Temperature-dependent Characterization of $Si\text{-}SiO_2$ Interface Passivation for Corona Charged Oxides

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As solar cells often operate at temperatures above room-temperature, the temperature-dependent device properties are vital to predict in-field devices performance. Corona-charged dielectric films have been shown to provide excellent surface passivation for silicon solar cells by means of field-effect. In research, they have also been used to investigate the recombination at the silicon-dielectric interfaces. However, to date, only little is known about the impact of temperature on the obtained passivation. This study investigates, for the first time, the performance of corona-charged silicon dioxide at elevated temperatures. The passivation quality is demonstrated to improve with increasing temperature above room-temperature. However, at high temperatures (>50 °C), a degradation of the surface passivation is observed. We ascribe this degradation to charge leakage in the silicon dioxide.

Introduction

A key requirement for high-performance silicon (Si) solar cells is the development of excellent surface passivation [1]. As elevated temperature generally has a detrimental impact on the solar cells performance [2], it is necessary to investigate the Si-dielectric interface, not only at standard testing conditions (STC) but also as a function of temperature. This understanding will allow better design of the surface passivation under real-world operating conditions.
Corona charging is a promising method to enhance the passivation quality using what is often-called the 'field effect passivation' [3], [4]. Furthermore, the ability of corona charge to manipulate the surface potential and interface band bending, without changing the interface state density (D_{it}) and the capture cross sections of electron and holes (σ_n and σ_p), aids in the investigation of the surface recombination in Si solar cells. This method has been used to study the Si-dielectric interface properties [4], [5] at STC, without variation in temperature. In this study, we investigate the recombination at the $Si\text{-}SiO_2$ (silicon dioxide) interface under varying temperature, excess carrier density (Δn), and dielectric fixed charge (Q_f). As $Si\text{-}SiO_2$ interface is used in many of the new contact passivating structures, the conclusions of this study will serve a wide variety of applications and cell device architectures.

Method

Phosphorus-doped, *n*-type float zone (FZ) Si wafers (planar surfaces) with resistivity of 1 Ω.cm and thickness of 200 µm are used in this study. All wafers underwent a Radio Corporation of America cleaning before thermally dry oxidation at 1000 °C. The oxidation time was modified to obtain a SiO_2 thicknesses of 100 nm. A custom-built corona discharge setup is then used to deposit positive charge onto the SiO_2 layer using a point-to-plane configuration. A hexamethyldisilizane (HDMS) treatment is used to produce a SiO_2 hydrophobic surface and thus, stabilise the corona charge for the duration of the characterisation measurements [6]. It is noted that bulk defects, that may exist in high-quality FZ wafers [7], were minimized by a thermal oxidation process.
Temperature- and injection-dependent effective lifetime (τ_{eff}) are measured using a custom-made lifetime tester based on the Sinton WCT-120 instrument. The photoconductance-based τ_{eff} is measured using both quasi-steady state (QSS) and transient modes in the temperature range from -50 ºC to 200 ºC. To monitor possible measurement-induced variations, τ_{eff} is measured at 30ºC before and after temperature scan.

Results and Discussion

Figure 1 shows injection-dependent τ_{eff} of a wafer with a 100 nm thick SiO_2 layer (a) with and (b) without corona charge, acquired between -50 ºC and 200 ºC. When comparing Figures 1a and 1b it is evident that the deposition of corona charge improves τ_{eff} by more than one order of magnitude in this specimen, where τ_{eff} above 2.5 ms at Δn = 1×10^{15} cm^{-3} at 30 °C is achieved. Figure 1a shows that τ_{eff} increases with increasing temperature for the entire Δn range, up to 125 °C. However, the temperature-dependence of τ_{eff} above 125 °C is not monotonic. After the high-temperature measurements, τ_{eff} is remeasured at 30 °C (pink triangle). The reduced τ_{eff} indicates that the high temperature measurements induce degradation. The temperature and injection-dependent τ_{eff} of the sister wafer, passivated by SiO_2 *without* corona charge, is given in Figure 1b. At low-temperature range, τ_{eff} reduces with increasing temperature at high to medium Δn range, whereas opposite trend is obtained at the medium to low Δn range. Improved τ_{eff} is observed with increasing temperature (for the entire Δn range) within the temperature range of 30 °C to 200 °C. No significant variation of τ_{eff} occurs after the completion of the temperature scan. This pinpoints that the τ_{eff} decay of the corona-charged wafer can be ascribed to a loss of charge at high temperatures, rather than a degradation of the chemical passivation quality or of the bulk lifetime.

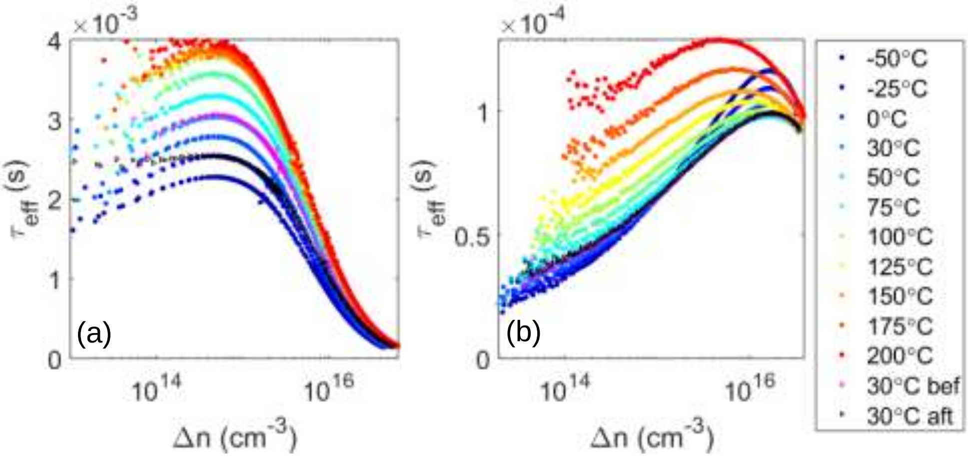

Figure 1. Temperature and injection dependent τ_{eff} for an *n*-type Si wafer passivated with 100 nm thick SiO_2 layer (a) with and (b) without corona charge.

Since the measured τ_{eff} of the sample without corona charge [Figure 1(b)] is dominated by surface recombination, we have modelled the temperature- and injection-dependent τ_{eff}, based on the extended SRH statistics [5], [8] (see Figure 2a). This SRH model is extended to consider the temperature dependency of different components (such as bandgap, thermal velocity, intrinsic carrier density and σ_n, σ_p). The discrepancy between the simulated and measured τ_{eff} at high injection level (see Fig. 2a) can be explained by the temperature-dependence of Auger recombination [9] which is not considered in this model. The obtained Si-SiO_2 interface defect parameters are summarized in Table I.

Table I. Si-SiO_2 interface defect parameters

Fixed dielectric charge Q_f (q/cm^2)	Interface trap density D_{it} (cm^{-2}eV^{-1})	Electron capture cross section σ_n (cm^2)	Electron and hole capture-cross-section ratio k (σ_n/σ_p)
1×10^{10}	1.3×10^{11}	$2 \times 10^{-16} exp\left(\frac{-0.01}{kT}\right)$	2

Figure 2b presents the extracted temperature and injection dependent surface recombination velocity (SRV) using the interface defect parameters from Table I, while Figure 2c shows the corresponding SRV when Q_f is increased to 1.6×10^{12} q/cm^2 (this value is closed to the amount of corona charge deposited on our sample). Interestingly, it is noted that the injection-dependence of SRV is reversed when higher amount of Q_f is presented in the SiO_2. Meanwhile, improved surface passivation (as indicated by a lower SRV) is observed with increasing temperature.

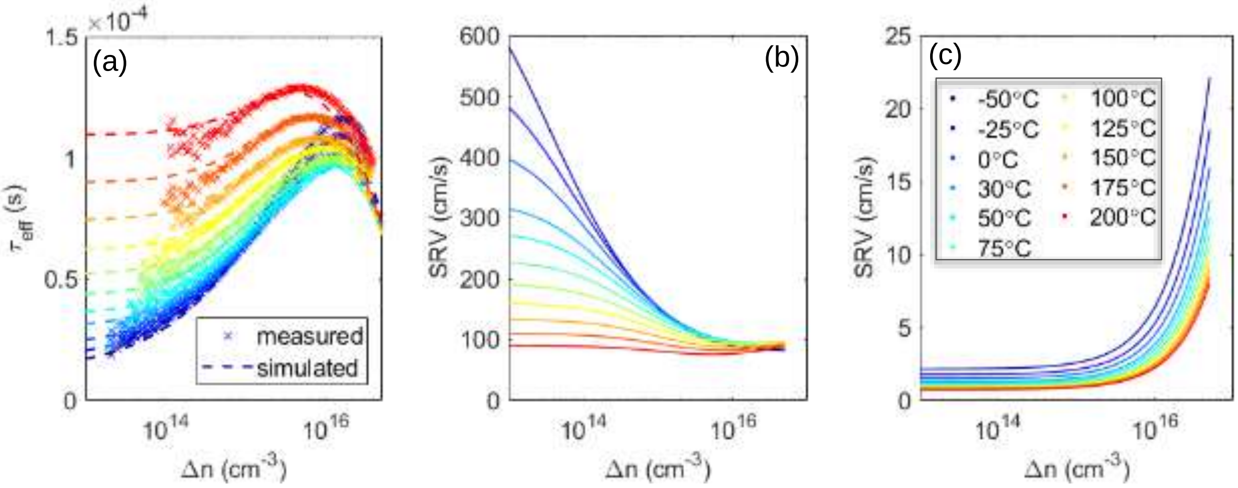

Figure 2. (a) Measured and simulated τ_{eff} for an *n*-type Si wafer passivated with 100 nm thick SiO_2 layer without corona charge. Extracted SRV with (b) $Q_f = 1\times10^{10}$ q/cm^2 and (c) $Q_f = 1.6\times10^{12}$ q/cm^2.

Conclusion

This work presents the first report of temperature-dependent surface recombination at the Si-SiO_2 interface. The observed dependence has been modelled by extending the SRH formalism to include temperature dependence. Our results will be highly valuable for future improvement and understanding of surface recombination in realistic cell operating conditions, as well as temperature-dependent device modelling for predicting and optimizing solar cell performance beyond STC. This study also emphasises that stability of charge needs to be improved for the corona-charged SiO_2 technology to fulfill its full potential at elevated operation temperatures.

References

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