Investigation of Harmonized Layers (HLs) Impact on Quantum Efficiency for N or P Type Emitter of cSi Solar Detector

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Abstract: - It is expected that passivation layer impact prominently on efficiency of solar detector and surface charges apparently varied on emitter types as well as passivation. In connection with the higher energy edge absorption of solar spectrum and photo current generation, compatible (SiO_2+Si_3N_4) harmonized layers (HLs) are introduced for surface effect mitigation and better photon management. Emitter junction effect on responsivity and/or external quantum efficiency (EQE) are also studied for PN, NP, P^+N, N^+P, P^+iN and N^+iP detectors with and without optimized coating/HLs even compared with the bare detectors. With optimized HLs, very intense solar band response and EQE are realized for both emitters and its junction characteristics are also found to be varied. These influences on photo response are found specifically. For P emitter EQE is found relatively better at the higher energy edge of solar spectrum while for N type emitter, improvement of EQE at near IR is precisely observed. Due to insertion of harmonized (passivation and anti-reflection; SiO_2+Si_3N_4) layers (HLs), surface charges effect for N or P emitter of Si detectors are not profoundly realized.

Key-Words: - Harmonized layers, different passivation layers, P and N emitters, quantum efficiency, active layer engineering

1 Introduction

Photo detector (PD) has massive claims in the field of energy, industry and future sensor applications [1-5]. For solar energy harvesting, the optical loss (reflection) and electrical loss due to surface recombination and active layer dependence are prominent. Out of two, electrical loss itself is expected to have a severe impact on improvement of its efficiency or its further technological development. The external quantum efficiency is determined by the antireflection coating while core efficiency is confirmed by its electrical characteristics and surface effect as well as junction parameters effects. Emitter layer with the passivation plus anti reflection layers as a whole may contribute jointly to make variation of its photo response or efficiency.

P type emitter favors to enhance underneath N layer with higher diffusion length of photo generated carrier and lower defect during processing (bulk) [6-7]. Thus it may enhance the shunt resistance. But contact with metal in the emitter fever to made junction rather than ohmic contact. In divergent, N type emitter favor to make ohmic contact with metal and ultimate reduces resistive drop whereas bulk P type Si wafer processing technology is well established. Even in solar cell technology, the dilemma of N and P emitter is now scope of potential research and it is caring out by several researchers all over the world [6-10]. The main issue is how surface parameters effect on performance of solar cell at maximum power point. To mitigate the surface effects, proper selection of passivation layer is important. Then proper selection of anti-reflecting layer to enhance solar energy absorption is highly desired.

As a passivation layer, it is now newly introduced Al_2O_3 [11-12]. But it is hexagonal structure and it may not match properly with underneath Si cubic structure. So there is a possibility of severe stacking fault or defects. As a cubic structure, SiO_2 is widely established passivation materials for Si based VLSI technology. The Si_3N_4 is favor to absorb high irradiance since its refractive index is higher than SiO_2. The harmonized coating as we mentioned previously seems to be effective due to nearly match between cSi and air [13]. To cope up with the higher energy edge absorption of solar spectrum in Si, compatible SiO_2/ (SiO_2+Si_3N_4) double or harmonized coating layers (HLs) are introduced for surface effect mitigation and photon management. Emitter junction effect on responsivity and external quantum efficiency (EQE) are also studied for PN, NP, P^+N, N^+P, P^+iN and N^+iP detectors with and without optimized coating even compared to bare detectors for SiO_2 layer impact analysis.

2 Experimental Procedure

N and P-type c-Si wafer based PN, NP, P^+N, N^+P, P^+iN and N^+iP detectors are fabricated based on TCAD software. Using different thickness SiO_2/SiO_2+Si_3N_4 coating (window) layers and responsivity analysis optimized double layer coating is designed for further simulation and analysis for the whole solar spectrum response. Besides that, effect with and without harmonized layers (HLs) and even non-optimized HLs layers on responsivity and EQE are also done. With optimized concentration of body doping and similar doping concentration for PN, NP, P^+N, N^+P, P^+iN and N^+iP detectors are analyzed in the simulation process. The effect of doping concentration on the response is also done by varying the doping and obtaining the optimum doping profile. In addition, analysis of PN, P^+N and P^+iN PD is also done by studying the junction capacitance, junction depth and body doping profile. In case of photo-conductive mode of operation study, 0.2 V is applied across the detector. Designed junction/window area is 1 mm^2, irradiation is 1W/cm^2 and responsivity unit is considered as A/W.

3 Result and Discussion

A photo detector works by converting photons that hit the junction to form voltage or current. Photo absorption or e-h pair generation within one diffusion length to the depletion edge is effective for the efficient conversion of photon into photocurrent. Fig. 1 shows the photo detector photocurrent density with different line edge of solar spectrum with and without passivation layers of different materials for both emitters.

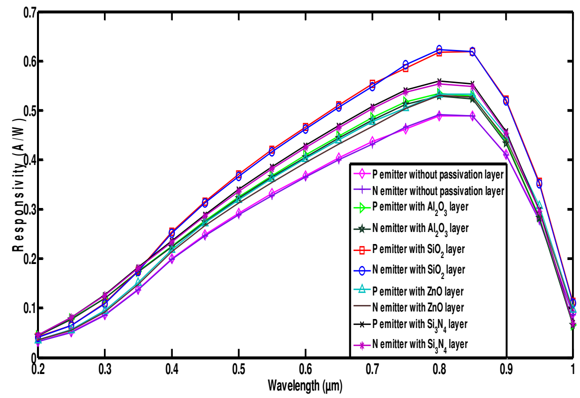

Fig. 1: Photodiode response with different passivation layer

By using Si_3N_4 passivation layer, current density or quantum efficiency is found higher in lower UV edge and vissible band. SiO_2 and aluminum oxide are also found to be effective but considering passivation effect with Si; Si_3N_4 and SiO_2 are found promising for HLs. Due to insertion of Si_3N_4 antireflection layer, the enhancement of photoelectron generation for whole visible band of the solar spectrum is precisely observed as compared to SiO_2 layer. As compared to single passivation layer, an application of Si_3N_4 layer improves the responsivity in high irradiance region [14]. Base on Snell's law, the effective incidence angle tends to move towards normalization (90 degree) when SiO_2 and an additional Si_3N_4 layer are inserted on SiO_2 layer on cSi. Besides that, trapped UV photon inside the high-refractive-index (n= 2.05) and permissible band gap (~5eV), Si_3N_4 materials bounded by air (n=1) and SiO_2 (n=1.57). So Si_3N_4 and SiO_2 refractive index geometric mean, $n1=\sqrt{(1.57*2.05)} = \sim 1.8$. It seems to be harmonized with the air to cSi interface. Thus due to HLs effect, enhancement of photon normalize and enhance absorption appears to be occurred in the active region of Si detector and generate photocurrent accordingly. Thus enhancement of photo response is clearly observed in our study.

The combination of SiO_2 and Si_3N_4 as HLs for the enhancement of solar energy harvesting of the whole solar spectrum is well intended. The significant difference in responsivity is found for introduction of different passivation layers with respect to the bare Si detector. So multi photon process for high energy edge or photon energy down conversion and low energy edge photon energy up conversion for photon management may responsible for the enhancement photo response as found such trend elsewhere [14-18].

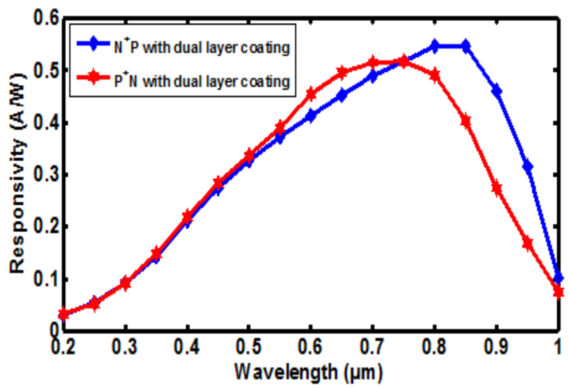

Fig. 2: P$^+$N and N$^+$P photodiode with SiO_2+Si_3N_4 coatings

To investigate the emitter and passivation layers impact on photon management, the photons absorption or photo current generation trend is also investigated in the study. Fig. 2 shows the optimised thickness dual coating or HLs SiO_2 (40 nm passivation) + Si_3N_4 (20 nm air interface, antireflection) on P$^+$N and N$^+$P Si detector. It appears that both P$^+$N and N$^+$P detectors have nearly similar responsivity at the higher energy edge but lower energy edge the variation of responsivity is not due to the HLs effect, it may be due to differences in active layer depth for P and N doping [18]. The effective absorption of solar irradiance at lower energy edge is dominated by deeper active layer that appears to be supported by N$^+$P device as a result increases the responsivity as compared by P$^+$N. But overall photo response is precisely observed higher as it published by other researches elsewhere [15-16].

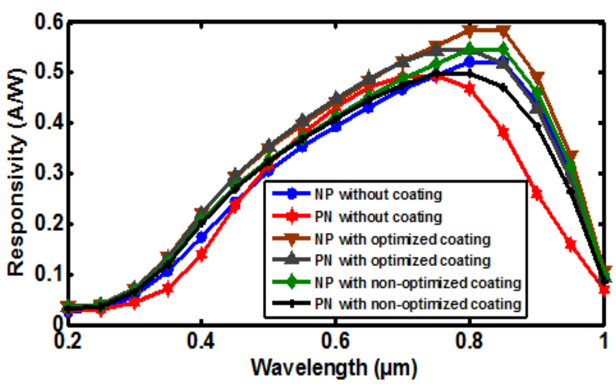

Fig. 3: PN/ NP PD with different doping at optimized /non- optimized HLs even without coating

The effects of emitters for different doping profile and with or without coating even optimized and non-optimized coated detector are also investigated in the study. From Fig. 3, it is realized that optimized coatings/ HLs impact for NP/PN detector. The responsivity is found the highest at ~ 850 nm for solar spectrum for NP detector. It is even higher than N$^+$P detector. From NP (Fig. 3) and N$^+$P (Fig. 2) detectors with optimized HLs, it appears that lower energy edge photons of solar spectrum are absorbed relatively at the depth of the junction appears to be response well by the active layer of NP detector as compared to the N$^+$P detector (usually shallow active as compared to NP). So enhancement of photo response is precisely found for NP is not due to HLs effect. The responsivity of NP detector is relatively higher as compared to PN detector. Both PN and NP detector without HLs is found the lowest response over the whole solar spectrum and it is due to the passivation and antireflection layer (HLs) effect. But differences between N and P type emitter without HLs are related to the disparity of uniformity between N and P emitters throughout the active layer (usually uniform for N emitter)[18].

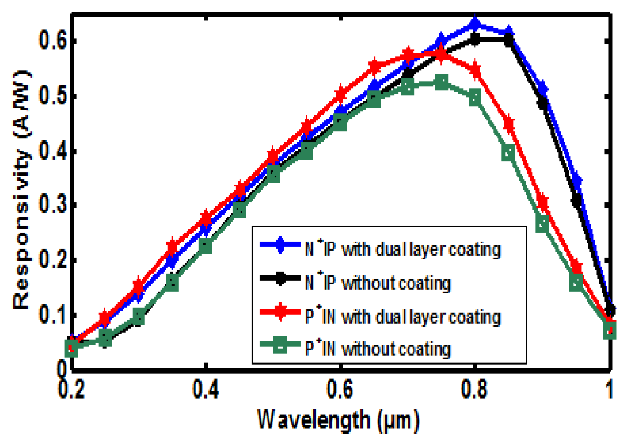

Fig. 4: P$^+$iN/ N$^+$iP photodiodes with and without coatings

Whether photon management by employing the optimized HLs or the active layer depth variation (depletion edge engineering) is more prominent for quantum efficiency or responsivity assessment are also investigated in the paper. The effects of active layer or depletion edge and HLs on photo response are shown in Fig. 4. From the result, it appears that the increment of depletion edge for insertion of addition intrinsic layer is increased the responsivity further at the low energy edge. N$^+$iP detector whether HLs or not is found the highest response. But due to optimized HLs, photo response is found better all over the spectrum as a part of photon management. P^+iN detector without HLs is found higher response compared to PN detector without coating as shown in Fig. 3. From this comparison it appears that the depletion width engineering is most important for quantum efficiency enhancement; where HLs or photon management supports it to enrich the response further. For the insertion of intrinsic layer in the PN/NP detector, the increment of response is found to increase sharply for particular band of solar spectrum in the visible range. So it might be very effective for faster response or to be improved bandwidth in case of optical communication or pulse response. The photo response of P^+iN, P^+N and PN of Si PD are observed based on different doping profiles. For optimized HLs, the variation of photo response between two emitters is due to differences of contact resistance effect and may be due to different depth of depletion edge [17].

To investigate the same emitter with different active layer depth for the variation of doping profile is also investigated and it is discussed below.

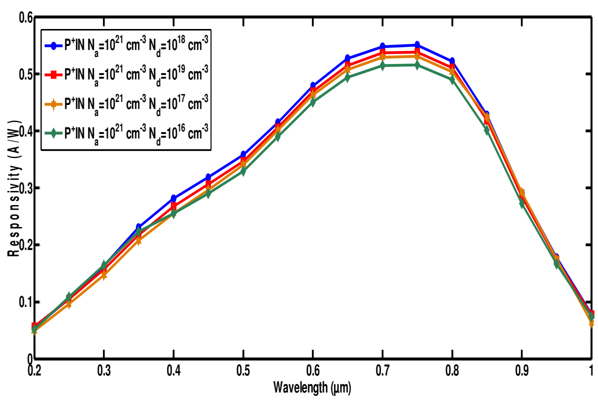

Fig. 5- P^+iN PD with different doping profiles

The response of the P^+IN device with different doping profiles is shown in Fig. 5. The best response is obtained with doping concentration $N_a=10^{21}$ cm^{-3} and $N_d=10^{18}$ cm^{-3}. The response at the UV range is linear these four doping profiles. Doping profile of $N_a=10^{21}$ cm^{-3} and $N_d=10^{16}$ cm^{-3} (green) shows a promising response from 200-400 nm but depreciate at higher wavelength. By adding the i-layer (intrinsic), impact can be seen to the overall response of the PD. More depth of active layer with the presence of this i-layer improves the overall response. In addition, more optically generated electron-hole pairs are allowed to generate and eventually increases the photo response since the P^+iN has a larger active region.

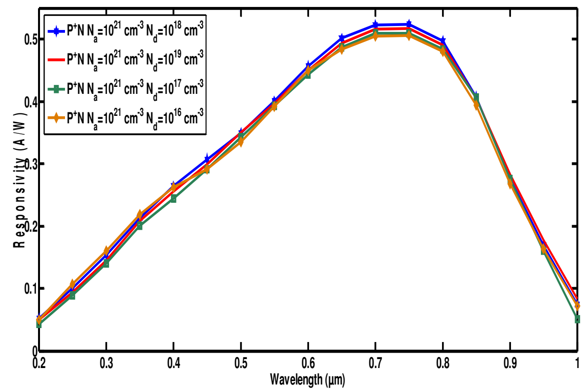

Fig. 6: P^+N PD with different doping profile

Fig. 6 shows the P^+N device response. The best response is shown with the doping profile of $N_a=10^{21}$ cm^{-3} and $N_d=10^{16}$ cm^{-3}. For overall response from 200 nm to 1000 nm, the best response is obtained with doping concentration of $N_a=10^{21}$ cm^{-3} and $N_d=10^{18}$ cm^{-3}. Absence of i-layer makes the depletion region is smaller and higher junction capacitance compared to P^+iN PD. The result of the absorption of photons in P^+N is the creation of electron-hole pairs in the depletion region which gives a lower responsivity compared to P^+iN. From the observation of Fig. 5 and 6, the linearity of P^+N and P^+iN is found almost similar.

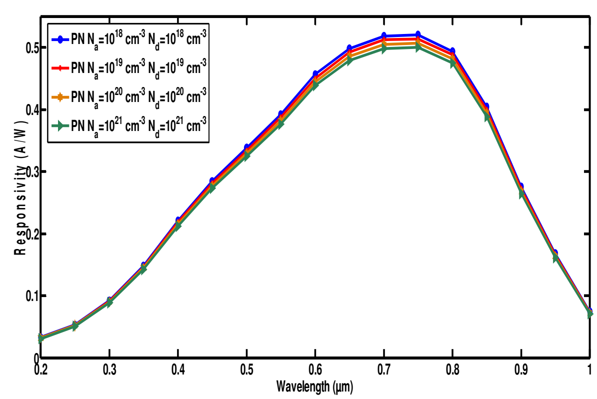

Fig. 7: PN PD with different doping profiles

Fig. 7 shows the response of the PN Si UV photo detector with different doping profile. It can be observed that the response is lower and not as linear P^+N and P^+iN PD especially in the UV solar spectrum. The same doping concentration on both junction P and N gives a major cause on the non-linearity, not only at lower wavelength but can be seen at overall performance. Higher junction capacitance in PN PD has a higher junction capacitance this results a poorer response and linearity of the device. The non-ionizing energy loss of the Si UV shown in Fig. 7 are believed to raise deep-level defect-states changing the electrical properties of the device active material, on setting relaxation-like and semi-insulating behaviour due to lattice disruption [18].

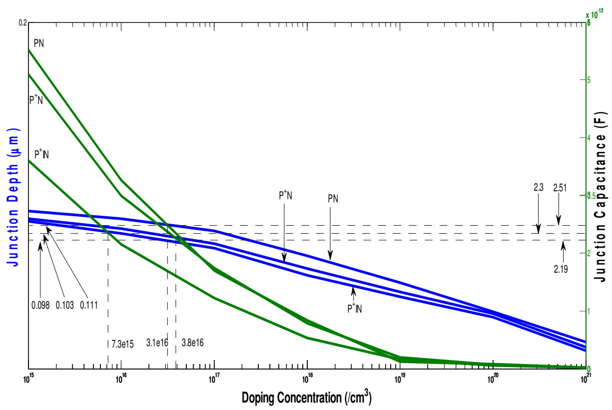

Fig. 8: Relationship between capacitance, junction depth and doping concentration

The capacitance in Si UV detector is changing with variation of doping concentration. However, the effect of the capacitance is not significant with the variation of wavelength for the whole response. At the same optimized doping profile, the capacitance does not vary drastically with wavelength. To the absorption of photon at UV spectrum, the absorption must be close to the top surface of the PD. Different intersection points are obtained by P^+iN, P^+N and PN PD. For PN PD, the intersection points are at $3.1\text{x}10^{16}$ cm^{-3}, 110 nm junction depth and capacitance of $2.51\text{x}10^{-12}$ F. On the other hand for the P^+N PD, the intersection points are at $3.8\text{x}10^{16}$ cm^{-3}, 98 nm junction depths, and $2.19\text{x}10^{-12}$ F. Finally for the P^+IN PD, the intersection points are at $7.3\text{x}10^{15}$ cm^{-3}, 103 nm depth and $2.3\text{x}10^{-12}$ F. These parameters value is then used to calculate the response time which is related to the bandwidth of the PD. From this relationship, it can be concluded that P^+N has a better response compared to P^+iN PD at the UV range as it gives lower capacitance and absorbed nearer to the surface.

PD	Capacitance (F)	Doping (cm^{-3})	Junction depth (nm)
PN	$2.51\text{x}10^{-12}$	$3.1\text{x}10^{16}$	110
P^+N	$2.19\text{x}10^{-12}$	$3.8\text{x}10^{16}$	98
P^+IN	$2.3\text{x}10^{-12}$	$7.3\text{x}10^{15}$	103

Table 1: Optimized parameter value

The transient response time is affected by capacitance and transit response time is affected by depletion width. Whenever the transient time is reduced, the transit time is increased and vice versa. Thus, an optimum value for each transit and transient time must be obtained and analyzed so that the detector can operate at its best performance. The bandwidth of it is greatly affected by these two response time. The bandwidth determines the overall response of the photo detector.

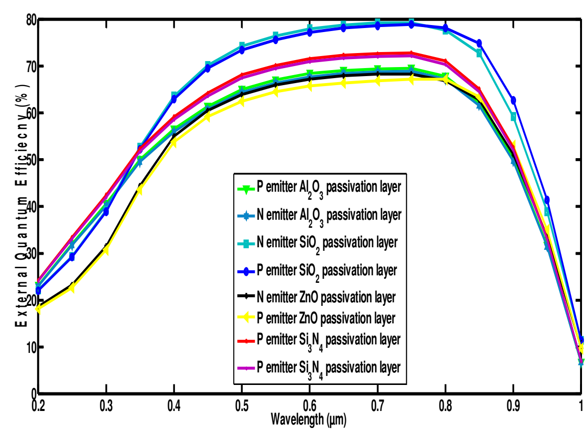

Fig. 9: Quantum Efficiency of PD with different passivation materials

Fig. 9 shows the quantum efficiency variation for N and P emitter with various passivation layers. It is found that the SiO_2 layer on cSi is achieved best efficiency as compared to other passivation layers.

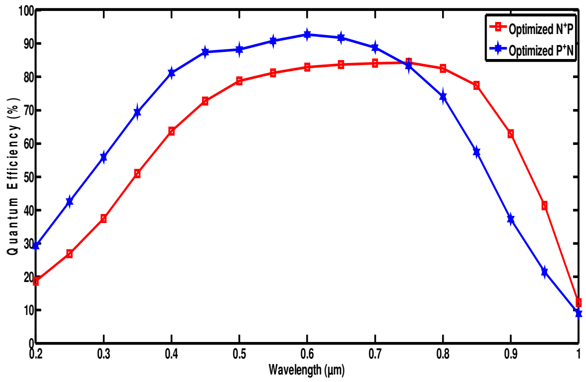

Fig.10: Quantum Efficiency of optimized N^+P and P^+N detector

Fig. 10 shows the quantum efficiency of N^+P and P^+N detectors as it responsivity is shown in Fig. 2. As it is explained before, the variation of quantum efficiency is realized due to different depth of active layer since diffusion length of photo generated hole is higher as compared to electron and depletion edge depth is also different for N and P emitters [17].

4 Conclusion

In this study, the impact of nano-coating HLs for photon management and active layer variation for P and N emitter based cSi detectors are studied. From the single passivation layer study, it appears that SiO_2 has achieved the best efficiency for cSi. Compared to single passivation, HLs is found promising for enhancement of quantum efficiency of both emitter based photo detector. So photon management is obviously occurred due to the nano-coating HLs. Significant impact of emitter is not realized in this study but similar doping profile may vary the active layer depth. Subsequently due to variation of emitter types, two different edges of solar spectrum efficiency differs a bit but not so significant. N emitter is found effective to increase photo-conversion efficiency at lower energy edge of solar spectrum while P emitter is effective for higher energy edge. Electrostatic effect due to various doping profile also impacts on quantum efficiency or responsivity. Si P^+N PDs have shown the best performance for higher energy (UV) band response as the study is revealed. For the implementation of HLs, higher conversion efficiency and immunity of emitter's on photo response signifies the novelty of the study.

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