Revised April 2004 • NREL/SR-520-35884

Subcontractor Report

Development of an In-Line Minority-Carrier Lifetime Monitoring Tool for Process Control during Fabrication of Crystalline Silicon Solar Cells

Annual Subcontract Report
June 2003

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Boulder, Colorado

National Renewable Energy Laboratory

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Contract No. DE-AC36-99-GO10337

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Prepared under Subcontract No. ZDO-2-30628-08

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Abstract:

As the production volumes of crystalline silicon manufacturing lines have grown in recent years, the demand for improved process control and process monitoring in manufacturing has increased. Since 1995, Sinton Consulting Inc. has been providing several tools to both Universities and industry for their R&D laboratories. For example, over 100 Sinton minority-carrier lifetime instruments are in use worldwide. The purpose of the work reported here is to adapt these successful R&D instruments and techniques to be directly applicable to process control and monitoring in production environments.

Under the PV Manufacturing R&D subcontract "Development of an In-Line, Minority-Carrier Lifetime Monitoring Tool for Process Control during Fabrication of Crystalline Silicon Solar Cells", Sinton Consulting developed prototypes for several new instruments for use in the manufacture of silicon solar cells. These instruments are based on two families of R&D instruments that were previously available, an illumination vs. open-circuit-voltage technique and the quasi-steady state RF photoconductance technique for measuring minority-carrier lifetime. Compared to the previous instruments, the new prototypes are about 20 times faster per measurement, and have automated data analysis that does not require user intervention even when confronted by challenging cases. For example, un-passivated multi-crystalline wafers with large variations in lifetime and trapping behavior can be measured sequentially without error. Five instruments have been prototyped in this project to date, including a block tester for evaluating cast or HEM silicon blocks, a CZ ingot tester, an FZ boule tester for use with long-lifetime silicon, and an in-line sample head for measuring wafers. The CZ ingot tester and the FZ boule tester are already being used within industry and there is interest in the other prototypes. For each instrument, substantial R&D work was required in developing the device physics and analysis as well as for the hardware. This work has been documented in a series of application notes and conference publications, and will result in significant improvements for both the R&D and the industrial types of instruments.

Acknowledgements: Special thanks to Victoria Nosal, Ed Witt, Christie Johnson, Carolyn Lopez and David Mooney for guiding us through this first proposal and subsequent DOE subcontract. Much of the technical work in this report was made possible by the contributions of Tanaya Mankad and Stuart Bowden.

Introduction.

The objective of this subcontract over its two-phase, two year duration is to design and develop improvements to the existing Sinton Consulting R&D minority-carrier lifetime testers. The envisioned improvements would enable the possibilities for performing various in-line diagnostics on crystalline silicon wafers and cells for solar cell manufacturing lines. This would facilitate manufacturing optimization and improved process control.

The scope of work for Phase I was to prototype industrial applications for the improved instruments. A small-sample-head version of the instrument was to be designed and developed in this effort. This new instrument was to be complemented by detailed application notes detailing the productive use of minority-carrier lifetime measurements for process optimization and routine process control.

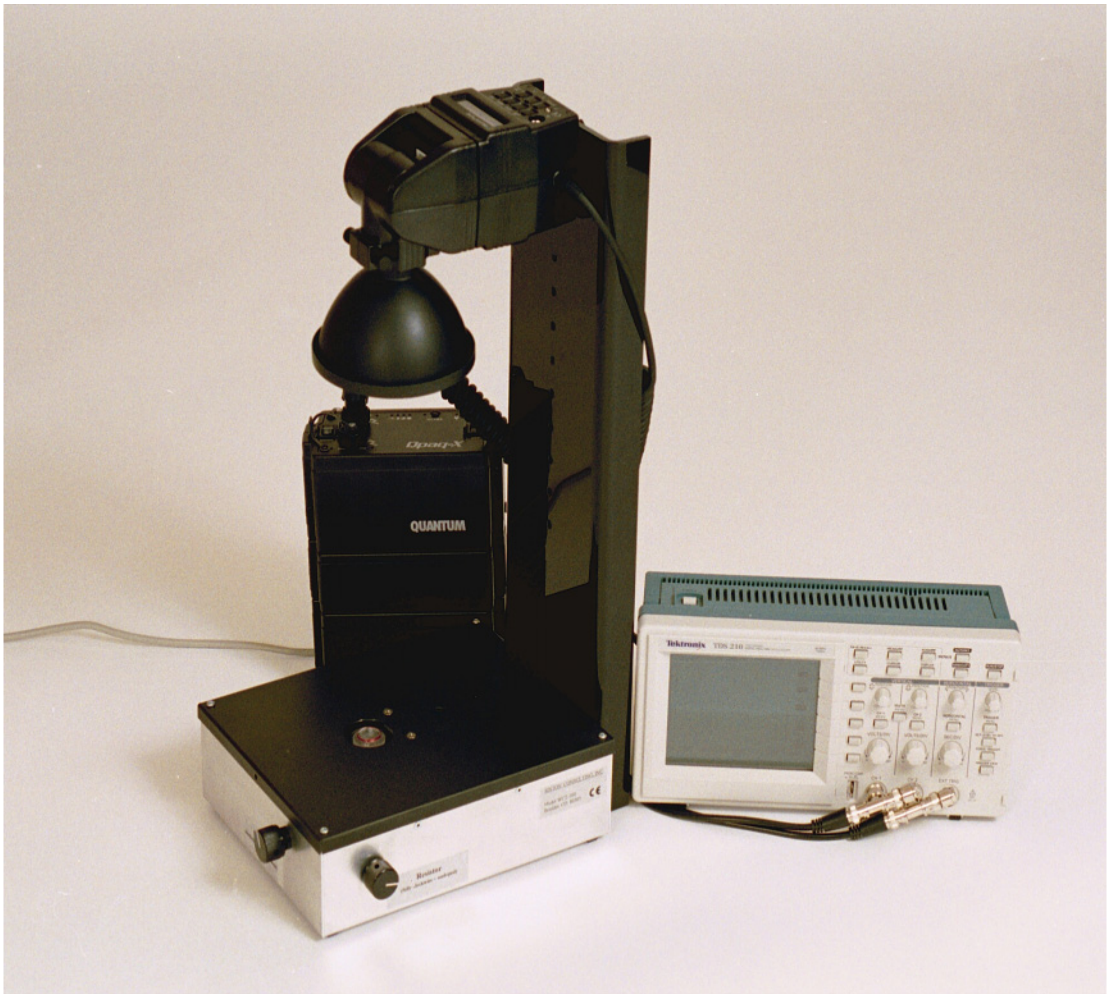


Fig. 1. The starting point for this subcontract. Over 100 Sinton Consulting lifetime testers are used worldwide. This instrument is primarily applied to taking detailed measurements on single wafers in an R&D setting. Industrial applications and industrial versions of this measurement technique will be discussed in this annual subcontract report.

Task 1. Prototype Industrial Applications Using Existing or Modified Instruments.

The R&D minority-carrier lifetime tester(1) from Sinton Consulting requires considerable skill and understanding for successful measurements. An important goal of Task 1 in this subcontract was to refine the instrument, the measurement procedures, and the software in order to eliminate the necessity of operator discretion and intervention for measuring individual wafers.

This goal was largely achieved by working with the original R&D instrument, the WCT-100, and optimizing the procedures, software analysis and the hardware. In the new procedure, the measurement is referenced to an undoped wafer instead of the dark conductance of the wafer under test. In this way, the instrument can be tuned once for an undoped wafer and then left unattended. Each measurement will then be taken referenced to this undoped wafer. By doing this, the full non-linear calibration curves for the instrument output response vs. conductance could be implemented. These calibration curves are also referenced to an undoped wafer. This improved the accuracy of the instrument as well as the usability. Some hardware improvements were incorporated in order to minimize the long-term instrument drift from this initial calibration.

In order not to lose sensitivity by referencing a conductance far from the conductance of the wafer under test, auto-scaling of the gain and voltage offset was implemented into the hardware and software. This improvement removed the necessity for the user to be an oscilloscope expert. Now, results from a novice user are rather indistinguishable from the results that an experienced scientist would obtain.

Data published from the R&D instrument generally uses the full injection-level lifetime curve in order to draw conclusions about the data. At the start of this project, it was thought that analysis simplifications would be required in order to achieve the high-speed measurements that would enable in-line wafer testing or block scanning. One of the first accomplishments of this work was to implement a fast data acquisition card to replace the digital oscilloscope previously used. This, in combination with better database implementation, allowed the complete R&D analysis to be so quick that these functions did not limit the rate at which data could be obtained, analyzed and logged. It was found that the inclusion of the full analysis allows the direct porting of methods used in the R&D labs to the industrial applications, without compromising the analysis flexibility or data quality. A new interface sits on top of the full data analysis in order to present the user with a limited spectrum of options completely specialized for the task at hand. In the background, the complete analysis is implemented and this reports back a simplified set of results to the user.

This results in a façade of a simple program and interface, while the results can have the same credibility as those that might be published from the R&D lab. An example of a simplified interface is presented under Task 2.

A demonstration of the implemented improvements is shown in Figure 1. One subtask of Task 1 was to demonstrate the Suns-V_{oc} technique(2) at high speed, suitable for automation. This technique allows the construction of a current-voltage curve as soon as the diffusion is formed on the wafer by simply probing the two polarity regions of the wafer. The open circuit voltage as a function of the illumination intensity is then measured and converted to a presentation analogous to the final solar cell I-V curve.

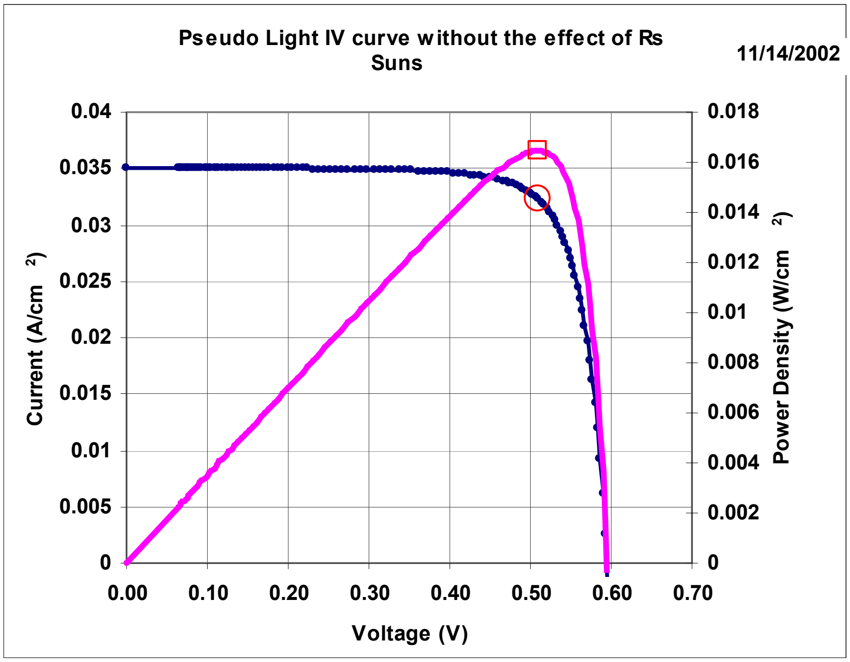


Fig. 2. The Pseudo-IV curve from a high-quality 100 cm^2 solar cell. This is the result that would be expected from a solar cell that had no series resistance.

It is most easily used after Al back-surface field formation, when the substrate is electrically accessible simply by placing the wafer on a conductive chuck. The resulting curve gives the upper bound possible for efficiency, since the data is taken under open-circuit conditions and involves no current flow. This illumination vs. open-circuit voltage technique was implemented using this new hardware and software interface. Fig. 2 and 3 show examples of data taken at a high rate, one wafer per two seconds.

This data in Figure 2 required that accurate voltage and illumination data be taken over two orders of magnitude (in illumination) within a fraction of a second. The fast data acquisition and analysis allows a large number of points to be taken at high resolution. The result has quite low noise. The longer term stability and standard deviation for a large number of measurements taken at high speed is shown in Fig. 3. For example, the measured "Pseudo fill factor" of this curve is 0.7906 +/- 0.0003, giving a standard deviation of 0.04% over these 3000 measurements taken in 100 minutes.

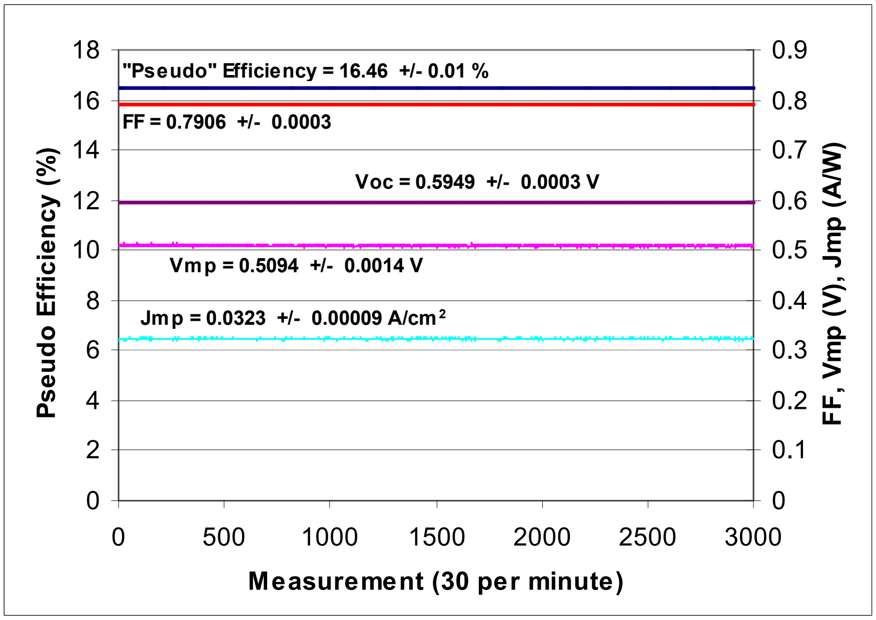


Fig. 3. A demonstration of the repeatability and speed of the measurement. 3000 measurements were taken on a single wafer at a rate of 30 per minute. With automation of the wafer handling, this could have been 3000 wafers.

Demonstration of the spectral response of the photoconductance was another subtask called out in Task 1. This was implemented on several instruments and used to optimize measurements on bare wafers and silicon blocks. This is reported under Task 2.

Task 2. Design, Engineer and Test a Small Sample Head Suitable for Use Inline.

The intention of this task was to develop a small sample-head version of the lifetime tester with the flexibility to address applications for inline wafer testing and measurements on industrial multi-crystalline and CZ blocks or boules of silicon. This task was expected to result in a prototype design that could be used as the basis for an instrument for industrial early-adopters of lifetime testing.

In fact, it quickly became obvious that this task should be accelerated, in order to obtain proof of concepts for the instruments. The ideal proof of concept is one that gives a portfolio of data analysis results that can be sent around in order to focus a discussion with industry on near-term as well as long-term applications of the instrument to particular problems. Once this is done, industrial interest drives easy cooperation with significant industry involvement including sample exchanges, discussions, and on-site experiments. This helps to define the most relevant and useful designs and requirements for the instruments.

This strategy resulted in prototypes of four different lifetime-test instruments in this first year. Two of these have already been placed in industry, and are generating published as well as unpublished data that is contributing to further improvements in the instruments and measurement techniques. The following will briefly introduce these four instruments, as well as a key result or two from each. These instruments are an ingot lifetime tester for use on CZ material prior to sawing(3), a block-test line-scanner for use on multicrystalline blocks prior to sawing, an FZ boule tester capable of characterizing the new generations of long-lifetime, low-cost FZ material to be used in low-cost 20% production silicon solar cells(4,5,6), and a small sample head suitable for integration into a production line as an in-line lifetime tester for each wafer at the start of the process(7) as well as at latter stages such as directly after the phosphorus diffusion(16).

A key enabling technology for these instruments was the design of a small, maneuverable instrument that could be placed on irregularly shaped samples (cylindrical, flat, etc.). Also, the light source was integrated into the instrument so that the illumination and the photoconductance sensing is from the same side of the sample. As shown in figure 1, the previous R&D instrument had open-air illumination giving a uniform, large area illumination on a wafer and a reference cell. The photoconductance sensor was underneath the wafer on the opposite side from the illumination. In order to measure blocks, this had to be changed so that the portion of the block that would be illuminated on one side was also the portion where the sensor would monitor photoconductance. The reference cell was made to be internal to the instrument as well. This compact design forms the basis for all four instruments in this section. Each instrument and analysis is different for the four applications. However, many of the design parts are in common, simplifying the manufacture of instruments to serve these different applications.

1. An instrument for measuring the lifetime on solar CZ silicon ingots.

This instrument was optimized to measure lifetime in the range of 1-100 microseconds on ingots that have no sample preparation. Ingots would simply be pulled from the existing processes and measured. This instrument is shown in Fig. 4, 5. Lifetime data from this instrument is shown in Fig. 6. The lifetime as a function of the wavelength of light is shown in comparison data from a transient measurement and simulations from PC1D(7).

With the critical lifetime to be measured normally in the range of 10 μs, the Quasi-steady-state photoconductance (QSSPC) method gives much more robust results than the transient PCD method with this instrument(1). Infra-red light is used as the excitation source. This light is absorbed deep within the silicon. Much of the photogeneration is deeper than the diffusion length in this material. In this case, the measured lifetime becomes relatively indicative of the bulk lifetime, even for as-sawn or as-ground surfaces with very high surface recombination velocities.

The theory for QSSPC on blocks of silicon within the range of solar silicon has be investigated, with the results developed into an application note(8). Some of these results were presented at the 2003 PVSEC conference in Osaka as well(7).

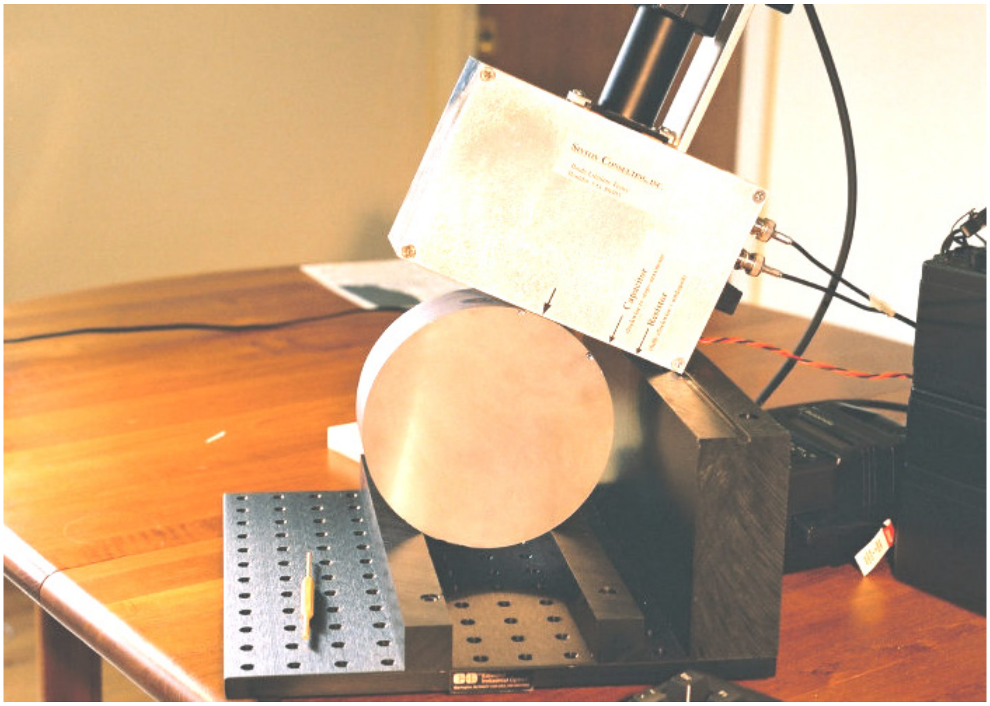


Figure 4. A small sample head used in a configuration allowing the measurement of the lifetime in CZ silicon ingots. A section of an ingot is shown here.

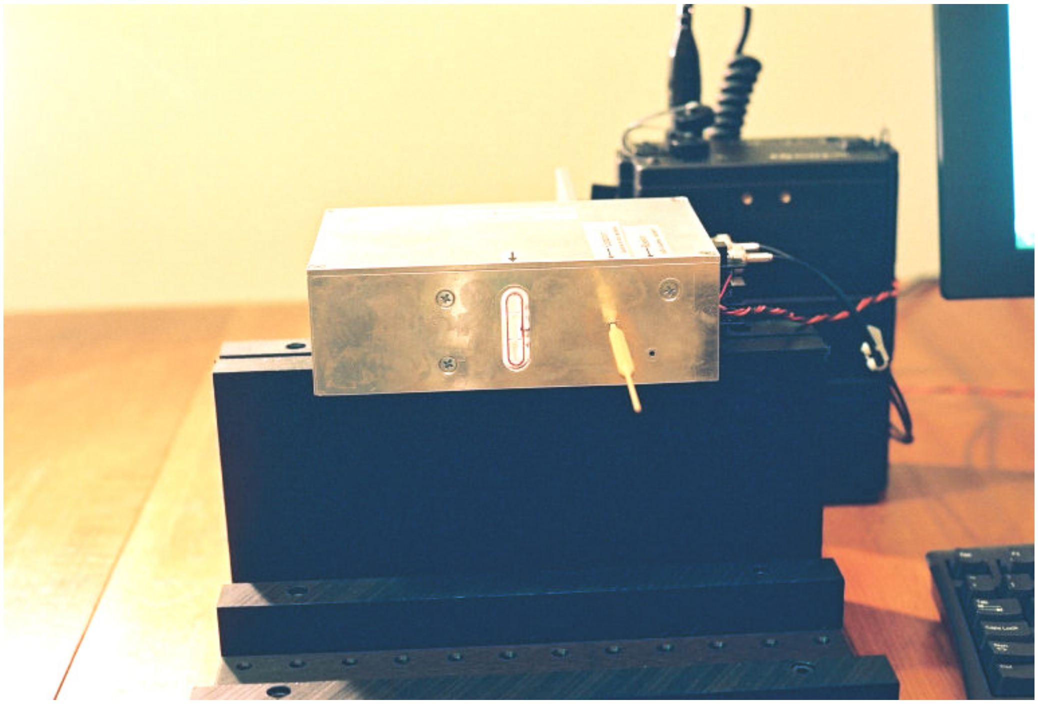


Fig. 5. The shape of the sensor is optimized for flexible measurements of blocks. The relatively large area gives a large photoconductance signal, and insures that the device physics of the analysis is primarily one-dimensional. The long slender shape of the sensor permits measurements on cylindrical shapes, since the sensor and illumination is nearly planar to the sensed portion of a cylindrical ingot when used in the geometry shown in Fig. 4.

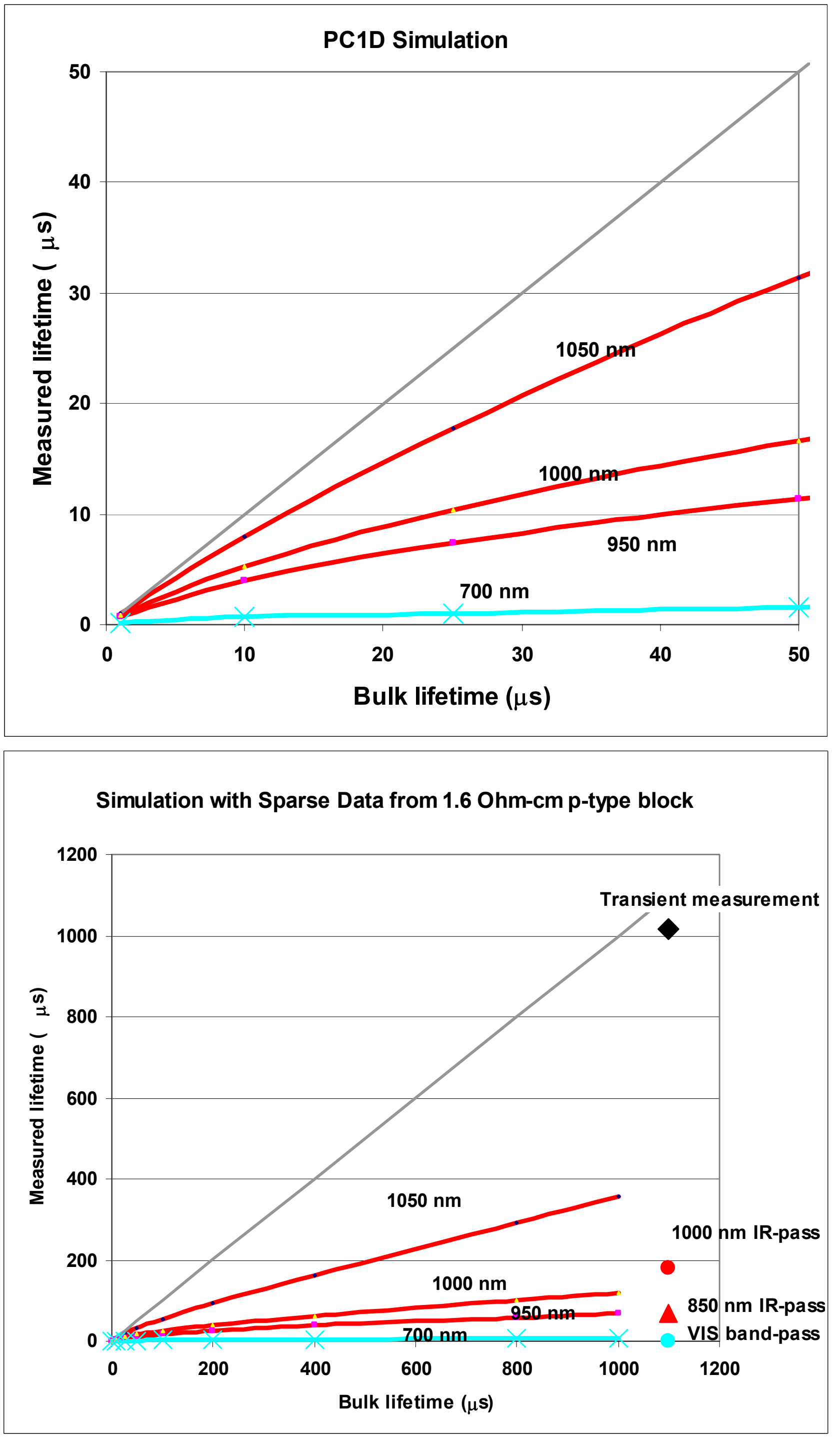
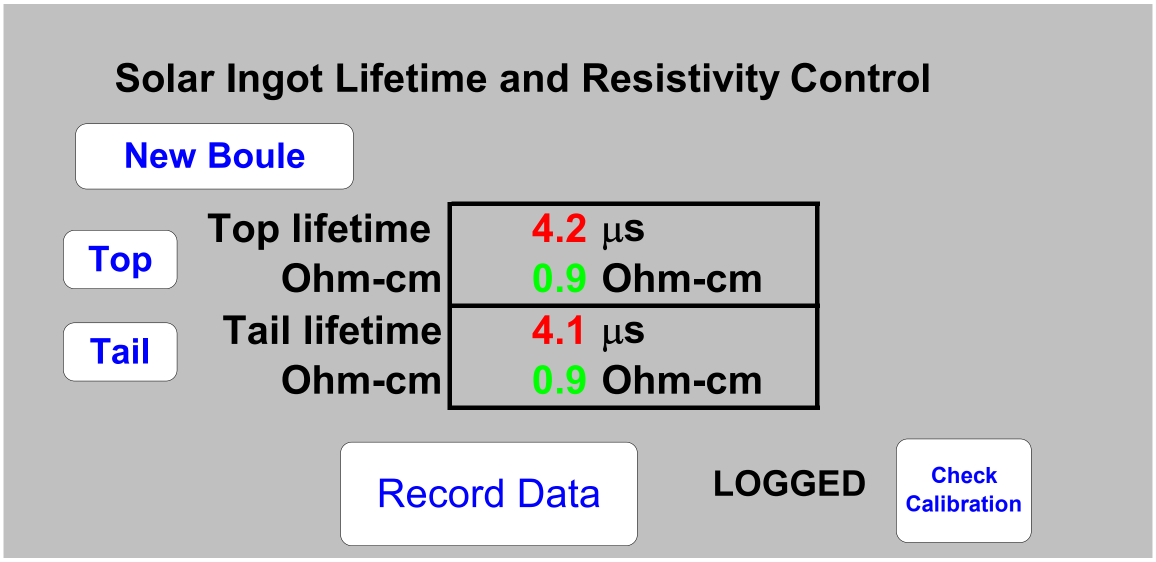


Fig. 6. QSSPC lifetime data from a CZ solar silicon instrument for 3 wavelengths of light (see Fig. 16). The top graph shows the simulation in the range of solar CZ silicon. This data was taken on a 1.6 Ohm-cm FZ sample as a calibration of the QSSPC method. The data is compared to a transient PCD measurement and simulation curves from PC1D.



Top lifetime 4.2 µs
Ohm-cm 0.9 Ohm-cm
Tail lifetime 4.1 µs
Ohm-cm 0.9 Ohm-cm

Fig. 7. An example of a simplified interface. Although the device physics analysis is done with the same completeness as in the R&D instrument, a small subset of user input and analysis output is displayed on the user interface. This standardizes the measurement for a wide range of user types. To the user, the system is simple and the data is repeatable. The analysis results are color coded. Red results "fail". green results "pass".

Figure 7 shows an example of a simplified user interface suitable for industrial application. In this case, the user pushes a button, and a window pops up to accept the sample name. To measure the silicon, the operator places the instrument on the sample and pushes a button ("top" or "tail"). When finished, the data is logged to the database. Unseen by the operator, the QSS analysis is applied with a fixed interpretation previously set up by the engineer. This data analysis can specify the injection level to report the result, a bias light analysis to correct for trapping, and any of the other analysis techniques common to the QSSPC method. This system results in very uniform data results that are simple to obtain and are rather operator independent since there is little discretion in the measurement or analysis at the operator level.

2. A Multi-Crystalline Block Scanner.

Figure 8 shows an instrument for measuring the lifetime of a multicrystalline block. This instrument performs a line scan down the length of the block, with high resolution (2 mm). This data can be used to determine the good region of the block from which to saw wafers. The data will also be used to optimize the growth process. Knowing the quality and spatial uniformity of the silicon directly after growth (and cutting into blocks) will allow short-loop optimization of the growth process. This information will be especially valuable since it can be done directly after growth, and it is independent of variations that might be introduced during wafer fabrication. Also, fabrication processes usually scrambles the wafer order, so that spatial information about the block is lost by the time the solar cell efficiency is determined.

A detailed view of the sense head is shown in Fig. 9. This arrangement, with a thin line of illumination, was optimized for the block-scan application. The long line averages over about ¼ of the width of the block. The thin dimension of the line is in the direction of the scan. Some data from a line scan is shown in Fig. 11. The transition between material that is suitable for fabricating solar cells, and material destined for re-cycling is fairly abrupt. The 2 mm resolution, coupled with a 1-2 mm step size will yield information sufficient to specify a cut to an accuracy of less than a millimeter.

Fig. 8 shows the apparatus after a line scan. The data is on screen, and shows the lifetime as a function of position, as well as the resistivity as a function of position. Another view of the instrument is shown in Fig. 10.

If desired, the instrument can do raster scans to accomplish a 2-D mapping. The present prototype is not automated for scanning in the second dimension, although a manual stage movement is incorporated in this 2nd axis.

As with the Solar CZ measurement, the preferred methodology of measurement and analysis with this equipment is the QSSPC method. Infra-red light creates photogeneration that extends into the silicon beyond a diffusion length from the surface. PC1D simulations give a good approximate calibration for the difference between "measured" and actual lifetime as shown in Fig. 6. A final correlation will probably be done by the industrial customer, by comparing the measured lifetimes to the resulting final solar cell efficiencies in order to map the complex relationship between the lifetimes as measured on as-grown materials with this method and the final solar cell efficiencies(3). Since the properties of the silicon wafer will change during high-temperature processing, the relationship between as-grown lifetime and final lifetime will be complex.

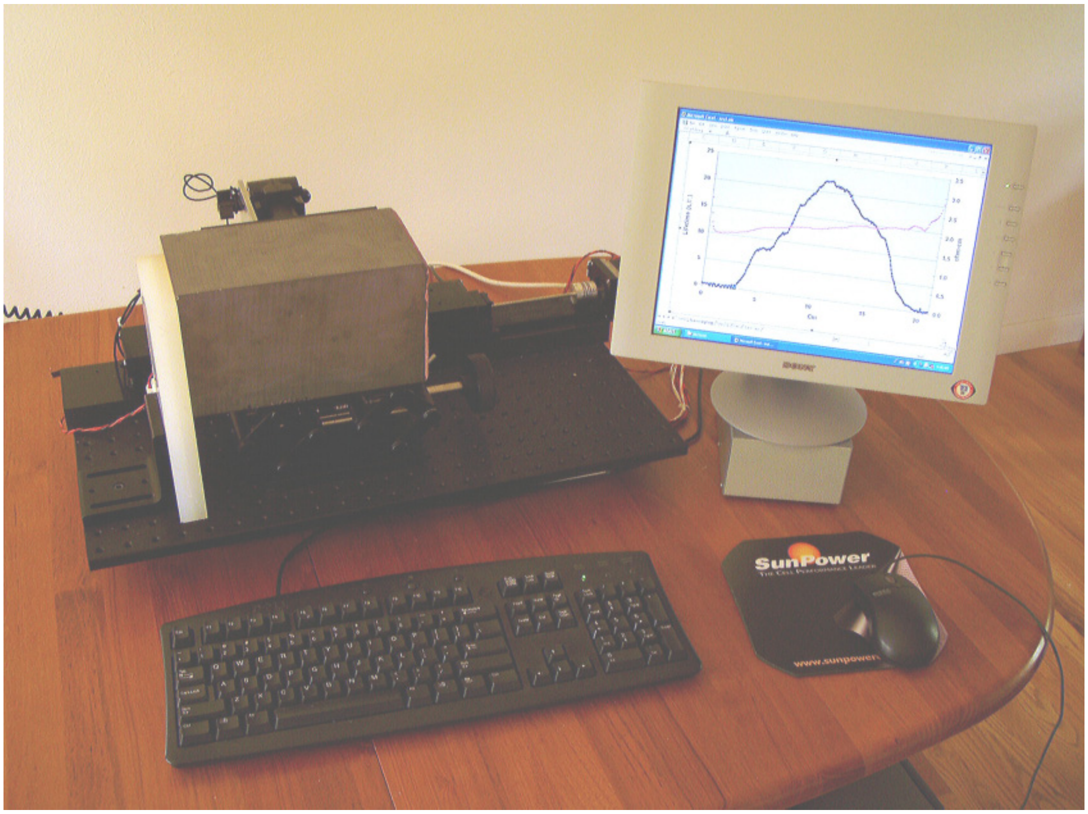


Fig. 8. This instrument performs line scans down the length of a Multi-crystalline silicon block. The sample head, (behind the block) is run along a computer-controlled stage.

Fig. 9. A detail of the block scanner, the sense head. This spot size is about 3 mm wide, and 30 mm high giving high resolution when stepped in the long (growth) axis of the block. The result is averaged over 30 mm in the axis perpendicular to the growth direction. The total illuminated area is large enough to give very good signal to noise.

Fig. 10. A different view of the block scanner indicating the sample head as it scans the block.

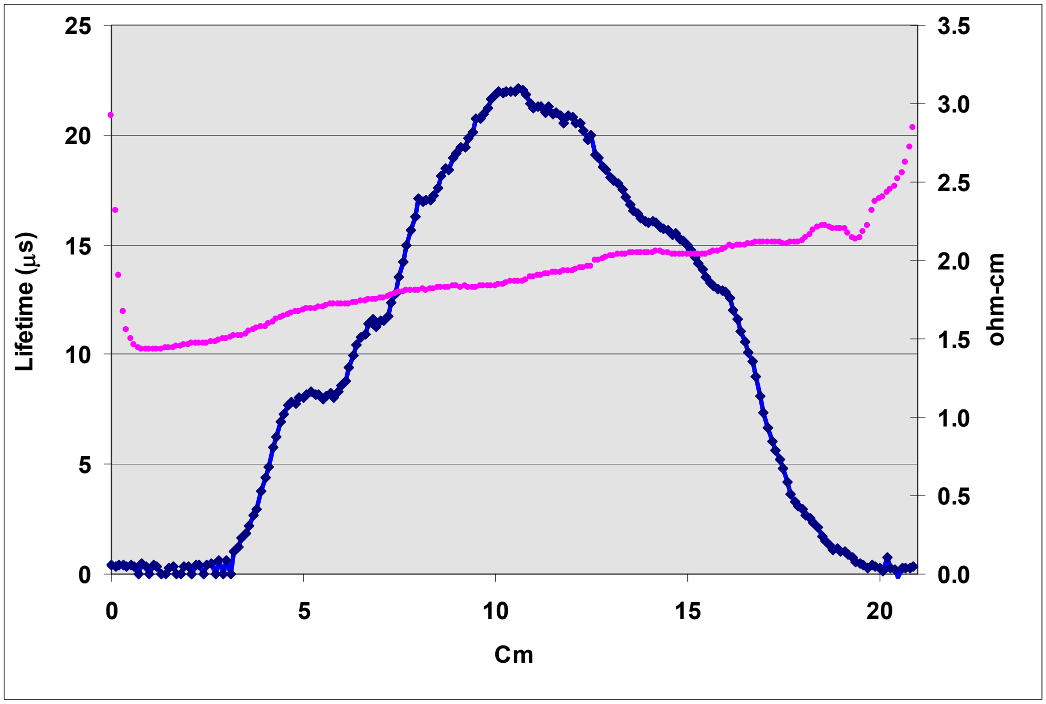


Fig. 11. A line scan. This data averages over 30 mm, about ¼ of the block width, yet has a 2-3 mm resolution in the growth direction. This data was taken at a 1 mm step size in the growth direction. Lifetime is in blue (left axis), resistivity in pink (right axis).

3. An Instrument for Measuring Lifetime on High-Lifetime FZ Boules.

This application is unique for the series of instruments, in that it utilized the transient PCD technique. In contrast to the QSSPC technique, for a transient measurement the light is abruptly terminated, and then the decay of the photoconductance in the dark is monitored. Data taken in this way is shown in Fig. 12.

This is the optimal situation for FZ silicon. This silicon typically has very high lifetime. Recombination at the surface would have a major effect on the measured lifetime of this material as determined by the QSSPC technique. By terminating the light abruptly, the surface recombination quickly eliminates electrons from near the surface. After this initial rapid decay, the measured lifetime asymptotically approaches the actual bulk lifetime. PC-1D simulations have been applied to verify this behavior, and study it in detail(9).

An instrument measuring an FZ boule is shown in Fig. 13. The instrument is nominally the same as the CZ instrument. However, the analysis is different, with an optimization for this high-lifetime material. In addition, more light of shorter wavelengths is used in the excitation to obtain the highest possible initial photoconductance, since the surface modes are allowed to decay away before the bulk lifetime is determined(8).

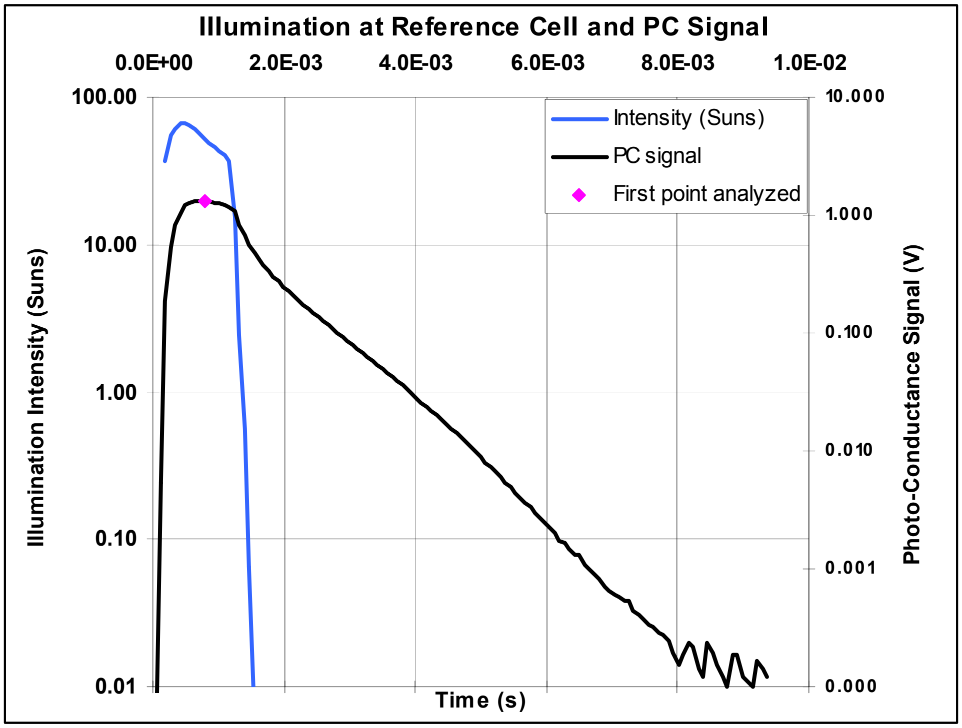


Fig. 12. A transient measurement on a 1.6 Ohm-cm p-type FZ boule of silicon. (sample courtesy of Jan Vedde, Topsil A/S).

Data from an 1.6 Ohm-cm p-type boule is shown in Fig. 13. In contrast to measurements on wafers, it is difficult to calibrate the injection-level scale precisely, since the carriers are not confined. They can diffuse deep into the bulk away from the RF sense head. This effect is a function of the diffusion length. As a result, the minority-carrier injection levels shown on the x axis are approximate.

At high injection levels, (which occur just after the light is extinguished), the measured lifetime is short as the surface recombination quickly annihilates the electrons near the surface. Boron-doped p-type material generally has lower lifetime at low injection levels than at higher injection, due to the bulk recombination. The competition between these trends leads to a maximum lifetime during this measurement at moderate carrier density. This lifetime, 1.4 ms for this boule, indicates that very long lifetime can be characterized despite the lack of surface passivation on the boule.

This instrument and measurement promises instant feedback to the grower for optimization of the material growth. In addition, it allows for specification of the boule for lifetime as a characteristic that can be given to the solar cell fabrication line or wafer customer. The layout of this instrument, with a boule to be measured, is shown in Fig. 14.

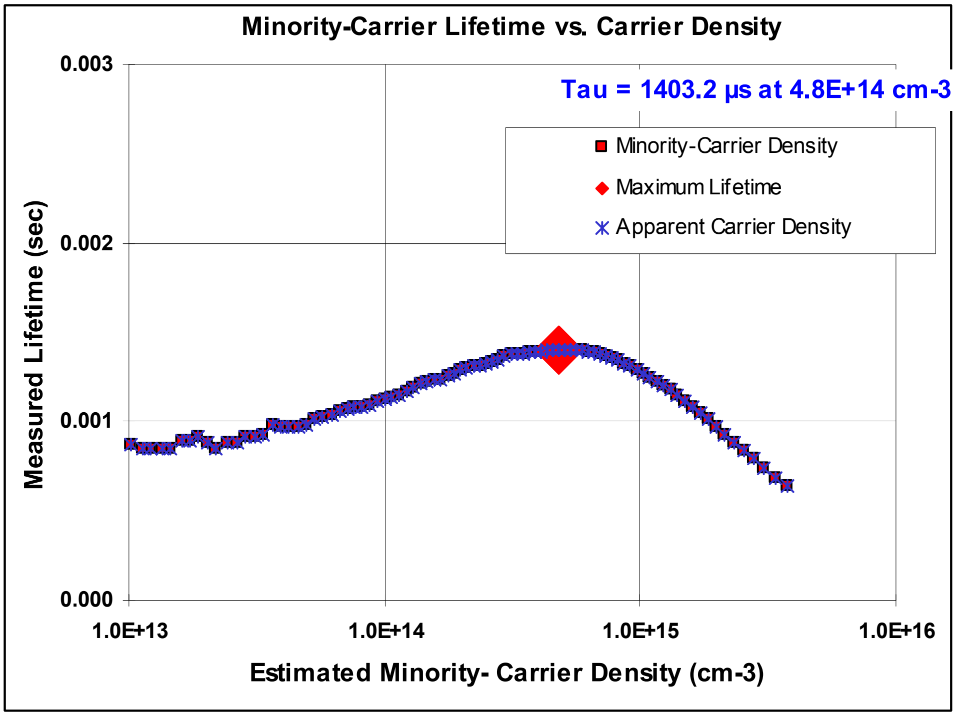


Fig. 13. Analyzed data from a transient measurement of a 1.6 Ohm-cm FZ boule of silicon. Despite a lack of an surface preparation, lifetimes exceeding 1 ms can be measured. The accuracy of the measurement results has been modeled in PC1D and detailed in an application note(8).

Figure 14. An instrument that was optimized for measurements on as-grown boules of high-lifetime float-zone silicon. (Photograph courtesy of Jan Vedde, Topsil A/S).

4. An Instrument for the rapid In-Line Measurement of Wafers.

The last instrument to be discussed here is a small sample head that was optimized for measuring wafers. This instrument is shown in Fig. 15. Again, for ease of automation, the internal light source configuration was used in contrast to the open-air method for the R&D instrument. However, this small sample head has a large illuminated sense area for very high sensitivity. This will allow for the measurement of unpassivated thin wafers. This case, unpassivated wafers with no surface recombination, is quite difficult to measure due to low effective lifetimes in the wafers, coupled with highly-variable levels of trapping, which tends to bury the signal that would be due to minority-carrier photoconductance(10).

This instrument applies a correction for trapping that is based on obtaining the full injection-level dependence of the measured lifetime(10). In addition, the wavelength dependence of the lifetime has been applied to better separate out the surface from the bulk effects in order to more accurately track the bulk lifetime(7,13). This was reported at the PVSEC in Osaka(7), and detailed in an application note as well(11). For the case of typical industrial solar cell wafers, (300-μm-thick, 1 ohm-cm p-type wafers) guidelines for QSSPC measurement have recently been detailed in a handbook(12). Fig. 16 shows a key result from this work. For wafers with good surface passivation, such as a phosphorus emitter diffusion with a grown oxide or nitride, the measured lifetime will correspond closely to the bulk lifetime, for lifetimes less than 50 µs. For unpassivated wafers 1-ohm-cm multicrystalline wafers, the lifetime has been determined to be greater than 1 x 10^5 cm/s by using the wavelength dependence of the measured lifetime to separate bulk and surface effects(7,13). Filters were integrated into the light path for the instrument shown in Fig. 15. This photon distribution from these filters is shown in Fig. 16. This instrument configuration enables straightforward application of the technique of Bail(13) to measure the surface recombination velocity. By noting the dramatically different lifetimes measured with visible and IR light (Fig. 17), the results from Fig. 15 could be used determine the surface recombination velocity.

This predictable high surface recombination allows a correction to be made to the lifetime data that will allow “good” from “bad” unpassivated wafers to be discriminated with better precision. The effect of this correction is shown in Fig. 18.

For this measurement to be valid, it has been found that the trapping correction is essential, therefore this correction is incorporated into the instruments intended for this application.

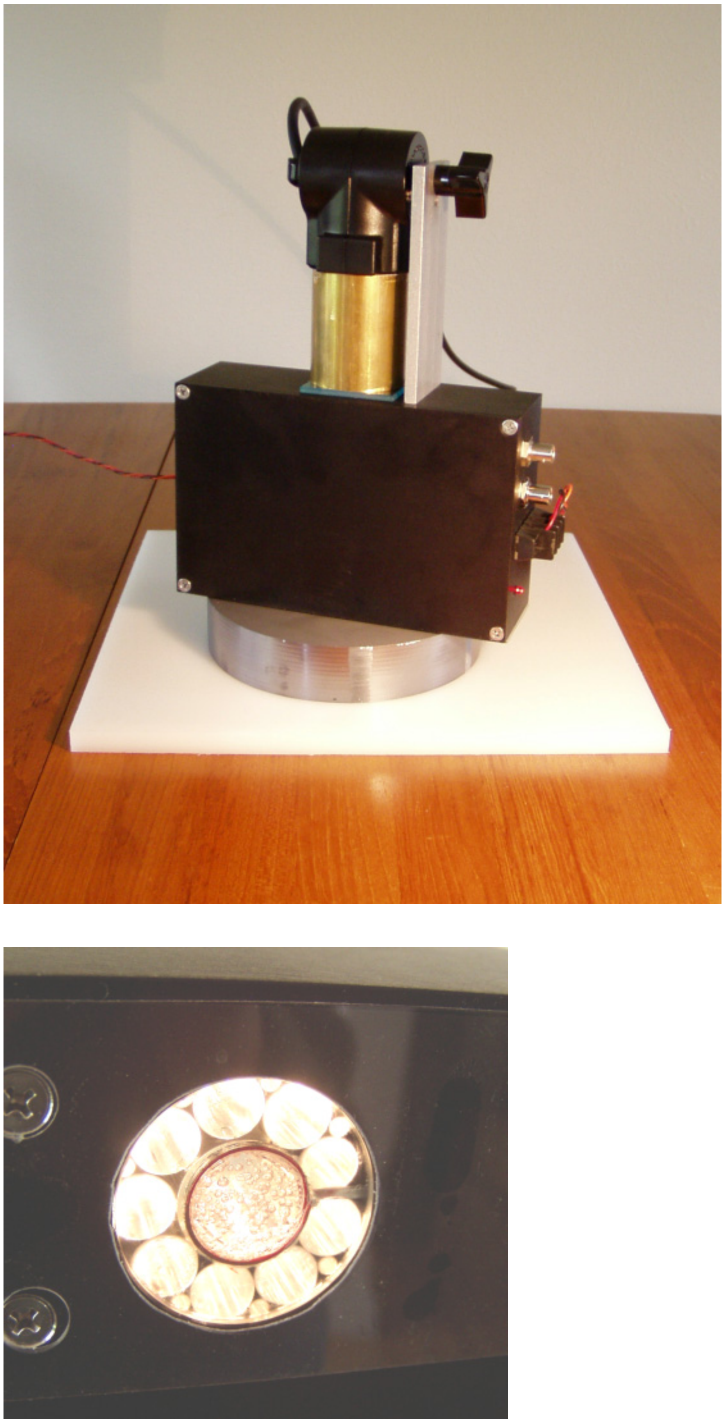


Fig. 15. This sample head is optimized for in-line measurements of wafers or flat surfaces of uniform blocks. The illuminated area is large, to enable high sensitivity for measuring unpassivated wafers just entering the process line, and giving very one-dimensional results on phosphorus-diffused wafers.

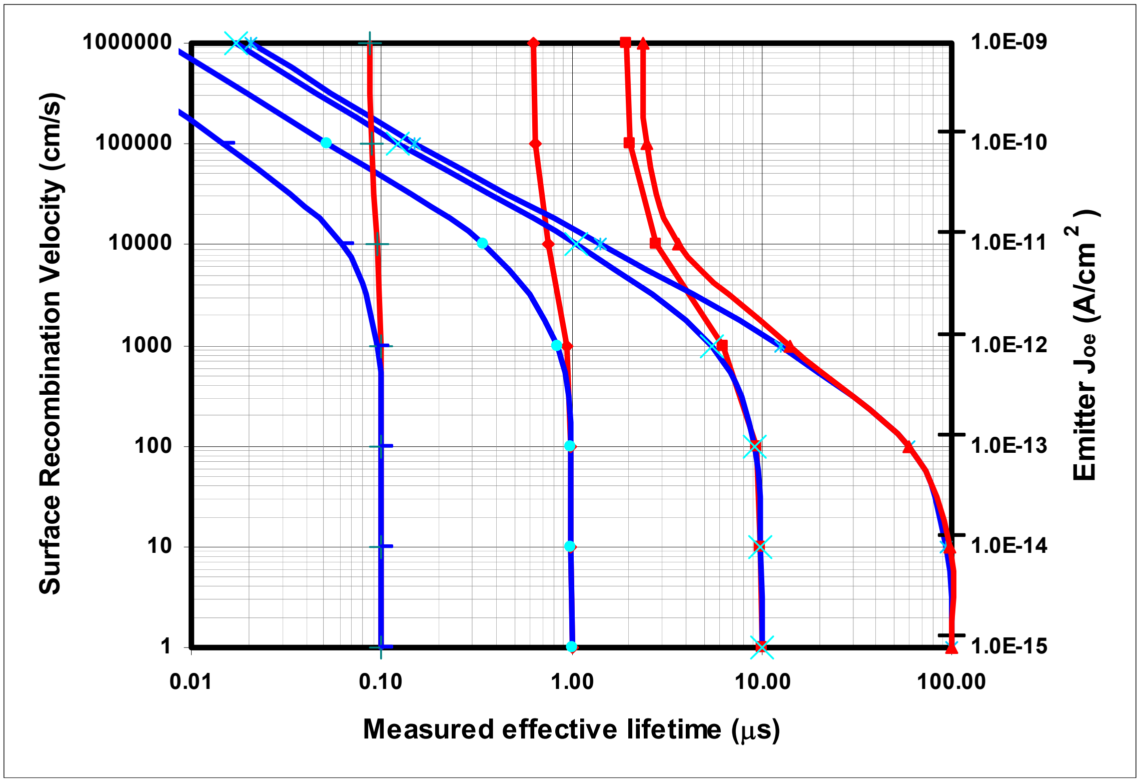


Fig. 16. The wavelength dependence of photoconductance has proven to be a powerful tool in R&D. These curves indicate the different lifetimes that would be measured on industrial 1 ohm-cm, p-type substrates with bulk lifetime of 0.1, 1, 10, and 100 μs, as a function of the surface recombination. For well passivated wafers, the measured lifetime is the bulk lifetime. For unpassivated wafers, the difference between the lifetime measured under blue and infra-red light can be used to accurately determine bulk lifetime and surface recombination velocity(Bail, Sinton).

Two application notes have been developed for the instrument in Fig. 15. The first is coupled with a special version of the software analysis, and is optimized for bare wafers(11).

The second application note is focused on measuring wafers after the phosphorus diffusion(16). There is already ample data from industry using the WCT-100 R&D instrument that the lifetime measured after the phosphorus diffusion is very predictive of the final solar cell efficiency. This measurement has been used to qualify both the process and the wafer at this stage, where the cost of screen print and final test can still be avoided if the wafer or emitter diffusion is bad. Also, any process problems can be quickly identified almost as soon as they occur giving unambiguous feedback very close to the source of the problem.

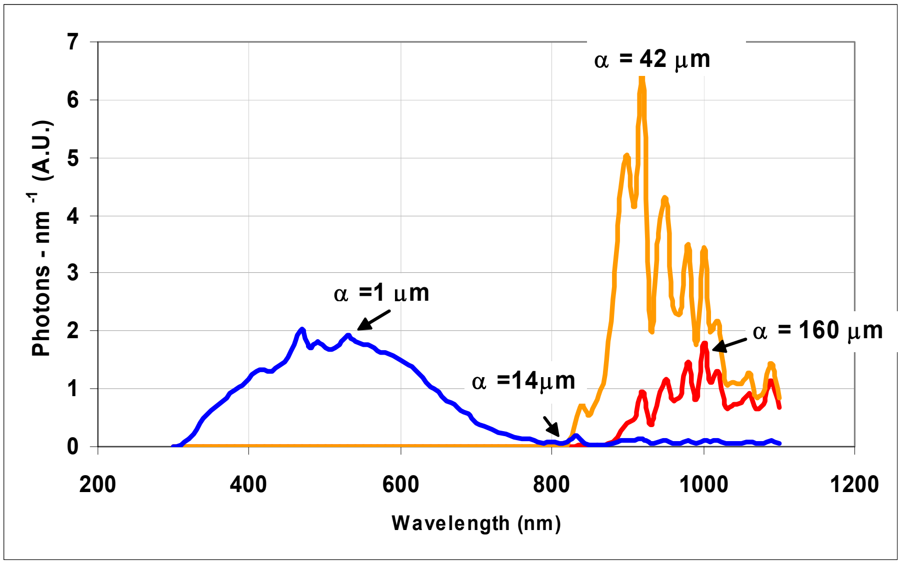


Fig. 17. The photon distribution that results from 3 filters and a flashlamp. The flashlamp spectrum was measured[14] and the filter characteristics were taken from specification sheets. The three filters are visible-pass, IR-pass with a 850 nm threshold, and 1000 nm IR-pass.

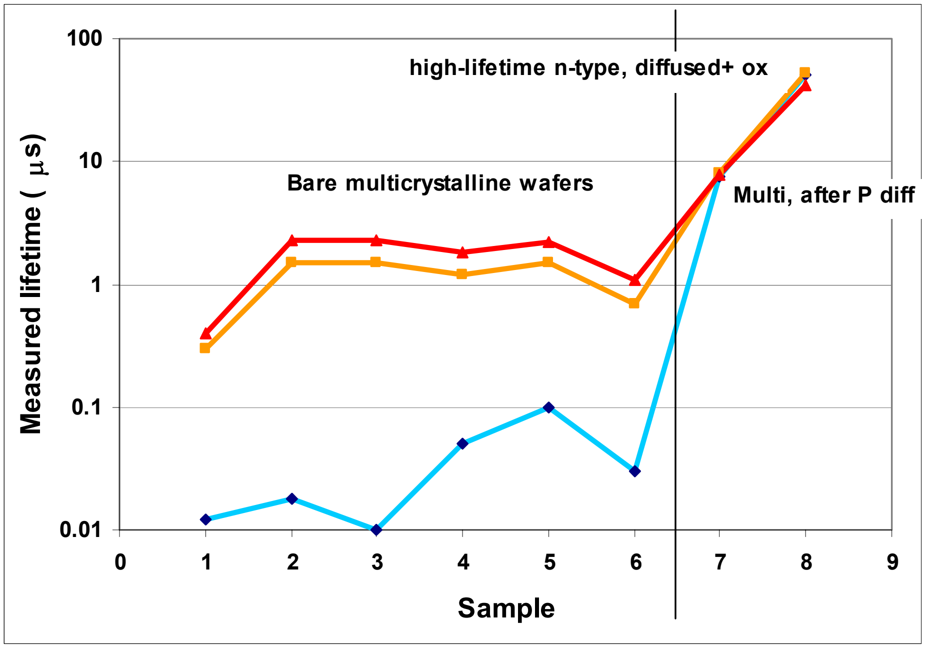


Fig. 18. The lifetime measured on industrial multi-crystalline wafers with a nominal resistivity of 1-ohm-cm. A much lower lifetime is measured using blue light, indicative of a surface recombination velocity greater than 10^5 cm/s. Once this high surface recombination velocity is verified for a sample, an analysis can be used to better estimate the true bulk lifetime of these samples. The passivated samples, shown on the right, have wavelength independent measured lifetimes, as predicted by the modeling in Fig. 16. The colors correspond to the three photon distributions shown in Fig. 16.

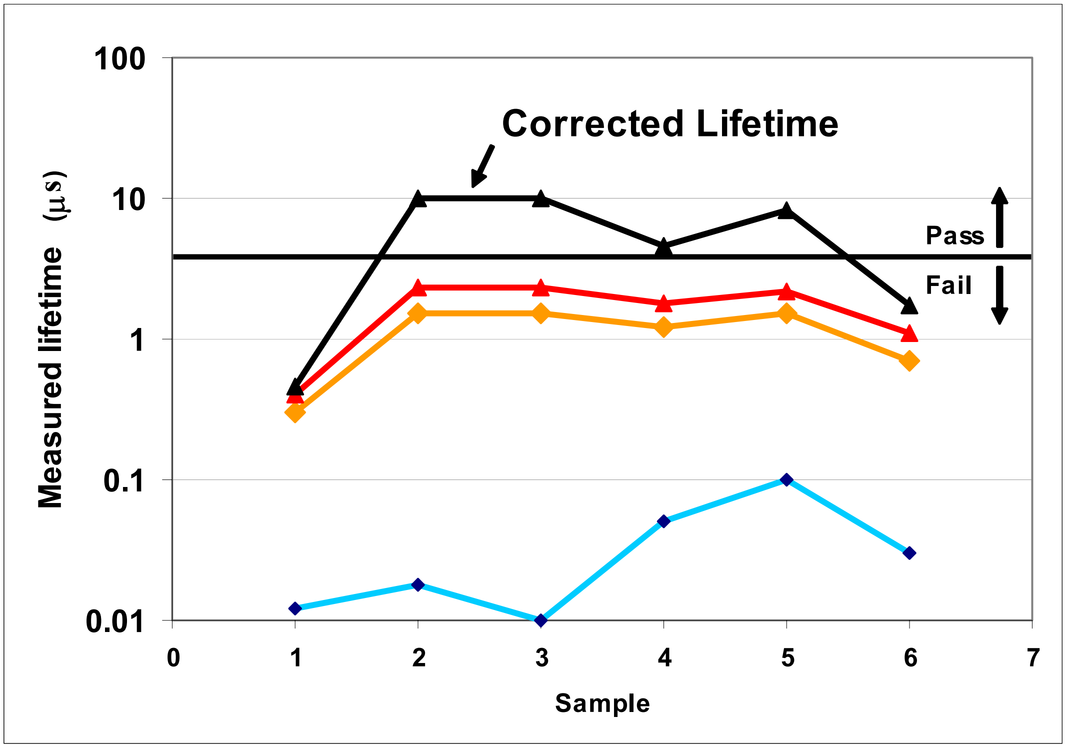


Fig. 19. The data from the bare multi-crystalline wafers from Fig. 18, also showing the correction that can be applied if the lifetime measured with visible light is much less than the lifetime measured with infra-red light. This correction, based on the sample thickness, removes the effect of the wafer thickness from the measured lifetime, and gives a much better approximation of the actual bulk lifetime than the measured lifetime does. This allows a more informed selection criteria for the acceptance or rejection of bare un-passivated wafers.

Task 3. Develop Application Notes for Industrial Use of Lifetime Testing in the Production Line.

The intent of this task was to develop application notes for industrial applications of the instrument. These notes should operate on several levels. First, they should allow a simple procedure to obtain immediate and valid results. Second, they should provide an explanation of the device physics connecting the measurement procedure and results solidly to the scientific basis for the measurement.

These notes have been completed for 4 applications:

1) Measurements on bare wafers(11). A special version of the software was constructed that is optimized to be very robust for this measurement. The application note details the basis for the measurement. The technique chosen for this optimization involves the spectral response of the measured lifetime to correct for the high-surface recombination velocity. The study and qualification of this technique was reported in a conference paper(7), as well as under the discussion of Task 2 in this report.

2) Measurements on relatively uniform blocks or boules of material. An application note details both the use of an optimized instrument and QSSPC to measure CZ solar silicon, and the use of transient PCD for measurements on FZ silicon. Some details of the QSSPC measurement were presented in a conference paper(11). The FZ analysis is as yet unpublished other than the application note itself(8).

3) Measurements on wafers after phosphorus diffusion, or after other good surface passivations. This application note(15) focuses primarily on the optimum measurement strategies for industrial wafers after the phosphorus diffusion, but has general discussion of other wafer types as well. The use of high-resistivity wafers to qualify a diffusion process is also covered. Some details that are particular to multi-crystalline wafers, and the interpretation of data from wafers with widely varying grain lifetimes was presented in a conference paper(15). This paper discusses the type of lifetime average that results from the circuit connection through the junction that is present during measurements on wafers after the phosphorus diffusion.

In addition to these application notes, several other activities are in progress. These include the complete specification of typical instruments for characteristics vs. ambient temperature range, the determination of the lifetime measurement accuracy that can be guaranteed, and traceability of lifetime measurements to a standard. This is ongoing, largely because rather than a “typical” instrument, we have developed 4 instruments during the Task 2 activities. As a result, the characterization of these instruments has been broad, across the varied instruments, rather than deep. More work remains to be done on MTBF and other longer-term characteristics of each individual type of instrument.

The function of measuring sheet resistance or resistivity with the conductance sensor in these instruments has been formalized in two applications. In the block scanner, this resistivity is measured and plotted as a function of position. For the wafer measurement tools, this function has been implemented so that the measurement is taken automatically whenever a lifetime is measured.

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(work developed with support from this subcontract is marked with an *)

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REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE April 2004	3. REPORT TYPE AND DATES COVERED Annual Subcontract Report June 2003

4. TITLE AND SUBTITLE Development of an In-Line Minority-Carrier Lifetime Monitoring Tool for Process Control during Fabrication of Crystalline Silicon Solar Cells: Annual Subcontract Report, June 2003	5. FUNDING NUMBERS PVP46101 ZDO-2-30628-08
6. AUTHOR: R.A. Sinton	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Sinton Consulting, Inc. 1132 Green Circle Boulder, Colorado 80305	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401-3393	10. SPONSORING/MONITORING AGENCY REPORT NUMBER NREL/SR-520-35884
11. SUPPLEMENTARY NOTES NREL Technical Monitor: D. Mooney	
12a. DISTRIBUTION/AVAILABILITY STATEMENT National Technical Information Service U.S. Department of Commerce 5285 Port Royal Road Springfield, VA 22161	12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words):* Under the PV Manufacturing R&D subcontract "Development of an In-Line, Minority-Carrier Lifetime Monitoring Tool for Process Control during Fabrication of Crystalline Silicon Solar Cells", Sinton Consulting developed prototypes for several new instruments for use in the manufacture of silicon solar cells. These instruments are based on two families of R&D instruments that were previously available, an illumination vs. open-circuit-voltage technique and the quasi-steady state RF photoconductance technique for measuring minority-carrier lifetime. Compared to the previous instruments, the new prototypes are about 20 times faster per measurement, and have automated data analysis that does not require user intervention even when confronted by challenging cases. For example, un-passivated multi-crystalline wafers with large variations in lifetime and trapping behavior can be measured sequentially without error. Five instruments have been prototyped in this project to date, including a block tester for evaluating cast or HEM silicon blocks, a CZ ingot tester, an FZ boule tester for use with long-lifetime silicon, and an in-line sample head for measuring wafers. The CZ ingot tester and the FZ boule tester are already being used within industry and there is interest in the other prototypes. For each instrument, substantial R&D work was required in developing the device physics and analysis as well as for the hardware. This work has been documented in a series of application notes and conference publications, and will result in significant improvements for both the R&D and the industrial types of instruments.

14. SUBJECT TERMS: PV; thin film; solar cell; manufacturing; process control; crystalline silicon; minority carrier; open-circuit voltage; photoconductance; quasi steady state; float-zone silicon; phosphorus diffusion;	15. NUMBER OF PAGES
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT UL