TEMPERATURE DEPENDENCE OF MINORITY CARRIER DIFFUSION LENGTH IN SOLAR CELLS PREPARED FROM LOWER PURITY SILICON

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ABSTRACT. Minority carrier diffusion length \( L_n \) in solar cells prepared from different samples of crystalline lower purity silicon - p-Si, resistivity 0.03 \( \Omega \cdot \text{cm} \) - 0.3 \( \Omega \cdot \text{cm} \) - was determined from steady state photoresponse measurements under monochromatic light conditions. In order to estimate the influence of the back side of a 300 \( \mu \text{m} \) thick device n\textsuperscript{+}p\textsuperscript{+}-solar cells were illuminated from front side and from back side. The resulting diffusion length at room temperature and the temperature dependence of \( L_n \) are considerably different in both cases thus suggesting that majority carriers contribute to the total light generated current in a solar cell. In order to minimize the influence of majority carriers on the determination of electron diffusion length n\textsuperscript{+}p-junctions and MIS structures without a back surface field were used to calculate the room temperature value of \( L_n \) for differently heat treated samples. A dependence of \( L_n \) on the concentration of a point defect at \( E_{\text{V}} + E_t = 0.32 \text{eV} \) was observed. The temperature dependent evaluation of the capture cross section of point defects from \( L_n \) measurements shows that more than one Coulomb attractive center is present in our samples.

1. INTRODUCTION

The solar cell output is directly correlated with minority carrier diffusion length [1]. Its high sensitivity to point defects in crystalline silicon makes it a parameter of superior importance. The purpose of the present work was to correlate minority carrier diffusion length with point defects observed in our samples by means of deep level transient spectroscopy [2]. The possibility to derive the temperature dependence of the capture cross section from temperature dependent diffusion length measurements was used to determine the nature of the potential responsible for the dominance of ionized impurity scattering in our samples of lower purity silicon. In order to estimate the influence of the back surface on steady state photoresponse measurements which were used to evaluate minority carrier diffusion length solar cells with a back surface field were illuminated from the back side.

2. EXPERIMENTAL

Material from two different manufacturers were used in our experiments. Material characteristics are summarized in table I. The iron content was obtained from DLTS studies [2]. Crystal Systems supplied us with wafers from recrystallized metallurgical meltstock obtained by the heat exchanger method [3]. Two different samples from Siemens Munich were prepared by conventional crystal pulling methods [4]. Three different types of light sensitive devices were prepared: (i) metal-insulator-semiconductor
structures (ii) \( n^+p \)-junctions and (iii) \( n^+pp^+ \)-devices. The wafers were cut in approximately 2cm x 2cm substrates. Surfaces were chemically polished and cleaned prior to solar cell preparation. Standard phosphorous diffusion techniques were used for planar abrupt pn-junction formation. In the case where samples were made with a back surface field (BSF) aluminium diffusion was done at the back side prior to metallization. In order to get a light sensitive back side aluminum grids were evaporated at the back side of the solar cell whereas the front side was completely metallized. MIS structures were prepared from substrates which were annealed at temperatures of 600°C, 730°C, 910°C and 1020°C for one hour in Argon. The minority carrier diffusion length at 300K was evaluated from the quantum efficiency in the wavelength range from 800nm to 1000nm using a method described by Stokes \[5\]. Absorption coefficient data necessary to determine \( L_n \) given by Schlosser \[6\] are tabulated in table II. The experimental set up used to evaluate \( L_n(T) \) is shown in fig.1. The intensity modulated light from an IR-LED irradiates the solar cell through a fibre glass cable. The light induced current is detected with a lock-in amplifier and recorded as a function of the measured temperature. The minority carrier diffusion length is calculated computer assisted with numerical methods. The temperature varies between 77K and 300K. The temperature dependence for the capture cross section assuming a single deep level given by Schlosser \[6\] results in the following relation between \( \sigma_n(T) \) and \( L_n(T) \) where \( C \) is constant as long as the total concentration of the point defect \( N_t \) equals the concentration of ionized deep levels:

\[
\sigma_n = C \left( \frac{T}{L_n} \right)^2
\]  

(1)

3. RESULTS AND DISCUSSION

The determination of room temperature values of the diffusion length in \( n^+pp^+ \)-devices made from material U1 exhibit a large difference depending whether the front or the back side is illuminated. In the first case \( L \) was 7.0 \( \mu m \) in the latter \( L \) varies between 38 \( \mu m \) and 67 \( \mu m \). Temperature dependent measurements of the diffusion length with illuminated front side result in a temperature dependence of \( L^{-2} \propto T^{-1.5} \) for \( T < 120K \) and \( L^{-2} \propto T^{-4.5} \) for \( T > 200K \). For samples where the back side was exposed to the light a dependence of \( L^{-2} \) with \( T+1.5 \) was observed. Since the sum of the two measured diffusion lengths at room temperature is smaller than the solar cell thickness we suggest that the solar cell can be treated as the sum of two individuals devices in series: one \( n^+p \)-cell and a \( pp^+ \)-cell. Thus the interpretation of the 2 different diffusion lengths is as follows: In the case of the illuminated front side the electron diffusion length is determined whereas the illumination of the back side yields in the hole diffusion length. In order to reduce a potential error occurring from an additional photocurrent at the backside of a solar cell which is due to majority carriers we used devices without back surface field for the evaluation of electron diffusion length. The influence of thermal treatment on the electron diffusion length is shown in fig.2. the coincidence between the enhancement of minority carrier diffusion length and the disappearance of the hole trap \( H_6 \) \[2\] at an annealing temperature of 600°C suggests to find out whether or not there exists a correlation between the concentration of this hole trap with an activation energy of \( E_{H_6} = 0.32eV \) and the electron diffusion length. As can be seen in fig.3 for concentrations of more than \( 1x10^{14}cm^{-3} \) \( L_n \) decreases fast with increasing \( N_{H_6} \). It shall be noted that this is true for all our samples. The rather surpri-
sing observation that the electron diffusion length is correlated with the concentration of a hole trap can be explained with the presence of two electron traps $E_1$ and $E_2$ reported in reference [2] which are always observed together with $H_6$.

Results of the temperature resolved determination of minority carrier diffusion length for pn-junctions prepared from material U1 and U2 are shown in fig.4. For solar cells made from material U2 the temperature dependence of $L_n$ can be separated into a region where $L_n$ is proportional $T^{-6.1}$ and a region where $L_n$ is proportional $T^{-4.0}$ according to $\sigma_n \propto T^{-4.1}$ in the first and $\sigma_n \propto T^{-2.0}$ in the latter case. It is generally accepted that the temperature dependence of the capture cross section is proportional to between $T^{-4}$ and $T^{-2}$ when the defect center is Coulomb attractive. The value of $\sigma_n$ varies between $10^{-12}\text{cm}^2$ and $10^{-15}\text{cm}^2$. For electrically neutral centers the temperature dependence is between $T^{-1}$ and $T^{+1}$. Typical capture cross sections are in the range of $10^{-17}\text{cm}^2$ to $10^{-15}\text{cm}^2$. Repulsive Coulomb centers exhibit only a weak temperature dependence. Capture cross sections are typically $10^{-20}\text{cm}^2$ smaller. That means that at least two Coulomb attractive centers are present in material U2. The temperature dependence of $L_n$ in material U1 results in $\sigma_n \propto T^{-1.4}$ which is in between the characteristic dependence for a neutral and a Coulomb attractive potential. Therefore it can be interpreted as the sum of at least one electrically neutral and one Coulomb attractive center.

4. CONCLUSIONS

From our results we conclude the following. In the case of a back surface field majority carriers can contribute to the total light generated current. Therefore calculations based on the assumption of merely minority carriers can be insufficient to describe the properties of a solar cell. We have observed a dependence of the electron diffusion length on the concentration of a point defect which is probably generated by the presence of iron in our samples. The temperature dependence of the capture cross section suggests that the minority carrier diffusion length and therefore the solar cell output are limited by at least two electrically active point defects present in our samples of lower purity silicon.

5. REFERENCES

2. V. Schlosser, K. Wendl, this volume
TABLE I: Properties of material used in our experiments

<table>
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<tr>
<th>PRODUCER</th>
<th>Crystal Syst.</th>
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<td>single c.</td>
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<td>3.5x10^{18}</td>
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<td>Fe -CONCENTRATION</td>
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<td>4.0x10^{15}</td>
<td>&gt; 3x10^{16}</td>
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<tr>
<td>NOTATION IN TEXT</td>
<td>U 1</td>
<td>U 2</td>
<td>U 3</td>
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CZ ... Czochralsky pulling    FZ ... Float zone process
HEM .. Heat Exchanger Method  d.f. = dislocation free.

TABLE II: Reciprocal absorption coefficient of silicon

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<th>Wavelength [nm]</th>
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<th>900</th>
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<td>( \alpha^{-1} ) [\mu m]</td>
<td>12</td>
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Fig. 1: Experimental setup to determine minority carrier diffusion length as a function of temperature.

Fig. 2: Influence of heat treatment on minority carrier diffusion length. Sample U1: ○ ... MIS structure, ● ... p/n junction. Sample U2: ▲ ... MIS structure, ▲ ... p/n junction.

Fig. 3: Dependence of electron diffusion length on the concentration of the point defect H6: $E_v + E_F = 0.32$ eV. ○ ... sample U1, ▲ ... sample U2, ● ... sample U3.

Fig. 4: Temperature dependence of capture cross section for ionized impurity scattering. ▲ ... sample U1, ○ ... sample U2.