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Impact of different capping layers on carrier injection efficiency between amorphous and crystalline silicon measured using photoluminescence

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ABSTRACT

Intrinsic amorphous silicon provides excellent surface passivation on crystalline silicon. It has previously been shown, that carriers that are photo generated in the amorphous silicon can be efficiently electronically injected into the crystalline silicon. A method to quantify the efficiency of such carrier injection using the spectral response of photoluminescence has recently been demonstrated. This is a contactless method and it can be applied to incomplete device structures. Here we use this technique to measure partially processed heterojunction devices with different capping layers to quantify their impact on the carrier injection efficiency. Silicon nitride capping on amorphous silicon is shown to have minimum impact on the high carrier injection efficiency of the amorphous layer but doped amorphous capping layer on the other hand were seen to have a strong effect on the carrier injection efficiency. A model was developed to understand the material properties of the amorphous layer. The reduction in carrier injection efficiency with doped amorphous silicon capping layers were attributed to the large defects in the doped layer.

1. Introduction

Amorphous silicon is commonly used in heterojunction (HJT) solar cells [1,2] and interdigitated back contact (IBC) solar cells [3,4] as a surface passivation layer on crystalline silicon (cSi). Although intrinsic amorphous silicon (aSi(i)) provides excellent surface passivation on cSi [5–7], it also has a large optical absorption under blue illumination and can thus limit the short circuit current of silicon heterojunction solar cells. This leads to a strong reduction in the quantum efficiency of the solar cell for illumination wavelengths < 400 nm. However, in a recent high efficiency IBC solar cell, the front surface was passivated with aSi (i) and capped with an anti-reflection layer [4], with internal quantum efficiency reported to be $> 90\%$ above 300 nm. This result indicates that there is minimal parasitic absorption loss in the aSi(i) in that configuration. The excess carriers generated via the light absorption in the front aSi(i) layer have previously been demonstrated to be weakly electronically injected into the cSi, adding to the cell's photocurrent [2,8–10]. The optical losses from absorption of the incident short wavelength light are thus partially compensated by this effect.

Photoluminescence (PL) is a contactless characterisation technique which measures the excess carriers in cSi under illumination. The spectral response of photoluminescence has been previously been shown to provide a relative measure of quantum efficiency of the device [11]. This technique was recently used to quantify the carrier injection between the aSi(i) and cSi layers on aSi(i) passivated wafers [12,13]. This work demonstrated that in aSi(i) passivated cSi samples, almost all the carriers generated in the aSi(i) layer are injected into the cSi bulk. As PL is a contactless method, this technique was applied without a complete device structure and performed on partially processed wafers. Previous methods to measure carrier injection were based on the short circuit current under monochromatic illumination and so are limited to fully processed devices. The above high carrier injection efficiencies of close to 100% were measured on devices with only aSi(i) passivation and no additional capping layers, such as the anti-reflection, highly doped aSi or transparent conducting oxide (TCO) layers, that are present in a solar cell. Here we expand upon the results from Ref [13] and measure the impact of different capping layers such as SiN_x, phosphorous and boron doped aSi (aSi(n), aSi(p)) on the carrier injection efficiency (β) between the aSi(i) and cSi layers.

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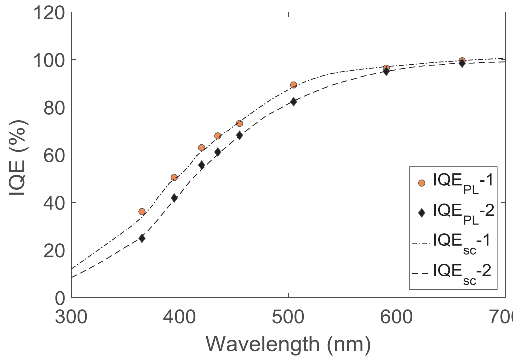

Fig. 1. Comparison between IQE$_{PL}$ and IQE$_{sc}$ for HJT devices with different capping layers. The 2 cells were made on the same substrate and had the different aSi(i) layer thicknesses.

2. Theory

For structures with a high effective lifetime, such as those studied here, the spectral response of PL provides a relative measure of the external quantum efficiency (EQE) [11,14]. Accounting for reflection then gives the IQE$_{PL}$:

$$IQE_{SC}(\lambda) \propto IQE_{PL}(\lambda) = \frac{I_{PL}(\lambda)}{N(\lambda)(1-R(\lambda))}, \quad (1)$$

where IQE$_{sc}$ is the conventional (short circuit current density based) internal quantum efficiency (IQE) of the device, IQE$_{PL}$ is the relative IQE measured from PL, $I_{PL}(\lambda)$ is the PL intensity per unit area, $N(\lambda)$ is the photon flux of incident light, $R(\lambda)$ is the reflection, and λ is the wavelength of incident light.

To validate the fundamentals of this technique, the relative IQE$_{PL}$ and the IQE$_{sc}$ for 2 HJT solar cells with different thicknesses of aSi(i) passivation were measured and are shown in Fig. 1. The front side of the cells is ITO-aSi(p)-aSi(i) and the rear side is ITO-aSi(n)-aSi(i), where ITO is Indium Tin Oxide conducting layer, aSi(p) is boron doped aSi and aSi(n) is phosphorous doped aSi. The aSi(i) layer thickness of the cells 1–2 were 8 nm and 14 nm respectively. The IQE$_{sc}$ for these cells were measured with a commercial monochromator based EQE system (PV Measurements) and by measuring the reflection (Perkin Elmer). The EQE was measured from the short-circuit current of the device and by varying the monochromatic light. A bias light was included to remove artefacts caused by the injection dependence of the minority carrier lifetime. The IQE$_{PL}$ was measured using the constant signal method [11] to ensure that the PL measurements are done at the same injection level. The angle of incidence for the illumination for both the measurements were kept between 0° and 10°. The IQE$_{PL}$ is scaled to match the IQE$_{sc}$ at the longest illumination wavelength (660 nm) at which PL was measured in this study. Good agreement is observed for all cells between the IQE$_{sc}$ and IQE$_{PL}$, validating the method.

These results reconfirm the fundamental principles of the measurement technique. The drop in IQE$_{sc}$ in the short wavelengths is due to the parasitic absorption losses in the aSi layers in the front surface. Next this technique is applied to partially processed device structures without any electrical contacts. Devices with the following structure are considered: *capping_layer-aSi(i)-cSi(n)-aSi(i)* as shown schematically in Fig. 2. For the device structures measured in this paper, surface recombination velocity at the front and rear surfaces of the cSi is assumed to be negligible. This is a crucial assumption for this technique. To confirm the validity of this assumption, all the devices were measured to have a minority carrier lifetime of over 0.5 ms. This results in a maximum surface recombination velocity of 50 cm/s, giving a maximum drop of 0.1% from the EQE at 300 nm. The internal quantum efficiency in the absence of parasitic absorption losses and surface recombination losses is close to unity. For a device structure with *n*

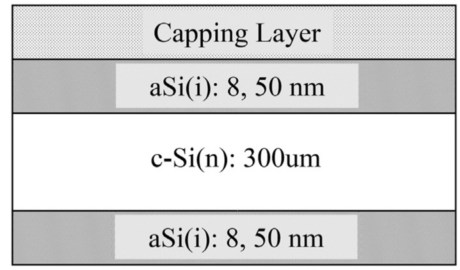

Fig. 2. Devices with the above structure were used for this study. The IQE$_{PL}$ with and without the capping layer was measured by measuring the PL from the rear or front side respectively.

number of parasitically absorbing thin film layers on top of a cSi base, and in the absence of carrier injection from any of the absorbing layers into the cSi base the IQE is given as

$$IQE(\lambda) = 1-\frac{J_R(\lambda)}{J_{inc}(\lambda)\times(1-R(\lambda))} - \sum_{i=1}^{n}\frac{J_{abs,i}(\lambda)}{J_{inc}(\lambda)\times(1-R(\lambda))} \quad (2)$$

with $J_{inc}(\lambda)$ the incident monochromatic photon flux, $J_{abs,i}(\lambda)$ the photon flux absorbed in the i^{th} layer deposited onto the crystalline silicon and $J_R(\lambda)$ the recombination current density in the cSi under short circuit conditions. The term with J_R represents carriers that are generated in the cSi that are not collected in the short circuit current, which is zero in an ideal case. For that scenario we can define an upper limit IQE$_{Max}(\lambda)$, i.e. the quantum efficiency in the absence of carrier injection and of carrier recombination:

$$IQE_{Max}(\lambda) = 1-\sum_{i=1}^{n}\frac{J_{abs,i}(\lambda)}{J_{inc}(\lambda)\times(1-R(\lambda))} = \frac{J_{cSi}(\lambda)}{J_{inc}(\lambda)\times(1-R(\lambda))}, \quad (3)$$

where $J_{cSi}(\lambda)$ the photon flux absorbed in the cSi. If none of the carriers absorbed in the thin film layers are collected in the cSi, then $IQE_{Max} = IQE_{PL}$.

If the appropriately scaled IQE$_{PL}$ is measured to be higher than the IQE$_{Max}$ for specific illumination wavelengths, then this suggests that carriers are being injected from the absorbing layers into the cSi. The carrier injection efficiency (β) can be determined quantitatively from the increase in IQE$_{PL}$ over IQE$_{Max}$. In this paper it is assumed that only the a-Si injects carriers into the cSi, whereas the capping-layer represents a sink for carriers i.e. the capping-layer does not inject carriers into the aSi(i) or cSi. Taking into account the carrier injection form aSi into the base, the IQE_β can be defined as,

$$IQE_\beta(\lambda) = \left(1 - \frac{\sum_{i=1}^{n} J_{abs,i}(\lambda)}{J_{inc}(\lambda)\times(1-R(\lambda))} + \frac{\beta\times J_{aSi}(\lambda)}{J_{inc}(\lambda)\times(1-R(\lambda))}\right) = \frac{J_{cSi}(\lambda)+\beta\times J_{aSi}(\lambda)}{J_{inc}(\lambda)\times(1-R(\lambda))}. \quad (4)$$

where $J_{aSi}(\lambda)$ is the photon flux absorbed in the aSi(i) layer. As IQE$_{PL}$ is a relative value, in this paper the IQE$_{PL}$ was multiplied by a scaling factor. The scaling factor was chosen in such a way that the IQE$_{PL}$ at the longest wavelength matches the IQE$_{Max}$. Ideally the longest wavelength must be chosen such that there is no absorption in the aSi(i) layers at that wavelength. In this study the longest wavelength at which the measurements were done is 660 nm. The aSi(i) layer does absorb $<$ 0.5% of the total photon flux. The β is calculated by fitting the IQE$_\beta$ with the scaled IQE$_{PL}$. As the shape of the IQE$_{PL}$ curve determines this fitting, the effect of the small amount of absorption in the aSi(i) layer at 660 nm wavelength illumination on the β is neglected.

3. Experimental setup

Double side polished n-type silicon wafers were used in all the devices studied. Two types of device structures were studied: 1) cSi(n)