

Extracting Interface Recombination Velocities from Double-Heterojunction Solar Cell Reverse-Recovery Characteristics

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Introduction

Silicon double heterojunction (DH) solar cells represent a possible future path for high-efficiency, low-cost solar power. These cells forgo doped p-n and n⁺-n (or p⁺-p) homojunctions diffused at ~900 °C in favor of < 200 °C-deposited selective heterojunction contacts, which block one type of carrier while allowing the other to pass freely[1]. One heterojunction injects minority carriers (blocking majority carriers), and the other blocks minority carriers to reduce dark current (Fig 1). The efficiency of these cells is highly dependent on the interface quality of their heterojunctions. To date there is no method that uses reverse recovery (RR) transients to extract the actual interface characteristics from finished devices – methods like pulsed photoconductivity used on test samples cannot be extended to final devices with 2 metallized interfaces. Here, we give a procedure for the independent extraction of interface parameters at both heterojunctions.

Approaches to Reverse Recovery

In an RR experiment, minority carriers are injected into the device base (bulk of the wafer) under forward bias J_f (Fig. 1); then, the device is placed under reverse bias (Fig. 2) and, for a short time (the recovery time, t_r), the reverse current J_r is approximately constant (set by the resistor) as these carriers are collected. Kingston [2] first analyzed RR in long-base ($\tau_p \ll W^2/D_p$ in n-Si, where W is wafer thickness) diodes. Later, Grove and Sah [3] looked at RR in short-base devices with Ohmic back contacts, finding $W^2/(\pi^2 D_p) \log[8(1+J_f/J_r)/\pi^2]$ for $J_r \leq J_f$ and $\pi W^2/(4D_p)[1+J_r/J_f]^{-1}$ for $J_r \geq J_f$. Typical DH devices on float-zone silicon are short-base (negligible base recombination) but with selective, rather than Ohmic, back contacts. Recombination may occur at one or both of these contacts. Recently, several studies [4] [5] have used Kingston's equation to extract bulk recombination times in single-sided heterojunction devices. However, although RR data from short-base or non-ideal heterojunction devices can be "fit" to Kingston's long-base equation, the result of that fitting cannot be used quantitatively to infer interface properties.

Back-interface effects

A selective back heterojunction increases the back-interface minority-carrier concentration, increasing the total amount of stored charge and thus the recovery time (Figs. 1, 3). Assuming extracted charge is proportional to stored charge, it is simple to relate this Δt_r to the back-interface recombination velocity s_{back} , as in [1]; however, as shown in Fig. 4, this approximation consistently underestimates s_{back} compared to its true value. An approach in which an effective lifetime is extracted via Kingston's equation and then related to s_{back} assuming high bulk lifetime is even more inaccurate. In our work, we numerically model the minority carrier profile in the wafer as a function of time, with s_{back} as a parameter to correctly fit the RR transient. As an example, for a true s_{back} of 300 cm/s, the method from [1] yields an s_{back} =201 cm/s, while the adaptation of Kingston's equation yields 81 cm/s.

Front-interface effects

The situation becomes more complicated when the front interface is also non-ideal (Fig. 5). In this case, the total stored charge is less than before for the same total current density—the remainder of the current is composed of recombination at that interface. In addition, front interface recombination consumes extra holes during the transient. The former effect can be easily incorporated into Grove and Sah's model by subtracting the recombination current from J_f in the formulas above. To determine the efficacy of this modelling approach, we compare model results to results from full device simulations performed in Synopsys Sentaurus; as shown in Fig. 6, this approximation (which neglects the $J_{r,front}$ effect) is accurate for $J_r > J_f$, ie, where $J_{r,front}$ is small compared to J_r .

To decouple the effects of front- and back-interface non-idealities, one first measures RR in a single-sided device with $s_{back}=\infty$. From this, one can extract an effective s_{front} . Then, one can measure the RR characteristics of a double-sided device and fit the new results subject to the condition $1 - J_{recom}/J_f = [1 + s_{front}/s_{back}(1 + Ws_{back}/D_p)]^{-1}$, which can be derived by considering hole profiles in the base with and without a selective back contact.

Conclusion

Because they determine dark current, the recombination characteristics of the selective contacts determine the efficiency of silicon heterojunction solar cells. Given the proper consideration of device assumptions and non-idealities in both forward and reverse bias, RR experiments allow the extraction of both front- and back-interface recombination in fully-contacted double-sided heterojunction devices.

[1] Nagamatsu *et al.*, *Appl. Phys. Lett.*, vol. 106, pp. 123906, 2015. [2] R. H. Kingston, *Proceedings of the IRE*, vol. 42, no. 5, pp. 829–834, 1954 [3] A. S. Grove and C. T. Sah, *Solid State Elec.*, vol. 7, pp. 107–110, 1962 [4] Prakoso *et al.*, *Organic Electronics*, vol. 42, pp. 269–274, 2017. [5] Jung *et al.*, *Nano Letters*, vol. 13, pp. 95–99, 2013

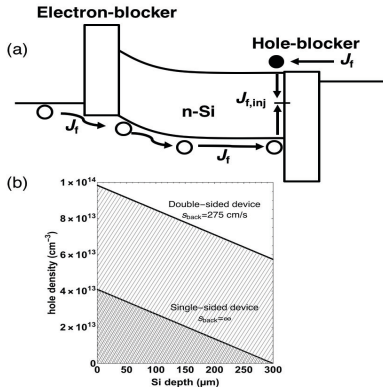


Fig. 1: (a) Band diagram of double-sided heterojunction device in forward bias and (b) comparison of initial hole profiles with and without a selective back contact to block holes. Shaded areas indicate stored minority carriers.

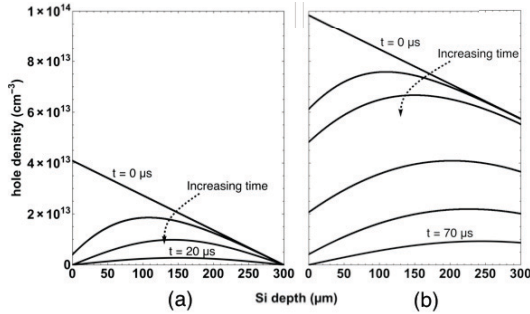


Fig. 3: Modeled hole profile over time for the same J_f and J_r in (a) a single-sided and (b) a double-sided n-Si device switched from forward to reverse bias at $t = 0$. $J_f = 2.53 \text{ mA/cm}^2$, $J_r = 6.0 \text{ mA/cm}^2$, and $s_{\text{back}} = 275 \text{ cm/s}$. Recombination velocity at the front interface s_{front} is assumed to be 0.

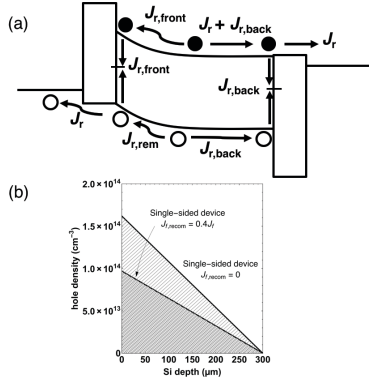


Fig. 5: (a) Band diagram of device with front-interface recombination velocity $s_{\text{front}} > 0$ during reverse-bias transient and (b) comparison of initial hole profiles in a single-sided device with and without front-interface recombination. The difference in stored holes can be measured by RR to determine the effective s_{front} .

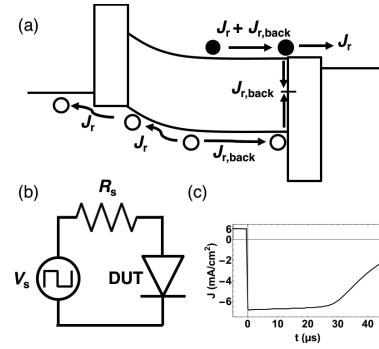


Fig. 2: (a) Band diagram of device during reverse-bias transient, (b) RR circuit, and (c) typical data showing reverse current transient due to stored minority carriers

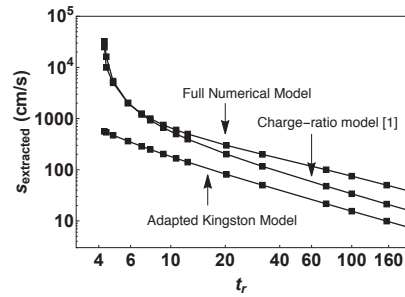


Fig. 4: Results of fitting RR transient for an extracted interface recombination velocity at the back interface s_{back} as a function of the experimental recovery time t_r in a double-sided n-Si device, using (i) a full numerical model, (ii) a geometric approximation as in [1], and (iii) an adaptation of the well-known Kingston equation. $W = 0.3 \text{ cm}$, $J_r/J_f = 3.0$. The correct output of the full model is not well-approximated by either of the simpler alternatives.

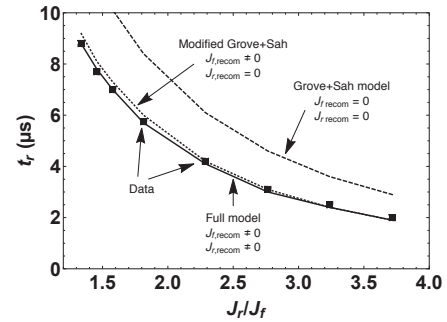


Fig. 6: Results of fitting recovery time in non-ideal short-base n-Si diodes. Curves are made with either (i) the basic short-base model [3], (ii) an analytical approximation of that model, or (iii) a full numerical approach. $W = 0.3 \text{ cm}$, $J_f = 18.2 \text{ mA/cm}^2$. The analytical modified Grove+Sah model provides a good fit to the data, and its predicted s_{front} matches the actual value. Note that curve (ii) is a worse approximation for smaller J_r/J_f .