# EVALUATING SILICON BLOCKS AND INGOTS WITH QUASI-STEADY-STATE LIFETIME MEASUREMENTS

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ABSTRACT: Recent progress has been made in identifying key features of multicrystalline blocks that can be used to predict the potential cell efficiency. Many of these studies use Quasi-Steady-State PhotoConductance (QSSPC) performed on wafers cut from different positions within the blocks. In these previous studies, the final efficiency of solar cells has been found to be primarily a function of the elements O and B, Fe, and the grain structure. All of these key factors have distinct "signatures" that can be characterized by minority-carrier lifetime tests and lifetime response to light soaking. These studies require calibration of the minority-carrier-injection level for precise measurements. The QSSPC method has recently been extended to map the lifetime in silicon blocks directly. This paper presents progress towards obtaining an absolute calibration for QSSPC block measurements in order to enable device physics studies on blocks as they exist in the production line. Detailed characterization of blocks of silicon prior to sawing provides data on silicon ingot growth and improves decisions on wafering. Results are presented for the determination of Fe concentration and trapping based on lifetime measurements. The combination of lifetime, Fe, and trapping data will provide much better prediction of wafer yield than lifetime data alone.

Keywords: Lifetime, Multi-crystalline, Photoconductivity

## 1 INTRODUCTION

Most previous work using the QSSPC method has determined the area-averaged lifetime over an area of approximately 4 cm diameter on wafers. Recently, this has been extended to measure the lifetime in blocks, boules or ingots as well[3]. In this paper, we will discuss spatially-resolved block measurements achieved by limiting the light to a well defined line as shown in Fig. 1. Using this line, an average lifetime is measured over the height of the line (30 mm), but a resolution of 2 mm is achieved in the width direction. This can be used for lines scans of multicrystalline blocks, with good resolution in the scan (growth) direction. Once the different geometry of blocks compared to wafers is taken into account, the standard QSSPC data analysis[1] can be performed on the resulting data giving the lifetime as a function of injection level. QSSPC measurements on wafers have been used to investigate trapping and Fe concentrations as well as for the measurement of lifetime[2]. This paper describes similar measurements taken directly on production silicon blocks.

## 2 CALIBRATION OF THE QSSPC METHOD FOR USE IN BLOCKS.

The difficulty of calibrating the instrument is illustrated by Fig. 2. When doing any recombination study, it is vital to know the minority-carrier density where the lifetime is measured. The photoconductance instrument measures the total photoconductance[1]. Fig. 2 shows the minority carrier density in the surface 2 mm that results from steady-state illumination of a 1-ohm-cm p-type block of silicon. The bulk lifetime is 2μs, the surface recombination velocity is $2x10^5$ cm/s[3] and the absorption depth of the light is 20 μm. We hypothesize that an appropriate choice for the carrier density that represents this type of distribution is given by the weighted average of the carrier density, where the weighting function is the carrier density. This gives the average carrier density seen by the average minority carrier. The resulting effective carrier density and depth is shown in Fig. 2. This is the carrier density that will be reported for a measured lifetime. In addition, since the electron mobility is dependent upon carrier density, this calculated carrier density is also used in the conversion of photoconductance to minority-carrier density. For this work, IR-pass filters were used in conjunction with a xenon flashlamp[3] rather than a monochromatic source as shown in Fig. 2. As a result, the functions illustrated by Fig. 2 were evaluated using PC1D to determine the minority-carrier density profiles that result from the photon distribution of the light from the flash and filter[6].

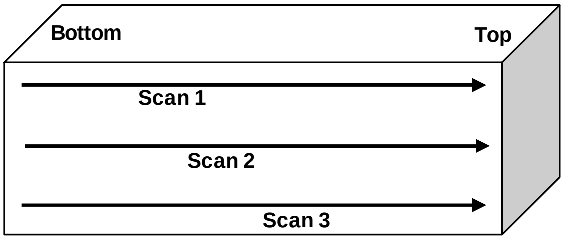

**Figure 1:** The photoconductance is determined by a 3 by 30 mm illumination pattern through the sensor, as shown top. This pattern is scanned across the block, giving high resolution in the growth direction. The growth direction of the block is left to right in this figure.

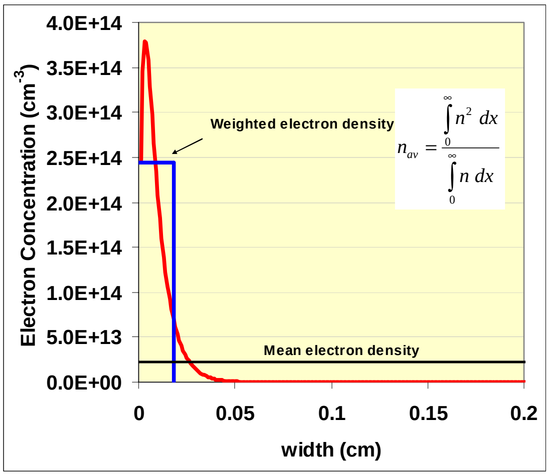

**Figure 2:** An illustration of the electron carrier density profile in the top 2mm of a silicon block, and the weighted carrier density used in the analysis and reported for each measurement.

A second challenge in measuring blocks is that the surface is not passivated. The resulting high-surface recombination will result in a measured lifetime that is much lower than the bulk lifetime. In this work, PC1D was used to evaluate the transfer function from the measured to bulk lifetime for the lifetime range and photon distribution in this experiment. This is shown in Fig. 3. The work will be detailed in a future publication[6].

## 3 MEASUREMENTS OF LIFETIME, TRAPPING, AND IRON CONCENTRATIONS

Unfortunately, it has been shown that the lifetime of as-grown multi-crystalline silicon is often only loosely correlated with the solar cell efficiency that will result. The high temperature processing and resulting gettering both fundamentally change the material during processing. However, measurements on wafers have indicated that if the Fe concentration is measured and the effect of it is removed from the lifetime data of as-grown material, then the solar cell efficiency can be predicted with much better accuracy[2]. The method is to light-soak the wafer and determine the dissolved Fe concentration by noting the change in lifetime at a specific calibrated minority-carrier density[2,4].

The lifetime profile in a line scan along the length of a block is shown in Fig. 4. The lower curve was taken before light soaking, and the upper curve directly after light soaking for two minutes. The light soaking was done using 400W of halogen light incident on a 3-cm-wide line down the length of the block. Over the course of a few hours, the lifetime returned to the initial value. This is another characteristic of Fe in Boron-doped silicon. Both before and after light soaking, this block shows very long lifetime. For long-lifetime homogeneous material, as is evident from the QSSPC results in Figure 4, transient photoconductance measurements can be performed with the same instrument to validate the QSSPC analysis methodology[3]. The resulting lifetime for the peak lifetime region of Figure 4 was 306 μs, as measured from the transient photoconductance decay.

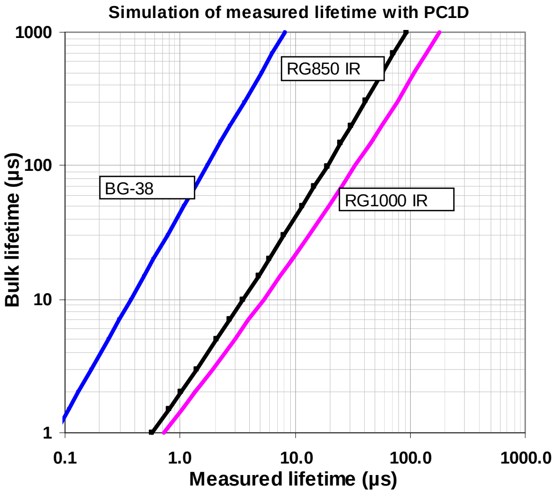

**Figure 3:** The transfer function from measured lifetime to bulk lifetime as evaluated using PC1D[9] for 1 Ohm-cm p-type silicon and the photon distribution in the filtered light source[3]. In this paper, data from the RG-850 filter is presented.

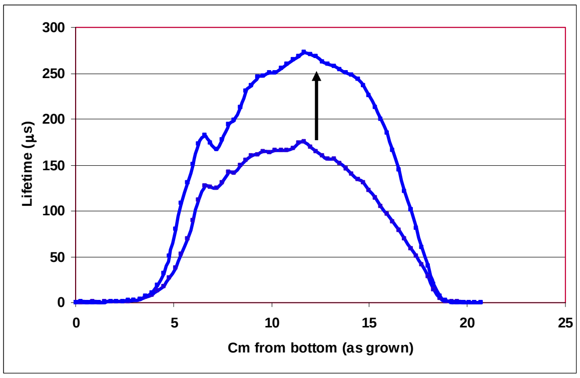

**Figure 4:.** A linescan along the length of a multicrystalline block directly before and after light soaking.

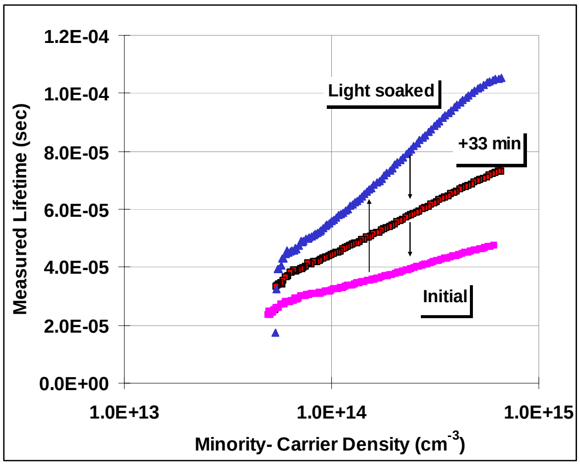

**Figure 5:** The injection-level dependence of the lifetime for a particular position on the block duplicates the main features of the dependence as previously measured on wafers[4]. However, the intersection of the curves is not at the 1-2E14 value previously measured for nitride-passivated wafers[4].

The analysis of the lifetime data presented by Macdonald et al.[4] was applied to lifetime data from 6 blocks of multicrystalline silicon. The results from one face from one block are shown in Fig. 6 and 7. The lifetime after light soaking is shown in Fig. 6. The three traces correspond to the lengthwise scans as shown in Figure 1.

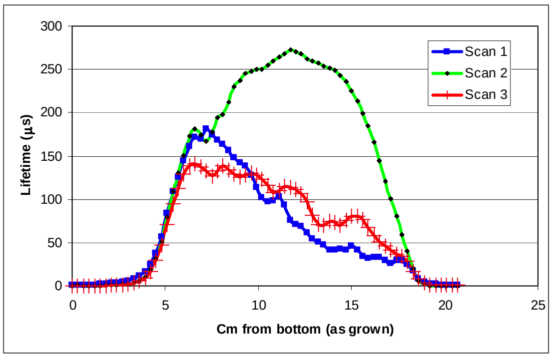

**Figure 6:.** Three linescans lengthwise up block C3-11523 after light-soaking.

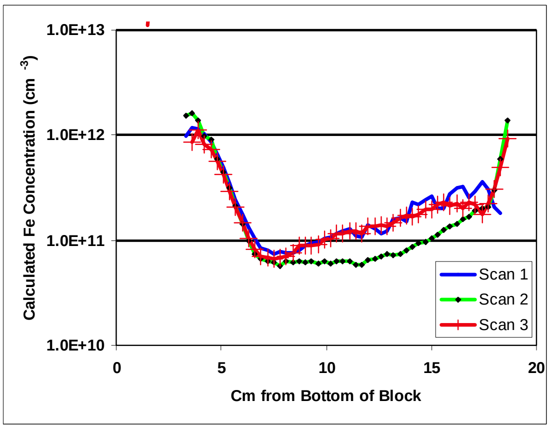

**Figure 7:.** For the regions with high lifetime, the data from the center block from the ingot, block C3-11523, was analyzed for iron concentration using the methodology of references (2) and (4).

This Fe profile, shown in Fig. 7, shows the same main features that have been found by Geerligs[2]. He did measurements on nitride-passivated wafers from differents regions of multicrystalline blocks. For some samples, he found the profile of Fe at the bottom of the block that is due to the solid-phase diffusion of Fe up from the bottom of the ingot (left in Figure 7) during the long times at high-temperatures after this material is solidified. The increase of Fe along the block is due to segregation of Fe into the melt during solidification, and the sudden increase at the top is highly-defected material where the remaining Fe (and other impurities) in the melt are frozen in. Some solid state diffusion "backwards" occurs giving a diffusion profile back into the top of the ingot.

The conversion of lifetime data to Fe concentration requires the minority-carrier density and resistivity of the material[4]. Both of these quantifies were measured at each point in the block. The 850 nm IR-pass filter was used in this work because more photons are available than with the RG-1000 filter. This permitted the data to be taken at higher injection levels, nominally $7 \times 10^{14}$ cm$^{-3}$ in high-lifetime regions and 85% of the maximum achieved carrier density in the low-lifetime regions where $7 \times 10^{14}$ cm$^{-3}$ was not reached.

Figure 8 illustrates a practical application of the measurement of lifetime and Fe concentration data. Here, the components of the recombination rate are plotted vs. position in the block. When the recombination due to Fe is subtracted from the measured recombination, the result is predictive of the cell efficiency since typical cell processing will remove or passivate Fe[2]. Figure 8 indicates that if a decision is made to keep wafers that will have diffusion lengths greater than the cell thickness, 1 cm more silicon would be used from the bottom of the block, and 0.5 cm more from the top compared to the same decision not taking the effects of Fe into account. This extra 1.5 cm could represent 45 wafers.

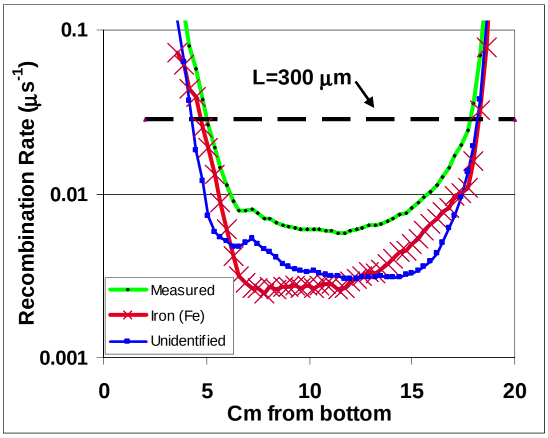

**Figure 8.** The recombination due to iron calculated for the concentrations shown in Fig. 7. When this is subtracted from the measured data, the result, "other" recombination, is predictive of cell performance[2]. The recombination rate where diffusion length equals cell thickness is shown for reference.

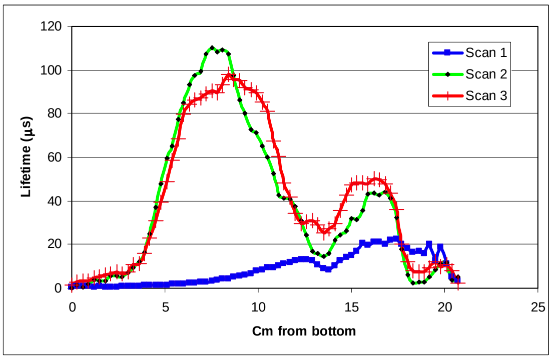

Figure 9. The lifetime scans for a corner block from the ingot, E1-11523, with an interesting lower-lifetime feature at 13 cm.

Figure 9 shows lifetime scans from one face of a corner block from an ingot. This lifetime scan shows an interesting dip in lifetime, for all three scans, at about 13-14 cm. The calculated Fe concentration from this block, Fig. 10, does not show any peak in the Fe concentration at this point, indicating that dissolved Fe is not the cause of this low-lifetime region. Another parameter that was measured in these line scans was the “trapping” as defined in references [7] and [8]. This trapping has been shown to correlate with poor crystalline quality, including dislocation densities [8]. In Fig. 11, there is a strong peak in the trapping at the point where the lifetime dips. For comparison, the trapping for the center block C-11523 is shown in Fig. 12. For C3-11523, the overall trapping levels are much lower than in the corner block E1-11523. A peak in the trapping at 17 cm in one of the scans does correlate with a drop in lifetime at that same spot in the lifetime scan. Again, this lifetime dip correlates better with this trapping than with the Fe concentration.

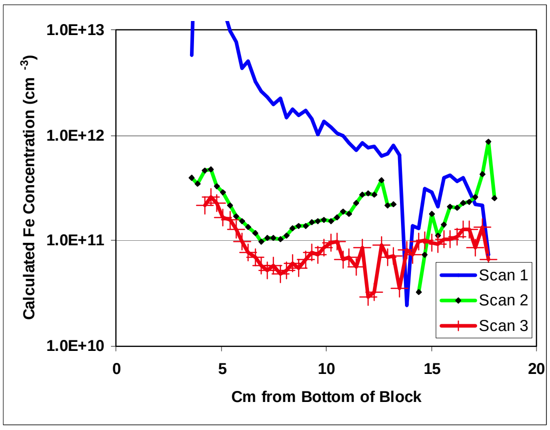

**Figure 10.** The calculated Fe concentrations for the corner block shown in Fig. 9. The low-lifetime feature at 13 cm is apparently not correlated with high dissolved Fe concentration. In contrast, the low lifetime of one edge, labeled “top” is directly correlated with the calculated Fe concentration.

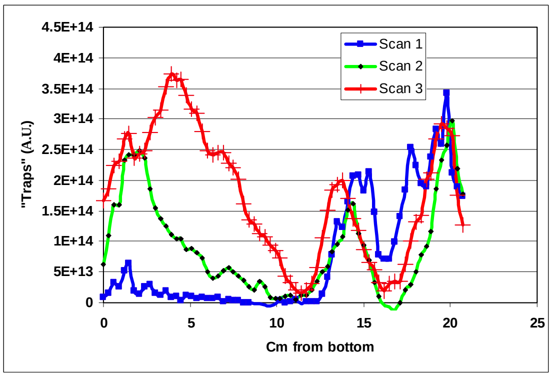

**Figure 11.** Trapping, as defined in Ref [7] and [8] vs. position from the bottom of the block shown in Fig. 9 and Fig. 10. The strong dip in lifetime at 13-14 cm correlates with this trapping parameter.

## 4 CONCLUSIONS

This paper presents a methodology for obtaining calibrated quasi-steady-state photoconductance measurements on Si blocks. This was demonstrated by measuring lifetime, Fe, and trapping on multicrystalline blocks. The results show similar trends to previous studies done on wafers cut from various positions in silicon blocks and surface passivated with a nitride deposition[2]. In regions where Fe is known to diffuse into the crystal from the crucible or is frozen into the crystal at the top of the ingot, high-levels of Fe were observed resulting in low lifetime. Some other low-lifetime regions were present that did not correlate with dissolved Fe. In this initial study, these regions appear to correlate with trapping. The distinction is important, as poor lifetime due to Fe contamination can recover due to gettering and hydrogen passivation in the cell process. Poor lifetime due to poor crystalline quality is likely to result in solar cells with poor efficiency[2].

The results in this paper support previous studies that indicate that better decisions can be made on which sections of a block to saw into wafers for processing and which sections to recycle [2]. This work demonstrates a method for obtaining this data on industrial blocks in the production process. This could provide immediate feedback to crystal growth in both research and industrial settings, as well as optimize the yields of wafered silicon into efficient solar cells.

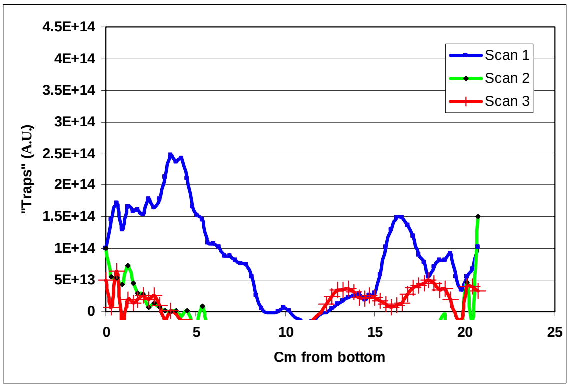

**Figure 12.** For the high-lifetime center block shown in Fig.s 6 and 7, the low lifetime dip also correlates with trapping, rather than with the Fe concentration.

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