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TEMPERATURE DEPENDENCE OF ABSORPTION COEFFICIENT IN SILICON OF LOWER PURITY

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ABSTRACT

We have derived the absorption coefficient of high purity and lower purity p-Si as a function of temperature between 80K and 420K from transmission measurements in the photon energy range of 1.1eV to 1.5eV. From these data the temperature dependence of the the indirect gap was calculated. A significant difference between both samples was observed. An additional term of the absorption in silicon which is not due to the fundamental transition increases linearily with decreasing temperature. It was found to be equal for both samples as long as the absorption coefficient is in the range between $100cm^{-1}$ and $300cm^{-1}$ and the temperature is less than 300K.

INTRODUCTION

Studies of the operation of silicon solar cells require the knowledge of the absorption coefficient α as a function of the temperature T and the photon energy E_{ph} [1,2,3]. In the long wavelength range λ > 800nm at room temperature the dependence of the light generated current on absorption coefficient and minority carrier diffusion length obays a relatively simple law [4]. In order to evaluate minority carrier diffusion length as a function of the temperature which is often favourable in the case of solar cells over the determination of minority carrier lifetime [5] the absorption coefficient has to be well documented for different quality silicon. The purpose of this work was to record the incident photon energy as a function of the temperature where the absorption coefficient remains constant. Hence the photosignal directly displays the variation of the minority carrier diffusion length with temperature. The transparency of this approach towards the temperature dependence of the absorption coefficient in silicon prompted us to extend our studies towards the fundamental edge.

EXPERIMENTAL

For our experiments we used a Spex Doublemate 1672 spectrometer. The wavelength was driven by a 4 pole stepper motor which could be operated from a computer controlled pulse source. The outcoming beam was splitted into two beams which

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were focused on two glass fibre cables. Into one light path the silicon plate was mounted. The intensity modulated signals - ν = 523 s^{-1} - were detected with Ge photodiodes and preamplified with two PAR 124A Lock-In amplifiers. Both glass fibres were lead through a LN_2-dewar in order to prevent errors due to changes in the transmission characteristics of the glass fibre at lower temperatures. Below 295K the temperature was varied by awaiting the warming up of the dewar. From 300K to 430K the system was heated by slowly increasing the current through a resisitor. This was done manually and caused the system to be instable around 300K to 330K. The two Lock-In signals were received by a HP-1000 computer. The ratio of transmitted and incident light I_t/I_0 was compared to a set point and the wavelength was adjusted to keep the ratio constant. In this feed back loop the reflectance was neclected. However recording of the changes of the reflectance during a temperature sweep show that it changes less than +/-2 percent absolute over the corresponding wavelength range. Due to the steep transmittance these changes in the reflectance will cause an error in the determined wavelength of less than 1 nm as long as the wavelength does not exceed 1050 nm at room temperature. The half width of our spectrometer was typically somewhat above 1 nm . This allows us to record the changes in photon energy as a function of temperature with appropriate accuracy in intervalls of 2K to 5K. At room temperature the absolute value of the absorption coefficient was determined from absolute transmittance measurements on 4 samples of different thicknesses from 100 µm to 450 µm. The experimental set up is shown in figure 1.

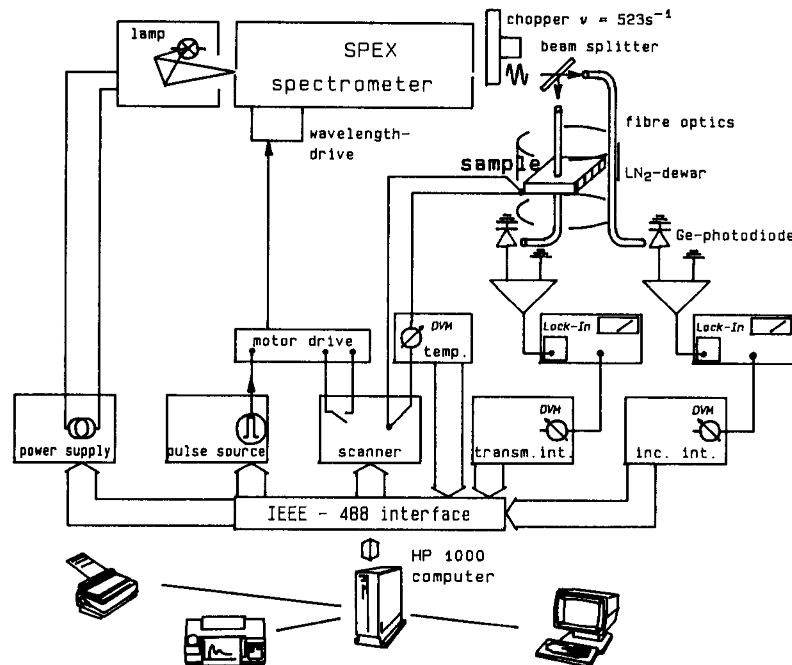

Fig.1:
Experimental setup for the temperature resolved determination of the absorption.

The method decribed above allows us to collect relatively simple a set of data-triples E_{ph},T,α since it requires only one sample, the temperature need not to be kept constant and no absolute measurements have to be performed once α is determined at room temperature. Furthermore the direct observation of $E_{ph}(T)$ with α= const is a great help during the visual inspection of the data.
Two samples of p-type silicon have been examined. Their properties are summarized in table I.

TABLE I: Properties of silicon we used in our experiments.

SAMPLE	high purity p-Si	lower purity p-Si
MELTSTOCK	CVD-deposited poly-Si	arc furnace metallurgical Si
CRYSTAL GROWTH	cruicibleless FZ	2 x CZ
HOLE CONCENTRATION	$10^{13}cm^{-3}$	$3.5x10^{18}cm^{-3}$ *)
IRON CONCENTRATION	-	> $3x10^{16}cm^{-3}$

FZ ... float zone processing CZ ... Czochralski pulling

*) compensated

RESULTS AND DISCUSSION

Since our experimental set up does not include insitu reflectance correction of the I_t/I_0 determination we were restricted to measurements as close as 0.05eV above the fundamental gap energy. Results at higher photon energies were used to evaluate the temperature dependence of the indirect gap energy $E_g(T)$. From the collected datatriples $(\alpha E_{ph})^{1/2}$ as a function of the photon energy at a constant temperature were selected. Two energy points were determined: (i) The extrapolation of the linear part of the curve to $(\alpha E_{ph})^{1/2}=0$, furtheron denoted with E_1, and (ii) in the case of high purity silicon the energy E_2 at that point where the first deviation of linearity of the plot occurs coming from higher towards lower energies. E_2 corresponds to the TO momentum-conserving phonon emission threshold of free-exiton creation [6]. In silicon of lower purity E_2 could not be resolved satisfactorily potentially due to the high density of states near the band edges. Neglecting a temperature dependence of the free-exiton binding energy E_{xb} = 14.7meV and the phonon energy $\hbar\omega_{TO}$ = 57.3meV [7] the temperature dependence of

$$E_2 = E_g + \hbar\omega_{TO} - E_{xb} \quad (1)$$

directly displays the temperature dependence of the indirect transition in silicon. For practical reasons the temperature dependence of both E_1 and E_2 was fitted with a 2nd order polynomal fit instead of the commonly used formula given by Varshni [8]. In figure 2 the results from the measurements on high purity silicon and fitted curves of E_1 and E_2 are shown. For comparison the theoretical curve given by Lautenschlager [9] is shown. Figure 3 displays the results obtained from the evaluation of E_1 as a function of temperature for the sample of lower purity silicon together with the experimental results from Bludau for high purity silicon [7] and our values for E_1 for high purity silicon.From figure 2 it can be seen that the temperature dependence of E_1 and E_2 are different. The difference can be expressed by the use of the polynomal fits as:

$$\Delta = E_1 - E_2 = -0.002eV - 1.58x10^{-4}eV/K + 3.31x10^{-7}\ eV/K^2 \quad (2)$$

Applying this correction to the values of E_1 for our sample of lower purity silicon yield a temperature dependence of the indirect transition which corresonds within our resolution to that one observed by Bludau [7] on high purity silicon between 80K and 250K. Towards higher temperatures a stronger dependence is observed in our sample of lower purity. There exists a significant difference between our results from high purity silicon and silicon of lower purity. Both curves show a much stronger dependence with temperature than the calculations of

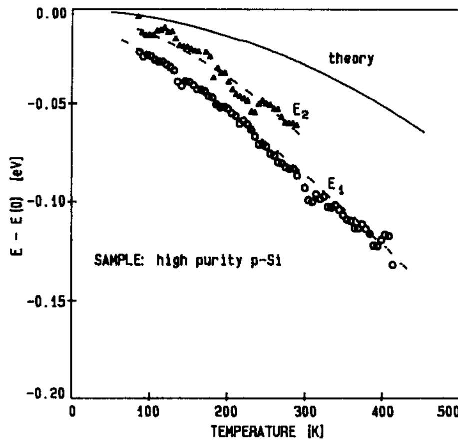

Fig.2: Temperature dependence of E_1: o ...measured, -·- ... 2nd order polynomal fit: $A = 1.226eV$, $B = -2.41x10^{-4}eV/K$, $C = -1.59x10^{-7}eV/K^2$, and E_2: ▲ ...measured, -·- ...2nd order polynomal fit: $A = 1.228eV$, $B = -8.26x10^{-5}eV/K$ and $C = -4.90x10^{-7}eV/K^2$. Theoretical curve from P. Lautenschlager et.al., Phys.Rev.B, 31 (1985) 2163.

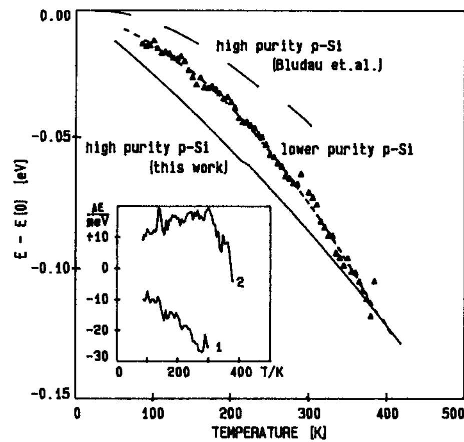

Fig.3: Temperature dependence of the indirect gap in silicon of lower purity: ▲ ...measured, -·- ...2nd order polynomal fit: $A = 1.202eV$, $B = -8.27x10^{-5}eV/K$, and $C = -5.63x10^{-7}eV/K^2$. The inset shows the difference between the values of lower purity silicon and high purity silicon: 1..results from Bludau et.al., J.Appl.Phys., 45 (1974) 1846, 2..this work.

Lautenschlager predict [9]. By the subtraction of E_1 from the photon energies we measured we obtain an additional contribution to the absorption which can be approximated with linear fits. This is shown in figure 4 for high purity silicon and figure 5 for lower purity silicon for different values of the absorption coefficient.

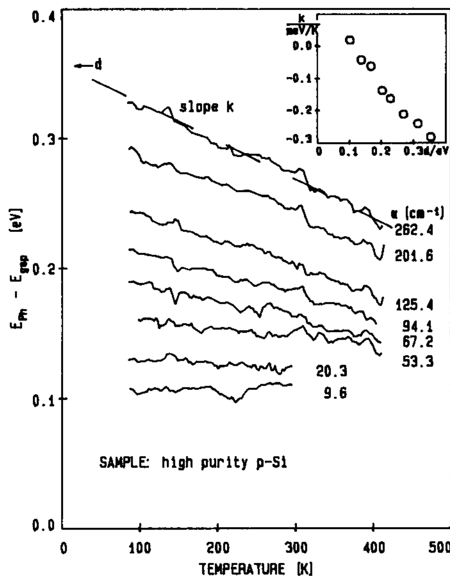

Fig.4: Reduced photon energy necessary to maintain constant absorption. The inset shows k and d values from linear least square fits.

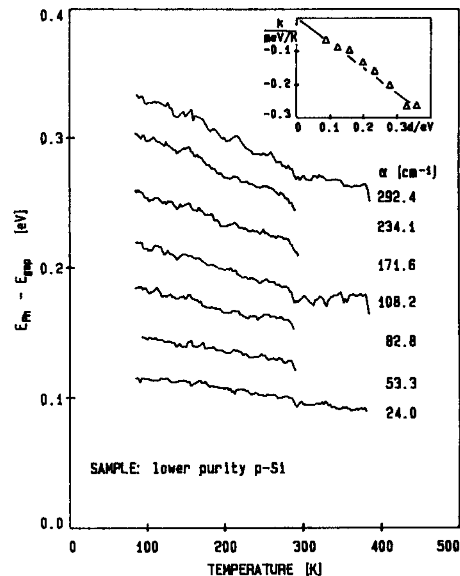

Fig.5: same as fig.4 but for lower purity silicon.

For high purity silicon the linearity is given over the whole temperature range whereas for silicon of lower purity the linear part of the curves is restricted to temperatures below 300K. Above 300K it seems that the energy difference $E_{ph}-E_{i}$ saturates and remain constant towards higher temeratures. This means that the absorption is merely due to the fundamental transition. The values of the slope k and the offset d = $E_{ph}-E_{i}$ at T=0K of the linear least square fits are shown in the two insets of figure 4 and 5. For high purity silicon k reverses sign at low energy differences whereas the negative value of k continuously decreases with lower energy differences towards 0 for $E_{ph}=E_{i}$. For energy differences large enough which means absorption coefficients of more than $100cm^{-1}$ the plot of k versus d is the same for high purity silicon and silicon of lower purity thus suggesting the same temperature dependence of this additional absorption besides the different fundamental transition in both samples. Above 250K the variation of the photon energy with temperature which is necessary to maintain constant absorption can be approximated for practical applications with a linear dependence as suggested by Weakliem [1]. However the values for the slope he derived from the determination of $\alpha(E_{ph})$ at 4 constant temperatures are much greater than we obtain with our method which directly displays the slope for constant absorption. For instance for E_{ph}=1.3eV Weakliem proposes a value of $-0.69x10^{-3}$ eV/K whereas we observe a value of $-0.52x10^{-3}$ eV/K in the case of lower purity silicon and $-0.57x10^{-3}$ eV/K for high purity silicon. The results we have obtained with our eperimental method show that there exist a signifcant difference in the temperature dependence of the absorption coefficient of lower purity silicon and high purity silicon. This difference is mainly due to the differnt behavior of the indirect transition in our samples. Although our method is not as sensitive as previously described ones [7] the relative simplicity in collecting data and their interpretation makes this method useful for the evaluation of the dependence of the absorption coefficient on the properties of silicon samples. We belive that further improvements in the experimental set up will considerably extend its use for further applications.

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