

Efficiency enhancement and transient photocapacitance characteristics of the silicon solar cell by graphene oxide

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Thin buffer layer of graphene oxide was introduced to improve the efficiency of the silicon based solar cell. The current-voltage characteristics of the solar cell was studied and observed that the device with graphene oxide as buffer layer has improved device characteristics. The efficiency of the silicon solar cell and without and with graphene oxide was observed to be 21.46% and 22.29%, respectively. The transient photoconductance and photocapacitance of the device was studied. It was observed that the photocurrent increases with illumination and reach back to original value after turning off the illumination. The transient photocapacitance measurement shows the presence of negative capacitance. The results indicate the potential of graphene oxide as buffer layer in production of the improved silicon solar cells.

Keywords: Graphene oxide, solar cell, silicon, efficiency, p-n junction

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1. Introduction

There has been a great research interest in improving the efficiency of the silicon solar cell beyond the theoretically limit of 31%. Silicon solar cells display low light absorption because of a low absorption coefficient due to its indirect band gap. Effective light absorption could be one of the methods to improve its efficiency. This could be achieved by using thin reflector film on the back of the device, surface texturing and/or incorporating nanoparticles on the surface. Among the suggested methods, incorporation of nanoparticles on the surface of silicon has attracted considerable attention due to its simplicity and effectiveness [1]. The presence of nanoparticles at the surface increases light absorption due to the plasmonic effect. Pillai et al. [2] have used silver nanoparticle for this and showed a 16 fold increase of photocurrent at in silicon-on-insulator structures and a 7 fold

enhancement of photocurrent in bulk cell. Gold nanoparticles have been used to enhance the photocurrent up to 80% [3]. On the other hand, carbon based materials are widely used in energy storage and conversion systems due to its superior physical and chemical properties such as mechanical strength, electrical conductivity, porosity, light weight and ability to functionalize with other materials [4]. Among other carbon based materials, graphene has attracted considerable attention for energy applications because of its outstanding thermal, mechanical, optical and electrical properties [5-7]. Recently, we have shown that incorporation of graphene in the dye sensitized solar cell (DSSC) could improve its efficiency by more than two times [8]. Many researchers have used graphene to enhance the efficiency of the dye sensitized solar cell [9-12]. Graphene oxide has been mostly used in dye sensitized solar cell to improve the efficiency. In this work we report improvement in the efficiency of silicon solar cell by using thin buffer layer of graphene oxide on the silicon surface. The transient photocurrent and photoconductance of the solar cell was investigated in detail.

2. Experimental details

A p-type silicon polished on one side (250-micrometer thickness, <100> oriented, 1-10 $\Omega\text{-cm}$) was used for preparation of solar cell. Firstly, the silicon substrate was cleaned by RCA process. The cleaned silicon wafer was textured with etching process. The phosphorus was diffused into silicon wafer at 850 $^{\circ}\text{C}$. Boron diffusion was done for back surface field. Graphene oxide was synthesized using the method described in our earlier work [8]. A thin layer of graphene oxide (1 mg/ml) was spin coated on the silicon substrate. The antireflection layer was coated by plasma enhanced chemical vapor deposition (PECVD) method. Al contact was deposited on the back side and the top contacts were prepared by silver using thermal evaporator. The schematic diagram of the solar cell is shown in Fig.1. The electrical characterization of the silicon solar cell was done using a KEITHLEY 4200 semiconductor characterization system. The intensity of illumination was measured using solar power meter.

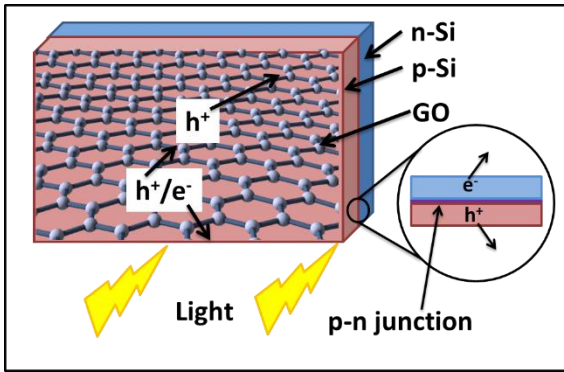


Fig.1: Schematics of fabricated solar cell.

3. Results and discussion

The photovoltaic test of silicon solar cell and GO incorporated silicon solar cell was studied under irradiation with white light from a 100 W Xenon arc lamp in ambient atmosphere. The current voltage characteristics of both the devices are shown in Fig.2. As seen in Fig.2, the device having thin layer of GO exhibited a photovoltaic characteristics. The fill factor (FF) of the solar cells was calculated using the relation [13]:

$$FF = \frac{(I_{\max} \times V_{\max})}{(I_{sc} \times V_{oc})} \quad (1)$$

where, $I_{\max}$ and $V_{\max}$ are the photocurrent and photovoltage for maximum power output, and I_{sc} and V_{oc} are the short-circuit photocurrent and open-circuit photovoltage, respectively. The overall energy conversion efficiency (η) of the solar cell was calculated using the following expression [13]:

$$\eta = \frac{(V_{oc} \times I_{sc} \times FF)}{P_{in}} \quad (2)$$

where, P_{in} is the power of the incident light. A fill factor of 0.57 and 0.55 was observed for the silicon and GO

incorporated silicon solar cell. The other device parameters are given in Table 1. As observed that the efficiency of the silicon solar cell is improved by having an additional layer of GO. The enhance efficiency is due to the suitable work function of GO for solar adsorption. Thin layer of GO traps the light and produces additional electron-hole pairs at the surface of the silicon. This electron-hole pairs is in addition to the electron-hole pairs generated at the p-n junction of the two silicon layers (Fig.1). The role of graphene oxide in effective charge separation and transportation is shown in Fig.3. The valance (-3.5 eV) and conduction (-5.0 eV) band of the graphene provide a cascading effect for the charges generated at the junction [14]. The conduction (-4.0 eV) and valance (-5.12 eV) band of silicon are lower than that of GO and thus graphene oxide buffer layer helps to improve the efficiency of the device. Jana et al [15] have observed an increase in the short circuit current in the incorporating silver (relative increase of 7.5%) and gold (relative increase of 6.1%) nanoparticles in silicon solar cell. Tong et al [16] have introduced silver nanoparticles and SiO_2 spacer layers on top of Si-based Schottky barrier solar cells to improve the efficiency of the solar cell. The best plasmonic cell obtained in their work achieved a power conversion efficiency improvement from 2.5% to 4.5%.

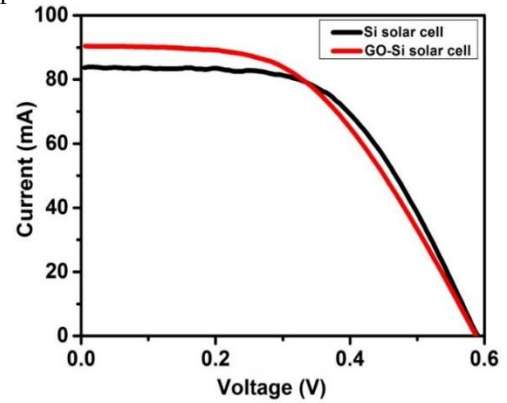


Fig.2: I-V characteristics of silicon and GO deposited silicon solar cells.

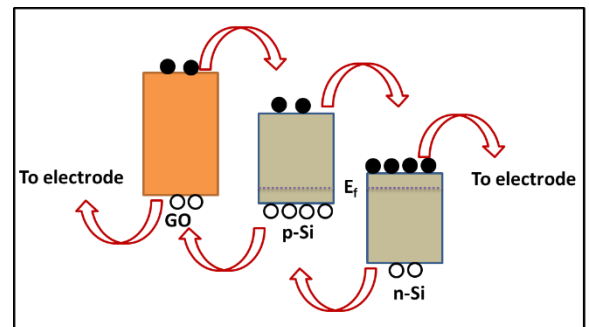


Fig.3: Band diagram of the GO based silicon solar cell.

Table 1: Photovoltaic properties of fabricated solar cells.

Device	I_{sc} (A)	V_{oc} (mV)	FF	η (%)
Silicon solar cell	8.34×10^{-2}	590	0.57	21.46
GO+Silicon solar cell	9.03×10^{-2}	588	0.55	22.29

The photo response of the silicon solar cell with GO layer was further investigated using transient photocurrent measurement. Fig.4 shows the variation of photocurrent with transient light. As seen, the photocurrent of the device increases rapidly with application of the light and remains almost constant until the light is switched off. After switching off the light, the current of the device decreases to its original value. The device photocurrent increases from 9.16×10^{-6} to 8.67×10^{-2} A after shining the light with intensity of 100 mW/cm². The increase in the photocurrent on illumination could be due to generation of additional free charge carriers. On the other hand, the decay in the photocurrent after switching off the illumination is due to trapping of the charge carriers in the deep levels.

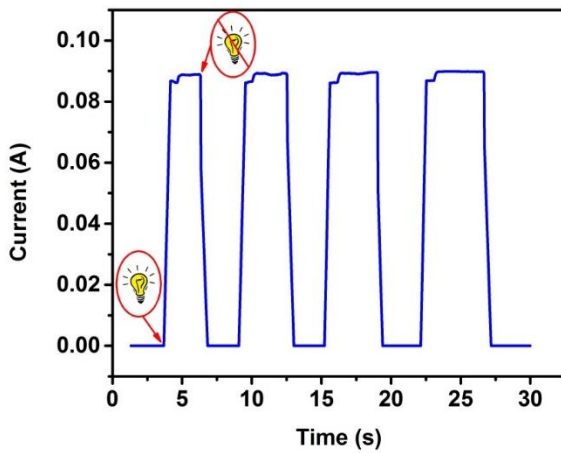


Fig.4: Transient photocurrent measurement of GO based silicon solar cell.

The effect of transient light on the capacitance and conductance of the device was also studied (Fig.5). As seen in the Fig.5a, the capacitance of the device decreases to negative capacitance after illuminating the device and reaches back to the original (positive capacitance) value after turning off the light. The conductance of the GO based solar cell increases on shining the light and again come back to its original value after switching off the light. The presence of negative capacitance has been also observed in hetero-junctions [17], light emitting diodes [18] and photo-detector [19]. Wu et al. [20] have explained the observation of negative capacitance by the loss of interface charges localized at metal/semiconductor interface due to impact ionization process.

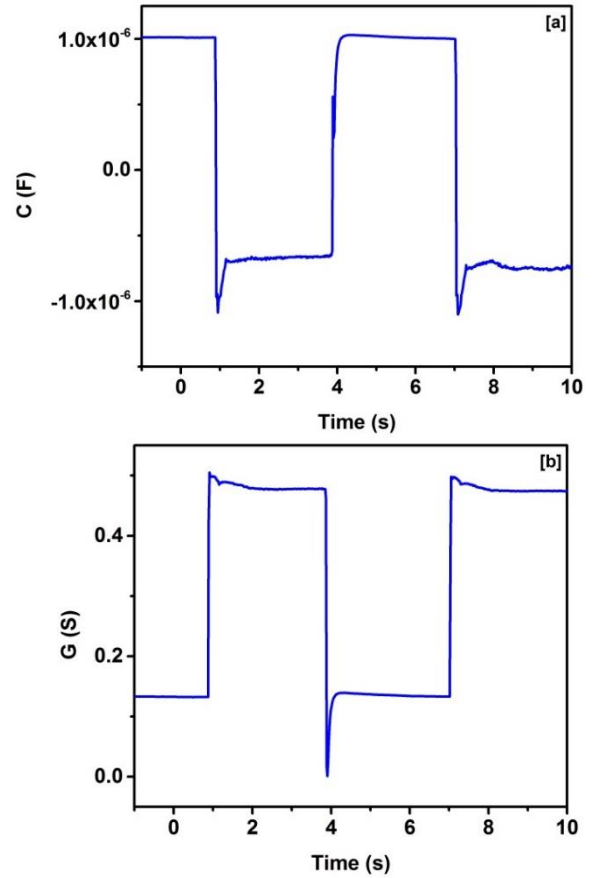


Fig.5: Transient photocapacitance (a) and photconductance (b) of GO based silicon solar cell.

The true value of the capacitance and conductance was calculated by correcting them for series resistance at the junction. The corrected capacitance (C_{ADJ}) and corrected conductance (G_{ADJ}) of the device were calculated using the following equations[21, 22]

$$C_{ADJ} = \frac{[G_m^2 + (\omega C_m)^2] C_m}{a^2 + (\omega C_m)^2} \quad (3)$$

$$G_{ADJ} = \frac{[G_m^2 + (\omega C_m)^2] a}{a^2 + (\omega C_m)^2} \quad (4)$$

$$\text{Where } a = G_m - [G_m^2 + (\omega C_m)^2] R_s$$

Where C_{ADJ} and G_{ADJ} are series resistance compensated capacitance and conductance respectively. Fig.6 shows the transient C_{ADJ} and G_{ADJ} behavior of the device. Gharbi et al [19] have observed negative capacitance in a-SiC:H/a-Si:H UV photodetectors. The observed negative capacitance values at high frequency have been interpreted as, due to the delayed minority carriers trapping at the two interfaces with the doped layers.

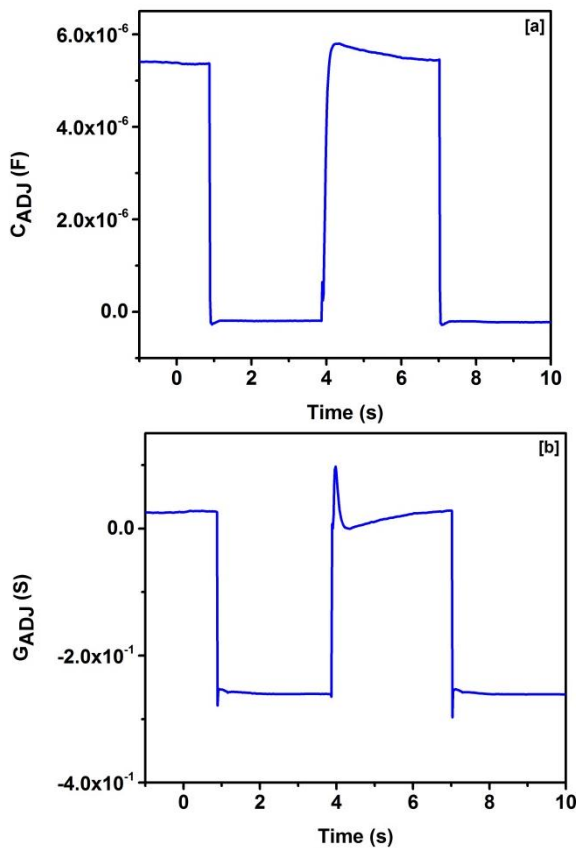


Fig.6: Transient C_{ADJ} and G_{ADJ} behavior of GO based silicon solar cell.

Conclusions

It was demonstrate that the thin buffer layer of graphene oxide could improve the efficiency of the silicon solar cell. The bandgap of the graphene oxide suitably matches with the silicon. The graphene oxide buffer layer not only helps in creation of electron-hole pairs but also provides cascading energy levels for effective separation and transportation of electron-hole pairs generated at p-n junction of the silicon solar cell.

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