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MINORITY CARRIER LIFETIME IN MONOCRYSTALLINE, POLYCRYSTALLINE AND AMORPHOUS SILICON SOLAR CELLS USING PHOTO-INDUCED OPEN-CIRCUIT VOLTAGE DECAY (OCVD) TECHNIQUE

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ABSTRACT: The photoinduced open-circuit voltage decay technique was used to investigate the minority carrier lifetime in several silicon solar cell samples. This convenient investigation technique allows a fast and accurate determination of the diffusion length of minority carriers in semiconductor materials and is an important technique in optimizing the solar cell performance. The quality and the efficiency of silicon solar cells depend on the minority diffusion length and this value could be calculated for monocrystalline, polycrystalline and amorphous silicon solar cells. The values obtained at room temperature are in good agreement with reference values.

Key words/phrases: Diffusion length, minority carrier lifetime, photo-induced open-circuit voltage decay, silicon photovoltaic solar cells.

INTRODUCTION

The most widely used material up to now for photovoltaic (PV) energy conversion is crystalline silicon (Si). A crystalline Si pn junction solar cell consists of a relatively small n-type emitter and a much thicker p-type base (Fig. 1a).

Sunlight enters the Si solar cell through the thin n-layer, which acts as a window and generates electron-hole pairs mainly in the thicker p-layer (Mazer, 1997). Due to the fact that crystalline Si is an indirect band gap semiconductor material, its absorption coefficient in the visible spectral range is relatively small, so that the p-layer has to be 100-500 μm thick. Conversion efficiencies of about 24 % are reported (Green *et al.*, 1995). To achieve good electrical properties, the material has to be of high quality and therefore the production costs are high.

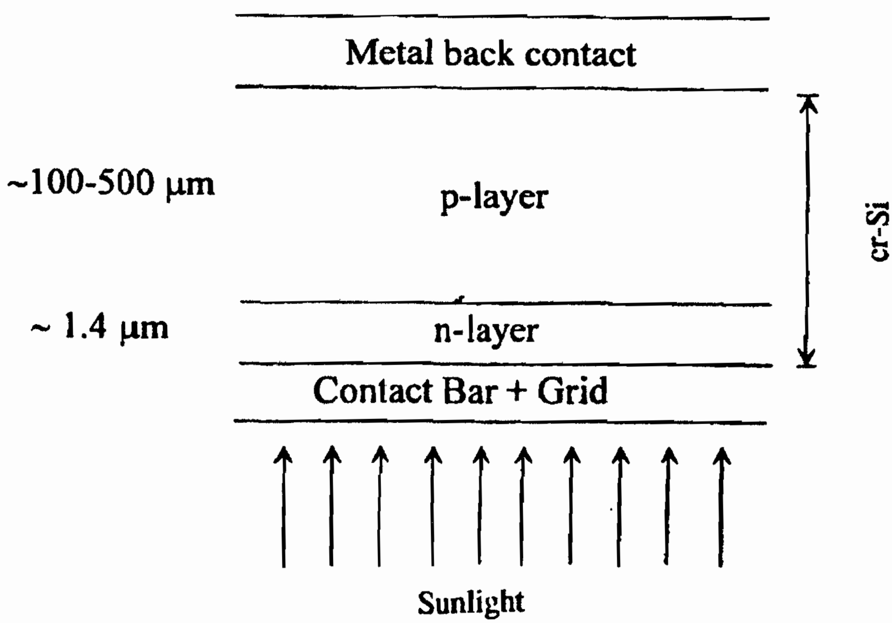

Fig. 1a. Schematic diagram of a crystalline silicon solar cell.

One possibility of reducing the costs of PV solar cells is the application of anti-reflecting coatings (AR) and texturing the back and front surfaces so that the light ray that is not absorbed in the first encounter is forced to go back and forth up to 20 times in a relatively thin cell before optical absorbed. The diffusion length in this material can be much smaller than in a crystalline pn junction solar cell, so that even thin (~30 μm), cheap, low quality poly-crystalline silicon can be used as active PV material (Fig. 1b).

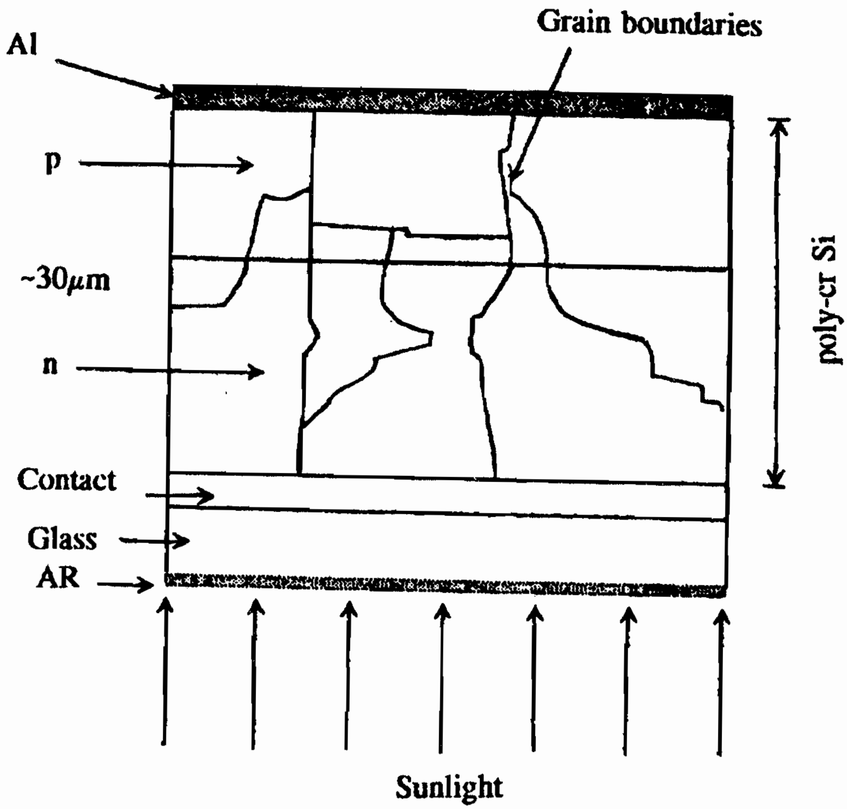

Fig. 1b. Schematic diagram of a thin film polycrystalline silicon solar cell (Ghosh *et al.*, 1980). AR abbreviates anti-reflection coating.

Grain boundary states play a dominant role in determining the electrical and photovoltaic properties of polycrystalline silicon by acting as traps and recombination centres. The recombination loss at grain boundaries is the predominant loss mechanism in these solar cells, reducing its efficiency below that of crystalline Si to a maximum efficiency of 17.8 % (Green *et al.*, 1995).

The breakthrough towards low-cost photovoltaics is expected from thin-film technology because of the prospect of low cost material usage and large area processing. A variety of possible thin-film materials exist, of which one is a-Si:H which is applied in amorphous-silicon based thin film solar cells (Markvart, 1994).

The optimum structure of an a-Si solar cell is the p-i-n structure (Fig. 1c). Both p and n layers have poor transport properties. Through the incorporation of an intrinsic (i) a-Si:H layer the transport properties are improved. Its trapping concentration inside the energy gap is much smaller and additionally the intrinsic electric field of the depletion region extends over the whole intrinsic layer. The optimum intrinsic layer is between 300 and 800 nm in thickness (Zhu *et al.*, 1995) and determines the performance of the solar cell. The i-layer is not completely intrinsic, but is slightly n-type. It is therefore preferable to have light enter the cell through a very thin (optically inactive) p-type layer, so that the region of maximum photo-generation in the i-layer is also the region of the highest electric field. In addition, there is a transparent conducting oxide (TCO) contact to the p-layer and an ohmic contact to the n-layer.

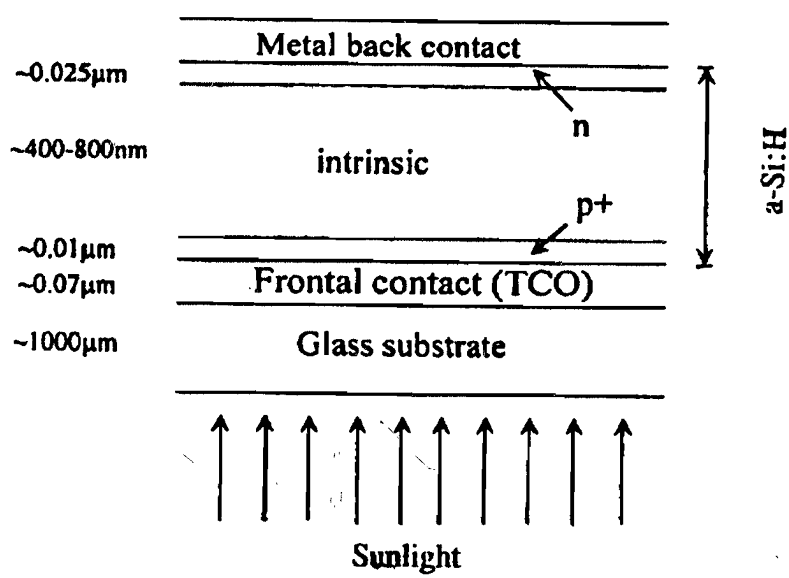

Fig. 1c. Schematic diagram of a thin film a-Si:H p-i-n solar cell (Markvart, 1994). TCO abbreviates transparent conducting oxide.

The absorption of light inside the i-layer creates additional defects and increases the density of trapping and scattering states and reduces the efficiency of the solar cell. This so called Staebler-Wronski effect (Staebler and Wronski, 1980) depends on the total number of photons absorbed. It therefore depends on the intensity of the light to which the cell is exposed, the duration of the exposure and on the thickness of the i-layer. To become commercially viable as power generators a-Si cells have to deliver over 10% stabilized efficiency after photodegradation (Markvart, 1994).

The minority carrier diffusion length has been widely used to characterize the quality of silicon solar cell materials before it is processed into solar cells, because it provides a prediction of the energy conversion efficiency that may be attained in the final cell (Saritas and McKell, 1988).

In this investigation the minority carrier lifetimes and diffusion length of laboratory made a-Si:H thin film p-i-n solar cells with different intrinsic layer thickness are determined using the photoinduced open-circuit voltage decay technique and are compared with those of commercially available crystalline, polycrystalline and amorphous silicon solar cells.

The applied photoinduced open-circuit voltage decay technique has the advantage to be simple and straight forward without requiring high-tech equipment but nevertheless achieving reliable and exact experimental results. Therefore this method is extremely useful for scientists working in semiconductor physics in developing countries.

THEORY

With the help of the photoinduced open-circuit voltage decay technique, excess minority carriers are created in a junction device using an external optical excitation that creates a brief forward current (Ramadan, 1989). After the excitation has been terminated the open-circuit voltage (V_{OC}) of the device is measured as a function of time and the minority carrier lifetime can be calculated in analysing the V_{OC} decay curve. This method is ideal for the investigation of the photoinduced properties of solar cells because of the use of light as excitation source. Depending on the intensity of the excitation source, three different regions of the V_{OC} decay curve can be distinguished.

I. High level injection

When the excess minority carrier concentration exceeds the majority carrier concentration in the base region of the solar cell, then the decay curve is linear and the minority carrier lifetime (τ) can be expressed as:

$$\tau = \frac{2kT}{q}\left|\frac{1}{dV_{OC}/dt}\right|, \tag{1}$$

where k is the Boltzmann constant, T is the absolute temperature, q is the elementary charge, and t is the time. In this investigation a strobe lamp was used as an excitation source with an intensity of 0.5 $mW(cm)^{-2}$ so that high level injection condition is not fulfilled.

II. Intermediate injection

In this region the excess minority carrier concentration in the base is greater than the thermal-equilibrium minority carrier concentration but less than the thermal-equilibrium majority carrier concentration. The V_{OC} decay curve is again linear and the lifetime can be calculated with the following expression:

$$\tau = \frac{kT}{q}\left|\frac{1}{dV_{OC}/dt}\right| \tag{2}$$

III. Low-injection

When the excess minority carrier concentration is less than the equilibrium minority carrier concentration, then the V_{OC} becomes less than kT/q and the V_{OC} decay approaches the time dependence:

$$V_{OC} = \frac{kT}{q}[\exp(qV(0)/kT) - 1]\exp(-t/\tau), \tag{3}$$

where V(0) is the open-circuit voltage at the termination of the excitation. This exponential decay can be superimposed by the decay of stored charges at the junction space charge region. The discharge rate is inversely proportional to the effective RC time constant of the solar cell, where R is the instantaneous cell resistance and C is the instantaneous junction capacitance. This discharge of the junction capacitance can slow down the last stage of the V_{OC} decay.

The assumption of this analysis is that the contribution of the heavily doped emitter to the photovoltage and the amount of excess charge stored in the space-charge region compared to that stored in the base is negligible.

Substituting the derived minority carrier lifetime τ in the Einstein equation for the diffusion length (Sze, 1993):

$$L = \sqrt{D\tau}, \qquad (4)$$

with the diffusion constant:

$$D = (kT/q)\mu_h, \qquad (5)$$

where μ_h is the mobility of holes in the respective material of the solar cell, the diffusion length can be calculated from

$$L = \sqrt{(kT/q)\mu_h \tau} \qquad (6)$$

EXPERIMENTAL METHODS AND MATERIALS

The photo-induced open-circuit voltage decay (OCVD) technique was applied with a xenon stroboscope from Griffin (Mod. 65) as an excitation source with a frequency of 255 Hz and an illumination intensity of 0.5 $mW(cm)^{-2}$ on the solar cell. The fall time of the strobe flash is very short compared to the decay time of the solar cells so that the xenon strobe is an abruptly terminated excitation source in this investigation. The V_{OC} of the solar cells was monitored with a 100 MHz digital storage oscilloscope from Hameg (Mod. 1007) with a high impedance input to prevent loading down of the measuring circuit. The experimental set-up is schematically displayed in Figure 2.

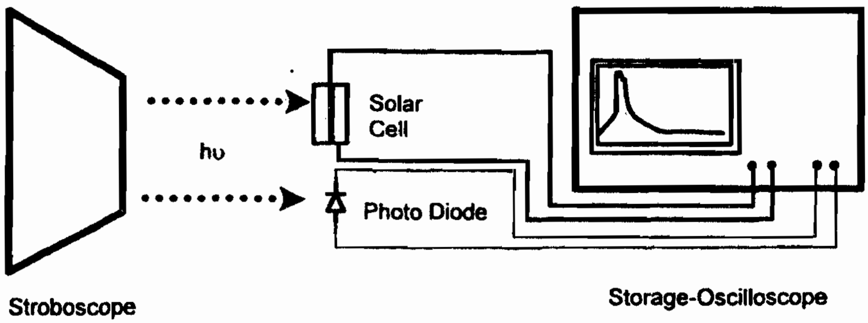

Fig. 2. Schematic diagram of a photo-induced open-circuit voltage decay (OCVD) technique set-up.

In addition to the solar cells, a very fast silicon p-i-n photodiode (Mod. SFH 202, τ_R = 5 ns) was placed in front of the stroboscope. Its photo-voltage was the input of the second channel of the oscilloscope and was utilised as a trigger reference. All measurements were made at room temperature.

This investigation was conducted with different solar cell systems (Table 1). The TCOPIN1 and TCOPIN2 samples consist of a glass substrate coated with a thin conducting oxide (SnO_2) on top of which a thin p-doped a-Si:H layer is deposited and on top of this an additional intrinsic a-Si:H layer is deposited which has different thickness for the different samples. An additional n-doped a-Si:H layer follows, on top of which is a silver coating as a back contact. These form a complete solar cell system. The TCOPIN1 and TCOPIN2 samples were produced by the glow-discharge method at the technology group of C. Beneking of Research Centre Jülich (Germany). The samples have an effective area of about 15 cm^2 and 9 cm^2, respectively.

Table 1. Solar cell parameters under standard condition: room temperature and white light illumination of 100 mW(cm)$^{-2}$. V_{OC} is the open-circuit voltage, I_{SC} the short-circuit current.

Solar cell type	Name	Manufacturer	Dimension (mm)	V_{OC} (mV)	I_{sc} (mA)	Efficiency (%)
Monocrystalline Si	Cr Si 1	Solarex	50 x 50	570	660	11.02[a]
	Cr Si 2			575	665	11.2[b]
Polycrystalline Si	Poly-cr Si		20 x 30	570	130	8.1[b]
Amorphous Si	Panasonic	Panasonic	37 x 82	5,520 = 8x690	31.9	5.8[c]
	TCOPIN 1	Research centre Jülich	30 x 50	780	182	5.95[a]
	TCOPIN 2		30 x 30	760	129	6.91[a]

a, Stutenbäumer and Mesfin Belayneh (1999); b, Solarex manual; c, Panasonic manual.

The amorphous solar cell from Panasonic consists of eight individual amorphous cells in series configuration encapsulated on a ceramic base with glass cover and has an effective area of about 30 cm^2.

The investigated monocrystalline solar cells and the polycrystalline solar cell are commercially available types produced by Solarex. The effective area of each monocrystalline Si cell is 25 cm^2 and that of the polycrysyalline Si cell is 6 cm^2.

RESULTS AND DISCUSSION

1. Crystalline silicon solar cells

Figure 3 shows the photo-induced open-circuit voltage decay curves of the investigated Cr Si 1 and Cr Si 2 crystalline Si PN junction solar cell samples. Even with the relatively low intensity [0.5 mW(cm)$^{-2}$] of the excitation strobe lamp nearly the same open-circuit voltage could be achieved as with standard conditions. The determined decay time dt of each sample, the resulting minority carrier lifetime τ and diffusion length L are shown in Table 2.

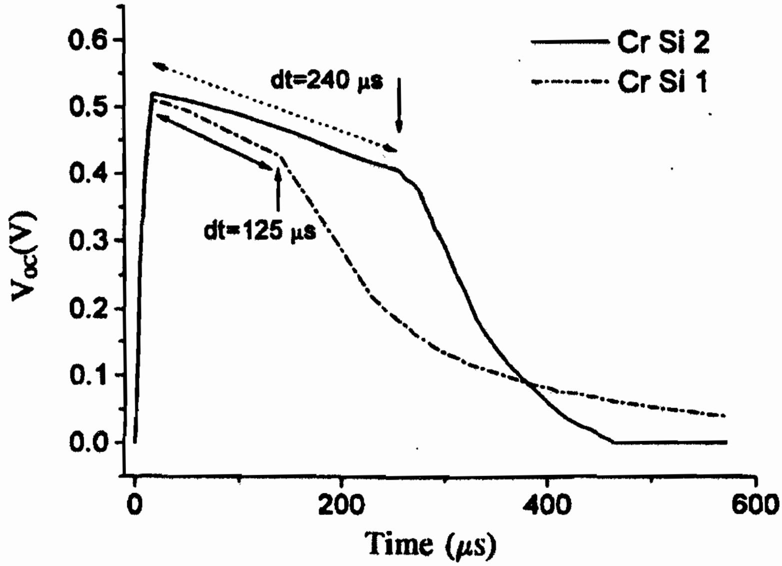

Fig. 3. **Photo-induced open-circuit voltage decay (OCVD) curves for the crystalline Si solar cell samples Cr Si 1 (dashed line) and Cr Si 2 (solid line).** The characteristic decay time dt is indicated. V_{OC} is the open-circuit voltage.

Table 2. **Results of the photo-induced open-circuit voltage decay (OCVD) technique measurements.** dV_{OC} is the change in the open-circuit voltage and dt is the decay time of the first section of the OCVD curve.

Solar cell	dV_{OC} (V)	dt (μs)	dV_{OC}/dt (V/s)	Minority carrier lifetime τ (μs)	Hole mobility μ_h (cm^2/Vs)	Diffusion length (μm)	Reference diffusion length (μm)
Cr Si 1	0.084	125	672	37.2	450 [a]	204.6	50–1200 [b]
Cr Si 2	0.114	240	475	52.6		243.3	
Poly-cr Si	0.136	20	6,800	3.68	40 [c]	19.2	4–20 [c]
Panasonic	0.864	36	24000/8=3000	8.33	10^{-2} [d]	1.44	0.035–2.0 [d]
TCOPIN 1	0.062	28	2,214	11.29		1.68	
TCOPIN 2	0.086	32	2,688	9.3		1.53	

a, Sze (1993); b, Saritas and McKell (1988); c, Ghosh *et al.* (1980); d, Madan (1988).

It can be observed in Figure 3 that the OCVD spectra consist of a nearly linear decay first part, whose time length gives the decay time of the intermediate injection condition dt, and of an exponentially decaying second part, which is the low injection part mostly determined by the RC time constant of the solar cell.

Compared with the Cr Si 2 sample, the Cr Si 1 sample has the shorter decay time dt, therefore a shorter minority carrier lifetime (τ) and a shorter diffusion length (L), resulting in a smaller efficiency.

Both experimentally determined diffusion lengths are in good agreement with literature values (Table 2), but are on the lower end of the referred value range. The reference values are obtained with state of the art laboratory samples, whereas the explored Cr Si samples of this investigation are commercially available solar cells whose material quality is less than the laboratory ones.

2. Polycrystalline silicon solar cells

The OCVD curve of the polycrystalline Si solar cell is very similar to that of crystalline cells. However, the determined decay time, dt, and the resulting minority carrier lifetime (τ) and diffusion length (L) (Table 2) are much smaller than that of the crystalline samples due to the relatively poor quality of the electrical properties of the material. Effective carrier lifetime in polycrystalline Si can be expressed in terms of grain size (Ghosh *et al.*, 1980). Compared with the literature values, the obtained result of $\sim 20\ \mu$m diffusion length would be the result of grain diameters f $\sim$ 200 μm, which is a relatively good value for a commercially available solar cell compared with the laboratory prepared samples.

3. Amorphous silicon solar cells

The measured OCVD curves of the TCOPIN1 and TCOPIN2 samples are presented in Figure 4. Again the decay curves consist of a linear first part, which gives the intermediate injection level decay time dt (see inset in Figure 4).

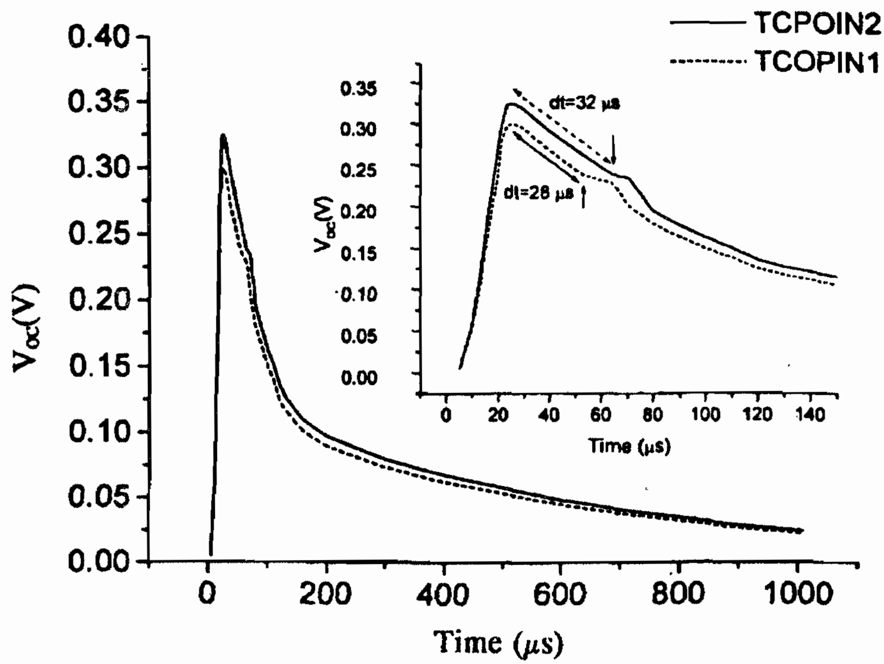

Fig. 4. Photo-induced open-circuit voltage decay (OCVD) curves for the amorphous thin film Si solar cell samples TCOPIN1 (dashed line) and TCOPIN2 (solid line). The inset displays the first magnified part of the curves and the characteristic decay time dt is indicated. V_{OC} is the open-circuit voltage.

For both solar cells the measured open-circuit voltages are considerably smaller than the values obtained under standard conditions (Table 1), because the excitation light source in this investigation could only reach 0.5 mW(cm)$^{-2}$ illumination intensity, which is only 0.5 % of the 100 mW(cm)$^{-2}$ of the standard condition. The open-circuit voltages of these cells are strongly intensity dependent and amorphous Si solar cells require a relatively high irradiance intensity to perform satisfactorily (Stutenbaeumer and Mesfin Belayneh, 1999).

The determined decay time, dt, of each sample and the resulting minority carrier lifetime, τ, and diffusion length, L, are shown in Table 2.

The determined diffusion length (Table 2) are smaller than that for the polycrystalline sample due t the poor electrical properties of the amorphous material. Especially the commercially available Panasonic solar cell has the lowest diffusion length and therefore the lowest efficiency (Table 1).

Compared with the TCOPIN2 sample the TCOPIN1 solar cell has the longer minority carrier lifetime and therefore a larger diffusion length.

The efficiency of the TCOPIN2 sample is consequently found to be greater than that of the TCOPIN1 sample (Table 1). The basic difference in the two samples is in the i-layer thickness [*i.e.*, the i-layer thickness of the TCOPIN1 sample is about 0.488 μm and that of the TCOPIN2 is about 0.983 μm, (Stutenbäumer *et al.*, 1999)]. Hence, it may suggest that as the i-layer thickness increases, the probability for the formation of electron-hole pairs increases which results in an increase in the photo-current. It is mainly due to an increase of the short-circuit current density (J_{sc}) that the variation in the efficiency is observed.

However, increasing the i-layer thickness has a disadvantage. It needs more material to have thick layers, which increases the cost of manufacturing. The recombination rate will also increase there by reducing the output current. The Staebler-Wronski effect will also be pronounced when the i-layer thickness is increased (Kruehler, 1993).

CONCLUSIONS

It is found that there is a strong relation between the different investigated cell types, minority carrier lifetime (τ) and diffusion length (L) (Figure 5). For crystalline Si solar cells, due to its far superior material quality, the minority carrier lifetime is $\sim$ 50 μs and the diffusion length $\sim$ 200 μm and these parameters are larger than for the polycrystalline Si ($\tau \sim$ 3 μs, L $\sim$ 20 μm) and a-Si:H solar cells ($\tau \sim$ 10 μs, L $\sim$ 1.5 μm), which are in the category of the least quality material properties.

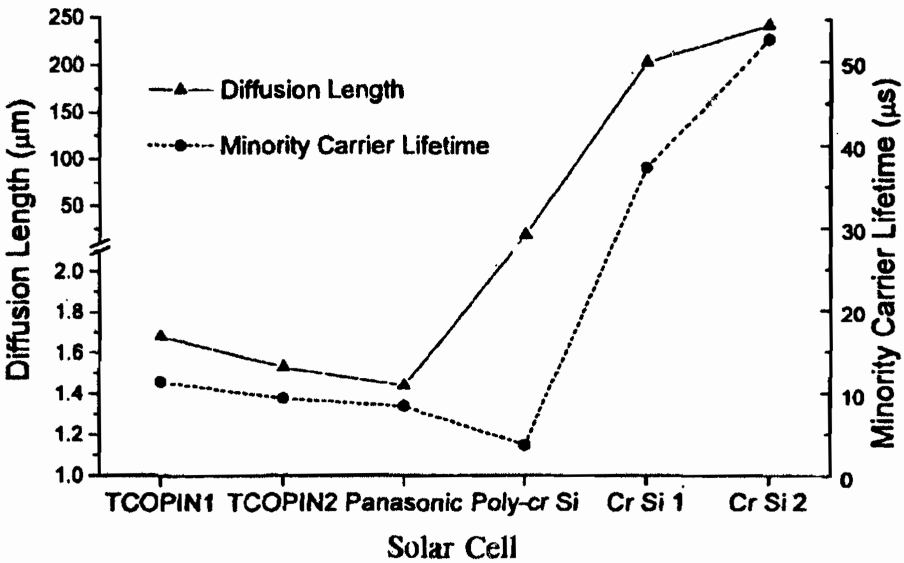

Fig. 5. Results for the photo-induced open-circuit voltage decay (OCVD) technique measurements of crystalline, polycrystalline and amorphous silicon solar cells. The diffusion length (solid line with triangle, left axes with break) and the minority carrier life time (dashed line with circles, right axes).

The measured minority carrier lifetime and its correlated diffusion length L are indicators of the attainable cell efficiency. The larger the minority carrier diffusion length, the larger is the efficiency of the solar cells.

The open-circuit voltage decay technique is a useful tool and low cost technique to investigate the efficiencies of crystalline, polycrystalline and amorphous silicon solar cells and should be used parallel to the common performance test methods.

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