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Determining lifetime in silicon blocks and wafers with accurate expressions for carrier density

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In recent years, many studies of silicon minority-carrier lifetime have been performed with quasi-steady-state photoconductance measurements. The method has been used to characterize the defect levels, surface passivation, and trapping effects in wafers by using absolutely calibrated data for minority-carrier lifetime versus minority-carrier injection level. This paper generalizes the quasi-steady-state photoconductance technique for use in thick wafers or blocks of silicon where the diffusion length or light absorption depth is much less than the sample thickness. The photogeneration and carrier diffusion profiles are calculated for special cases of interest. The measured effective lifetimes can then be used to estimate the bulk lifetime in the material, and report this lifetime at an appropriate average minority-carrier density for the measurement conditions. In this way, the results and measurement methodologies previously developed for use on wafers can be applied to single- or multi-crystalline silicon ingots or thick wafers. In thick silicon samples, long-wavelength weakly absorbed light can be used to reduce the effects of surface recombination on the measurement giving important advantages compared to the case of measuring unpassivated wafers. The generalization presented here offers advantages for accurately determining the bulk lifetime of silicon material prior to sawing into wafers and without requiring surface passivation.
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I. INTRODUCTION

Quasi-steady-state photoconductance (QSSPC) is a widely used technique for the determination of minority-carrier lifetimes in semiconductor wafers.[1] The salient feature of the QSSPC method is that it provides the carrier lifetime at a precisely calibrated carrier density, and so is an indispensable tool in devices such as solar cells where the lifetime governs device performance.[2,3] Utilizing the carrier lifetime as a function of calibrated carrier density allows the measurement of the bulk minority-carrier lifetime, surface recombination velocity,[4] emitter (or other diffused regions) recombination current,[5] and iron concentration[6] and predicts solar cell open-circuit voltage without requiring contacts (implied V_{oc}).[1] Finally, as a contactless measurement, QSSPC can be used at anytime in the process sequence. QSSPC measurements are typically performed on wafers where the carrier density is approximately constant across the sample. This paper extends the QSSPC technique to cases with arbitrary carrier-density profiles such as blocks of silicon (whether they be single-crystalline ingots or multi-crystalline bricks).

Measuring the lifetime of silicon before it is cut into wafers has significant theoretical as well as practical advantages. After cutting the block into wafers, most of the free electrons in the sample are never far from the surfaces either during a photoconductance measurement or device operation. Either the surfaces dominate the lifetime measurement or special sample preparation is required to minimize the electrical activity of the surfaces. In a block, it is possible to use light that is primarily absorbed deep in the material so that the effect of the surface recombination is minimized.

Practically, measuring the lifetime on the block gives immediate feedback about the ingot growth process. It is also possible to target sections of the block for further processing. Only the high quality sections of the ingot need to be cut into wafers. The low quality material can either be discarded or further treated with a remelt process to improve lifetime. Alternatively, measuring the lifetime on the initial block and recording the position means that it is possible to sort the wafers at the start of processing and tune the cell process for different quality wafers coming from the different sections of the block. Photovoltaic production facilities now comprise several production lines so it is possible to optimize each line for a class of wafers.

While sorting wafers at the start of the process opens up the possibility of increasing the flexibility of production lines, the results need to be reliable so that high quality wafers are not erroneously discarded. It is known that lifetime alone at the start of the process is an insufficient criterion for predicting solar cell performance.[7] Some wafers with low initial lifetimes respond well to the process gettering and hydrogenation while other wafers do not recover. However, further analysis of the lifetime data identifies the cause of low lifetime material, for example, determining the iron concentration and the extent of trapping effects. The extended analysis techniques require an accurate measurement of the lifetime as a function of injection level.

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The goal of QSS block measurement is to determine the bulk minority-carrier lifetime of the material *at each* carrier density while reporting the effective carrier density accurately. The resulting data can then be interpreted in detail in order to predict the potential for each wafer to yield a solar cell with the specified efficiency for the production line.

II. QUASI-STEADY-STATE PHOTOCONDUCTANCE

At steady state conditions, the total generation and recombination across the entire device is equal such that

$$\tau_{\mathrm{eff}} = \frac{\Delta n W}{G_{\mathrm{cum}}}, \tag{1}$$

where τ_{eff} is the effective lifetime including recombination in the bulk and at surfaces, Δn is the increase in minority-carrier density due to illumination, and W is the width of the device. G_{cum}, the cumulative photogenerated carriers across the device, is determined by monitoring the amount of light falling onto the reference cell combined with the sample reflectivity and silicon absorption.

The carrier density Δn is determined by monitoring the photoconductivity σ of the sample with an inductively coupled coil. The increase in wafer conductivity due to illumination is then converted to an increase in carrier density by dividing by the wafer width W and by the electron, μ_n, and hole, μ_p, mobilities. The mobilities must be known in the material, and are well characterized in silicon.[8]

$$\Delta n = \frac{\Delta \sigma}{q[\mu_n(\Delta n) + \mu_p(\Delta n)]W}. \tag{2}$$

The factors Δn and W appear in both Eqs. (1) and (2), raising the possibility of calculating only $\Delta n W$ (cumulative increase in carriers over the whole device) and substituting this into Eq. (1) in order to find τ_{eff}. However, the mobilities μ_n and μ_p are also a function of carrier density so we need to know the actual carrier *density* increase (Δn) and not the total increase in carriers $\Delta n W$.

The mobility is a slowly varying function of carrier density so only a good approximation of the carrier density is required in order to convert photoconductance accurately into carrier densities using Eq. (2). The carrier density also needs to be determined because the minority-carrier lifetime in silicon is frequently a strong function of carrier density in photovoltaic silicon.[9] The lifetime in high injection is often a factor of 10 higher than at low-level injection and the measured lifetime under low-level injection also varies widely with injection level. Any statement of lifetime requires that the carrier density also be given in order to ensure the relevance to solar cell operation and a comparison of lifetime data between laboratories. The variation in lifetime has important implications for solar cell design since it can cause solar cell efficiency to change with illumination level. It is also responsible for lower than expected fill factors in some cases.[2]

For a wafer with perfectly passivated surfaces and completely uniform generation, the carrier density is the same everywhere and the determination of lifetime from photoconductivity follows that outlined above. In the case where the minority-carrier density varies across the sample (due to surface recombination or short diffusion length), it is then necessary to determine an *average* carrier density. Typically, the average carrier density is determined by calculating the arithmetic mean by dividing the cumulative increase in carriers across the device by the device width. The arithmetic mean works well for wafers where the carrier density is approximately constant across the device. Even in cases where the carrier density is not completely uniform, the effect on the analysis is often predictable and can be taken into account.[3]

In blocks under illumination from light which has an absorption depth less than the sample thickness, the carrier distribution is highly skewed toward the illuminated surface and the arithmetic mean is inappropriate. Only the very front section has an increase in carrier density and most of the block is inactive. This paper demonstrates that replacing the arithmetic mean by a weighted average gives a more meaningful average carrier density allowing the QSSPC approach to be extended to blocks and wafers. It also describes how using an effective width rather than the actual device width is appropriate during the measurement process. While this is especially important for blocks, it also applies to wafers in some cases. In addition to accurate lifetime analysis, methods have been developed to show how the lifetime as a function of carrier density can be used to determine the concentration of iron.[6] The dissolved iron concentration is calculated by measuring the change in lifetime at a specific calibrated minority-carrier density.[10] Finally, QSSPC (in common with other lifetime measurements) determines the effective lifetime of carriers in the device. The effective lifetime is a combination of the bulk lifetime and that at the surfaces. A final achievement of this paper is that it provides a robust conversion from the measured effective block lifetime to the actual bulk lifetime of the silicon material.

III. DETERMINATION OF AVERAGE CARRIER CONCENTRATION

A key step in the analysis for lifetime in blocks is to define a new average carrier concentration. Using the simple arithmetic mean tends to under report the average of the carrier density. Figure 1 shows the carrier density in a block of silicon material when illuminated by monochromatic light. Except for infrared light, wavelengths exactly at the band edge for silicon, the generation of carriers is confined to the first few millimeters of the block, even for high lifetime material. The mean carrier density in a wafer measurement is typically calculated by dividing the total carrier density by the width of the sample (in this case, 10 cm). This mean electron density introduces a dependence on the sample thickness even when the thickness has become irrelevant (since the carrier-density profile is independent of thickness for thick samples).

The carrier concentration in the block is better described by a weighted average rather than using the simple arithmetic mean. The weighted average carrier concentration Δn_{avg} that we propose is the carrier concentration weighted by the carrier concentration,

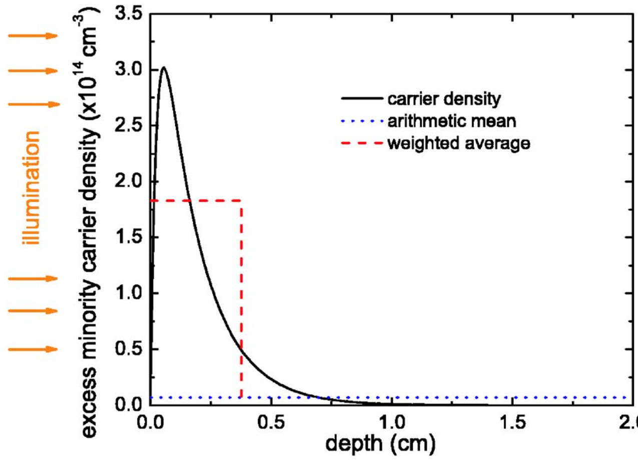

FIG. 1. (Color online) Carrier density in silicon block with 1000 nm light and carrier lifetime of 1 ms (solid line). The total width of the block is 10 cm and in most of the sample, there is no generation of carriers. The profile is described by a weighted average of the carrier density (dashed line) rather than the arithmetic mean (dotted line).

$$\Delta n_{\rm avg} = \frac{\int_0^\infty \Delta n^2 dx}{\int_0^\infty \Delta n dx}. \tag{3}$$

The weighted average then takes into account only those sections of the device that have an excess light induced carrier concentration. Areas of the device (such as the back section of a block) that have no excess carriers are automatically discarded from the analysis.[11]

We can also define an effective width $W_{\rm eff}$ for the high concentration region which is the total excess carrier concentration divided by the average carrier concentration as determined in Eq. (3),

$$W_{\rm eff} = \frac{\left(\int_0^\infty \Delta n dx\right)^2}{\int_0^\infty \Delta n^2 dx}. \tag{4}$$

In practice, the effective width is an extremely useful parameter. The QSSPC analysis spreadsheets[12] require the entry of the (wafer) width for every analysis. Therefore, this construct represented by Eqs. (3) and (4) transforms a measurement of bulk silicon into a standard wafer measurement as far as the lifetime analysis is concerned.

The total carrier concentration is then the product of $\Delta n_{\rm avg}$ and $W_{\rm eff}$,

$$\int_0^\infty \Delta n dx = \Delta n_{\rm avg} W_{\rm eff}. \tag{5}$$

A. Solution to carrier profiles with monochromatic light

By determining expressions for the carrier concentration Δn in a device, we can then use the definitions in the previous section to determine the weighted average carrier density, the effective width, and relationship between the measured effective lifetime and the actual bulk lifetime of the material.

The derivation of the analytical solution assumes that there is no electric field in the wafer and that the light is monochromatic with no surface reflection. These simplifications are addressed in the numerical modeling in the next section. The derivation of carrier profiles proceeds from the general semiconductor continuity equations. For notational convenience, the analysis is given for p-type material with electrons as minority carriers but it is equally applicable to n-type material.

For the case of monochromatic light shining on a piece of silicon, the carrier concentration is given by[13]

$$\Delta n(x) = Ae^{x/L} + Be^{-x/L} + \left(\frac{\alpha N_s \tau_b}{(1-\alpha^2 L^2)}\right)e^{-\alpha x}, \tag{6}$$

where x is the distance from the front of the sample, Δn is the excess minority-carrier density, α is the absorption coefficient of light, N_s is the photons/s passing into the sample, τ_b is the bulk minority-carrier lifetime, and L is the bulk minority-carrier diffusion length. The constants A and B are determined by the boundary conditions in each specific case of wafer or block. The following sections discuss specific cases and apply boundary conditions to get the exact carrier profile for the given boundary conditions.

1. Block with infinite surface recombination velocity

The case of a block of material with infinite surface recombination is pictured in Fig. 1. For a block, the thickness is considered infinite so that as $x \to \infty$ then $\Delta n \to 0$ and so $A=0$. Additionally, the front surface of a grown silicon block is unpassivated so that the carrier concentration at the front is zero, i.e., $\Delta n(0)=0$. Applying these two boundary conditions to Eq. (6) and simplifying gives the carrier profile

$$\Delta n(x) = \left(\frac{\alpha N_s L^2}{(\alpha^2 L^2 - 1)D}\right)(e^{-x/L} - e^{-\alpha x}). \tag{7}$$

Integrating across the width of the device (in this case from $x=0$ to ∞) gives the total increase in carrier concentration:

$$\Delta n_{\rm total} = \left(\frac{N_s L^2}{(\alpha L + 1)D}\right). \tag{8}$$

Applying Eq. (1) in the form $\tau_{\rm eff} = \Delta n_{\rm total}/G_{\rm cum}$ gives

$$\tau_{\rm eff} = \frac{\tau_b}{\alpha L + 1}. \tag{9}$$

This provides a relationship between the effective lifetime $\tau_{\rm eff}$ that would be measured by an instrument and the actual bulk lifetime τ_b. Applying Eqs. (3) and (4) to the carrier profile gives the weighted average carrier density and the effective width:

$$n_{\rm avg} = \left(\frac{\alpha N_s L^2}{(\alpha L + 1)^2 2D}\right). \tag{10}$$

$$W_{\rm eff} = 2\left(L + \frac{1}{\alpha}\right). \tag{11}$$

Using the results from Eqs. (9)–(11), the analysis of a block of silicon illuminated by a monochromatic light source such as a laser proceeds according to the previously developed techniques for wafers except that $W_{\rm eff}$ is used instead of the actual sample width.

2. Passivated block

In the case of a fully passivated block, there is no recombination at the surfaces and the only recombination takes place in the bulk of the material. While this case rarely occurs in practice, it confirms the analysis technique through equating the actual lifetime with the measured lifetime so that τ_{eff} equals τ_b. The simplest case is where all the generation takes place at the front surface of the block as would be the case for short wavelength light illumination and

$$W_{\text{eff}} = 2L. \tag{12}$$

For very large values of the absorption coefficient α, Eqs. (11) and (12) become equivalent despite the change from an unpassivated to a fully passivated surface. As α increases, the peak of the carrier density moves to the surface and the surface recombination velocity only affects the carrier profile at an infinitesimally small region right at the surface, leaving the rest unchanged. The surface recombination determines the amplitude of the carrier profile but not its shape so that W_{eff} is independent of the surface condition for large α. As the block is usually unpassivated and short wavelength light with a high α produces a very low signal level, long-wavelength light is preferred during measurement.

3. Wafer with arbitrary surface recombination

The most general case arises when both surfaces impact the carrier density and the surface recombination can take any value. While the previous cases are sufficient to describe blocks, the most general case is required to analyze an arbitrary wafer. For example, when the minority-carrier diffusion length or the absorption coefficient are comparable to, or less than, the wafer thickness, the most general case must be used. The derivation of the weighted average carrier concentration and the effective width follows a similar procedure as the derivation of carrier profiles in the case of blocks. An analytic expression can be determined for the n_{avg}, W_{eff}, and the relationship between measured lifetime and bulk lifetime. However, the expressions are complex with no concise simplifications for arbitrary surface recombination. A spreadsheet can be used to evaluate the analytical expressions but a numerical solution is generally of more practical use.[14] In special cases such as infinite or zero surface recombination, the equation above reduces to expressions previously derived.[3] Figure 2 illustrates a typical case where the weighted average is significantly different to the arithmetic mean of the carrier profile.

B. Multiple wavelength light

One extension to the analytical model is to the case of multiple wavelength light. This extends Eq. (3) to

$$\Delta n = \sum_{i=1}^{M} \left(\frac{\alpha_i N_i L^2}{(\alpha_i^2 L^2 - 1)D} \right) (e^{-x/L} - e^{-\alpha_i x}), \tag{13}$$

where α_i is the absorption coefficient at each wavelength and N_i is the flux of photons entering the silicon block. The summation provides a mechanism to evaluate the response of any illumination source rather than just that from a monochromatic light source as a laser. The calculations are readily implemented using a spreadsheet.

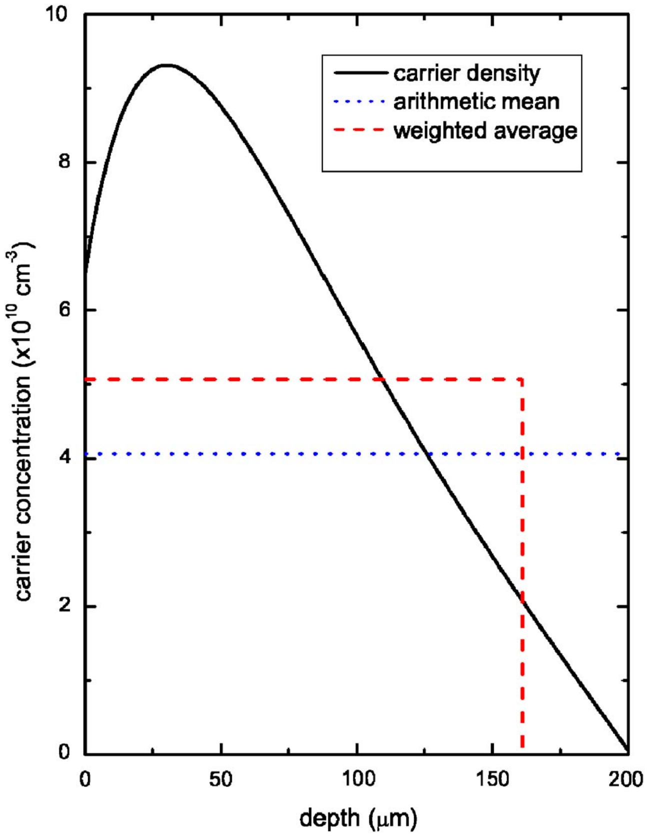

FIG. 2. (Color online) Spreadsheet evaluation for a wafer with front and rear surface recombination velocities of 100 and 25 000 cm/s, respectively, bulk lifetime of 5 μs, and illuminated with 880 nm light having an absorption coefficient of 400 cm^{-1}. The arithmetic mean is 20% lower than the weighted average.

IV. NUMERICAL MODELING

The analytical models operate under specific cases and provide the necessary background theory. For a more complete model of the measurement device, it is often necessary to take into account aspects that are not easily modeled analytically and are best implemented with a numerical modeling tool such as PC1D.[15] The use of PC1D simplifies the evaluation of cases such as the use of the measured flashlamp spectrum, and samples with a wide variety of surface recombination properties. A further advantage of using PC1D is that it allows the incorporation of effects for which there are no analytical models, such as the internal reflection of light inside the wafer (light trapping), lifetime as function of carrier density, and electric fields caused by variation in carrier concentration (drift-diffusion model).

For a simple comparison of computation techniques, consider the case of a block with infinite front surface recombination of Sec. III A 1 with 1 Ω cm material and illumination of 1000 nm light. Figure 3 shows the comparison of the analytical model of Eq. (9) to the PC1D model as a function of the bulk lifetime. Over a bulk lifetime range of 1 μs to 1 ms the difference between the analytical and nu-

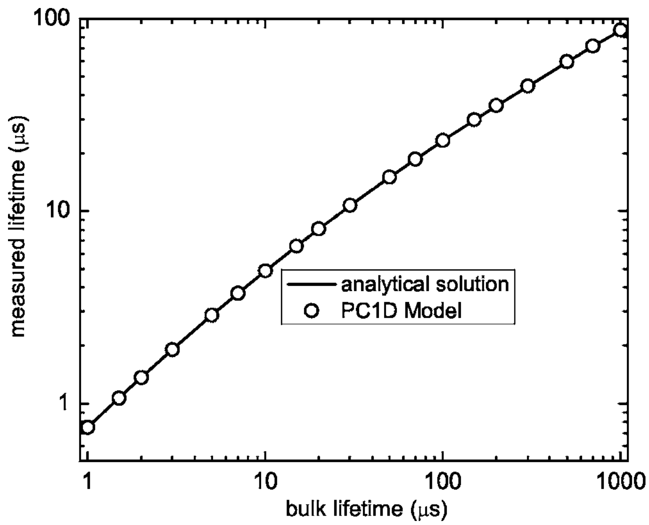

FIG. 3. Comparison of analytical model to PC1D numerical model. The light intensity has been adjusted to ensure a consistent minority-carrier density of 10^{14} cm^{-3}.

merical lifetime models is less than 1%. The two methods also give the effective width of Eq. (11) with an error of less than 1%.

V. INSTRUMENT SETUP

The models discussed so far use a monochromatic light source. A more practical alternative is to use a filtered broadband light source that results in a narrow range of wavelengths. Experimental QSSPC systems use a xenon flashlamp source to access a wide range of illumination intensities (0.1–100 W/cm^2), as shown in Fig. 4. The experimental setup is similar to those described previously for measuring wafers,[1] but with the difference that the new configuration has the illumination on the same side as the sense coil and so can be used to measure either blocks or wafers.

To restrict the light to a narrow range of wavelengths, filters are placed in front of the flashlamp. The spectrum of the flashlamp and the transmission of three Schott filters are shown in Fig. 5. The filter responses shown in the graph are for the amount of light transmitted into the silicon block since it is this quantity that determines the generation of carriers. In the modeling process, the lamp spectrum is fed into PC1D. PC1D includes an optical model that accounts for reflection losses at the silicon surface.

A silicon solar cell is used as a reference cell to determine the light intensity. In this work, the difference in spectral response of the reference cell (that determines the incident photon density) and the silicon block under test was accounted for explicitly based on a comparison of the modeled block infrared response with the measured reference cell spectral response.

The analytical model assumed an infinite surface recombination velocity. For the numerical model, the front surface recombination velocity is set to a more realistic figure of 200 000 cm/s (Ref. 16) for p-type boron doped silicon. During the simulations, the minimum required thickness was used in order to have the highest possible node resolution in

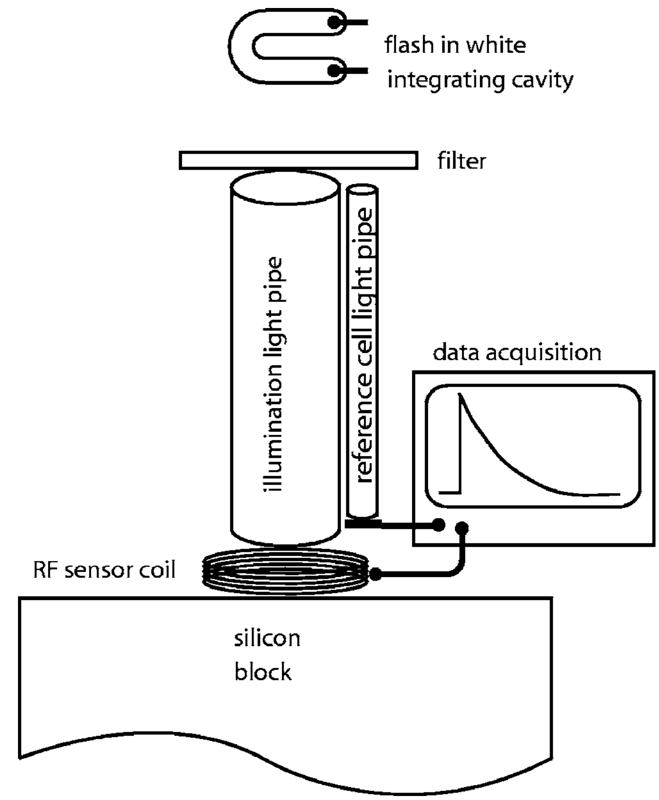

FIG. 4. Experimental setup for the measurement of lifetime in blocks of silicon. Lifetime in the block is determined from measurements of light intensity and photoconductivity.

the simulation while still integrating to a depth sufficient to include at least 99% of the photogenerated carriers.

Modeling the silicon block and flashlamp using PC1D allows us to take into account all the precise details of the experimental setup in order to determine a transfer function between the measured lifetime and the actual bulk lifetime. Large changes, such as the use of a different filter or light source, would require a new transfer function to be calculated. Small changes, such as lamp aging, could be monitored by comparing results from two or more filters (for ex-

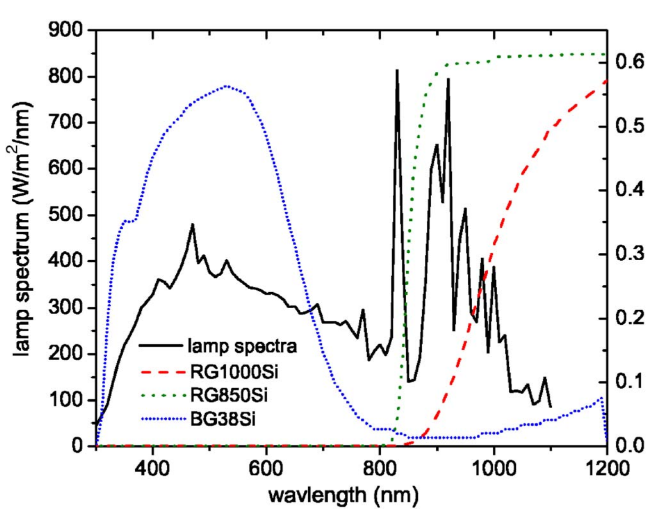

FIG. 5. (Color online) Flash lamp spectrum and the transmission into silicon for each filter. The filter curves are the transmission of the Schott filter multiplied by the transmission into a bare piece of silicon.

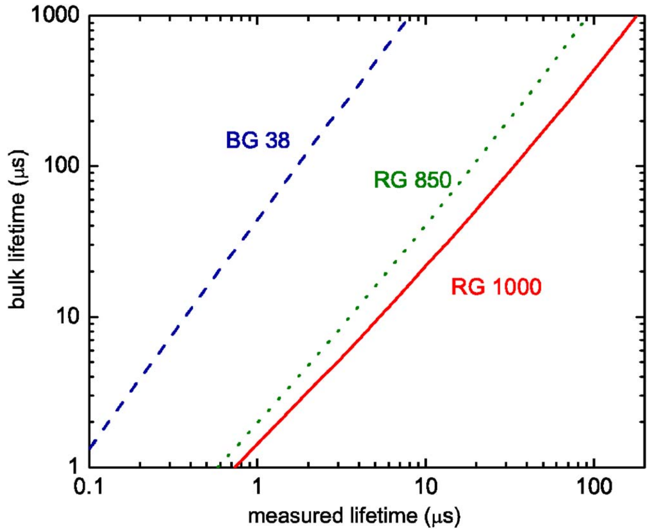

FIG. 6. (Color online) Bulk lifetime as determined from the measured (effective) lifetime for a 1 Ω cm block of material with surface recombination velocity of 200 000 cm/s at the front surface.

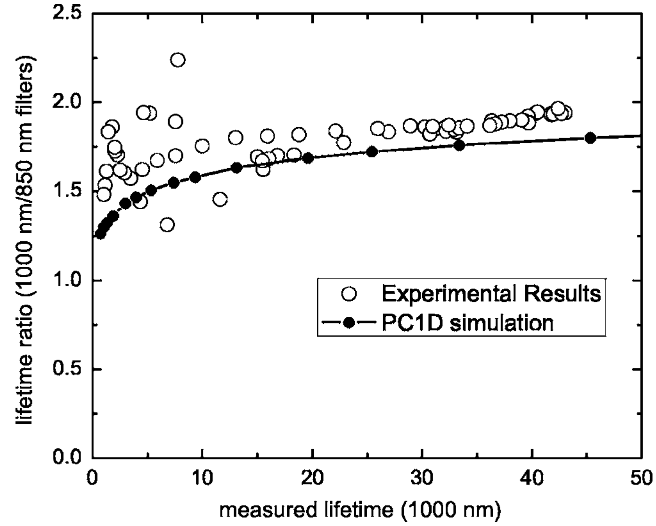

FIG. 7. Comparison of experimental data on a multicrystalline block with the theoretical prediction for two different filters.

ample, the 850 and 1000 nm filters shown in Fig. 6). We expect effects due to lamp aging to be small.

Figure 6 shows the transfer function for 1 Ω cm *p*-type material and with three different filters and allows the measured lifetime from the instrument to be directly converted to an actual bulk lifetime. While such plots are dependent on material resistivity due to changes in carrier mobilities, the change is small and can be neglected compared to other experimental error over a wide range of conditions. For example, if the sample resistivity is varied from 0.5 to 5 Ω cm while still using the data in Fig. 6 (determined for 1 Ω cm), the bulk lifetime would change by less than 5%. The resistivity of the silicon material can be checked during the measurement from the dark conductivity of the sensor coil.

The usual objective of the method is to determine the bulk lifetime of a block of material from an external illumination.The determination of the bulk lifetime of a block of material proceeds as follows:

(1) Measure τ_{eff} at a particular carrier density by assuming a typical W_{eff}.
(2) Calculate τ_{bulk} from the transfer function, Fig. 6.
(3) Calculate L based on τ_{bulk}
(4) Recalculate W_{eff} using the new τ_{bulk}.
(5) Recalculate τ_{eff} using the new W_{eff}.
(6) Iterate steps (2)–(6) to self-consistency.

We have found that using Schott filters RG 850 and RG 1000 (Fig. 5) provide sufficient light intensity but that the light is absorbed deep enough in the bulk to overcome problems with surface recombination.

Measuring the same sample with different filters will give different measured lifetimes, but there should be consistency between the measured values and the PC1D calculations. By measuring with two different filters, the validity of the technique can be checked for a large set of measurements with material that varies in lifetime over a wide range. Figure 7 shows the ratio of lifetimes measured on a multicrystalline silicon brick using the RG 1000 and RG 850 filters, and the comparison with PC1D calculations. There is quite good general agreement so the estimated bulk lifetimes based on the conversion differ by only 12% for bulk lifetimes greater than 3 μs. The longer-wavelength infrared-pass filter resulted in systematically slightly higher lifetime. The difference is likely due to the subsurface saw damage on the block that causes a 5 μm dead layer at the surface and has a greater effect on the 850 nm infrared-pass filter. The PC1D calculations assumed a very high surface recombination velocity of 2×10^5 cm/s and is confirmed by measurements using filter BG 38 which only passes visible light that is absorbed very close to the surface. For the sample shown in Fig. 7, the measured lifetime using BG 38 is very low as predicted by Fig. 6.

Further refinements to the accuracy of the measurements are possible by modeling specifics of the equipment setup but are not expected to change the measured values by more than 10%. For instance, the white reflective cavity of the flashlamp (Fig. 4) will have a small effect on the spectra as will the slightly differently fields of view of the reference cell and the block illumination. The $1/e$ sense depth of the coil was measured at 3 mm and was found to have only a marginal effect on the PC1D modeling.

VI. CONCLUSIONS

The strength of a QSSPC lifetime measurement is that the lifetime is reported as a function of the calibrated carrier density in a silicon sample. Previously, this was discussed in the context of silicon wafers. This paper developed a generalization that permits the same to be done for data taken on thick wafers, ingots, or blocks of silicon.

To determine the effective carrier density, a weighted average is calculated where the weighting factor is the carrier concentration itself. Using the weighted average carrier density then allows use of the correct mobility so that the conversion from photoconductance to carrier concentration is accurate. The resulting data can be presented as a lifetime versus carrier density plot, which is the form required for device physics interpretations of defect and trapping effects in the bulk silicon. This permits a sophisticated analysis of the silicon bulk lifetime measured on blocks or ingots of silicon without surface passivation before sawing the block into wafers.

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