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(54) Title: SYSTEM AND METHOD FOR DETERMINING SURFACE RECOMBINATION VELOCITY

(57) Abstract: System and method of determining a front surface recombination velocity of a semiconductor sample, the method including the steps of: measuring an experimental photoluminescence of the sample; calculating a corresponding theoretical photoluminescence of the sample using a diffusion length distribution of the sample and for an arbitrary constant front surface minority carrier density; determining an actual front surface minority carrier density as a function of the experimental and the theoretical photoluminescence; and determining the front surface recombination velocity using the determined actual front surface minority carrier density.
SYSTEM AND METHOD FOR DETERMINING SURFACE RECOMBINATION VELOCITY

FIELD OF INVENTION

Embodiments of the present invention provide systems and methods for determining the surface recombination velocity of a semiconductor sample, in preferred embodiments employing external irradiation to quantify the surface passivation of semiconductor materials, particularly for solar cell applications.

BACKGROUND

Silicon solar cells are now used extensively throughout the world to generate electricity. These cells may be made from mono- or multicrystalline silicon wafers. These wafers are usually p-doped, with a surface diffusion of n-type dopants performed on the front side of the wafer to form a p-n junction a few hundred nanometers below the surface. The manufacturing process for high-performance solar cells requires a high quality starting material, and a reliable, sustainable performance of the manufacturing equipment. In order to achieve this high-performance goal, it is necessary to monitor the wafer quality during various stages of the manufacturing process.

One important step for obtaining a high energy conversion efficiency of a silicon wafer solar cell is the proper passivation of both wafer surfaces, which would otherwise induce unacceptable electrical losses by surface recombination of photo-generated electron-hole pairs. In order to determine if proper passivation has been achieved, it is desirable to test the solar cell during the manufacturing process. Unfortunately, even though surface passivation is one of the most critical steps for achieving high energy conversion efficiencies of silicon wafer solar cells, there is currently no system or method available that allows the extraction of this important data in a direct way and that provides sufficiently reliability or robustness for research or industry.

Present techniques for measuring the surface recombination velocity, where a low or preferably zero surface recombination velocity is equivalent to a good passivation, are time consuming. Moreover, they are restricted to small, point-like areas or averages
over a large area and require the assumption of certain boundary conditions. Measuring the distribution of the recombination velocity across the surface of a large solar cell can only be performed on selected samples in a laboratory. These techniques are not suitable for the fast in-line control of the manufacturing processes in a real production line.

It would therefore be a great improvement in the art if a system and method could be developed that addresses one or more of the problems discussed above.

SUMMARY

One aspect of the present invention provides a method of determining a front surface recombination velocity of a semiconductor sample, the method including the steps of: measuring an experimental photoluminescence of the sample; calculating a corresponding theoretical photoluminescence of the sample using a diffusion length distribution of the sample and for an arbitrary constant front surface minority carrier density; determining an actual front surface minority carrier density as a function of the experimental and the theoretical photoluminescence; and determining the front surface recombination velocity using the determined actual front surface minority carrier density.

In alternate embodiments, the step of determining the front surface recombination velocity may include balancing the generation and the recombination of the electron-hole pairs for a steady-state illumination condition.

In further embodiments, the method may further include determining a bulk recombination based on the diffusion length distribution of the sample. The step of balancing the generation and the recombination of the electron-hole pairs may include neglecting a back surface recombination. The step of determining the actual front surface minority carrier density may include neglecting a penetration depth of an incident light onto the sample. The step of balancing the generation and the recombination of the electron-hole pairs and determining the actual front surface carrier density may include iteratively solving a diffusion equation as a function of surface recombination velocities at the front surface and at a rear surface respectively as boundary conditions.
In other embodiments, the step of determining the front surface recombination velocity may include considering the generation and the recombination of the electron-hole pairs for a time varying illumination condition. The method may further include determining the diffusion length distribution of the sample. The step of determining the diffusion length distribution may include luminescence imaging.

In further embodiments, the method may further include removing the effect of variations of a luminescence intensity in the luminescence imaging resulting from variations of the actual front surface minority carrier concentration of the sample by taking a ratio of two spectral parts for generating a luminescence image from which the diffusion length is determined.

An alternate aspect of the present invention provides a system for determining a front surface recombination velocity of a semiconductor sample, the system including: means for measuring an experimental photoluminescence of the sample; means for calculating a corresponding theoretical photoluminescence of the sample using a diffusion length distribution of the sample and for an arbitrary constant front surface minority carrier density; means for determining an actual front surface minority carrier density as a function of the experimental and the theoretical photoluminescence; and means for determining the front surface recombination velocity using the determined actual front surface minority carrier density.

Another aspect of the present invention provides a data storage medium having computer code means stored thereon for instructing a computing device to execute a method of measuring a surface recombination velocity of a semiconductor sample, the method including the steps of: measuring an experimental photoluminescence of the sample; calculating a corresponding theoretical photoluminescence of the sample using a diffusion length distribution of the sample and for an arbitrary constant front surface minority carrier density; determining an actual front surface minority carrier density as a function of the experimental and the theoretical spectra; and determining the front surface recombination velocity using the determined actual front surface minority carrier density.
BRIEF DESCRIPTION OF THE DRAWINGS

Embodiments of the invention will be better understood and readily apparent to one of ordinary skill in the art from the following written description, by way of example only, and in conjunction with the drawings, in which:

Figure 1 illustrates a block diagram of one embodiment of a system for calculating a surface recombination velocity of a semiconductor;

Figure 2 is a flow chart illustrating one embodiment of a method for calculating a surface recombination velocity of a semiconductor using the system of Figure 1;

Figure 3 is a graph illustrating simulation results of a method for calculating a surface recombination velocity according to an example embodiment;

Figure 4 is a graph illustrating the luminescence intensity from a silicon sample as calculated from the diffusion equation shown as a function of the surface recombination velocity $S_0$, according to an example embodiment;

Figure 5 is a flow chart illustrating an alternate embodiment of a method for calculating a surface recombination velocity of a semiconductor using the system of Figure 1; and

Figure 6 is a block diagram showing a computer system that may be used for implementing a system and method according to an example embodiment.

DETAILED DESCRIPTION

Embodiments of the present invention provide systems and methods for using a non-contact method employing external irradiation to quantify the surface passivation of semiconductor materials, particularly in solar cell semiconductors.
Embodiments of the present invention employ luminescence which is detected for example with a CCD- or CMOS- camera. In this way, a measurement is advantageously performed on multiple locations of a large sample area simultaneously, by detecting the emission image with a camera. This can be done in a short time, e.g. less than 1 second in an example embodiment, provided the distribution of the diffusion length or the bulk life time of the minority carriers is already determined by a complementary method. Embodiments of the present invention allow the measurement of the spatially resolved surface recombination velocity, and thus the surface passivation, in a direct way, hence, without the need of experimentally inaccessible boundary conditions. In this way, the absolute level of surface passivation and its spatial uniformity can advantageously be accessed in one measurement which can offer enormous advantages in research and development as well in manufacturing.

In the measurement technique of example embodiments, recombination losses occurring in the bulk of a sample are separated from recombination losses at the sample's front and rear surfaces. The total recombination losses affect the concentration of minority carriers at the sample's front surface. The bulk recombination rate can be derived from the bulk minority carrier diffusion length, which can be determined by a complementary method. The total minority carrier concentration that contributes to the luminescence from the sample is derived from the luminescence intensity. A preferred embodiment employs a constant illumination intensity, to exploit that the recombination rate in equilibrium/steady state condition is equal to the generation rate. The generation rate can be calculated from the incident light intensity and the optical properties of the sample under investigation. However, it will be appreciated that the present invention can also be applied under time varying conditions, if desired, by suitable mathematical consideration of the time dependency, leading to more complex calculations, but without departing from the spirit or scope of the present invention. The front surface recombination rate is advantageously determined by the difference of the total recombination rate and the sum of the bulk recombination rate and the rear surface recombination rate.

Figure 1 provides a block diagram of a system 100 for calculating the recombination velocity of a sample according to an example embodiment of the present invention. The
system 100 includes a light source 110 which emits light 112 onto a sample, here in the form of a semiconductor 120. As a result of absorption of the light 112 in the semiconductor 120 and spontaneous radiative recombination of resulting electron-hole pairs in the semiconductor 120, luminescence is emitted from the semiconductor 120, as shown with reference numeral 122. The luminescence 122 may pass through one or more filters 130. This filtered light 132 is then received at a camera 140, which calculates a luminescence intensity, and provides this calculated data to a data processing unit 700 via data path 142.

In this embodiment, the light source 110 generates light suitable for inducing luminescence (i.e., photoluminescence) in silicon, and is used to illuminate the semiconductor surface 120. In a preferred embodiment, the light source 110 is a laser capable of providing coherent monochromatic light 112 to the surface 120. The wavelength of the laser light 112 may be chosen to be as far away from the luminescence 122 wavelength as possible. In a further preferred embodiment, the wavelength may be between about 200 to 900nm for a silicon sample. It is understood that other types of light sources 110 and wavelengths may also be used.

The semiconductor sample 120 may be in the form of a bare wafer, e.g., an unprocessed silicon sample, a partially processed or fabricated semiconductor device, or a fully processed or fabricated semiconductor device.

Filtering is applied to the generated luminescence 122 in this example embodiment to reduce the spectral content of the luminescence 122 above or below specified wavelengths or both (for example by using a short pass filter, a long pass filter or a band pass filter, respectively). The filter or filters 130 may be implemented separately, or as part of the camera 140. The filter or filters 130 may comprise, by way of example but not limitation, dielectric stacks.

The luminescence 122 from the semiconductor 120 is captured with the camera 140. In this regard, the embodiments of the invention may be applied to image portions of arbitrary size. In a preferred embodiment, the camera 140 is an imaging device comprising an array with more than one individual sensor, such as a CCD camera or any other pixel detector. Each pixel collects the luminescence from a limited area on the
semiconductor 120, thereby creating an image for the entire semiconductor 120. The camera may be a digital camera having a silicon CCD array and can be provided with a digital interface (e.g., USB or Firewire) or storage media (e.g., a DV tape or memory stick) for communication of recorded images. In alternate embodiments, the camera 140 may be a Complementary Metal Oxide Semiconductor (CMOS) imaging device, or other imaging device known to those of skill in the art.

The camera 140 converts the received light into a luminescence measurement which is then digitized and sent to the data unit 700 for processing.

Figure 2 shows a flow-chart 200 illustrating a method for calculating the recombination velocity of a sample using the according to an example embodiment using the system shown in Figure 1. The method 200 is presented using a simple case of a homogeneously doped p-type silicon wafer with a bulk diffusion length much smaller than the wafer thickness. The surface of the wafer is illuminated homogeneously by the light source, which is strongly absorbed by the wafer and inducing photoluminescence, shown as step 202 in Figure 2. The generated minority carriers distribute themselves by diffusing from the surface into the interior of the wafer.

In this example case, recombination of holes and electrons at the rear surface of the wafer does not affect the minority carrier concentration at the surface of the wafer as the bulk diffusion length is much smaller than the wafer thickness. Moreover, for the purposes of illustration in this example embodiment, it is assumed that inhomogeneities in the bulk diffusion length of the silicon wafer 120 occur laterally on a length scale much larger than a diffusion length. These assumptions allow a one-dimensional analysis of the minority carrier distribution in an example embodiment, from the wafer surface into the interior of the wafer.

At step 204, two luminescence images are taken with the camera using different wavelength pass filters, and at step 206, the diffusion length and lateral variations of the diffusion length across the surface area of the wafer are determined from the luminescence measurements using the technique described in P. Würfel et al., J. Appl. Phys. 101 (2007) 123110, the contents of which are hereby incorporated by cross-reference. Broadly, two different parts in the frequency spectrum of the emitted
luminescence intensities are captured using appropriate filters. By taking the ratio of the two spectral parts of the luminescence for every image pixel, the effect due to variations in the minority carrier concentration at the wafer surface 120 can be eliminated. While the method described in P. Würfel et al. is used in this example embodiment, it will be appreciated that other techniques understood in the art may be used in different embodiments to determine the diffusion length and lateral variations of the diffusion length such as spectral light beam induced current (LBIC). The advantages of using the method described in P. Würfel et al. in this example embodiment include that it can be implemented and performed using the same system according to one example embodiment described above with reference to Figure 1.

At step 208, a luminescence image is constructed by calculating the intensity value of each image pixel from the diffusion length distribution obtained in step 206, and assuming an arbitrary but constant value of the surface recombination, i.e. an arbitrary but constant surface concentration \( n_{ref}(0) \).

More particular, the luminescence intensity of photons with energy \( h\omega \) emitted from a silicon wafer is calculated with the y- and z-axis (both axes are orthogonal to each other and lie on the plane of the wafer surface) and the x-axis which is perpendicular to the wafer plane (compare Figure 1). Strongly-absorbed incident light predominantly generates electron-hole pairs close to the surface, from where the minority carriers diffuse into the bulk of the wafer, in the x-direction. The distribution of the minority carriers (electrons in a p-doped wafer) \( n_e(x,y,z) \), having a diffusion length \( L_e \) is

\[
n_e(x, y, z) = n_e(0, y, z) \exp(- x/L_e(y, z))
\]

(1)

where \( n_e(0,y,z) \) is the minority carrier distribution at the wafer surface.

The photon current density \( j_r \) emitted in the photon energy range \( d\hbar\omega \) by the luminescence effect is governed by the generalized Planck emission law (see, for example, P. Würfel, Physics of Solar Cells, Wiley-VCH 2005, the contents of which are hereby incorporated by cross-reference), which can be approximated by
\[ j'_{\omega}(\omega, y, z) = \frac{n_{h}(0, y, z) n_{h}}{n_{e}^{2}} \frac{(\hbar \omega)^{2} d\omega}{4 \pi^{2} h^{2} c^{2} \exp(\hbar \omega/kT)} \exp(-\alpha x) \exp\left(\frac{-x}{L_{e}}\right) \alpha \int_{0}^{\alpha L_{e}} \exp\left(-1 + \frac{x}{L_{e}}\right) dx \]

where \( n_{e} \) is the intrinsic carrier concentration, \( \alpha \) is the wavelength dependent absorption coefficient, \( n_{h0} \) is the hole and electron densities, respectively, \( k \) is the Boltzmann constant and \( T \) is the temperature.

In Equation (2), the emitted photon current density thus depends on the surface concentration and on the diffusion length \( L_{e} \) which both may vary along the \( y \) and \( z \) directions. A resulting signal intensity detected by the camera can be given by the emitted photon current in Equation (2) after introducing a calibration factor \( C \), which contains the transmittance of the optical system, such as the filters and lenses, and the sensitivity of the camera. For simplicity of illustration of the example embodiment, \( C \) is chosen to be 1. However, it is understood that actual values for example obtained by calibration of the system by a known sample may be used in different embodiments.

On the other hand, for a known/measured \( L_{e}(y, z) \), the emitted photon current \( j_{r, ref} \) for a constant front surface recombination and thus front surface concentration \( n_{r, ref}(y, z) \) is equal to

\[ j_{r, ref}(\omega, y, z) = \frac{n_{r, ref}(0, y, z) n_{h}}{n_{e}^{2}} \frac{(\hbar \omega)^{2} d\omega}{4 \pi^{2} h^{2} c^{2} \exp(\hbar \omega/kT)} \alpha \frac{L_{e}}{1 + \alpha L_{e} L_{e}} \exp\left(-\frac{1 + \alpha L_{e} L_{e}}{L_{e}}\right) \]

(3)

It has been recognised by the inventors that the actual surface concentration \( n_{r}(0, y, z) \) can thus advantageously be obtained in this example embodiment by dividing a measured photon current density, represented by Equation (2) after introducing the calibration factor, by the calculated reference photon current in Equation (3):

\[ n_{r}(0, y, z) = n_{r, ref}(0, y, z) \frac{j_{r, ref}(\omega, y, z)}{j_{r, ref}(\omega, y, z)}. \]  

(4)
Thus, at step 210, the "real" front surface recombination, i.e. front surface velocity $S_0(y,z)$ is obtained from a balance of generation ($G_{yb}$) and recombination ($R_{eh}$) of the electron-hole pairs in the wafer under steady state conditions in this example embodiment. More particular, this balance can be expressed as:

$$J_r^{ab} = \int_0^d G_{ab} \, dx = \int_0^d R_{eh} \, dx = n_e(0,y,z) S_0(y,z) + \frac{1}{\tau_e(y,z)} \int_0^d n_e(x,y,z) \, dx + n_e(d,y,z) S_e(y,z), \tag{5a}$$

where $J_r^{ab}$ is the absorbed photon current density, which is given by:

$$J_r^{abs}(y,z) \approx \left( J_d - R j_{\text{ref}} \right) \alpha_{\text{ref}}, \tag{5b}$$

where $J_r^{ref}$ is the incident photon flux, $R$ the reflection of the sample at the incident light wavelength, and $\alpha$ the absorption coefficient of the sample at the incident light wavelength.

The total generation is governed by the absorbed photon current density from the external illumination. The total recombination consists of recombination at the front surface of the wafer, recombination in the bulk characterized by a bulk lifetime $\tau_e$ and recombination at the wafer's rear surface (which can be neglected in this example embodiment as the bulk diffusion length is much smaller than the wafer thickness). Thus, Equation (5) can advantageously be simplified as:

$$J_{r,obs} \approx n_e(0,y,z) S_0(y,z) + \frac{n_e(0,y,z) \tau_e}{L_e} = n_e(0,y,z) \left[ S_0(y,z) + \frac{D_e}{L_e} \right], \tag{6}$$

where $L_e^2 = D_e \tau_e$ has been used, where $D_e$ is the bulk diffusion coefficient.

Finally, the recombination velocity at the front surface of the wafer is obtained as follows:

$$S_0(y,z) \approx \frac{J_{r,obs}}{n_e(0,y,z)} - \frac{D_e}{L_e(y,z)}, \tag{7}$$
In different embodiments, in which the penetration of the incident light and the recombination at the rear surface are not negligible, the analysis is a more complex. For known penetration depth of the incident light and diffusion length of the minority carriers, their distribution follows from solving the diffusion equation as a function of the surface recombination velocities at the front and at the rear as boundary conditions. (This is the "full calculation" with which the simplified analysis described above with reference to equation (7) is compared below) The surface recombination velocities are then adjusted to make the emitted intensity calculated from the calculated carrier distribution equal to the experimentally observed intensity. Since both recombination velocities must be known in such different embodiments, an iterative procedure is used by turning the sample around and making the rear surface the front surface which is illuminated and from which the luminescence is measured.

Figure 3 is a graph illustrating simulation results of a method for calculating a surface recombination velocity according to an example embodiment. The "performance" of the simplified model in this example embodiment is tested at one single point, i.e. according to an one dimensional model by using $S_0$ as input model for a full calculation and then applying the simplified model (Equations 6 and 7) described above.

A typical silicon sample is used for this simulation and its spatial distribution of the minority carrier density is derived as accurately as possible by solving the exact diffusion equation as a function of $S_0$. From the carrier density distribution, the luminescence intensity is calculated as described in P. Würfel et al.

This calculated luminescence intensity serves as an experimental result for the simulation and is then used to derive the front surface recombination velocity $S_0$ using the simplified equation 7. It is clear that due to the approximations in the simplified model the extracted values of $S_0$ 306 differ from the real $S_0$ values 308 especially for very low ($< 5 \text{ cm/s}$) or high ($> 10^4 \text{ cm/s}$). However, the simplified model works very well in the most relevant range for photovoltaic application ($10^-10^4 \text{ cm/s}$).

For the simulation results illustrated in Figure 3, a silicon sample was illuminated with 100 mW/cm² of light with a wavelength of 700 nm (absorption coefficient 2200 cm⁻¹). The
silicon sample is p-doped ([B]=10^16 cm^-3) and has a thickness of 300 µm. The electron diffusion length is \( \ell_e = 100 \) µm, and the surface recombination velocity at the rear is \( S_r = 100 \) cm/s. The minority carrier distribution is calculated by solving the diffusion equation, fully accounting for the non-zero penetration of the incident light, recombination at the front surface and rear surface, and radiative and non-radiative recombination in the bulk. From the minority carrier distribution, the luminescence intensity is then calculated as a function of the front surface recombination velocity \( S_0 \).

As mentioned above, with the knowledge of the diffusion length (or the bulk lifetime \( \tau_r \)), but not the front and rear surface recombination velocities, this luminescence intensity (derived from the accurate model) is then used in the simplified model to derive the front surface recombination velocity, \( S_0 \)-result, which is represented in Figure 3 as a function of the "real" front surface recombination velocity \( S_0 \). For the parameters used, which are typical for silicon used for solar cell manufacturing, the results of the simplified model agree well with the "real" values in the important range of surface recombination velocities from 10 cm/s to \( 10^4 \) cm/s.

It is believed that the results of the simplified model deviate from the "real" values for small values of \( S_0 \) because of the neglect of the rear side recombination in the simplified model. The deviation at large values of \( S_0 \) is believed to be because the real carrier distribution is no longer decreasing exponentially from the surface inwards as a result of the non-zero penetration depth of the incident light.

Better agreement between "experiment" and modelling can be obtained, if the accurate model (i.e., the solution of the diffusion equation) is also used instead of the simplified model in the calculation of the front surface recombination velocity, i.e. not only for the calculation of the "experimental results". The necessary knowledge of the penetration depth of the incident light does advantageously not pose a problem in such embodiments, since it is equal to the inverse of the absorption coefficient, which is a well established quantity for silicon. The knowledge of the recombination velocity at the rear is believed to be less stringent, since recombination at the rear is much smaller than at the front for front side illumination. In addition, it can be obtained iteratively by illuminating the sample from the rear and following the above procedure.
Figure 4 is a graph, designated generally with reference numeral 400, illustrating the luminescence intensity (axis 402) from the silicon sample as calculated from the diffusion equation shown as a function of the surface recombination velocity \( S_o \) (axis 404). The intensity values are normalized to the luminescence intensity for zero surface recombination. As can be seen from curve 406 in Figure 4, at small and at large values of the surface recombination velocity, the variation of the luminescence intensity is rather small. It may thus in any event be difficult to determine reliable values of the surface recombination velocity.

Thus, the effort to obtain accurate values from an accurate model in embodiments of the present invention may not always be preferred over an embodiment using the simplified model. Considering that experiments will always be subjected to instrumental and other measurement errors, the small variation in the luminescence intensity at small and large values of \( S_o \) may not be sufficient to obtain reliable values of \( S_o \) when they are either small or large. Furthermore, there may be no need for a precise knowledge in these ranges for practical applications, e.g. in quality testing of semiconductor samples. If the luminescence intensity is comparable to the case of zero surface recombination, it indicates that the surface passivation may be treated as sufficient for its typical application, e.g. in silicon wafer solar cells. If the luminescence intensity is an order of magnitude smaller, then the surface passivation may be treated as unacceptable. The medium range, in which the simplified model provides good sensitivity (compare Figures 3 and 4), is the range which is preferably studied for such practical applications.

Figure 5 is a flow chart illustrating an alternate embodiment of a method 500 for calculating a surface recombination velocity of a semiconductor using the system of Figure 1. The method 500 includes a first step of measuring an experimental photoluminescence of the sample, as shown with reference numeral 502. The method 500 then includes a step of calculating a corresponding theoretical photoluminescence of the sample using a diffusion length distribution of the sample and for an arbitrary constant front surface minority carrier density, as shown with reference numeral 504. The method 500 then provides for a step of determining an actual front surface minority carrier density as a function of the experimental and the theoretical photoluminescence, as shown with reference numeral 506. The method 500 then provides a final step of determining the front surface recombination velocity using the determined actual front
surface minority carrier density, as shown with reference numeral 508. These steps may be performed as previously described with reference to Figure 2.

Some portions of the description above are explicitly or implicitly presented in terms of algorithms and functional or symbolic representations of operations on data within a computer memory. These algorithmic descriptions and functional or symbolic representations are the means used by those skilled in the data processing arts to convey most effectively the substance of their work to others skilled in the art. An algorithm is here, and generally, conceived to be a self-consistent sequence of steps leading to a desired result. The steps are those requiring physical manipulations of physical quantities, such as electrical, magnetic or optical signals capable of being stored, transferred, combined, compared, and otherwise manipulated.

Unless specifically stated otherwise, and as apparent from the following, it will be appreciated that throughout the present specification, discussions utilizing terms such as "scanning", "calculating", "determining", "replacing", "generating", "initializing", "outputting", or the like, refer to the action and processes of a computer system, or similar electronic device, that manipulates and transforms data represented as physical quantities within the computer system into other data similarly represented as physical quantities within the computer system or other information storage, transmission or display devices.

The present specification also discloses apparatus for performing the operations of the methods. Such apparatus may be specially constructed for the required purposes, or may comprise a general purpose computer or other device selectively activated or reconfigured by a computer program stored in the computer. The algorithms and displays presented herein are not inherently related to any particular computer or other apparatus. Various general purpose machines may be used with programs in accordance with the teachings herein. Alternatively, the construction of more specialized apparatus to perform the required method steps may be appropriate. The structure of a conventional general purpose computer will appear from the description below.
In addition, the present specification also implicitly discloses a computer program, in that it would be apparent to the person skilled in the art that the individual steps of the method described herein may be put into effect by computer code. The computer program is not intended to be limited to any particular programming language and implementation thereof. It will be appreciated that a variety of programming languages and coding thereof may be used to implement the teachings of the disclosure contained herein. Moreover, the computer program is not intended to be limited to any particular control flow. There are many other variants of the computer program, which can use different control flows without departing from the spirit or scope of the invention.

Furthermore, one or more of the steps of the computer program may be performed in parallel rather than sequentially. Such a computer program may be stored on any computer readable medium. The computer readable medium may include storage devices such as magnetic or optical disks, memory chips, or other storage devices suitable for interfacing with a general purpose computer. The computer readable medium may also include a hard-wired medium such as exemplified in the Internet system, or wireless medium such as exemplified in the GSM mobile telephone system. The computer program when loaded and executed on such a general-purpose computer effectively results in an apparatus that implements the steps of the preferred method.

The invention may also be implemented as hardware modules. More particularly, in the hardware sense, a module is a functional hardware unit designed for use with other components or modules. For example, a module may be implemented using discrete electronic components, or it can form a portion of an entire electronic circuit such as an Application Specific Integrated Circuit (ASIC). Numerous other possibilities exist. Those skilled in the art will appreciate that the system can also be implemented as a combination of hardware and software modules.

The method and system of the example embodiment can be implemented on a computer system 700, schematically shown in Figure 6. It may be implemented as software, such as a computer program being executed within the computer system 700, and instructing the computer system 700 to conduct the method of the example embodiment.
The computer system 700 can include a computer module 702, input modules such as a keyboard 704 and mouse 706 and a plurality of output devices such as a display 708, and printer 710. The computer module 702 can be connected to a computer network 712 via a suitable transceiver device 714, to enable access to e.g. the Internet or other network systems such as Local Area Network (LAN) or Wide Area Network (WAN).

The computer module 702 in the example includes a processor 718, a Random Access Memory (RAM) 720 and a Read Only Memory (ROM) 722. The computer module 702 also includes a number of Input/Output (I/O) interfaces, for example I/O interface 724 to the display 708, and I/O interface 726 to the keyboard 704. The components of the computer module 702 typically communicate via an interconnected bus 728 and in a manner known to the person skilled in the relevant art.

The application program can be supplied to the user of the computer system 700 encoded on a data storage medium such as a CD-ROM or flash memory carrier and read utilizing a corresponding data storage medium drive of a data storage device 730. The application program is read and controlled in its execution by the processor 718. Intermediate storage of program data maybe accomplished using RAM 720.

In some embodiments, the computer system 700 may also be used to control the light source 110, movement of the wafer 120, movement of the filters 130, and the operation of the camera 140 (compare Figure 1).

The example embodiments described allow monitoring of the surface passivation level at various stages of solar cell fabrication, employing luminescence, induced in the solar cell by external irradiation, as a non-contact method to quantify the surface passivation and preferably suitable in all stages of solar cell processing.

It will be appreciated by a person skilled in the art that numerous variations and/or modifications may be made to the present invention as shown in the specific embodiments without departing from the spirit or scope of the invention as broadly described. The present embodiments are, therefore, to be considered in all respects to be illustrative and not restrictive.
1. A method of determining a front surface recombination velocity of a semiconductor sample, the method comprising the steps of:
   - measuring an experimental photoluminescence of the sample;
   - calculating a corresponding theoretical photoluminescence of the sample using a diffusion length distribution of the sample and for an arbitrary constant front surface minority carrier density;
   - determining an actual front surface minority carrier density as a function of the experimental and the theoretical photoluminescence; and
   - determining the front surface recombination velocity using the determined actual front surface minority carrier density.

2. The method as claimed in claim 1, wherein determining the front surface recombination velocity comprises balancing the generation and the recombination of the electron-hole pairs for a steady-state illumination condition.

3. The methods claimed in claims 1 or 2, further comprising determining a bulk recombination based on the diffusion length distribution of the sample.

4. The method as claimed in claim 2, wherein balancing the generation and the recombination of the electron-hole pairs comprises neglecting a back surface recombination.

5. The method as claimed in any one of the preceding claims, wherein determining the actual front surface minority carrier density comprises neglecting a penetration depth of an incident light onto the sample.

6. The method as claimed in any one of claims 2 to 3, wherein balancing the generation and the recombination of the electron-hole pairs and determining the actual front surface carrier density comprise iteratively solving a diffusion equation as a function of surface recombination velocities at the front surface and at a rear surface respectively as boundary conditions.
7. The method as claimed in claim 1, wherein determining the front surface recombination velocity comprises considering the generation and the recombination of the electron-hole pairs for a time varying illumination condition.

8. The method as claimed in any one of the preceding claims, further comprising determining the diffusion length distribution of the sample.

9. The method as claimed in claim 8, wherein determining the diffusion length distribution comprises luminescence imaging.

10. The method as claimed in claim 9, further comprising removing the effect of variations of a luminescence intensity in the luminescence imaging resulting from variations of the actual front surface minority carrier concentration of the sample by taking a ratio of two spectral parts for generating a luminescence image from which the diffusion length is determined.

11. A system for determining a front surface recombination velocity of a semiconductor sample, the system comprising:
   - means for measuring an experimental photoluminescence of the sample;
   - means for calculating a corresponding theoretical photoluminescence of the sample using a diffusion length distribution of the sample and for an arbitrary constant front surface minority carrier density;
   - means for determining an actual front surface minority carrier density as a function of the experimental and the theoretical photoluminescence; and
   - means for determining the front surface recombination velocity using the determined actual front surface minority carrier density.

12. A data storage medium having computer code means stored thereon for instructing a computing device to execute a method of measuring a surface recombination velocity of a semiconductor sample, the method comprising the steps of:
   - measuring an experimental photoluminescence of the sample;
   - calculating a corresponding theoretical photoluminescence of the sample using a diffusion length distribution of the sample and for an arbitrary constant front surface minority carrier density;
determining an actual front surface minority carrier density as a function of the experimental and the theoretical spectra; and
determining the front surface recombination velocity using the determined actual front surface minority carrier density.
START

ILLUMINATE THE SAMPLE UNIFORMLY TO INDUCE PHOTOLUMINESCENCE

COLLIMATE THE LIGHT AND TAKE AT LEAST TWO PHOTOLUMINESCENCE IMAGES WITH DIFFERENT HIGH-WAVELENGTH-PASS FILTERS

CALCULATE THE BULK DIFFUSION LENGTH ACCORDING TO WUERFEL ET AL.

CALCULATE PHOTOLUMINESCENCE IMAGE ASSUMING CONSTANT FRONT SURFACE RECOMBINATION

CALCULATE "REAL" FRONT SURFACE RECOMBINATION BY IMAGE PROCESSING OF THE CALCULATED AND MEASURED PHOTOLUMINESCENCE IMAGE

END

Figure 2
measuring an experimental photoluminescence of the sample

502

calculating a corresponding theoretical photoluminescence of the sample using a diffusion length distribution of the sample and for an arbitrary constant front surface minority carrier density

504

determining an actual front surface minority carrier density as a function of the experimental and the theoretical photoluminescence

506

determining the front surface recombination velocity using the determined actual front surface minority carrier density

508

500

Figure 5
INTERNATIONAL SEARCH REPORT

International application No.  
PCT/SG2010/00011

A. CLASSIFICATION OF SUBJECT MATTER

Int. Cl.

GOIN 21/63 (2006.01)  
HOIL 27/142 (2006.01)

GOIN 21/88 (2006.01)  
HOIL 31/042 (2006.01)

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

WPI/EPOQUE/INSPEC & keywords (recombination, velocity, luminescence, minority, carrier, diffusion, length, passivation and similar terms)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

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<th>Category*</th>
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<th>Relevant to claim No.</th>
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<td>A</td>
<td>US 2006/023781 1 A1 (THOMAS et al) 26 October 2006  See abstract.</td>
<td>-1-12</td>
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[X] Further documents are listed in the continuation of Box C  [X] See patent family annex

* Special categories of cited documents

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Date of the actual completion of the international search  11 May 2010

Date of mailing of the international search report  17 MA 2010

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<td>EP 2059792</td>
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Due to data integration issues this family listing may not include 10 digit Australian applications filed since May 2001.

END OF ANNEX