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Recent Advances Of Transition Metal Oxide Passivated Contacts For Performance Improvemrnt Of Crystalline Silicon Solar Cells

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Abstract: The global energy issue can be alleviated by encouraging the development of solar energy. Photovoltaic solar cells have an efficiency range of 20-25%, which is less than the theoretical maximum of 29.43% due to energy losses and technological challenges. The maximum efficiency for silicon heterojunction technology (SHJ) is 26.7%, but this is still lower due to parasitic absorption and Auger recombination. To address these issues, asymmetric carrier-selective un-doped heterocontacts made of transition metal oxide (TMO) can be used, which improve performance with an open-circuit voltage of 745 mV, a short-circuit current density of 41 mA/ cm^2, a fill factor of 77%, and a power conversion efficiency of almost 25%.

***Index Terms* - Passivated contacts, c-Si solar cells, transition metal oxide, efficiency.**

1. Introduction

Renewable energy sources such as solar, wind, thermal, and biomass are being investigated for their application in modern life. Crystalline silicon solar cells (c-Si) are the industry standard for photovoltaic (PV) conversion, however they suffer energy losses and have technological limits [1-2]. SANYO, a Japanese business, created silicon heterojunction technology (SHJ), or herojunction with an intrinsic thin layer (HIT), which offers the best efficiency (26.7%) but suffers from parasitic Auger recombination losses and low thermal stability. Traditional doping processes necessitate high temperatures and specialized equipment [3-4].The study aims to improve c-Si solar cells using thin carrier selective connections made from transition metal oxide (TMO), which have shown higher effectiveness than conventional doped cells. The goal is to provide energy at a levelized cost, with the effectiveness of molybdenum trioxide's hole-selective contact and titanium oxide's electron-selective contact with a SiO_2 thin layer being enhanced [5-9].

2. Novel Design of TMO's Passivated Contacts Silicon Solar Cell

The c-Si solar cell has a SHJ/HIT structure, which replaces p- and n-type a-Si:H hole and electron selective contacts, as well as the passivation layer, with MoO_3, TiO_2, and ultrathin SiO_2. Transition metal oxide (TMO) contacts use band offsets to extract one carrier type while blocking others. Thermal evaporation, pulse laser deposition, and atomic layer deposition are all methods for depositing TMO contacts at low temperatures that do not require hazardous dopants. The cell accommodates various electron affinities, band gaps, and defect stoichiometry tenability [10-13]. The c-Si solar cell has a SHJ/HIT structure, which replaces p- and n-type a-Si:H hole and electron selective contacts, as well as the passivation layer, with

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Fig.1. TMOs contact solar cell and carrier selective contacts [19-20]

3. Carrier Selectivity and Transport Mechanism

TMOs with partially full d-orbitals and oxygen 2p-orbitals provide dense and stiff structures with appropriate work functions. Stoichiometric TMO materials, such as MoO_3, become insulators due to empty d-states, rendering them inefficient as solar cells. Metal contact maintains high work function and inversion/accumulation layers [21-23. MoOx is great for c-Si solar cells due to its high work function values and low temperature deposit, whereas TiOx is appropriate for SHJ solar cells]. Substoichiometric MoOx is a preferred hole transporter in solar cells due to its high WF (>5.5 eV) and broad bandgap, which promotes hole accumulation at the silicon surface. Some TMOs are hole- or electron-selective, whereas transition metal oxide (TMO) compounds have oxygen vacancies, which impact their electrical properties and charge transport pathways. ETL materials are n-type wide band gap semiconductors with a small conduction band offset that blocks holes [24-26]. TiO_2, a typical ETL material, is often employed in c-Si solar cells because of its electron-selective contact and low conduction band offset [27-30]. HTL materials, such as MoO_3, have a small valence band offset, which allows holes to pass readily while inhibiting electrons due to a large conduction band offset. HTL is produced by gap states and work function, and a hole-selective TMO with a low work function may not have enough band alignment to transmit carriers efficiently from one band to another. TMO materials have a greater work function and a wider conduction band, allowing holes to traverse via band-to-band tunneling [31-35].

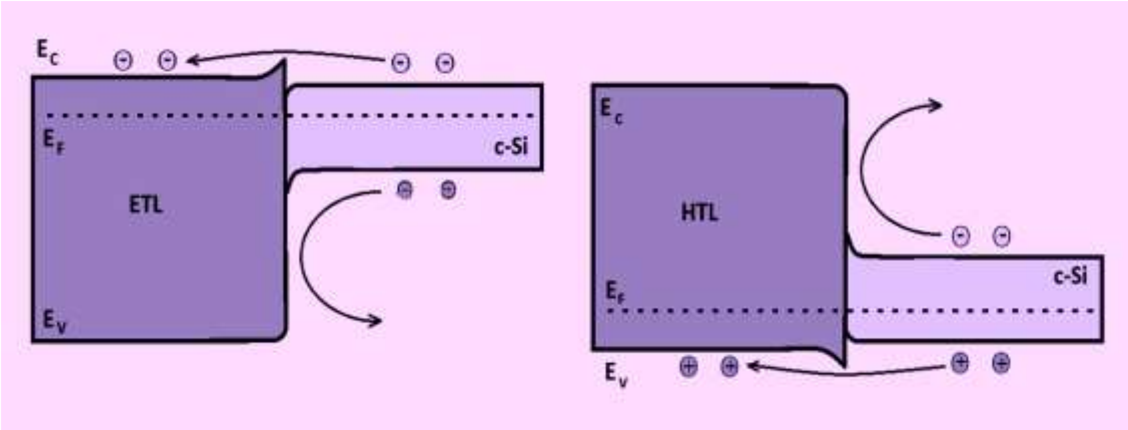


Fig.2. Electron– hole selective contact mechanism

4. Experimental Method for Fabrication

The silicon wafer is cleaned using two RCA solutions: RCA I and RCA II. The RCA I cleanser consists of 27% ammonium hydroxide, 30% hydrogen peroxide, and 5 parts DI water. After heating, add 65 mL of hydrogen peroxide and place the wafer in a beaker for 15 minutes. The RCA II cleanser consists of 6 parts DI water, 27% hydrogen chloride, and 30% hydrogen peroxide. The wafer is then dipped in 2% hydrogen HF, washed with DI, and dry. The wafer is polished on both sides, with a thickness of 180 µm and resistivity of 1-2 Ω.cm. It is coated with 1.2 nm SiO_2 and 05 nm TiO_2 on one side and 07 nm MoO_3 on the other. Transparent conducting oxide (ITO) thin films of 70 nm are grown over a molybdenum trioxide layer using PLD at a fluence of 250 mJ/cm^2, a substrate temperature of 200°C, and an oxygen pressure of 10 milli-Torr [36-40].

5. Characterization

A. X-ray diffraction (XRD) pattern

The Bruker D8 X-ray diffraction meter uses an x-ray wavelength of 0.154 nm (Cu K-ὰ). Bragg's diffraction equation is $2d\sin\theta = n\lambda$, where λ is X-ray wavelength, d is atomic layer separation, θ is glancing angle, and n is an integer. The XRD pattern verifies the crystalline structure of TiO_2 and MoO¬3, displaying more peaks compared to conventional TMOs. The study also investigated the existence of nanostructured TiO_2 and MoO_3 films on a Si substrate, as evidenced in the XRD pattern on the Si substrate in Figures 3 and 4.

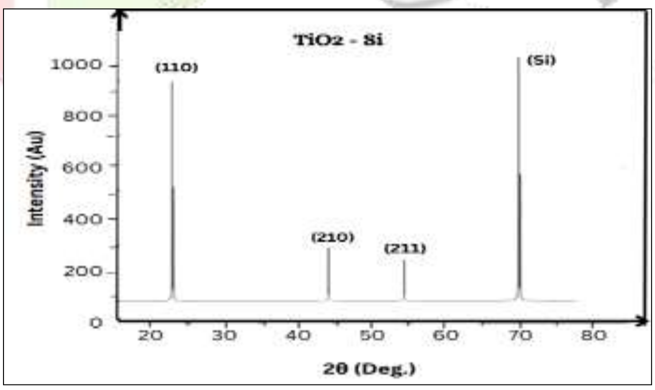


Fig.3. XRD of TiO_2 on Si substrate

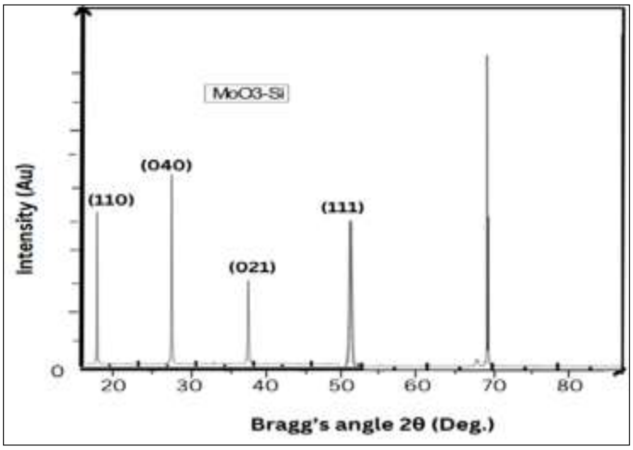


Fig.4. XRD of MoO_3 on Si substrate

B. Characterization by AFM.

The two-dimensional AFM image of titanium oxide, which is 5 nm thick, reveals a well-formed crystalline structure with a smooth, uniform surface and little height variations. The 3D image provides detailed visualization and shows subtle changes as well as superb film with few flaws.

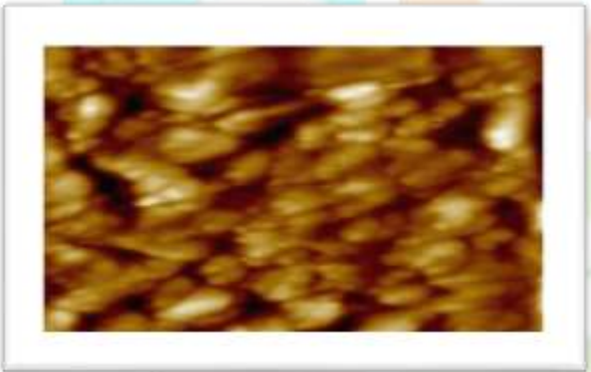


Fig.5. AFM Image of MoO_3 in 2D and 3D

C. Characterization by XPS.

The binding energy of TiO_2 has its first peak at 458.7 eV, and in stichiometry, TiOx, when x< 2 is 457.0 eV, the binding energy is lowered, as shown in figure: 6. In the silicon 2p state, the Si-Si binding energies of Si-O-Ti and Si-O-Si are 99.5 eV, 99.5 eV, and 102.9 eV, respectively in figure: 7. Intensity of two states in XPS of MoO_3 on silicon wafer are display $3d_{5/2}$ and $3d_{3/2}$, as well as O-1s, which has its own peak, figure: 8 depicts the molybdenum 3d state and the oxygen 1s state. The graph depicts peaks representing the presentation of molybdenum atoms on the Si wafer. These XPS images reveal the chemical state of TiO_2, MoO_3, and their surface makeup. The graph depicts peaks representing the presentation of molybdenum atoms on the Si wafer. These XPS images reveal the chemical state of TiO_2, MoO_3, and their surface makeup.

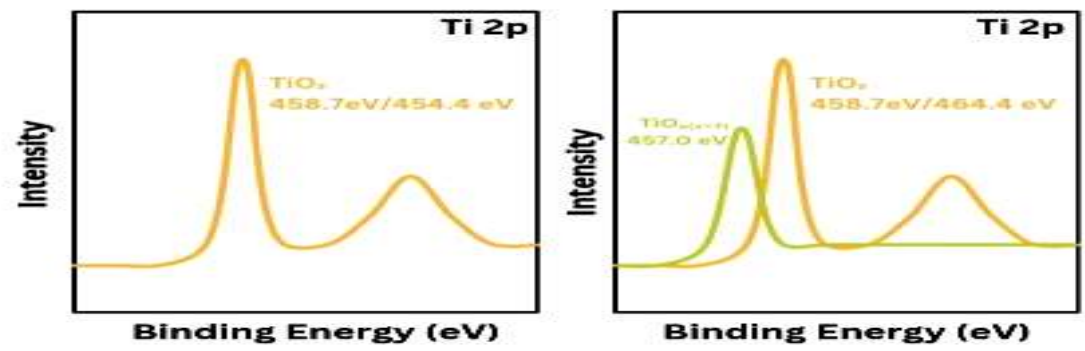


Fig.6.. Titanium 2p state binding energy peaks

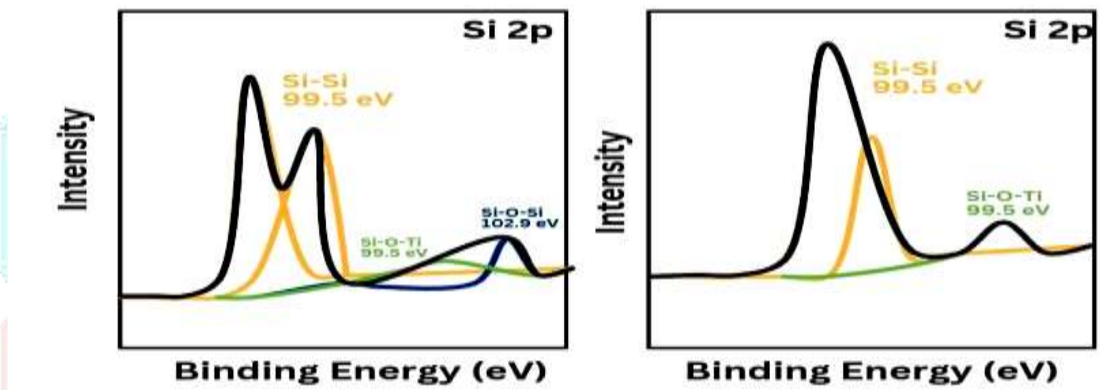


Fig.7. Si 2p binding energy peak

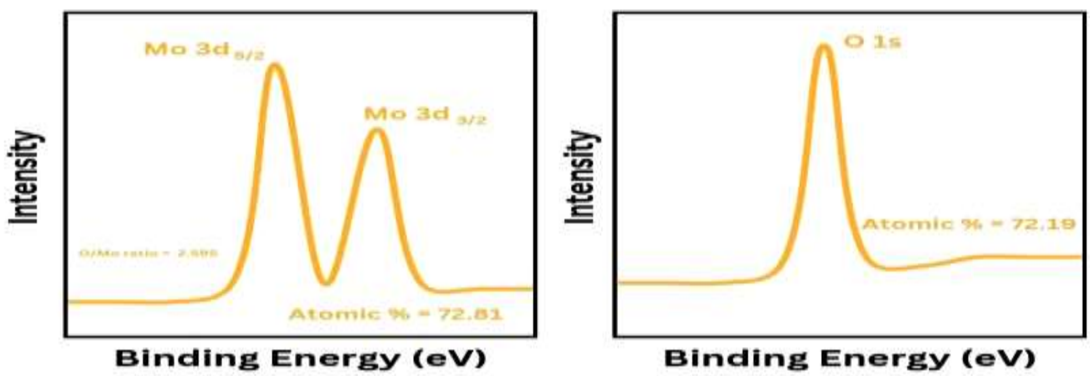
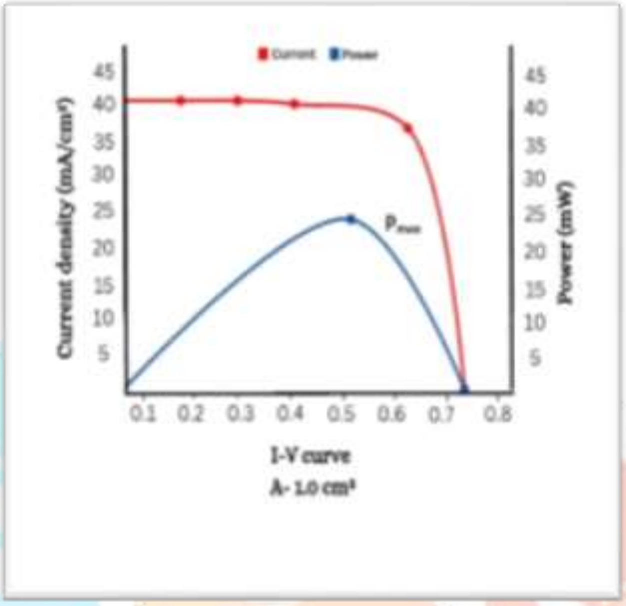


FIG 8. MOO 3 STATES 3D$_{5/2}$ AND 3D$_{3/2}$ & O- 1S BINDING ENERGY PEAK

6. I -V & P-V CHARACTERISTICS OF SOLAR CELL

Figure 12 depicts a solar cell's (J-V) graph. The J-V measurement system configuration includes the solar simulator (model SS50AAA), the Keithley source measure unit, the temperature-controlled measuring chuck, and a computer unit for software support. Using the J-V and P-V characteristic curves, we can calculate the fill factor, open circuit voltage (V_{oc}), short circuit current (I_{sc}), and short circuit current density (J_{sc}). The numerical values of the solar parameters are derived as Jsc = 40.32 mA/cm^2, FF = 81.6%, V_{oc} = 0.745V, and the calculated power conversion efficiency (PCE) is 24.52%. A= 1 cm^2



Date:	2024/5/09
Type:	H-BSS-1403
Repeat time:	3
Isc :	40.32 [mA]
Voc :	0.745 [V]
Pmax :	24.52 [mW]
Ip_{max}:	37.84 [mA]
Vp_{max} :	0.648[V]
FF:	81. 6%
Eff:	24.52[%]
Jsc :	40.32[mA/cm^2]
M.Temp :	25℃
Irr. :	1000/m^2
Ref. D No:	JETp-C01W

Cal. Val. of Ref: 122.91 [mA at 1000/m^2

Scan mode Isc to Voc

Fig.9. J-V and P-V Curve of Solar Cell and its data

Calculation of the FF and efficiency by using the formula

$$FF = \frac{Vmp.Imp}{Voc.Isc}$$

$$FF = \frac{24.52mW}{0.745 \times 40.32\ mA}$$

$$FF = \frac{24.52}{30.0384}$$

FF=.8162,

FF = 81.627% ,

FF = 81.6%

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

$$PCE = \frac{0.745 \times 403.2 \times 0.8162}{1000} \times 100\ \%$$

PCE = 0.24517×100 %

PCE = 24.52%

PCE of 24.52% had been achieved.

7. Result and Discussion

All deposition elements are evaluated using XRD, AFM, and XPS, while the thickness and composition of the thin film are assessed using a depth profilometer. Silicon solar cells include TMO connections, hole-selective MoO_3 contacts, and electron-selective TiO_2 contacts. The deposition thicknesses of TiO_2, MoO_3, and SiO_2 are 5 nm, 7 nm, and 1.2 nm, respectively. Our testing confirmed the validity of the V_{oc} of 745 mV, JSC of 40.32 mA/cm^2 FF of 81.6%, and efficiency at 24.52%. Appropriate TMO contacts that maximize the c-Si energy band can improve efficiency.

8. CHALLEGES AND FUTURE PERSPECTIVES

TMO contacts face challenges in energy-level alignment and conveyance, with defects and trap-assisted tunnelling being key contributors. Experimental methods cannot directly determine electron or hole-selective contact[44-45]. Imports of modules and raw materials cause high manufacturing costs and low efficiency in the solar industry. Metal plating on silicon wafers is costly and difficult to achieve high conductivity. Solar cell installation is expensive and inaccessible, and removal and replacement might be difficult. Solar panels require long-term durability and reliability, which necessitates a significant quantity of ground or rooftop area. Solar cells are less efficient at night or in low-light settings, while storage batteries can be costly and unsustainable.

The project's goal is to advance c-Si solar cell technology through novel designs, passivated connections, light trapping techniques, complex cell topologies, surface texturing, clean manufacturing processes, and silicon component recycling. Sustainable manufacturing techniques, ecologically friendly materials, and recycling technologies are crucial for minimizing the environmental impact of solar cell production and end-of-life disposal. Rechargeable lithium-oxygen batteries and quinone, an organic battery that can store solar energy for several days, can assist to lower renewable energy costs. Hybrid solar cells, which mix successful SHJs and field-passivated IBCs, are becoming more common. Passivating connections in IBC cells improve efficiency beyond 26.7% while simplifying fabrication [46-49].

9. CONCLUSION

The silicon-based technique includes dopant-free c-Si solar cells with passivating connections. Heterojunction solar cells outperform homojunction c-Si solar cells in terms of efficiency, thermal stability, sustainability, and thermal budget. They can be employed with less expensive materials and more efficient designs. The device's performance was improved by merging a passivated SiO_2/TiO_x stack with a front SiO_2/MoO_x layer, whichresulted in an open-circuit voltage of 745 mV, a short-circuit current density of 40.32 mA/cm^2, an 81.6% fill factor, and a conversion efficiency of 24.52%. The ITO's fundamental properties include high transparency, a wide bandgap, high conductivity, low contact resistance, and appropriate carrier selectivity. A unique SHJ structure was developed by using MoOx and TiOx as hole- and electron-selective contacts, respectively, and then passivated using an ultrathin SiO_2 sheet. This approach is dopant-free, cost-effective, and has the potential to minimize manufacturing complexity. Silicon photovoltaic (PV) technology is now surpassing competitors due to its maturity and ability to make low-cost, high-efficiency solar cells.

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