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Passivation quality control in poly-Si/SiO$_x$/c-Si passivated contact solar cells with 734 mV implied open circuit voltage

HyunJung Park[a], Hyomin Park[a], Se Jin Park[a], Soohyun Bae[a], Hyunho Kim[a], Jee Woong Yang[a], Ji Yeon Hyun[a], Chang Hyun Lee[a], Seung Hyun Shin[a], Yoonmook Kang[b], Hae-Seok Lee[b,*], Donghwan Kim[a]

[a] *Department of Material science and Engineering, Korea University, 145, Anam-ro, Seongbuk-gu, Seoul 02841, Korea*
[b] *KU-KIST Green School Graduate School of Energy and Environment, Korea University, 145, Anam-ro, Seongbuk-gu, Seoul 02841, Korea*

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ABSTRACT

Passivation quality of poly-Si contacts with different phosphorus doping concentration were investigated in this study. Intrinsic poly-Si layers were deposited by LPCVD on a tunnel oxide surface, followed by n + poly-Si doping and hydrogenation. For lightly doped poly-Si contacts with phosphorus concentration of 2.1×10^{19} cm^{-3}, higher temperatures and longer times increased iV_{OC} achieving maximum value of 734 mV, as poly-Si grain size increases from 13 nm to 40 nm. However, for heavily doped poly-Si contacts with phosphorus concentration of 1.1×10^{20} cm^{-3}, iV_{OC} decreased from 731 mV to 696 mV as annealing time increased from 10 to 60 min because Auger recombination rate increased from 9.3 fA/cm^2 to 21.6 fA/cm^2 as phosphorus in-diffusion occurs. The contact resistance of poly-Si contacts was also investigated to achieve a high fill factor. Finally, a poly-Si/SiO$_x$/c-Si passivated contact solar cell using a poly-Si contact on the back and boron diffused emitter on the front was fabricated. As a result, high efficiency of 21.1% solar cell was achieved with V_{OC} of 665 mV, J_{SC} of 40.6 mA/cm^2, and fill factor of 78.3%.

1. Introduction

Recombination losses at the interface between the metal contact and doped-semiconductor region is a major efficiency-limiting factor in solar cells. To reduce losses from metal-semiconductor contact recombination, the concept of passivated contact was introduced. A tunnel oxide passivated contact (TOPCon) solar cell [1] is composed of a n + poly-Si/SiO$_x$/c-Si contact on the rear side and boron doped emitter on the front side, and has a reported highest efficiency of 25.8% [2,3]. One major method to form poly-Si/SiO$_x$/c-Si passivated contacts is to deposit an amorphous silicon layer (a-Si) and crystallized a-Si onto poly-Si with subsequent annealing. Another way is to use the low-pressure chemical vapor deposition method (LPCVD) for poly-Si deposition, which provides better crystallinity. Using LPCVD-deposited poly-Si/SiO$_x$/c-Si passivated contact (hereafter, poly-Si contact), some groups reported poly-Si contact solar cells using $POCl_3$ diffusion method and the highest efficiency was 21.5% [4,5]. Also, some groups reported poly-Si contact solar cells formed by ion implantation method to form n + doping on i-poly-Si layer which achieved the highest efficiency of 21.2% [6–10]. About iV_{OC} values, about 730 mV was obtained using crystallized a-Si passivated contact [9,11] and LPCVD deposited poly-Si passivated contact [12]. The highest iV_{OC} of 749 mV was reported by ISFH [13] for the latter with phosphorus implantation. Although many groups involved poly-Si contact, the relation between the poly-Si layer and passivation is still unclear because researchers focused on the tunnel oxide quality. However, characteristics of the poly-Si layer also affect on passivation quality of poly-Si contacts according to its annealing condition and doping concentration. Thus, we focused our study, to better understand the effect of the poly-Si layer on passivation quality, on the grain-size growth and phosphorus in-diffusion. High efficiency was achieved with a tunnel-oxide-passivated contact solar cell with a homogeneous boron emitter on the front and poly-Si contact on the rear.

For the experiments, the poly-Si contacts were annealed at different temperatures and times, and with different phosphorus doping concentrations, in the poly-Si layer. Passivation quality was determined using iV_{OC} and J_0 measured by the quasi-steady-state photoconductance (QSSPC) method [14]. The J_0 values are determined under the high

* Corresponding author.
E-mail addresses: jung1029@korea.ac.kr (H. Park), solar@korea.ac.kr (H.-S. Lee).
URL: http://solar.korea.ac.kr (D. Kim).

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injection assumption. The relationship between passivation and annealing temperature and time was analyzed using the grain-size growth effect. The size of the grains of the poly-Si layer was measured using grazing-incidence X-ray diffraction (GI-XRD) and Scherrer's equation [15]. The impact of the doping concentration of the poly-Si layer on phosphorus in-diffusion and contact resistance was also investigated. Finally, a solar cell with a poly-Si contact at the rear was fabricated and the cell efficiency was measured.

2. Experimental method

Symmetric poly-Si contact samples for lifetime measurement were prepared on 6-in. 180 µm-thick n-type Cz wafers with resistances of $1-2\ \Omega\cdot$cm. Saw damage on the wafer surfaces were etched using KOH solution. A thin silicon oxide layer for tunneling oxide with a thickness of 1.2 nm was grown on the wafer surface by dipping the wafer into H_2O_2 solution at 80 °C for 10 min [16]. After tunnel oxide formation, an intrinsic poly-silicon layer with thickness of 450 nm was deposited on both sides of the samples using LPCVD with silane precursor gas at 600 °C. To dope the intrinsic poly-Si layer, two different phosphor-silicate glasses (PSG) with doping concentrations of 2.8×10^{21} cm^{-3} and 4.6×10^{20} cm^{-3} were formed on the wafer surface. The PSG with a low doping concentration was deposited using plasma-enhanced chemical vapor deposition (PECVD) at 310 °C, and the PSG with a high doping concentration was formed by $POCl_3$ diffusion in a tube furnace. The subsequent annealing at 800–950 °C for 10–60 min was conducted in the same tube furnace used for the $POCl_3$ diffusion. Hereafter we call the samples heavily doped (HD), lightly doped (LD), and undoped or intrinsic (UD) poly-Si contacts, respectively. The effects of annealing on poly-Si contacts passivation quality were investigated by measuring iV_{OC}, J_0, and on the lifetime using the QSSPC method after hydrogenation. For the hydrogenation at the interface of n + poly-Si/SiO_x/c-Si, silicon nitride films were deposited using PECVD and subsequently annealed in the rapid thermal process chamber (RTP) at 600 °C for 15 min. Silicon nitride layer was removed by HF dipping. We measured the average grain size of the poly-Si layer using GI-XRD and high-resolution electron backscatter diffraction (HR EBSD). Doping concentration profiles from the surface to the crystalline silicon substrate were measured using secondary ion mass spectroscopy (SIMS), and contact resistance was determined using transmission line measurement (TLM) on the lifetime measurement samples after QSSPC measurement. Finally, a solar cell structure with a poly-Si contact on the back and B diffused emitter with Al_2O_3/SiN_x stack passivation layer on the front was fabricated and the efficiency was measured Fig. 1.

3. Results and discussions

3.1. Poly-Si passivation quality as a function of annealing condition

First, the effect of annealing temperature on UD and LD poly-Si contacts was investigated. The as-deposited (as-dep) poly-Si/SiO_x/c-Si sample before annealing showed a very low iV_{OC} of 580 mV. As shown in Fig. 2 (a), after undergoing the hydrogenation process without annealing, the iV_{OC} of this as-dep sample increased to 665 mV. However, this iV_{OC} value was still low compared with the symmetric UD sample annealed at 875 °C without hydrogenation, which achieved an iV_{OC} of 673 mV. This result indicates that the as-dep poly-Si contacts structure cannot achieve interface passivation without hydrogenation or an annealing process. From Fig. 2 (a), the iV_{OC} of the UD poly-Si contacts increased from 658 mV to 694 mV as annealing temperature increased from 800° to 950°C. The same result was found for the LD poly-Si contacts sample: the iV_{OC} increased as annealing temperature increased. This two results indicate that the poly-Si contacts passivation quality is

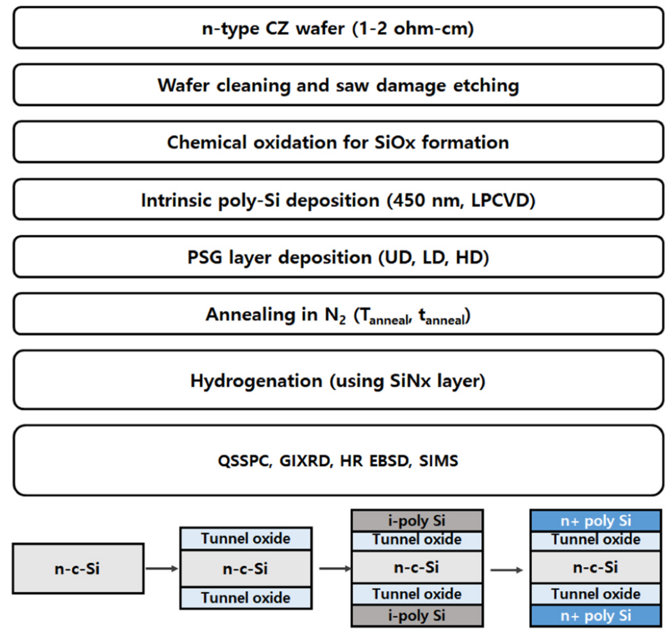

Fig. 1. Experimental procedures to fabricate symmetrical tunnel oxide passivated contact samples.

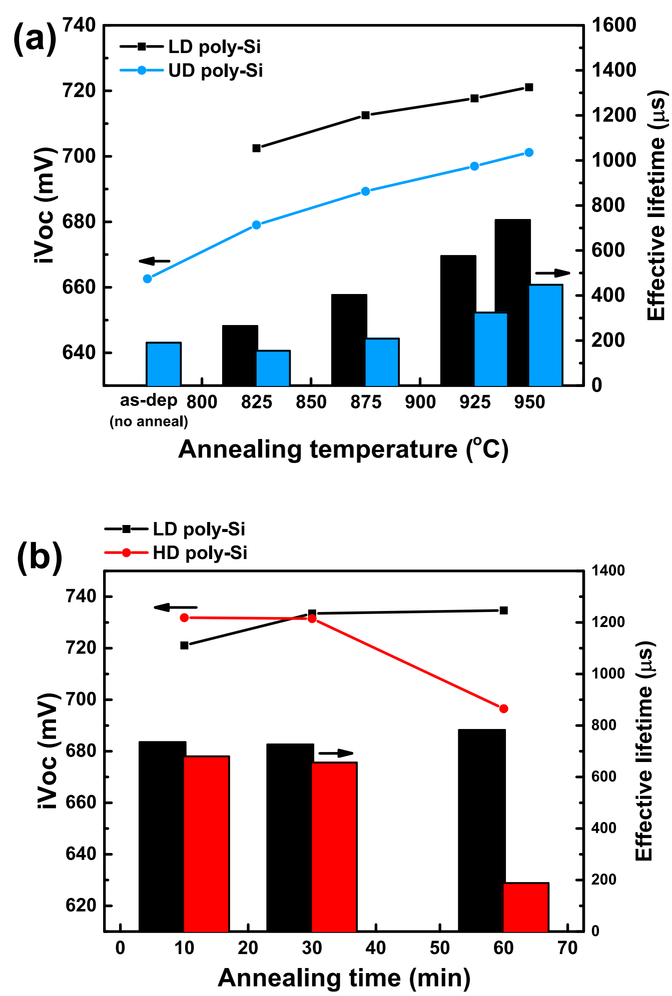

Fig. 2. Implied open circuit voltage and effective lifetime of poly-Si contacts as a function of (a) annealing temperature and (b) time.