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Determination of minority carrier diffusion length from distance dependence of lateral photocurrent for side-on illumination

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ABSTRACT

A method of measurement of diffusion length L in p type c-Si wafers based on the lateral collection of minority carriers is reported. In this method, wafer requires a p–p$^+$ junction on entire back surface and an n$^+$–p interface on a part of the front surface leaving the rest part as bare for illumination. A photocurrent I_{sc} is generated when a rectangular area of a part of the bare front surface in the vicinity of the n$^+$–p interface is illuminated with a laser beam. The magnitude of I_{sc} varies with the normal distance d between the electron collecting n$^+$–p interface and the nearest edge of the illuminated region. The slope Φ of the normalized I_{sc} vs. d curve is used to determine a parameter $\sinh^{-1}\theta$, which has a linear relation with d. The reciprocal of the slope of $\sinh^{-1}\theta$ vs. d curve in the linear region gives the diffusion length L. The value of L is less susceptible to error due to the effect of S_f of bare silicon surface if the linear region of $\sinh^{-1}\theta$ vs. d curve lies in the region of smaller d values. The present method has an advantage over the other methods in that it does not depend on the intensity of the illumination and absorption coefficient of Si. Additionally, method has no limitation in terms of wafer thickness to diffusion length ratio and is applicable to all practical L values.

1. Introduction

The cheap availability of solar photovoltaics energy is foremost quest for the present day R&D in the field of photovoltaics. The approaches to make solar photovoltaics cost effective lie in better utilization of available material with improved highly efficient solar cell designs [1]. In case of dominated c-Si wafer based solar cell, the wafer, as base material, is much more important for high efficiency solar cell production. The quality of wafer used in solar cell production can be judged well with the measurement of minority carrier diffusion length L in Si wafer. It is also very much desirable to measure L under the condition of illumination prior to fabrication of p–n junction to avoid heating of wafers during the junction fabrication at temperature above 850 °C.

Surface photovoltage (SPV) method [2,3] and Photocurrent generation (PCG) method [4] are used for direct measurement of L in Si wafers. The former uses a naturally existing depletion layer at the surface to generate photovoltage on illumination. The SPV generated with monochromatic radiation of different wavelengths of the given intensity is measured and L is determined from the plot of the surface photovoltage vs. the absorption coefficient. The method has a severe limitation in that it is valid only if the thickness of the wafer is 3 times or larger than the diffusion length [5,6]. The PCG method [4] requires formation of a p$^+$ (n$^+$) accumulation layer on one side of the p (n) wafer and an n$^+$ (p$^+$) inversion layer on the other side. The wafer is illuminated with monochromatic radiation from accumulation layer side and the diffusion length is determined from the slope of the photocurrent density vs. illumination intensity characteristics. The method is applicable for determining L smaller or larger than the wafer thickness and is valid as long as ratio of wafer thickness to diffusion length is larger than 0.6. The PCG method [4] is sensitive to the quality of accumulation layer, which is formed by depositing a semitransparent metal layer on the wafer, which may degrade on exposure to air and lead to determining of smaller values of L [7]. Recently a Laser Beam Induced Current (LBIC) method [8] has been reported for determining L in Si wafers. The method was applied under low level injection condition and was found to be valid if thickness of the wafer was larger than 4L. For wafer thickness less than 4L it was found to give erroneous results.

In this work, we present a method for the measurement of L in c-Si wafer, which is based on lateral collection of photo-generated carriers due to side-on illumination with a monochromatic band gap radiation like in the LBIC method. Normalized experimental short circuit current density J_{sc} is plotted as a function of distance d and

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the change of the slope of the curve is utilized to determine the diffusion length L. The value of L determined using PCG method [7] is also presented for comparison.

2. Experimental

Two chemically and mechanically polished Cz Si wafers, 50 mm diameter, ⟨1 0 0⟩ orientation, 400 ± 10 μm thickness, p type, B doped and of 1.0 Ω cm resistivity were taken. Thereafter an p^+ accumulation layer was created on one side of the wafer by depositing a ~50 nm semitransparent layer of Pd and an n^+ inversion layer on half portion of opposite side of the wafer by depositing an ~80 nm Al layer using thermal evaporation under vacuum. As shown in Fig. 1, the part of the wafer covered with metals on both side acquired a structure akin to n^+–p–p^+ and was capable of generating a photocurrent on illumination at a bare portion of wafer on front or from the Pd side on back and was thus suitable for measurement of L by both the side-on illumination being reported in this work and the PCG method. We shall present in the following the details of L measurement for one specimen P-1 using the side-on illumination method and compare it with the PCG method.

2.1. Diffusion length measurement using PCG method

The diffusion length measurement was first done using PCG method [4]. For this the both side covered portion of the wafer was illuminated from Pd covered back side of the wafer with a beam of circular aperture area 1.0 cm^2 of laser beam used and the I_{sc} was measured for various intensities in 25–40 mW cm^{-2} range. The short circuit current density J_{sc} was (computed by dividing I_{sc} with the illuminated area) plotted against input intensity P_{in} on a linear scale and ζ, the slope of the straight line that passes through the origin, was measured. The L was determined from the slope ζ and the reflectivity r_λ of Pd covered surface. The care was taken to store the wafers in vacuum before and soon after the measurement of J_{sc}–P_{in} characteristics to ensure a very low recombination velocity of minority carriers at the Pd coated back surface of the wafer [7].

2.2. I_{sc}–d measurement using side-on illumination

The specimen prepared for measurement of L with side-on illumination method was mounted on a gold plated brass jig with its n^+ side and the bare silicon surface on top and Pd coated surface at the bottom. A diode laser beam with fixed intensity 40 mW cm^{-2} (λ=789, DL 100-TOPTICA) was passed through a beam expander, a collimator and a rectangular aperture of dimension 10 mm × 1.5 mm. It illuminated the bare silicon surface normally as shown in Fig. 1. The jig was kept in a micropositioner (STANDA-USA) and was moved towards the illuminated rectangle in step of 20 μm to vary the normal distance d between the induced n^+–p interface at A and the nearest edge B of the illuminated rectangle. The steady state short circuit photo current I_{sc} between the front and back metal contacts was measured using a Keithley model 2420 source-meter.

The intensity of illumination was measured in cases of both PCG and side-on illumination methods using a reference silicon solar cell supplied by PV Measurements Inc. USA. The reflectivity R_λ of Pd covered back side, were measured using a spectrophotometer SHIMADZU model UV 3101 PC.

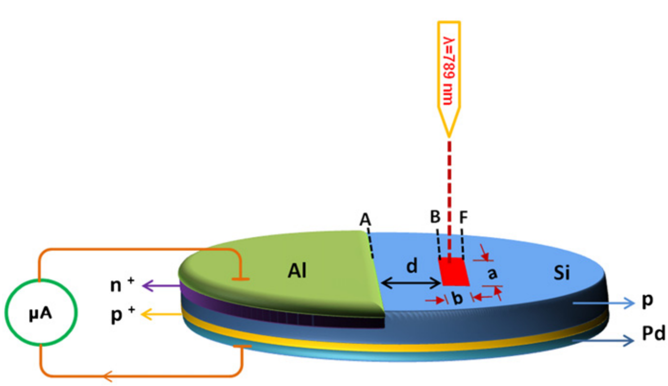

Fig. 1. Schematic diagram of the side-on illumination structure.

3. Theoretical

Consider Fig. 2, where point A (x=0), marks the n^+–p interface (Al–Si) an induced n^+–p junction that can collect photogenerated electrons from the bare Si portion. Let us illuminate the bare p region with a visible monochromatic light (such as the laser light of λ=789 nm used experimentally in this case) that has an absorption depth of ~10 μm or so in silicon. The illuminated area is a rectangle of length 'a' and width 'b'. The side 'a' is parallel to the induced n^+–p junction interface at A the intensity of illumination is uniform throughout the illuminated rectangle. Typically, a=10 mm and b=1.5 mm, and 'b' is substantially more than 3 times of the expected value of L in the wafer.

The intensity profile of the illuminated rectangle is a step function, where the intensity is uniform across the length 'a' and the width 'b' of the rectangle. Here, we consider movement of photogenerated carriers in the p-region in one direction (i.e. x-direction) only, i.e. from B to A. Fig. 2 also shows the intensity profile of illumination, which is nearly step function (or complementary error function) in nature and is represented as

$$I = \frac{I_0}{2} erfc\left(\frac{d-x}{\beta}\right)$$

where I_0 is the maximum intensity of the illumination within the illuminated rectangle region and I is the intensity at a distance x from point A and β is an arbitrary constant describing the shape of the intensity distribution in the x-direction. The value of β is very small in comparison with d and x and ensures I=0 in the un-illuminated $0 < x < d$ region and a steep change in the value of I near x=d such that I=I_0 for $x > d$.

As the monochromatic light is incident normally to the wafer surface the carriers will be generated under the illuminated area

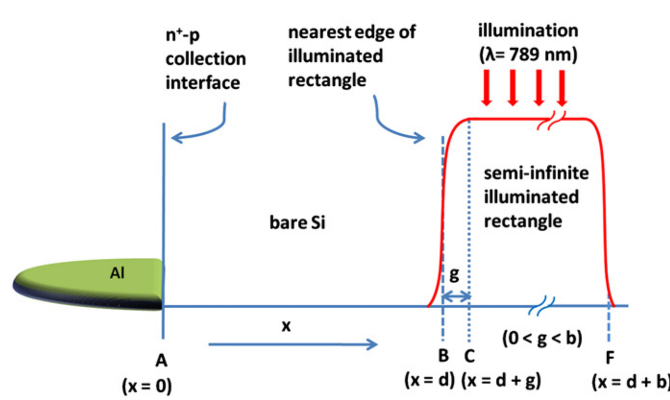

Fig. 2. Schematic of intensity of illumination in the bare silicon region. Photogenerated carriers are generated under semi-infinite illumination rectangle and move towards the collection point A (x=0) by diffusion from point B (x=d) and point C (x=d+g) within the illumination rectangle where intensity profile is uniform.

along the wafer thickness due to absorption of the light and thus perpendicular to the x-direction. Since the p^+ accumulation layer at the bottom surface provides Back Surface field (BSF) the recombination at the back ($z=t$) where z is the direction along wafer thickness t is negligible. For simplification we also ignore recombination of minority carriers at the front surface. Therefore we assume that under steady state, the photogenerated carriers will undergo recombination only in the p-region and not at the front and back surfaces while moving in the x-direction from point B to A and in doing so are collected at the induced n^+–p junction interface at A. We shall show later that the flow of photogenerated carriers along the wafer thickness would not affect the final results significantly.

The one dimensional current continuity equation for minority carriers (electrons in the p-region) between the n^+–p interface at $x=0$ and the illuminated rectangle under steady state can be written as

$$\frac{1}{q}\frac{dJ_n}{dx} = \frac{n-n_p}{\tau} - G(x). \tag{1}$$

In Eq. (1) J_n is the minority carrier current density, n is the minority carrier density, n_p is the equilibrium minority carrier density and τ is lifetime of minority carriers. $G(x)$ is the photogeneration rate of minority carriers and is defined as

$$G(x) = \frac{G_0}{2}\,\mathrm{erf}c\left(\frac{d-x}{\beta}\right), \tag{2}$$

where

$$G_0 = \frac{n_{ph}(1-R_\lambda)(1-e^{-\alpha_\lambda t})}{t}.$$

The nature of $G(x)$ follows from the intensity profile

$$I = \frac{I_0}{2}\,\mathrm{erf}c\left(\frac{d-x}{\beta}\right),$$

where G_0 corresponds to I_0. In the above expressions, G_0 is average photogeneration rate at $x>d$ along the wafer thickness t, n_{ph} is the photon flux of the incident monochromatic light of a wavelength λ, R_λ is the reflectance of illuminated surface and α_λ is the absorption coefficient of incident light in Si.

In the present case the drift component of current density J_n can be ignored and therefore Eq. (1) becomes

$$\frac{d^2n}{dx^2} = \frac{n-n_p}{L^2} - \frac{c}{2}\,\mathrm{erf}c\left(\frac{d-x}{\beta}\right), \tag{3}$$

where $L^2=D_n\tau$; D_n is the diffusion coefficient of the minority carriers and c is a constant defined as $c=G_0/D_n$.

The solution of Eq. (1) can be written as

$$n = c_1 e^{(x/L)} + c_2 e^{(-x/L)} + n_p + \frac{cL^2}{4}\left[e^{\left(\frac{x}{L}-\frac{d}{L}+\frac{\beta^2}{4L^2}\right)}\mathrm{erf}\left(\frac{d}{\beta}-\frac{x}{\beta}-\frac{\beta}{2L}\right)\right] + \frac{cL^2}{4}\left[e^{\left(-\frac{x}{L}+\frac{d}{L}+\frac{\beta^2}{4L^2}\right)}\mathrm{erf}\left(\frac{d}{\beta}-\frac{x}{\beta}+\frac{\beta}{2L}\right)\right] + \frac{cL^2}{2}\left[\mathrm{erf}c\left(\frac{d-x}{\beta}\right)\right], \tag{4}$$

where c_1 and c_2 are constants, whose values can be computed applying the following boundary conditions:

(i) $n=n_p$ at $x=0$,

and

(ii) $\dfrac{dn}{dx}=0$ at $x=d+g$

The condition (i) is attributed to the minority carrier collection nature of the n^+–p interface present at $x=0$. On the other hand, the condition (ii) signifies that, practically, the photogenerated carriers of distance beyond $x=(d+g)$ do not have to flow towards the collection interface.

The short circuit current density J_{sc} can be obtained using the relation

$$J_{sc} = qD_n\left.\frac{dn}{dx}\right|_{x=0}. \tag{5}$$

Eq. (4) helps obtain an expression for $\frac{dn}{dx}\big|_{x=0}$, which is then used in Eq. (5) to obtain an expression for J_{sc} as

$$\begin{aligned} J_{sc} = {} & \frac{qG_0L}{4}\left[e^{\left(\frac{g}{L}+\frac{\beta^2}{4L^2}\right)}\mathrm{erf}\left(\frac{d}{\beta}-\frac{\beta}{2L}\right)\mathrm{sech}\left(\frac{d+g}{L}\right)\right] \\ & -\frac{qG_0L}{4}\left[e^{\left(-\frac{g}{L}+\frac{\beta^2}{L^2}\right)}\mathrm{erf}\left(\frac{d}{\beta}+\frac{\beta}{2L}\right)\mathrm{sech}\left(\frac{d+g}{L}\right)\right] \\ & +\frac{qG_0L}{4}\left[e^{\left(\frac{g}{L}+\frac{\beta^2}{4L^2}\right)}\mathrm{erf}\left(\frac{g}{\beta}+\frac{\beta}{2L}\right)\mathrm{sech}\left(\frac{d+g}{L}\right)\right] \\ & -\frac{qG_0L}{4}\left[e^{\left(-\frac{g}{L}+\frac{\beta^2}{4L^2}\right)}\mathrm{erf}\left(\frac{g}{\beta}-\frac{\beta}{2L}\right)\mathrm{sech}\left(\frac{d+g}{L}\right)\right] \\ & +\frac{qG_0L}{2}\left[\mathrm{erf}c\left(\frac{d}{\beta}\right)\tanh\left(\frac{d+g}{L}\right)\right]. \end{aligned} \tag{6}$$

Since β is very small in comparison with g, d and L the conditions; $d/\beta \gg \beta/2L$, $g/\beta \gg \beta/2L$, $\beta^2/4L^2 \to 0$ are generally satisfied in practice.

Then, for $d/\beta>3$ and $g/\beta>3$; $\mathrm{erf}(d/\beta)=1$, $\mathrm{erf}(g/\beta)=1$, $\mathrm{erf}c(d/\beta)=0$ and Eq. (6) is simplified to

$$J_{sc} = qG_0L\left[\frac{\sinh(g/L)}{\cosh((d+g)/L)}\right]. \tag{7}$$

For $d\to 0$, Eq. (7) further reduces to

$$J_{sc} = qG_0L\tanh\left(\frac{g}{L}\right). \tag{8}$$

Here, Eq. (8) shows the maximum current density, generated when illumination rectangle just touches the n^+–p interface collection point.

The normalized short circuit current density J_{scn} can be obtained by dividing Eq. (7) by (8) as

$$J_{scn} = \cosh\left(\frac{g}{L}\right)\mathrm{sech}\left(\frac{d+g}{L}\right). \tag{9}$$

3.1. Methodology for determination of L using Eq. (9)

Eq. (9) represents the J_{scn}–d curve. The slope $\phi = dJ_{scn}/dd$ of this curve can be obtained as

$$\phi = -\frac{1}{L}\cosh\left(\frac{g}{L}\right)\mathrm{sech}\left(\frac{d+g}{L}\right)\tanh\left(\frac{d+g}{L}\right). \tag{10}$$

Putting $d\Phi/dd=0$ we obtain the maximum slope Φ_m which is given by

$$\Phi_m = -\frac{1}{2L}\cosh\left(\frac{g}{L}\right). \tag{11}$$

This occurs at a value d which satisfies the condition

$$\sinh\left(\frac{d+g}{L}\right) = 1. \tag{12}$$

Using Eqs. (11) and (12) in (10) we get

$$\frac{\phi}{\phi_m} = 2\,\mathrm{sech}\left(\frac{d+g}{L}\right)\tanh\left(\frac{d+g}{L}\right). \tag{13}$$

Eq. (13) yields a relation

$$\sinh^{-1}\theta = \frac{d}{L}+\frac{g}{L}, \tag{14}$$

where

$$\theta = \frac{1 \pm \sqrt{1-(\phi/\Phi_m)^2}}{\phi/\Phi_m}. \tag{15}$$

In certain ranges of d that may be identified by $d_1 < d < d_2$, Eq. (14) may show a linear relation between $\sinh^{-1}\theta$ and d. For such cases the slope of the line represented by Eq. (14) is equal to the reciprocal of L. Here, θ has two roots θ^+ and θ^- which are given by

$$\theta^+ = \frac{1 + \sqrt{1-(\phi/\Phi_m)^2}}{\phi/\Phi_m}, \tag{16a}$$

and

$$\theta^- = \frac{1 - \sqrt{1-(\phi/\Phi_m)^2}}{\phi/\Phi_m}. \tag{16b}$$

Thus, in practice, the linear region of $\sinh^{-1}\theta^+$ vs. d or $\sinh^{-1}\theta^-$ vs. d curve can be used to determine the diffusion length L from the measurement of slope of the curve with the d-axis.

4. Result and discussion

The diffusion length measurements on P-1 and P-2 were done using PCG method [4] just after the specimens were taken out from the vacuum to avoid the degradation of accumulation layer due to exposure of air [7]. For specimen P-1, the input parameters are used as t=400 μm, D_n=25 cm^2 s^{-1}, λ=789 nm, α_λ=1000 cm^{-1}, R_λ=0.546 for L measurement using PCG method and calculated L=102 μm. Soon after the measurements the specimens were again stored in vacuum. The values of L are listed in Table 1.

Subsequently the specimens were taken out of vacuum and the present method (side-on illumination method) was used for determination of L. The laser light of λ=789 nm of illumination intensity 40 mW cm^{-2} was used and the short circuit current I_{sc} was measured by varying d between 0 to 500 μm. For specimen P-1 the short circuit current I_{sc} varied from a maximum value 33.43 μA for $d \to 0$, to 1.13 μA for d=500 μm. All the values of I_{sc} were normalized with respect to maximum I_{sc} value 33.43 μA. The normalized I_{sc} values are same as the normalized short circuit current density J_{sc}, referred to earlier as J_{scn} in Eq. (9) and therefore we have plotted J_{scn} values against d values for P-1 in Fig. 3. It may be pointed out that the d values are in μm and are not normalized. These J_{scn}, d values were fitted into a polynomial of order five

$$J_{scn} = B_0 + B_1 d + B_2 d^2 + B_3 d^3 + B_4 d^4 + B_5 d^5, \tag{17}$$

and thus obtained theoretical curve is also plotted in Fig. 3. It can be seen that the experimental data fitted excellently well in to the theoretical curve given by Eq. (17). The values of constants are B_0=1.00598, B_1=9.87381E-5 μm^{-1}, B_2=−6.00376E-5 μm^{-2}, B_3=3.04544E-7 μm^{-3}, B_4=−5.84465E-10 μm^{-4} and B_5=3.98493E-13 μm^{-5}.

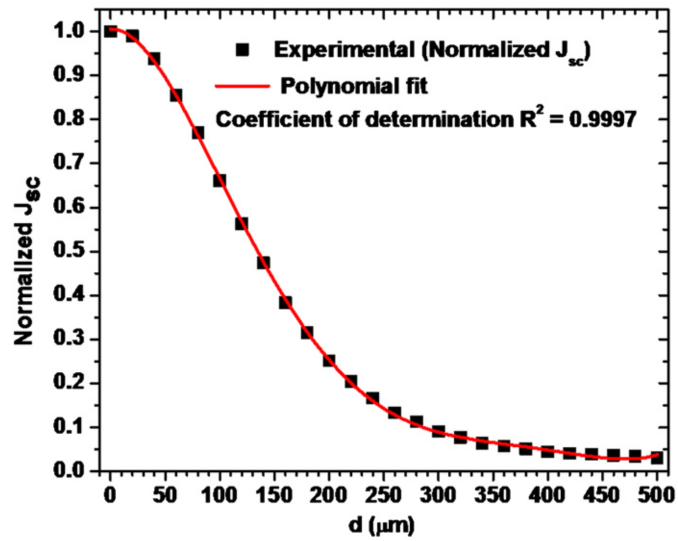

Fig. 3. Variation of normalized experimental short circuit density J_{scn} with distance d for specimen P-1. The theoretical curve is a polynomial in which the experimental data has been fitted.

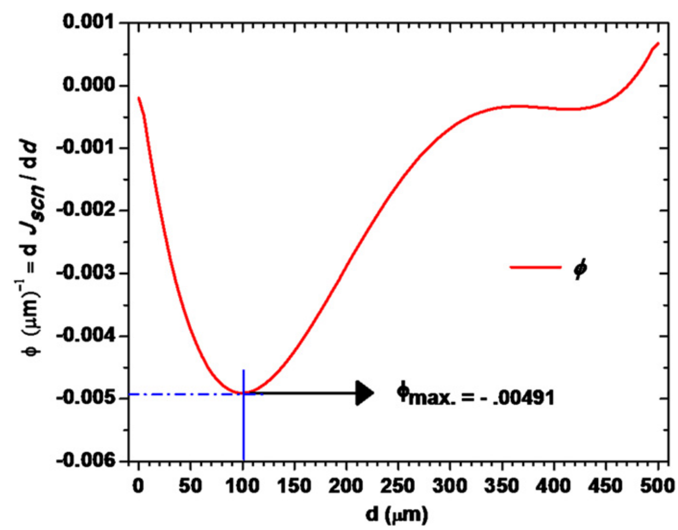

Fig. 4. Variation of slope Φ of J_{scn} vs. d curve for specimen P-1. Φ_m is the maximum numerical value of Φ.

Differentiating the theoretical J_{scn} vs. d curve of Fig. 3 the values of Φ as a function of d were determined. These values of Φ are plotted against d in Fig. 4. This curve give the maximum value of slope Φ_m=.00491 (μm)$^{-1}$ at d=101 μm. From the values of Φ and Φ_m the values of (θ^+ and θ^-) were determined and then $\sinh^{-1}(\theta)$ vs. d curves were plotted in Fig. 5.

Fig. 5 shows that for $\theta=\theta^-$ the $\sinh^{-1}(\theta)$ vs. d curve is linear in $5 < d < 85$ μm range, whereas, for $\theta=\theta^+$ the $\sinh^{-1}(\theta)$ vs. d curve is linear in $120 < d < 180$ μm range. Slope of these curves yielded the value of L=115 μm corresponding to $5 < d < 85$ μm range and L=106 μm corresponding to $120 < d < 180$ μm range.

The slightly smaller values of L obtained using J_{scn} vs. d data for higher d values ($120 < d < 180$ μm) may be due to some deleterious effect of front surface recombination velocity S_f on the measured I_{sc} values.

We may assume that the back surface recombination velocity S_b is negligibly small due to the presence of the p$^+$ accumulation

Table 1
Comparison of diffusion length L measured by side-on illumination method and PCG method of specimen P-1.

Diffusion length L (μm)		
Side-on illumination method		**PCG method**
(in $5 < d < 85$ μm range) 115	(in $120 < d < 180$ μm range) 106	102

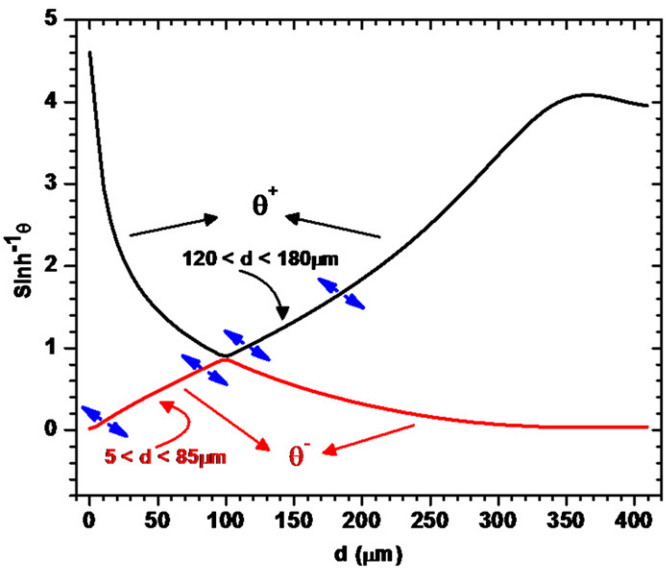

Fig. 5. Variation of $\sinh^{-1}\theta$ with distance d for specimen P-1. θ is related with Φ according to Eq. (15). The reciprocal of the slope of $\sinh^{-1}\theta$ vs. d curve gives diffusion length L.

layer at the back surface and following Hull [9] we may assign a value 2×10^3 cm/s (and 10^4 cm/s) to S_f for our chemically and mechanically polished bare silicon surface of P-1. Using this value of S_f in expression $\tau_s=(t/S_f)+(4/D_n)(t/\pi)^2$ given by Sproul [10] we calculated the value of surface lifetime τ_s as 46 μs (and 30 μs). The values of other parameters used in calculation of τ_s were t=400 μm, D_n=25 cm^2 s^{-1}. This value 46 μs (and 30 μs) of τ_s along with τ_{eff}=4.48 μs (obtained from the measured values of L i.e. L_{eff}=105.82 μm for P-1 in $120<d<180$ μm range of d)when in turn used in expression $(1/\tau_{eff})=(1/\tau_b)+(1/\tau_s)$ gave bulk lifetime τ_b=4.96 μs (and 5.27 μs). This value of τ_b gave the bulk diffusion length L_b=111.4 μm corresponding $S_f=2\times10^3$ cm/s and length L_b=114.7 μm corresponding to $S_f=10^4$ cm/s. It may be noted that both these values of L_b are very close to the values of L=115 μm determined by the present method using the J_{scn} vs. d data of $5<d<85$ μm range. This shows that the effect of S_f in the measurement of L using the present method has been negligible in the $5<d<85$ μm range. The use of an effective surface passivation layer on the bare silicon surface may be able to reduce the difference in the values of L obtained using the regions of smaller and higher d values.

So determined value of L for P-1 using the J_{scn} vs. d data of $5<d<85$ μm range are also listed in Table 1. The value of L determined using the PCG method is slightly smaller and this may be due to the back surface recombination velocity S_b, though assumed negligible may have been significantly high. The recent work [7] on application of PCG method shows that when S_b is not negligible the value of L determined using PCG method is smaller than the true value of bulk diffusion length.

The values of L determined with the side-on illumination method were found reasonably close to that determined using PCG method. The side-on illumination method does not depend on the intensity of the illumination and absorption coefficient of Si. Additionally, method has no limitation in terms of wafer thickness to diffusion length ratio and is applicable to all practical L values.

5. Conclusion

A method, referred to as the side-on illumination method, based on lateral collection of minority carriers, for determination of the diffusion length L in p-type c-Si wafer was developed. In this method, the a structure, akin to n^+–p–p^+, is formed on the wafer by creating a p^+ accumulation layer on the back side and an n^+ inversion layer on a half portion of the front side. A suitable monochromatic light, such as the laser light of λ=789 nm used in this work, illuminates a rectangular area in the bare silicon region on the front side and generates a current due to lateral collection of photogenerated carriers at the (n^+–p) interface. The photo current is varied by changing the normal distance d between the illuminated rectangle and the (n^+–p) interface. The slope Φ of the normalized J_{scn} vs. d curve is used to determine a parameter $\sinh^{-1}\theta$, which depends on Φ. The reciprocal of the slope of $\sinh^{-1}\theta$ vs. d curve in the linear region gives the diffusion length L. The value of L is less susceptible to error due to the effect of S_f of bare silicon surface if the linear region of $\sinh^{-1}\theta$ vs. d curve lies in the region of smaller d values. The present method does not require the measurement of intensity of illumination.

We applied the side-on illumination method to a specimen P-1 and determined L=115 μm using the $5<d<85$ μm range. The photocurrent generation (PCG) method gave L=102 μm. The slightly smaller value of L obtained with PCG method may be due to the effect of back surface recombination velocity S_b being ignored in PCG method. The side-on illumination method, when using smaller d region, may be less susceptible to the errors due to S_b than the PCG method.

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