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Optimization of the Geometric Design of Silicon Solar Cells under Different Temperature

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Abstract: In today's world, the sudden increase in greenhouse gases has led to drastic climate changes, primarily caused by thermal power plants, vehicles and industry. As a result, there's an urgent need for innovative, environmentally friendly solutions to generate electricity. Among these green solutions, solar energy stands out, especially through photovoltaic solar panels. In this study, we focused on photovoltaic panels that harness electricity through silicon-based cells. We studied various microscopic physical phenomena that occur in these solar cells using PC1D, a solar cell modeling program widely used in research. In addition, we used PC1D to simulate solar cell performance on various materials such as Si, GaAs and others. Our investigations included the effects of P and N layer concentration, surface texture exposed to sunlight, anti-reflective coatings (ARC), and temperature on solar cell efficiency. The simulations showed an efficiency of 20.81% under certain conditions: P thickness of 200 µm, N thickness of 2 µm, and temperature of 20°C.

Key words: Silicon, energy, current, power, efficiency, solar cell.

1. Introduction

Over the last two decades, swift urbanization and rapid industrialization have notably shaped the increase in global energy demand. Solar power stands out as a crucial energy source, meeting this demand cost-effectively and in an environmentally friendly manner. Improving the efficiency of solar cells is seen as a crucial step towards strengthening the market presence of silicon-based solar energy.

Numerous studies have focused on this software, such as Galib et al., which examined the enhancement of monocrystalline silicon-based solar cell efficiency. The simulation reveals that the optimal value for the p-type doping concentration is $1\times10^{17}cm^{-3}$, while the n-type doping concentration is $1\times10^{18}cm^{-3}$. It includes a diffusion length of 200.3 µm, surface texturing on both sides with depths ranging from 2-3 µm and an angle of 54.74 degrees, a refractive index of 2.019, and a thickness of 74 nm. Following the simulation, the solar cell efficiency reached 20.35% [1]. In another study, he employed surface passivation using SiO_2 and Si_3N_4 ARC layers, ultimately achieving an efficiency of 20.67% [2].

Additionally, Arafat et al conducted a parametric study on a monocrystalline silicon wafer to enhance its efficiency. He set the following parameters: textured surface with heights ranging from 1 to 2 µm at angles of 70 degrees, a base p-type doping concentration of $1\times10^{16}cm^{-3}$, an n-type emitter doping concentration of

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$1\times10^{18}cm^{-3}$, refractive indices of 1.48 and 2.015, resulting in a conversion efficiency of 23.14% [3].

Furthermore, Gokul et al. explored the optimization of monocrystalline silicon solar cells, achieving a solar cell efficiency of 19% with an apparent resistivity of 1 Ω.cm, an apparent lifetime of 2ms, an n+ emitter doping concentration of $1\times10^{20}cm^{-3}$, a shallow back surface field doping concentration of $1\times10^{18}cm^{-3}$, and a surface recombination velocity maintained between 102 and 103cm/s [4].

Mandong et al. explored how geometric parameters impact voltage (V_{oc}), current density (J_{sc}), and efficiency through both PC1D simulations and practical experimentation. They found that the simulation outcomes aligned well with the real cell outcomes. In general, the simulated results slightly exceeded the actual cell parameters, with an efficiency of 18.5% in simulations compared to 17.7% in practical observations [5].

A model simulated by PC1D was used to interpret and refine the geometric and thermal parameters to maximize the efficiency of monocrystalline silicon-based solar cells. The primary objective of the simulation was to analyze how refinement of these parameters contributes to the evolution of efficiency in a Si solar cell.

This study focuses on the analysis of a solar cell with a PN junction, with particular emphasis on considering the thickness of the N-layer under solar irradiation. The primary objective was to develop physical models and solution approaches to evaluate the efficiency, peak electrical power and current-voltage characteristics of the solar cell. A parametric analysis was also carried out to determine how the efficiency is affected by the geometry of the PN structure and temperature variations.

2. Theory and methods

We consider a p-type silicon wafer with an area of 100 cm^2 that was chosen for simulating solar cells. The doping level of the emitter (n-type) was 1×10^{18} cm^{-3}, with its thickness ranging from 1µm to 2 µm. Additionally, the base doping level (p-type) was 1×10^{17} cm^{-3}, with its thickness ranging from 200 µm to 300 µm, assuming a uniform doping profile. Also, we check the temperature from 20 to 25°C. We selected the condition AM (air mass) 1.5 G and 100-time steps to observe time progression.

Fig.1 illustrates the schematic structure of the model, with Table 1 detailing the basic parameters of the Si solar cell simulated in the PC1D software. Anizan et al. delved into the investigation of contact resistance, noting that for the lowest emitter, the contact resistance reaching the highest value was $1\times10^{6}\Omega$. Meanwhile, in terms of the basic contact resistance, the lowest value resulting in the highest outcome was 0.00015Ω [6]. Moreover, the front and back contacts are responsible for gathering mobile charge carriers, while the absorber, emitter, and back surface field manage the generation and movement of these carriers.

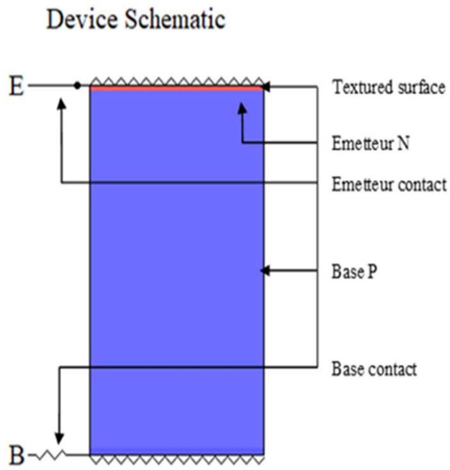

Fig. 1 Model of Si solar cell

Table 1 Parameters for the simulation

Parameters	Values [Unit]
Device area	100 cm^2
Emitter/Front contact	1×10^{-6} Ω
Base/Back contact	1.5×10^{-3} Ω
Thickness	300 µm
Rear diffusion (P)	1×10^{18} cm^{-3}
Bulk recombination (lifetime)	$\tau_n = \tau_p$= 24.18 µs

Constant intensity	$0.1 W\ cm^{-2}$
Spectrum	AM 1.5G

The optically generated current is directly linked to the incoming photon flux, which can be calculated based on the incident power, ascertaining the count of photons incident on the solar cell's surface:

$$F_0 = \frac{P_{in}}{E} \quad (1)$$

Here:

- F_0 is stands for the photon flux incident on the surface per unit area [w/m²/μm],
- E is the energy of the photon which is contingent upon its frequency,
- Pin is the input power flow.

The Poisson equation is utilized to compute the generation of the electric field, a process contingent upon carrier densities:

$$\frac{\partial E}{\partial x} = \frac{\rho}{\varepsilon} \quad (2)$$

where ρ is the charge density and ε is permittivity.

The current density can be determined as:

$$J = J_n + J_p \quad (3)$$

with the Diffusion of electrons is:

$$J_n = \mu_n . n . \nabla E_{Fn} \quad (4)$$

and the Diffusion of holes is:

$$J_p = \mu_p . p . \nabla E_{Fp} \quad (5)$$

where J_n and J_p are the current densities of electrons and holes in a semiconductor device, respectively. n and p are the electron and hole densities, respectively. μn and μ_p are the mobility of E_{Fn} and E_{Fp}, respectively.

In this context, μ_n stands for electron mobility, and μ_p denotes hole mobility. Temporarily, D_n the electron and holes, and ∇E_{Fn} and ∇E_{Fp} are the diffusion coefficients commonly representing the difference in electron and hole quasi-Fermi energies and D_p represent the diffusion coefficients for electrons and holes, respectively.

The refractive index of ARC is:

$$\eta_{ARC} = \sqrt{\eta_{air} \times \eta_{ARC}(\lambda_0)} \quad (6)$$

And the thickness of ARC is:

$$d = \sqrt{\frac{\lambda_0}{4 \times \eta_{ARC}}} \quad (7)$$

In this context, η_{air} denotes the refractive index of air, while η_{ARC} represents the refractive index of an anti-reflection coating at a specific wavelength λ_0. Upon closer examination of Eq.6, it becomes evident that the refractive index of the ARC relies on both the refractive index of air and the wavelength-dependent refractive index of a particular anti-reflection coating. However, despite this dependency, the value on the right-hand side of Eq.7 was not incorporated either within the equation itself or within the simulation [7].

3. Results and Discussion

In this simulation, a uniform doping profile was assumed. The AM (Air Mass) 1.5 G condition was used to simulate sunlight. After the simulation, the efficiency of the solar cell was determined to be 20.43%. The results indicate that at a thickness of 200 μm for type p and 2 μm for type N, the efficiency peaked at 20.43%.

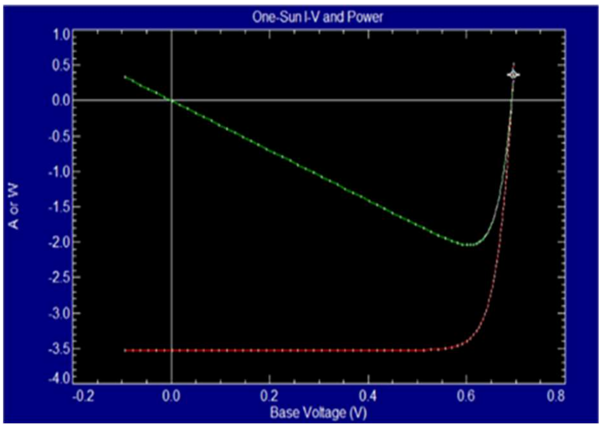

Fig. 2 I-V and P-V curve of solar cell

In Fig.2, the red line illustrates the I-V curve, while the green line represents the P-V curve of the solar cell. The current-voltage (I-V) curve of a solar cell displays all potential combinations of its current and voltage outputs, whereas the power-voltage (P-V) curve shows all possible combinations of its power and voltage outputs. The point on the I-V curve where both the current and voltage are at their maximum is referred to as the Maximum Power Point (MPP). In the P-V curve, the MPP signifies the point where power reaches its highest value. Within the I-V and P-V curves, the maximum power point is denoted as Pm. Additionally, the maximum voltage and maximum current are designated as V_m and I_m, respectively.

The distribution of energy within the space charge region (SCR) or its immediate vicinity is crucial as long as electron-hole pairs are separated within this zone. This consideration encompasses the feasibility of the structure through various deposition techniques.

Throughout this study, we independently adjusted the thicknesses of the P and N layers along with the temperature (T) as outlined below:

- Adjusting the P layer thickness (ranging from 200µm to 300µm) while maintaining the thicknesses of the N layers and temperature (T) constant.
- Modifying the N layer thickness (ranging from 1µm to 2µm) while keeping the P layer thicknesses in the optimal value and temperature (T) constant.
- Altering the temperature (T) (ranging from 300K to 320K) while keeping the P and N layer thicknesses in the optimal value.

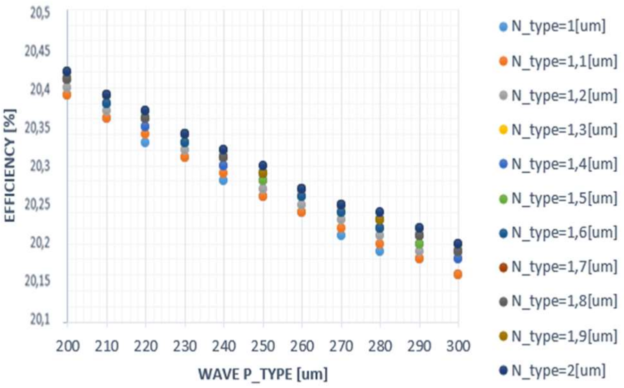

Fig. 3 The effect of N-type and P-type wafer in the efficiency

In Fig.3, we investigate the impact of the N-type and P-type wafers on the efficiency of the solar cell. An efficiency of 20.42% is achieved with an N-layer thickness of 2µm and a P-layer thickness of 200µm.

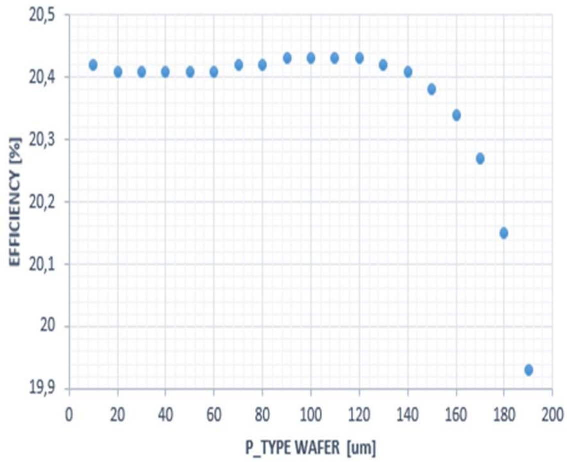

Fig. 4 The effect of rear P type wafer in the efficiency

In Fig.4, we examine the impact of the rear P-type wafer on the efficiency of the solar cell. An optimal efficiency value of 20.43% is observed for a rear P-layer thickness of 100µm.

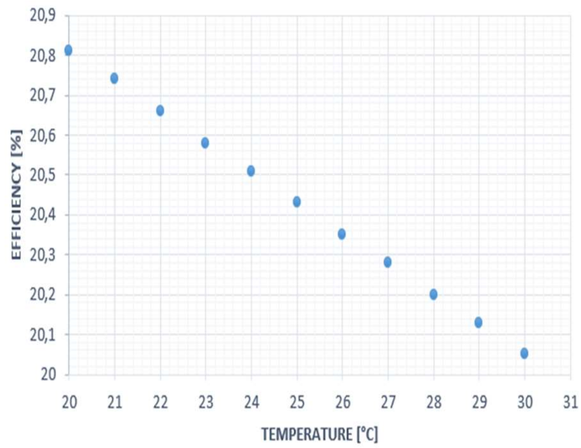

Fig. 5 The effect of temperature in the efficiency of solar cell

In Fig.5, it's noticeable that efficiency decreases as temperature rises, indicating that temperature has an impact on the energy gap.

Eq.8 presents the relationship between temperature and the energy gap:

$$E_g = E_0 + \frac{\alpha\, T^2}{T+\beta} \tag{8}$$

Where E_0 is the energy gap at O°K, and α and β are constants [8].

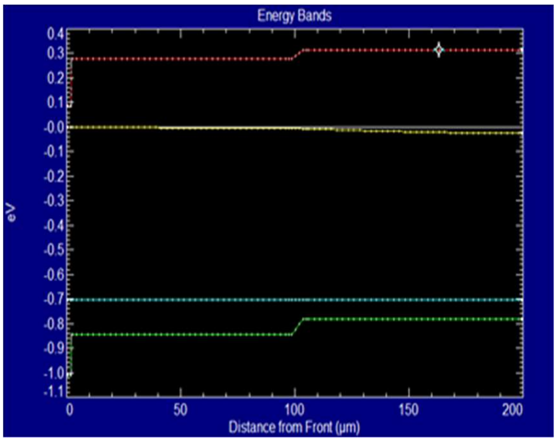

Fig. 6 The Energy gap of solar cell

Fig.6 illustrates the band gap between the valence band (green) and the conduction band (red) where electron movement occurs. Therefore, the increase in the gap due to rising temperature signifies the cause of the decrease in solar cell efficiency.

4. Conclusions

The study proposes a new approach to achieve a high efficiency solar cell for industrial applications. Therefore, the characteristics of Si wafers were carefully studied to understand the parametric optimization in PC1D numerical simulation to achieve high efficiency for Si solar cells. The results showed that a 2µm thickness of the N-type wafer, 200µm thickness of the P-type wafer, with 100µm thickness of the back P-type wafer, and a temperature of 20°C, respectively, can achieve a higher efficiency of 20.81%. In the solar cell manufacturing process, the wafer thickness can be adjusted based on simulated values. The photovoltaic industry is focusing on solar cells with thin wafers of <150µm. During the actual manufacturing of solar cells, optimized process parameters are controlled, including temperature, etc. Simulating these parameters in advance to determine optimal process parameters significantly reduces manufacturing costs. Future work will use these optimized process parameters to fabricate the actual solar device and compare experimental results with simulated results.

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