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Improvement of the SRH bulk lifetime upon formation of n-type POLO junctions for 25% efficient Si solar cells

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ABSTRACT

Carrier-selective contact schemes, like polysilicon on oxide (POLO), provide low contact resistivities while preserving an excellent passivation quality. These junctions offer an important additional feature compared to a-Si/c-Si heterojunctions. We find that the formation of *n*-type POLO junctions lead to a huge increase of the Shockley-Read-Hall (SRH) lifetime of the substrate, a prerequisite for highly efficient solar cells. The SRH lifetime improvement can be observed for both bulk polarities and for a variety of bulk resistivities. Thus we suggest that the highly doped POLO junction getters impurities that have more or less symmetric SRH capture cross sections. We are able to achieve SRH lifetimes of > 50 ms. By applying POLO junctions to interdigitated back contact cells, we achieve cells with an efficiency of 25%.

1. Introduction

Passivating contacts in combination with the interdigitated back contact (IBC) cell design enable the so far highest energy conversion efficiencies of up to 26.6% for single junction silicon solar cells [1]. Currently, two types of passivating contacts are used for IBC cells: a-Si/c-Si heterojunctions and polycrystalline on oxide (POLO) junctions [2,3].

POLO junctions, as used in this work, exhibit high temperature stability which might be beneficial for industrialization applying conventional high temperature process techniques. Furthermore we find that even for high quality FZ wafers the Shockley-Read-Hall (SRH) limitation of bulk lifetime can be significantly reduced during the high-temperature *n*-type POLO junction formation step. We systematically study this aspect on different bulk polarities and resistivities. Finally we use these results to prepare IBC solar cells with an independently confirmed efficiency of 25% and an efficiency potential exceeding 26%.

2. Experimental

We use *n*-type and *p*-type FZ wafers with resistivities between 1.5 Ωcm and 90 Ωcm. The samples are either passivated with Al_2O_3 or with POLO junctions. The latter are prepared as follows. After thermal oxidation (~ 2.2 nm), 225 nm intrinsic polysilicon (poly-Si) is deposited by low pressure chemical vapour deposition. The poly-Si is *ex situ* doped by ion implantation, either with boron ($N_A \approx 1 \times 10^{20}\,cm^{-3}$), phosphorus ($N_D \approx 2 \times 10^{20}\,cm^{-3}$), or both (*n*-type counter-doped ($N_D \approx 1 \times 10^{20}\,cm^{-3}$) [4]). After junction formation (990–1080 °C), all samples are characterized by photoconductance decay method (PCD). Emitter saturation current densities (J_{0e}) are extracted by applying the method of Kane & Swanson [5]. The measured effective lifetimes were decomposed into limitations implied by the surface (using the J_{0e} values), by Auger and radiative recombination (using the model of Richter et al. [6]), and by the SRH recombination within the substrates. The lifetime of the surface recombination (τ_{surf}) is calculated by using following equation: $\tau_{surf} = (q \times n_i^2 \times W)/([\Delta n + n_0 + p_0] \times J_{0e})$. With q the elementary charge, n_i the intrinsic charge carrier density, W the substrate width, Δn the excess carrier density and n_0/p_0 the equilibrium chare carrier densities. An injection-independent SRH lifetime (τ_{SRH}) was used as a fitting parameter in order to reproduce the measured effective lifetimes. Any injection dependency of τ_{SRH} would lead to an unreasonable amount of fit parameters (capture cross sections, energetic position of the trap level, etc.), possibly causing unreliable results. From this simplification, the relative uncertainty of the extracted lifetimes represents the uncertainty of the measurement itself, which is around 20% [6]. Fig. 1 shows an exemplary comparison of τ_{SRH} determination using the intercept method of Kane & Swanson (Fig. 1a) and the above described fitting procedure of the measured trend of τ_{eff}

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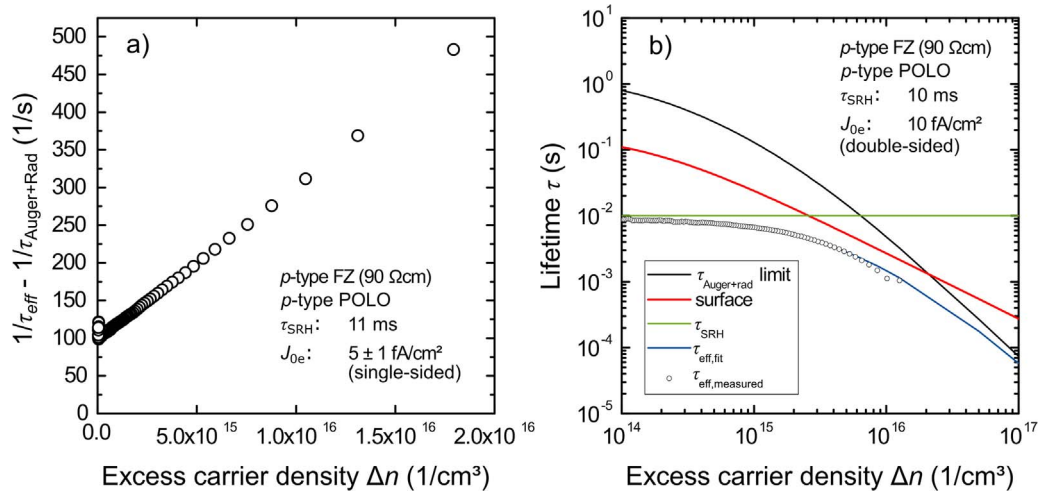

Fig. 1. a) inverse minority carrier lifetime, corrected for Auger and radiative recombination [6] and b) measured lifetime and its single components as a function of the excess carrier density of a *p*-type POLO junction on *p*-type FZ substrate (90 Ωcm). The junction is formed at 1050 °C.

as a function of the excess carrier density (Fig. 1b). Both methods are in good agreement, although τ_{SRH} after Kane & Swanson tends to give slightly higher τ_{SRH} values (11 ms instead of 10 ms in this case). This trend is also observed in multiple lifetime analysis on various other samples (not shown here).

Based on the observation of an improvement of τ_{SRH} upon gettering in *n*-type POLO junctions, we include this step into the fabrication process for interdigitated back contact solar cells [3].

3. Results and discussion

3.1. Improvement of the SRH lifetime upon junction formation

The impact of the POLO junction formation is found to be very similar for all substrate polarities and resistivities. Therefore the results will exemplary be discussed by means of the 90 Ωcm *p*-type substrates. Here we first focus on samples annealed at 1050 °C since this is around the optimum for the used interfacial oxide [7]. In Fig. 2, the measured effective lifetimes are plotted as a function of the excess carrier density after POLO junction formation. Furthermore, the modelled contributions from the surfaces, the bulk (τ_{SRH}) as well as Auger and radiative recombination are also shown. Around the implied maximum power point (MPP, $\Delta n \approx 2 \times 10^{15}\,cm^{-3}$) the effective lifetime in the sample with *p*-type POLO junctions is limited by a comparatively low τ_{SRH} value of 11 ms (Fig. 2a). This is different for the samples with *n*-type POLO junctions (Fig. 2b & c). Here much higher τ_{SRH} values of 50 ms are obtained. These modelled values of τ_{SRH} can only be considered as lower limits since even higher values of τ_{SRH} do not impact the effective lifetime characteristic anymore.

Additionally the corresponding implied *J-V* curves are given in Fig. 3. Compared to Fig. 2 some extra information can be recognized. For the *p*-type POLO junctions the slope of the curve significantly changes across the displayed voltage range (Fig. 3a) which is not the case for the *n*-type POLO junctions (Fig. 3b & c). This behavior is mirrored in the extracted ideality factors at the MPP of 1.27 for *p*-type POLO, 1.00 for *n*-type POLO and 1.03 for counter-doped *n*-type POLO junctions. This strong decrease in ideality factor around MPP comes in hand with an increases implied fill factor (*ipFF*) after *n*-type POLO junction formation. Here an *ipFF* of 84.4% for *p*-type POLO and up to 86.2% for *n*-type POLO junctions is extracted. Our hypothesis for this improvement is a very effective external gettering of recombination-active impurities by the *n*-type POLO layers. The corresponding effects and mechanisms are discussed in the following sections.

Fig. 4 summarizes the extracted τ_{SRH} values for all investigated base resistivities and polarities. After cleaning and surface passivation with Al_2O_3 (but apart from that "out-of-box"), the *p*-type wafers have SRH lifetimes around 14 ms except for the 3.7 Ωcm material (~ 1 ms). The *n*-type substrates feature SRH lifetimes of 4 ms and 10 ms after Al_2O_3

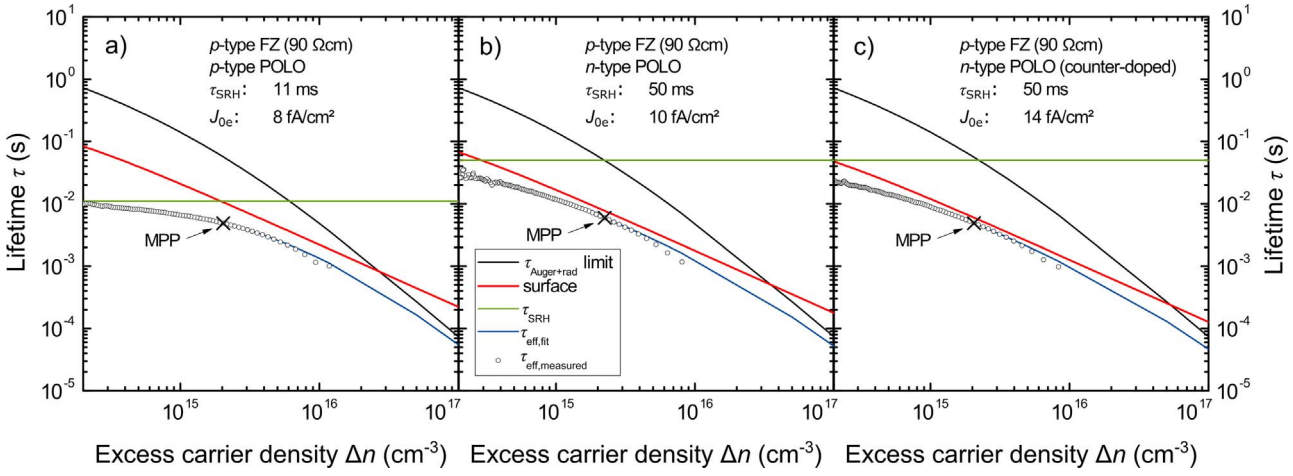

Fig. 2. Measured effective carrier lifetimes as a function of the excess carrier density on *p*-type substrates. a) *p*-type POLO, b) *n*-type POLO and c) *n*-type counter-doped POLO junctions. The modelled charge carrier lifetimes for Auger and radiative, SRH and surface recombination are also shown. J_{0e} accounts for the total value of a double-sided sample. All samples are annealed at 1050 °C.