

# LOWEST SURFACE RECOMBINATION IN N-TYPE OXIDISED CRYSTALLINE SILICON BY MEANS OF EXTRINSIC FIELD EFFECT PASSIVATION

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**ABSTRACT:** Surface recombination remains a major factor limiting the efficiency of silicon solar cells. The post-processing of dielectric films used as surface coatings has been previously demonstrated an effective technique to improve their passivation quality. In this paper extrinsic methods are demonstrated to produce the lowest reported surface recombination velocity in solar relevant n-type silicon. Recombination velocities below 2.8 cm/s at an injection of  $10^{15} \text{ cm}^{-3}$ , are achieved using extrinsic field-effect passivation, or  $< 0.6 \text{ cm/s}$  when using combined extrinsic chemical and extrinsic field effect passivation. These are equivalent to emitter saturation current densities  $J_0 < 1.4 \text{ fA/cm}^2$  and  $0.6 \text{ fA/cm}^2$ .

**Keywords:** surface passivation, dielectric film, IBC silicon solar cell

## 1 INTRODUCTION

Recombination at surfaces and interfaces continues to be a limiting process on the path to high performance silicon solar cells. Despite their high potential efficiency, back contacted crystalline silicon cells are especially susceptible to recombination at the front surface [1]. Substantial progress has been made towards developing dielectric coatings that provide near optimal passivation to back contacted cells [2].

Their passivation quality relies on two main mechanisms. First, the reduction of defect state density at the silicon-dielectric interface by satisfying dangling bonds, and second, the presence of net charge in the dielectric which helps reduce the concentration of minority carriers at the surface, thus reducing their availability for recombination. These two mechanisms are jointly exploited in a single or double layered dielectric coating – e.g. silicon dioxide, silicon nitride or aluminium oxide.

In addition to the layer's passivation properties, minimal parasitic optical absorption and matching refractive index must also be optimised during a single dielectric deposition process. As a result, there exists a trade-off between the best chemical, field effect and optical properties in the dielectric film. An approach by which the properties of a dielectric coating can be improved after deposition has been previously suggested and referred to as extrinsic passivation as opposed to intrinsic passivation which is only achieved by tuning of the deposition process [3]. Forming gas or post-metallization anneals are well-known processes by which chemical passivation can be improved after dielectric deposition. These processes aim to introduce and/or diffuse hydrogen to the dielectric-silicon interface [4].

Another extrinsic process that can be used to improve field effect passivation is the external addition of charge onto or into the dielectric [5]. This method has been widely used at research scale, yet industrial adoption is hindered by the lack of stability of the extrinsically added charge. Addressing the stability problem is an ongoing research topic and noteworthy progress has been presented in [6,7]. Moreover, the striking effectiveness of extrinsic field effect passivation has only been highlighted recently [3]. In the present work we report the lowest recombination observed on oxidised silicon wafers using extrinsic field-effect passivation by means of corona discharge. Despite high temperature processing, effective lifetimes of up to 5 ms are possible on 1  $\Omega\text{cm}$  n-type float zone Si.

This passivation performance exceeds that reported by Kerr and Cuevas for the so called *alnear* [8], and that achieved using a double layer thermal oxide and silicon nitride [9–11]. Such surface passivation leads to outstanding performance of interdigitated back contact cells as simulated using Quokka 2.2.4 [12]. These results highlight the improvement possible via extrinsic passivation methods. The potential for increased performance with negligible cost make such methods likely to become industrially relevant once the stability issue is resolved.

## 2 EXPERIMENTAL METHODS

Float zone 1  $\Omega\text{cm}$  n-type 4 inch 200  $\mu\text{m}$  thick silicon wafers were oxidised in a Centrotherm tube furnace at 1050  $^\circ\text{C}$  in a dichloroethylene (DCE) atmosphere to produce 100 nm oxide films as base passivation. The wafers were then split into two batches of wafers, and one was annealed (FGA) in forming gas (5% $\text{H}_2$ /95%Ar) for 25 minutes at 425  $^\circ\text{C}$  immediately after oxidation. Effective lifetime was then recorded using Sinton photo-conductance decay (PCD) measurements as the oxide films were charged on both sides using a corona discharge apparatus optimised for uniformity, as described in [3].

Deposited charge was monitored between every step using Kelvin Probe surface potential measurements. The charge concentration was extracted assuming that all charge was situated at the surface of the dielectric, and that the potential drop inside the silicon was negligible:  $Q_{\text{corona}} = \epsilon_{\text{SiO}_2}/t * [\Phi_{\text{sm}}/q - V_{\text{KP}}]$ , where  $t$  is the thickness of the oxide,  $\Phi_{\text{sm}}$  is the semiconductor to metal work function difference, and  $V_{\text{KP}}$  is the backing potential measured from Kelvin Probe.

A schematic of the corona discharge apparatus is shown in **Figure 1.a**. The rate of charge deposition was determined by the corona current  $i_c$ , which in turn was adjusted by setting the corona potential  $V_c$  and distance  $d_c$ . Three different conditions were used in these experiments as illustrated in **Figure 1.b**. The corona current was set to  $\sim 3\text{--}5 \mu\text{A}$  which allowed deposition of charge in reasonable time steps ( $\sim 50 \text{ s}$ ). This same charging process can be used industrially in a time scale of seconds by applying a higher current using this very simple apparatus.

A photo-luminescence (PL) lifetime measurement was performed on Wafer 4 using a BTi imaging PL system to evaluate the lifetime across the entire wafer, **Figure 1.c**.

Here, the count number was calibrated to a Sinton PC lifetime tester. Several poor lifetime spots were observed. Uniformity of the field effect passivation was demonstrated in [13], thus indicating that the recombination is induced by interface defect states, or poor bulk lifetime. Most likely the former but not further comments can be made here.

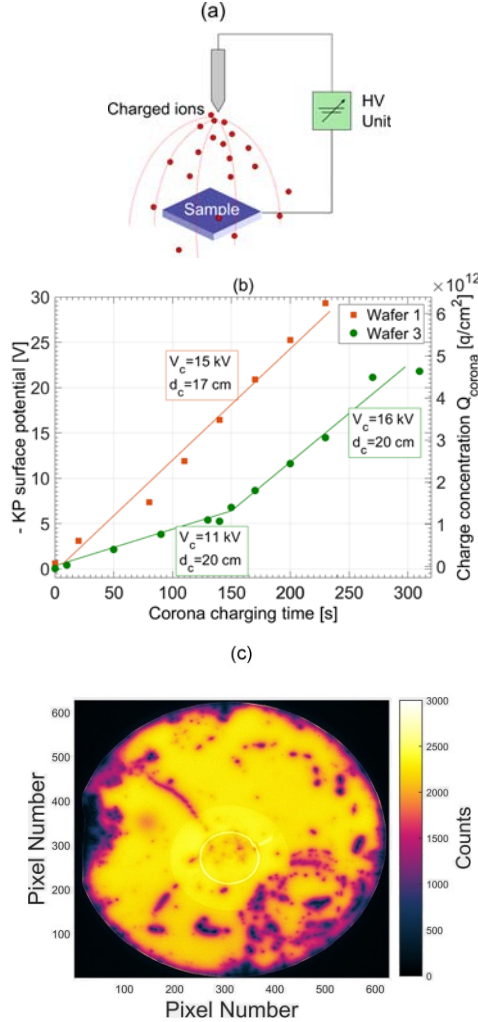


**Figure 1:** a. Scheme of corona discharge on top of oxidised silicon samples, b. Rate of charge deposition for different corona discharge conditions, c. PL image of Wafer 4 when corona charge has been uniformly deposited to improve surface passivation extrinsically.

### 3 EXTRINSIC SURFACE PASSIVATION OF C-SI

Upon corona charge deposition, the recombination rate at the silicon surface is reduced via field effect passivation. This is illustrated in **Figure 2** where PCD effective lifetime is plotted against minority carrier injection level for incrementally higher dielectric charge concentrations. Lifetimes exceeding 5 ms have been achieved using extrinsic methods to improve the passivation quality of  $SiO_2$  films. Both chemical and field effect passivation are clearly contributing towards the overall passivation quality of these wafers. Wafers 2 and 4 were included to show repeatability. The lack of uniformity of passivation techniques, especially at the

edges of the specimen [14], has recently been reported as one of the factors that limit the overall passivation quality. The substantially higher lifetimes achieved here corroborate previous studies where lifetime was limited by recombination at the edge of the specimens. The peak in lifetime observed in the shape of the lifetime curves for wafers 1 and 2 indicate that the total lifetime is limited by a bulk or near surface recombination. Bulk is likely to arise in high temperature processes as recently pointed out by Grant et al [15]. It is not possible to conclude if such a mechanism is eliminated during FGA for wafers 3 and 4 since these were oxidised using a different process.

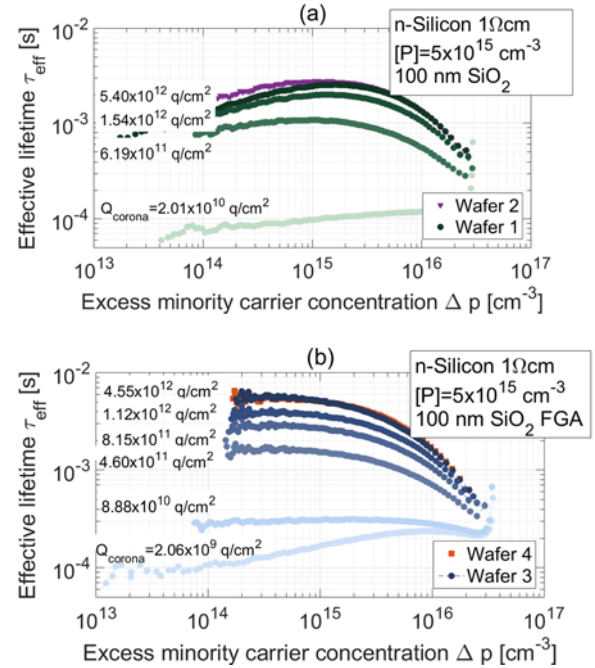


**Figure 2:** Effective lifetime of n-type c-Si as a function of injection level and corona deposited charge for a. Only oxidised wafers, and b. oxidised and FGA wafers.

### 4 SRV AND $J_{0E}$ IN EXTRINSICALLY PASSIVATED C-SI

Upper limits to surface recombination velocity (SRV) have been extracted using Richter's [16] parametrisation of intrinsic lifetime for 1  $\Omega cm$  ( $5 \times 10^{15} cm^{-3}$  donors) crystalline silicon, where  $SRV_{UL} < (1/\tau_{eff} - 1/\tau_{int})W/2$ . **Figure 3.a** and **b** illustrate the measured SRV as a function of injection level for different concentrations of dielectric charge. A SRV below 2.8 cm/s was calculated for the maximum charge concentration in an oxidised wafer at  $10^{15} cm^{-3}$  carrier injection. Furthermore, a SRV < 0.6 cm/s was achieved on a wafer that underwent FGA prior to corona charge depositions. **Figure 3.c** illustrates the calculation of emitter saturation current densities using Kane and Swanson's [17] method as implemented in Sinton's lifetime software version 4.6.0 using Richter's  $\tau_{Bulk}$  correction. The emitter saturation current densities were  $J_{0e} = 0.5 fA/cm^2$  and  $1.36 fA/cm^2$  respectively. When calculated using approximation (3) in [18],  $J_{0e} = SRV * qn_i^2 / (N_{dop} + \Delta p)$ , the current densities increase to 1.5 fA/cm<sup>2</sup> and 7 fA/cm<sup>2</sup>. To the best of our knowledge, such surface recombination parameters are the lowest reported for 1  $\Omega cm$  n-type c-Si passivated with a single layer of

thermal SiO<sub>2</sub>. Prior to the extrinsic field effect passivation achieved by the corona discharge, the SRV was ~100 cm/s and  $J_{0e}$ = 253 fA/cm<sup>2</sup> for oxidised wafers, and SRV was ~60 cm/s and  $J_{0e}$ =152 fA/cm<sup>2</sup> for oxidised and FGA wafers.

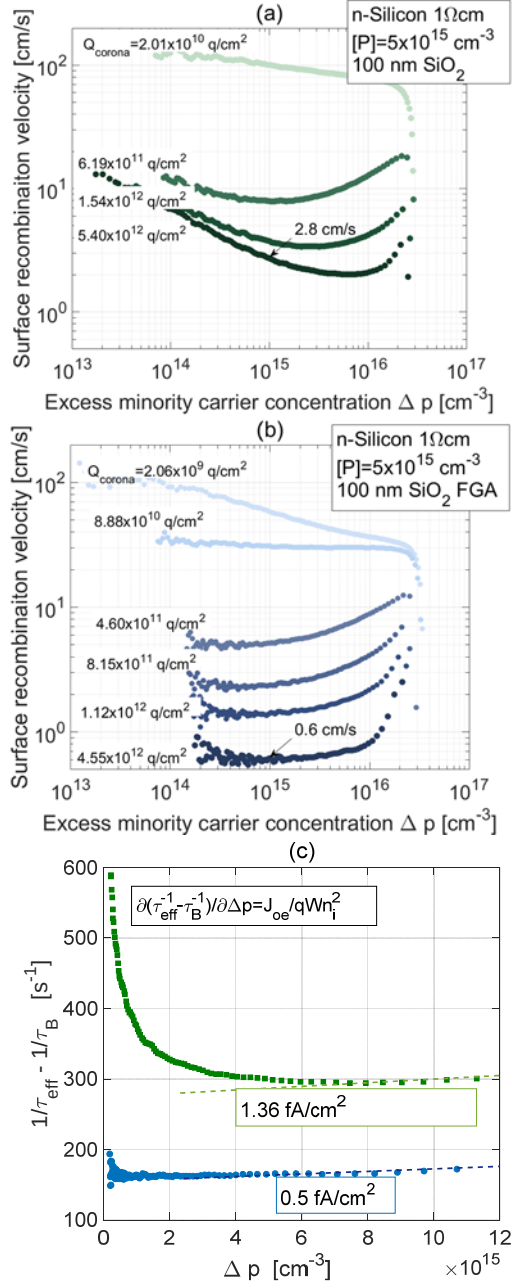


**Figure 3:** Surface recombination velocity as a function of injection level and corona deposited charge for a. Oxidised-only wafers, and b. Oxidised and FGA wafers, c. Extraction of emitter saturation currents for optimally passivated silicon wafers.

## 5 THE EFFECT OF FRONT SURFACE RECOMBINATION ON IBC CELL PERFORMANCE

Interdigitated back contact cells were simulated using Quokka 2.2.4 [12] following the parameters reported by Fell in [19]. The model was altered to evaluate the effect of the front surface passivation. The dark recombination current density at the front surface was varied in the range of values found in Section 4. **Figure 4.a** illustrates a

typical meshing of the unit cell studied, including the n, p, metallised and contacted regions.  $J_{0e}$  values ranging from 0.1 to 1000 fA/cm<sup>2</sup> were simulated. The equivalent SRVs are displayed in the x-axis in **Figure 4.b**. Here it is evident that cell performance is strongly dependent on passivation of the front surface, when the quality of the passivation is poor (SRV>100 cm/s). A ~2% gain in efficiency is possible when reducing recombination from ~100 cm/s to below 1 cm/s (3 fA/cm<sup>2</sup>) –i.e. from ~21 to 23% efficiency. Open circuit voltage and short circuit current have a comparable dependency with front surface recombination.

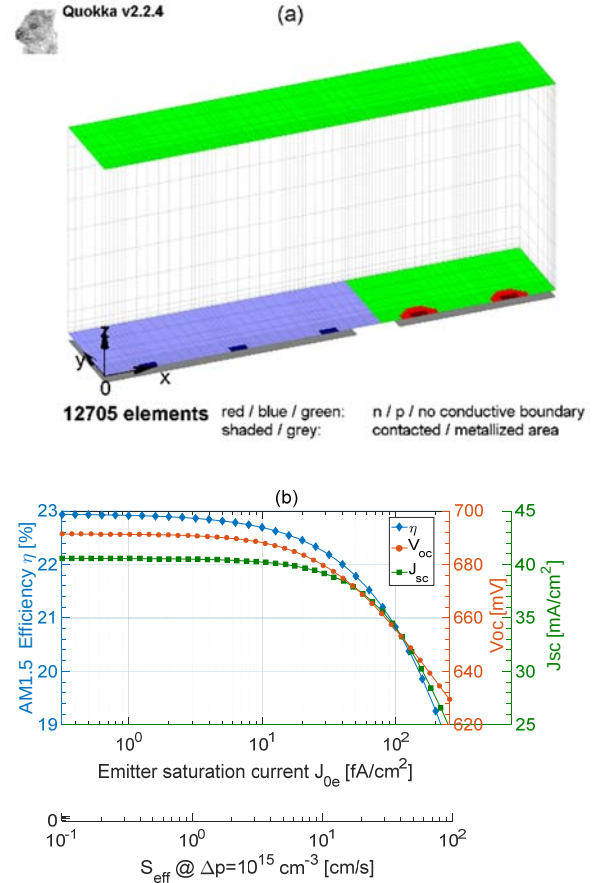


**Figure 4:** a. Quokka model and mesh for simulation of IBC cell performance as a function of front surface passivation, b. IBC cell performance parameters for a change in the front surface passivation quality.

## 6 CONCLUSIONS

This work has shown that extrinsic passivation methods are a very powerful and cost effective tool to improve the overall efficacy of surface passivation, and that they can translate into improved performance in solar cells. SRVs below 0.6 cm/s and  $J_{0e}$  of 0.5 fA/cm<sup>2</sup> were achieved on a 4-inch wafer by improving the passivation quality of thermally grown SiO<sub>2</sub> using corona charge. These are the lowest reported on 1 $\Omega$ cm n-type material with a single passivation coating. The potential for these methods to be industrial exploited is hindered by the stability of the passivation obtained – which is a continuing subject of study. The effectiveness and speed of passivation, however, makes this a promising contender for the industrial manufacture of solar cells.

## 7 ACKNOWLEDGMENTS

RS Bonilla is the recipient of an EPSRC (UK) Postdoctoral Research Fellowship, EP/M022196/1. PR Wilshaw and PG Hamer acknowledge the support from EPSRC grant EP/M024911/1. Data published in this article can be downloaded from <http://ora.ox.ac.uk>. All authors are thankful to Martin Hermle and Christian Reichel at Fraunhofer ISE for provision of silicon material, and to Radka Chakalova for her extensive help in the cleanroom.

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