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InGaN photocell significant efficiency enhancement on Si – an influence of interlayer physical properties

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SUMMARY

Nearly similar molar ratio of In and Ga in indium gallium nitride (InGaN) /Si photocells prefers to match InGaN conduction level energy to Si valance energy band for ohmic contact between two cells. At high temperature fabrication process, InGaN–Si interface shows highly defecting prone. Considering those tussles, InGaN-based/Si-based double-junction tandem solar cell was designed and fabricated. $In_{0.4}Ga_{0.6}N$ cell was fabricated on Si photocell by implementing $AlN/SiO_2/Si_3N_4$ interlayers. Interlayer influence on quantum efficiency of InGaN cell was studied under ideal irradiance AM1.5 solar spectrum at 300°K. Because of insertion of interlayers between InGaN and Si; the gradual efficiency enhancement with respect to the overlayer h-GaN (a = 3.183 nm) plane lattice was found to 8.3%, 5.9% and 5.1% for AlN (a = 3.11 nm), for SiO_2 (a = 4.9 nm) and for Si_3N_4 (a = 7.76 nm), respectively. AlN was found to be an excellent and SiO_2 as preferable interlayer compared with Si_3N_4. Coherence (in-plane lattice matching) of nano-interlayer appears to reduce photonic electro-migration hurdle between InGaN and Si; therefore, progressive enrichment of efficiency was realized.

KEY WORDS

InGaN photocell; in-plane lattice; interlayer; significant; efficiency

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1. INTRODUCTION

Linear carrier transport properties of Si with photon energy makes preferable materials for energy-related opto-electronic applications. The low material cost, advanced processing technology and reasonable conversion efficiency makes its attractive as photo energy material [1]. Efficiency is the major issue for energy conversion technologies. Because of the limitation of longer edge photonic conversion, Si-based photocell cell efficiency has certain limit. To improve the efficiency, active cell is preferable to implement on Si cell that can efficiently convert visible and longer edge photon [2]. Band gap matching constraint and photonic conversion turns difficulties to materialize multi-junctions for solar cell technology. Considering these issues, InGaN/Si double-junction photocells are found to be the best alternative [3]. InGaN variable band gap for adjustable In–Ga molar ratio could able to harvest different photon energies. It acts properly in higher irradiative environment even at high dislocation densities. Its compatible mobility with Si permits to match photo-current harvest as series cells. Direct transition wide-band edge InGaN large piezoelectric constant allows controlling surface recombination. Currently, InGaN/Si photocells with different techniques of modelling are found theoretically attractive [2–4]. In this design process, intense solar irradiance absorbed by the top InGaN cell seems to heat generation prone. Thermal conduction process is also well recognized by Si wafer [4]. InGaN also shows a better radiation resistance to avoid surface damage in terrestrial and space applications. For that reason, researchers are currently keen to study InGaN/Si energy technologies to optimize theoretical performance. It may be mentioned that the efficiency of photocell is highly dependent on interface, lattice matching, quantum properties and thermodynamic impact as well [2].

For commercial production purposes, complex fabrication process has certain limit was explained

theoretically elsewhere [3,4]. In realistic growth approach, because of large in-plane lattice mismatch between Si and InGaN, the defects affect the conversion efficiency. This problem also leads to phase separations and miscibility due to diffusion into the base Si materials. Thus, suitable interlayer or photonic absorption layer is preferred to ensure the matching between the two active cells. Thermal lattice mismatch was reported by *Krost et. al* in 2002 stating that cracking of GaN on Si usually occurs because of the large thermal mismatch of GaN with Si. The thermal stress can be reduced considerably by insertion of low-temperature AlN interlayer, introducing multiple AlGaN/GaN interlayers and growing on pre-patterned substrates and other means [5–7]. The traps at the InGaN/Si interface exhibit dissimilar properties at the SiO_2/Si interface photo-conversion phases. Currently, thermally grown SiO_2 used as a gate dielectric for Si-based metal oxide semiconductor (MOS) devices fabrication process, it possesses unique and well-established electronic properties. Even microstructure developed on SiO_2-based InGaN/Si has higher photo-conversion knack [8]. The given structure was found to increase current density in both top and bottom cells by reducing the recombination effects [9]. Besides, SiO_2 and Si_3N_4 are steadily transparent for visible band of solar spectrum. In addition to complementary metal oxide semiconductor (CMOS) technologies, SiO_2 is also well-known materials as a passivation for Si-based photo detector technology [10]. Si_3N_4 is one of the potential coating materials against degradation of detecting device even in highly irradiative environment and temperature. The lattice/interface properties, microstructure, thermodynamic and compositional features are crucially influenced InGaN photonic enhancement [9,11,12]. These growth strategies are also complex as compared with the AlN and SiO_2 interlayer-based matured technologies on Si for CMOS and GaN-based opto-electronic systems. These interlayers in-plane lattice are also nearly matched to h-GaN. Thus, the InGaN/Si photocells fabrication using AlN, SiO_2 and Si_3N_4 interlayers was performed in between Si and InGaN. Interlayers arrangement and it trends for consistency between InGaN photocell on Si and its photonic conversion and efficiency were investigated in this study.

2. EXPERIMENTAL METHODS

The structure as shown in Figure 1 was fabricated using wxAMPS software as developed by Prof. Rockett and Dr. Yiming Liu of University of Illinois Urbana-Champaign (UIUC) and Prof. Fonash of Pennsylvania State University. The solar cells were grown on an n-type silicon substrate. P-type layer was fabricated by boron doping for 0.5 µm, and subsequently, interlayer was formed as discussed below. For a given layer, subsequent doping profile was fixed using simulation software. Because permittivity, band gap, carrier affinity, carrier concentrations, mobility and doping are crucial factors to determine its diffusion length, the parameters were assigned for certain depth of doping. Three different

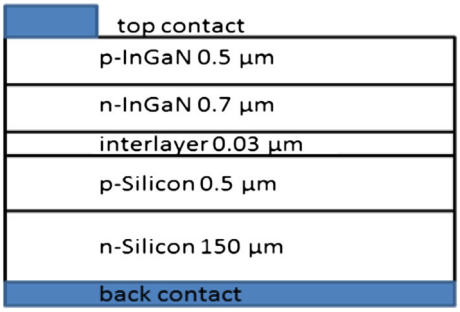

Figure 1. Structural setup of the solar cell.

experiments had been conducted: without interlayer, with AlN and SiO_2 interlayer and with Si_3N_4 interlayer.

Composition of $In_{0.4}Ga_{0.6}N$ with $E_g = 1.99$ eV was used in all three experiments as its conduction level to be matched with Si valance level. The output characteristics were studied under AM1.5 solar spectrum at 300°K. The doping concentrations used for each layer were $5 \times 10^{17}\,cm^{-3}$ (p-InGaN), $5 \times 10^{18}\,cm^{-3}$ (n-InGaN), $6 \times 10^{17}\ cm^{-3}$ (p-Si) and $6 \times 10^{17}\,cm^{-3}$ (n-Si). The calculations for electrical and optical properties for each layer were performed using the standard characteristics equations of a tandem solar cell [13–17]. InGaN is chemically an n-type semiconductor because of the presence of nitrogen in the composition. Mg was used to dope into the InGaN in order to make it p-type [18,19].

3. RESULT AND DISCUSSION

3.1. Effect of interlayers on quantum efficiency

Figure 2 presents the internal quantum efficiency (IQE) of the four conducted experiments. It is found that the insertion of AlN interlayer has better IQE as compared with SiO_2, Si_3N_4 and without interlayer. The difference in the IQE can be seen at high-energy spectrum. The difference is probably due to the recombination at the surface of the cells. When carriers are generated near the surface and blue light for example is absorbed very close to the surface, quantum efficiency at high-energy edge,

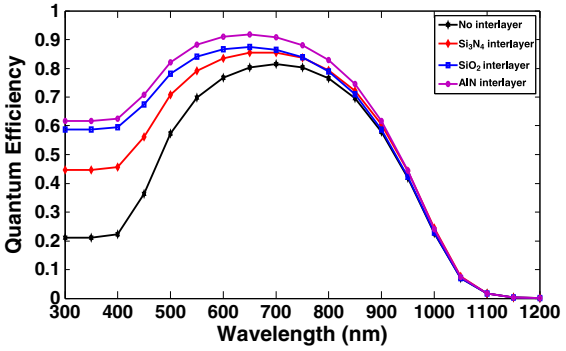

Figure 2. Quantum efficiency for different interlayers.

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which absorbed very close to the surface, will be affected by the front surface recombination.

Presence of interlayer leads to a higher generation rate, and it is more significant at the wavelength $\lambda < 600$ nm. The internal quantum efficiency (IQE) is also affected by reflection and diffusion length. When $AlN/SiO_2/Si_3N_4$ is introduced between the Si and InGaN, the absorption was found to improve further, and it enhanced the diffusion length. The highest quantum efficiency was recorded at the wavelength of 650–700 nm. The surface recombination and diffusion length in the bottom cell tends to shift the peak to lower energy edge. The properties of AlN, SiO_2 and Si_3N_4 itself differs from each other. At 400 nm, the refractive indexes of AIN, SiO2 and Si_3N_4 are 2.2, 1.57 and 2.05, respectively. SiO_2 permits selective diffusions into silicon wafer. Besides, the difference in band gap, Si (1.1 eV), AlN (6.2 eV), SiO_2 (9 eV) and Si_3N_4 (5 eV), much affected the overall response of the solar photovoltaic (SPV). Because of combination of p-type and n-type semiconductor, electron from n-region near p–n junction is likely to diffuse into the p-region. As these electrons diffuse, positively charged ions (donors) are left in the n-region.

3.2. Effect of interlayers on current density

On the contrary, holes from the p-type region near the p–n junction start to diffuse into the n-region. As we analysed the current density behaviour based on the structure in Figure 1, the bottom cell (Si) was arranged with InGaN layer determining the current density with the presence/absence of interlayer.

It can be seen that the recombination occurs in the bottom cell affecting its overall performance. In-plane lattice mismatches between Si and InGaN are found very high. Direct growth of InGaN layer on Si (without buffer or interlayer) offers in-plane mismatch from 7.81% to 17%; depending on the content of indium and gallium [20]. As a result, the series configuration between two cells and better ohmic contact are problematic issues [21]. Direct growth of InGaN on Si results in the InGaN diffused into the bottom Si cell and hampers the growth cell quality. Carrier recombination at localized states arises because of this lattice mismatch, which leads to lower J_{sc}. Moreover, cracking of GaN on Si usually occurs because of the large thermal mismatch between GaN and Si [6,7].

Figure 4 shows the pattern of current density with Si3N4 interlayer is almost the same without interlayer, but it gives lower recombination rate, hence produce greater current density as compared with result shown in Figure 4. At 0.08 –0.1 µm, it can be observed that J_n and J_p stay constant at a deeper position from the bottom cell. The final alignment and function of InGaN cell is expected to be strongly dependent on the starting substrate type, orientation, substrate pre-treatment, type of buffer or interlayer and growth conditions. The recombination rate as shown in Figures 3 and 4 is not desired. Si_3N_4 as an interlayer is not matched with carrier density level, and that is the reason of prolonged static stage at the interface.

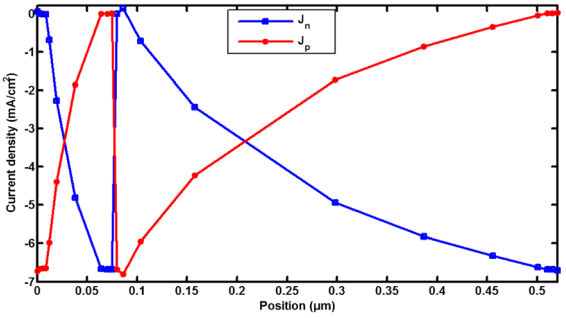

Figure 3. Current density without interlayer.

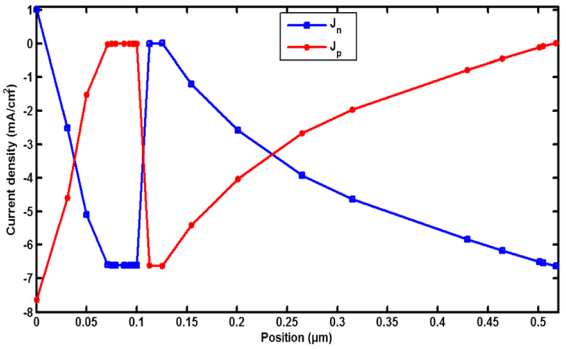

Figure 4. Current density for Si_3N_4 interlayer.

Thus, Si_3N_4 not seems to be suitable to use as an interlayer between Si and InGaN photocell.

Figure 5 shows SiO_2 interlayer-based current density at the bottom cell. SiO_2 was found an ideal in this case. It is found to be properly matched with the interface carrier density. Unlike Si_3N_4, cells with SiO_2 as its interlayer give less recombination rate. The type and amount of recombination rate in the cell are very much affected the minority carrier lifetime and the diffusion length. The recombination rate depends on the defects present in the material. Defects may refer to the doping concentration, dopants or proven by Si CMOS technology; SiO_2 interface is better than without or even Si_3N_4 interface in aspect of better passivation. Its dangling bond formed microstructure preferring to enhance near ultraviolet properties of the material itself. Less interface defects are shown by SiO_2, and this is proven by Si-fabrication technology, which uses SiO_2 as gate interface. Even though both SiO_2 and Si_3N_4 are just as transparent for high-energy edge of solar spectrum, but the interface traps at the nitride/Si interface exhibit contradictory properties from those at the SiO_2/Si interface.

As shown in Figure 6, InGaN/AlN/Si structure was found higher current density compared with SiO_2 and Si_3N_4 interlayers. It can be said that the Si junction beneath the InGaN layer has efficiently converts photons into photo-current and works well as a solar photovoltaic cell with the presence of AlN as interlayer. When a thin AlN interlayer was introduced between InGaN and Si, electron

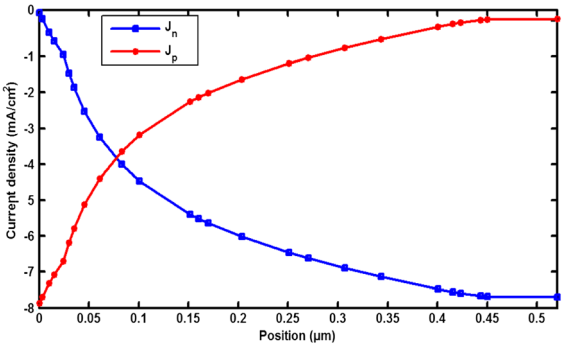

Figure 5. Current density for SiO_2 interlayer.

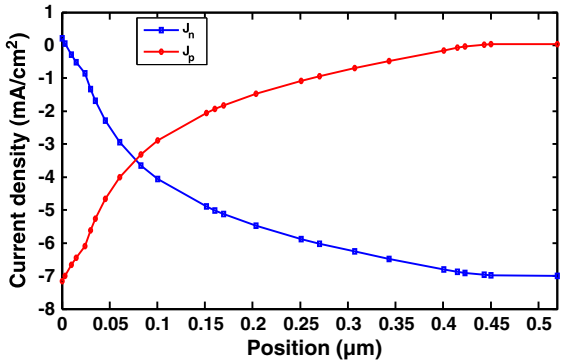

Figure 6. Current density for AlN interlayer.

mobility at high electron sheet densities was found to increase. Growth of InGaN on AlN interlayer indicates a better matching so that higher absorption of photons is highly reasonable.

In the case of AlN, it was found better than SiO_2 because AlN has a smaller lattice mismatch with the InGaN layer also made better ohmic contact [20]. So, AlN is expected to show less stacking fault and indirectly promotes better performance on Si-based double-junction tandem solar cell. Besides, a thin AlN interlayer is able to boost electron mobility at high electron sheet densities and indirectly improves the device performance. The thickness of the interlayer also affects the overall performance of the solar cell as this interlayer seems to be insulating. We also need to consider the diffusion of the interlayer into Si substrate during fabrication process. Too thick AlN will obstruct the flow of current from top cell to the bottom cell. Thus, 30 nm is found to be an ideal thickness for InGaN/Si solar cell interlayer.

The characteristics shown in Table I are important to determine the performance of SPV-based on different interlayers. One can see that the SiO_2 offers a higher V_{oc}, J_{sc}, fill factor and efficiency compared with Si_3N_4. The addition of SiO_2/Si_3N_4 nano-interlayer in Si–InGaN improves the J_{sc} by 5.79% and 2.21%, respectively, compared with the absence of interlayer. The valid reason of it is found form the interruption at the interface as discussed below.

3.3. Effect of interlayer thickness on theoretical efficiency

From Figure 7, it was realized that the thickness of the interlayer also impact on the efficiency of the InGaN/Si. Because Si and InGaN lattice mismatch is higher, therefore, a thin layer of AlN is introduced to design InGaN/Si tandem cell. To evaluate its effect of efficiency, different thickness AlN and SiO_2 interlayers were deposited in this process with optimized 45% In content. From the result, it appears that thick interlayer may limit the photonic electro-migration from the top InGaN–Si cell, and very thin may incapable to avoid defects and Si diffusion problems. Therefore, the variance of efficiency of SiO_2 and AlN interlayers was realized. In this analysis, optimum thickness was found about 30 and 40 nm for SiO_2 and AlN interlayer, respectively.

In Figure 8, it was found that the InGaN photonic conversion is related to in-plane lattice match with interlayers as coherence concept. Using GaN in-plane lattice as reference with $a = 3.185\ A^o$, the AlN in-plane lattice, $a = 3.11\ A^o$, followed by SiO_2, $a = 4.9\ A^o$, and Si_3N_4, $a = 7.76\ A^o$, AlN and GaN only have about 2.4% in-plane lattice mismatches seem to allow InGaN growth iso-electronically as a result improves the conversion efficiency. On the other hand, SiO_2 and GaN show in-plane lattice mismatch 35% whereas Si_3N_4 and GaN have a difference of 59% in terms of in-plane lattice mismatch. Si_3N_4 has shown a big difference of in-plane lattice mismatch. Both AlN and Si_3N_4 have high dielectric constant 8.5 and 7.5, respectively, whereas Si_3N_4 shows lower efficiency than SiO_2 for $k = 3.9$. The efficiency of these cells was not found to be influenced by the coulomb field/electrostatic properties.

The efficiency of InGaN cell growth on AlN and SiO_2 interlayers was found 8.38% and 5.85%, respectively. In our precise junction study, the improvement of current density was found by using AlN and SiO_2 interlayers.

Table I. Output characteristics of the InGaN photocell based on different interlayer.

	No interlayer	AlN interlayer	SiO_2 interlayer	Si_3N_4 interlayer
V_{oc} (V)	1.5886	1.8185	1.6371	1.5912
J_{sc} (mA/cm^2)	6.4706	6.9130	6.8454	6.6136
FF (%)	48.439	66.6923	52.2130	48.8326
Efficiency (%)	4.9791	8.3840	5.8513	5.1390

AlN interlayer with proper molar ratio was found effective to series resistance and ohmic contact as referred elsewhere [21]. In case of SiO_2, oxide-faced Si (SiO_x–Si bonds) is dominant to exciton efficient microstructure formation and relatively less mismatch [22–23]; therefore, it could improve the efficiency. The efficiency improvement of nearly 3% was found by Dahal R. *et al.* [11] and 5.95% by Bor Wen Liou [12] applying multi quantum well (MQW) structure on InGaN/Si was reported in the literature. Nearly matched interlayers in-plane lattice with appropriate molar ratio ($In_{0.45}Ga_{0.55}N$) and proper thickness of interlayer (shown in Figure 7) also appear to improve the theoretical efficiency. Thus, the in-plane lattice properties could be influenced higher photonic conversion, and as a result, efficiency improves significantly. This result was also found very similar (27–30%) as mentioned in our literature previously [3,4].

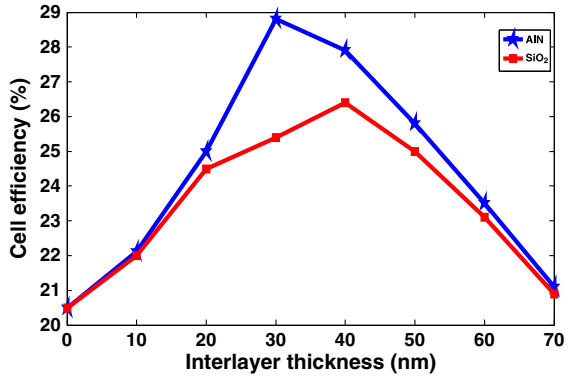

Figure 7. AlN and SiO_2 thickness dependent theoretical efficiency evaluation.

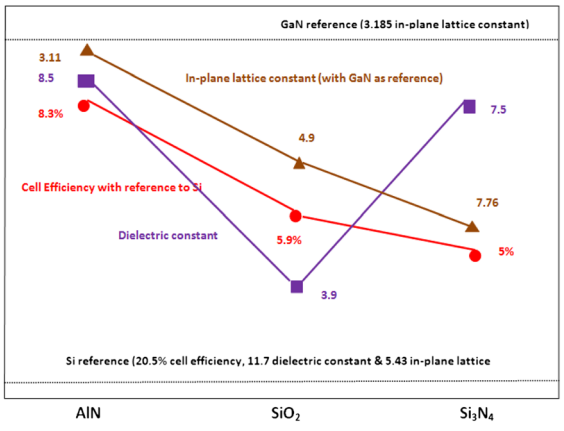

Figure 8. Efficiency (relative) plot with respect to dielectric and in-plane lattice constant.

4. CONCLUSION

The AlN, SiO_2 and Si_3N_4 interlayers in InGaN/Si double-junction photocell fabrication process and its features were investigated. From the comparative efficiency assessment with respect to the base Si cell, it was found that the interlayer rather acts to stimulate over layer photonic conversion with Si base cell without execution of its own electrostatic possessions. From precise junction study, it was observed that InGaN is not suited well for direct or even Si_3N_4 interlayer-based growth on silicon wafer. AlN was found to be an excellent, and SiO_2 exhibited to be preferable interlayer (structure) for Si-based InGaN/Si double-junction tandem photocell as compared with Si_3N_4 interlayer. It appears that the suitable interlayer and its thickness are highly effective for photonic possession to minimize electro-migration at the surface, and thus, it promotes quantum and overall efficiency as well. Subsequently, proper interlayer could be referred as an in-plane lattice functional consistent to the overgrowth active layer for InGaN/Si double-junction photocells.

APPENDIX :

=> => CRITICAL REVISIONS ARE REQUESTED AS FOLLOWS:

- Increasing the number of authors at this stage is treated as completely unethical. You must stick to original authorship.

Response: The authorship the manuscript has been maintained as suggested

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- English needs a proper and professional editing.

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- Omit Figure 2.

Response: Figure 2 has been omitted

- Submit the revised paper as single file with all illustrations at the end in a highlighted manner for all revisions.

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- Submit an itemized response sheet to list all points and responses.

The Response sheet has been attached herewith

- State the specific objectives in detail and explain how this paper is different from others.

Response: The previous studies had done for theoretically [3,4] and also actual [11,12] efficiency assessment. Those studies both theoretical and actual efficiency assessment were introduced complex internal structures and commercial purposes those structure are bit difficulties to materialize. So in photonic aspect more familiar structure with optimized InGaN molar ratio we have introduced to fabricate InGaN photocell on Si. It could be more effective.

- Conduct a performance assessment and present the efficiency graph.

The efficiency of InGaN cell growth on AlN and SiO_2 interlayers was found 8.38% and 5.85%, respectively. In our precise junction study, the improvement of current density was found by using AlN and SiO_2 interlayers. AlN interlayer with proper molar ratio was found effective to series resistance and ohmic contact as referred elsewhere [21]. In case of SiO_2, oxide-faced Si (SiO_x–Si bonds) is dominant to exciton efficient microstructure formation and relatively less mismatch [22,23], therefore it could improve the efficiency. The efficiency improvement of nearly 3% was found by *Dahal R et al.* [11] and 5.95% by *Bor Wen Liou* [12] applying MQW structure on InGaN/Si was reported in the literature. Nearly matched interlayers in-plane lattice with appropriate molar ratio ($In_{0.45}Ga_{0.55}N$) and proper thickness of interlayer (shown in Figure 7) also appears to improve the theoretical efficiency. Thus, the in-plane lattice properties could be influenced higher photonic conversion as a result efficiency improves significantly. This result was also found very similar (27-30)% as mentioned in our literature previously [3,4].

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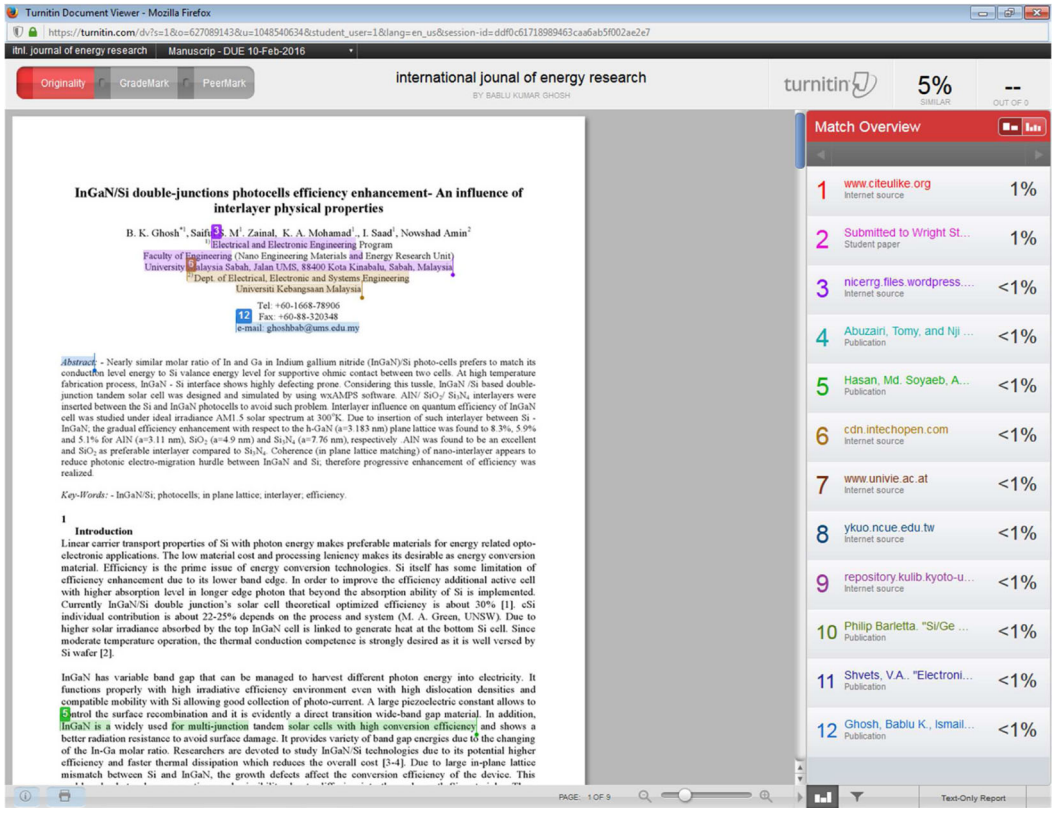

InGaN/Si double-junctions photocells efficiency enhancement- An influence of interlayer physical properties

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Abstract - Nearly similar molar ratio of In and Ga in Indium gallium nitride (InGaN)/Si photo-cells prefers to match its conduction level energy to Si valance energy level for supportive ohmic contact between two cells. At high temperature fabrication process, InGaN - Si interface shows highly defecting prone. Considering this tussle, InGaN /Si based double-junction tandem solar cell was designed and simulated by using wxAMPS software. AlN/ SiO_2/ Si_3N_4 interlayers were inserted between the Si and InGaN photocells to avoid such problem. Interlayer influence on quantum efficiency of InGaN cell was studied under ideal irradiance AM1.5 solar spectrum at 300°K. Due to insertion of such interlayer between Si - InGaN; the gradual efficiency enhancement with respect to the h-GaN (a=3.183 nm) plane lattice was found to 8.3%, 5.9% and 5.1% for AlN (a=3.11 nm), SiO_2 (a=4.9 nm) and Si_3N_4 (a=7.76 nm), respectively. AlN was found to be an excellent and SiO_2 as preferable interlayer compared to Si_3N_4. Coherence (in plane lattice matching) of nano-interlayer appears to reduce photonic electro-migration hurdle between InGaN and Si; therefore progressive enhancement of efficiency was realized.

Key-Words: - InGaN/Si; photocells; in plane lattice; interlayer; efficiency.

1 Introduction

Linear carrier transport properties of Si with photon energy makes preferable materials for energy related opto-electronic applications. The low material cost and processing leniency makes its desirable as energy conversion material. Efficiency is the prime issue of energy conversion technologies. Si itself has some limitation of efficiency enhancement due to its lower band edge. In order to improve the efficiency additional active cell with higher absorption level in longer edge photon that beyond the absorption ability of Si is implemented. Currently InGaN/Si double junction's solar cell theoretical optimized efficiency is about 30% [1]. eSi individual contribution is about 22-25% depends on the process and system (M. A. Green, UNSW). Due to higher solar irradiance absorbed by the top InGaN cell is linked to generate heat at the bottom Si cell. Since moderate temperature operation, the thermal conduction competence is strongly desired as it is well versed by Si wafer [2].

InGaN has variable band gap that can be managed to harvest different photon energy into electricity. It functions properly with high irradiative efficiency environment even with high dislocation densities and compatible mobility with Si allowing good collection of photo-current. A large piezoelectric constant allows to control the surface recombination and it is evidently a direct transition wide-band gap material. In addition, InGaN is a widely used for multi-junction tandem solar cells with high conversion efficiency and shows a better radiation resistance to avoid surface damage. It provides variety of band gap energies due to the changing of the In-Ga molar ratio. Researchers are devoted to study InGaN/Si technologies due to its potential higher efficiency and faster thermal dissipation which reduces the overall cost [3-4]. Due to large in-plane lattice mismatch between Si and InGaN, the growth defects affect the conversion efficiency of the device. This

Some arrangement of reference have also made as follows to complement the reviewer comment: state the specific objectives in detail and explain how this paper is different from others.

The following references are omitted and introduced new references there for effective follow of content in introduction part.

3. Chrobák P, Zálešák M, Opluštil M, Sehnálek S, Vincenec J. Photovoltaics panels–Economic return based on the real effectiveness. *WSEAS Transactions on Environment and Development.* 2014.**10**:320-328

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- New reference has been introduced for better comparison

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