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Optical and electrical characterization of poly-Si/SiO_x contacts and their implications on solar cell design

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Abstract

The scope of this paper lies on the phenomenon of free-carrier absorption (FCA) in heavily phosphorus-doped poly-Si layers, applied at solar cells featuring poly-Si/SiO_x passivating contacts at the rear. Firstly, FCA is investigated on test structures featuring poly-Si contacts of different thickness and doping level. Secondly, these passivating contacts are integrated into the rear of solar cells featuring a boron-diffused emitter at the front. The infrared (IR) response of the solar cells is analyzed and FCA losses are quantified. In agreement with theory, it is shown that J_{sc} losses due to FCA increase with poly-Si doping level and thickness. For instance, a total J_{sc} loss of ~0.5 mA/cm² is obtained for a 145 nm thick poly-Si layer with a doping concentration of 1.9×10^{20} cm^{-3}.

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1. Introduction

Carrier-selective and passivating contacts can be ascribed a key role in improving the efficiency of crystalline silicon solar cells [1-5]. Recently, researchers at Kaneka achieved a new world-record of 26.6% efficiency by integrating the a-Si:H/c-Si heterojunction (HJT) into an IBC solar cell structure. Apart from that, passivating contacts which are based on an ultrathin SiO_x layer and a heavily-doped silicon film (e.g. poly-Si [6-9], SIPOS, or TOPCon [5]) have become an appealing alternative to heterojunction solar cells. This technology not only reduces minority carrier recombination to a level almost similar to HJT but also offers a higher tolerance to high-temperature processes, such as diffusion and firing [10, 11]. Hence, such passivating contacts hold the promise of a more cost-effective back-end process sequence.

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While there are plenty of papers dealing with the electrical properties of passivating contacts, such as surface passivation and contact resistivity, few papers deal with their optical properties. It has been shown that the absorption coefficient α of poly-Si resembles c-Si [12] and, thus, is lower than α of a-Si. Nevertheless, poly-Si contacts at the front side of a solar cell absorb about 0.5 mA/cm²/10 nm poly-Si [13]. By placing the passivating contact solely on the rear and using a homojunction at the front, parasitic absorption losses in the blue wavelength regime are avoided. Still the red response of the solar cell is affected by parasitic absorption losses, which separate into free carrier absorption (FCA) in poly-Si and absorption by the metal contact. On a lab scale, an efficiency of up to 25.7% has been achieved [14]. A first attempt to fabricate a comparable solar cell using industry-proven techniques resulted in an efficiency of 20.7% [10]. Among other losses, one significant loss was ascribed to FCA in the 200 nm thick, heavily P-doped poly-Si films at the rear.

Although, the absorption of infrared (IR) light due to FCA has been extensively studied for c-Si [15-17], the effect of poly-Si doping level and thickness has not been studied on solar cells yet. This paper addresses the optical and electrical characterization of n-type poly-Si/SiO_x contacts. Firstly, surface passivation of the poly-Si contacts is studied as a function of doping level and poly-Si thickness. Secondly, FCA coefficient is determined from spectrophotometer measurements. Finally, solar cells with poly-Si/SiO_x rear contact are shown and the impact of FCA is revealed.

2. Experimental details

2.1. Preparation and characterization of test structures

Symmetrical lifetime samples featuring different passivating contacts were realized on planar, (100) oriented n-type 1 Ωcm wafers. The following contact configurations were realized:

1) 35 nm poly-Si with $N_D = 5.5x10^{19}$ cm^{-3} ([P] = $1.5x10^{15}$ cm^{-2})
2) 90 nm poly-Si with $N_D = 1.19x10^{20}$ cm^{-3} ([P] = $3x10^{15}$ cm^{-2})
3) 145 nm poly-Si with $N_D = 1.29x10^{20}$ cm^{-3} ([P] = $4x10^{15}$ cm^{-2})
4) 145 nm poly-Si with $N_D = 1.67x10^{20}$ cm^{-3} ([P] = $5x10^{15}$ cm^{-2})
5) 145 nm poly-Si with $N_D = 1.90x10^{20}$ cm^{-3} ([P] = $6x10^{15}$ cm^{-2})

To this end, the wafers were cleaned according to the RCA procedure and a thin oxide layer was grown in boiling nitric acid. The poly-Si contacts were fabricated by low-pressure chemical vapor deposition (LPCVD) of intrinsic amorphous silicon and subsequently ion implantation of phosphorus (P) was performed. The ion dose and implantation energy were adjusted to the individual layer thicknesses. All wafers were then annealed at 850 °C for 30 min and finalized by a hydrogen passivation step at 425 °C for 25 min (RPHP [18]).

2.2. Preparation of solar cells and test structures

2x2 cm² solar cells were realized on n-type 1 Ωcm wafers with a thickness of 200 µm. The cells feature a homogeneous 150 Ω/sq boron emitter at the front which is well passivated by a stack of Al_2O_3 and SiN_x. At the rear passivating contacts as described in Sec. 2.1 were realized. Moreover, for the reference solar cells TOPCon featuring the same tunnel oxide layer but a PECVD SiC(n) layer was formed at the rear. Upon the high-temperature anneal the LPCVD a-Si films turned poly-crystalline while the a-SiC film remained amorphous as outlined in Ref. [19]. It should be noted that the poly-Si films had to be removed from the front by reactive ion etching as the LPCVD process always coats both sides of the wafer, in contrast to the PECVD TOPCon approach, which is strictly single sided.

The cells received an H-pattern grid on the front by means of thermal evaporation of Ti, Pd, and Ag and the lift-off technique. The contact fraction was about 1% and the shading due to the front metallization was ~1.1%. Thereafter, the solar cells were subjected to a hydrogenation process (RPHP) at 425 °C for 25 min. Finally, the rear side was metallized by thermal evaporation of Ag which makes a good contact and, more importantly, ensures a very high rear reflection.