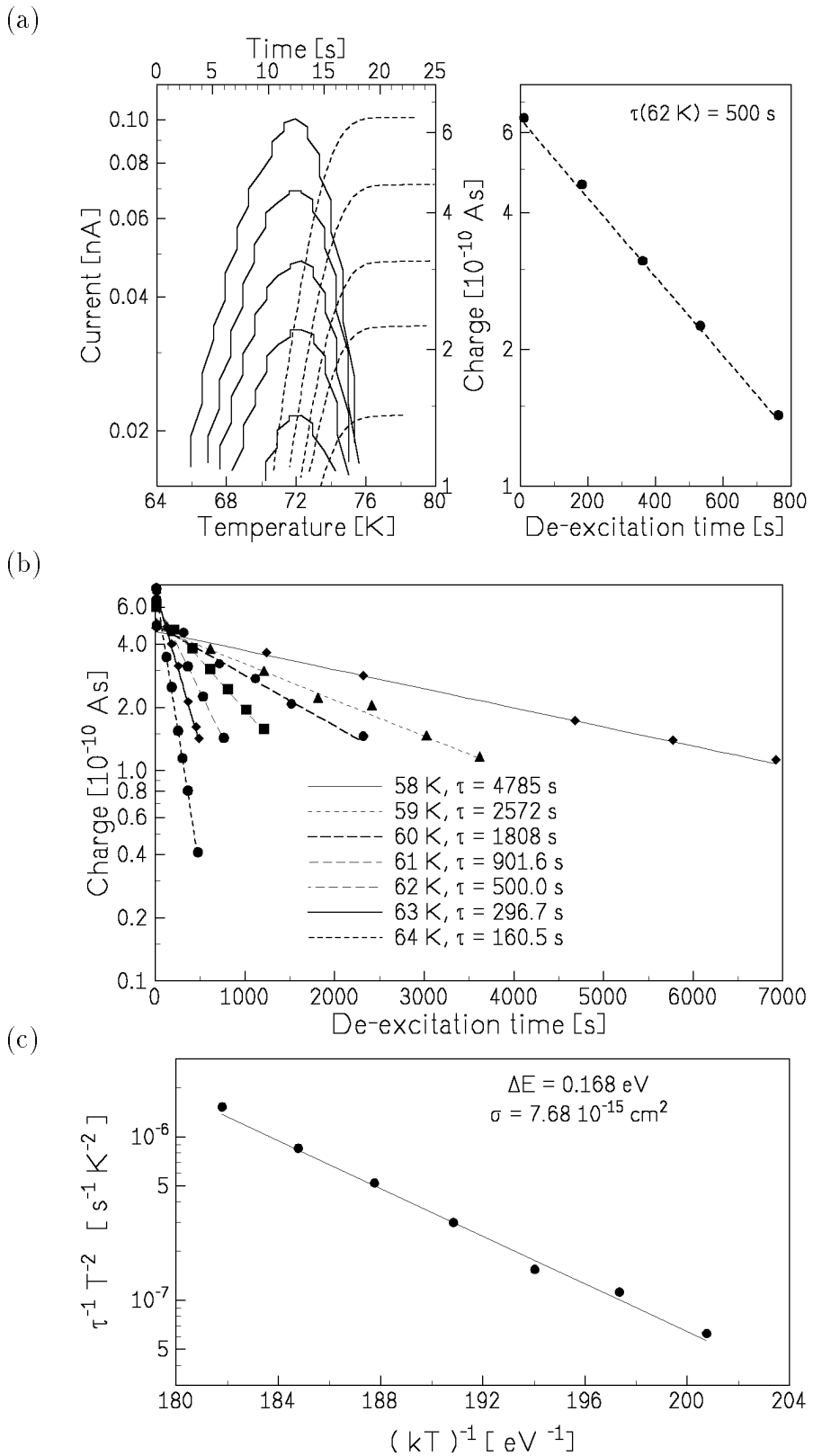


Figure 7.19: Determination of energy level parameters by the delayed heating method. (Sample M10610, Φ = 4.26·10^{12} cm^{-2}, I_f =2 mA, t_f = 30 s) (a) left : A-centre peak after various de-excitation times at 62 K (solid line). Also shown is the integral of current over time (broken line). (a) right : Emitted charge versus de-excitation time 62 K leads to emission time constant $1/\tau$. (b) : Time constants determined for different temperatures. (c) : Emission rate ($1/\tau$) versus temperature (Arrhenius-plot).

values of the emitted charge determined for various de-excitation times at the lowest temperature (58 K) to $t_d = 0$ s a lower value of emitted charge is found than for the extrapolation of the values obtained at the highest temperature (64 K). This behaviour will be discussed in sec. 7.2.3.

While about 40 measurements are necessary to obtain the Arrhenius-plot shown at the bottom of the fig. 7.19, the integral and the deconvolution method require only a single record of the peak. Both methods were applied to the same measurement and the results obtained are in good agreement (see fig. 7.20). Note that also the trap concentration is a result of the fit and agrees well with the value calculcated from eq. 4.65. A single peak has been used to demonstrate the deconvolution method in comparison with the other methods, although the term 'deconvolution' becomes suitable only if several peaks overlap.

In contrast to the delayed heating method which bases on the emission of carriers at a constant temperature, both the integral and the deconvolution method depend very sensitively on an exact measurement of the increasing temperature during the heating. From the difference of the results obtained from the delayed heating on the one hand and from the integral and deconvolution method on the other hand the error in temperature during the heating is estimated to be about 1.3 K ($T_{true} - 1.3K = T_{meas}$). The shift originates from a temperature gradient during the heating, hence the sample temperature is slightly higher than the temperature at the thermometer.

Method of Analysis	ΔE_C [eV]	σ_n [cm^2]
Delayed Heating	0.168	$7.7{\cdot}10^{-15}$
Integral Method	0.162	$3.7{\cdot}10^{-15}$
Deconvolution (Fit)	0.162	$4.5{\cdot}10^{-15}$

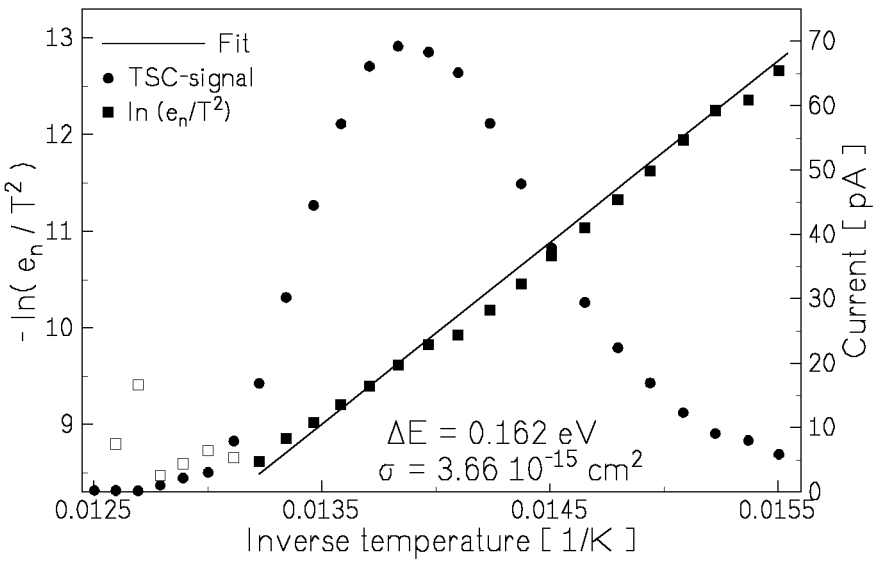
Table 7.10: Results of different methods of peak analysis.

7.2.3 Dependence on Measurement Conditions

In this section the influence of parameters such as reverse bias voltage, filling current, duration and temperature of current injection on the TSC-spectrum will be discussed.

It is apparent that the number of occupied traps depends on the amount of injected charge. This in turn depends on the duration of the filling pulse t_f and the filling current I_f. However, the variation of the filling time between 2 s and 23 s with a filling current of 21.2 μA leads to only little change in the TSC-spectrum. Only the 150 K peak structure (H1 and E6) increases, while the smaller peaks below 130 K do not change (see fig. 7.21). The increase of the 150 K peak structure is shown in the inset of fig. 7.21, where the emitted charge is plotted versus filling time. In the short time range a strong increase can be observed. But with increasing filling time the trap filling becomes less efficient indicating a saturation.

(a)



(b)

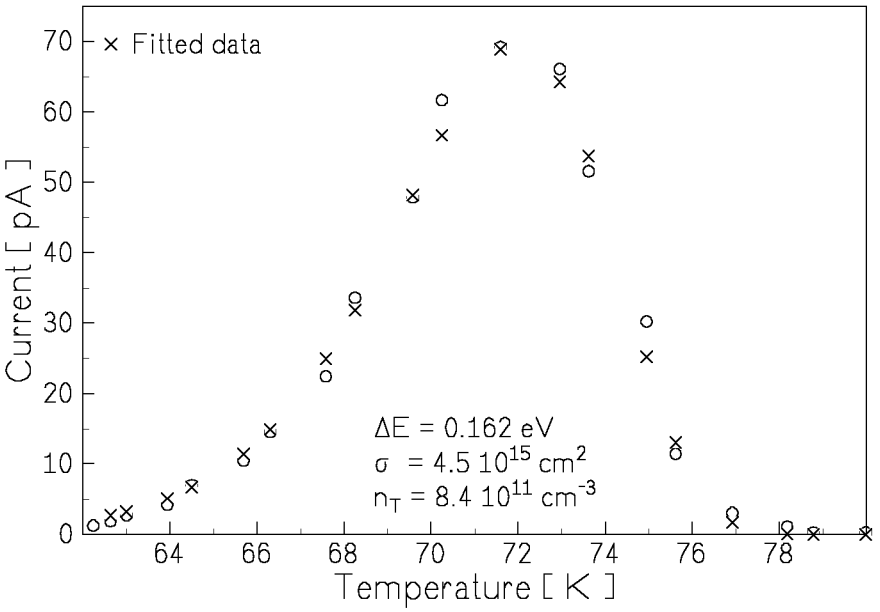


Figure 7.20: Determination of energy level parameters by the integral method (a) and the deconvolution method (b). The analysed measurement has been taken from the series of measurements made for the delayed heating (T_{start} = 62 K, t_d = 180 s). The trap concentration determined from the current integral is $n_{T,0} = 8.24{\cdot}10^{11}$ cm^{-3}. The corresponding value obtained by the deconvolution method agrees very well.

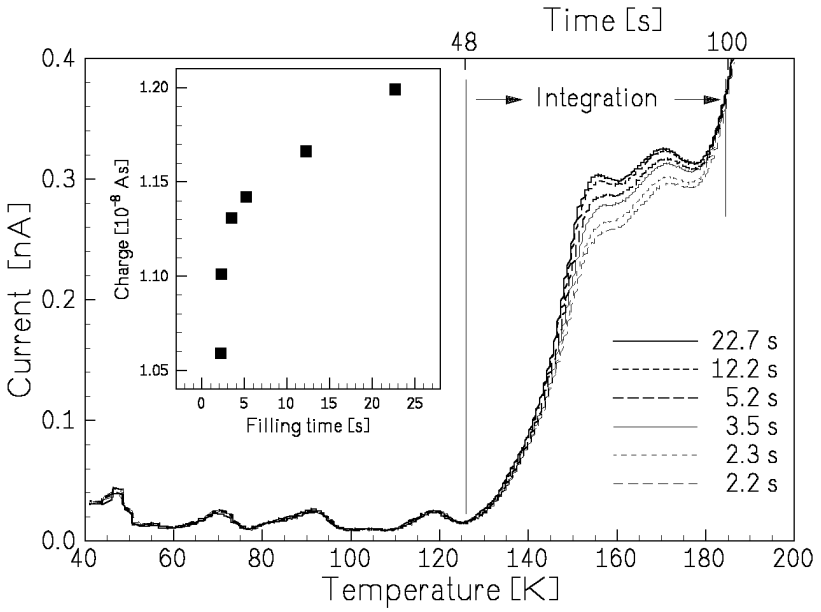


Figure 7.21: TSC-spectra with filling times as parameter, I_f = 21 μA. The inset shows the amount of charge emitted in the temperature range 125 K to 185 K calculated by integration of current over time. (MUEA06, $\Phi = 2.14{\cdot}10^{13}$ cm^{-2}).

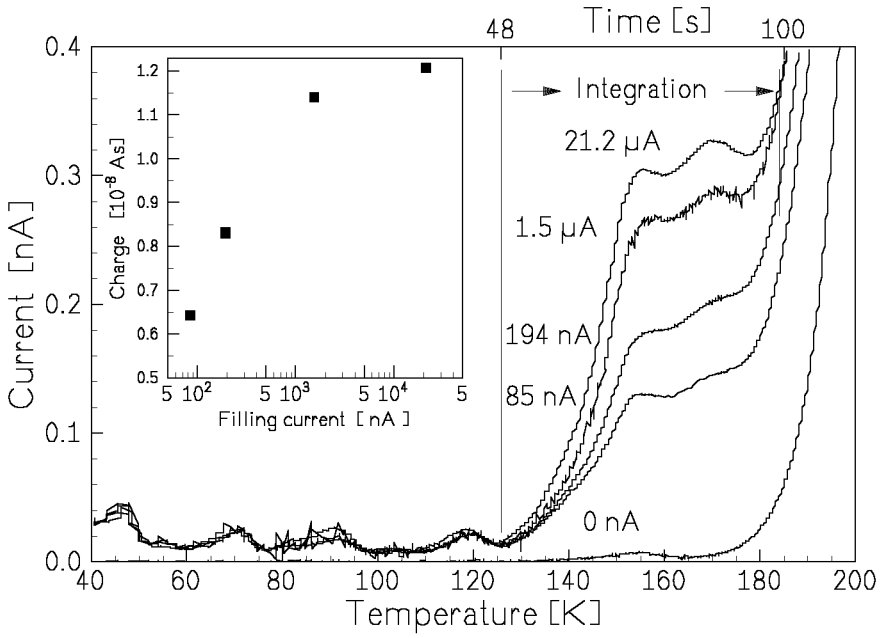


Figure 7.22: TSC-spectra with filling current as parameter, t_f = 23 s. The inset shows the amount of charge emitted in the temperature range 125 K to 185 K calculated by integration of current over time. (MUEA06, $\Phi = 2.14{\cdot}10^{13}$ cm^{-2}).

A similar behaviour can be observed if the filling current is varied. Fig. 7.22 shows how the spectra change due to the variation of the filling current between 0 and 21 μA. The filling time was kept constant at $t_f = 23$ s. Again mainly the 150 K peak structure is affected, while the smaller peaks below 130 K do not change. A simple explanation is to assume that the higher number of traps corresponding to the 150 K peak structure require also a higher number of charge carriers to achieve complete filling than the small number of traps corresponding to the peaks below 130 K. The effect of saturation is even more pronounced in the inset of fig. 7.22 where the filling current is plotted in a logarithmic scale. The results obtained by variation of filling time and filling current are combined in fig. 7.23. The emitted charge is plotted versus injected charge Q_f ($Q_f = I_f \cdot t_f$). It can be seen that above Q_f=3·10^{-4} As no significant increase of the emitted charge can be achieved. The emitted charge saturates at about 1.2·10^{-8} As corresponding to a concentration of occupied traps n_T= 2.14·10^{13} cm^{-3} !

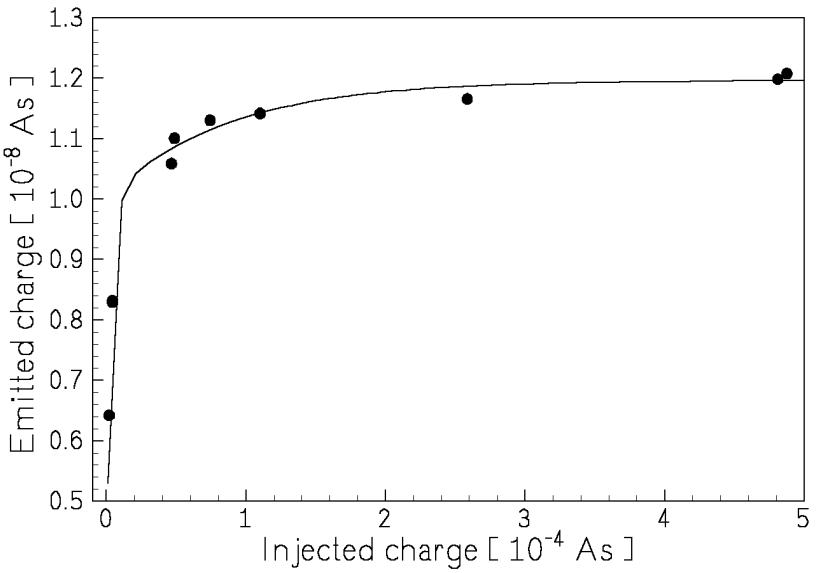


Figure 7.23: Charge emitted in the temperature range 125 K to 185 K versus injected charge. Saturation occurs at about 1.2·10^{-8} As. The straight line guides the eye.

A further very important parameter is the filling voltage V_f. As observed also by other experimenters [139] a minimum forward bias voltage has to be applied to inject a forward current. The situation is shown in fig. 7.24. Down to 200 K the forward characteristic looks rather the same as expected from eq. 4.9. Below 200 K (nearly) no current is flowing at lower voltages. If the minimum voltage is reached, suddenly the current increases very rapidly. The effect on the TSC-spectrum is shown in fig. 7.25. For filling voltages of up to 10 V the injection current is very small ($I_{fill} < 10$ μA) and accordingly also the peaks. However, for 20 V and higher voltages the maximum current (limited by the K487 to 2 mA) is flowing and a high level of trap-filling is achieved. The subsequent emission of charges provides a pronounced spectrum.

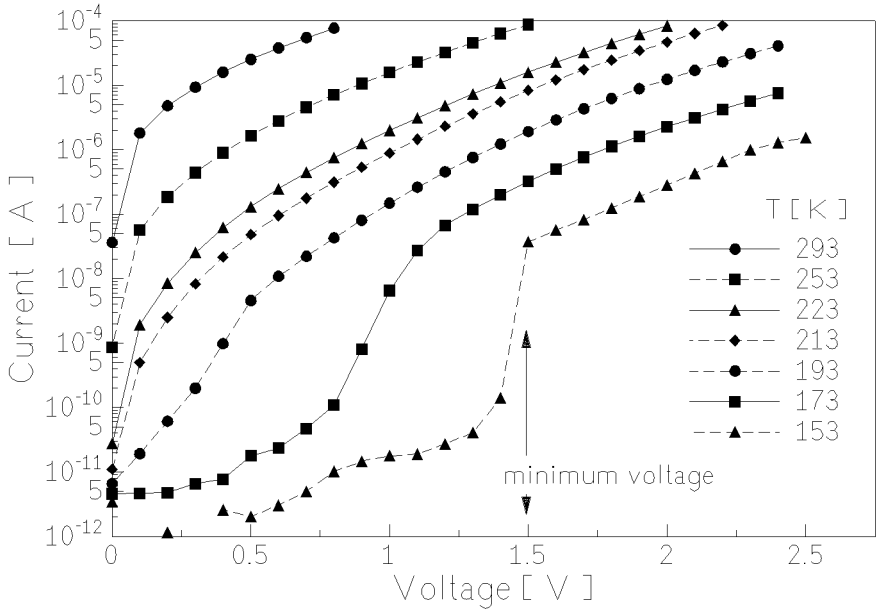


Figure 7.24: Forward current characteristics with temperature as parameter (MUEA21, $\Phi = 1.66{\cdot}10^{13}$ cm^{-2}).

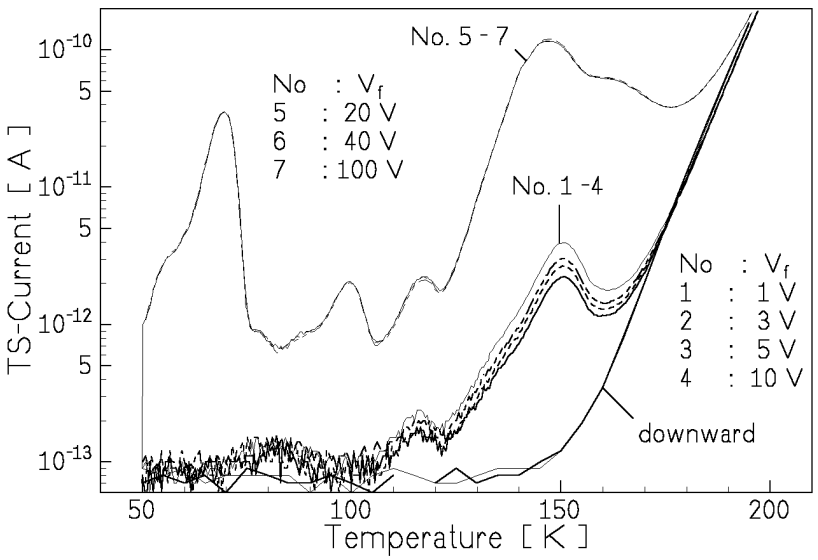


Figure 7.25: TSC-spectra recorded after different filling voltages, $t_f = 23$ s, maximum filling current 2 mA (M20708, $\Phi = 4{\cdot}10^{13}$ cm^{-2}).

The minimum voltage increases with decreasing temperature. At very low temperatures it is impossible to control the current by variation of the voltage. Once the current is flowing the voltage can be reduced to a value below the minimum voltage without any observable current decrease. This phenomenon is called *ignition* [140]. Furthermore it has been found [9] that the minimum voltage needed for injection increases with fluence. E.g. it was not possible to inject current into a sample irradiated with $\Phi \approx 10^{15}$ cm^{-2} even with a forward bias V_f= 500 V !

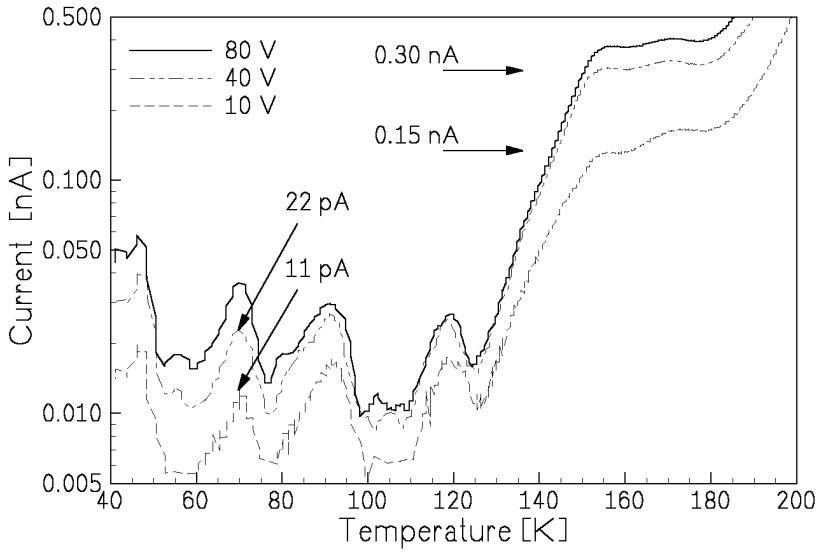


Figure 7.26: TSC-spectra for different bias voltages (10, 40, 80 V), $V_{fd}(RT)$ = 36 V (MUEA06). Note that the peak heights increase about a factor of 2 if the reverse bias voltage changes from 10 to 40 V.

TSC-spectra as measured with 3 different bias voltages are shown in fig. 7.26. The room temperature depletion voltage of the sample was V_{fd}= 36 V. The applied bias voltages were chosen in order to distinguish three cases :

1.) Only half of the detector volume is depleted (10V),
2.) the detector is totally depleted but not over-biased (40V) and
3.) the detector is drastically over-biased (80V).

It follows from eq. 4.59 that the TSC-signal depends on the depleted volume as long as $V < V_{fd}$. Considering also eq. 2.24 the height of the TSC-peaks is expected to increase linearly with $\sqrt{V}$. As can be seen in fig. 7.26 the height of the peaks indeed doubled due to the increase of the applied voltage by a factor of 4. However, also for voltages above V_{fd} the peaks increase, indicating that the depletion voltage is higher at 70 K than at room temperature. This is demonstrated more detailed in fig. 7.27 using two samples with depletion voltages of V_{fd}= 52 V andV_{fd}=12 V respectively .

[9] but not investigated systematically

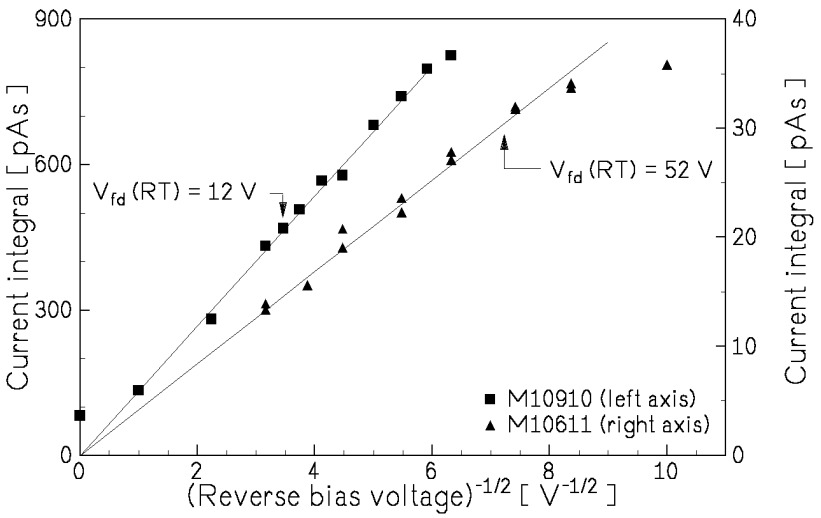


Figure 7.27: Emitted charge (current integral) of peak E3 versus $\sqrt{V}$ for 2 samples : M10611 : $\Phi = 4.39{\cdot}10^{12}$ cm^{-2}, and M10910 : $\Phi = 1.98{\cdot}10^{13}$ cm^{-2}.

The height of peak E3 is plotted versus the square root of the applied reverse bias. It is evident that even at 70 K the width of the SCR depends linearly on $\sqrt{V}$. For the sample with the higher depletion voltage a saturation can be observed at about 64 V. This is a value slightly above the depletion voltage at room temperature. But the situation becomes very clear in case of the sample with the lower depletion voltage. Even at 40 V no saturation occurs indicating that the voltage needed for full depletion at 70 K is much higher than the room temperature value. The temperature dependence of the depletion voltage has been considered already in sec. 6.1.4, but a decrease of V_{fd} with falling temperature had been observed instead of an increase. However, the temperature range was limited to T >80 K and the samples under investigation were exposed to very much lower fluences.

Very strong implication on the TSC-spectrum has also the starting temperature of the measurement, which is also the filling temperature. In fig. 7.28 TSC-measurements started at different temperatures are shown. Because the spectra measured in the temperature range between 34 K and 42 K look rather similar they are not shown, but significant change can be seen in the range from 42 K to 50 K. The peaks E3 andH1 increase with increasing starting temperature, while the peaks E4 and P5 decrease (see inset 1 of fig. 7.28). Above 50 K no further variation of the peak H1 can be observed. The height of the peaks E3, E4,P5 and H1 are plotted versus starting temperature in fig. 7.29. Between 42 K and 50 K the height of peak H1 increases linearly with the starting temperature. The peaks E4 and P5 do not change with filling temperature up to 42 K but become smaller for filling temperatures above 42 K. The peak height of E3 exhibits a more complicate behaviour. It decreases with increasing filling temperature, reaches a maximum at 43 K and then increases again. A possible and simple explanation for the behaviour of the