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Tunnel Nitride Passivated Contacts for Silicon Solar Cells Formed by Cat-CVD

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Abstract

An ultra-thin silicon nitride (SiN_x) layer formed by catalytic chemical vapor deposition (Cat-CVD) is used to replace the Si dioxide (SiO_2) layer of a tunnel oxide passivated contact (TOPCon) solar cell. The passivation quality of c-Si with a stack of the ultra-thin SiN_x and n-type amorphous or microcrystalline Si, also formed by Cat-CVD, is significantly improved by annealing at 850 °C, probably due to the formation of a back surface field (BSF) layer. Cat-CVD SiN_x with thicknesses of up to 2.5 nm can have sufficient tunneling conduction, which is much larger than the upper limit thickness of a tunneling SiO_2 of ~2 nm. The ultrathin SiN_x having functions of surface passivation and carrier tunneling and the unification of the formation method for the tunneling and conductive layers will lead to the realization of tunnel nitride passivated contact solar cells.

1. Introduction

Recently, crystalline silicon (c-Si) solar cells with a full-area carrier selective contact passivated by a tunneling silicon dioxide (SiO_2) layer on rear side have been proposed, which are referred to as tunnel oxide passivated contact (TOPCon) solar cells [1]. To form the passivated contacts, there are three process steps: (i) formation of an ultra-thin SiO_2 layer, usually performed by wet-chemical oxidation or thermal oxidation, (ii) deposition of a doped Si layer, in which plasma-enhanced chemical vapor deposition (PECVD) and low-pressure CVD (LPCVD) are commonly used, (iii) an indispensable "activation" for this contact by high-temperature annealing. The fabrication process of TOPCon solar cells can be simplified by unifying the method of thin-film formation in the steps (i) and (ii).

Catalytic CVD (Cat-CVD) is one of the best ways for the formation of tunneling and doped Si films, because of its advantages such as higher material efficiency and plasma-damage-less nature. Si nitride (SiN_x) films formed by Cat-CVD is known to have excellent passivation ability on c-Si surfaces [2], and the replacement of SiO_2 in TOPCon solar cells to ultra-thin Cat-CVD SiN_x will lead to the simplification of the fabrication process [3]. In this study, we investigated the passivation quality and tunneling conductivity of Cat-CVD doped Si/SiN_x passivated contact. We mainly focused on the influences of SiN_x thickness and the phosphorus doping concentration of the doped Si layer.

2. Experimental details

We used mirror-polished n-type 1–5 Ωcm (100)-oriented floating-zone (FZ) Si wafers with a thickness of 280 μm, which were cleaved into 20×20 mm^2 pieces. After RCA cleaning, the wafers were carried into a Cat-CVD chamber immediately. The wafers were pre-heated up to a setting temperature (T_{sub}) in hydrogen atmosphere, and then SiN_x layers were deposited on both sides of the wafers. SiN_x layers with various thicknesses in a range of 1.8–4.2 nm were deposited to investigate the dependence of SiN_x. Subsequently, n-type amorphous Si (a-Si) or microcrystalline Si (μc-Si) films with a thickness of ~25 nm were deposited on both sides of SiN_x layers. T_{sub}, catalyzer temperature (T_{cat}), pressure (P_g), and gas flow rates for the deposition of SiN_x, a-Si, and μc-Si films are summarized in Table I.

To activate the contact, an annealing was conducted in a furnace at 850 °C for 1 hour in N_2 atmosphere, by which a-Si or μc-Si will be crystallized into polycrystalline Si (poly-Si). The effective minority carrier lifetime (τ_{eff}) of the c-Si samples was measured by microwave photoconductivity decay (μ-PCD) before and after the annealing. Ti/Ag electrodes with an area of 1 cm^2 were deposited on both sides by vacuum evaporation. The *I–V* characteristics of the samples were measured using a semiconductor parameter analyzer, from which carrier tunneling through thin SiN_x was evaluated. We also separately prepared the samples for the evaluation of contact resistance with electrodes on one side of the samples with various intervals. In the latter structure, μc-Si with a PH_3 flow rate of 100 sccm was chosen as a doped Si layer.

Table I Deposition conditions for SiN_x, a-Si, and μc-Si films.

	T_{sub} (°C)	T_{cat} (°C)	P_g (Pa)	Gas flow rate (sccm)			
				SiH_4	NH_3	H_2	PH_3 (2.25%)
SiN_x	200	1800	1.0	3	50	40	-
a-Si	250	1800	1.0	20	-	-	10–300
μc-Si	250	1800	1.0	10	-	10	10–200

3. Results and discussion

Fig. 1 shows the *J–V* curves of the samples with SiN_x with various thickness. The samples with SiN_x with thicknesses of 1.8 and 2.5 nm show a linear *J–V* characteristics and have resistances of 0.11 and 0.18 Ωcm^2, respectively. This clearly demonstrates that SiN_x with a thickness of up to 2.5 nm has a sufficient carrier tunneling ability. As the thickness of SiN_x increases, the *J–V* curves become nonlinear and their slopes near the origin of coordinates decreases severely, which indicates the attenuation of the tunnel effect. The maximum thickness of SiN_x for carrier tunneling is ~2.5 nm, which is much larger than that of SiO_2 of 2.0 nm [5]. According to the theoretical analysis, the most possible reason is that SiN_x has a lower band offset for tunneling electrons.

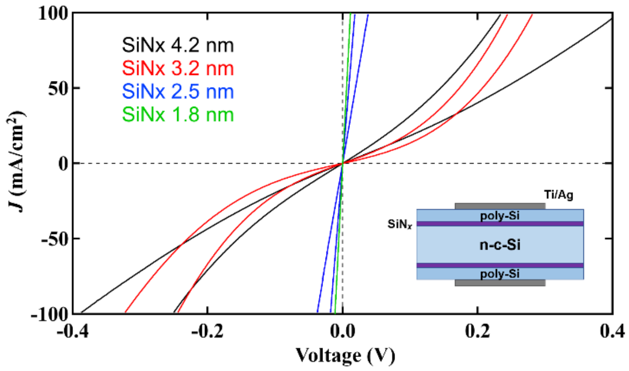

Fig. 1 J–V curves of samples with SiN_x with various thickness.

Fig. 2 shows τ_{eff} as a function of SiN_x thickness. Annealing at 850 °C leads to a large increase in τ_{eff}, while the increase of τ_{eff} is weakened by the increase in SiN_x thickness. The high-temperature annealing may result in the diffusion of phosphorus (P) atoms from doped Si into c-Si and a heavily doped layer is formed on the c-Si surface. This may act as a back surface field (BSF) layer and contribute to an improvement in passivation quality. One possible reason for a decrease in τ_{eff} is that thicker SiN_x layer prevents the diffusion of P atoms into c-Si more severely and the field-effect passivation becomes weaker.

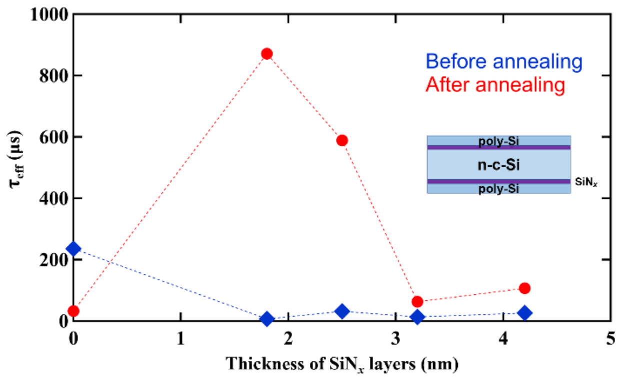

Fig. 2 τ_{eff} as a function of SiN_x layer before and after annealing.

Fig. 3 shows τ_{eff} after annealing as a function of the He-diluted PH_3 flow rate during the deposition of a-Si or μc-Si. τ_{eff} and PH_3 flow rate, i.e. P concentration, clearly show a strong positive correlation at a low PH_3 flow rate. τ_{eff} then gradually decreases with further increase in PH_3 flow rate.

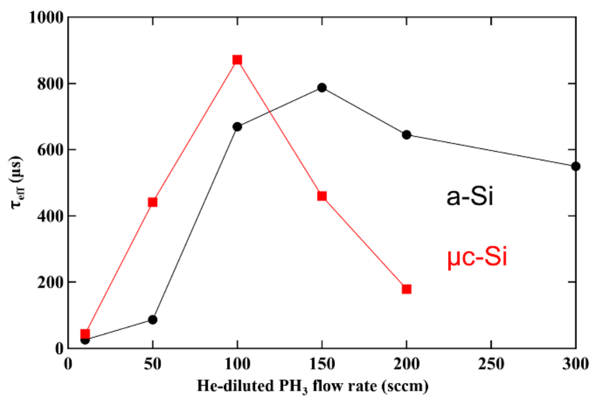

Fig. 3 τ_{eff} after annealing as a function of He-diluted PH_3 flow rate.

The increase in τ_{eff} can be easily understood as the formation of stronger BSF layer by more P diffusion. The successive reduction in τ_{eff} might be related to the worse quality of doped Si films themselves induced by a reduction of the partial pressure of SiH_4 during the deposition of the Si films. The maximum τ_{eff} of ~0.8 ms obtained in this experiment indicates high passivation quality of the n-type Si/ultra-thin SiN_x stacks.

Fig. 4 shows the measured resistance of the samples for the contact resistance measurement as a function of electrode interval. The resistivity of the Si substrate (ρ_{sub}) calculated from the slope is 1.03 Ωcm, which is lower than that of untreated Si wafer of 3–4 Ωcm measured on a quasi-steady-state photoconductance (QSSPC) equipment. One possible reason for the lowering of ρ_{sub} is the contribution of lateral conduction in a BSF layer. The contact resistance estimated from the intercept is 0.014 Ωcm^2. This value is low enough to for the utilization of c-Si solar cells. The stacked films consisting of n-type Si and ultra-thin SiN_x, both prepared by Cat-CVD, can thus combine high passivation ability and sufficient tunneling conductivity, and will be utilized to the passivated contact of c-Si solar cells.

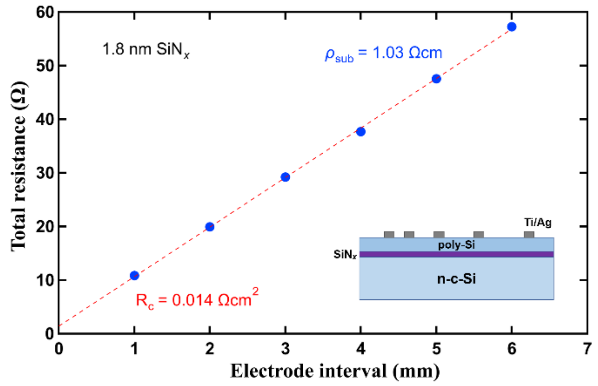

Fig. 4 Measured resistance as a function of electrode interval. The schematic of the sample structure is also shown in the inset. The dashed line indicates the result of linear fitting.

4. Conclusion

We realized ultra-thin Cat-CVD SiN_x with functions of high surface passivation ability and sufficient carrier tunneling. The maximum thickness of SiN_x for carrier tunneling is found to be as thick as ~2.5 nm. The dependence of P concentration on τ_{eff} indicates that the formation of BSF layer may be the primary reason for an improvement in the passivation quality. Contact resistance is estimated to be 0.014 Ωcm^2, which is low enough to be used for the passivated contact of c-Si cells, instead of conventional TOPCon structures with SiO_2.

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