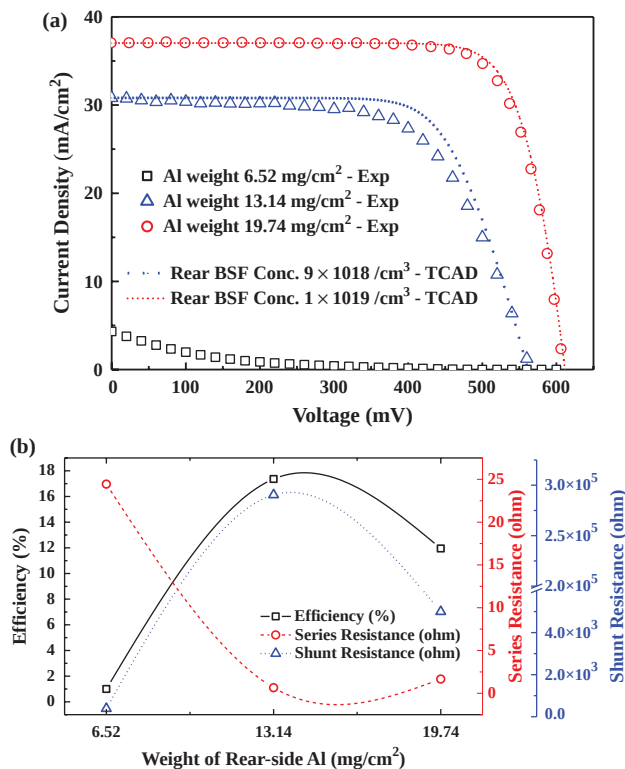
Firing temperature profile (°C)	Slope (°C/sec)	Real peak temperature (°C)
450–500–600–940	64.13	759.5
450–500–600–960	69.15	765
500–700–700–920	70.82	756.5

that higher V_{OC} and efficiency could be obtained when the BSF thickness was over 7 μm . It has been reported that to obtain higher V_{OC} and fillfactor (FF), the back surface field thickness should be at least 7 μm .

The weight of Al per unit area depending on the number of the screen-printing process was measured using an electronic scale. The weight of Al was shown to be 6.52, 13.14 and 19.74 mg/cm^2 by single, double and triple printing on the back of the n -type c-Si wafers. The amount of Al is a very important factor in the Al- p^+ rear-side emitter formation process using then-type c-Si solar cell due to the thickness, concentration, discontinuity and uniformity of BSF, which is strongly related with the amount of Al on the back-side. The importance of Al is discussed in more detail further on in this paper.

The LIV characteristics of the proposed structure solar cells with different amounts of Al on the back of the cells were observed with a global spectrum of AM 1.5, as shown in Figure 2(a) and Table II. The cell with 13.14 mg/cm^2 of Al achieved the best efficiency. The current density (J_{SC}), V_{OC} , FF, and the conversion efficiency of the n -type c-Si solar cell using an Al- p^+ rear-side emitter were 37.09 mA/cm^2 , 609 mV, 77.45%, and 17.36%, respectively. When using 6.52 mg/cm^2 of Al, cell performance was very poor due to the front electrode over-firing because of the thin and discontinuous Al in the BSF region.

Also, 19.74 mg/cm^2 of the Al sample demonstrated low characteristics compared to samples of 13.14 mg/cm^2 . Because, Al paste at the back places the wafer under compressive stress due to the expansion coefficient gap between Si and Al during the co-firing process. As a result, 19.74 mg/cm^2 of Al demonstrated poorer print cell characteristics than 13.14 mg/cm^2 of Al due to the wafer bowing from compressive stress between electrode at the back and the Si surface. These results show that the amount of Al directly influences the thickness and uniformity of the emitter during the formation of the Al- p^+ emitter. Also, not enough thermal energy was transferred to form the Al-Si alloying emitter because the amount of printed Al was too thick. It means that a printed Al layer that is too thick roles to the thermal blocker and does not form enough carrier concentration to develop contact resistance and electric fields in the emitter region. It has been proven that TCAD fitting results using SILVACO simulation are experimental. In that experiment, the carrier concentration was changed

**Fig. 2.** (a). Light-induced current voltage (LIV) measurements of three difference conditions on the rear of the Al weight and fitting results in relation to TCAD simulation for the rear BSF concentration expectation. (b). Efficiency, series and shunt resistance analysis in relation to the weight of the rear Al.

from 9×10^{18} atoms/ cm^3 to 1×10^{19} atoms/ cm^3 . In TCAD simulation syntax, carrier concentration and emitter thickness were changed simultaneously due to Al-Si alloying mechanisms, the concentration and thickness of the Al- p^+ layer. In the TCAD results, the amount of Al at the rear was affected by the concentration and thickness of the Al- p^+ emitter region.

Figure 2(b) shows an Al- p^+ rear-side emitter c-Si solar cell efficiency, series resistance and shunt resistance correlation trend using an amount of printed Al at the rear. As mentioned above, the 6.52 mg/cm^2 of the printed sample of Al was over-firing due to thin Al at the back. The electrode over fired due to the thin Al, and this led to a shunting problem in the cell. The conversion efficiency showed poor characteristics due to high series resistance and low

Table II. Light I - V characteristics of Al- p^+ emitter solar cells with different weights of Al.

	Al 6.52 mg/cm^2	Al 13.14 mg/cm^2	Al 19.74 mg/cm^2
V_{OC} (mV)	480	609	560
J_{SC} (mA/cm^2)	4.31	37.09	30.8
FF (%)	9.65	77.45	69.32
Eff. (%)	1	17.36	11.95

shunt resistance, which were the result of over-firing in the electrode region.

Also, 19.74 mg/cm² of the Al sample demonstrated enough series resistance, but the shunt resistance was too low compared to the 13.14 mg/cm² samples. In 19.74 mg/cm² of the Al sample experienced a bowing problem due to the thermal expansion coefficient gap between Si and Al. The bowing problem led to cell parameter decreases and shunt resistance characteristics, such as current density and open-circuit voltage due to an increase in the bulk defect site.

The Al- p^+ rear-side emitter was analyzed using a Scanning Electron Microscope (SEM). Figures 3(a)–(c) shows that the thickness, discontinuity and uniformity of the BSF

depending on the single, double and triple-printed Al- p^+ rear-side emitter cells, respectively. The Al-BSF junction depth is dictated by two parameters:

- (i) deposited Al thickness and
- (ii) peak alloying temperature.

The following expression is widely used to estimate the Al-BSF thickness W_{BSF} :⁹

$$W_{BSF} = \frac{t_{Al} \cdot \rho_{Al}}{\rho_{Si}} \left[\frac{F(T)}{1 - F(T)} - \frac{F(T_o)}{1 - F(T_o)} \right] \quad (1)$$

Where t_{Al} represents the as-deposited Al thickness, ρ_{Al} and ρ_{Si} are the density of Al and Si, respectively, $F(T)$ is the Si atomic weight percentage of the molten phase at the peak alloying temperature, and $F(T_o)$ is the Si atomic weight percentage at the eutectic temperature (constant). $F(T)$ and $F(T_o)$ are obtained from the Al–Si phase diagram. Using Eq. (1), the Al-BSF junction depth is calculated to be $\sim 10 \mu\text{m}$. In Figures 3(a) and (c), 6.52 mg/cm² and 19.74 mg/cm² of the sample demonstrated discontinuity in the BSF region. These discontinuities in the BSF region were the main reason for the decrease in cell characteristics. The SEM image in Figure 3(b) shows a BSF thickness of $7 \mu\text{m}$, which is in good agreement with the calculated thickness without discontinuities. It has been reported that the emitter thickness should be at least $7 \mu\text{m}$ in order to obtain good V_{OC} and FF.

Figures 4 and 5 show the dark I – V measured result and numerically calculated recombination, generation and saturation current density characteristics at a quasi-neutral region (qnr, N_1), space charge region (scr, N_2) and saturation current density (J_{01} and J_{02}). We measured the current in the potential range of 0 mV $\sim$ 750 mV. The current of the p – n junction diode can be separated into two regions; one is the space charge region recombination/generation and the other is a quasi-neutral region recombination/generation. They are related to the dark J – V curve.¹⁰ In the Two-diode model, this deviation is taken into account by including a second diode. The second diode expresses the generation and recombination currents within the space charge region. Generally, the second

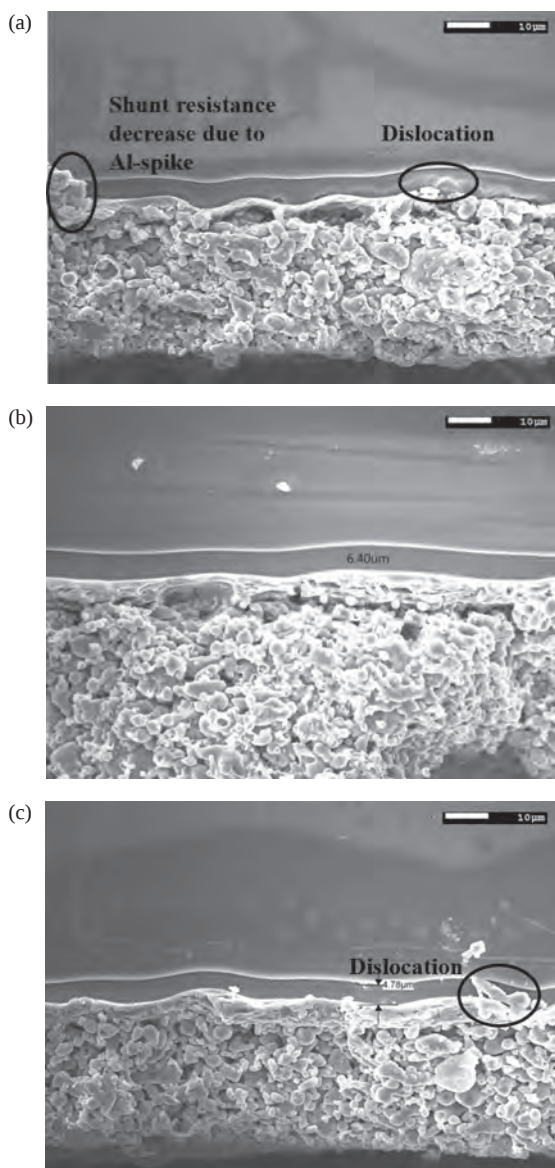


Fig. 3. (a). SEM image of 6.52 mg/cm² Al weight at the rear. (b). SEM image of 13.14 mg/cm² Al weight at the rear. (c). SEM image of 19.74 mg/cm² Al weight at the rear.

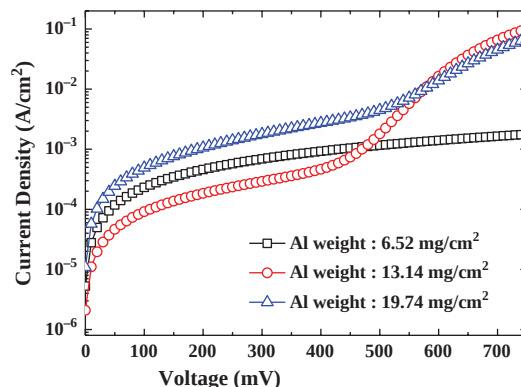


Fig. 4. Dark current–voltage measurement results in relation to variations in Al weight at the rear.

diode is described by an ideality factor of $n_2 = 2$. When the amount of Al was 6.52 mg/cm^2 , the back surface field was not fully formed. This led to current leakage, high series resistance (R_s), and a decrease in V_{OC} and J_{SC} . The increased series resistance and decreased parallel resistance (R_{sh}) resulted in a sharp decline in the fill factor. An aluminum content that is too low obstructed the good formation of the back surface field due to the discontinuity of Al.

As a result, the leakage current increased leading to poor solar cell performance. When the amount of Al was 13.14 mg/cm^2 , the uniform Al- p^+ rear-side emitter was formed having low R_s and high R_{sh} . Thus, it also had good V_{OC} and J_{SC} . As mentioned above, when the amount of Al was 19.74 mg/cm^2 , wafer bowing occurred during co-firing because the coefficient expansion of Al is larger than that of Si. Bowing caused physical stress on the wafer and this bowing resulted in low V_{OC} , J_{SC} , higher R_s and lower R_{sh} . In summary, the highest efficiency was achieved with 13.14 mg/cm^2 of Al.

Also, in Figure 5, the saturation current density J_{01} and J_{02} determined the proposed efficiency of the cell structure. In the case of the 6.52 mg/cm^2 of a printed Al sample, J_{01} and J_{02} were 1.92×10^{-3} and $1.02 \times 10^{-3} \text{ mA/cm}^2$, respectively. The over-firing and shunting problem induced high saturation in the current density in 6.52 mg/cm^2 of the printed Al sample. The J_{02} value at 19.74 mg/cm^2 showed higher saturation current density compared to the 6.52 mg/cm^2 sample of the printed Al due to the wafer bowing effect during the co-firing process. The bowing effect was caused by the thermal expansion coefficient gap between Al and Si.

Generally, saturation current density and recombination/generation characteristics in the quasi-neutral region and space charge region determined cell characteristics and performance.

Figure 6 shows a quantum efficiency n -type Al- p^+ rear-side emitter solar cell depending on the amount of Al at the rear. 6.52 mg/cm^2 of the printed Al sample resulted in quantum efficiency of nearly zero at all measured wavelengths ranging from 300 nm to 1100 nm . This means that the p - n junction was broken by the shunting problem due

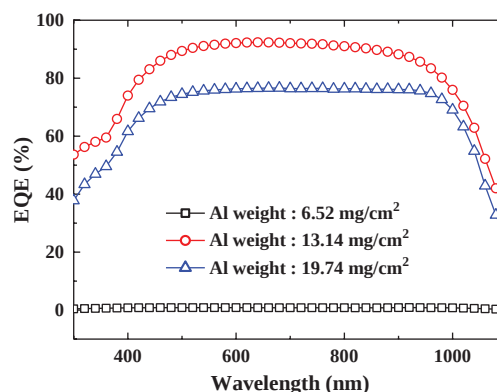


Fig. 6. Quantum efficiency n -type Al- p^+ rear emitter solar cells in relationship to the amount of Al amount at the rear.

to over-firing during the co-firing process. 19.74 mg/cm^2 of the printed Al sample showed relatively low quantum efficiency compared to the 13.14 mg/cm^2 amount of printed Al sample. In the short wavelength, the front side of the electrode was not adequately formed due to the Al layer being too thick at the rear. The wafer bowing effect caused by the thermal expansion gap between Al and Si was determined to have lower middle wavelength quantum efficiency. The long wavelength was lower because the Al- p^+ layer was not adequately formed. This was because it was too thick.

It was found that the SEM image and TCAD fitting were above the figures. Finally, the amount of Al amount at the rear for the n -type Al- p^+ emitter determined quantum efficiency at all ranges of the measured wavelength.

4. CONCLUSION

The high and stable lifetime of n -type silicon materials are a vital and promising prerequisite for modern solar cells. This advantage of n -type Si wafers is utilized for manufacturing simple and industrially feasible high-efficiency solar cells. By using a highly simple process, we have developed an Al- p^+ rear-side emitter solar cell that obtained 17.3% efficiency on n -type phosphorous doped $1\text{--}3 \text{ } \Omega\text{-cm}$ Cz Si material. Furthermore a BSF thickness of $7 \text{ } \mu\text{m}$ was achieved with 13.14 mg/cm^2 of Al paste. The front and back contacts were formed using the screen-printing method and the Al- p^+ rear-side emitter was formed by co-firing the aluminum. In conclusion, these results show the high potential of easy-to-make and industrially feasible screen-printed aluminum-alloyed rear p^+ emitters for n -type silicon solar cells. Thus, n^+np^+ solar cells on high-quality n -type silicon wafers become a promising alternative to commonly produced p -type cells.

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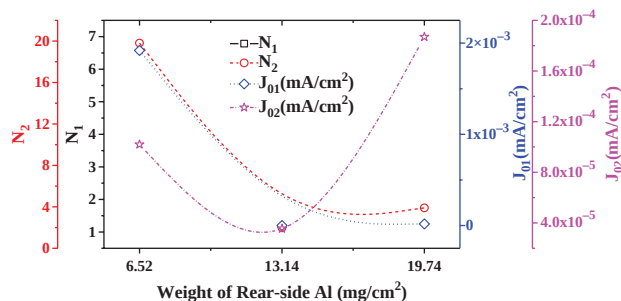


Fig. 5. Trend of quasi-neutral region (qnr, N_1), space charge region (scr, N_2) and saturation current density (J_{01} and J_{02}) in relation to variations in Al weights at the rear.

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