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Passivating contacts for silicon solar cells based on boron-diffused recrystallized amorphous silicon and thin dielectric interlayers

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ABSTRACT

A technique to make poly-Si (p^+)/SiO_x contacts for crystalline silicon solar cells based on doping PECVD intrinsic amorphous silicon (a-Si) by means of a thermal BBr_3 diffusion process is demonstrated. The thickness of the a-Si layer and the temperature of the boron diffusion are optimized in terms of suppressing carrier recombination and transport losses. Different interfacial layers are studied, including ultra-thin SiO_x grown either chemically or thermally, and stacks of SiO_x and SiN_x. While the double SiO_x/SiN_x interlayers do not achieve the desired performance, both kinds of single SiO_x layers produce satisfactory passivating contacts, with both a low recombination current and a low contact resistivity. By adjusting the boron diffusion temperature, recombination current parameter J_0 values of ~16 fA/cm^2 to ~30 fA/cm^2 have been obtained for structures with initial a-Si thicknesses of 36–46 nm, together with a contact resistivity of ~8 mΩ cm^2.

1. Introduction

Recombination at the interface between metal and silicon eventually limits the maximum attainable efficiency of conventional dopant-diffused silicon solar cells. Besides restricting the contact area and introducing a heavily doped region under the metal, placing a self-passivating layer between metal and silicon is an effective approach to overcome such limitations. Passivating contact structures based on an ultra-thin silicon oxide layer and a doped silicon layer having a polycrystalline, amorphous, or mixed phase are being actively developed. The implementation of such approach to the rear side of n-type silicon solar cells has recently led to a 25.1% conversion efficiency [1]. Based on different doping technologies, thermal diffusion [2,3], in-situ doping by CVD [4] and ion implantation [5–7], both n-type electron-selective and p-type hole-selective contacts have been formed. From these recent results, n-type silicon-film contact structures usually show a better passivating performance than p-type silicon-film passivating contacts. The n-type passivating contacts typically have a range of recombination current parameter values in the vicinity of ~10 fA/cm^2 [2–4,7] with one report of ~1 fA/cm^2 [5]. On the other hand, p-type passivating contacts typically present a higher recombination current of about ~20 fA/cm^2 [4,5,7] with one report of ~4.5 fA/cm^2 [5]. This difference in performance was already observed between p–n–p and n–p–n polysilicon emitter bipolar junction devices [8,9]. N-type polysilicon emitters have shown significant current gain enhancements, by a factor up to 30, while p-type polysilicon emitters can only increase the current gain by a factor of 10 [9]. Several explanations were offered in previous studies: boron has a larger diffusivity than phosphorus in polysilicon layers, fewer ionized boron atoms are segregated in the grain boundaries of polysilicon layers [9,10], the boron atom tends to induce more interface defects and oxide charges in the Si/SiO_2 interface system, due to the penetration of boron into the substrate [11].

In this work, we present a detailed study of p-type passivating contacts by means of boron diffusion, thin silicon dielectric layers, and amorphous silicon layers. The paths to obtaining an optimized p-type passivating contact are identified. There are three parameters that need to be investigated: the a-Si thickness, the interfacial layer, and the boron diffusion temperature. In those optimization steps, the recombination current parameter, sheet resistance and contact resistance are measured, as indicators of the self-passivating and selective transport qualities of an optimized structure. Firstly, the effect of a-Si thicknesses is investigated for three diffusion temperatures. Secondly, four different interfacial layers: a single chemical oxide, a single thin thermal silicon oxide, and two sets of SiN_x/chemical oxide double layers with SiN_x refractive index values of 2.5 and 3.0, are studied as a function of the boron diffusion temperature. The influence of a-Si thickness, interfacial layer conditions, diffusion temperature and low temperature anneal in forming gas (FGA) show a clear path to

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form optimized boron diffused poly-Si passivating contacts. In this work, we refer to the a-Si layer after the high temperature boron diffusion process as poly-Si, which is consistent with the terminology used in Ref. [12].

2. Experimental procedure

Samples for measuring the recombination parameter J_{0c}, and the contact resistivity ρ_c, were prepared separately. P-type FZ silicon wafers with high resistivity ($\sim$100 Ω cm) and thickness of 470 μm were used for measuring J_{0c}, while p-type FZ silicon wafers with low resistivity ($\sim$0.5–1 Ω cm) and thickness of 200–250 μm were prepared for ρ_c measurements. Two types of thin oxide layers were studied: a thin chemical oxide and a thermal oxide layer. A thickness of $\sim$1.4 nm chemical oxide was grown by immersing silicon wafers (both J_{0c} samples and ρ_c samples) into a 68 wt% nitric acid solution at a temperature of 90 °C. A thermal oxide layer with a similar thickness of $\sim$1–1.3 nm, was prepared thermally in a quartz tube by means of dry oxidation process at 600 °C. During the 400 °C PECVD film deposition, some of chemical oxide samples received a stack of SiN_x and a-Si:H layers, while other chemical oxide samples and all thermal oxide samples were coated with intrinsic a-Si only. Two different 14 nm thick SiN_x layers with refractive indices (at a wavelength of 632 nm) of 2.5 and 3.0 were deposited in the SiN_x/a-Si:H stack structure. The J_{0c} samples were prepared with a symmetrical layer structure on both sides, while the ρ_c samples had a one side passivating contact structure. After PECVD film deposition, both J_{0c} samples and ρ_c samples were doped with boron atoms by using BBr_3 as a diffusion source at a temperature ranging from 870 °C to 980 °C. A fixed 30 min of BBr_3 deposition and a subsequent 30 min drive-in in nitrogen at the same temperature were used for all diffusion temperatures.

After removing the boron silicate glass (BSG) layer, J_{0c} was measured at room temperature by transient photoconductance decay (PCD) [13] and quasi-steady state photoconductance (QSSPC) [14] at an excess carrier density in the range of $\Delta n = 0.5 - 1\times10^{15}cm^{-3}$, both before and after forming gas (95% Ar, 5% H_2) annealing (FGA) at 400 °C for 30 min. The Cox and Strack method was used to extract ρ_c values from the contact resistivity samples which have various sizes of circular aluminium contacts on top of the poly-Si layers [15]. Ten circular aluminium contacts with diameters of 0.06 ± 0.002 cm, 0.11 ± 0.002 cm, 0.15 ± 0.002 cm, 0.20 ± 0.004 cm, 0.24 ± 0.009 cm, 0.31 ± 0.02 cm, 0.41 ± 0.006 cm, 0.61 ± 0.004 cm, 0.79 ± 0.01 cm and 0.98 ± 0.08 cm, were fabricated. Error values, as indicated in the following figures, are calculated by accounting both errors of the wafer thickness and errors of the circular aluminium contact sizes. The resolution of the contact resistivity measurement strongly depends on the resistivity and thickness of the silicon substrate. In our case, the minimum contact resistivity that can be detected is 5 mΩ cm^2, indicated as dashed lines in the graphs that show the contact resistivity measurements. The electrically active boron dopant concentration in the p^+poly-Si/SiO_x contact structure was measured by the electrochemical capacitance–voltage technique (WEP Wafer Profile CVP21). The final dopant profiles were calibrated by the same scaling factor that is used to correct the boron dopant profiles in mono-crystalline silicon, which was determined by matching the boron dopant profile to the measured sheet resistance.

3. Optimization of the a-Si thickness and the boron diffusion

3.1. Dopant profile

After the growth of a $\sim$1.4 nm chemical oxide layer, the second step in the formation of the contact structure is to deposit a layer of un-doped a-Si. The thickness of this layer needs to be optimized in conjunction with the boron diffusion process. On the one hand, it is very important, as we shall see below, that the entirety of the silicon layer is doped with a high concentration of boron atoms. Some boron atoms diffuse across the thin oxide and into the silicon wafer, and this can also have an impact on the final performance of the contact. On the other hand, the boron diffusion consumes a certain amount of the deposited silicon, reducing the final thickness of the layer. In the BBr_3 diffusion process, boron oxide (B_2O_3) is formed on the silicon surface, and introducing boron into the silicon requires a surface reaction between B_2O_3 and silicon [16].

To explore such trade-off, we prepared samples with a-Si layer thicknesses of 29 nm, 36 nm, 46 nm, 55 nm and 90 nm, and subjected them to three different diffusion temperatures, 920 °C, 960 °C and 980 °C. The boron profiles corresponding to the lowest

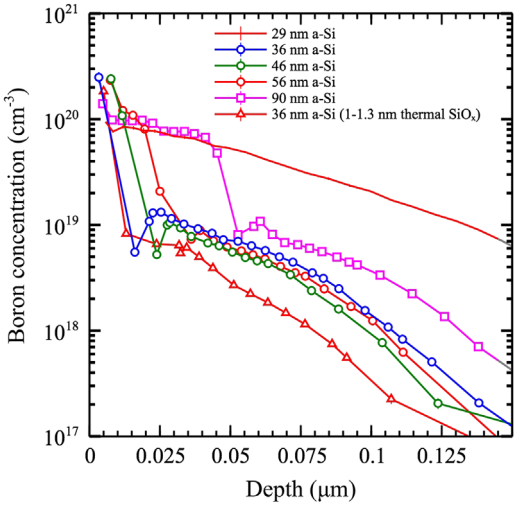

Fig. 1. Boron doping profiles of poly-Si/SiO_x/c-Si passivating contact at diffusion temperature of 920 °C for different thicknesses of the deposited a-Si layer.

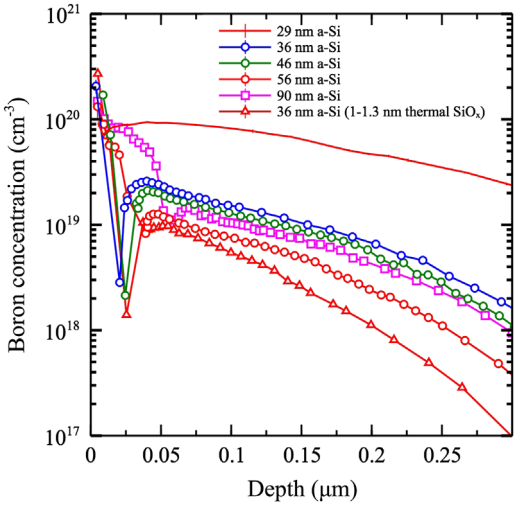

Fig. 2. Boron doping profiles of poly-Si/SiO_x/c-Si passivating contact at diffusion temperature of 980 °C for different thicknesses of the deposited a-Si layer.