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Influence of aluminum workfunction and capping dielectric thickness on the performance of local back surface field solar cell using numerical simulation

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ABSTRACT

High efficiency partial rear contact solar cells forms a Metal-Insulator-Semiconductor (MIS) stack in the rear side. Aluminum is used as a local back surface field (localized heavily doped pregion) and a hole contact. The workfunction difference between the aluminum contact and the c-Si(p) causes inversion in the silicon surface of the MIS structure. The surface inversion affects the quality of passivation and hence, the performance of the solar cell which requires further understanding. In this work, we have analysed the influence of aluminum on surface passivation in two passivation stacks namely (i) AlO_x/SiN_x and (ii) SiO_x/SiN_x using Sentaurus TCAD simulation.

Our simulation result shows that in case of positive dielectric stack (SiO_x/SiN_x), aluminum workfunction enhances the passivation (effective surface recombination velocity <15 cm/s) for the injection condition of 2×10^{13} cm^{-3} which is common at the rear side of AlLBSF solar cell. But, in negative dielectric stack (AlO_x/SiN_x), aluminum workfunction influence is negligible since it is surpassed by high negative fixed charge density. In addition, we have varied the capping layer (SiN_x) thickness in the dielectric stack to alter the aluminum influence on the crystalline silicon surface. It shows up to 1.0% absolute improvement in the efficiency for reduced SiN_x thickness in the SiO_x/SiN_x stack for the fixed charge density of 2×10^{11} cm^{-2}, interface trap density of 5×10^{11} cm^{-2}, assumed electron and hole capture cross section of 10^{-14} cm^2 and 4×10^{-16} cm^2 respectively. This is solely attributed to the aluminum workfunction influence on the rear passivation.

1. Introduction

International Technology Roadmap of PhotoVoltaics (ITRPV) predicts that the market share of rear passivated solar cells is expected to increase considerably in the coming years (up to 35% in the year 2025 compared to 5% in 2014) (ITRPV, 2015). Aluminum Local Back Surface Field (Al-LBSF) solar cell delivers high energy conversion efficiency. It is due to the low rear surface recombination velocity <20 cm/s in comparison with the traditional blanketed Al-BSF cell in which rear surface recombination velocity in the range of 200–600 cm/s (Dullweber et al., 2011). The rear dielectric layer or stack provides (i) reduction of trap density (chemical passivation) and (ii) alteration to the surface carrier concentration (field effect passivation) which in turn reduces the surface recombination velocity. Previously Al-LBSF solar cell has shown efficiency improvement of 1.0% absolute, compared to Al-BSF solar cell (Cacciato et al., 2013).

The rear side of Al-LBSF solar cells usually have a metal insulator semiconductor structure. Aluminum is used as rear metal for the hole contact and stack of SiO_x/SiN_x or AlO_x/SiN_x is used for passivating the p-type silicon surface. The role of fixed charge density (Q_f), interface trap density (D_{it}) and their dependence on the deposition condition and thickness of the dielectric are well studied (Aberle et al., 1992; Dingemans and Kessels, 2012; Duttagupta et al., 2015). But the influence of workfunction of aluminum metal on the rear surface passivation needs to be established further.

Abbreviations: c-Si(p), boron doped crystalline silicon; Q_{wf}, equivalent charge density due to workfunction difference between aluminum and c-Si(p) (qcm^{-2}); Q_f, fixed charge density due to the dielectric layer at the interface of dielectric and c-Si(p) (qcm^{-2}); Q_{it}, trapped charge density at the interface traps of dielectric and c-Si(p) (qcm^{-2}); D_{it}, trap density at the interface of dielectric and c-Si(p) (cm^{-2} eV^{-1}); S_{eff}, effective surface recombination velocity (cm/s); cn, cp, capture cross section of electrons and holes (cm^2).

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Workfunction difference between aluminum metal and c-Si(p) induces band bending in the rear surface, which affects the magnitude of passivation irrespective of dielectric stacks. Workfunction difference induced surface band bending is similar to the role of fixed charge density in the dielectric layers. Hence, in this work, we quantify the band bending due to workfunction difference using equivalent charge density as Q_{wf}.

Fig. 1 shows the schematic representation of the equivalent charge density due to the aluminum workfunction influence (Q_{wf}). Band bending equivalent to the positive charge density (Q_{wf}) of 2×10^{11} cm^{-2} is previously reported for cSi(p)/SiO_2/Al stack for SiO_x thickness of 105 nm. Since Al layer is electrically connected to the silicon, a limited number of electrons will leave the aluminum and a positive charge layer is built up at the Al-dielectric interface which is the reason for electron accumulation (Aberle et al., 1992). Earlier, the aluminum workfunction influence is studied for thermal oxidation where chemical passivation is good. Hence, the effect of workfunction difference on the passivation can be disregarded. But, the passivation stack used in LBSF solar cell has more D_{it} and Q_f than thermal oxidation. Hence, the influence of aluminum should be considered for those stacks which is carried out in this work.

In this work, it is shown that aluminum metal helps the surface passivation indirectly. To make things simple, we have started the analysis using simple test structure with and without the aluminum contact in Section 3.1. We have studied the test structures for both AlO_x/SiN_x and SiO_x/SiN_x passivation stack. In addition, we have varied the thickness of intermediate SiN_x thickness in the MIS structure to alter the aluminum influence on the cSi(p) surface in Section 3.2. Actually, this intermediate SiN_x layer is used as capping layer in the rear stack which is used to improve the stability of stack during firing of contacts. Finally, to quantify the aluminum workfunction influence in terms of terminal characteristics, we have simulated the AlLBSF cell for different SiN_x thickness in Section 3.3.

2. Simulation setup

In this work, Sentaurus TCAD is used for numerical simulation (Synopsys, 2015) which solves Poisson, electron and hole continuity equation self-consistently. In this section, models used for each interface in stacks: (i) cSi(p)/AlO_x/SiN_x/Aluminum and (ii) cSi(p)/SiO_x/SiN_x/Aluminum are discussed first. The interface of each layer plays a vital role in the accurate extraction of S_{eff}. Then, we verify the S_{eff} extraction using extended SRH mechanism validated with the experimental result. Finally in this section, we discuss the parameters and models used for Al-LBSF cell-level simulation.

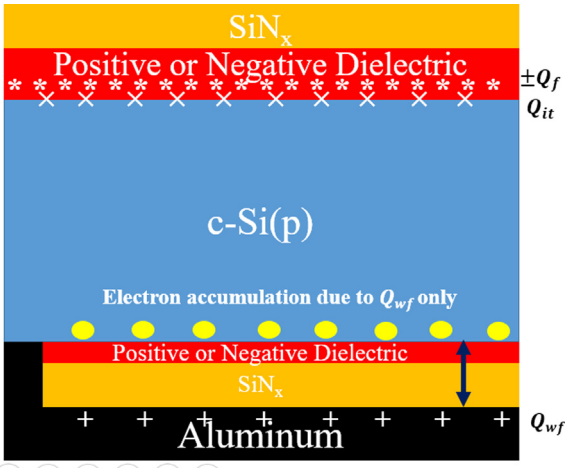

Fig. 1. Schematic structure showing the charges used in this work. Q_{wf} is aluminum workfunction induced charge equivalent, Q_f and Q_{it} are fixed charge density and interface trap density due to the dielectric stack. The dielectric with zero Q_f and zero Q_{it} is assumed to segregate the Q_{wf} alone.

2.1. SiN_x/aluminum interface

From the rear side of the solar cell, the first interface forms between the Aluminum metal and SiN_x. In this, the role of aluminum workfunction is critical in creating the band bending in cSi(p) surface. According to the interface dipole theory, the value of the metal workfunction depends on the dielectric over which it is deposited and it is experimentally verified (Yeo et al., 2002). We have taken the effective workfunction value for aluminum as 4.2 eV since aluminum is deposited over the SiN_x (whereas vacuum workfunction value is 4.06 eV). This interface is common for both the stacks.

2.2. AlO_x/SiN_x and SiO_x/SiN_x interface

The second interface from the rear side is formed between AlO_x and SiN_x, in case of negative dielectric and between SiO_x and SiN_x in case of positive dielectric. Usually, SiN_x is added in this stack as a capping layer for providing the better firing stability and hence, we have not included any physical model in this interface.

2.3. c-Si(p)/AlO_x and c-Si(p)/SiO_x interface

The third interface from the rear side forms the crucial interface between c-Si(p) and AlO_x in case of negative dielectric and between c-Si(p) and SiO_x in case of positive dielectric. Usually semiconductor insulator interface is modeled using fixed charge density (Q_f), interface trap distribution (D_{it}), nature of the trap and capture cross section of interface traps. Previously, lot of work (Black and McIntosh, 2013; Saint-Cast et al., 2011; Werner et al., 2012) has been done in modeling the interface properties of cSi (p)/AlO_x and cSi(p)/SiO_x. It is done using the experimental measurement of capacitance-voltage (C-V) and conductanc evoltage (G-V) characteristics. Recently, Black and McIntosh (2013) have introduced a constant capture cross section model for Atmospheric Pressure Chemical Vapour Deposition (APCVD) of AlO_x. It showed good match with their experimental result (S_{eff} calculated from Photo-conductance experiment) which is used in this work. D_{it} mentioned for c-Si(p)/AlO_x interface is the midgap trap density value of the interface trap distribution. For c-Si(p)/SiO_x interface, interface trap density is modeled using uniform constant distribution with the assumed constant capture cross section value shown in Table 1 using (Aberle et al., 1992; Duttagupta et al., 2015).

2.4. Calibration of effective surface recombination velocity

The quality of the surface passivation is determined by the values of S_{eff} which is used here to study the metal influence on the surface passivation. We have used, widely employed extended Shockley-Read-Hall (SRH) method described in (section V of (Black and McIntosh, 2013)) which is given as,

$$S_{eff} = \frac{U_s}{\Delta n} \tag{1}$$

where surface recombination rate (U_s) is given by,