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Diffusion length and junction depth determination based on spectral response measurements of mono- and polycrystalline silicon solar cells

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Abstract. The minority carrier diffusion lengths L_n and L_p and the junction depth d of silicon solar cells were determined by measuring the spectral response of different cells and the optical absorption coefficient of the base material. Using a simplified diffusion model we could apply a least-square fit in the visible and near IR wavelength region in order to extract the parameters L_n , L_p , and d . Results obtained from monocrystalline and polycrystalline silicon solar cells are compared.

1. Introduction

Spectral response measurements provide detailed information about the wavelength dependence of the conversion efficiency η of photovoltaic solar cells. Other important cell parameters, like short-circuit current I_{sc} and open-circuit voltage V_{oc} , series and shunt resistance, doping level, and junction width W are readily supplied by I - V and C - V measurements.

The most important parameter characterizing the electronic properties of the semiconductor material is the minority carrier diffusion length (denoted L_n and L_p for electrons and holes, respectively). It is usually determined by the constant surface photovoltage method (SPV) based on the method of Goodman [1]. In this technique the light intensity which is necessary to produce a constant surface photovoltage at different wavelengths near the absorption edge is plotted versus the inverse of the absorption coefficient $\alpha(\lambda)$. In the case of a p - n junction solar cell the open-circuit voltage will be kept constant. Under certain conditions a straight line can be fitted to the resulting plot and the diffusion length is obtained from the intercept at zero light intensity.

A slightly modified method was described by Stokes et al. [2] where the short circuit current I_{sc} is kept constant. They take advantage of the linear relation between I_{sc} and V_{oc} for small values of V_{oc} (I_o is the saturation current):

$$V_{oc} = \frac{kT}{q} \ln \left(\frac{I_{sc}}{I_o} + 1 \right) \approx \frac{kT}{q} \frac{I_{sc}}{I_o}. \quad (1)$$

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In this paper we use the spectral response measurement together with a simplified diffusion model in order to extract not only the base minority carrier diffusion length but also the emitter diffusion length and the junction depth in photovoltaic cells. The model we employed is valid for mono- and polycrystalline silicon solar cells [3]. In contrast to the SPV method the spectral response method (SR) is experimentally simple since the measured quantity need not be kept constant. Furthermore by including data from the visible region beyond the absorption edge all three parameters L_n , L_p , and d can be extracted simultaneously in a multi-parameter fit to the data.

The SR method cannot be applied in the simple form described below to amorphous silicon solar cells since a drift model rather than a diffusion model would be required [4] and the resulting quantities are drift lengths rather than diffusion lengths [5].

2. Measurement technique

The apparatus we set up for spectral response measurements is shown in Fig. 1. Light from a halogen lamp (ELH, 50 W) is passed through a Czerny-Turner type monochromator (focal length 175 mm, aperture f/3.4, wavelength range 350–950 nm) and focused on the solar cell shunted with a $10\ \Omega$ resistor. The short-circuit current is measured from the voltage drop across this resistor.

Since the light intensity on the cell was relatively small (0.5 to $20\ \mu\text{W}/\text{cm}^2$) we used a lock-in amplifier to reduce the noise level. At the same time the apparatus became immune to influence from ambient light. Furthermore, the lock-in technique allows one to measure the spectral response under white light bias.

A HP-87 microcomputer system, including an analog-to-digital converter, a monochromator control modul, and disc storage, was employed to read the analog

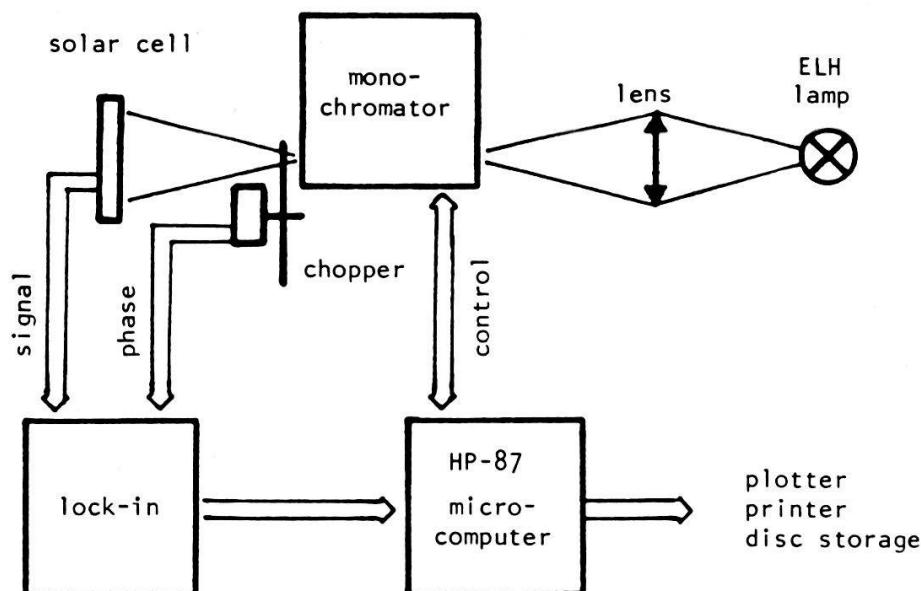


FIGURE 1
Experimental set-up for spectral response measurements.

signal from the lock-in amplifier output and the wavelength position of the monochromator. For the determination of the diffusion lengths the results were transferred onto a VAX 780 computer, where adequate software for the data analysis was available.

3. Spectral response curves

As a first step the absolute energy flux distribution $P_{\text{ref}}(\lambda)$ of the light emerging from the monochromator had to be measured carefully with a broadband pyrometer (flat response from 0.2 to 50 μm) at zero ambient light level and constant ambient temperature.

Next the solar cell response $I_m(\lambda)$ was measured with the apparatus described above. Then the (relative) spectral response SR is defined as (c_0 is a normalization factor):

$$\text{SR}(\lambda) = c_0 \frac{I_m(\lambda)}{P_{\text{ref}}(\lambda)}. \quad (2)$$

Figure 2 shows the spectral response of two monocrystalline silicon solar cells. The cell labelled GP has a response adapted to the human eye; its blue and red response is weak. Also shown is an amorphous silicon solar cell (SA) which has a weak long wavelength response due to the higher bandgap in amorphous silicon ($E_g \sim 1.7 \text{ eV}$) as compared to crystalline silicon ($E_g \sim 1.1 \text{ eV}$). Figure 3 shows typical examples of polycrystalline cells. Measurements with and without white bias light ($\sim 100 \text{ mW/cm}^2$) did not show any significant differences in the spectral response.

During the measurements special care was taken to assure reproducible results. The overall precision is about 5%, as was verified with a calibrated EG & G 701 photovoltaic cell.

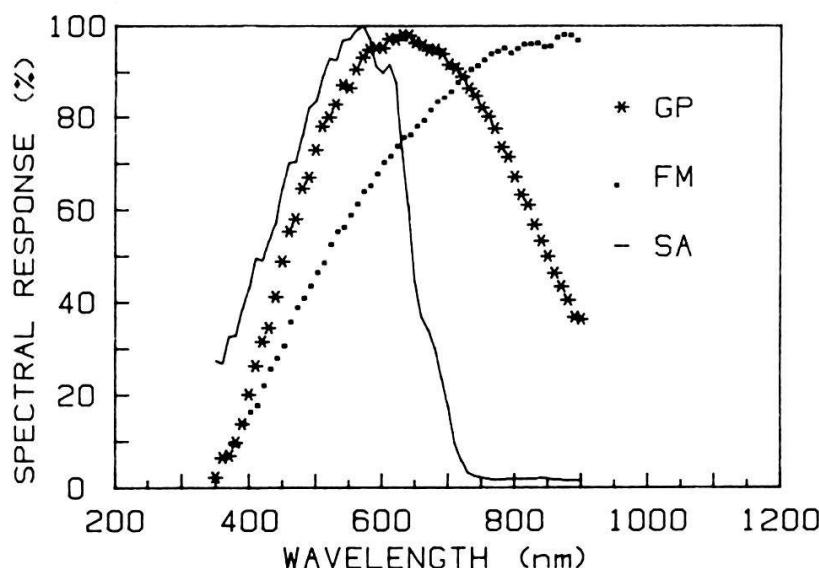


FIGURE 2
Spectral response of two monocrystalline (GP, FM) and an amorphous silicon (SA) solar cell.

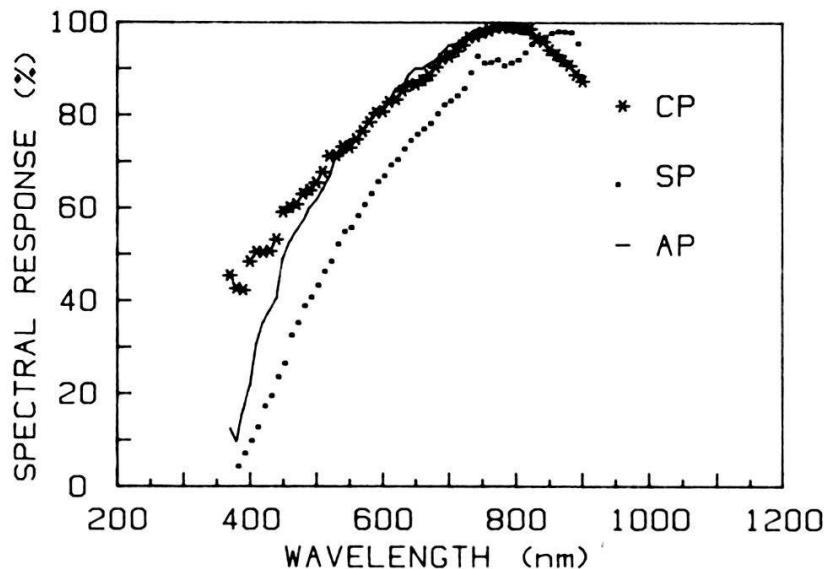


FIGURE 3
Spectral response of three polycrystalline cells

Table I gives a list of the cells we have measured together with the overall conversion efficiency η , the reflection coefficient R at the He-Ne laser wavelength $\lambda = 633$ nm, and thickness T . The efficiency was determined from the maximum power point on the I - V curve measured under a solar simulator with approximately AM 1.5 spectral distribution.

Table I
Conversion efficiency η , reflection coefficient R at $\lambda = 633$ nm, and thickness T for the measured solar cells.

Cell	Type	η [%]	R [%]	T [μm]
FM	mono-Si np	12.5	5.6	380
GP	mono-Si np	7.5	5.5	400
CP	poly-Si pn	10.8	2.6	380
AP	poly-Si np	10.0	4.5	300
SP	poly-Si np	8.7	4.7	360
SA	amorphous Si	3.0	~7.0	0.7

4. Determination of parameters

The following analysis procedure is based on a simplified diffusion model, as described in Ref. 3, suitable for monocrystalline and polycrystalline solar cells. Figure 4 illustrates the example of a n - p junction. The incident flux $\Phi_{\text{in}}(\lambda)$ is attenuated in the emitter and base region according to

$$\Phi(\lambda) = (1 - R(\lambda))\Phi_{\text{in}}(\lambda)e^{-\alpha(\lambda)x} \quad (3)$$

where $\alpha(\lambda)$ is the absorption coefficient, $\Phi(\lambda)$ is the photon flux at distance x and wavelength λ in units of photons per $\text{cm}^2 \text{ sec}$. Figure 5(a) depicts the wavelength dependence of the measured reflection coefficient $R(\lambda)$. The values of R at He-Ne laser wavelength are listed in Table I.

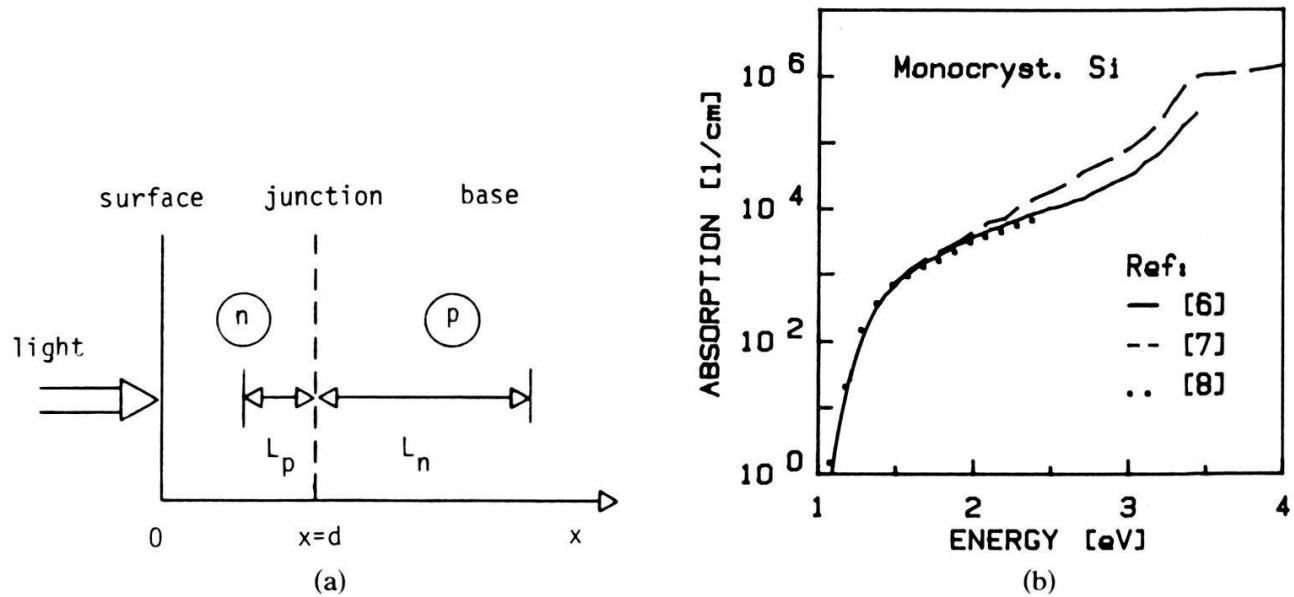


FIGURE 4
(a) Diffusion model for a *n*-*p* junction (L_n , L_p are electron and hole diffusion lengths, resp., d is the junction depth). (b) Absorption coefficient of monocrystalline silicon in Refs 6, 7, and 8.

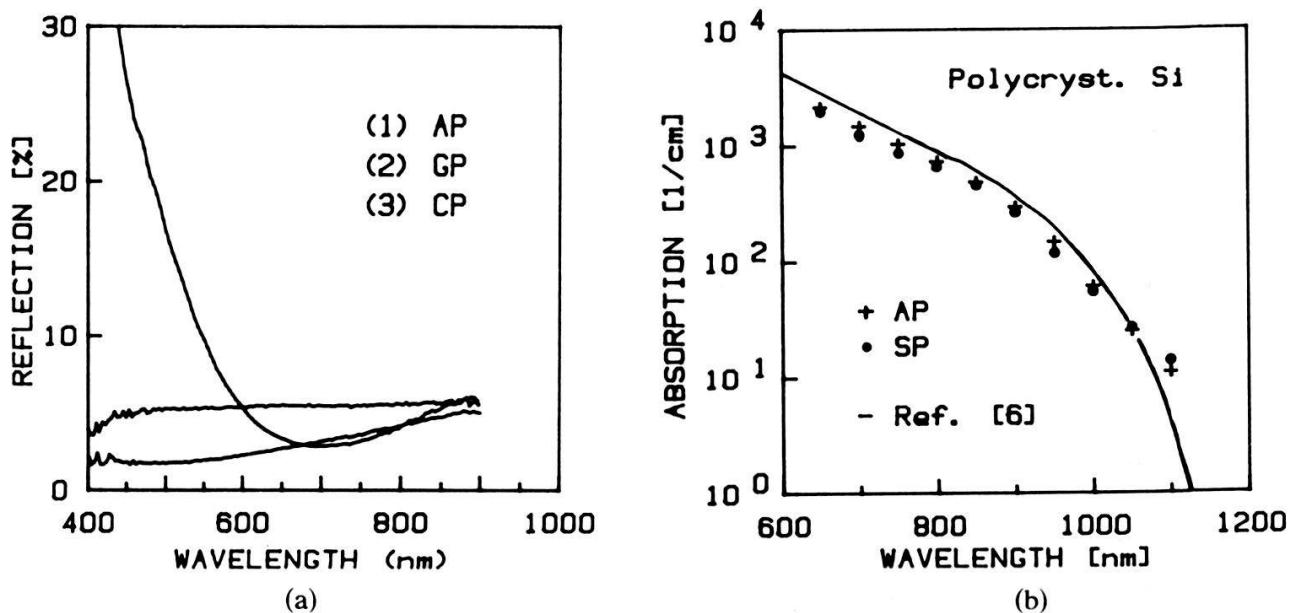


FIGURE 5
(a) Measured reflection coefficients of solar cells. (b) Measured absorption coefficient of polycrystalline silicon. Data for monocrystalline silicon from Ref. 6 is also shown.

Multiplying equation (3) by the absorption coefficient α will yield the number of electron-hole pairs created at a given distance x . In order to obtain the total photocurrent I_{sc} and the resulting quantum efficiency QE, the number of minority carriers (i.e. holes created in the emitter region and electrons from the base region), their distance to the junction, and their diffusion length have to be taken into account. After integration over the cell thickness the following result is obtained [3]:

$$QE \sim \frac{\alpha L_p}{1 - \alpha L_p} (e^{-\alpha d} - e^{-d/L_p}) + \frac{\alpha L_n}{1 + \alpha L_n} e^{-\alpha d} \quad (4)$$

Since the photon density is proportional to the wavelength for constant energy flux the quantum efficiency and the measured spectral response are related by $SR \sim QE \times \lambda$.

Absorption data

A crucial quantity in equation (4) is the optical absorption coefficient $\alpha(\lambda)$. For the analysis of monocrystalline silicon cells we used data from Dash and Newman [6]. As shown in Fig. 4(b), recent measurements by Aspnes [7] and low energy data published by Braunstein [8] agree well with the older measurements of Dash and Newman in the wavelength range that we used in our analysis. Except for heavily doped material (doping level $N_D > 2 \times 10^{18} \text{ cm}^{-3}$) the doping effect is small for monocrystalline silicon in the region above the bandgap [9]. In highly efficient solar cells the doping level is kept below $5 \times 10^{17} \text{ cm}^{-3}$ in order to avoid Auger recombination which would degrade the minority carrier lifetime and hence the diffusion length [10].

In the case of the polycrystalline cells we went through the tedious procedure of chemically etching (in $\text{HF:HNO}_3:\text{CH}_3\text{COOH}=3:5:3$) and mechanically polishing (with alumina powder of 5 and $1 \mu\text{m}$ grain size) small parts of $\sim 1 \text{ cm}^2$ down to thicknesses of ~ 20 , 80, and $250 \mu\text{m}$ in order to measure the optical transmission in a Cary spectrophotometer. Then the modified spectral response apparatus was used to measure the slowly varying reflectance of the samples. Finally the absorption coefficient $\alpha(\lambda)$ was determined from the transmission and reflectance and plotted in Fig. 5(b). For comparison the data from ref. 6 is included. The precision of the measurement, which is dependent on the precision of the thickness measurement and the transmission and reflection data, is estimated to be $\sim 10\%$.

Assumptions

The following simplifying assumptions have been made in equation (4):

- (1) $W \ll d$, i.e. carrier creation in the junction region has been neglected. Though we did not measure W , one could check this condition with C-V measurements. Typical values [10] range from $W = 0.04$ to $0.15 \mu\text{m}$ for high efficiency cells. This is to be compared to the results for d in Table III ranging from 0.7 to $1.4 \mu\text{m}$.
- (2) $\alpha(\lambda)$ is the same throughout the cell thickness. Sometimes a 'dead surface' layer is present which degrades the UV response. We have limited the wavelength range to $\lambda > 400 \text{ nm}$ in order to exclude detrimental effects on the analysis.
- (3) $L \ll T$, i.e. the diffusion length is smaller than the cell thickness. This is the case for the measured cells as can be seen from Tables I and III. If a 'back surface field' is present in order to enhance the long wavelength response or if $L \geq T$, then the analysis would lead to effective diffusion lengths only.

Long wavelength approximation and comparison with SPV method

For long wavelength photons, where $\alpha d \ll 1$, most of the light is absorbed in the base region. Therefore, the first term in equation (4) can be neglected and one gets:

$$QE \sim \frac{\alpha L_n}{1 + \alpha L_n} \quad \text{or} \quad 1/QE \sim L_n + 1/\alpha. \quad (5)$$

Hence the electron diffusion length L_n can be determined by plotting $1/QE$ versus $1/\alpha$ and reading $-L_n$ at $1/QE = 0$. Figure 6 shows examples of such plots.

In order to check whether the spectral response method together with the long wavelength approximation of equation (5) yields the same results if compared to other methods, we have used three different techniques for one of our samples. First, a polycrystalline silicon solar cell of type SP was analyzed with the SR method as described above. Second, the modified SPV technique [2] was applied with $I_{sc} = \text{const}$.

Finally, the base material was measured in a constant open-circuit voltage SPV apparatus where V_{oc} is capacitively collected via an electrolyte solution in contact with the sample surface as described in [5, 11]. The results are in good agreement for all three methods as is shown in Fig. 6. The diffusion lengths are listed in Table II.

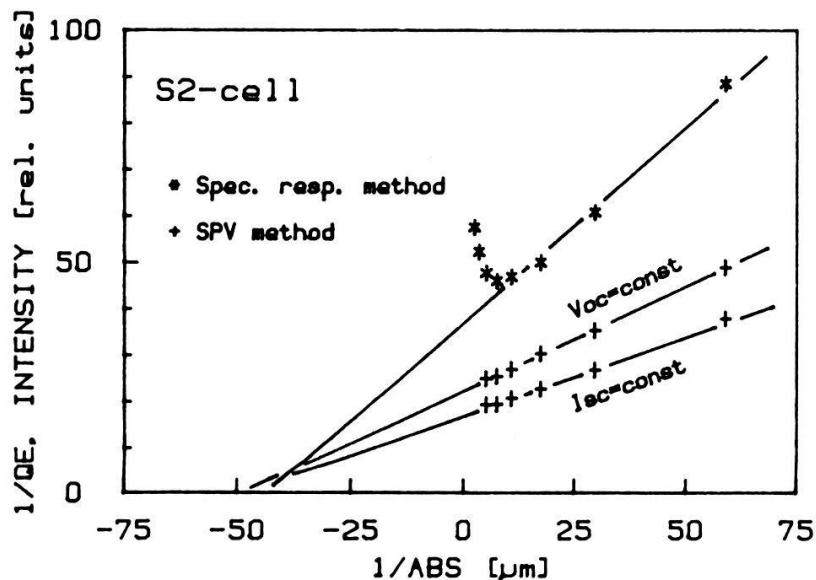


FIGURE 6

Comparison of the spectral response method with the SPV method in the near IR region. The diffusion length L_n can be read from the intercept of the straight line with the $1/\alpha$ axis.

Table II
Diffusion length of a polycrystalline silicon cell using different methods.

Method	Condition	Result: L_n [μm]
1 Spectral Response (SR)	—	44.1 ± 4.2
2 Surface Photovoltaic (SPV)	$V_{oc} = \text{const}$	48.8 ± 0.9
3 Surface Photovoltaic (SPV)	$I_{sc} = \text{const}$	46.8 ± 1.3

Multi-parameter fit

Including the data from the visible region, too, a multi-parameter fit was applied in order to extract all three parameters L_n , L_p , and d from equation (4). The last-square fit routine we used (HFIT) is part of the HBOOK program library developed at CERN [12] and runs on a VAX 780 computer. This routine calculates the parameters and standard deviations from the data points, including measurement errors, and the parametric function.

Figure 7 shows the $1/\text{QE}$ versus $1/\alpha$ plot for two of the cells. The superimposed fit result (full line) shows the validity of equation (4) in these cases.

The results together with the final χ^2 -value per degree of freedom are listed in Table III. For the $p-n$ type cell (CP) the diffusion length given by the large wavelength region (equation (5)) is L_p rather than L_n . For one of the cells (AP) large uncertainties for the fitted parameters and a large χ^2 -value were obtained, so the straight line fit for $\lambda > 750 \text{ nm}$ was done only.

Values for L_n range from $3.3 \mu\text{m}$ (GP) to $152 \mu\text{m}$ (FM). The GP cell with poor diffusion length is a low cost monocrystalline silicon cell, whereas the excellent value of $152 \mu\text{m}$ is reached in a high efficiency screen printed cell. For polycrystalline cells the spectral response may depart from the ideal behaviour of

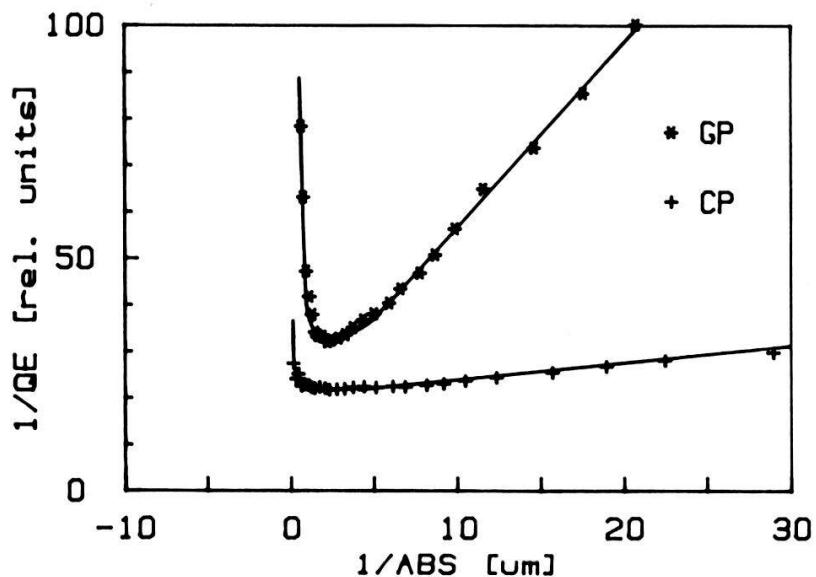


FIGURE 7
Plot of $1/\text{QE}$ versus $1/\alpha$ for a monocrystalline (GP) and a polycrystalline cell (CP). The full line is the resulting multiparameter fit to equation (4).

Table III
Multi-parameter fit results for diffusion lengths and junction depth

Cell	L_n [μm]	L_p [μm]	d [μm]	χ^2/DF	Remarks
FM	152 ± 21	0.6 ± 0.2	0.7 ± 0.2	0.21	high efficiency
GP	3.3 ± 0.3	0.6 ± 0.1	1.3 ± 0.1	0.15	low cost cell
CP	5.5 ± 4	58 ± 5	1.4 ± 0.7	0.16	bases is n -type
AP	62 ± 5	—	—	0.17	linear fit
SP	110 ± 13	0.2 ± 0.1	0.7 ± 0.1	0.41	

equation (4) not only due to high surface recombination velocity which will affect mainly the blue response but also due to recombination phenomena at grain boundaries [13]. This may explain the relatively large X^2 -value for the cell SP.

5. Conclusion

We have employed a least-square fit method to determine the diffusion lengths and the junction depth in monocrystalline and polycrystalline silicon solar cells from spectral response data. Compared to other methods (e.g. using SEM as described in Ref. [14]) a modest level of equipment is needed. Since the analysis is based on a simplified diffusion model, care has to be taken in choosing the appropriate spectral region. As it is usually done in the conventional SPV method, the base minority carrier diffusion length can readily be extracted from a straight line fit to the near IR data.

In addition we have shown that by including the visible region a multi-parameter fit allows to determine also the emitter diffusion length and, in most cases, the junction depth.

Acknowledgement

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