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Sensitivity analysis of two-spectrum separation of surface and bulk components of minority carrier lifetimes

Jed Brody *, Ajeet Rohatgi

School of Electrical and Computer Engineering, Georgia Institute of Technology, University Center of Excellence for Photovoltaics Research and Education, Atlanta, GA 30332, USA

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Abstract

Performing quasi-steady-state lifetime measurements using two different illuminating spectra provides quantitative information about bulk lifetime (τ_b) and surface recombination velocity (S). This paper motivates the investigation of this relatively new method by demonstrating that the conventional method of iodine/methanol passivation for the extraction of τ_b, which is then used to calculate S for a dielectric, may fail for solar-grade materials such as string ribbon silicon. To facilitate the use of the two-spectrum method, first we introduce a novel empirical procedure for the determination of the constant of proportionality between the short-circuit current of the reference cell and the average generation rate (G_{av}) in the test wafer. Then a sensitivity analysis is performed to show that the method of using a white light spectrum and an infrared spectrum to obtain information about τ_b and S also has serious limitations in certain cases: only a lower bound can be placed on τ_b for τ_b greater than about 10 μs, and only an upper bound can be placed on S for S less than about 1000 cm/s. Our analysis demonstrates that in order to use the two-spectrum method to specify τ_b and S within a factor of about 2–20 when experimental uncertainty is ±10%, the quality of both the bulk of the material and the surface passivation must be somewhat poor. Precision may be improved by reducing experimental uncertainty. To illustrate the requirement that bulk and surface recombination must be high in order to use the two-spectrum method with the greatest precision, the method was applied to nitride-passivated float zone and cast multicrystalline silicon wafers of different resistivity. Only an upper limit to S (165 cm/s) was inferred for the easily passivated float zone wafer, whereas both upper and lower limits to S were extracted for the less effectively passivated heat-exchanger method (HEM) multicrystalline wafers. The analysis yielded $1200 < S < 4200$ cm/s for the 1.4 Ω cm HEM wafer and $3000 < S < 20000$ cm/s for the 0.2 Ω cm wafer after the nitride was annealed at 850 °C. The 0.2 Ω cm HEM wafer was also measured before the nitride was annealed. The two-spectrum method provided a τ_b range that remained nearly unchanged, while the S range was much higher for the as-grown SiN_x. This indicates that the 850 °C anneal improves surface passivation without passivating the bulk of the HEM material.

Keywords: Photoconductance; Recombination; Bulk; Surface

1. Introduction

Silicon solar cells are frequently coated with a dielectric film such as SiN_x to reduce reflection, to hydrogenate bulk defects, and to passivate the surface. There is often a need to determine the resulting bulk lifetime (τ_b) and surface recombination velocity (S). While the effective lifetime (τ_{eff}) determined by a photoconductance measurement is influenced by both of these parameters, it is important to be able to separate their effects in order to deduce their values. If τ_b is known, S can be calculated from the measured τ_{eff} [1], which is always less than τ_b ($1/\tau_{eff} = 1/\tau_b + 2S/W$ for

* Corresponding author. Tel.: +1-404-894-0336; fax: +1-404-894-4832.

E-mail address: gte436k@prism.gatech.edu (J. Brody).

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low S). One method for the determination of bulk recombination is the application of an extremely effective surface passivation, such as corona discharge [2] or immersion in an iodine/methanol solution [3], which causes S to be negligibly small for high-quality wafers. With surface recombination practically eliminated, a measurement of τ_{eff} yields τ_b. While the use of iodine has been shown to be convenient, reliable, and effective for reducing S below 5 cm/s on monocrystalline materials [3], it is not obvious that this method should be expected to work on low-quality, solar-grade materials such as string ribbon silicon. The method would clearly fail if τ_{eff} measured when the wafer is passivated by a dielectric is greater than τ_{eff} measured when the wafer is passivated by iodine. If we identified the latter with τ_b, then calculated S would be less than zero for the dielectric passivation, which is meaningless. The possible failure of the iodine passivation method motivates the search for new methods for the separation of τ_b and S.

Two recent methods have been suggested for the separation of surface and bulk recombination by two different photoconductance measurements of the same wafer; no temporary surface passivation is required. Nagel et al. [4] showed theoretically that for $S > 1000$ cm/s and $\tau_b < 10$ μs, S and τ_b can be extracted from two 400 nm illumination τ_{eff} measurements: one transient (in which generation can be approximated as an impulse function) and one steady state. Since a transient measurement can only be made when the light pulse is much less than τ_{eff}, and since τ_{eff} is much less than 10 μs under the given conditions, a light pulse of duration much less than 10 μs must be used to make the transient measurement. This precludes the use of the popular laboratory flash lamp whose decay constant ranges from 18 μs to 2.3 ms.

The second method, described by Bail and Brendel [5], uses two quasi-steady-state photoconductance (QSSPC) measurements performed under two illumination spectra: blue and infrared (IR). Based on an exact calculation of the generation profiles and the excess carrier distributions throughout the wafer, they determine which values of S and τ_b yield the measured photoconductances under blue and IR illumination. While their method is meticulously precise, it requires knowledge of the spectral dependence of the following: the photon flux, the external quantum efficiency (EQE) of the reference cell used to measure the photon flux, and the front and rear reflectance of the test wafer. This paper extends Bail and Brendel's idea as follows: a calibration procedure is proposed to circumvent the need for knowledge of photon flux spectral density and reference cell EQE; the steady-state equations linking S, τ_b, and τ_{eff} are elucidated; and the sensitivity of this method for various combinations of S and τ_b is assessed. Our sensitivity analysis evaluates for the first time how the uncertainty in the extracted values of S and τ_b depends on their true values. These results are validated by applying the technique to a high-quality float zone wafer and two lower-quality multicrystalline wafers.

2. Comparison of the effectiveness of iodine/methanol passivation of ribbon and float zone silicon

If the iodine/methanol passivation frequently used to determine τ_b for monocrystalline silicon wafers were just as effective with low-lifetime materials, then there would be no need for a new method such as Bail and Brendel's. In order to investigate the effectiveness of iodine passivation of solar-grade silicon materials, string ribbon silicon wafers of three resistivities (0.7, 1.5, and 3 Ω cm) were coated with passivating dielectrics. Three wafers of each resistivity were passivated with one the following films: plasma-deposited nitride, thermal oxide, and an oxide/nitride stack. For comparison, a high-resistivity float zone wafer was treated with a thermal oxide. The effective lifetimes of all wafers were measured. Subsequently, the dielectric layers were removed, and the wafers were cleaned and immersed in the iodine/methanol solution described in [3]. The same iodine/methanol solution was used on the float zone and ribbon wafers. The effective lifetimes of all wafers were again measured. Results are shown in Fig. 1.

Using iodine, the measured effective lifetime of the float zone wafer was 7.9 ms, corresponding to a maximum S of less than 2 cm/s. It is extremely difficult to exceed this level of surface passivation with a dielectric layer, and thus this method works well on monocrystalline materials. On the other hand, half of the eight ribbon wafers measured were less well passivated by iodine than by the dielectric layers. Thus the method of determining S by extracting τ_b using iodine fails for this set of wafers; half the results would be meaningless ($S < 0$), and the other half would be suspect, given that iodine seems incapable of reducing S to insignificant

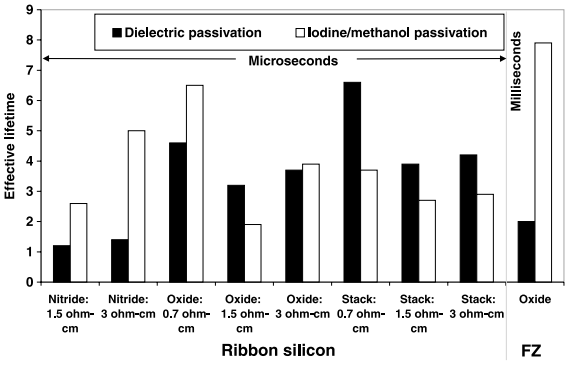

Fig. 1. The effectiveness of iodine passivation of ribbon silicon. "Stack" refers to an oxide/nitride stack passivation.