EFFECTS OF ACTIVE LAYER THICKNESS ON THE PERFORMANCE OF POLYCRYSTALLINE p-β-$FeSi_2$(Al)/SI HETEROJUNCTION SOLAR CELLS*

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A Bag*, S Mallik and CK Maiti

VLSI Engineering Laboratory, Dept. of Electronics and ECE,
Indian Institute of Technology, Kharagpur
*E-mail: abag@iitkgp.ac.in

Abstract: *Active layer thickness dependence of photovoltaic (PV) properties of heterojunction solar cells fabricated using Al-alloyed polycrystalline p-type β-iron disilicide [p-β-$FeSi_2$(Al)]/ n-Si(100) is reported. Rapid thermal annealing (RTA) at 650°C was used for the formation of polycrystalline β phase of $FeSi_2$ which was confirmed by x-ray diffraction (XRD). Prior to deposition of active β-$FeSi_2$(Al) layer, a thin Al interlayer (~8 nm) was deposited, which got dissolved in underlying Si layer during RTA and formed a heavy Al-doped epitaxial-Si (p^+-Si) interfacial layer. Indium-tin-oxide (ITO) was used as top electrode. The current density-voltage and photo response characteristics of the solar cells with different active layer thicknesses (~ 50 to 135 nm) measured at room temperature are reported. Under air mass (AM) 1.5 illumination, the maximum conversion efficiency was found to be 2.18% with a short circuit current density of ~18.28 mA/cm^2 and open-circuit voltage of ~425 mV. The solar cells showed a series resistance of 213.6 Ω and a shunt resistance of 481.5 Ω which resulted in a fill factor of 28.05%.*

Keywords: *β-$FeSi_2$, Solar Cell, Efficiency, Open-Circuit Voltage, Short Circuit Current*

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1. INTRODUCTION

In the last few decades, ever increasing demand for alternative renewable energy sources have stimulated new scientific research in the field of inorganic photovoltaic (PV) devices especially attempts are being made to increase the efficiency. In general, the inorganic PV devices suffer from poor features such as poor quality of active layers and relatively rough interface between the film and the substrates. Although overcoming these difficulties increases the cell efficiency up to a certain level, introduction of an electron blocking antireflection layer over the active layer may improve PV cell properties further [1]. The active layer of a photovoltaic cell plays an important role to increase cell efficiency as the active layer contributes to photocurrent generation. Thus, it is essential to optimize the active layer thickness in solar cells. It is expected that for a particular active layer thickness the device parameters (J_{sc}, η etc.) shall reach the maximum and beyond that the device parameters will degrade due to increase in the recombination of photogenerated carriers in the active layer [2-3]. In this work, we study the effects of active layer thickness in ITO/p-β-$FeSi_2$(Al)/ p^+-Si/n-Si(100) Heterojunction solar cell performance.

2. EXPERIMENTAL

The photovoltaic devices fabricated comprise of a layer of p-β-$FeSi_2$ (Al)/p^+-Si/n-Si(100) sandwiched between transparent indium tin oxide (ITO) anode and metal cathode. Fig. 1 displays a

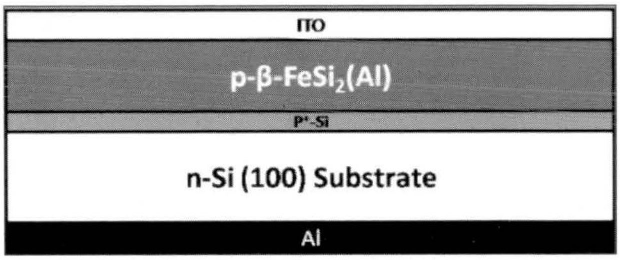

Fig 1. A Schematic of ITO/p-β-FeSi2(Al)/ p^+- Si/n-Si(100) Heterojunction Solar Cells

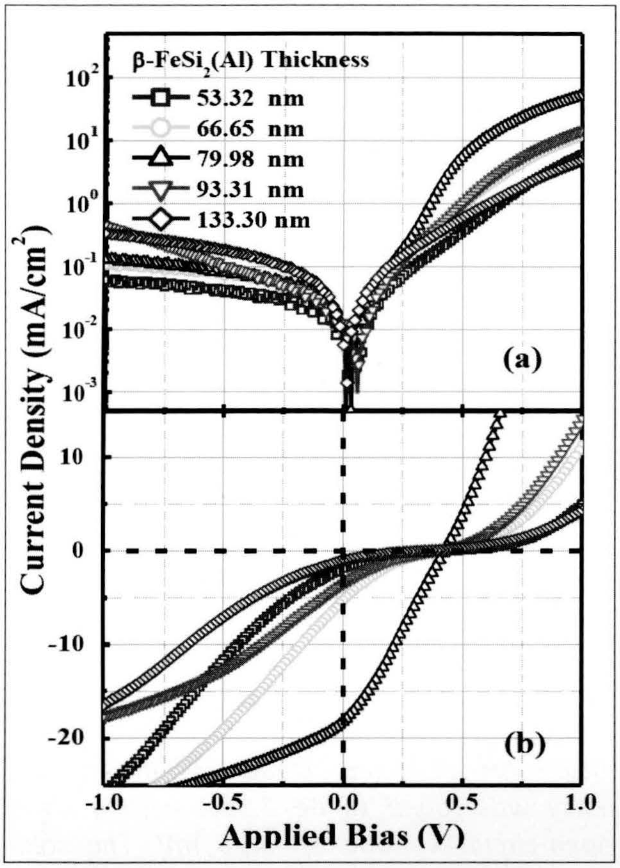

Fig 2. Current Density-Voltage Characteristics of ITO/p-β-FeSi$_2$(Al)/p$^+$-Si/n-Si Heterojunction Solar Cells (a) In Dark and (b) Under AM 1.5 Illumination (100 mW/cm^2) Simulated Solar Irradiation Condition

Table 1. Average Value of J_{sc}, V_{oc}, FF, and η of ITO/p-β-FeSi$_2$(Al)/p+-Si/n-Si(100) Heterojunction Solar Cells Under AM 1.5 Illumination (100 mW/ cm^2) Simulated Solar Irradiation Condition

Thickness (nm)	J_{sc} (mA/cm^2)	V_{oc} (mV)	FF (%)	η (%)
53.32	1.899	430	13.733	0.11
66.65	5.312	415	15.543	0.34
79.98	18.281	425	28.048	2.18
93.31	3.522	385	16.425	0.22
133.30	1.086	350	16.086	0.06

schematic of ITO/p-β-FeSi$_2$ (Al)/p$^+$-Si/n-Si(100) Heterojunction solar cell. All the solar cells were fabricated on Si substrates of n-type (100) orientation, with resistivity of ~ 5 Ω-cm. Before the device fabrication, substrates were cleaned using standard RCA process followed by etching in 1% dilute hydrofluoric acid (HF) solution to remove the native oxide layer. After cleaning, the substrates were immediately loaded in the magnetron sputtering chamber. The chamber was then evacuated to a base pressure of 4.0 ×10^{-6} mbar. Al was deposited at room temperature by co-sputtering of stoichiometric FeSi$_2$ target and pure Al target in Ar ambient and the thickness (~ 50 to 135 nm) of the FeSi$_2$(Al) films was controlled by changing the time of deposition. Prior to deposition of active β-FeSi$_2$(Al) layer, a thin Al interlayer (~ 8 nm) was deposited at room temperature by rf magnetron sputtering for all the devices. The samples were then subjected to RTA in N$_2$ ambient (with 1 lt/min flow rate) at temperature of 650°C with a ramp rate 10°C/sec and dwell time 2 min (ULVAC-RIKO, MILA-3000). During RTA, the Al interlayer got dissolved in the underlying Si layer and formed a heavily Aldoped epitaxial-Si (p$^+$-Si) interfacial layer. Finally, Heterojunction solar cells were fabricated by sputter deposition of ITO (~ 100 nm thick) as top electrode (area ~0.086 cm^2) and Al as Ohmic back electrode contact. Current density-voltage (*J-V*) characteristics of the devices in dark and under air mass (AM) 1.5 illumination (XES-151S) with a power density of 100 mW/cm^2 were measured using Agilent B1500A semiconductor device analyzer. The polycrystalline β-phase formation after RTA (≥650°C) was confirmed by x-ray diffraction (results not shown).

3. RESULTS AND DISCUSSION

A comparison of the *J-V* characteristics of ITO / p-β-FeSi$_2$(Al) / p$^+$-Si / n-Si(100) heterojunction solar cells (having different active layer thickness) under dark condition is shown in Fig. 2(a). The devices exhibit typical rectifying diode characteristics as expected from Heterojunction devices sandwiched between electrodes having different work function. Reverse bias current typically 3–4 orders of magnitude lower than the forward bias current at room temperature suggest that a p–n Heterojunction has been formed. The *J– V* characteristics under AM 1.5 (100 mW/cm^2) simulated solar irradiation conditions of the same devices are displayed in Fig. 2(b). A maximum ~2.18% power conversion efficiency is achieved for the cells having ~80 nm active β-FeSi$_2$(Al) layer. The key parameters of the devices for different active layer thickness are listed in Table 1. The fill factor (FF) and the power conversion efficiency (η) of the device was measured using the relations:

$$FF = \left(\frac{I_m \times V_m}{I_{sc} \times V_{oc}} \right) \qquad \text{.....................................(1)}$$

and $$\eta = \left(\frac{V_{oc} \times I_{sc} \times FF}{P_{in}} \right) \qquad \text{..........................(2)}$$

Where V_{oc} is the open-circuit voltage, I_{sc} is the short circuit current, FF is the fill factor, η is the power conversion efficiency and P_{in} is the incident light power density, I_m and V_m are the current and voltage at the maximum power point.

A plot of J_{sc} vs β-$FeSi_2$(Al) layer thickness for a series of Heterojunction solar cells illuminated with AM 1.5 light, having different active layer thicknesses is shown in Fig. 3(a). Change in cell efficiencies (η) with active layer thickness are shown in Fig. 3(b). Maximum J_{sc} and η values are found for devices with ~80 nm active layer thickness. Variation of η with active β-$FeSi_2$(Al) layer thickness confirms that active layer contributes to the photocurrent generation. At a thickness larger than 80 nm, values of these parameters decrease, which is due to the recombination of the photogenerated carriers in the β-$FeSi_2$(Al) layer. This implies that the diffusion length of the minority carriers of the β-$FeSi_2$(Al) layer is expected to be 80 nm.

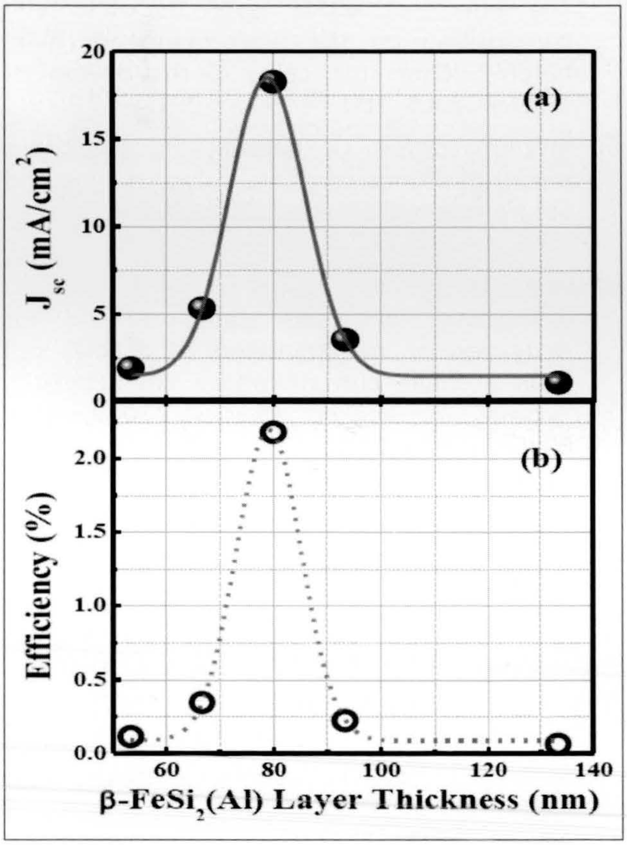

Fig 3. Dependence of (a) Short-Circuit Current Density (J_{sc}), and (b) Power Conversion Efficiency (η) Under AM 1.5 Illumination (100 mW/cm^2) Simulated Solar Irradiation on β-$FeSi_2$(Al) Layer Thickness in ITO/p-β-$FeSi_2$(Al)/p+-Si/n-Si(100) Heterojunction Solar Cells

The variation in the thickness of the active layer of the solar cell also affects the open circuit voltage (V_{oc}) value. Fig. 4(a) shows that V_{oc} varies nonlinearly with β- $FeSi_2$(Al) layer thicknesses. A maximum V_{oc} of ~ 430 mV was found for the device having ~ 53 nm active layer and is smaller compared to theoretically expected value. The reason for such a low V_{oc} may be due to the

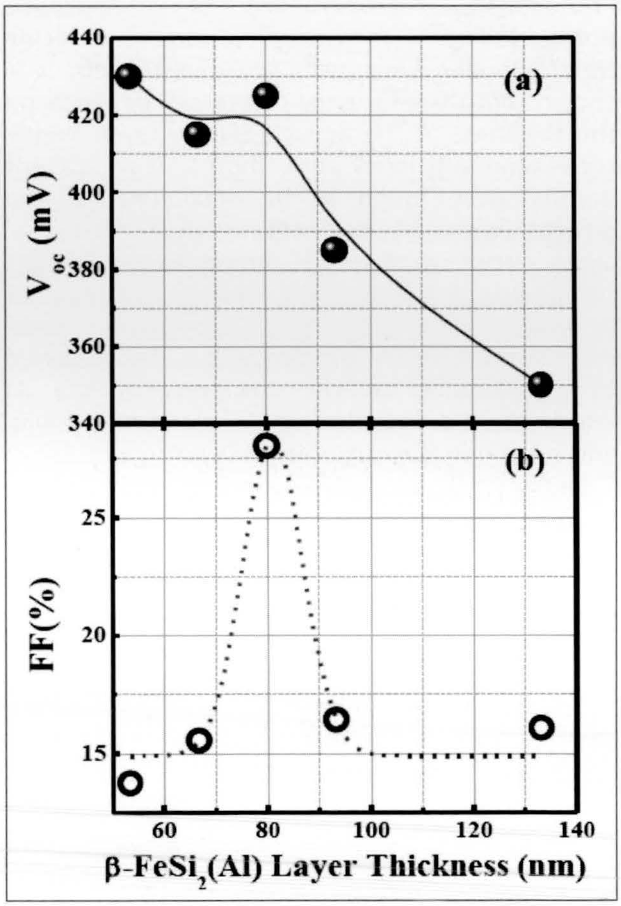

Fig 4. Dependence of (a) Open-Circuit Voltage (V_{oc}), and (b) Fill Factor (FF) Under AM 1.5 Illumination (100 mW/cm^2) Simulated Solar Irradiation on β-$FeSi_2$(Al) Layer Thickness in ITO/p-β-$FeSi_2$(Al)/p+-Si/n-Si(100) Heterojunction Solar Cells

diffusion of iron atoms in the depletion region. The diffused iron atoms also act as trap centers for the photogenerated carriers, which reduce not only the V_{oc} but also reduce the J_{sc} [2]. Fig. 4(b) shows the variation of fill factor where the device having maximum efficiency, shows maximum *FF* of 0.28. The small *FF* is attributed to the high series resistance of the solar cell [4-5]. From the slope of the I – V curve at $I = I_{sc}$ (V = 0), the shunt resistance (R_{sh}) has been extracted using the model proposed by Ishibashi et al. [6]. The device shows a shunt resistance of 481.5 Ω and a high series resistance (R_s) of 213.6 Ω which confirms the reason of small fill factor of the devices. Since the device efficiency is proportional to the product $J_{sc} \times V_{oc} \times FF$, most of the increase in the device efficiency results from the increased J_{sc} and *FF* rather than V_{oc} [7].

4. CONCLUSION

Photovoltaic properties of Al-alloyed polycrystalline p-type β-iron disilicide Heterojunction solar cells are investigated. It is shown that the efficiency of the cell depends on the thickness of the active $FeSi_2$(Al) layer. Power conversion efficiency and short circuit current density were found to be maximum for the devices with 80 nm active layer thickness. Open circuit voltage was found to be smaller compared to theoretically expected value due to iron diffusion in the depletion region. Further improvement in PV efficiency may be obtained by optimization of the thickness of the Al interlayer and introducing an electron-blocking anti-reflection layer over active layer.

5. Acknowledgement

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6. REFERENCES

1. Dalapati, GK; Liew, SL; Wong, ASW; Chai, Y; Chiam, SY; Chi, DZ: Photovoltaic characteristics of p-β-FeSi2(Al)/n-Si(100) heterojunction solar cells and the effects of interfacial engineering, 'Applied Physics Letter', 2011, 98, 013507-1-013507-3.
2. Shaban, M; Nakashima, K; Yokoyama, W; and Yoshitake, T: Photovoltaic Properties of n-type β-FeSi2/p-type Si Heterojunctions, 'Japanese Journal of Applied Physics', 2007, 46, L667-L669.
3. Shaban, M; Kondo, H; Nakashima, K; and Yoshitake, T: Electrical and photovoltaic properties of n – type Nanocrystalline-FeSi2/p-Type Si Heterojunctions Prepared by Facing-Targets Direct-Current Sputtering at Room Temperature, 'Japanese Journal of Applied Physics', 2008, 47, 5420-5422.
4. Moulé, AJ; Bonekamp, JB; Meerholz, K: The effect of active layer thickness and composition on the performance of bulk-heterojunction solar cells, 'Journal of Applied Physics', 2006, 100, 094503-1-094503-7.
5. Stutenbaeumer, U; Mesfin, B: Equivalent model of monocrystalline, polycrystalline and amorphous silicon solar, 'Renewable Energy', 1999, 18, 501-512.
6. Ishibashi, K; Kimura, Y; Niwano, M: An extensively valid and stable method for derivation of all parameters of a solar cell from a single current-voltage characteristic, 'Journal of Applied Physics', 2008, 103, 094507-1-094507-7.
7. Ryu, MS; Cha, HJ; Jang, J: Effects of thermal annealing of polymer: fullerene photovoltaic solar cells for high efficiency, 'Current Applied Physics', 2010, 10, S206–S209 ◘

- *"Don't take rest after your first victory because if you fail in second, more lips are waiting to say that your first victory was just luck."*
- *"All Birds find shelter during a rain. But Eagle avoids rain by flying above the Clouds."*
- *"Learning gives creativity Creativity leads to thinking Thinking provides knowledge Knowledge makes you great."*
- *"- If you fail, never give up because F.A.I.L. means "First Attempt In Learning" - End is not the end, if fact E.N.D. means "Effort Never Dies" - If you get No as an answer, remember N.O. means "Next Opportunity". So Let's be positive."*
- *"Man needs difficulties in life because they are necessary to enjoy the success."*
- *"Be active! Take on responsibility! Work for the things you believe in. If you do not, you are surrendering your fate to others."*

- Avul Pakir Jainulabdeen Abdul Kalam