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Fabrication of Low-cost and High-efficiency Crystalline Silicon Solar Cells Using Polymeric Carrier Selective Contacts

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Abstract

Crystalline silicon (c-Si) solar cells are the leading choice in the photovoltaic market due to their dependability and long-term stability, but lowering production costs and increasing efficiency remain key issues. Organic semiconductors use carrier-selective contacts based on doped amorphous silicon layers and transition metal oxides to simplify and lower the production costs of efficient crystalline silicon solar cells. Polymers are rapidly being used in photovoltaics as flexible substrates, photoanode films, and platinum-free counter electrodes, providing potential alternatives for increased efficiency and cost savings. The study looks into the use of organically conjugated molecules with silicon (Si) heterojunctions for effective photovoltaic. Polymers such as N2200, PCBM, Spiro-OMeTAD, PTAA, PEDOT:PSS, P3HT, and polymers with naphthalene diimide and perylenediimide cores were employed to create an asymmetrical silicon heterocontact with approximately 21% efficiency. The organic/Si electronic coupling interaction contributes to the production of high-quality silicon heterocontact for solar cells and other optoelectronic devices at low temperatures, solution processing, and lithography-free procedures.The paper looks at the design, manufacturing, and performance of c-Si solar cells with polymeric electron and hole selective contacts, as well as their material properties, fabrication processes, device architecture, and future research prospects.

Keywords: Electron-Selective Polymers, Hole-Selective Polymers, Heterocontact, crystalline silicon solar cells, efficiency

INTRODUCTION

The global demand for renewable energy sources has led to significant advancements in photovoltaic technologies, with c-Si solar cells being the most widely used due to their sustainability and longevity. However, high production costs necessitate developing low-cost supplies and procedures.

Solar cells constructed around heterojunctions, with a world-record power conversion efficiency of 26.7%, are being developed which is less than its theoretical maximum limits (Shockley-Queisser limit) 29.43% due to energy losses [1,2]. However, fabrication of SHJ with doped a-Si:H contacts is complicated, emits hazardous gases, has parasitic absorption, and is expensive. Organic molecules have been used as electron and hole transport layers (HTLs) in passivated contact with silicon in c-Si solar cells using simpler fabrication procedures [3–5]. These contact materials are carrier-selective, reducing parasitic absorption and Auger recombination. Polymeric carrier-selective contacts, such as electron-selective and hole-selective polymers, offer a promising solution for low-cost, high-efficiency crystalline silicon solar cells. These connections provide high charge carrier

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selectivity, ease of processing, and compatibility with existing c-Si technologies. They have low material costs, solution processability, and configurable electronic characteristics, making them ideal for c-Si solar cell integration [6,7]. Organic semiconductors, which are tunable by chemical engineering, have the potential to provide charge carrier-selective contacts for semiconductor absorption. Polythiophenes, such as poly(3-hexylthiophene) (P3HT) and poly(3,4-ethylenedioxythiophene) (PEDOT), have been widely investigated as hole-selective contacts for c-Si [8–10].

*PEDOT:*PSS is becoming increasingly popular in solar cells due to its high work-function, passivation effect, and transparent conductive qualities. It has been stated that c-Si solar cells can achieve PCEs of more than 20%. Other organic compounds, such as PEO (polyethylene oxide), Liq (8-hydroxyquinolinolato lithium), (C60 pyrrolidine tris-acid) CPTA, and amino acids, have also demonstrated interesting photovoltaic properties [11,12]. L-histidine, an amino acid, has a PCE of 17.9% in c-Si(n) cells. Polyethylenimine (PEI) has been identified as a useful ETL for organic solar cells. The work shows that branching PEI (b-PEI) reduces contact resistivity at interfaces, resulting in a champion PCE of 19.4%. PTAA is a hole-selective contact for c-Si solar cells. The material is identical to p-type c-Si and has a low valence band offset and a large coduction band offset, which block the electron [13,43]. On hybrid silicon solar cells, Al2O3/PTAA rear contact achieves an impressive 20.2% efficiency. We achieved 20.58% efficiency by fabricating a polymeric hole- and electron-selective heterocontact with SiO_2 passivation. This article explores the use of polymers as electron transport materials, hole transport materials, or templating agents in solar cells to improve their performance, stability, and longevity [14,15,43].

MATERIALS AND METHODS

Electron-Selective Polymers

Effective electron extraction and hole blocking rely on electron-selective interactions. Conducting polymers, like poly(3-hexylthiophene) (P3HT) and branched polyethylenimine (b-PEI), offer good film-forming properties, high conductivity, and tunable energy levels, making them ideal for c-Si interfaces [16–18].

Branched- poly-ethylenimine (b-PEI)

b-PEI is employed as an electron selective contacts in silicon solar cells, attaining a 19% power conversion efficiency when combined with a b-PEI interlayer silicon wafer and metal contact(Al) [19,20]. b-PEI molecular structure shown in Figure 1.

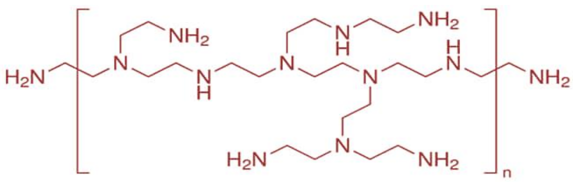
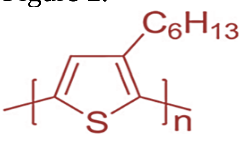


Figure 1. Branched Polyethyleneimine (b-PEI) structure [6]

P3HT: It is a semiconducting polymer with suitable energy levels for electron extraction from c-Si. Its semicrystalline nature allows for efficient charge transport, although optimizing its morphology is crucial for high performance. Its ability to form a uniform film on c-Si ensures efficient electron extraction and minimizes recombination losses [20, 21,1]. P3HT molecular structure shown in Figure 2.



P3HT

Figure 2. Poly(3-hexylthiophene) (P3HT) structure [4].

Hole-Selective Polymers

Polymers such as PTAA, PANI, etc. have demonstrated potential as hole-selective contacts, which are required for efficient hole extraction and electron blocking [22, 23, 2].

Polyaniline (PANI): PANI is a potential material for holes selective contact (HSC) because of its stability and compatibility with solution processing. It is a conductive polymer with tunable electronic characteristics. It is appropriate for interacting with c-Si due to its stable and adjustable characteristics, which guarantee effective hole extraction and reduce recombination losses [24, 25,4]. PANI molecular structure shown in Figure 3.

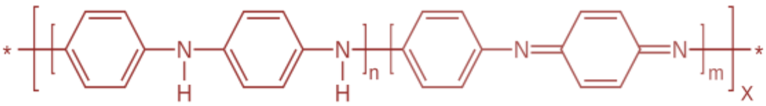


Figure 3. Polyaniline (PANI)structure [3].

PTAA (Poly-bis(4-phenyl)(2,4,6-trimethylphenyl)amine)

PTAA is a high-performance hole transport substance with outstanding stability and energy levels for hole extraction. It can be processed from a solution, making it appropriate for c-Si solar panels [26, 27,3]. PTAA has strong band alignment with p-type c-Si, with a little valence band offset of around 0.1 eV and a significant conduction band offset of about 2.2 eV for efficient electron blocking. When paired with the Al_2O_3 passivation interlayer, PTAA provides low contact resistance and moderate surface passivation on p-type c-Si surfaces. On hybrid c-Si solar cells, a full-area hole-selective Al2O3/PTAA rear contact achieves an impressive 20.2% efficiency [28, 43]. The PTAA molecular structure shown in Figure 4.

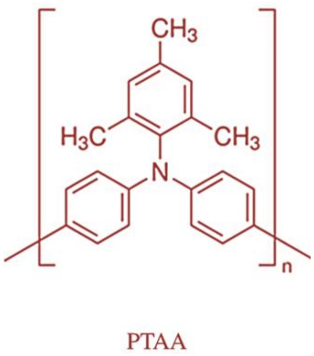


Figure 4. PTAA structure [1].

Device Architecture and Fabrication Technique

In c-Si solar cells, the front contact is often a transparent conductive oxide (TCO) layer such as indium tin oxide, while metal grid electrodes are utilized for electrical contacts, allowing for both light ingress and conductivity. To ensure efficient charge collection, the back contact is frequently coated with metal [29,30,6]. Passivation layers are required to reduce surface recombination, and materials like as silicon dioxide, aluminum oxide, and silicon nitride are often utilized. Electron-selective and hole-selective polymeric layers are placed on the wafer sidewalls to improve charge extraction and recombination losses. Surface passivation, deposition of hole and electron selective polymer layers, and électrode production are all required to integrate polymer-based heterocontacts into c-Si solar cells. Surface passivation is critical for decreasing recombination losses at interfaces [31,32,8]. To achieve optimal device performance, polymer layers are deposited utilizing spin coating, thermal evaporation, pulse laser deposition, and atomic layer deposition. High-quality passivation can be produced with SiO_2 or chemical treatments. TCOs, such as indium tin oxide, or metal grid electrodes, form electrical connections. The choice of electrode material and deposition method has a considerable impact on device performance [33,34,7]. Novel design of polymeric heterocontact c-Si solar cell shown in Figure 5. The polymeric c-Si heterojunction front and rear contacts are formed on a polished n-type silicon wafer (float zone) with thickness 250μm, resistivity 2 Ω.cm with orientation [100]. Cleaning with RCA I and RCA II solution and dip into HF of 2% for 5 then washing by DI water and dried in air. Pulsed laser deposition deposits a thin passivation layer of silicon oxide on both sides of a wafer with a thickness of 1.2 nm. The organic hole-selective material solution-processed PTAA is deposited on front surface l by spin coating 4000 rpm for 60 s under the specified coating and annealing conditions [35,36,8]. The device's front surface was coated with 70 nm ITO using pulse laser deposition, followed by thermal evaporation with a 100-nm-thick silver grid in a 1 × 1 cm^2 window opening. On the rear side of the wafer, an electron-selective polymer branched polyethylenimine (b-PEI) is deposited on a c-Si substrate by spin coating at 2000 rotations per minute for 20 minutes after being annealed at 130°C for 15 minutes in ambient air. A 200 nm coating of silver on a 1x1 cm2 substrate by thermal evaporator completes the solar cell fabrication process [37, 38, 9].

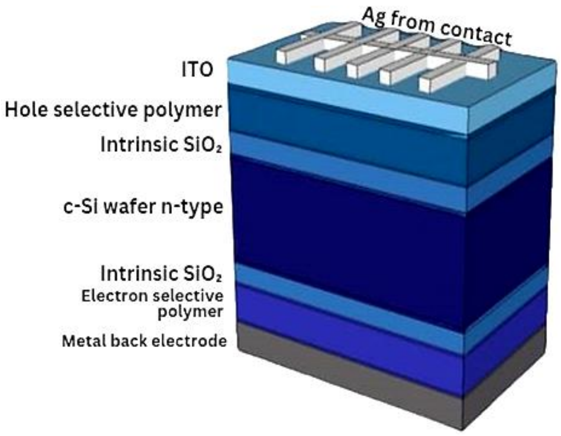


Figure 5. Novel design of polymeric heterocontact c-Si solar cell [39].

Electrical Device Characterization

The current density-voltage (J-V) electrical characteristics were evaluated using a solar simulator under normal conditions, and all standard solar cell parameters are calculated from J-V curves as shown in Figure 6.

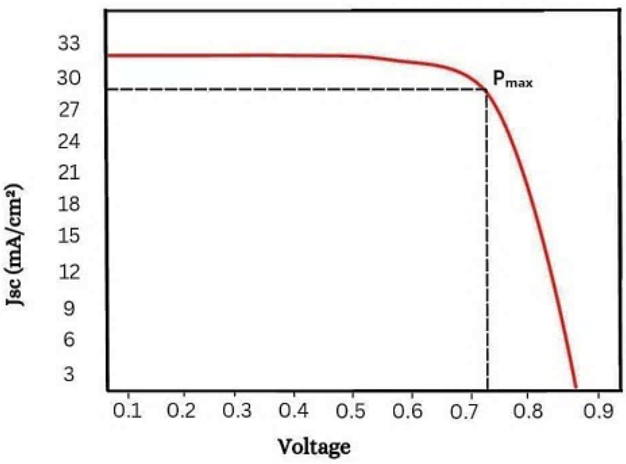


Figure 6. J-V electrical characteristics.

Open-circuit voltage V_{oc}=0.859V, Short circuit current I_{sc}=31.2mA/cm^2, J_{sc}=312 A/m^2

V_{pmax}=0.71V,I_{pmax} =29 mA/cm^2 20.59, P_{max}=20.59 mW

$$FF=\frac{Pmax}{Voc\times Isc}=\frac{20.59}{0.859\times 31.2}=\frac{20.59}{26.8}=0.768 =76.8\%$$

$$PCE=\frac{Pout}{Pin}\times 100\%$$

$$PCE=\frac{Voc\times Jsc\times FF}{1000}\times 100\%$$

$$PCE=\frac{\mathbf{0.859\times 312\times 0.768}}{\mathbf{1000}}\times \mathbf{100}\%$$

$$PCE=\frac{205.83}{1000}\times 100\% = 20.58\%$$

Fill factor (FF) 0.768, and efficiency 20.58% are obtained.

CHALLENGES AND FUTURE TRENDS

Designing innovative polymer hole transport materials with high hole mobility and a suitable energy level configuration is difficult [39,40,11]. Future research should focus on improving electronic properties, stability, and compatibility with c-Si, developing scalable fabrication processes for large-area devices, and investigating strategies to improve the long-term stability of polymer-based heterocontacts under real-world operating conditions to fully realize their potentialin c-Si solar cells [41,42,12].

RESULT AND DISCUSSION

Polymeric carrier selective contacts have demonstrated potential for enhancing c-Si solar cell efficiency, with power conversion efficiencies surpassing 20.5% [43]. We have fabricated c-Si solar cell with polymeric carrier selective heterocontact and achieved a fill factor of 0.768 and an efficiency 20.58%, and more improvements are envisaged through material optimization and device architecture. Polymers face major stability challenges since they degrade when exposed to light, heat, and moisture. Encapsulation methods and stable polymer compositions are critical. This paper examines the current use of polymers in solar cells, including their benefits, practical obstacles, and future solutions, as well as their practical application [15, 16, 1-3].

CONCLUSION

Because of their unique features, ease of production, and compatibility with existing technologies, polymer-based electron-selective and hole-selective heterocontacts represent a viable approach for low-cost, high-efficiency c-Si solar cells. More research and development are required to overcome hurdles and fully exploit the potential of these heterocontacts in the solar sector. The photovoltaic community can help push the next wave of high-performance, low-cost c-Si solar cells by combining breakthrough polymer materials and creative production techniques.

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