in the following T_m may vary a few K due to different time windows and plotted coefficients.

E1 (T_m = **30 K**) :
Both peaks, E1 and E2 appear in the spectra already before irradiation. Because most of the measurements were made with the liquid nitrogen cryostat and T_m is below the boiling point of nitrogen, the peaks were not investigated systematically.

E2 (T_m = **60 K**) :
From the specific measurement shown in fig. 7.1 an energy- level at 0.1 eV has been determined. Thus the assignment to the C_i-C_s complex in state B or to the magnesium donor state is possible (but see also E1).

E3 (T_m = **80 K**) :
This peak is correlated to the very well known V-O complex. However, this defect is known to be radiation induced and hence the V-O complex does not explain the occurrence of the peak before irradiation. The peak occurs in a temperature range which is very close to the boiling point of liquid nitrogen. Thus in some cases (certain coefficients in combination with long time windows) the peak can not be recorded completely.

E4 (T_m = **120 K**) :
In high resistivity material this peak occurs already before irradiation and exhibits a metastable behaviour. Because the direct analysis of this peak failed a superposition of energy levels has to be assumed. In case of low resistivity material peak E4 seems to be dominated by a single energy level.

E5 (T_m = **170 K**) :
This energy level is detected also already before irradiation. It is assumed to be generated during the oxidation.

E6 (T_m = **230 K**) :
Peak E6 is the dominant one after irradiation, but there are at least 2 energy levels which contribute.

E7 (T_m = **270 K**) :
This energy level is found only prior to irradiation in SB-samples made of high resistivity material.

A detailed description of the peaks occurring before irradiation is given in sec. 7.1.2. The radiation induced peaks are discussed in sec. 7.1.3.

The detection of hole traps was possible only with the p^+-n -samples or p-type SB-detectors, respectively. The investigation has been focused on electron traps in n-type silicon, hence the results on hole traps are presented at the end of this chapter in sec. 7.1.6.

Because silicon detectors for the application in high energy physics have to be made from high resistivity material [1], the main subject of this investigation is silicon

[1] Note however, that for low energy physics no use should be made of low resistivity material.

ρ [Ωcm]	$N_{eff,0}$ [cm^{-3}]	Oxide-passivated	Wafer
6	$8{\cdot}10^{14}$	no	933
100	$4{\cdot}10^{13}$	no	938
2000	$3{\cdot}10^{12}$	no	93A
4000	$1{\cdot}10^{12}$	no	939*
6000	$7{\cdot}10^{11}$	yes	936 †
7000	$6{\cdot}10^{11}$	yes	941
3000	$2{\cdot}10^{12}$	yes	M2/1

Table 7.1: Material used for the DLTS investigation. Geometry etc. see sec. 5.1. Also samples from wafer 911 with properties similar to 941 were used. † p-type, * after irradiation it was not possible to record proper spectra.

with a resistivity $\rho > 1$ kΩcm . However, since the E-centre (V-P) is supposed to play a significant role in radiation damage of silicon, also material of higher phosphorus concentration, i.e. lower resistivity has been used. The material under investigation is compiled in tab. 7.1. Furthermore the influence of the oxidation has been checked by comparing between oxide-passivated and non-passivated wafers.

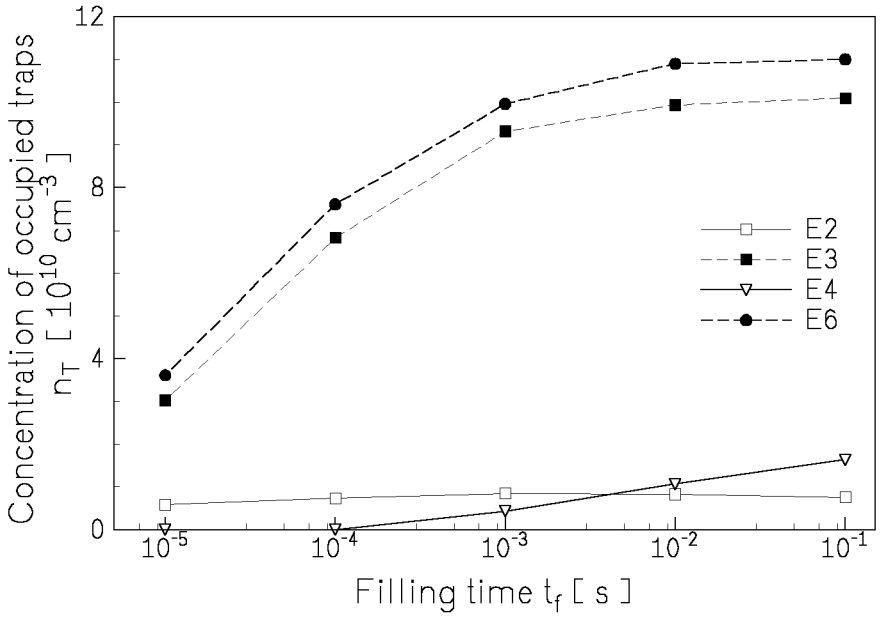

Figure 7.2: Concentration of occupied traps as function of filling time. Five complete spectra were recorded and analysed according to eq. 4.53. E4 increases by a factor of 4 between 1 ms and 100 ms. (M20610, Φ =9.51$\cdot 10^{10}$ cm^{-2}). Note that the capture process (see eq. 2.36) depends on both, the capture coefficient and concentration of free electrons : $r_a \propto c_n n$.

The measurements discussed in the following sections were chiefly performed using the following parameters :

Reverse bias	V :	10 or 20 V,
Filling voltage	V_f :	4 or 0 V,
Filling time	t_f :	1 ms,
Time window	t_w :	20, 200, 2000 ms,
Averaging		200, 20, 8.

The reverse bias voltage was either 10 V or 20 V. The non-zero filling voltage (4 V) had to be used for the oxide-passivated samples. Due to the MOS structure at the edge of the electrode the CV-curve deviates from the $1/\sqrt{V}$-dependence. In order to keep away from that voltage range V_f=4 V is used. For comparison the measurements with non-passivated samples were performed with the same filling voltage.

The number of occupied traps can be changed by variation of the filling time. For a correct determination of the trap concentration it is necessary to reach a complete filling. In fig. 7.2 the peak heights of E2, E3, E4 and E6 are plotted versus filling time. It can be seen that for $t_f \geq 1$ ms all peaks saturate, but not E4. The peak height of E4 does not saturate even for $t_f > 100$ ms. Thus in order to keep the measurement time as short as possible $t_f = 1$ ms has been chosen. Note that the transients were recorded up to 200 times for subsequent averaging. A longer filling time than 1 ms would increase the duration of a DLTS-measurement tremendously.

The long time needed to completely fill the E4-traps indicates a repulsive Coulomb potential as it is expected if the trap is already occupied by a first electron. It is very likely, that the double charged divacancy corresponds to peak E4. Note however, that for material with higher doping concentration the capture process r_a is expected to be faster, because it is proportional to the concentration of free electrons (see eq. 2.36).

Three different time windows were used in one temperature scan order to cover a wide temperature range in the Arrhenius-plot. The transients recorded with a time window t_w= 20 ms are average of 200 measurements, transients with t_w= 200 ms are average of 20 measurements, and transients with t_w= 2 s are average of 8 measurements. Since for each time window 18 coefficients were calculated 54 spectra are obtained from every temperature scan. However, the best signal to noise ratio [85] and the most pronounced spectra are provided by the b_1 and a_1 coefficients which are therefore shown exclusively in the following.

7.1.2 Energy Levels before Irradiation

Already before irradiation the spectra of the high resistivity samples are rather complex as it is shown in fig. 7.3. In the spectra of the low resistivity non-passivated material no peaks could be found.

All levels found in the non-irradiated material are summarised in tab. 7.2. Because a significant difference of ΔE_C and σ_n for corresponding peaks from different materials has not been found, the average values of results on individual samples are listed without distinguishing the origin. The trap concentration is also listed in

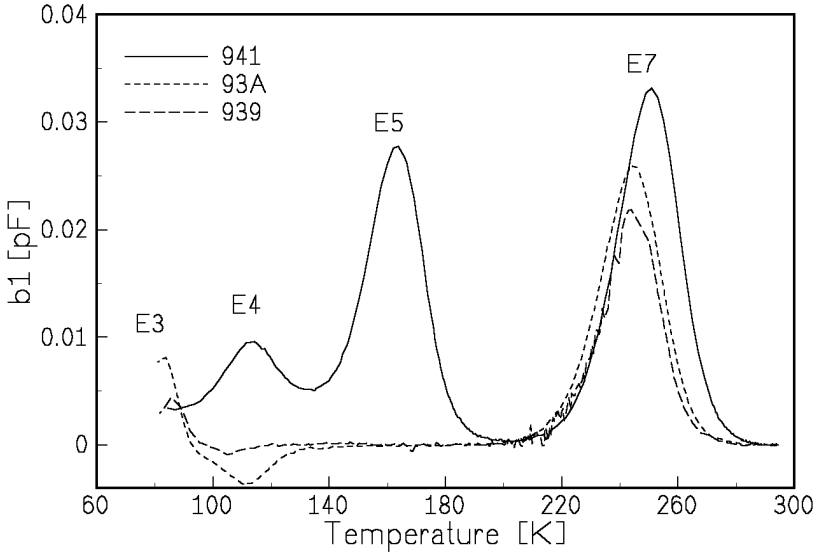

Figure 7.3: Spectra before irradiation. For each type of sample a characteristic spectrum is shown. Peaks E1 and E2 see fig. 7.1.

	ρ [Ωcm]		6	100	4000	2000	7000	3000
	$N_{eff,0}$ [cm^{-3}]		$8{\cdot}10^{14}$	$4{\cdot}10^{13}$	$1{\cdot}10^{12}$	$3{\cdot}10^{12}$	$6{\cdot}10^{11}$	$2{\cdot}10^{12}$
	Oxide-passivated		no	no	no	no	yes	yes
Label			933	938	939	93A	941	MPI
	ΔE_C $[eV]$	σ_n $[cm^2]$	n_T $[10^9\ cm^{-3}]$					
E1	0.06	$6.1\ 10^{-16}$	-	-	-	-	4	(3)
E2	0.12	$1.1\ 10^{-14}$	-	-	-	-	6	-
E3	0.15	$2.7\ 10^{-15}$	-	-	2 ± 1	40 ± 6	-	-
E4	0.24	$1.6\ 10^{-14}$	-	-	-	-	5 ± 2	-
E5	0.26	$1.5\ 10^{-17}$	-	-	-	-	24 ± 5	-
E7	0.53	$3.5\ 10^{-15}$	-	-	4 ± 2	16 ± 6	23 ± 9	-

Table 7.2: Energy levels in non-irradiated n-type material. The standard deviation of ΔE_C is always smaller than 0.01 eV. The standard deviation of σ_n is about 50%. Results from a p^+-n -sample can be found in tab. 7.3

average values, but separately for each material it has been detected in. No number is given if the peak did not occur in the spectrum.

Before irradiation the peaks **E1** and **E2** were detected only in that sample (941G16) which was measured at temperatures below 80 K. Similar energy levels are reported for so-called 'thermal donors', ΔE_C= 0.06 eV and ΔE_C= 0.12 eV [125, 126] which are found in Czochralski grown silicon by Hall effect measurements after heat treatment at 450°C. However, this temperature is considerably lower than

the temperature during the oxidation process (T $\approx$ 1000°C) and thus the assignment is not cogent. The E1-level could also be interpreted as the ionisation energy of arsenic ΔE_C= 0.054 eV [127].

As outlined already in the introduction of this chapter the energy and cross section obtained from peak **E3** correspond to the very well known parameters of the A-centre (V-O complex). Also the level parameters of the C_i-C_s-complex match the determined energy level and cross section. However, both defects are confirmed as to be radiation induced and thus by none of the defects the occurrence of peak E3 in undamaged silicon can be explained. Because before irradiation the peak is seen only in the spectra of non-passivated samples it can be assumed that the corresponding defect anneals out during the high temperature step of the oxidation process.

Before irradiation peak **E4** has been found only in the oxide-passivated high resistivity material. The occurrence of peak E4 depends on the measurement condition. The first spectrum shown in fig. 7.4 was recorded after the sample was cooled-down without reverse-bias. The peak can be seen very clearly at 130 K. Before the subsequent measurement the sample was cooled-down, while a reverse-bias (10 V) was applied. The peak is totally vanished. The peak disappears also if a reverse-bias is applied before the sample is cooled down. A re-appearance of the peak could be seen neither after a long time ($t \approx 2$ days) in thermal equilibrium nor after a strong forward current injection (1 mA for 15 min). However, after irradiation at the same temperature again a peak occurs which also exhibits a metastable behaviour. The

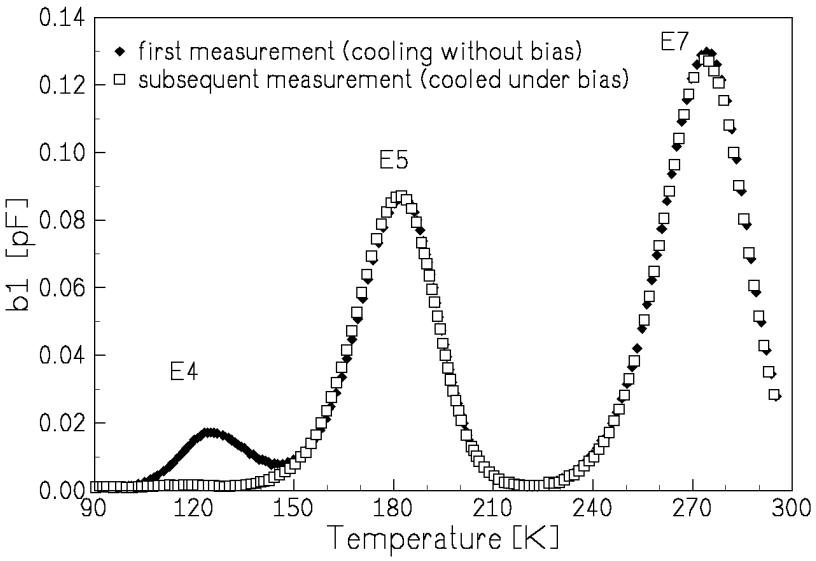

Figure 7.4: Multistable defect level in DLT-spectrum before irradiation.

effect of a multistable defect causing a peak at the same temperature the double charged divacancy occurs at has been reported by Chantre [63], who found that the corresponding defect can be cycled through various configurations with different energy levels. But he did not observe this effect before irradiation.

It is not possible to apply the *direct analysis* to peak E4 and as can be seen in fig. 7.7.a it can not be recalculated [2] by the results obtained from the *analysis of maxima*. Thus peak E4 has to be regarded as a superposition of at least 2 levels. But no defects are known which could reproduce peak E4 by superposition.

Peak **E5** has been found also only in the spectra of high resistivity SB- samples with oxide (941). The energy and the significant small cross section are in good agreement with defect parameters reported by Verbitskaya et al. [128] : ΔE_C= 0.27 eV and σ_n= $1{\cdot}10^{-17}$ cm^2. The corresponding defect occurs only after heat treatments at temperatures above 1000°C as applied during the oxidation process. Because the peak E5 appears not in the spectra of non-passivated samples it is very likely that it is generated during the oxidation process.

Peak **E7** occurs in the spectra of all high resistivity samples, either oxide-passivated or not. But it is not seen in the spectra of the p$^+$-n -samples. Thus the only difference is the gold electrode, and it is very likely to assume gold acceptors to cause the E7-peak, because both parameters, ΔE_C as well as σ_n agree very well with the data of the acceptor level of gold (ΔE_C= 0.54 eV, σ_n= 2.18 $\cdot 10^{-15}$ cm^2, [129]) which is evaporated on the silicon. However, the diffusion of gold into the bulk requires temperatures up to 600-700°C ([102], see also [130]) which are not reached during the evaporation or afterwards. The non-occurrence of the E7-peak in the low resistivity material is due the low concentration which is below the detection limit.

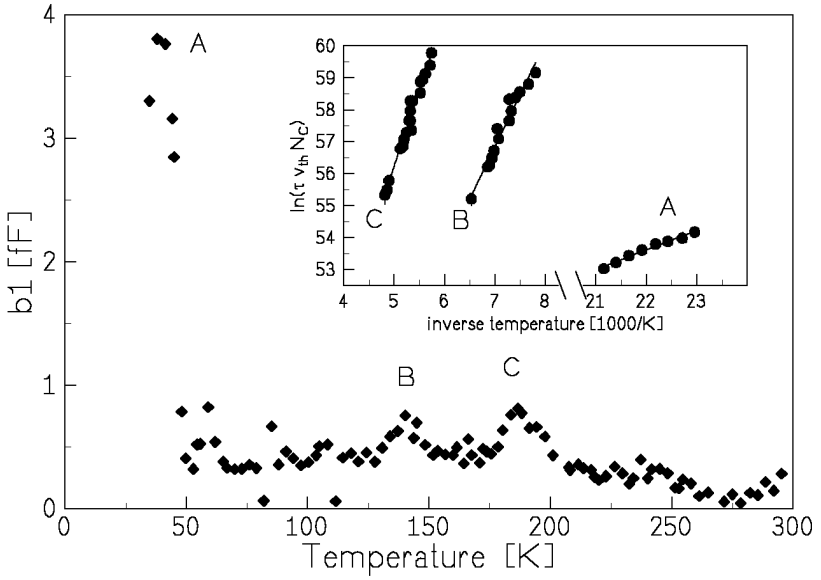

Figure 7.5: DLT-spectra of a p$^+$-n -sample (M20709) before irradiation.

Most of the DLTS measurements made on the p$^+$-n -samples did not show a spectrum. The energy levels found in one of the p$^+$-n -samples (see tab. 7.3) do not

[2] In contrast to a simulation which is based on fitted parameters the recalculation applies the results as determined from a specific measurement. If the recalculation does not match the measured peak, the result has to be called in question.

match those listed in tab. 7.2. The DLT-spectrum and the corresponding Arrhenius plot are shown in fig. 7.5. It can be seen that the peaks labelled A,B,C are very small compared to the peaks shown in fig. 7.3. By comparison of the peak temperature (T $\approx$ 40K) it can be concluded that Peak A corresponds with E1, also the concentration is comparable. The fact that in one case it was possible to detect very low impurity concentrations demonstrates on the one hand the high sensitivity of the DLTS-system (see sec. 4.2.3)and on the other hand the high pureness of the material.

Label	ΔE_C $[eV]$	σ_n $[cm^2]$	n_T $[cm^{-3}]$
A	0.05	$4 \cdot 10^{-18}$	$3 \cdot 10^{9}$
B	0.28	$2 \cdot 10^{-15}$	$5 \cdot 10^{8}$
C	0.41	$7 \cdot 10^{-14}$	$6 \cdot 10^{8}$

Table 7.3: Energy levels detected in a specific non-irradiated p^+-n -sample (M20709).

7.1.3 Energy Levels after Irradiation

After irradiation the peaks E3, E4 and E6 occur in the DLT-spectra of all samples independent of the material. Fig. 7.6 shows a spectrum of a low resistivity sample (933), which contains only the irradiation induced peaks. In the following the determined energy levels, cross sections, and other peak properties are discussed in detail. As far as possible the corresponding defects are identified. A brief summary of the results is compiled in tab. 7.4.

The dominant peak is **E6** as can be seen in fig. 7.6. The direct analysis of the peak E6 is impossible, because the measured capacitance transients can not be described by a simple exponential function (see eq. 4.26). For the same reason the analysis of maxima leads to an only seemingly reasonable result ($\Delta E_C \approx 0.43$ eV and $\sigma_n \approx 10^{-15}$ cm^2) which does not allow the recalculation of the measured peak. Hence strong indication is given that peak E6 is caused by the superposition of at least 2 energy levels. It is commonly assumed in the literature (see e.g. [131, 132]) that the E-centre (V-P) and the divacancy (V-V$^-$) are those 2 levels. In order to investigate in which ratio both defects contribute it has been tried to deconvolute the peak E6 by using 2 defect levels with parameters similar to those of the E-centre and the divacancy. The level parameters

$\Delta E_C = 0.39$ eV, $\sigma_n = 4 \cdot 10^{-15}$ cm^2, (E6a) and
$\Delta E_C = 0.44$ eV, $\sigma_n = 1 \cdot 10^{-15}$ cm^2 (E6b) (see sec. 3.3)

were used as starting parameters for a 'fit by eye' procedure. These level parameters and corresponding concentrations (two triples $\Delta E_C, \sigma_n, n_T$) were varied until the simulation [3] was in good agreement with the measured data. Note that

[3] The simulations were performed using the DLTS-software (see sec. 5.3).

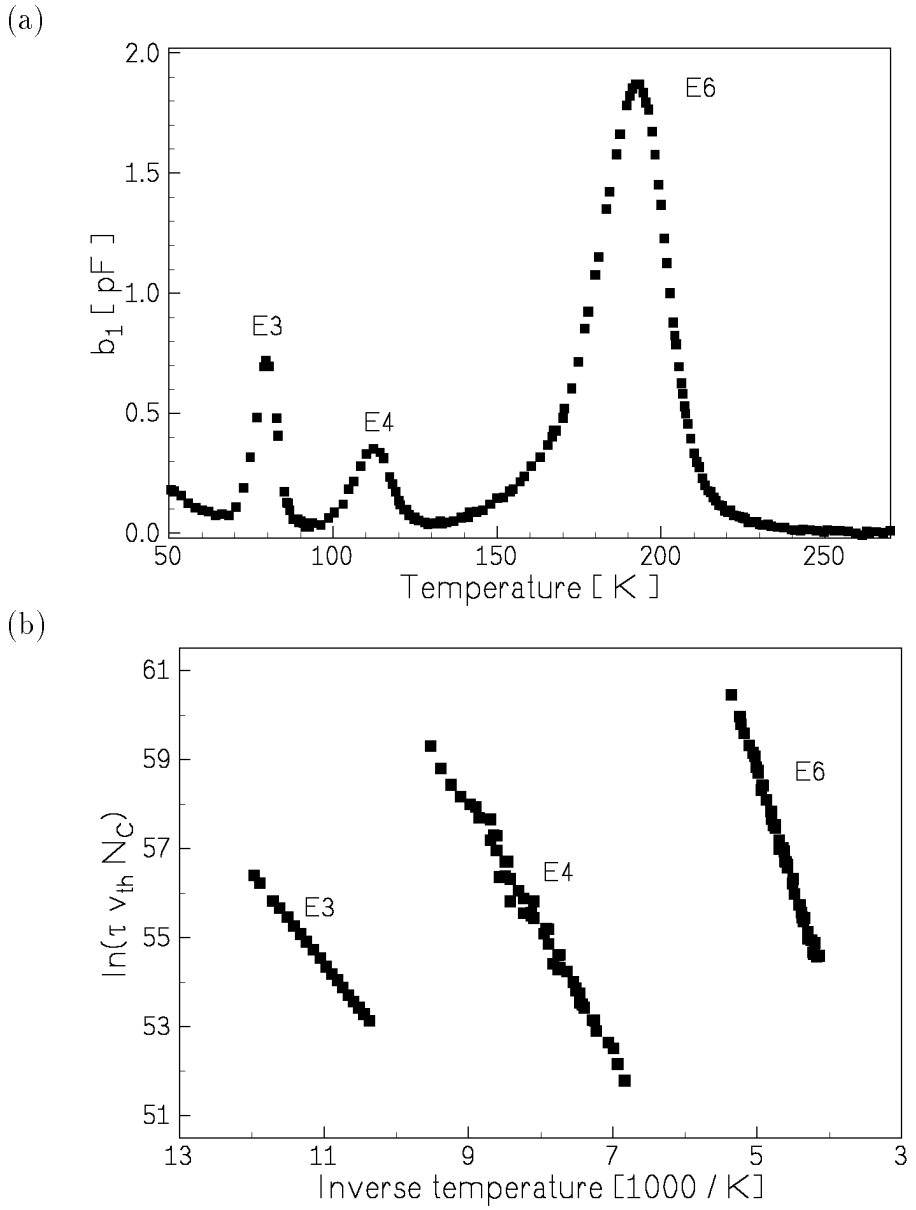

Figure 7.6: (a) : Characteristic spectrum after irradiation (933G34, $\Phi = 1.53 \cdot 10^{13}$ cm^{-2}). Pre-irradiation peaks E5 and E7 do not occur in the spectra of this material. (b) : Corresponding Arrhenius-plot, note that the axis of inverse temperature is running downward.

not only the coefficient b_1 had to be fitted, but also the temperature dependence of the other recorded coefficients and their behaviour for different time windows. While the values of n_T were varied from sample to sample, the values of $\Delta E_C, \sigma$ were required to be the same for all measurements. The following parameters were found to match the recorded coefficients of all measurements discussed in the next section :

(I) $\Delta E_C = 0.39$ ($\pm 0.5\%$) eV $\quad \sigma_n = 1.2 \cdot 10^{-15}$ ($+30\%, -10\%$) cm^2,
(II) $\Delta E_C = 0.42$ ($\pm 0.5\%$) eV $\quad \sigma_n = 1.0 \cdot 10^{-15}$ ($+30\%, -10\%$) cm^2.

(I) is assumed to correspond with the divacancy, because these values are in excellent agreement with data reported by Kimerling [51] (see sec. 3.3). Consistently (II) should to correspond with the E-centre.

For demonstration a few of the simulated curves are compared with the measured values in fig. 7.7. Additionally the curves are shown, which were recalculated using the parameters which resulted from the analysis of the maxima.

In case of the non-passivated samples peak **E4** is obviously dominated by a single energy level :

$$\Delta E_C = 0.25 \text{ eV and } \sigma_n = 5 \cdot 10^{-15} \text{ cm}^2.$$

These parameters are result of direct analysis. A recalculation of the peak agrees very well with the measured data (see fig. 7.8). The assignment of E4 as the double charged divacancy (V-V$^=$) which often is quoted in the literature (e.g. [47, 131, 132]) is based on the similar value of ΔE_C (see sec. 3.3). But the value of the electron cross section is significantly higher than expected for a trap-level which is already negatively charged. In case of the oxide-passivated material also after irradiation the

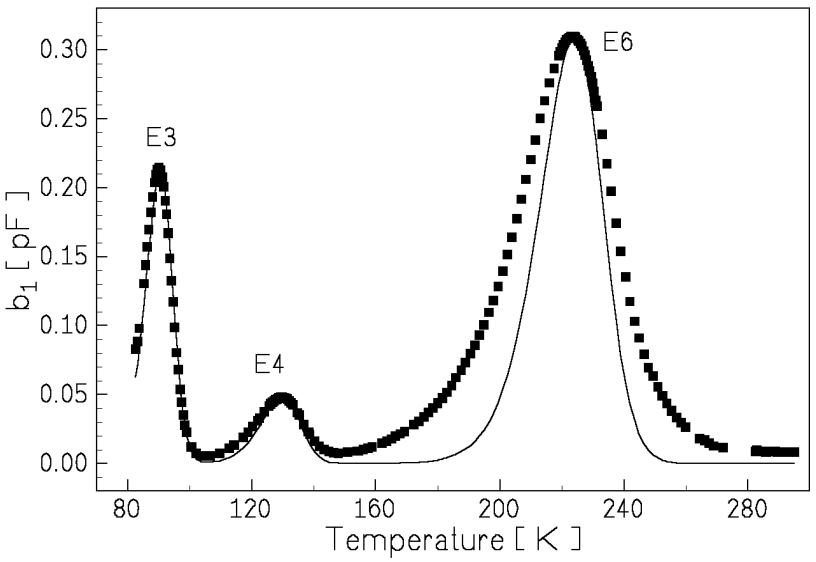

Figure 7.8: Recalculation of a spectrum measured with 100 Ωcm-material (938G21, $\Phi = 9.98 \cdot 10^{11}$ cm^{-2}). Peaks E3 and E4 are reproduced very well, indicating the detection of single levels (V-O and V-V$^=$). But the recalculation does not match peak E6. Obviously more levels than one contribute.

determination of level parameters is possible only by applying the analysis of maxima and the recalculation of the peak shows only poor agreement with the measurement as it is shown for example in fig. 7.7a. Thus again it has to be assumed that more defect-levels than one contribute to peak E4. Probably the peak which has been seen already prior to irradiation has still considerable influence. Moreover the peak found in the spectra of the passivated material exhibits the metastable behaviour