

NiO_x Hole Transport Layers Enable Industrial-Scale, Large-Area

Heterojunction Solar Cells with Efficiencies Approaching 24%

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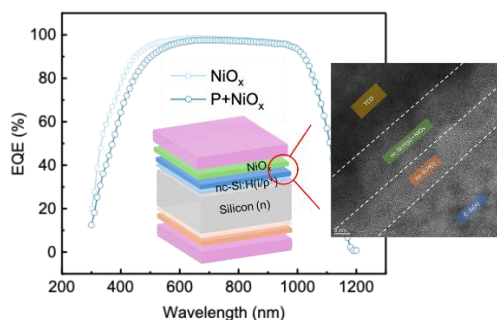
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Abstract- Transparent passivated contacts (TPCs) have recently emerged as a promising strategy for enhancing the performance of silicon heterojunction (SHJ) solar cells, particularly with the development of efficient hole transport layers (HTLs). In this study, an optimized, a scalable NiO_x hole transport layer was successfully implemented on industrial-scale SHJ solar cells with an area of 220.5 cm² via electron beam physical vapor deposition (EB-PVD). A NiO_x HTL enables, a short-circuit current density (J_{sc}) of 40.06 mA/cm², but the open-circuit voltage (V_{oc}) was limited to 512 mV due to interfacial recombination. To address this, an ultra-thin p-type microcrystalline silicon (nc-Si:H(p⁺)) buffer layer with a thickness of 5 nm was inserted between the nc-Si:H(i) and NiO_x layers, forming an nc-Si:H(i)/nc-Si:H(p⁺)/NiO_x hetero-structure. This interfacial engineering strategy effectively suppressed carrier recombination, resulting in a substantial increase in the V_{oc} to 746 mV. The high passivation was accompanied by an enhancement carrier collection as seen by a fill factor of 81.96%, thereby enabling a power conversion efficiency (PCE) of 23.89% - among the highest for NiO_x-based SHJ solar cells. This study demonstrates the feasibility of integrating a novel dopant-free hole transport layer into industrial-scale, large-area silicon solar cells through rational interface engineering.

Keywords- SHJ solar cells; NiO_x; hole transport layers; electron beam physical vapor deposition; interface buffer layer

Graphical Abstract-



1. Introduction

The world is undergoing a rapid shift towards fossil-free energy sources in our effort to mitigate climate change. Solar energy has recently risen as a major clean energy source capable of TW scale expansion, attracting significant attention.¹⁻³ Currently, silicon-based solar cells dominate solar energy deployment, accounting for over 90% of market share.^{4,5} Among these, silicon heterojunction (SHJ) solar cells, offer unique advantages: high efficiency, low temperature coefficient, high bifaciality, and low degradation.^{6,7} SHJ are considered a key technology enabling the next-generation of solar cells with efficiencies in the 26%-28%.⁸⁻¹² Specifically, the optimization of the charge carrier transport layers have played a critical role to enable the optimization of SHJ solar cells. Highly transparent passivated contacts (TPCs) are unique nanolayer materials capable of selectively transporting charge of one polarity while avoiding losses. TPCs are currently under extensive research as they are the key enablers for ultra-high efficiency SHJ. LONGi Solar, for example recently reported employing p-type nanocrystalline silicon as the TPC to improve charge carrier transport and reduce contact resistivity.¹³ Additionally, a group in Julich used nc-SiC:H as the TPC, achieving excellent passivation and high conductivity.¹⁴ The Olindo group utilized MoO_x, WO_x, and V₂O_x materials along with excellent interface processing methods to fabricate high-efficiency silicon heterojunction solar cells.¹⁵⁻¹⁷ Although numerous TPC materials have been investigated, research on the application of NiO_x, a wide-bandgap material, in silicon heterojunction solar cells remains limited.

Nickel oxide (NiO_x), thin films have been widely used as a hole transport layer (HTL) in perovskite solar cells.¹⁸⁻²¹ They exhibit favorable hole transport properties and high light transmittance, fulfilling advantageous criteria for highly TPC applications in silicon heterojunction solar cells. However, existing studies have identified two major technical bottlenecks: insufficient intrinsic conductivity leads to restricted carrier transport, and severe interface recombination causes losses in open-circuit voltage.²²⁻²⁴ To address these issues, current mainstream solutions involve doping with other elements to enhance conductivity or adding passivation layers to improve interface properties.²⁵⁻²⁷ Unfortunately, the V_{oc} is still lower than conventional SHJ solar cells and current methods are severely limited by process complexity. For example, Zhang et al. employed annealing treatment for the passivation layer,²⁸ driving costs up and posing significant barriers to industrialization.²⁹⁻³³

Previous studies have also used atomic layer deposited (ALD) to demonstrate NiO_x that enables remarkable short-circuit current density (J_{sc}) but exhibiting limited open-circuit voltage (V_{oc}). To address the current limitations, the present work engineers a new family of NiO_x nanolayer films via electron beam evaporation under modulated oxygen partial pressures. We show that it is possible to attain superior electrical properties and optical transmittance. Furthermore, we propose the insertion of an ultrathin interlayer of hydrogenated microcrystalline silicon with boron doping (nc-Si:H(p⁺)). This interlayer establishes effective passivation, thereby synergistically enhancing hole transport characteristics and achieving a substantially improved V_{oc} via the exploitation of NiO_x optoelectronic properties.

We successfully scaled the device area to 220.5 cm² (industrial standard size) and constructed a full-scale device structure consisting of: Ag/TCO/nc-Si:H(n⁺)/nc-Si:H(i)/c-Si(n)/nc-Si:H(i)/NiO_x/TCO/Ag. Experimental data demonstrated that the optimized device achieved an outstanding J_{sc} of 40.06 mA/cm² when illuminated from the NiO_x side. Subsequent insertion of an intermediate nc-Si:H(p⁺) layer significantly increased the V_{oc} from 0.516 V to 0.746 V. Notably, compared to conventional nc-Si:H(p⁺), we use an ultrathin layer only requiring one quarter of current layer thickness. This substantially lowers material consumption and processing time, enhancing the commercial viability of SHJ cells. The final device structure encompasses a, nc-Si:H(i)/thin-nc-

Si:H(p⁺)/NiO_x architecture as an effective hole transport contact, reaching a power conversion efficiency of 23.89%. Here is the current highest efficiency for nickel oxide-based silicon heterojunction solar cells, with the previous record being 20.29% achieved by Zhang's group (3.56*3.73 cm²).³⁴ In summary, high-quality NiO_x films were obtained through oxygen partial pressure engineering during, electron-beam evaporation, addressing large-area fabrication challenges, and the incorporation of a 5-nm ultra-thin doped microcrystalline silicon interlayer effectively passivated the interface to enabled a high-performance hole-selective NiO_x TPC.

2. Results and Discussion

2.1. Structural, optical and electronic properties of NiO_x thin films

NiO_x films (dubbed 0, 1, 2 and 3) were deposited on cleaned silicon wafers and analyzed via X-ray diffraction (XRD), as shown in Figure 1a. The XRD pattern of NiO_x-0 shows diffraction peaks corresponding to Ni(OH)₂. During its preparation, the chamber was evacuated to 8×10⁻⁴ Pa, where trace amounts of air might still remain; consequently, the primary component of the as-prepared film is Ni(OH)₂. As the oxygen flow rate increases (NiO_x-1 to NiO_x-3), the Ni(OH)₂ peaks gradually diminish while NiO peaks emerge. Furthermore, the NiO grows predominantly with a (200) crystallographic orientation.³⁵⁻³⁷

SEM analysis was performed on NiO_x films prepared under different oxygen partial pressures. As shown in Figure 1b. The NiO_x-0 film (deposited without oxygen) exhibited small, densely packed grains with a highly planar morphology. With increasing oxygen partial pressure, the grain size progressively expanded, transitioning from small, rounded particles to larger, elongated grains with well-defined boundaries. The evolution toward larger grains reduces the density of grain boundaries, which suppresses charge carrier scattering and can likely lead to improve carrier mobilities. This structural refinement aligns with the observed enhancement in charge carrier transport between the NiO_x-1 and NiO_x-3 films, as discussed later in regards to Figure 1.

To analyze the chemical composition of NiO_x films prepared under different oxygen partial pressures, XPS analysis was conducted on NiO_x(1-3) films. Figure 1c-e illustrate the photoelectron intensity in the vicinity of the Ni 2p binding energies. The observed spectra was analyzed in Advantage and modelled to separate the different components of the Ni bonded states. The three predominant bonding configuration were metallic Ni 2p, Ni(OH)₂ and NiO. Our XPS data indicated that, with increasing oxygen partial pressure, the content of NiO bonds within the films gradually increased, while the concentration of Ni(OH)₂ progressively decreased. As will be evident next, these results indicate that higher quality NiO_x films require increased portions of NiO bonding rather Ni(OH)₂. XPS exhibits higher accuracy than XRD and provides more precise information on the internal composition of NiO_x films.

NiO_x (0-3) films were subsequently deposited on top of the 5nm intrinsic microcrystalline layers nc-Si:H(i), on both sides of Si substrate. These specimens allowed to investigate the effect of oxygen partial pressure on the minority carrier lifetime within the films. Minority carrier lifetime is a critical indicator of defect density at the interface between the thin films and Si. A higher lifetime corresponds to fewer interface defects and reduced non-radiative recombination centers, thereby enhancing carrier collection efficiency. As shown in Figure 1f, the minority carrier lifetime of the silicon wafer exceeded 1000 μs after nc-Si:H(i) deposition. However, upon depositing NiO_x films, the lifetime

sharply decreased to less than 200 μs across all groups, indicating significant defect-induced recombination within the NiO_x films. Comparative analysis revealed that the NiO_x -3 film (deposited under the highest oxygen partial pressure of 1.0×10^{-2} Pa) exhibited a comparatively higher minority carrier lifetime, suggesting reduced defect density compared to other groups.

NiO_x (0-3) films were then deposited on glass substrates for UV-Vis analysis to investigate the effect of oxygen partial pressure on optical properties. As shown in Figure 1g, the transmittance values of NiO_x (0-3) films (70 nm thick) were 1.909%, 34.371%, 74.460%, and 75.131% (average value in the wavelength range of 300nm-1200nm), respectively. These results indicate that increasing oxygen partial pressure enhances film transmittance, which reduces parasitic absorption of light and improves overall device performance.

Furthermore, NiO_x films were deposited on 220.5 cm^2 silicon wafers for sheet resistance measurements to evaluate film uniformity and electrical properties. Sample preparation was carried out on a silicon wafer with a sheet resistance of 5.9 Ω/sq . As summarized in the Supplementary Materials, Figure S1 and Table S1, the sheet resistance values at five randomly selected points on each wafer exhibited minimal variation, confirming excellent film uniformity suitable for large-area applications. Average sheet resistances (across the 220.5 cm^2 area) are plotted in Figure 1h demonstrating a non-monotonic trend: the resistance initially increased and then decreased with higher oxygen partial pressures. The NiO_x -3 film exhibited the lowest sheet resistance of 10.399 Ω/sq , highlighting its superior electrical conductivity.

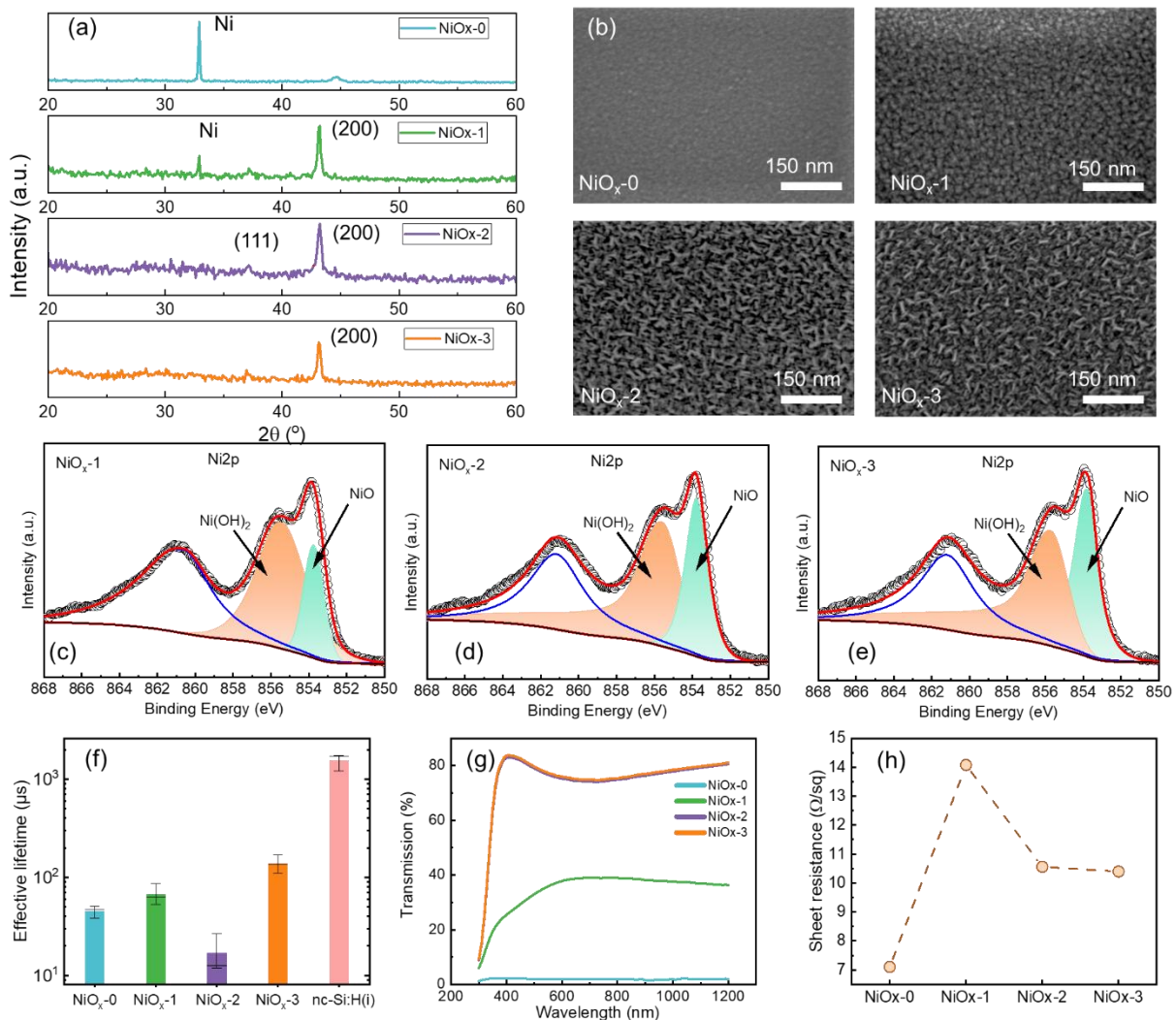


Figure 1. Structural, chemical and optoelectronic properties of NiO_x (0-3) thin films (a) XRD spectra, (b) SEM surface micrographs, (c)-(e) XPS spectra, (f) Effective minority carrier lifetimes, (g) Spectral transmittance, and (h) Sheet Resistance.

2.2 Silicon heterojunction solar cells based on NiO_x nanolayer films.

Heterojunction solar cells were fabricated based on the structure Ag/TCO/nc-Si:H(n⁺)/nc-Si:H(i)/c-Si(n)/nc-Si:H(i)/NiO_x/TCO/Ag as shown in Figure 6. These used NiO_x as the hole transport layer, and their current-voltage (J-V) characteristics were evaluated as presented in Supplementary Table S2. The J-V results demonstrate that the overall device performance progressively improved with increasing oxygen partial pressure in the NiO_x deposition process. In the best case, the presence of our new NiO_x film on the front surface led to achieving a J_{sc} of 40.05 mA/cm². However, the V_{oc} remained limited to 512 mV, which could be attributed to substantial non-radiative recombination losses caused by inherent defects and inadequate interface passivation quality within the device architecture, particularly at the hole-extracting contact. Subsequently, we investigated the optimal thickness of NiO_x-3 as the hole transport layer, as shown in Figure S2. The thickness demonstrating superior performance and consistency was 15 nm as initially indicated by the instrument, though this value was later corrected by TEM characterization. Excessively thin NiO_x layers result in non-uniform deposition, while overly thick NiO_x layers impede charge carrier transport. All subsequent investigations regarding the stacked nc-Si:H(p⁺)/NiO_x structure utilized the optimized NiO_x-3 at 15 nm.

The inferior passivation performance of NiO_x as a standalone hole transport layer, which led to the suppressed V_{oc}. To address this issue, we introduced an ultrathin nc-Si:H(p⁺) interlayer of 5 nm between nc-Si:H(i)/NiO_x interface. Figure 2a shows, the minority carrier lifetimes measured when using the added ultrathin nc-Si:H(p⁺) layer. It is clear that the combination of nc-Si:H(p⁺)/NiO_x provided large enhancements in passivation as observed by effective lifetimes in excess of 2 ms. Further improvement is also observed after transparent conductive oxide (TCO) deposition. The 75% thickness reduction compared to standard p⁺-layers not only minimizes material consumption but also shortens fabrication time by reducing plasma-enhanced chemical vapor deposition cycles. These results highlight the dual functionality of the optimized nc-Si:H(p⁺)/NiO_x double layer:

- 1) effective defect passivation through hydrogen termination of dangling bonds at the c-Si(n)/NiO_x interface, and
- 2) maintained hole transport efficiency via optimized band alignment despite reduced thickness.

The synergetic enhancement in lifetime after TCO integration suggests additional field-effect passivation from the conductive oxide, likely through interfacial dipole formation that mitigates recombination by tuning the population of carriers at the interface.³⁸

The photoluminescence (PL) characteristics of silicon wafers with different thin-film structures (Figure 2b) revealed critical insights into defect evolution. Bare NiO_x films exhibited high-density of interface defects at the hole contact. Notably, the introduction of the nc-Si:H(p⁺) layer induced a significant PL intensity enhancement, confirming effective chemical passivation of interface states through hydrogen-mediated dangling bond termination. Subsequent TCO deposition further increased the PL intensity, indicating secondary passivation through field-effect modulation.

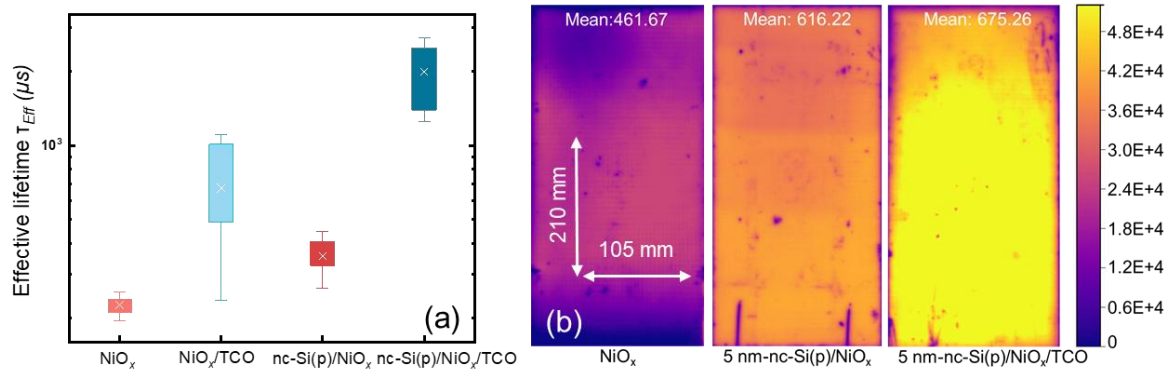


Figure 2. (a) Comparison of minority carrier lifetimes for different film structures. (b) Comparison of photoluminescence (PL) characteristics for different structural configurations.

The heterojunction solar cells incorporating an $nc-Si:H(p^+)/NiO_x$ bilayer as the hole transport layer were fabricated with the architecture illustrated in Figure 6, and their corresponding current-voltage characteristics are presented in Figure 3a. As shown in Figure 3a, devices employing stand-alone NiO_x exhibited high short-circuit current density ($J_{sc} = 40.05\text{ mA/cm}^2$) but suffered from low open-circuit voltage ($V_{oc} = 512\text{ mV}$) due to insufficient interface passivation. The introduction of the ultrathin $nc-Si:H(p^+)$ interlayer significantly enhanced V_{oc} to 746 mV through improved chemical passivation of NiO_x interfacial defects, while inducing a controlled J_{sc} reduction to 39.044 mA/cm^2 caused by the inherent parasitic absorption in the p-type microcrystalline silicon layer. The optimized device achieved a fill factor of 81.96% and power conversion efficiency of 23.887% (p-side illuminated), representing the highest reported performance for large-area (220.5 cm^2) heterojunction solar cells using NiO_x -based hole transport layers. The EQE measurements revealed distinct photoresponse characteristics for the two hole-transport-layer (HTL) configurations in silicon heterojunction (SHJ) solar cells. As shown in Figure 3b, the device employing NiO_x as the HTL exhibited an EQE of 39.74 mA/cm^2 , outperforming the $nc-Si:H(p^+)/NiO_x$ -based counterpart (EQE = 38.7 mA/cm^2), particularly in the short-wavelength regime (300–500 nm). This enhancement suggests that the standalone NiO_x HTL facilitates superior photon-to-carrier conversion efficiency for high-energy photons. In contrast, the diminished short-wavelength EQE of the $nc-Si:H(p^+)/NiO_x$ -integrated device stems from parasitic absorption within the p-type microcrystalline silicon ($nc-Si:H(p^+)$) layer, which partially absorbed incident photons before they reached the charge-separation interface. Meanwhile, we fabricated HJT solar cells with the structure of $Ag/TCO/nc-Si:H(n^+)/nc-Si:H(i)/c-Si(n)/nc-Si:H(i)/nc-Si:H(p^+)$ (conventional thickness)/TCO/Ag. The IV and EQE measurements were performed, as shown in Fig. S3. When only $nc-Si:H(p^+)$ was used as the hole transport layer, the fabricated cell exhibited an open-circuit voltage of 0.72 V, a short-circuit current density of 38.89 mA/cm^2 , a fill factor of 78.10%, and a power conversion efficiency of 21.82%. All these values are lower than those achieved with the $nc-Si:H(p^+)$ (thinned)/ NiO_x stack as the hole transport layer.

A series of 10 silicon heterojunction solar cells employing NiO_x thin films or $nc-Si:H(p^+)/NiO_x$ stacked structures as hole transport layers (HTLs) were fabricated to investigate operational consistency. Figure 3c, shows cell parameters across all cells tested. The NiO_x -based cells exhibited significantly higher J_{sc} compared to those with the bilayer configuration. However, the incorporation of $nc-Si:H(p^+)$ led to remarkable improvements in both V_{oc} and FF. The enhanced V_{oc} can be attributed

to reduced internal defects within the transport layer, as corroborated by minority carrier lifetime measurements. This defect reduction effectively suppresses non-radiative recombination centers while improving carrier transport efficiency. Although the introduction of the nc-Si:H(p⁺) layer causes parasitic absorption, leading to a slight degradation in the J_{sc} in the bilayer device, the significant enhancement in V_{oc} combined with a moderate improvement in FF synergistically enhances the overall device performance. The optimized carrier dynamics and suppressed recombination pathways ultimately resulted in superior power conversion efficiency. Notably, all fabricated devices demonstrated excellent batch-to-batch consistency, confirming the reliability of our fabrication protocol. Subsequently, we applied the nc-Si:H(p⁺)/NiO_x structure to the rear side of the solar cell, fabricating a silicon heterojunction cell with the structure Ag/TCO/NiO_x/nc-Si:H(p⁺)/nc-Si:H(i)/c-Si(n)/nc-Si:H(i)/nc-Si:H(n⁺)/TCO/Ag. Ten cells were selected for IV testing, and the results are shown in Figure S5. When the nc-Si:H(p⁺)/NiO_x structure is placed on the rear side of the cell, the optimal cell efficiency is only 16.54%, failing to leverage the advantage of NiO_x as a wide-bandgap semiconductor with good light transmittance.

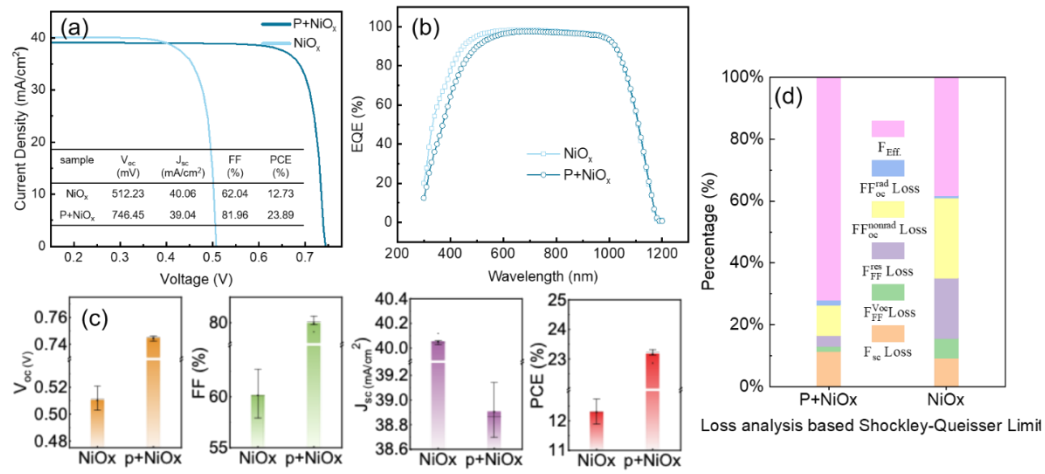


Figure 3. (a) current-voltage (I-V) characteristics of the fabricated heterojunction solar cells. (b) EQE characterization of SHJ solar cells using NiO_x and nc-Si:H(p⁺)/NiO_x as hole transport layers. (c) Performance consistency test of heterojunction solar cells with NiO_x or nc-Si:H(p⁺)/NiO_x as HTL. (d) Loss analysis of heterojunction solar cells employing nc-Si:H(p⁺)/NiO_x and NiO_x as HTL.

A loss visualization analysis was conducted for heterojunction solar cells employing NiO_x and nc-Si:H(p⁺)/NiO_x as HTL, categorizing performance losses into five key quality factors: (1) Photocurrent loss, (2) FF loss attributed to V_{oc} reduction, (3) FF loss induced by series and parallel resistances, (4) Nonradiative recombination-induced voltage loss, and (5) Voltage loss arising from the mismatch between the actual absorption coefficient and the idealized step-function approximation.³⁹

$$\begin{aligned}
 F_{sc} &= J_{sc} / J_{sc}^{SQ} \\
 F_{FF}^{Voc} &= FF_0 (V_{oc}^{real}) / FF_0 (V_{oc}^{SQ}) \\
 F_{FF}^{res} &= FF^{real} / FF_0 (V_{oc}^{real}) \\
 F_{oc}^{nonrad} &= V_{oc}^{real} / V_{oc}^{rad} \\
 F_{oc}^{rad} &= V_{oc}^{rad} / V_{oc}^{SQ}
 \end{aligned}$$

The visualization of the five quality factors, as illustrated in Fig. 3d, reveals the following insights: For the F_{sc} (orange), the energy loss in devices employing a NiO_x HTL is lower than that observed with the nc-Si:H(p⁺)/NiO_x bilayer. This indicates reduced photocurrent losses arising from ineffective photon absorption and conversion when using NiO_x alone, which correlates with the

higher J_{sc} values measured in IV characterization for NiO_x -only HTL devices. The green section corresponds to FF degradation induced by V_{oc} reduction, the purple section represents FF losses attributed to series and parallel resistances, and the yellow section denotes voltage losses caused by nonradiative recombination. Collectively, these three components demonstrate that the incorporation of the nc-Si:H(p^+) passivation layer reduces non-radiative recombination of charge carriers and enhances their hole capture probability, resulting in an increase of the V_{oc} from 0.51 V to 0.75 V and the FF from 62.04% to 81.96%. This phenomenon aligns with the lower minority carrier lifetime and diminished photoluminescence (PL) intensity observed in devices lacking the nc-Si:H(p^+) passivation layer.

2.3 Interface chemical and electronic structure

STEM analysis was performed on the front hole selective nanolayer contact of the fabricated heterojunction solar cells. A HAADF micrograph is, shown in Figure 4a illustrating the microcrystalline nature of both the Si and NiO_x nanolayers. A chemical analysis was conducted via an in-situ EDS detector, with the resulting chemical maps illustrated in Figure 4b. These results demonstrate that after NiO_x deposition, Ni diffused into the nc-Si:H(p^+) layer, while significant Ni accumulation was also observed within the TCO film. The total thickness of the nc-Si:H(p^+)/ NiO_x composite layer is approximately 10 nm. Minority carrier lifetime measurements of different device architectures (as illustrated in Fig. S4) revealed that the nc-Si:H(p^+)/ NiO_x /TCO structure exhibited superior minority carrier lifetime compared to the nc-Si:H(p^+)/TCO counterpart. This enhancement could be attributed to the mitigation of sputtering damage during TCO deposition as well as increased field effect surface passivation from the interfacial electronic screening from the NiO_x layer. This increase in passivation occurs despite the partial diffusion of Ni into the TCO and mc-Si layers.

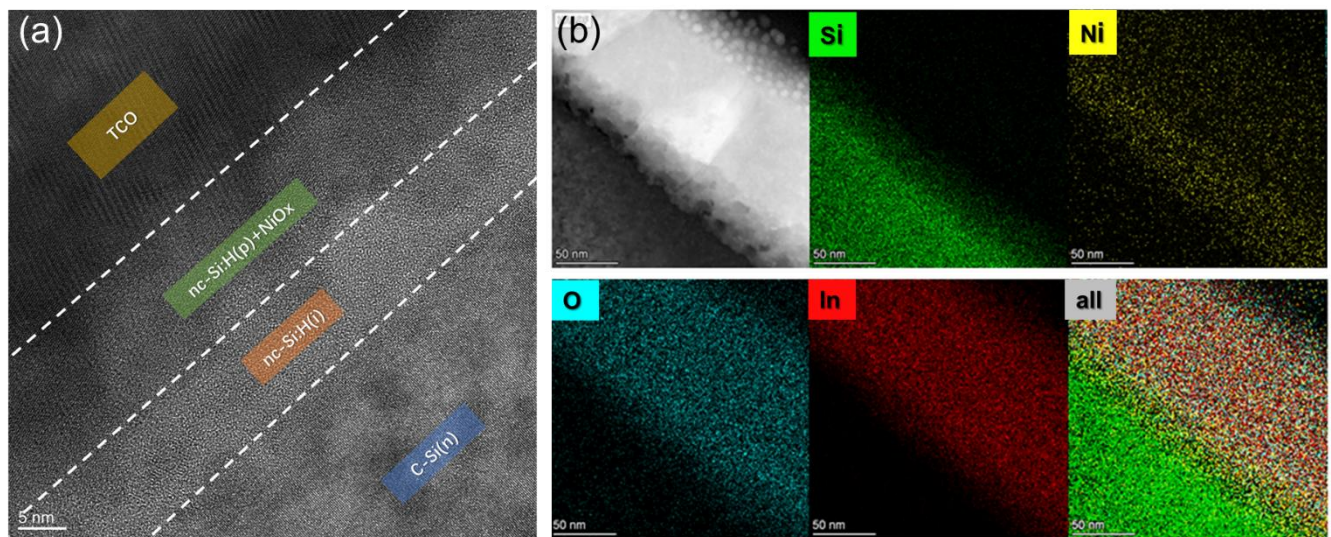


Figure 4. (a) STEM micrograph of the front hole passivating nanolayer contact for the heterojunction solar cells. (b) energy dispersive X-ray compositional analysis of the NiO_x interface nanolayers.

UPS measurements were employed to determine the work functions and valence band positions of all layers across the structure. The UPS data sets and band edge fittings are, included in Supplementary Fig.S7. The bandgap of NiO_x is illustrated in the Fig.S6, while that of the nc-Si:H(i) and nc-Si:H(p^+) was obtained via spectroscopic ellipsometry. The following set of energy relationships was followed to calculate the conduction and valence band positions of each layer were

determined, as presented in Table 2.

$$\delta n = E_g - \delta p$$

$$\chi = \Phi - \delta n$$

$$Ev = \delta p - \Phi$$

$$\Delta E_c = \chi_{ucSi(i)} - \chi_{NiO_x/ucSi(p)}$$

$$\Delta E_v = E_{g_{ucSi(p)}} - E_{g_{ucSi(i)}} - \Delta E_c$$

Where Φ indicates work function, δp distance from Fermi level to valence band maximum, E_g is the material band gap energy, Ev is valence band maximum, χ is electron affinity, δn is distance from Fermi level to conduction band bottom, ΔE_v is valence band offset, ΔE_c is conduction band offset. The energy band diagram is plotted in Figure 5. When only the NiO_x layer is present, due to its work function being lower than that of nc-Si:H(i), it induces an upward band bending at the interface, thereby blocking electron transport and reducing carrier recombination on the hole transport side. The ΔE_c of NiO_x is 1.99 eV, while that of nc-Si:H(p^+) is 0.35 eV, indicating that NiO_x has a larger conduction band offset compared to nc-Si:H(p^+), which can prevent electrons from entering the hole transport layer and reduce carrier recombination. The ΔE_v of NiO_x is 0.32 eV, while that of nc-Si:H(p^+) is 0.40 eV, showing that NiO_x has a smaller valence band offset compared to nc-Si:H(p^+), which can enhance hole transport. As a result, the use of NiO_x leads to better cell performance compared to using nc-Si:H(p^+) alone. In the nc-Si:H(i)/nc-Si:H(p^+)/ NiO_x structure, nc-Si:H(p^+) primarily provides a protective role, reducing the damage to nc-Si:H(i) caused by electron beam evaporation of NiO_x , thus improving the overall passivation performance.

Table 2. Data required for constructing the energy band diagram.

sample(eV)	Φ (eV)	Δp (eV)	E_g (eV)	Ev (eV)	X (eV)	Δn (eV)	ΔE_v vs nc-Si (i) (eV)	ΔE_c vs nc-Si (i) (eV)
nc-Si:H(i)	3.80	1.10	1.70	4.90	3.20	0.60		
nc-Si:H(p^+)	3.34	1.16	1.65	4.50	2.85	0.49	0.40	0.35
NiO_x	3.54	1.04	3.37	4.58	1.21	2.33	0.32	1.99

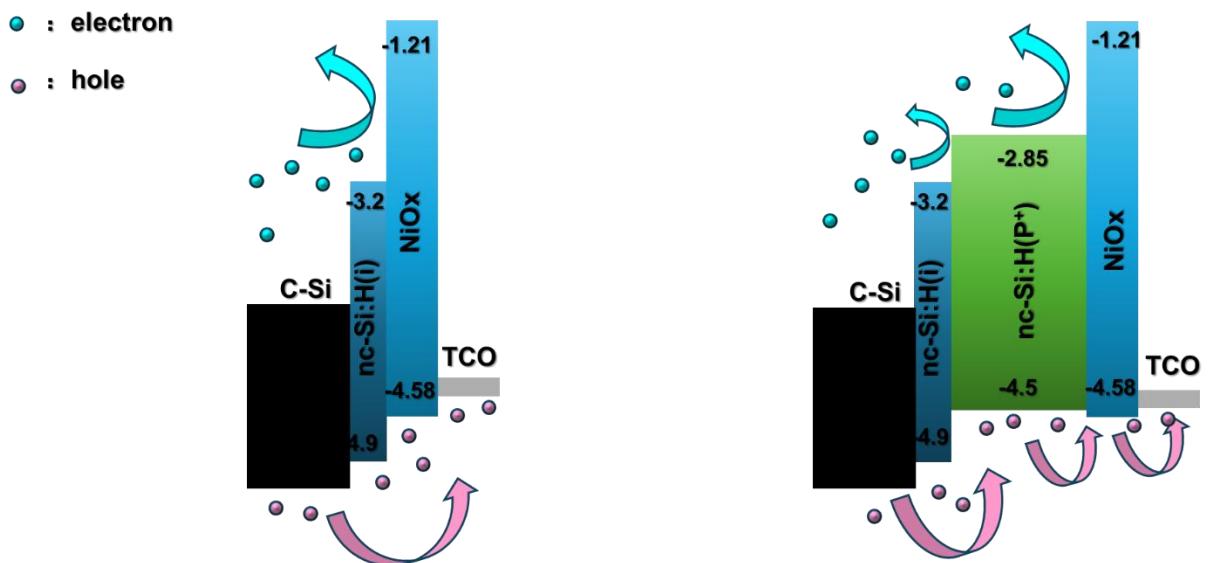


Figure 5. Schematic illustration of carrier transport in nc-Si:H(i), nc-Si:H(p^+), and NiO_x

3. Conclusion

This work proposes a cost-effective, scalable electron-beam evaporation process to fabricate large-area (220.5 cm^2) NiO_x thin film with desired electrical conductivity and optical transmittance through compositional control. Experimental results reveal that the NiO_x films prepared under high oxygen partial pressure exhibited the highest optical transmittance and the lowest sheet resistance, which can be attributed to the increased grain size, suppressed Ni(OH)_2 content within the film, and enhanced NiO phase concentration. When employed as a hole transport layer, the device achieves a short-circuit current density (J_{sc}) of 40.06 mA/cm^2 . By inserting an ultra-thin-nc-Si:H(p^+) layer at the nc-Si:H(i)/ NiO_x interface, the minority carrier lifetime improved, interfacial recombination was markedly suppressed, and V_{oc} increased from 0.51 V to 0.75 V . The resulting solar cell achieved an efficiency of 23.89% , representing the highest reported efficiency for NiO_x -based heterojunction solar cells to date. Loss analysis showed that under the insertion of nc-Si:H(p^+) layer, the nonradiative recombination of the device is markedly reduced, and the carrier's capture probability is increased, thereby improving V_{oc} and FF. The band model clarifies the feasibility of the nc-Si:H(p^+)/ NiO_x structure: the large conduction band offset blocks electrons from entering the hole transport layer, while the favorable valence band offset facilitates efficient hole transport. This work demonstrates the feasibility of efficiently and reliably integrating NiO_x -based materials into large-area SHJ solar cells, emphasizing the importance of interface engineering in achieving high-performance SHJ solar cells. For this structure, we can also apply it to perovskite tandem solar cells, thereby reducing tandem layers and enhancing the performance of the tandem cells.

4. Methods

The silicon wafers were Radio Corporation America (RCA) cleaned and textured, followed by deposition of intrinsic hydrogenated microcrystalline silicon [nc-Si:H(i)] layers on both sides via plasma-enhanced chemical vapor deposition (PECVD). Using PECVD at a deposition pressure of 5 Torr , nc-Si:H (p^+) was deposited by introducing silane, hydrogen, and diborane into the chamber, while nc-Si:H (n^+) was deposited by introducing silane, hydrogen, and phosphine into the chamber. The NiO_x film was then deposited via electron-beam evaporation. NiO_x films (denoted as $\text{NiO}_x\text{-0}$, $\text{NiO}_x\text{-1}$, $\text{NiO}_x\text{-2}$, and $\text{NiO}_x\text{-3}$) were deposited using a Ni metal target in an electron-beam evaporation system under oxygen partial pressures of 0 Pa , $1.0 \times 10^{-3} \text{ Pa}$, $7 \times 10^{-3} \text{ Pa}$, and $1.0 \times 10^{-2} \text{ Pa}$, respectively. Transparent conductive oxide (TCO) layers were coated on both sides using reactive plasma deposition (RPD), and front/rear electrodes were formed by screen printing. The process sequence is shown in Figure 1 along with the layer structure of our SHJ solar cells. Specific thickness and related parameters are subject to confidentiality agreements and thus cannot be disclosed.

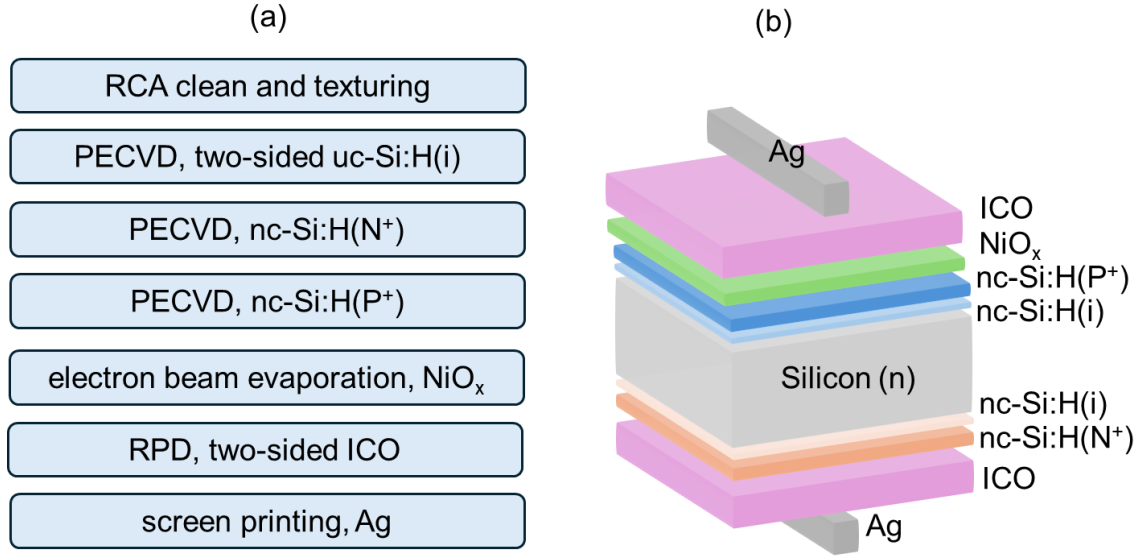


Figure 6. (a) Processing sequence for solar cell fabrication. (b) Layer order structure for front and back contact silicon heterojunction solar cells.

The minority carrier lifetime was measured using a Sinton Instruments WCT-120 lifetime tester (USA). the following four minority carrier lifetime test structures were systematically fabricated and characterized: nc-Si:H(i)/c-Si(n)/nc-Si:H(i); nc-Si:H(n+)/nc-Si:H(i)/c-Si(n)/nc-Si:H(i)/NiO_x; nc-Si:H(n+)/nc-Si:H(i)/c-Si(n)/nc-Si:H(i)/nc-Si:H(p+)/NiO_x; TCO/nc-Si:H(n+)/nc-Si:H(i)/c-Si(n)/nc-Si:H(i)/nc-Si:H(p+)/NiO_x/TCO. Crystal structures were analyzed using a Bruker D8 Advance X-ray diffractometer (XRD, Cu-K α radiation, $2\theta = 10^\circ - 80^\circ$). Surface morphology was characterized by scanning electron microscopy (SEM, ZEISS Auriga). Chemical composition, valence states, and elemental ratios were determined via X-ray photoelectron spectroscopy (XPS, Thermo Scientific ESCALab250, Al K α source, $h\nu = 1486.6$ eV). Optical properties were measured using a UV-vis spectrophotometer (Hitachi U-4100). Ultraviolet photoelectron spectroscopy (UPS) was conducted via a multifunctional photoelectron spectrometer ESCALAB Xi+. Transmission Electron Microscope (TEM) was carried out in an FEI Talos F200X G2 (Thermo Fisher Scientific, USA), equipped with a Super-X energy-dispersive X-ray spectroscopy (EDS) system. Focused Ion Beam-Scanning Electron Microscope (FIB-SEM) was used to create lamellae samples for TEM analysis. An FEI Scios 2 HiVac (Thermo Fisher Scientific, USA) was used, which integrated an Oxford Xplore 30 system for energy dispersive spectroscopy (EDS). The instrument for testing PL is a BT Imaging LIS-R3

Conflict of Interest

The authors declare no conflict of interest

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Data availability statement:

The data that support the findings of this study are available on request from the corresponding author.

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