

FT 1030  
HERA - DLTS

Theory Manual

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**PhysTech GmbH**

**Hall, DLTS, Customized Physical Measurement Equipment**

Am Mühlbachbogen 55d, D-85368 Moosburg

Tel.: +49 (0) 8761 74633 / Fax: +49 (0) 8761 74634

homepage: [www.phystech.de](http://www.phystech.de) eMail: [info@phystech.de](mailto:info@phystech.de)



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## Literature

The following gives a short list of literature. In '<>' there are the main keywords.

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ISBN 0-471-24139-3 <Kinetic, DLTS>
- 5) [www.s-provencher.com](http://www.s-provencher.com) <Laplace>
- 6) D. Pons, J. Appl. Phys. 55, 3644 (1984) <Capture>
- 7) G. Goto, S. Yanagisawa, O. Wada, H. Takanashi, Jap. J. Appl. Phys. 13, 1127 (1974)  
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- 8) C. T. Sah, H. S. Fu, Phys. Stat. Sol. (a) 11, 297 (1972) <MIS>
- 9) K. Yamaski, M. Toshida, T. Sugano, Jap. J. Appl. Phys. 18, 113 (1979) <MIS, Nss>
- 10) P. van Staa, H. Rombach, R. Kassing, J. Appl. Phys. 54, 4014 (1983) <Oxide states>
- 11) D. K. Schroder, IEEE Trans. Electron Devices 19, 1018 (1972) <MIS, Inversion>
- 12) M. Zerbst, Z. Angew. Phys. 22, 30 (1966) <MIS, Zerbst>
- 13) C.T. Sah et al., Appl. Phys. Lett. 20, 193 (1972) <TSCAP, TSC>
- 14) Z-Q. Fang, D.C. Look et al., Material Science Forum, Vol. 527 – 529 (2006) <TSC>
- 15) S. Weiss, Dissertation 1991

**Note:** This manual contains only the important equations. For more details look in the English translation of [15] DIman\_Weiss\_Eng.Pdf. Chapter 2 of the Theory Manual is expanded in comparison to [15].

## Symbol explanation

$a_n$	n-th cosine coefficient
$b_n$	n-th sine coefficient
$c_n$	n-th complex Fourier coefficient (only chapter 3)
$c_n^D$	n-th discrete Fourier coefficient
$c_{n,p}$	Capture rate for electrons resp. holes (not chapter 3)
$c'_{n,p}$	Capture coefficient for electrons resp. holes
$d_{ox}$	Thickness of isolator
$e_{n,p}$	Emission rate for electrons resp. holes
$f(t)$	Continuous function
$f_k$	Discrete sampling values
$g_m$	Sum of space charge region depending generation rates [ $\text{cm}^{-3}\text{s}^{-1}$ ]
$g_v$	Volume generation rate
$g_{SL}$	Lateral surface generation rate
$k$	Boltzmann constant (not chapter 3)
$l_{n,p}$	Diffusion length for electrons resp. holes
$l'_{n,p}$	Effective diffusion length for electrons resp. holes
$m_0$	Mass of electron
$m_{n,p}^*$	Effective mass of electrons resp. holes
$n$	Concentration of electrons in the conductance band [ $\text{cm}^{-3}$ ]
$n_i$	Intrinsic concentration [ $\text{cm}^{-3}$ ]
$n_s$	Concentration of occupied surface states [ $\text{cm}^{-2}$ ]
$n_F$	Concentration of charged states [ $\text{cm}^{-2}$ ]
$n_G$	Concentration of generated minority carriers [ $\text{cm}^{-2}$ ]
$n_I$	Concentration of occupied isolator traps [ $\text{cm}^{-2}$ ]
$n_T$	Concentration of occupied traps [ $\text{cm}^{-3}$ ]
$n_0$	Concentration of free carriers [ $\text{cm}^{-3}$ ]
$p$	Concentration of holes in the valence band
$q$	Elementary charge (see page 18)
$t$	Time (see page 43)
$t_P$	Fill pulse width
$-t_0$	Time between end of charging pulse and 1. sampling value
$v_{th,n,p}$	Thermal velocity of electrons resp. holes
$x$	Position
$A$	Amplitude of a function
$B$	Offset of a function
$C$	Capacitance
$C_{ox}$	Capacitance of isolator
$C_A$	Capacitance after end of pulse ( $=C(0)$ )
$C_P$	Capacitance at fill pulse
$C_R$	Capacitance at reverse bias in equilibrium
$D_{n,p}$	Diffusion constant for electrons resp. holes

$E$	Energy
$E_i$	Intrinsic level
$E_C$	Energy level of the conductance band
$E_F$	Fermi level
$E_T$	Energy level of the trap center
$E_V$	Energy level of the valence band
$E_\sigma$	Activation energy of the capture cross section
$F$	Fourier-Transform of $f$ (only chapter 3)
$F$	Area (not chapter 3)
$G_b$	Sum of space charge region independent generation rates [ $\text{cm}^{-2}\text{s}^{-1}$ ]
$G_D$	Diffusion rate
$G_S$	Generation rate of surface states
$G_U$	Generation rate calculated from voltage transients
$I$	Current
$L$	Distance intersection Fermi level and trap level
$N$	Numbers of sampling values
$N_{ss}$	Interface state density [ $\text{cm}^{-2}\text{eV}^{-1}$ ]
$N_{C,V}$	Effective density of states of electrons resp. holes [ $\text{cm}^{-3}$ ]
$N_I$	Concentration of isolator traps [ $\text{cm}^{-3}\text{eV}^{-1}$ ]
$N_S$	Shallow donor concentration [ $\text{cm}^{-3}$ ]
$N_T$	Trap concentration [ $\text{cm}^{-3}$ ]
$Q$	Charge
$S$	Generation velocity
$S_0$	Generation velocity (no charges at the surface)
$T$	Temperature
$T_W$	Period with
$U$	Voltage
$U_D$	Diffusion voltage
$U_{FB}$	Flat band voltage
$U_{HL}$	Voltage across the semiconductor
$U_P$	Voltage of fill pulse
$U_R$	Reverse bias
$W$	Width of space charge region
$W_A$	Width of space charge region after end of pulse
$W_P$	Width of space charge region at $U_P$
$W_R$	Width of space charge region at $U_R$
$W^*$	Width of generation
$X_{n,p}$	Entropy factor for electrons resp. holes

$\Delta t$	Sampling interval
$\Delta C$	Amplitude of capacitance transient
$\varepsilon$	Dielectric constant of semiconductor
$\varepsilon_{ox}$	Dielectric constant of oxide
$\varepsilon_0$	Dielectric constant of vacuum
$\lambda$	$= W - L$
$\nu$	Frequency
$\sigma_{n,p}$	Capture cross section for electrons resp. holes
$\tau$	Time constant
$\tau_c$	Capture time constant
$\tau_e$	Emission time constant
$\tau_G$	Inversion time constant
$\tau_0$	Life time (Generation life time)
$\hat{\tau}$	$= \log(\tau/T_W)$
$\omega$	Circle frequency
$\omega_0$	Base frequency
$\xi$	Factor for length of generation region
$\mathcal{E}$	Electrical field

## Index explanation

$c$	at the capture process
$e$	at the emission process
$n$	for electrons (not chapter 3)
$p$	for holes
$C$	for the conductance band
$P$	at pulse voltage
$R$	at reverse bias
$T$	for the trap level
$V$	for the valence band

# 1. Schottky diode

## 1.1 C/V and I/V curves

### 1.1.1 C/V curve

The capacitance  $C$  of a Schottky contact with the area  $F$  is:

$$C = \frac{\varepsilon F}{W} \quad (1.1)$$

$W$  is the width of the space charge region,  $\varepsilon = \varepsilon_0 \varepsilon_r$  the dielectric constant. For a homogenous distribution of the shallow concentration  $N_S$  yields the integration of the Poisson equation to:

$$W = \sqrt{\frac{2\varepsilon(U + U_D)}{qN_S}} \quad (1.2)$$

$q$  is the elementary charge,  $U_D$  the diffusion voltage and  $U$  an external voltage. From this follows:

$$C = F \sqrt{\frac{\varepsilon q N_S}{2(U + U_D)}} \quad (1.3)$$

The linear form of this equation is:

$$\frac{1}{C^2} = \frac{2}{\varepsilon F^2 q N_S} (U + U_D) \quad (1.4)$$

By the linear regression you get from the slope  $N_S$  and from the intersection  $U_D$ . You can calculate the barrier height  $\phi_B$  from  $U_D$  by the following equation:

$$q\phi_B = qU_D + (E_C - E_F) \quad (1.5)$$

$$E_C - E_F = kT \ln\left(\frac{N_C}{N_S}\right) \quad (1.6)$$

### 1.1.2 Pulse capacitance $C_P$

The reverse bias capacitance will every time measured. The capacitance during the pulse can be measured or calculated. In the second case you get this value from:

$$C_P = F \sqrt{\frac{\varepsilon q N_S}{2(U_P + U_D)}} \quad (1.7)$$

$$U_D = \frac{F^2 \varepsilon q N_S}{2C_R^2} - U_R \quad (1.8)$$

$N_S$  you get from the C/V-curve. This equation takes into account only a temperature dependence of  $U_D$  but not of  $N_S$ .



### 1.1.3 Shallow doping profiles

The following equations are the 4 possibilities in the software:

$$N_S(x) = \frac{2C^2}{q\varepsilon F^2}(U + U_D) \quad (1.9)$$

$$N_S(x) = \frac{2}{q\varepsilon F^2} \left( \frac{d\frac{1}{C^2}}{dU} \right)^{-1} \quad (1.10)$$

$$N_S(x) = \bar{N}_S(x) + \frac{1}{2}x \frac{d\bar{N}_S(x)}{dx} \quad \text{with } \bar{N}_S \text{ from (1.9)} \quad (1.11)$$

$$N_S(x) = \bar{N}_S(x) + \frac{1}{2}x \frac{d\bar{N}_S(x)}{dx} \quad \text{with } \bar{N}_S \text{ from (1.10)} \quad (1.12)$$

The standard method is 2, but from the physics the method 4 is the best. Another expression for eqn. (1.10) is:

$$N_S(x) = -\frac{C^3}{q\varepsilon F^2} \frac{dU}{dC} \quad (1.13)$$

The depth  $x$  you can calculate by:

$$x = \frac{\varepsilon F}{C} \quad (1.14)$$

### 1.1.4 I/V curve

$$I(U) = I_S \left( \exp \left( \frac{qU}{nkT} \right) - 1 \right) \quad (1.15)$$

$n$  is the ideality-factor or  $n$ -factor, in the software called  $n$ -fac. The saturation current is:

$$I_S = FA^*T^2 \exp \left( \frac{-q\phi_B}{kT} \right) \quad (1.16)$$

$A^*$  is the Richardson constant corrected by the effective mass:

$$A^* = A \frac{m_n^*}{m_e} \quad (1.17)$$

$m_n^*$  is the effective mass for electrons,  $m_e$  is the electron mass. If  $qU \gg nkT$ , then follows:

$$I(U) = I_S \exp \left( \frac{qU}{nkT} \right) \quad (1.18)$$

The linear form of this equation is:

$$\ln(I) = \ln(I_S) + \frac{q}{nkT} U \quad (1.19)$$

By the linear regression you get from the slope  $n$  and from the intersection  $I_S$ . With eqn. (1.16) you can calculate the barrier height  $\phi_B$ :

$$q\phi_B = kT \ln \left( \frac{F A^* T^2}{I_S} \right) \quad (1.20)$$

From  $\phi_B$  you can calculate  $U_D$  by eqn. (1.5).

### 1.1.5 Richardson plot

$$J_S = \frac{I_S}{F} \quad (1.21)$$

To get  $\phi_B$  from the eqns. above you must know the Richardson constant. You can calculate  $\phi_B$  without  $A^*$  by the Richardson plot:

$$\ln \left( \frac{J_S}{T^2} \right) = \ln(A^*) - \frac{q\phi_B}{k} \frac{1}{T} \quad (1.22)$$

By the linear regression you get from the slope  $\phi_B$  and from the intersection  $A^*$ . This plot you can make in the C/V–I/V–module, menu 2.1.1. For this you must measure the I/V–curves at different temperatures and make the evaluation in menu 2.6.5, so that you get  $J_S$  resp.  $I_S$  for different temperatures.

In the tempscan evaluation module, menu 6.4.5.5.4, there is a plot similar to the Richardson plot:

$$\ln \left( \frac{J_R}{T^2} \right) = \ln(A^*) - \frac{q\phi_B}{k} \frac{1}{T} \quad (1.23)$$

Note that in this plot you have the reverse bias current and not the saturation current as necessary for the true Richardson plot. So your data obtained by this evaluation are not the correct values although they were called as in the true Richardson plot!

## 1.2 DLTS-transients

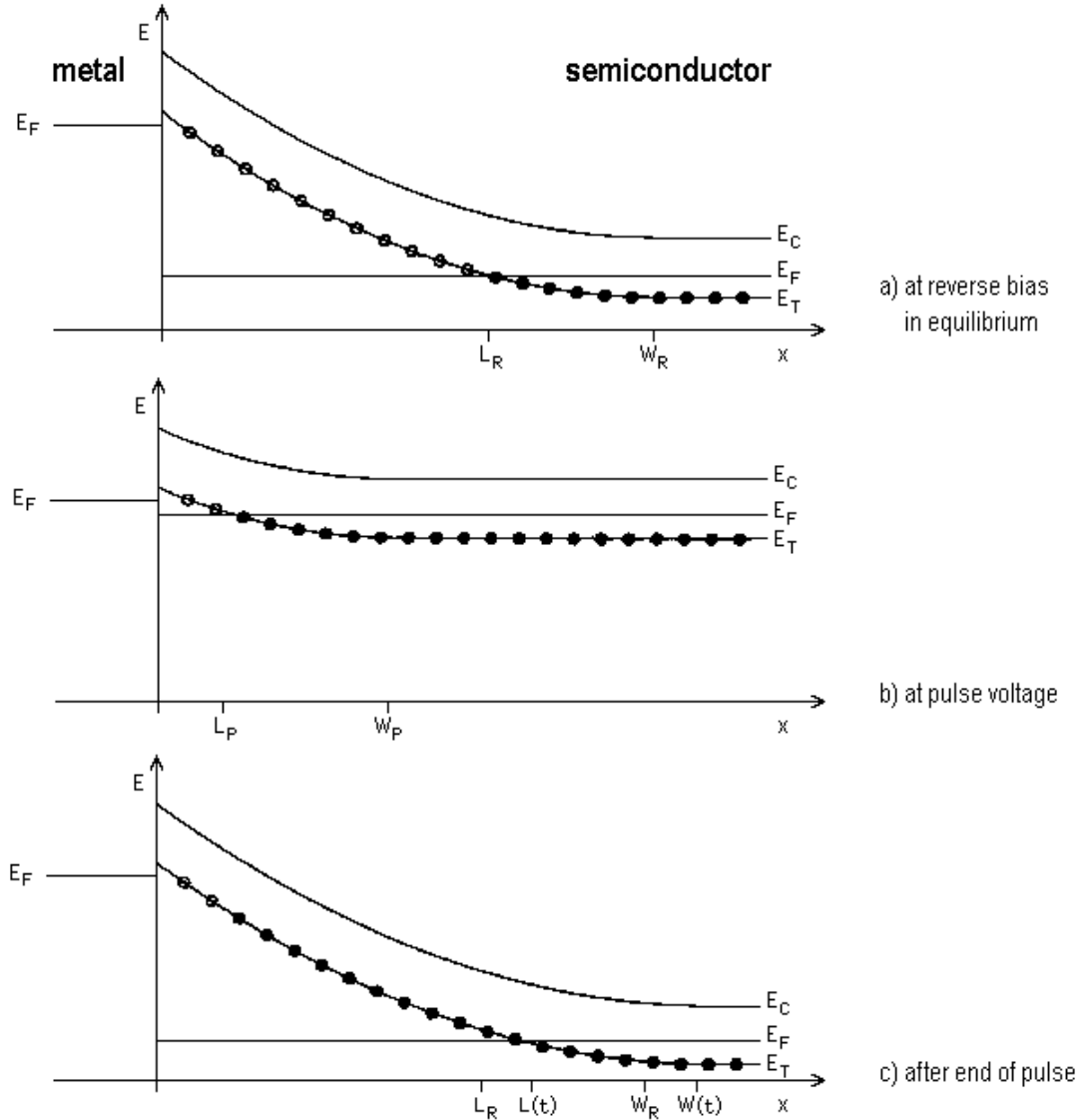


Abb. 1.1: Band diagram of a Schottky-diode

### 1.2.1 Transients

For  $N_T \ll N_S$  is the following equation valid for the capacitance DLTS method (C-DLTS):

$$C(t) = C_R - \Delta C \exp(-t/\tau_e) \quad (1.24)$$

$$\Delta C = C_R \frac{N_T}{2N_S} \frac{L_R^2 - L_P^2}{W_R^2} \quad (1.25)$$

$$L_{R,P} = W_{R,P} - \lambda \quad (1.26)$$

The index  $R$  resp.  $P$  means the value at reverse bias  $U_R$  resp. at pulse voltage  $U_P$ .  $\Delta C$  is the transient amplitude.

**Note:**  $L_R$  and  $L_P$  will be called  $x_R$  and  $x_P$  in the software and in the Software Manual.

The equation above contains the lambda shift. The distance  $\lambda = W - L$  is voltage independent at a homogenous distribution:

$$\lambda = \sqrt{\frac{2\varepsilon(E_F - E_T)_0}{q^2 n_0}} \quad (1.27)$$

$(E_F - E_T)_0$  is the distance between trap- and Fermi level in the undisturbed semiconductor. The program takes here your energy value from the Arrhenius plot or from the sample parameters.

For voltage transients (U-DLTS) is valid:

$$U(t) = U_R - \Delta U \exp(-t/\tau_e) \quad (1.28)$$

$$\Delta U = \frac{q\varepsilon F^2 N_T}{2C_R^2} \frac{L_R^2 - L_P^2}{W_R^2} \quad (1.29)$$

For the reverse bias is valid:

$$U_R = \frac{q}{2\varepsilon}(N_S - N_T)W_R^2 + \frac{q}{2\varepsilon}N_T L_R^2 - U_D \quad (1.30)$$

If you select the reverse bias and the pulse voltage in such kind that  $L_P \approx 0$  and  $\lambda \ll W_R$ , so are the amplitudes approximately:

$$\Delta C \approx C_R \frac{N_T}{2N_S} \quad (1.31)$$

$$\Delta U \approx \frac{q\varepsilon F^2}{2C_R^2} N_T \quad (1.32)$$

For the current transient you get in this case:

$$I(t) - I_R = \frac{1}{2}qFW_R N_T \frac{1}{\tau_e} \exp(-t/\tau_e) \quad (1.33)$$

In the software the normal plots for transients are  $C_R - C(t)$ ,  $U_R + U(t)$  for n-type,  $U_R - U(t)$  for p-type and  $I(t) - I_R$ .

### 1.2.2 Trap concentration

From eqn. (1.25) and (1.29) you get the exact trap concentration:

$$N_T = 2N_S \frac{\Delta C}{C_R} \frac{W_R^2}{L_R^2 - L_P^2} \quad \text{for C-DLTS} \quad (1.34)$$

$$N_T = \Delta U \frac{2C_R^2}{q\varepsilon F^2} \frac{W_R^2}{L_R^2 - L_P^2} \quad \text{for U-DLTS} \quad (1.35)$$

In the program these values will be called  $N_{Ts}$  or trap concentration calculated with the space charge region. The plots of doping profiles are called  $N_T(x)$ , but are calculated by the exact equations.

For the approximation after eqn. (1.31) and (1.32) you get:

$$N_T = 2N_S \frac{\Delta C}{C_R} \quad \text{for C-DLTS} \quad (1.36)$$

$$N_T = \Delta U \frac{2C_R^2}{q\varepsilon F^2} \quad \text{for U-DLTS} \quad (1.37)$$

In the program these values will be called  $N_T$ , trap concentration or approximated trap concentration. This is the standard calculation of  $N_T$  in the literature or with standard DLTS-systems.

### 1.2.3 Analysis of $N_T$ -doping profiles

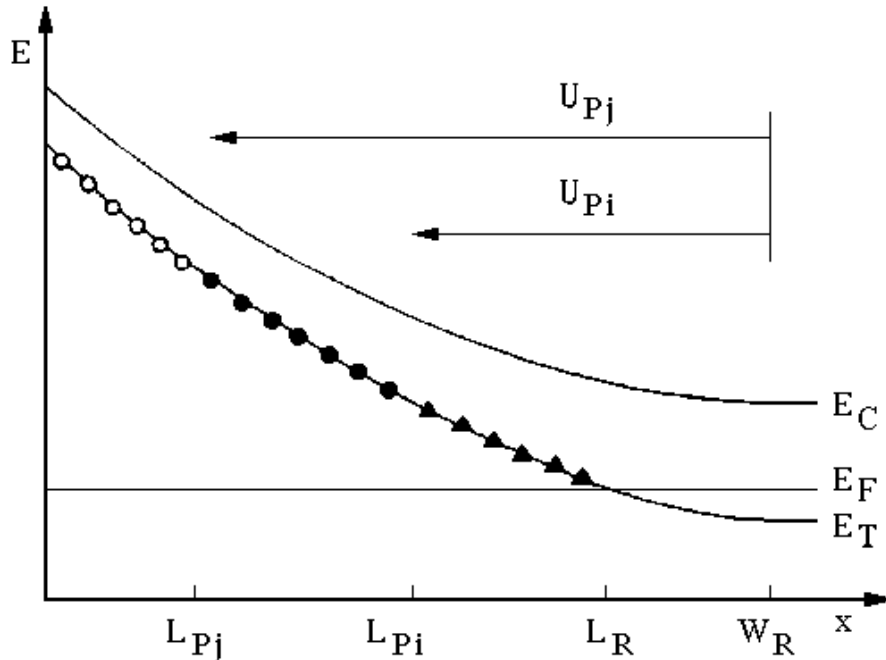


Abb. 1.2: Doping profile technique at the band diagram of a n-Schottky-diode

**a) Measurement at constant reverse bias, variation of pulse voltage, building difference of transients**

At the U-DLTS-method you get from the integration of the Poisson equation for the voltage transient  $U_i(t)$  with the pulse voltage  $U_{Pi}$ :

$$U_i(t) - U_R = -\frac{q}{\varepsilon} \int_{L_{Pi}}^{L_R} x N_T(x) \exp(-t/\tau_e) dx \quad (1.38)$$

$$U_R = \frac{q}{\varepsilon} \left( \frac{N_S W_R^2}{2} - \int_{L_R}^{W_R} x N_T(x) dx \right) - U_D \quad (1.39)$$

For the difference of two transients with pulse voltages  $U_{Pj}$  and  $U_{Pi}$  are only the traps between  $L_{Pj}$  and  $L_{Pi}$  relevant for the signal:

$$U_{ji}(t) := U_j(t) - U_i(t) = -\frac{q}{\varepsilon} \int_{L_{Pj}}^{L_{Pi}} x N_T(x) \exp(-t/\tau_e) dx \quad (1.40)$$

With the definition of a medium trap concentration you get the following approximation:

$$U_{ji}(t) \approx -\frac{q}{2\varepsilon} (L_{Pi}^2 - L_{Pj}^2) \bar{N}_T(x_{ji}) \exp(-t/\tau_e) \quad (1.41)$$

$$x_{ji} := \frac{L_{Pj} + L_{Pi}}{2} \quad (1.42)$$

The amplitude of charge is then:

$$\Delta U_{ji} = -\frac{q}{2\varepsilon} (L_{Pi}^2 - L_{Pj}^2) \bar{N}_T(x_{ji}) \quad (1.43)$$

You can calculate the medium trap concentration following:

$$\bar{N}_T(x_{ji}) = -\frac{2\varepsilon}{q} \frac{\Delta U_{ji}}{(L_{Pi}^2 - L_{Pj}^2)} \quad (1.44)$$

For the C-DLTS-method you get approximately:

$$\bar{N}_T(x_{ji}) = \frac{2N_S \varepsilon^2 F^2}{C_R^3} \frac{\Delta C_{ji}}{(L_{Pi}^2 - L_{Pj}^2)} \quad (1.45)$$

$\Delta C_{ji}$  is the amplitude difference of the two capacitance transients.

For this technique you must make a isothermal measurement with variation of  $U_P$ , for more details look in the Software Manual S3.3.6.2.1 profile mode 1. In the evaluation menu you can get also a  $N_T(x)$ -plot without building of differences. This yields normally to a big error because you have in this case a very brought  $x$ -range.

**b) Measurement at constant pulse voltage, variation of reverse bias, building difference of transients**

This technique is analog to technique (a). The disadvantage of this method is that the relevant charges are at the intersection Fermi/trap level. For this technique you must make a measurement and evaluation as described in chapter S3.3.6.2.1 of the Software Manual as profile mode 2.

**c) Measurement at variation of reverse bias and pulse voltage**

A profile analysis is also possible without building of differences:

$$\bar{N}_T(x_i) = 2N_S \frac{\Delta C_i}{C_{Ri}} \frac{W_{Ri}^2}{L_{Ri}^2 - L_{Pi}^2} \quad \text{for C-DLTS} \quad (1.46)$$

$$\bar{N}_T(x_i) = \Delta U \frac{2C_{Ri}^2}{q\epsilon F^2} \frac{W_{Ri}^2}{L_{Ri}^2 - L_{Pi}^2} \quad \text{for U-DLTS} \quad (1.47)$$

This technique will be described as profile mode 3 in S3.3.6.2.1.

## 1.3 Kinetic

### 1.3.1 Emission

For the with electrons filled traps  $n_{Te}$  is valid during the emission process:

$$n_{Te}(t) = N_T \exp\left(-\frac{t}{\tau_e}\right) \quad (1.48)$$

$$\text{with } \tau_e = \left(\sigma_n v_{th,n} X_n N_C \exp\left(-\frac{E_C - E_T}{kT}\right)\right)^{-1} \quad (1.49)$$

$N_T$  is the trap concentration,  $X_n$  the entropy factor,  $\sigma_n$  the capture cross section for electrons and  $\tau_e$  the emission time constant. In the software  $\tau_e$  is called time constant, emission time constant, tau or tau.e.

The emission rate is the reziproke value of the emission time constant:

$$e_n = 1/\tau_e \quad (1.50)$$

You get the thermal velocity  $v_{th,n}$  and the state density  $N_C$  from:

$$v_{th,n} = \sqrt{\frac{3kT}{m_n^*}} \quad (1.51)$$

$$N_C = 2 \left(\frac{2\pi m_n^* kT}{h^2}\right)^{\frac{3}{2}} \quad (1.52)$$

$m_n^*$  is the effective mass for electrons. Transforming of eqn. (1.49) yields to the Arrhenius-equation:

$$\ln(\tau_e v_{th,n} N_C) = \frac{E_C - E_T}{k} \frac{1}{T} - \ln(X_n \sigma_n) \quad (1.53)$$

By the linear regression you get from the slope  $E_C - E_T$  and from the intersection the product  $\sigma_n X_n$ . This equation contains the  $T^2$ -correction.

In the program  $\sigma_n X_n$  will called as capture cross section, sigma or sig. In the library part of the software the name is Sigma Arrhenius, Sigma-Arrh or sig-Arrh.

One of the text possiblity for the y-axis of the Arrhenius plot is  $\ln(\text{tau} * T^2 * C)$ .  $C$  means here all constants of  $v_{th,n} N_C$  except of the temperature. So  $C$  is  $\frac{v_{th,n} N_C}{T^2}$  for electrons and  $\frac{v_{th,p} N_V}{T^2}$  for holes. tau of the y-axis-text is the emission time constant  $\tau_e$ .



### 1.3.2 Capture

For the with electrons filled traps  $n_{Tc}$  is valid during the capture process:

$$n_{Tc}(t) = N_T \left( 1 - \exp \left( -\frac{t}{\tau_c} \right) \right) \quad (1.54)$$

$$\text{with } \tau_c = \frac{1}{\sigma_n v_{th,n} n_0} \quad (1.55)$$

$\tau_c$  is the capture time constant. In the software  $\tau_c$  is called capture time constant or tau.c. Following is valid:

$$c_n = \sigma_n v_{th,n} n_0 = 1/\tau_c \quad \text{capture rate} \quad (1.56)$$

$$c'_n = \sigma_n v_{th,n} \quad \text{capture coefficient} \quad (1.57)$$

$$n_0 = N_C \exp \left( -\frac{E_C - E_F}{kT} \right) \quad (1.58)$$

The program takes  $N_S$  as  $n_0$ .

In the program  $\sigma_n$  will called as capture\_c cross section, sigma\_c or sigmaC. In the library part of the software the name is Sigma Capture or sig-Capt.

## 2. MIS

### 2.1 Kinetic of surface states

The concentration of occupied surface states during the **capture** is:

$$n_{sc}(t) = \int_{E_{FR}}^{E_{FP}} N_{ss}(E) (1 - \exp(-t/\tau_c(E))) dE \quad (2.1)$$

For the **emission** process is valid:

$$n_{se}(t) = \int_{E_{FR}}^{E_{FP}} N_{ss}(E) \exp(-t/\tau_e(E)) dE \quad (2.2)$$

$$\tau_e(E) = \frac{1}{\sigma_n(E) v_{th,n} X_n N_C} \exp\left(\frac{E_C - E}{kT}\right) \quad (2.3)$$

$n_s(t)$  is the total number at time  $t$  in the energy interval  $(E_{FR}, E_{FP})$  occupied surface states per area. The dimension is  $\text{cm}^{-2}$ .  $N_{ss}$  is the density (concentration) of surface states in  $\text{cm}^{-2} \text{eV}^{-1}$ .

#### 2.1.1 Energy dependent capture cross section

Eq. 2.1 and 2.2 can be simplified, if for the cross section in the energy interval of interest the following energy dependence holds:

$$\sigma_n(E) = \sigma_{n0} \exp\left(-\gamma \frac{E_C - E}{kT}\right) \quad (2.4)$$

$$\gamma = \frac{kT}{E_{\sigma 0}} \quad (2.5)$$

In this definition  $E_{\sigma 0}$  has the opposite sign as in [15].

If one replaces

$$E_{0c}(t) = \frac{kT}{\gamma} \ln(t/\tau_{sc}) \quad (2.6)$$

$$\tau_{sc} = \frac{1}{\sigma_{n0} v_{th,n} n_0} \quad (2.7)$$

we get for the **capture** process

$$n_{sc}(t) = \int_{E_{FR}}^{E_{FP}} N_{ss}(E) \left(1 - \exp\left(-\exp\left(\gamma \frac{E_{0c} - (E_C - E)}{kT}\right)\right)\right) dE \quad (2.8)$$

For  $\gamma > 0$  we get following approximation:

$$n_{sc}(t) = N_{ss}(E_{0c}(t) - (E_C - E_{FP})) \quad (2.9)$$

$$= N_{ss} \left( \frac{kT}{\gamma} \ln(t/\tau_{sc}) - (E_C - E_{FP}) \right) \quad (2.10)$$

For  $\gamma < 0$  we get following approximation:

$$n_{sc}(t) = N_{ss}(E_C - E_{FR} - E_{0c}(t)) \quad (2.11)$$

$$= N_{ss} \left( E_C - E_{FR} - \frac{kT}{\gamma} \ln(t/\tau_{sc}) \right) \quad (2.12)$$

The last equationa are only valid for  $E_C - E_{FP} < E_{0c}(t) < E_C - E_{FR}$ .  
If one replaces

$$E_{0e}(t) = \frac{kT}{1 + \gamma} \ln(t/\tau_{se}) \quad (2.13)$$

$$\tau_{se} = \frac{1}{\sigma_{n0} v_{th,n} X_n N_C} \quad (2.14)$$

$$(2.15)$$

we get for the **emission** process

$$n_{se}(t) = \int_{E_{FR}}^{E_{FP}} N_{ss}(E) \exp(-\exp((1 + \gamma) \frac{E_{0e} - (E_C - E)}{kT})) dE \quad (2.16)$$

For  $1 + \gamma > 0$  we get following approximation:

$$n_{se}(t) = N_{ss}(E_C - E_{FR} - E_{0e}(t)) \quad (2.17)$$

$$= N_{ss} \left( E_C - E_{FR} - \frac{kT}{1 + \gamma} \ln(t/\tau_{se}) \right) \quad (2.18)$$

For  $1 + \gamma < 0$  we get following approximation:

$$n_{sc}(t) = N_{ss}(E_{0e}(t) - (E_C - E_{FP})) \quad (2.19)$$

$$= N_{ss} \left( \frac{kT}{1 + \gamma} \ln(t/\tau_{se}) - (E_C - E_{FP}) \right) \quad (2.20)$$

The last equations are only valid for  $E_C - E_{FP} < E_{0e}(t) < E_C - E_{FR}$ .

### 2.1.2 Energy independent capture cross section

$$n_{sc}(t) = (1 - \exp(-t/\tau_c)) \int_{E_{FR}}^{E_{FP}} N_{ss}(E) dE \quad (2.21)$$

$$n_{se}(t) = \int_{E_{FR}}^{E_C - E_0(t)} N_{ss}(E) dE \quad (2.22)$$

with substitutions

$$\tau_{sc} = \frac{1}{\sigma v_{th,n} n_0} \quad (2.23)$$

$$\tau_{se} = \frac{1}{\sigma v_{th,n} X_n N_C} \quad (2.24)$$

$$E_0(t) = kT \ln(t/\tau_{se}) \quad (2.25)$$

### 2.1.3 Nss approximation

If Nss depends only weakly on the energy so following approximation of the last equations is valid:

$$n_{sc}(t) = N_{ss}(E_{FP} - E_{FR}) (1 - \exp(-t/\tau_c)) \quad (2.26)$$

$$n_{se}(t) = N_{ss}(E_C - kT \ln(t/\tau_{se}) - E_{FR}) \quad (2.27)$$

$$n_{se}(t, t_P) = N_{ss}(1 - \exp(-t_P/\tau_c)) (E_C - kT \ln(t/\tau_{se}) - E_{FR}) \quad (2.28)$$

The last equation for the emission process takes into account a not complete filling of the capture process. Eq. 2.27 will be used for the DLTS standard Nss evaluation of an emission transient.

### 2.1.4 Surface traps

A special case are surface states with a discrete discrete energy (not continuous), we call it surface traps.

$$n_{sc}(t) = N_{sT} (1 - \exp(-t/\tau_c)) \quad (2.29)$$

$$n_{se}(t) = N_{sT} \exp(-t/\tau_e) \quad (2.30)$$

$$n_{se}(t, t_P) = N_{sT} (1 - \exp(-t_P/\tau_c)) \exp(-t/\tau_e) \quad (2.31)$$

$N_{sT}$  is the concentration of traps on the surface, its dimension is  $cm^{-2}$ .

## 2.2 Kinetic of oxide (isolator) states

The capture cross section of oxide (isolator) states can depend on the energy and on the distance:

$$\sigma_n(E, x) = \sigma_n(E) \exp(-x/d_0) \quad (2.32)$$

$x$  is the positive distance between semiconductor-isolator interface and the oxide states.  $d_0$  is the tunnel constant. For the capture and emission process is valid:

$$n_{Ic}(t) = \int_{E_{FR}}^{E_{FP}} \int_0^{d_{ox}} N_I(E, x) (1 - \exp(-t/\tau_c(E, x))) dx dE \quad (2.33)$$

$$n_{Ie}(t) = \int_{E_{FR}}^{E_{FP}} \int_0^{d_{ox}} N_I(E, x) \exp(-t/\tau_e(E, x)) dx dE \quad (2.34)$$

$n_I(t)$  is the total number at time  $t$  occupied oxide states per area in  $\text{cm}^{-2}$ ,  $N_I$  is the concentration of oxide states in  $\text{cm}^{-3} \text{eV}^{-1}$  and  $d_{ox}$  is the thickness of the oxide.

### 2.2.1 Standard approximation

We can assume following approximations if the capture cross section don't depend on the energy:

$$n_{Ic}(t) = N_I d_0 (E_{FP} - E_{FR}) \ln(t/\tau_{sc}) \quad (2.35)$$

$$n_{Ie}(t, t_P) = N_I d_0 \ln(t_P/\tau_{sc}) (E_{FR} - kT \ln(t/\tau_{se}) + kT \ln(t_P/\tau_{sc})) \quad (2.36)$$

We can interpret  $d_x = d_0 \ln(t_P/\tau_{sc})$  as a x-limit which divides the occupied states from the empty states.

The emission process is much more complex as the last equation describes. So it is only valid under some conditions. It will be discussed more accurate in the next chapter. The standard approximation takes only range (c) into account, see next chapter and [10]. The DLTS program uses this approximation for the standard evaluation of oxide states.

The medium energy now is not  $E_0$  but:

$$E_{mid} = E_0(t) - kT \ln(t_P/\tau_{sc})/2 \quad (2.37)$$

We denote the last part of the equation above as oxide correction.

### 2.2.2 Range emission

In [10] an enhanced model for the emission process of oxide states will be introduced. It divides the emission in ranges (a) until (f). If one replaces

$$E_0(t) = kT \ln(t/\tau_{se}) \quad (2.38)$$

$$E_P(t) = E_0(t) - kT d_x/d_0 \quad (2.39)$$

$$d_x = d_0 \ln(t_P/\tau_{sc}) \quad (2.40)$$

we get following approximations for the emission process:

$$\text{a) } n_{Ie}(t) = N_I d_x (E_{FP} - E_{FR}) \quad (2.41)$$

$$\text{b) } n_{Ie}(t) = N_I d_x \left( E_{FP} - E_{FR} - \frac{(E_0 - E_{FP}^*)^2}{2(E_0 - E_P)} \right)$$

$$\text{c) } n_{Ie}(t) = N_I d_x (E_{FR}^* - E_0 + (E_0 - E_P)/2)$$

$$\text{d) } n_{Ie}(t) = N_I d_x \left( \frac{E_{FP} - E_{FR}}{E_0 - E_P} ((E_{FR}^* + E_{FP}^*)/2 - E_P) \right)$$

$$\text{e) } n_{Ie}(t) = N_I d_x \frac{(E_{FR}^* - E_P)^2}{2(E_0 - E_P)}$$

$$\text{f) } n_{Ie}(t) = 0$$

$E_{FR,P}^*$  means here  $E_C - E_{FR,P}$ . The software uses these equations for the analytical transient simulation of oxide states. When selected 'integration', then a numerical integration will be done by eq. 2.34.

### 2.2.3 Oxide traps

A special case are oxide states with a discrete discrete energy (not continuous), we call it oxide traps.

$$n_{Ic}(t) = \int_0^{d_{ox}} N_{IT}(x) (1 - \exp(-t/\tau_c(x))) dx \quad (2.42)$$

$$n_{Ie}(t) = \int_0^{d_{ox}} N_{IT}(x) \exp(-t/\tau_e(x)) dx \quad (2.43)$$

$N_{IT}$  is the concentration of traps in the isolator, its dimension is  $cm^{-3}$ .

We can assume following approximations:

$$n_{Ic}(t) = N_{IT} d_0 \ln(t/\tau_{sc}) \quad (2.44)$$

$$n_{Ie}(t, t_P) = N_{IT} d_0 \ln(t_P/\tau_{sc}) \ln(t/\tau_{se}) \quad (2.45)$$

As at oxide states the approximation for the emission is only valid under some conditions. A more accurate model uses also various emission ranges.

## 2.3 Transients and coefficients

$n_{sc}$ ,  $n_{se}$ ,  $n_{Ie}$  and so on of the previous chapters can be treated as 'area states', so we call a general now  $n_F$ . For the capacitance transient (C-DLTS) and voltage transient (U-DLTS) we get:

$$C_R - C(t) = f_C(n_{FR} - n_F(t)) \quad (2.46)$$

$$f_C = \frac{C_R^3}{\varepsilon F N_S C_{ox}} \quad (2.47)$$

$$U(t) - U_R = f_U(n_F(t) - n_{FR}) \quad (2.48)$$

$$f_U = \frac{qF}{C_{ox}} \quad (2.49)$$

With this definitions the transient change is proportional to  $f_X n_F(t)$ , where  $f_X$  is  $f_C$  or  $f_U$ .

**Note:** In the following  $b_n$  denotes the nth sine coefficient, a corresponding consideration is valid for the cosine coefficients.

The transients of the most processes in the last chapter follow a logarithmic time law. No analytical solution exist for the the Fourier coefficients of a logarithmic time law. Therefor we calculate it numerically. The logarithmic time law was only an approximation for a double-exponential one, it means  $\exp(-t/\tau)$  where  $\tau$  depends exponential on the energy or depth. This double-exponential time law will be used for the numerical calculation of the Fourier coefficients. We simulate the analytical coefficients of a exponential time law (eq. 3.11) under variation of tau. We search the expected (mean) value of the  $b_n$  versus tau curve by integration. Generally the centroid (expected value) of a  $\hat{b}_n(z)$ -distribution is given by the following equation:

$$\langle z(\hat{b}_n(z)) \rangle = \frac{\int_{z_R}^{z_P} \hat{b}_n(z) z dz}{\int_{z_R}^{z_P} \hat{b}_n(z) dz} \quad (2.50)$$

For more details look in chapter 3.3.5 of [15].

As a result we get the expected value  $\langle \tau \rangle$ , called in the following  $\tilde{\tau}$ , and  $\tilde{b}_n$  which is the  $b_n$  value in  $\langle \tau \rangle$  of the  $b_n$  versus tau curve. Because the amplitude was 1 at the simulation,  $\tilde{b}_n$  is a normalization factor. In the Software Manual it will be called  $b'_n$ ,  $\langle \tau \rangle$  will there be called  $\tau'$ .

For the Fourier  $b_n$  of the logarithmic transients is valid:

$$b_n = N_F f_X \tilde{b}_n \quad (2.51)$$

The equation includes the general value  $N_F$ . It is the concentration of charged interface/oxide states per area, its dimension is  $cm^{-2}$ . In the case of the emission of interface states is  $N_F = kTN_{ss}$ , in the case of the emission of oxide states is  $N_F = kTN_I d_x$ .  $N_F$  don't include a temperature normalization, so its behavior is very similar to the amplitude. On the other hand we can use  $N_F$  as a general evaluation value which don't depend on the physical model for the capture or emission process, except the assumption of a logarithmic time law:

$$N_F = \frac{b_n}{\tilde{b}_n f_X} \quad (2.52)$$

### 2.3.1 Surface states

The equations of the previous chapters give for the **emission** process of surface states:

$$b_n = N_{ss} kT f_X \tilde{b}_n \quad (2.53)$$

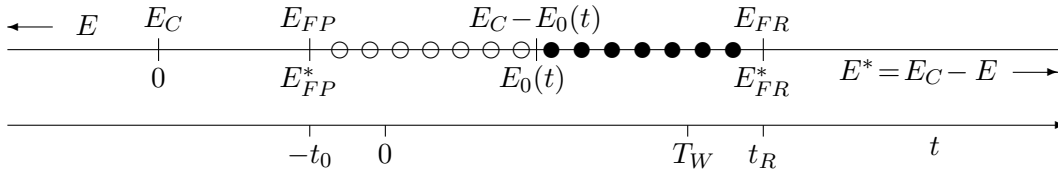
This yields on the other hand to  $N_{ss}$ :

$$N_{ss} = \frac{b_n}{\tilde{b}_n} \frac{1}{f_X kT} \quad (2.54)$$

This is the standard evaluation for surface states.

$\tilde{b}_n$  comes from the normalization (centroid) over the logarithmic time law, the expected tau value is  $\tilde{\tau}$ . The medium energy is:

$$E_C - E = kT \ln(\tilde{\tau}/\tau_{se}) \quad (2.55)$$



The picture above shows the behaviour of the emission process with energy and time. While the energy  $E$  increases to the conductance band,  $E^*$  was defined in such a way that it increases towards the valence band; and the zero point of  $E^*$  is located at  $E_C(x=0)$ .



### 2.3.2 Oxide states

We get for the for the capture **process** of oxide states:

$$b_n = N_I d_0 \ln(t_P/\tau_{sc})(E_{FP} - E_{FR})f_X \tilde{b}_n \quad (2.56)$$

We get for the for the standard approximation of the **emission** from oxide states:

$$b_n = N_I d_0 \ln(t_P/\tau_{sc})kT \tilde{b}_n f_X \quad (2.57)$$

$$= N_I d_x kT f_X \tilde{b}_n \quad (2.58)$$

$$d_x := d_0 \ln(t_P/\tau_{sc}) \quad (2.59)$$

From this equation you can calculate  $N_I d_0$ . This is the standard evaluation for oxide states. If you make in the software a standard evaluation for surface states you get a Nss-value as result. In the case of oxide states you can interpret this value as  $N_I d_x$ , its definition is for the standard emission:

$$N_I d_x = \frac{b_n}{\tilde{b}_n} \frac{1}{kT f_X} \quad (2.60)$$

Note that  $d_x$  depends at the standard emission also on the pulse width.

The medium energy is:

$$E_{mid} = kT \ln(\tilde{\tau}/\tau_{se}) - kT \ln(t_P/\tau_{sc})/2 \quad (2.61)$$

A special case is the measurement at 2 different pulse widths. The difference of both measurements yields to a simple equation:

$$b_n(t_{P1}) - b_n(t_{P2}) = N_I d_0 f_X \tilde{b}_n kT \ln(t_{P1}/t_{P2}) \quad (2.62)$$

The advantage of this equation is that the capture cross section is not necessary for the calculation of  $N_I d_0$ .

### 2.3.3 Range emission

In [10] an enhanced model for the emission process of oxide states will be introduced. It devides the emission in ranges (a) until (f). We have adapt this model for the Fourier coefficients and get following approximations for the emission process:

$$\text{b) } b_n = N_I d_0 f_X \tilde{b}_n (-(E_C - E_{FP}) + kT \ln(\tilde{\tau}/\tau_{se})) \quad (2.63)$$

$$\text{c) } b_n = N_I d_0 f_X \tilde{b}_n kT \ln(t_P/\tau_{sc})$$

$$\text{d) } b_n = N_I d_0 f_X \tilde{b}_n (E_{FR} - E_{FP})$$

$$\text{e) } b_n = N_I d_0 f_X \tilde{b}_n (kT \ln(t_P/\tau_{sc}) + E_C - E_{FR} - kT \ln(\tilde{\tau}/\tau_{se}))$$

Range (a) and (f) yields to  $b_n = 0$ , eq. 2.63c is identical with eq. 2.57.

The difference of 2 measurements with different pulse widths yields in range (b) and (e) to the same simple equation as given in eq. 2.62.

Three important different types of coefficient curves exist:

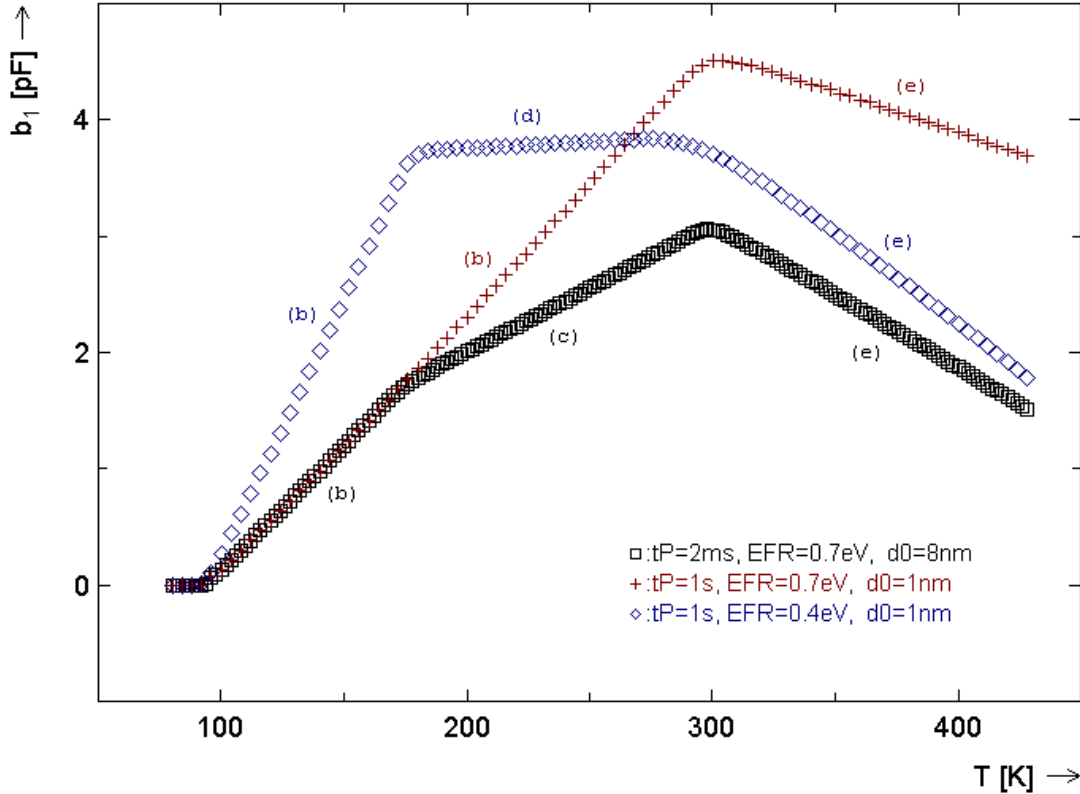
- Tempscan:  $b_n$  versus temperature  $T$ ;  $t_P$  and  $T_W$ , which yields to  $\tilde{\tau}$ , are fix.
- Periodscan:  $b_n$  versus  $\tilde{\tau}$ , coming from  $T_W$ ;  $t_P$  and  $T$  are fix.
- Capture:  $b_n$  versus  $t_P$ ;  $T$  and  $T_W$  are fix.

The voltages  $U_R$  and  $U_P$  define the Fermi level  $E_{FR}$  and  $E_{FP}$ . Depending on the variation parameter and the range we get different curves which enable various evaluations. The standard evaluation is the plot  $N_I d_0$  versus the medium energy.

We call the ranges by its behaviour for the tempscan or period scan:

- (b) increment
- (c) proportional (tempscan) resp. fix (period scan)
- (d) plateau
- (e) decrement

The following shows a tempscan with different curves. Not all ranges exist always. The behaviours dependson  $d_0$ ,  $E_{FR}$  and  $E_{FP}$ .



### 2.3.4 Range regression

We can transform the equations above in such way that we get a linear curve  $b_n$  versus  $T$ ,  $\tau(T_W)$  or  $t_P$  when  $N_I d_0$  is energy independent. In the following the y-axis is  $b_n$ , the slope of the linear curve will be denoted as  $M$ , the intersection with the y-axis as  $B$ . The temperature dependence of the thermal velocity will be neglected at the tempscan curves. The equations list the results by the linear regression in the various emission ranges:

**Capture regression:** x-axis =  $\ln(t_P)$

$$N_I d_0 = \frac{M}{\tilde{b}_n f_X k T}, \quad \tau_{sc} = \exp(-B/M), \quad \text{Range (c)} \quad (2.64)$$

$$N_I d_0 = \frac{M}{\tilde{b}_n f_X k T}, \quad E_C - E_{FR} = kT \left( \frac{B}{M} + \ln\left(\frac{\tilde{\tau} \tau_{sc}}{\tau_{se}}\right) \right), \quad \text{Range (e)} \quad (2.65)$$

$$N_I d_0 = \frac{M}{\tilde{b}_n f_X (E_{FR} - E_{FP})}, \quad \tau_{sc} = \exp(-B/M), \quad \text{Capture} \quad (2.66)$$

**Temperature regression:** x-axis =  $T$

$$N_I d_0 = \frac{M}{\tilde{b}_n f_X k \ln(\tilde{\tau}/\tau_{se})}, \quad E_C - E_{FP} = -\frac{B}{M} k \ln\left(\frac{\tilde{\tau}}{\tau_{se}}\right), \quad \text{Range (b)} \quad (2.67)$$

$$N_I d_0 = \frac{M}{\tilde{b}_n f_X k \ln(t_P/\tau_{sc})}, \quad \text{Range (c)} \quad (2.68)$$

$$E_{FR} - E_{FP} = \frac{B}{N_I d_0 \tilde{b}_n f_X}, \quad \text{Range (d)} \quad (2.69)$$

$$N_I d_0 = \frac{M}{\tilde{b}_n f_X k} \left( \ln\left(\frac{t_P \tau_{se}}{\tilde{\tau} \tau_{sc}}\right) \right)^{-1}, \quad E_C - E_{FR} = \frac{B}{N_I d_0 \tilde{b}_n f_X}, \quad \text{Range (e)} \quad (2.70)$$

$$N_I d_0 = \frac{M}{\tilde{b}_n f_X k} \frac{1}{\ln(t_{P1}/t_{P2})}, \quad \text{Difference (c) and (e)} \quad (2.71)$$

**Period scan regression:** x-axis =  $\ln(\tau)$

$$N_I d_0 = \frac{M}{\tilde{b}_n f_X k T}, \quad E_C - E_{FP} = -\frac{B}{M} - kT \ln(\tau_{se}), \quad \text{Range (b)} \quad (2.72)$$

$$N_I d_0 = \frac{B}{\tilde{b}_n f_X k T \ln(t_P/\tau_{sc})}, \quad \text{Range (c)} \quad (2.73)$$

$$N_I d_0 = -\frac{M}{\tilde{b}_n f_X k T}, \quad E_C - E_{FR} = kT \left( \frac{B}{M} - \ln\left(\frac{t_P \tau_{se}}{\tau_{sc}}\right) \right), \quad \text{(e)} \quad (2.74)$$

$$N_I d_0 = \frac{M}{\tilde{b}_n f_X k T} \frac{1}{\ln(t_{P1}/t_{P2})}, \quad \text{Difference (c) and (e)} \quad (2.75)$$

### 2.3.5 Tunnel constant

The tunnel constant  $d_0$  can be calculated when the saturation pulse width  $t_{Ps}$  was reached. Then  $d_x$  is the oxide thickness  $d_{ox}$ . This yields to:

$$N_I d_{ox} = N_I d_x \quad (2.76)$$

$$= N_I d_0 \ln(t_{Ps}/\tau_{sc}) \quad (2.77)$$

From this we can calculate the tunnel constant by:

$$d_0 = \frac{d_{ox}}{\ln(t_{Ps}/\tau_{sc})} \quad (2.78)$$

Because  $N_I d_0$  can be calculated by the equations of the previous chapters, we get also  $N_I$ .

## 3. Theory of DLTFs

### 3.1 Fourier Transform

In the following we assume a digital system, which scans the analog signal  $f(t)$  with an analog-digital converter (ADC) in  $N$  discrete equidistant times  $k\Delta t$ ,  $k = 0, 1, \dots, N-1$ .  $\Delta t$  is the sampling interval. For  $f(t)$  we postulate periodicity. The period width  $T_W = N\Delta t$  contains  $N$  intervals with the  $N+1$  real values  $f_0, \dots, f_N$ .

For the subsequent comparison of measured and calculated values the following definitions are relevant:

a) Continuous (analytical) Fourier coefficients  $c_n$  of the Fourier series (not the analytical Fourier transformation!):

$$c_n = \frac{1}{T_W} \int_0^{T_W} f(t) \exp(-in\omega_0 t) dt \quad (3.1)$$

with

$$\omega_0 = \frac{2\pi}{T_W} \quad (3.2)$$

In case  $f(t)$  is real, then the cosine coefficients  $a_n$  and the sine coefficients  $b_n$  are real, too, and represent real and imaginary parts of  $c_n$ :

$$c_n = \frac{1}{2}(a_n - ib_n) \quad (3.3)$$

b) Discrete (numerical) Fourier Transform (DFT):

$$F_n = \sum_{k=0}^{N-1} f_k \exp(-2\pi ink/N) \quad (3.4)$$

As the sampling values are real, only  $N/2$  independent  $F_n$  exist. The following relation exists between DFT and discrete Fourier coefficients  $c_n^D$ :

$$F_n = Nc_n^D \quad (3.5)$$

The exact reconstruction of a continuous time signal  $f(t)$ , using discrete sampling values, is only possible if  $f(t)$  is spectrally limited, and if the sampling frequency  $1/\Delta t$  is more than twice the highest frequency of  $f(t)$  (sampling theorem). The Nyquist frequency is half the sampling frequency. Spectral overlaps (aliasing effect) occur if the sampling theorem is not fulfilled.

Equation (3.4) represents the exact numerical integration according to the trapezium rule only if  $f_0 = f_N$ . Without this restriction the numerical integration rule takes the following form:

$$F_n = \frac{f_0}{2} + \sum_{k=1}^{N-1} f_k \exp(-2\pi i n k / N) + \frac{f_N}{2} \quad , \quad n = 0, 1, \dots, N-1 \quad (3.6)$$

If the function shows a discontinuity at the scan limit, i.e.  $f_0 \neq f_N$ , then a correction is necessary if discrete and continuous coefficients are to be compared. For the analytical case the peripheral points  $f(0)$  and  $f(T_W)$  are null sets. To avoid executing the correction for each  $F_n$ ,  $f_0$  can be defined as follows for the input values of the DFT:

$$f'_0 := \frac{f_0 + f_N}{2} \quad (3.7)$$

Numerical execution of the DFT can be done most efficiently with the FFT (Fast Fourier Transform) algorithm.

## 3.2 General idea of DLTFs

The general idea of the DLTFs (Deep Level Transient Fourier Spectroscopy) is as follows:  $N$  measuring values are sampled from a capacitance transient, and the discrete Fourier coefficients  $c_n^D$  are formed by numerical Fourier transformation. Based on an adequate theory for the charging of deep levels a certain time dependence of the transient is assumed. This function is developed into a Fourier series, and its continuous coefficients  $c_n$  are calculated.

Assuming that the numerical coefficients originate from just this postulated function, the free parameters of the function can be determined by a comparison of the numerical and the analytical coefficients, usually in several ways.

Additionally, it is immediately possible to check the basic theory by an appropriate selection of the number of Fourier coefficients. As each coefficient contains information about the entire transient, specific ratios of some coefficients are characteristic for different signal forms.

Generally it would not be reasonable to use the entire frequency spectrum quantitatively for the evaluation. Starting with the assumption of a low-frequency active signal being overlapped by high-frequency noise signals, usually only the lowest orders will be evaluated.

In most cases it is favourable to adjust optimally the period width for each transient. In the software such a tempscan will be called tempscan with variable period width.

### 3.3 Direct evaluation

With the DLTFs method a direct evaluation for each transient is possible. 'Direct' means that the evaluation values, for example the time constant, will be calculated direct from the transient and not 'indirect' by the maximum of a temperature curve.

#### 3.3.1 Exponential law of time

The following discusses a real exponential law of time:

$$f(t) = A \exp\left(-\frac{t + t_0}{\tau}\right) + B \quad (3.8)$$

Where  $A$  is the *amplitude*,  $B$  the *offset* and  $\tau$  the *time constant*. For this real function following Fourier coefficients are obtained:

$$a_0 = \frac{2A}{T_W} \exp(-t_0/\tau)(1 - \exp(-T_W/\tau))\tau + 2B \quad (3.9)$$

$$a_n = \frac{2A}{T_W} \exp(-t_0/\tau)(1 - \exp(-T_W/\tau)) \frac{\frac{1}{\tau}}{\frac{1}{\tau^2} + n^2\omega_0^2} \quad (3.10)$$

$$= 2A \exp\left(-\frac{T_W}{\tau} \frac{t_0}{T_W}\right)(1 - \exp(-T_W/\tau)) \frac{\frac{T_W}{\tau}}{\frac{T_W^2}{\tau^2} + 4\pi^2 n^2}$$

$$b_n = \frac{2A}{T_W} \exp(-t_0/\tau)(1 - \exp(-T_W/\tau)) \frac{n\omega_0}{\frac{1}{\tau^2} + n^2\omega_0^2} \quad (3.11)$$

$$= 2A \exp\left(-\frac{T_W}{\tau} \frac{t_0}{T_W}\right)(1 - \exp(-T_W/\tau)) \frac{2\pi n}{\frac{T_w^2}{\tau^2} + 4\pi^2 n^2}$$

The second equations are equivalent transformations of the first ones. The  $\tau/T_W$  normalization is here better recognizable.

We get for  $t_0/T_W = \text{const}$  a normalized curve  $a_n(\tau/T_W)$  resp.  $b_n(\tau/T_W)$ , which is independent from  $N$  and  $t_0/\Delta t$ . Further curves are  $b_n$  versus  $\tau$  at fix  $T_W$ ,  $b_n$  versus  $T_W$  at fix  $\tau$  and  $b_n$  versus  $1/T_W$  at fix  $\tau$ .

We get following relations to check whether the transient is exponential:

$$\begin{aligned} \text{a)} \quad & a_k < a_n < \frac{k^2}{n^2} a_k \quad \text{for } n < k \\ \text{b)} \quad & \frac{n}{k} b_k < b_n < \frac{k}{n} b_k \quad \text{for } n < k \\ \text{c)} \quad & \frac{b_n}{a_n} \frac{a_k}{b_k} = \frac{n}{k} \end{aligned} \quad (3.12)$$

For the coefficients 1. and 2. order we get (in the software called 'exponential class'):

$$\frac{b_2}{2b_1} \frac{a_1}{a_2} = 1 \quad (3.13)$$

The amplitude of the signal, and consequently the concentration of deep centers, can be calculated from each coefficient, for example from  $b_n$ :

$$A = b_n \frac{T_W}{2} \frac{\exp(t_0/\tau)}{(1 - \exp(-T_W/\tau))} \frac{\frac{1}{\tau^2} + n^2 \omega_0^2}{n \omega_0} \quad (3.14)$$

The time constant can be obtained from the ratio of two coefficients. There exist three principally different possibilities:

$$\begin{aligned} \text{a) } \tau(a_n, a_k) &= \frac{1}{\omega_0} \sqrt{\frac{a_n - a_k}{k^2 a_k - n^2 a_n}} \\ \text{b) } \tau(b_n, b_k) &= \frac{1}{\omega_0} \sqrt{\frac{k b_n - n b_k}{k^2 n b_k - n^2 k b_n}} \\ \text{c) } \tau(a_n, b_n) &= \frac{1}{n \omega_0} \frac{b_n}{a_n} \end{aligned} \quad (3.15)$$

It is a considerable advantage that here only ratios of coefficients and neither amplitude nor offset will be used.



### 3.4 Tempscan maximum analysis

With the Fourier coefficients is also a tempscan maximum analysis possible as at the conventional DLTS method. At this maximum analysis you define by the period width  $T_W$  your time constant for the coefficient maximum. This value is only valid in the maximum and depends from  $T_W$ ,  $T_W/t_0$  and the type of coefficient. This value will be calculated numerical by simulation (variation of tau at fix  $T_W$  and  $t_0$ ) and maximum search of the coefficient(tau) curve from eq. 3.11 resp. 3.13.

### 3.5 Isothermal evaluation

With the Fourier coefficients is also an isothermal maximum analysis possible as ICTS or frequency scan. For this method the period width will be variated at a fix temperature. From the maximum of this curve you get the time constant. With a numerical calculation by simulation of eq. 3.11 resp. 3.13 you get from your  $T_W$ -axis a tau-axis. The tau value is only valid in the coefficient maximum.

## 4. Tempscan - Maximum Analysis, Correlation Functions

### 4.1 Conventional DLTS

The first measurement equipment used for measuring the emission process (equ. 1.48) does not allow the measurement of the complete transient (equ. 1.24) as done with the DL8000 system. As fast data acquisition was not available. Therefore a data reduction method has been developed (Lang et al.) using so called correlators. The output of this correlator is one value per transient called  $\delta C$  (delta C) value. This  $\delta C$  value depends on

1. The transients Amplitude
2. The transients time constant
3. The kind of correlator
4. The correlator parameters.

1 and 2 are the desired measurement results, 3 and 4 the known correlator parameters. It is always a difference and the correlation function  $F(t)$  is defining how the difference is calculated from the transient signal.

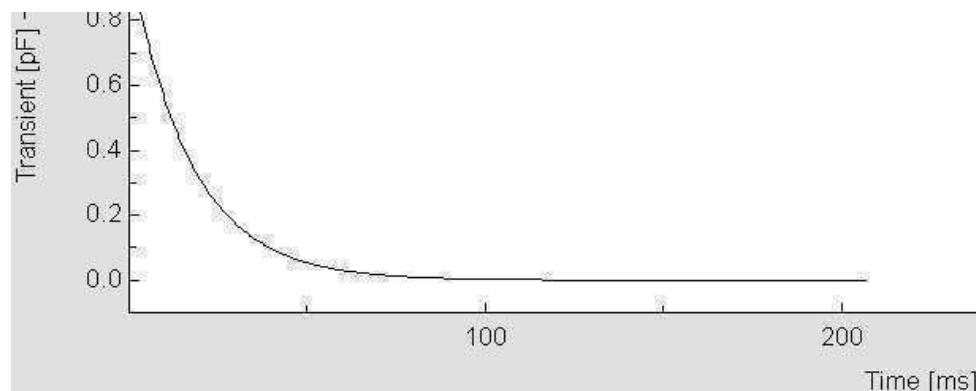
In general it's calculated by the integral over the product of the measurement function (transient) and the correlation function normalized by the period width  $TW$  (time range the transient has been measured, e.g. 204 ms, as shown below).

$$\delta C = 1/TW * \text{Integral}[(C(t)*F(t))dt]_{t=0 - TW}$$

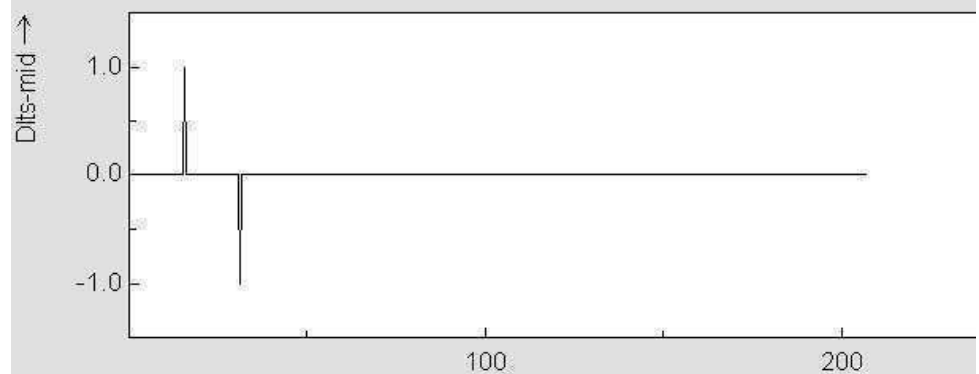
Two main kinds of correlators had been available at that times, the Box-car integrator and the Lock-in amplifier. Both are realized by electronic hardware and differ only in the used correlation function  $F(t)$  (also called weighting function).

fig. 4.1

emission  
transient



Box-car  
correlation  
function



E.g. the Box-car correlator (fig. 4.1) consists of delta functions:  $F(t_1) = 1$ ,  $F(t_2) = -1$  and the complete correlation function is given by:

$$F(t) = 0 \Big|_{t > t_1, t_2} + F(t_1) + F(t_2) \quad \text{Box-car correlator function}$$

$\delta C$  is then given by  $\delta C = C(t_1) - C(t_2)$ .

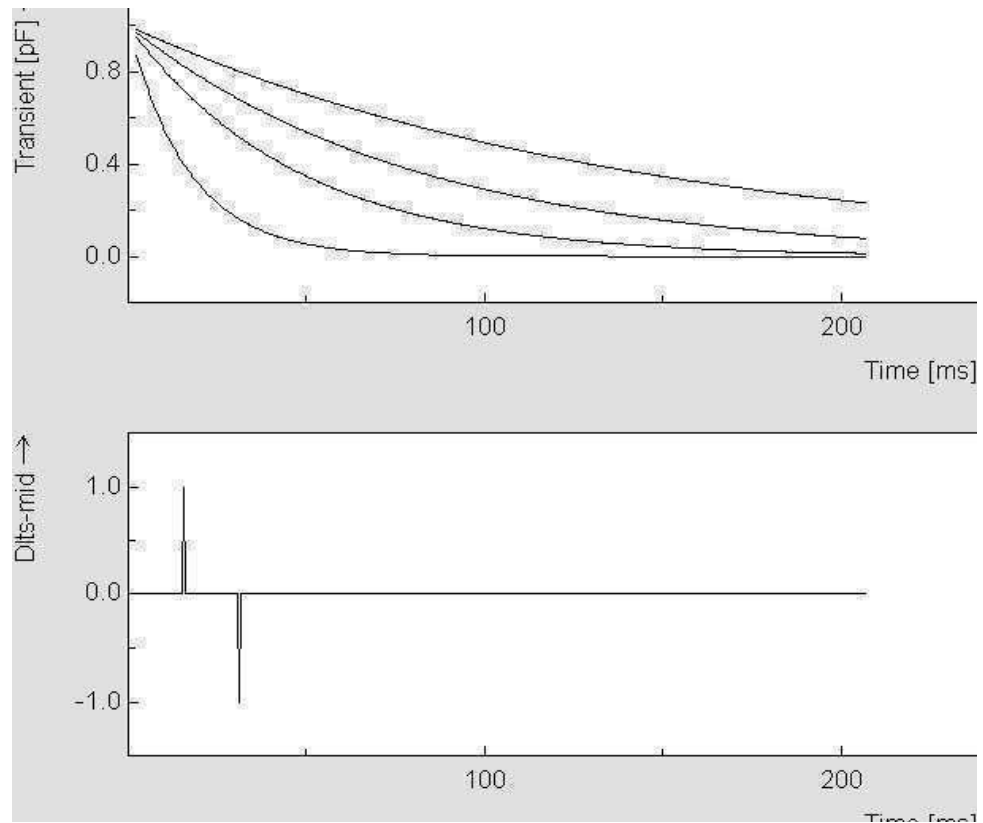
This dC value is not sufficient to calculate the transient amplitude and time constant (1. and 2 from above). Therefor an additional parameter has to be varied and the dC value has to be measured as a function of this parameter, the temperature.

For constant correlator parameters ( $t_1$  and  $t_2$ )  $\delta C$  depends only on the transient values. The transient changes with the temperature in timeconstant and amplitude (equ. 1.24, 1.49). This can now be used to measure the transient timeconstant and the amplitude by changing the temperature and measuring  $\delta C$  as a function of the temperature., the so called tempscan. The pictures below (fig. 4.2) show some emission transients at different temperatures and the used box-car correlation function. The result,  $\delta C$  vers. temperature is shown on the next page (fig. 4.3). (as a standard we change the transient sign to positive transients and therefor also to a positive  $\delta C$  signal)

fig. 4.2

Transients of the same trap level at 270K, 260K, 255 and 250K (bottom to top)

Box-car correlation function



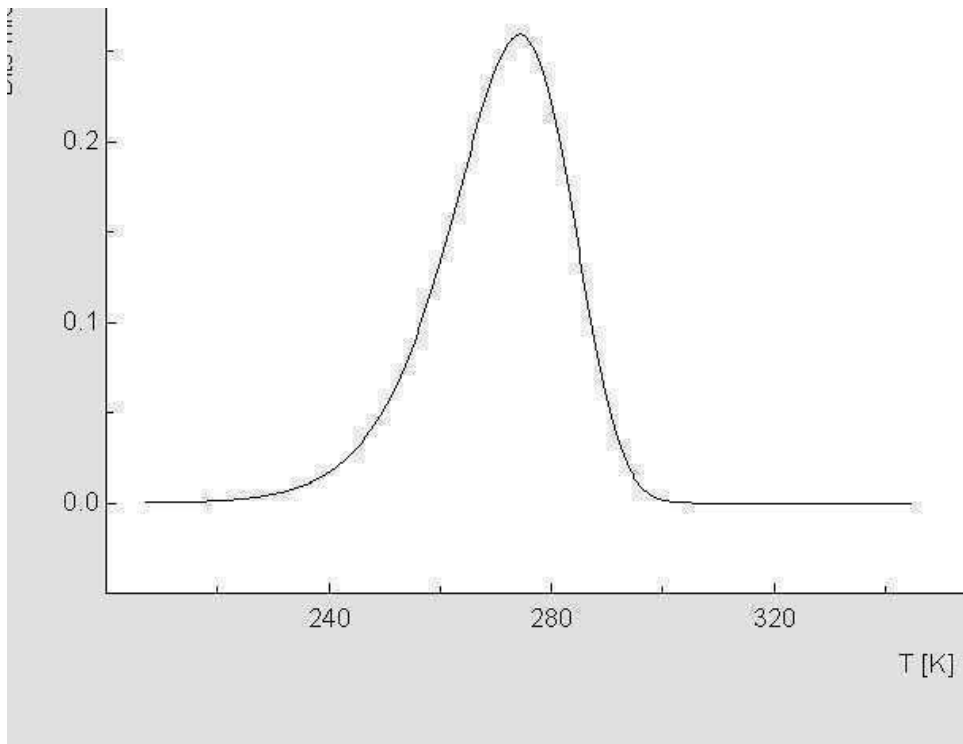


fig. 4.3

$\delta C$  (named DLTS mid) as the function of the temperature (tempscan signal) as the result of several transients and the Box-car correlation function as shown above.

At the maximum of this tempscan signal (and only at the maximum) the timeconstant of the transient and the transient amplitude can be calculated if,

1. The transient signal is exponential
2. The measurement parameters during the tempscan do not change
3. The correlation parameters (box-car:  $t_1$ ,  $t_2$ ) do not change.

For the box-car and lock-in correlation function analytical expressions can be calculated, for other correlation functions normally no analytical solutions can be given, only numerically calculated results can be given. But these ones are as exact as the analytical ones.

e.g. for the Box-car the timeconstant can be calculated by:

$$\tau_{e,\max} = (t_1 - t_2) / \ln(t_1/t_2) \text{ at } T_{\max}$$

The height of the tempscan signal is proportional to the  $\Delta C$  value (transients amplitude equ. 1.25 and 1.31). The factor  $A$ ,  $\delta C = A \cdot \Delta C$ , depends also on the correlation function and parameters. For the Box-car correlation this factor  $A$  is again quite easy to handle. It can be calculated analytically and becomes for  $t_1/t_2 = 2$ ,  $A = 4$ .

Because the first DLTS system were not computer controlled this easy calculations had been a big advantage. But the biggest advantage had been, that the measurement of a quite a fast signal, the capacitance transient, had been transformed into a slow measurement, the tempscan signal. This gives the user plenty of time for averaging the signal using signal integrators just behind the correlator, and the measurement time can be selected independently from the transient timeconstant by selecting the temperature ramp. On the other hand, for each measured time constant one complete temperature cycle has to be done. For using the Arrhenius plot  $\ln(\tau)$  vers.  $1/T$  (equ. 1.53) to calculate a traplevel energy several (at least 4) cycles have to be done with different correlator parameters.

## 4.2 Digital DLTS

For digital DLTS systems like the DL8000 all physical principles are the same. The emission time constants at different temperatures and the amplitude of the emission transients have to be determined out of the capacitance transient signal. But a lot of problems the first DLTS systems have to face to can now be solved by using computers and fast digital data acquisition. In opposite to the conventional DLTS systems the DL8000 DLTS measures the complete transient as a  $C(t)$  array and transfers the data into a computer system. Using a Fourier transformation and the **direct evaluation** (chapter 3.) the time constant (equ. 3.15) and the transient amplitude (equ. 3.14) can be evaluated for every measured transient at any temperature. Each of the measured transients can be used for the Arrhenius plot. Therefore, only one tempscan (or better temperature cycle) is now necessary for determining the energy of a trap. Each transient measurement is independent from the next or former one. It's not combined by integration filters as in conventional DLTS systems. Therefore also measurements with varied measurement parameters (pulse width, reverse bias voltage etc.) can be done in one temperature cycle. The **direct evaluation** works perfect on **single exponential** transients caused by one isolated trap level, and is part of the tempscan evaluation software.

Overlapping levels causing non exponential transients are not so easy to evaluate. All theories are based on only one level with a single exponential transient. Having overlapping signals, it has to be decided in which range of the measurement (mainly temperature range) the results can be approximately handled as a single emission process. The software gives help for this decision, it calculates quality factors for the exponentiality of each transient (**exp class**) and for the validity of the direct evaluation (**tau class**). The direct evaluation can use the classes for its evaluation and uses only transients better than a particular class value. But at the end the user has to trust this evaluation, and for that he has to have signals he can look at in an easy way to see what's really in the sample. This signal is again the  $\delta C$  signal, the tempscan.

Similar to the conventional DLTS a  $\delta C$  signal is calculated using a correlation function. **But in the digital DLTS system the correlator is not a hardware function but a software one.** By software much more correlators can be realized than by hardware. Also the limitation on only one correlator is not given any more. The transient is in the memory and the software can calculate as many  $\delta C$ 's using different correlation functions as useful. We are calculating 28 different ones. How every correlation function looks like is shown and explained in chapter 4.3. Measuring transients now as function of the temperature similar to the conventional DLTS, we get not only one tempscan, but 28 with different maxima at different temperatures defining different time constants  $\tau$ . That means, with a **maxima analysis** of these tempscan signals we get 28 value pairs ( $\tau, T$ ) for use in an Arrhenius plot after one temperature cycle. It's our opinion, that the Arrhenius plot should be the final result. This plot is in principle averaged over several correlation functions and over the temperature and gives so far the most reliable result. The tempscan signals are very good for visualisation of the results and for discussions. But at the end we leave it to the user.

The transients that are combined to a tempscan have to have exact the same measurement parameters. Specially the period width  $T_w$  as the measurement variable has to be exactly the same if several measurements should be combined. But, because every transient measurement is independent from each other, the transients with the same e.g.  $T_w$  have not to be measured in a row. Other transients can be measured in between. Our software can handle 16 different measurement files measured with 16 different measurement parameters. All these files can be measured in one temperature cycle and every one gives 28 different tempscan signals that can be used for the Arrhenius plot or other evaluations.

The tempscan maximum height and the maximum location at the temperature axis as well as the time constant at the maximum is different for every correlation function. The normalization

factor A and the maximum time constant for every correlation function has to be known at the used measurement parameters ( $T_w$  and  $t_0$ ). This is normally not any more possible to do in analytical way as using the Box-car correlator (above). The software is calculating these values in a numerical way without any restriction to the measurement parameters. The user is free in selecting these parameters and not any more limited to some values.

The correlation functions differ in sensitivity and energy resolution, means normalization factor A and halfwidth of the tempscan signal. A good compromise is the b1 coefficient (sin 1. order) that used as a standard in the software. In general does have the very energy resolvable function a bad sensitivity (up to a factor of 100 below b1), but for overlapping signal of high amplitude, these ones can give a lot of more informations about the kind of the overlapping.

During the maximum analysis of a temperature scan all measured  $\delta C$  tempscan signal of the different correlation functions are shown one after the other, and the user has to define each maximum. The time constants, the temperature and the normalized amplitude (and some other values) of these maxima are stored in an Arrhenius array and can be used for an Arrhenius plot and evaluation as the final result of the measurement.

### 4.3 Correlation functions

28 different correlation functions are used for calculating the  $\delta C$  values. They are classified into **sinbased** correlation functions (named bx), **cosinbased** ones (named ax) and other ones containing mainly rectangular correlation functions as box-car or lock-in.

For each correlation function the function itself, the tempscan and period width scan is shown on the following pages. Tempscan and period width scan are calculated for a trap level with  $E_T = 0,55$  eV and a capture cross section of  $1E-14$  cm<sup>2</sup> as explained in chapter 4.1. for the example of the Box-car correlation function.

Two correlation functions are shown on one page in 3 plots and one parameter box each. The bottom right plot shows the correlation function itself, on the left the result of a period width scan signal is shown, the top left plot gives the tempscan signal.

The parameter box (top, right) gives all measurement (simulation) parameters and the specific values of the shown correlation function. These values depend partly on the measurement parameters and are partly independent of it, define therefore the characteristics of the correlation function itself. The correlation functions differ in sensitivity and energy resolution. This different behaviour can be used during the maximum analysis. For very low signals close to the detection limit of the DLTS system, only the  $\delta C$  values (tempscan signals) of the correlation functions with the best signal to noise ratio (SNR) can be used the other correlation functions may not give a signal in the tempscan. For overlapping signals with high amplitudes the more energy resolving correlation functions may give not only one maximum, but can resolve the different overlapping levels that then can also be defined as a second or third maximum and analysed in an Arrhenius plot. Which correlation function is sensitive or energy resolving can be seen by the specific values in the parameter box explained below.

Name : The name of the particular correlation function (here b1). Appears on every plot of the tempscan of this function on the y axis.

ArNo. : The position of this correlation function in an Arrhenius plot file and when it's shown during the maximum analysis.

Points : No. of data points measured per transient. A measurement parameter.

Tw : The period width. (see theory above and hardware manual for more details).  
A measurement parameter.

t0 : The delay time after pulse (recovery time). A measurement parameter.

Tw/t0 : Effective period widths for the evaluation in terms of the recovery time  
-eff

Amp : The amplitude factor at the maximum. The height of the maximum of the tempscan  
Max : from this correlation function is the measured transients amplitude multiplied by this factor. On the other hand, the amplitude of the emission signal is calculated using this measured signal by dividing the maximums height by this factor. It's used in all so called **normalized** plots of the tempscans to calculate the correct amplitude or trap concentration. This factor is a value defining the sensitivity of the particular function. High value: very sensitive, small value: not so sensitive.  
The value is independent of the measurement parameters and the measured signal (trap energy, concentration and capture cross section). It's a specific value of the correlation function.

tauMax: Gives the time constant at the maximum. This value depends on the measurement parameters, but not on the signal. Every emission process will give the maximum when getting this time constant during the temperature scan. During a maximum analysis, this value is always calculated due to the used measurement parameters Tw and t0.



tauMax: Similar to that above, but given in terms of the period width Tw.  
/Tw

Temp : The temperature at the maximum. This value is the only one directly depending on  
Max the measured signal, the emission process and the trap energy and capture cross  
section. (calculated for  $E_T=0,55\text{eV}$ ,  $\sigma_T=1,0\text{E-}14\text{ cm}^2$ ). It's so far the final  
measurement result for this correlation function. It also depends on the measurement  
parameters.

Integ : Integral over the tempscan signal of this correlation function.

<tau/  
Tw> : Statistic value. The expected maximum of the timeconstant in parts of the period  
width. This value (compared to that one above: tauMax/Tw) does not take into  
account the different slopes of the shoulders of the ITS (period width scan) signal.

width : The halfwidth of the tempscan signal. This is a value for the energy resolution of the  
correlation function. A small value stands for a high energy resolution, a large value  
for a standard resolution.

width : Similar to above, but for period width scan signals.  
rate

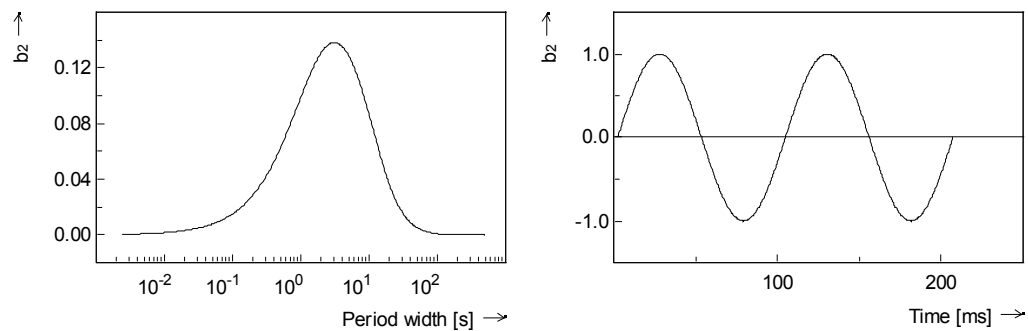
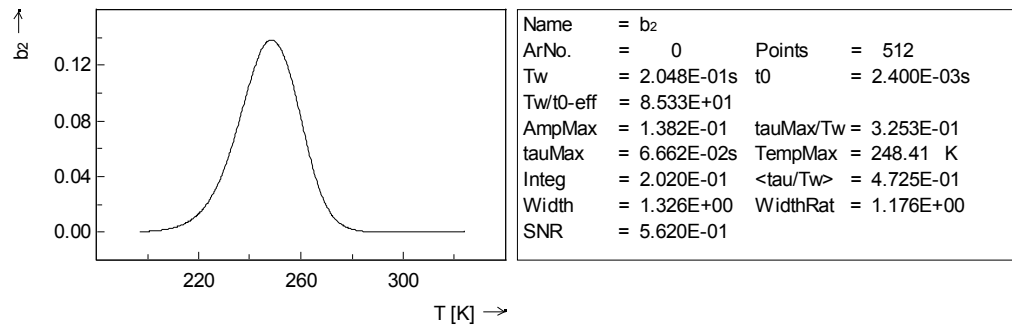
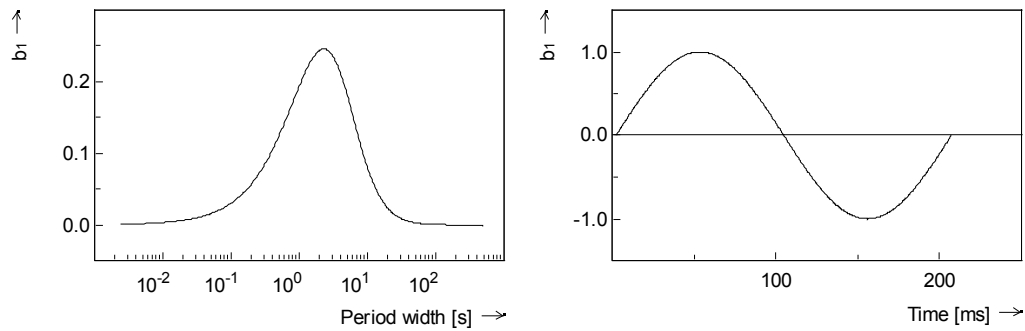
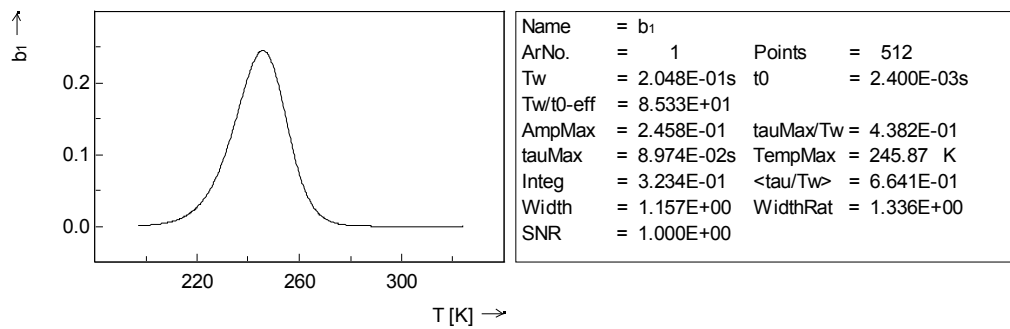
SNR : Signal to noise ratio. It defines the sensitivity of this correlation function. The value  
is normalized to the b1 correlation function.

Name	=	b1		
ArNo.	=	1	Points	= 512
Tw	=	2.048E-01s	t0	= 2.400E-03s
Tw/t0-eff	=	8.533E+01		
AmpMax	=	2.458E-01	tauMax/Tw	= 4.382E-01
tauMax	=	8.974E-02s	TempMax	= 245.87 K
Integ	=	3.234E-01	<tau/Tw>	= 6.641E-01
Width	=	1.157E+00	WidthRat	= 1.336E+00
SNR	=	1.000E+00		

## Correlation functions

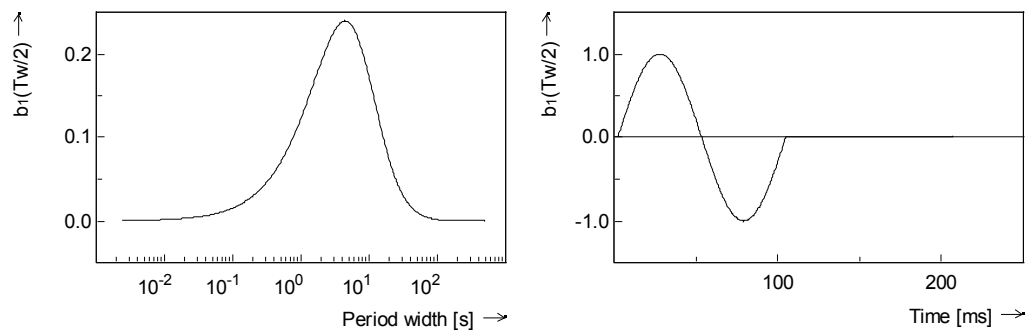
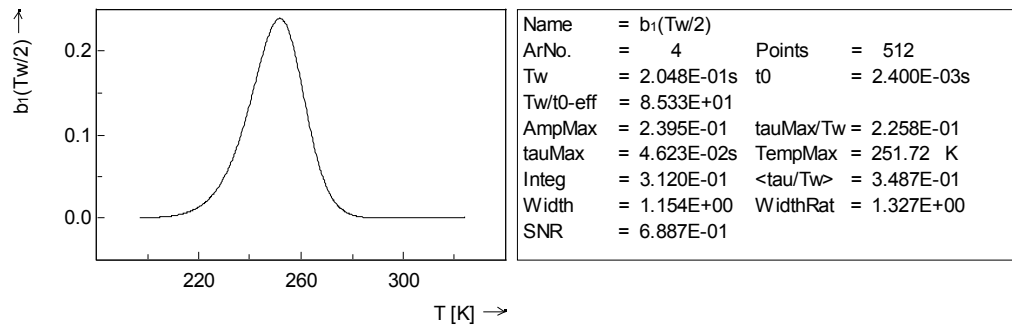
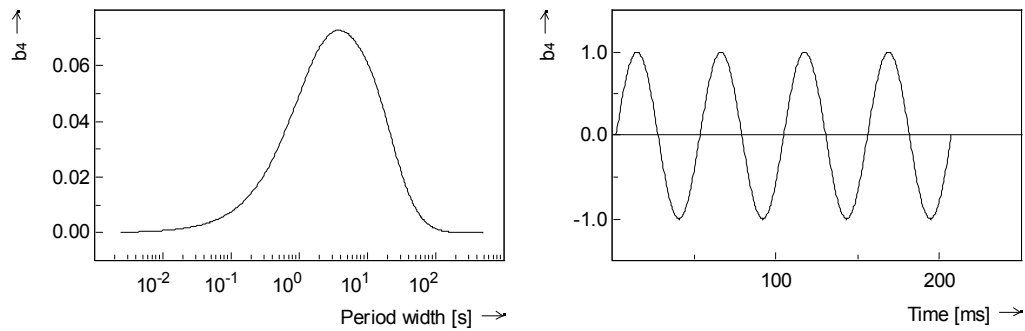
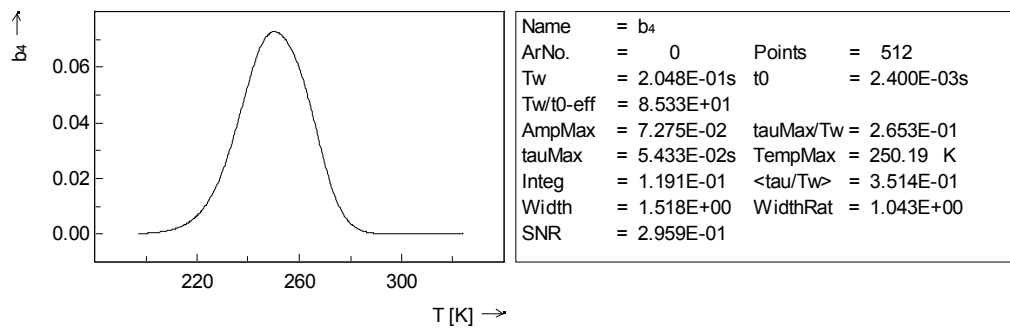
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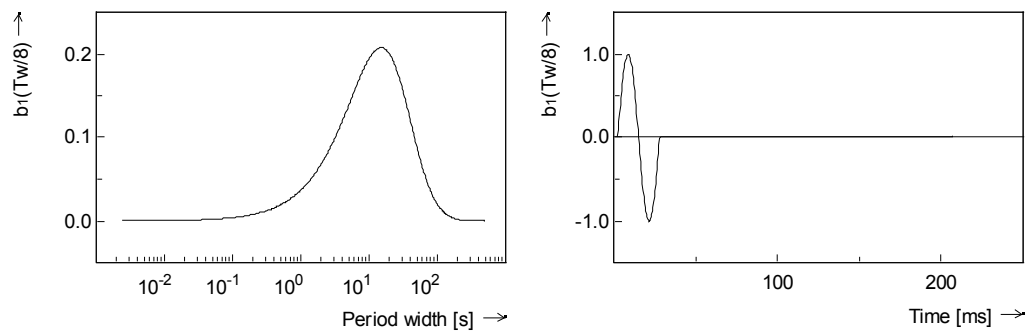
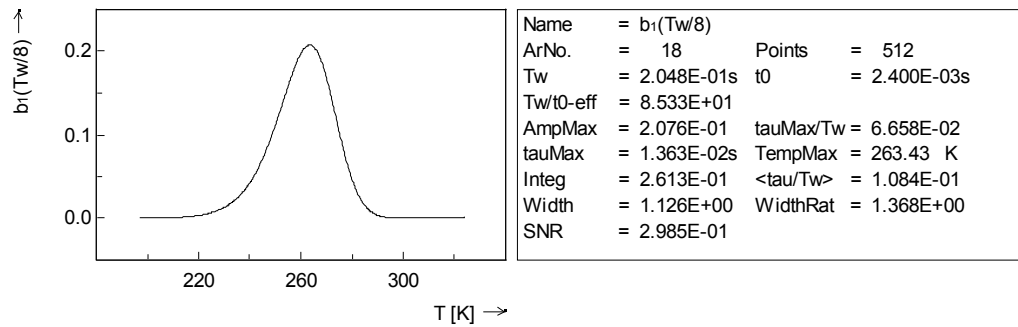
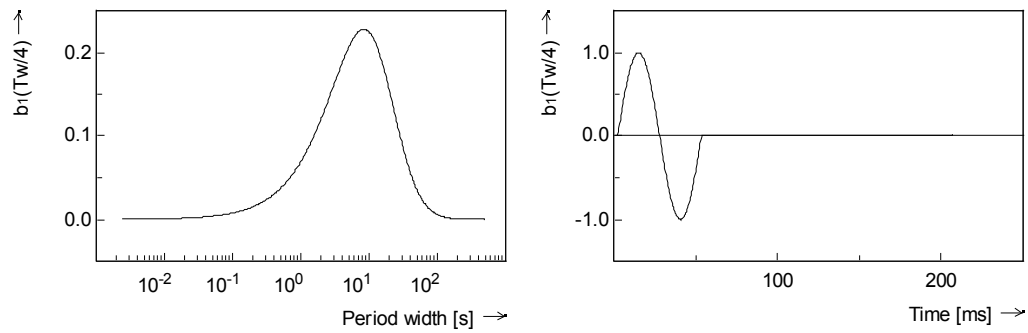
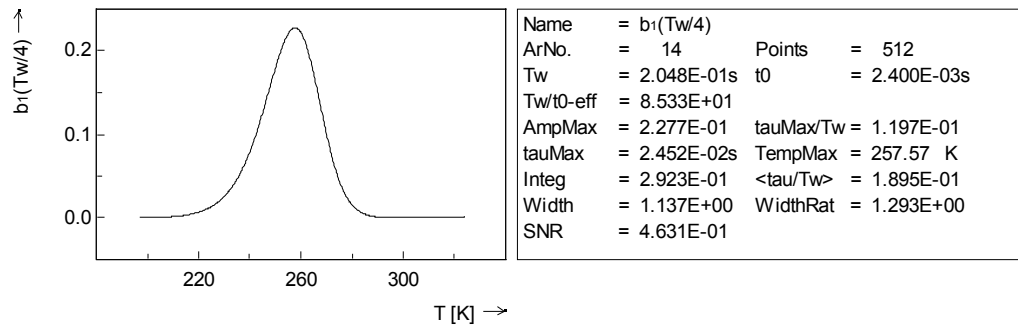
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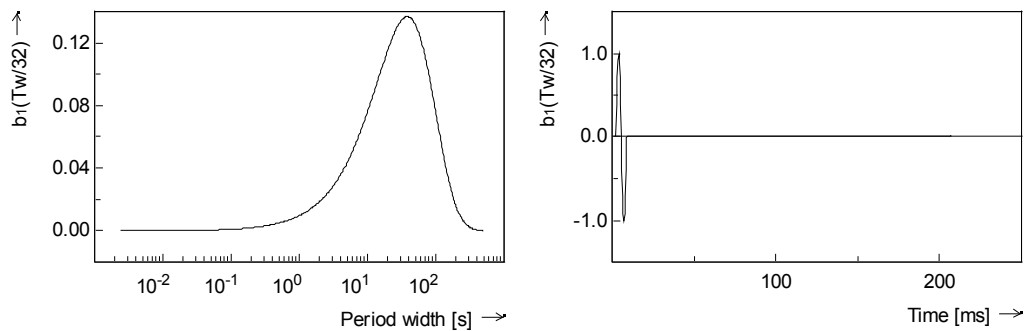
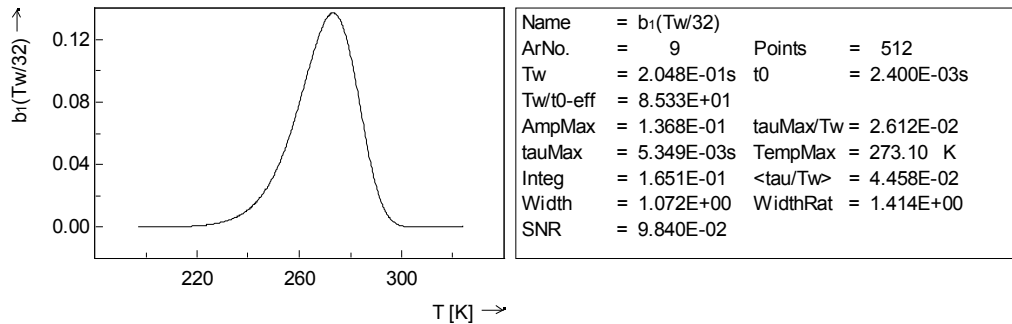
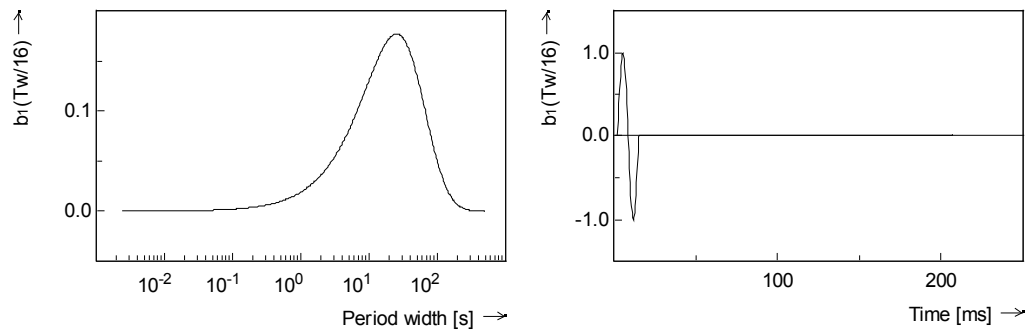
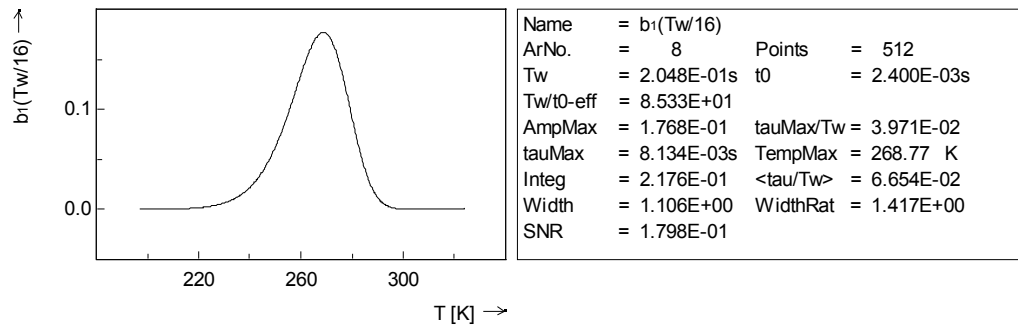
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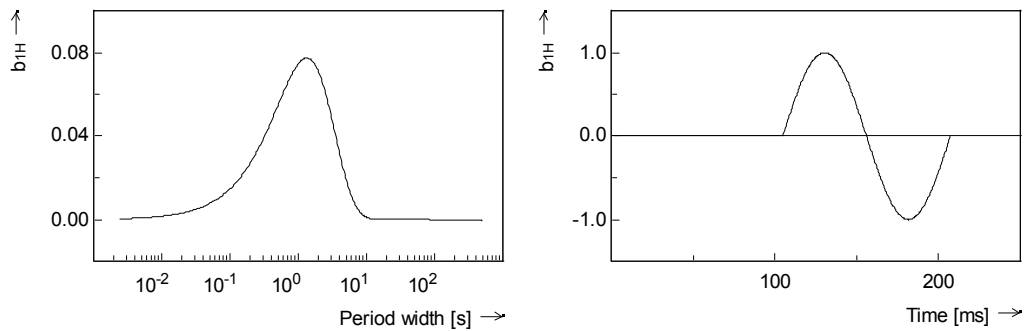
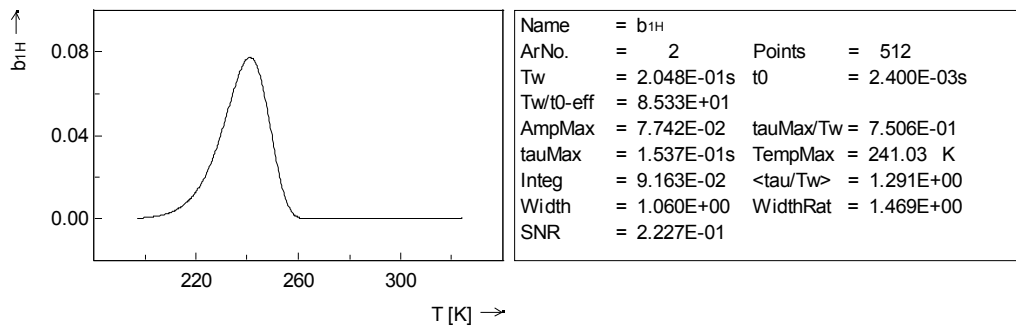
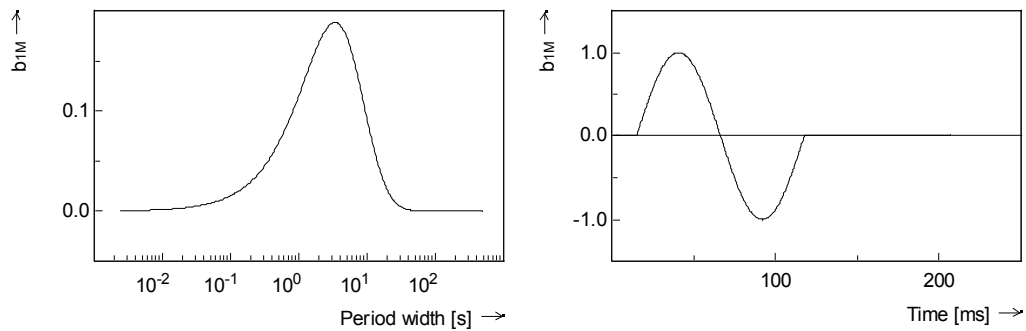
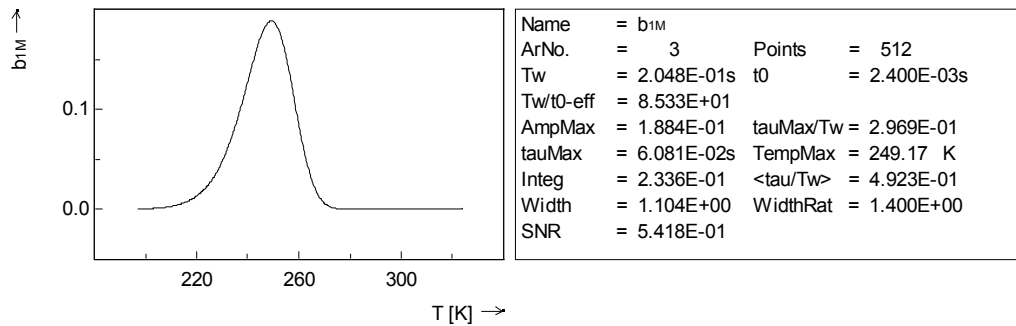
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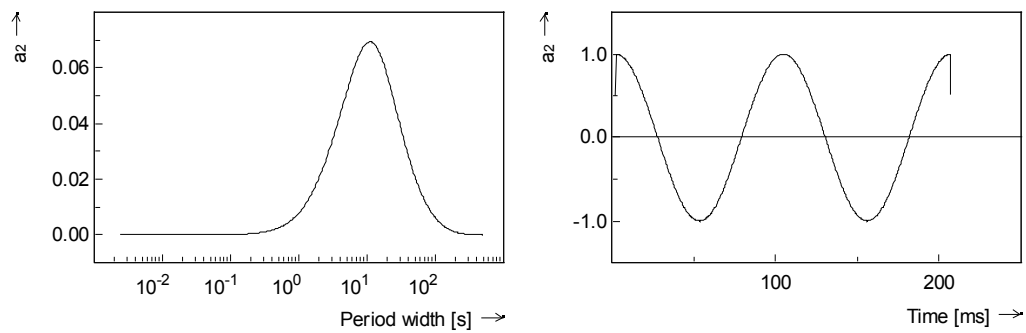
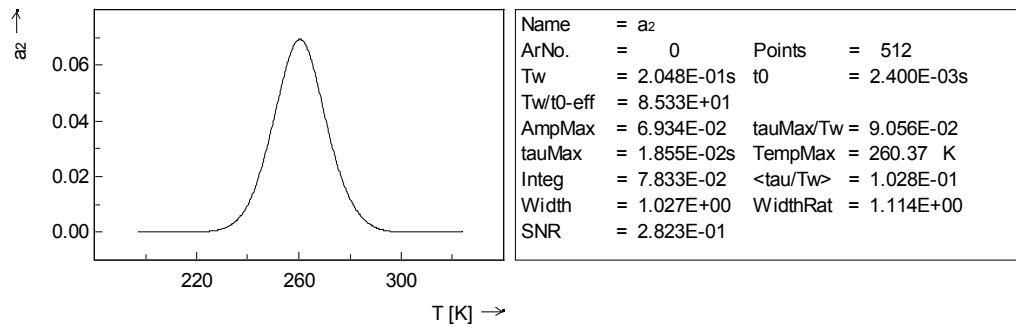
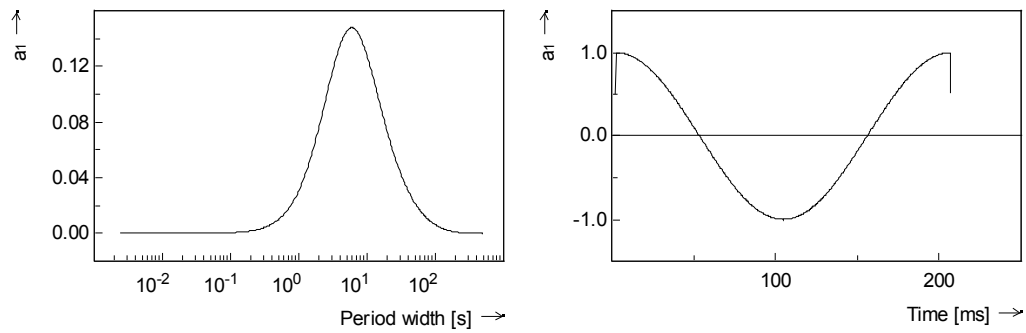
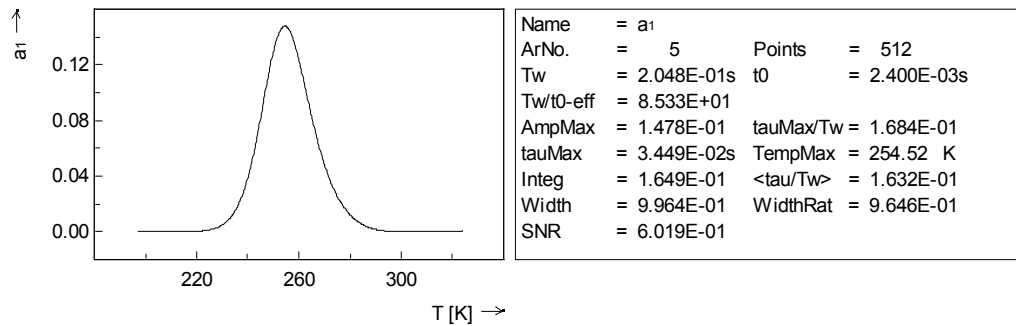
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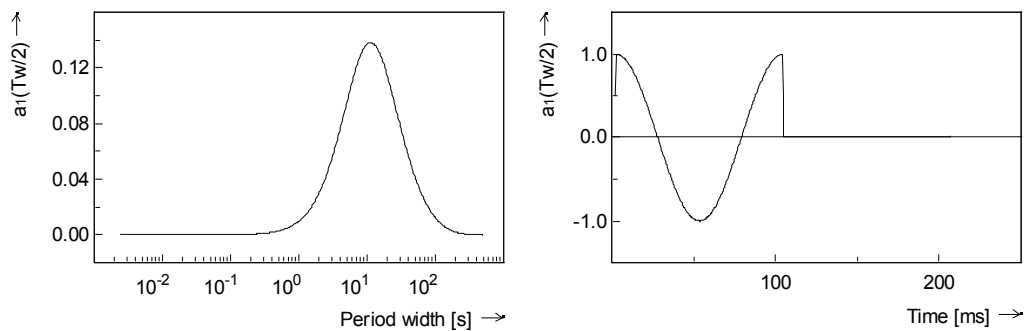
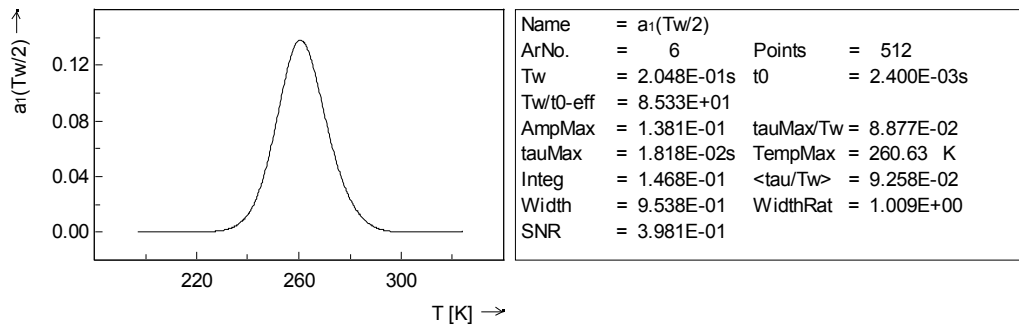
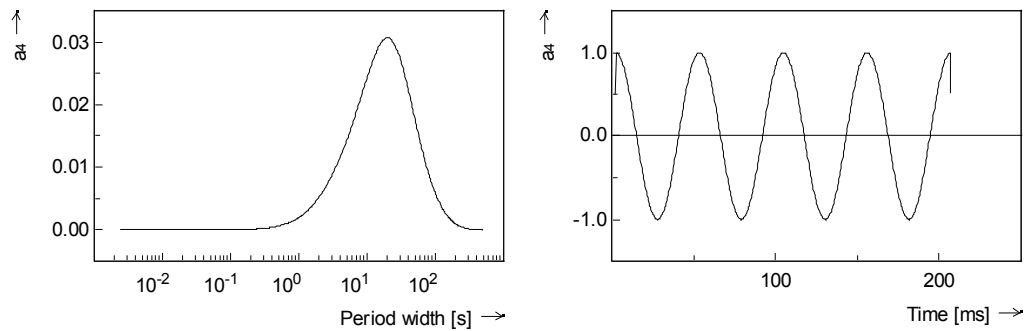
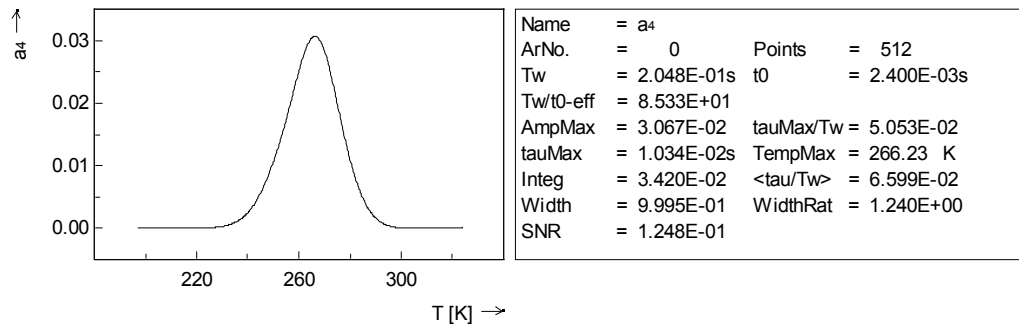
## Correlation functions





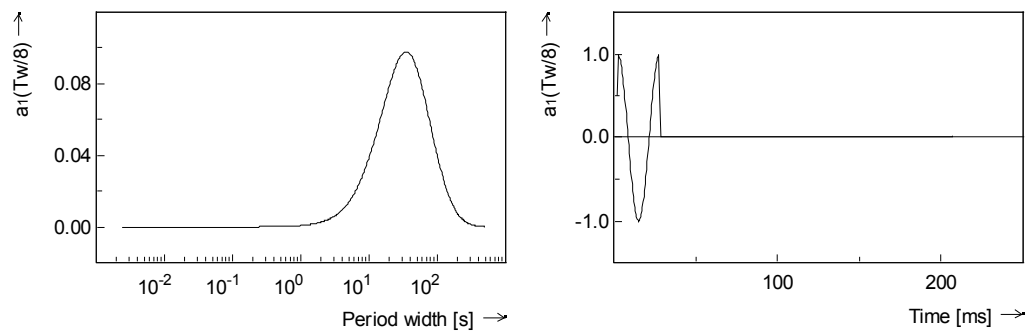
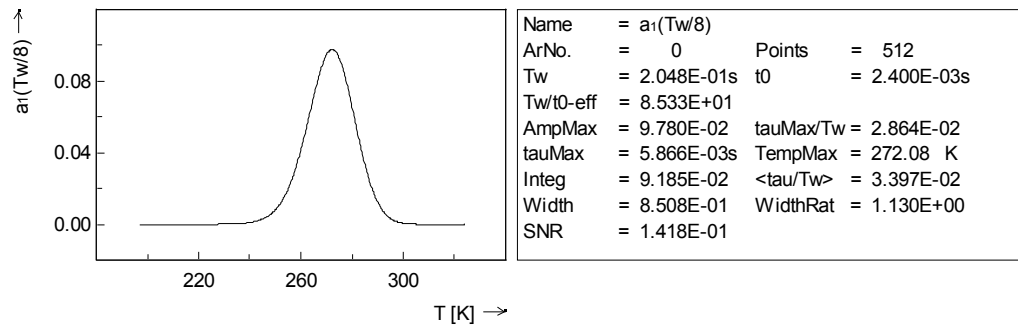
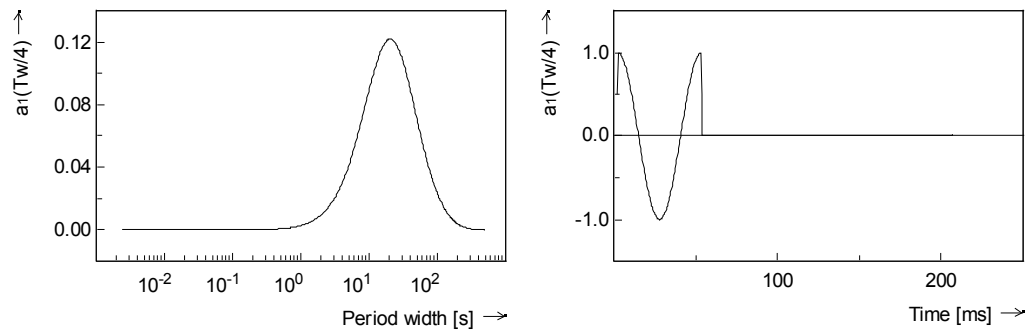
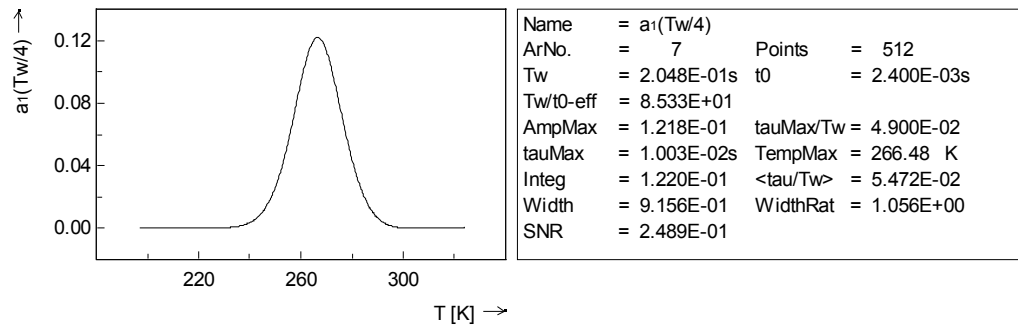
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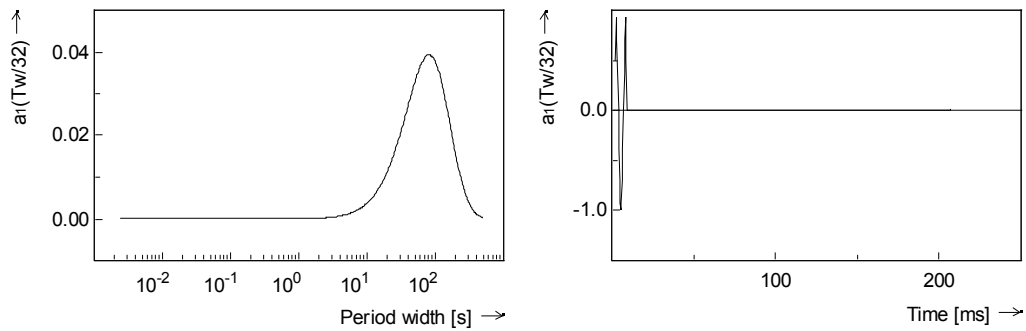
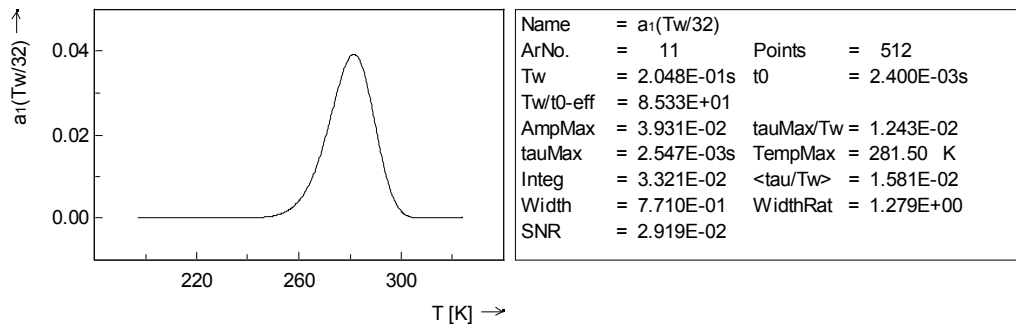
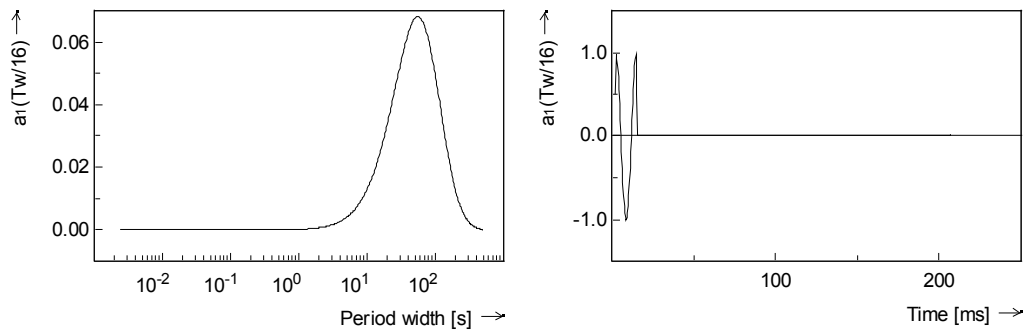
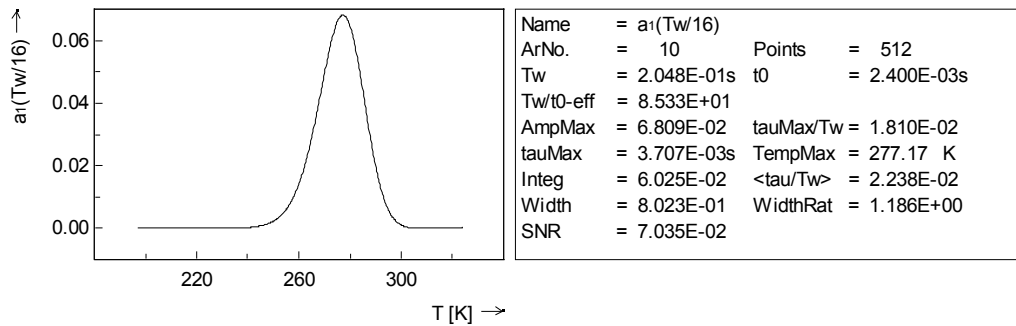
# DTS Manual

## Correlation functions



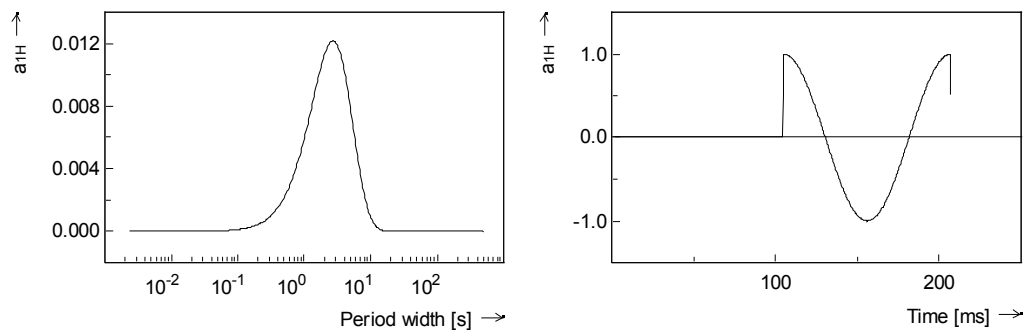
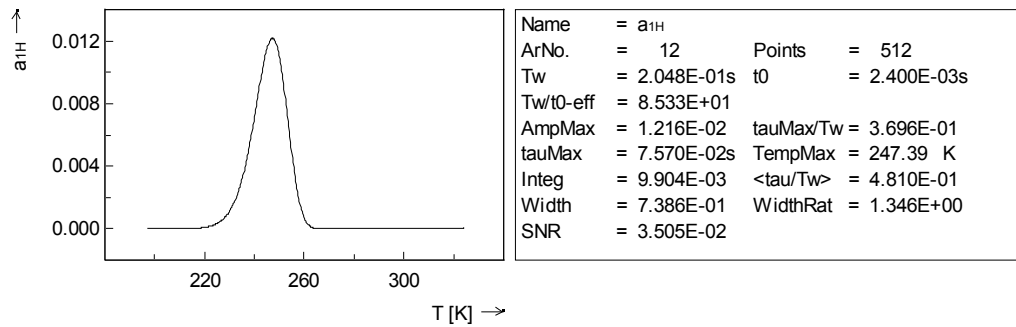
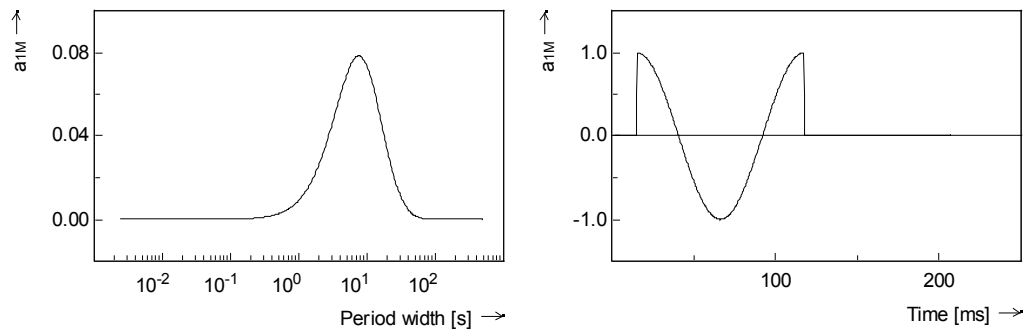
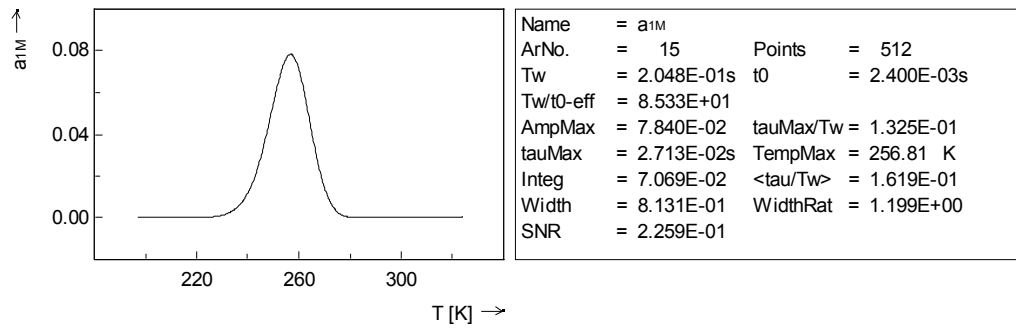
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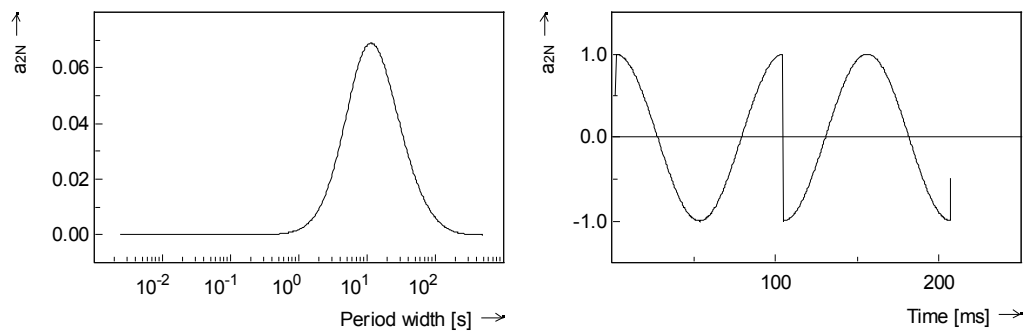
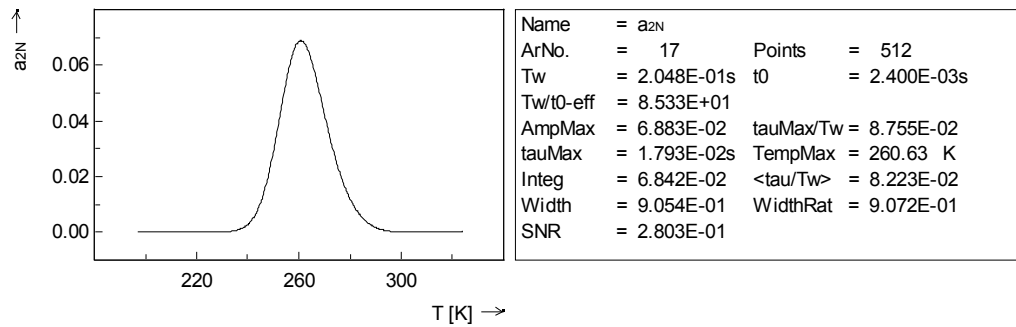
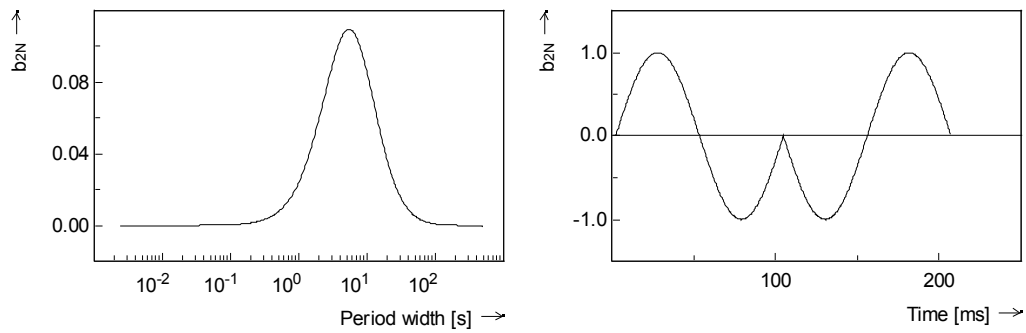
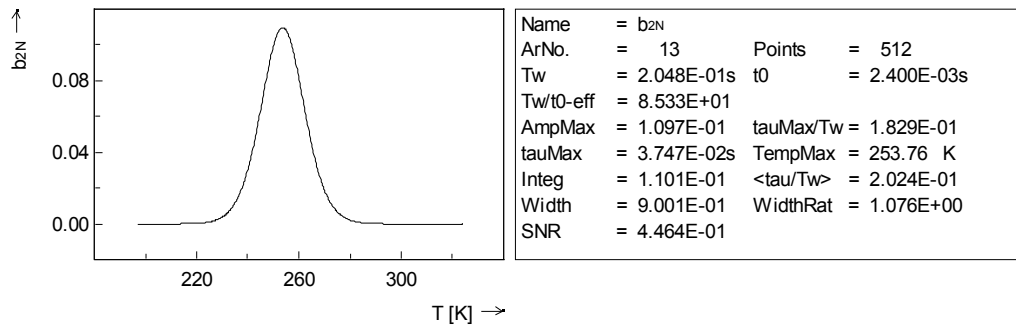
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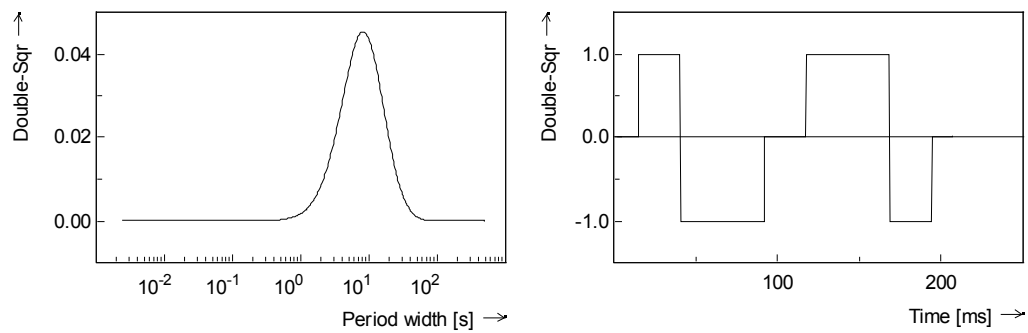
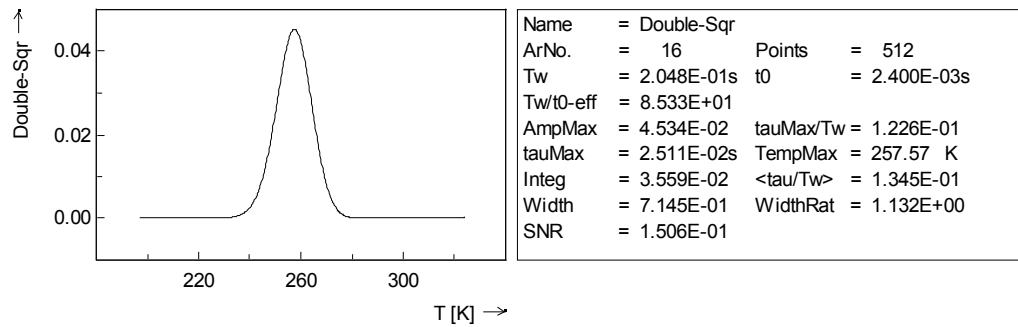
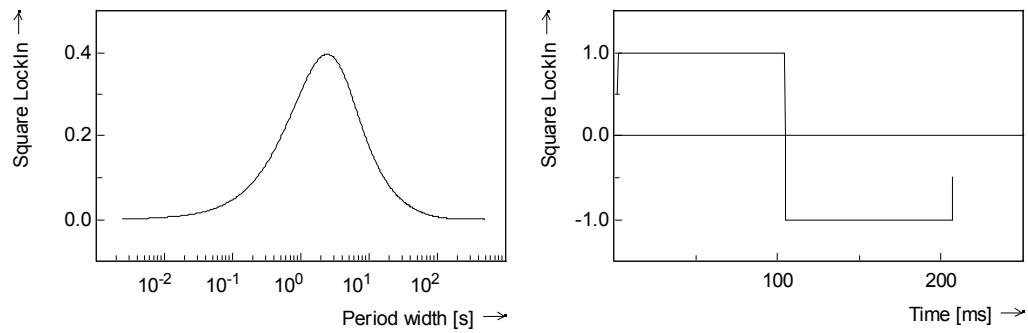
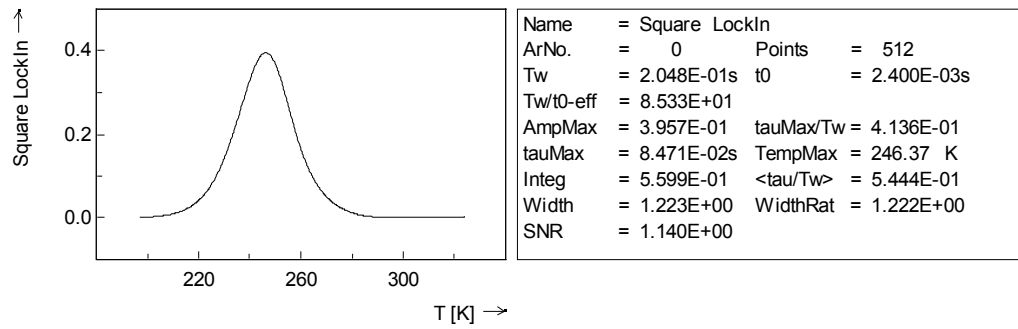
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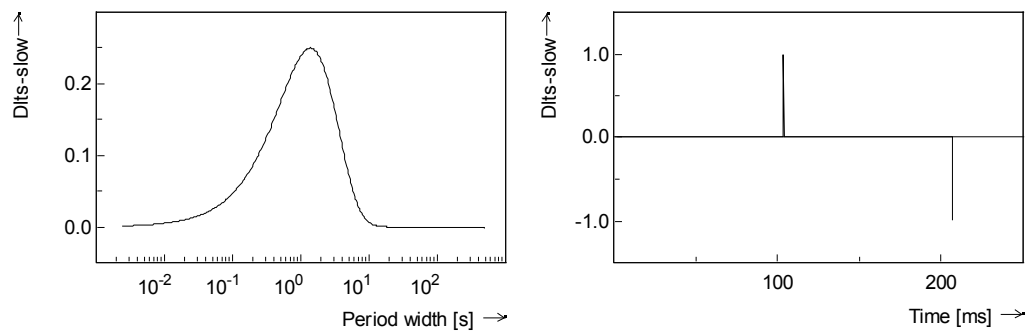
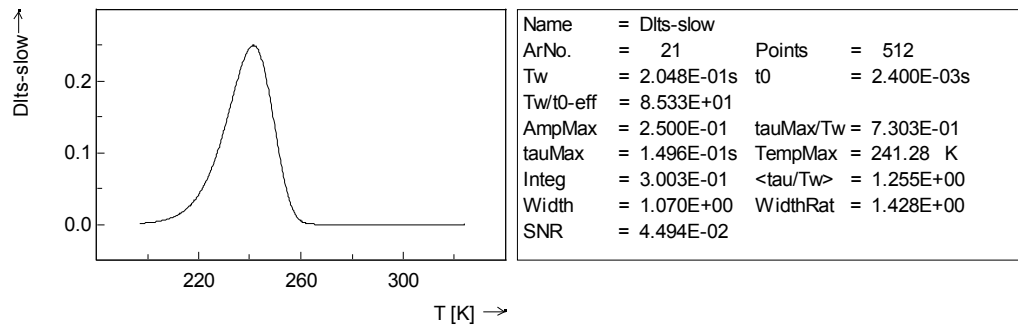
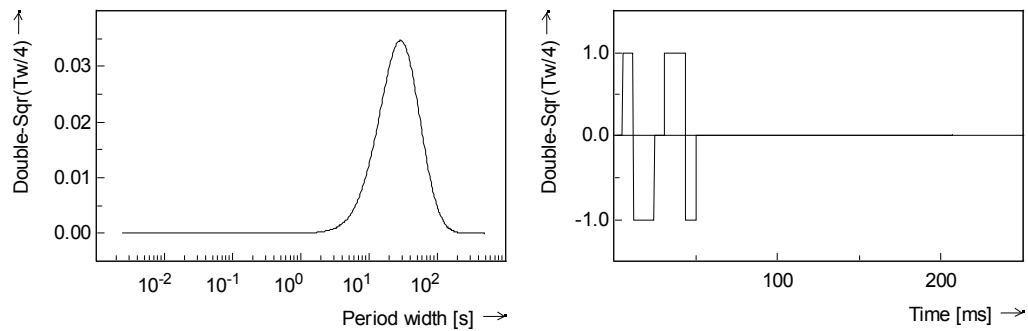
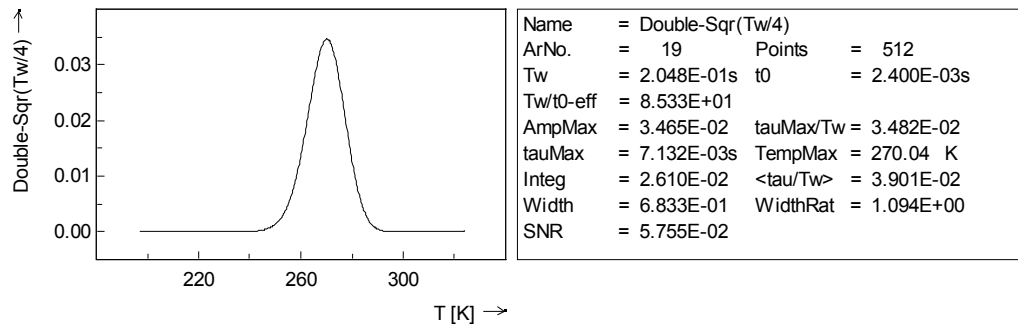
# DTS Manual

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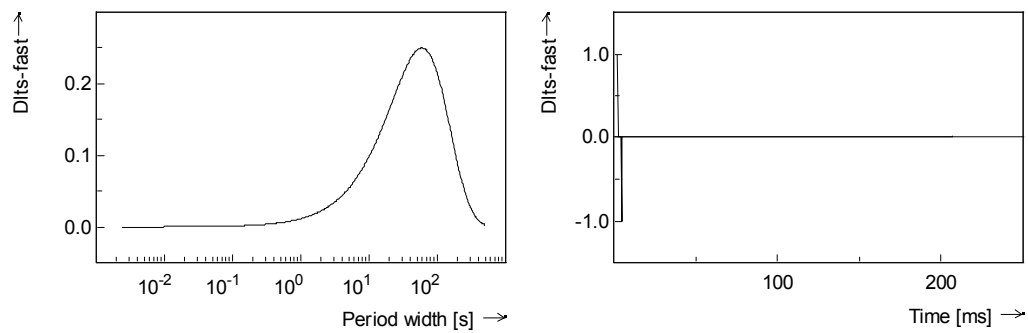
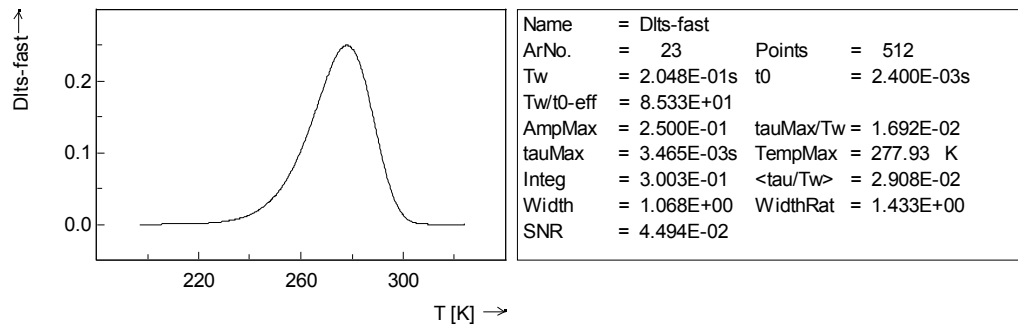
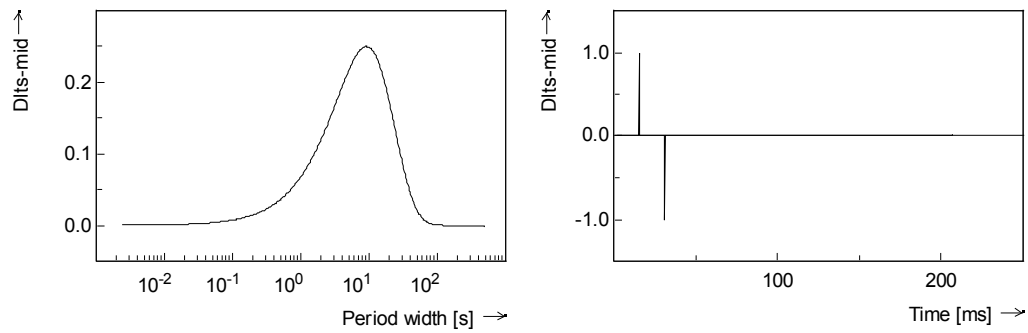
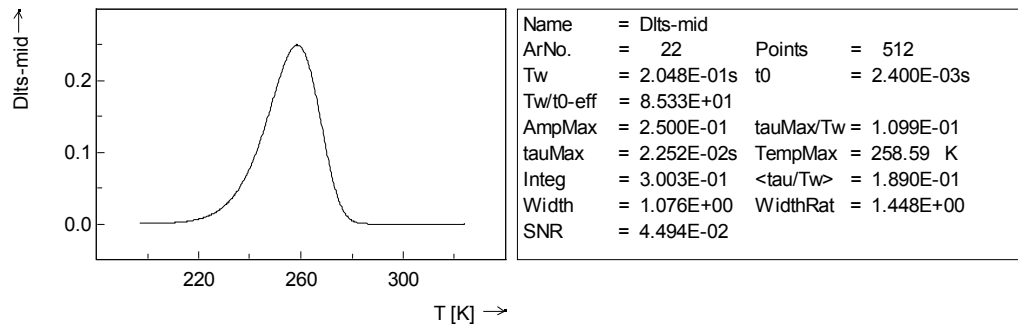
# DTS Manual

## Correlation functions



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## ITS Isothermal Transient Spectroscopy

In opposit to tempscan measurements of the Digital DLTs are these kind of measurement done at a fixed defined temperature. Transient measurements are done under systematically automatic variation of one or two measurement parameters. The aims of these measurements are : Trapconcentration profiles, direct traplevel capture cross section determination, field dependance emission determination but also emission time constant measurements for Arrhenius plot determination for trap energy and capture cross section calculation. Two different kinds of are supported:(formulars see DLTS theory chpt.1.2-1.3)

### 1. Direct Transient analysis

emission transient measurements under variation of bias voltage and pulse voltage condition for a direct analysis of every transient and the results if it.

### 2. Period widths scan analysis

emission transient measurements under variation of the period width  $T_w$  (**so called Periodwidth scan**) and one other parameter like bias/pulse voltage or sample temperature for a maximum analysis.

Both measurements do have its advantages.

The **direct transient analysis** is quite a fast tool for measureing and evaluating the above values. It also works well for sensitive signals if the no. of averages is high enough (measurement time). Every measured transient can be (but must not be) saved. The software supports automatically the desired (and only the desired) evaluation due to the kind of parameter variation (use:evaluate) as there are:

Transient measurement with **constant  $T_w$**  and variation of:

	Evaluation
Pulse voltage @ fixed reverse bias voltage	- Trapcon. prof.1, field dependance
Reverse bias voltage @ fixed pulse voltage	- Trapconcentration profile 2
Rev. bias and pulse voltage @ fixed pulse <b>hight</b>	- Trapconcentration profile 3
Pulse width @ fixed voltages (linar)	- Capture cross section (Traplevel)
Pulse width @ fixed voltages (logarithmic, MOS)	- Capt. cross sect. (Surface States)

A necessity for these measurements with reliable results is a very stable (better 0,1 K) temperature. Also the value for the periodwidth  $T_w$  should be selected carefully.  $T_w$  should be 3 to 8 times the emission time constant of the transient (see example below) to be in an optimal time scale and sensitivity range. This guaranties a very well measured transient(s) with a good resolution to evaluate the changes of the transient results (amplitude or  $\Delta C$ , timeconstant  $\tau$ ) with the varied measurement parameters. All above is valid for the use of measurements with constant period width. The DLTS system also offers same measurements using so called **variable periodwidth** transient measurements. Compared to the constant periodwidth measurements these ones does have advantages as well as limitations as there are:

1. The transient measurement is optimized automatically by the software. Only the start value for  $T_w$  has to be defined that way, that a transient is detected.
2. The software follows up  $T_w$  due to a change of the transients timeconstant  $\tau$  caused by the

variated parameter.

3. Due to the fact, that  $T_w$  is not constant,  $\Delta C$  values can not be compared to the variated parameter. Only the Amplitude (for trapconcentration profiles or capture cross section determination) or the directly evaluated time constant  $\tau$  (for field dependance emission determination) for an evaluation vers. the variated parameter.

As a standard the constant period width measurements should be used. Only if a large timeconstant variation with the variated parameter is observed, a variable period width measurement is useful.

The use of the Isothermal Transient measurements should be shown on an example. It is a capture cross section determination of a trap level. That means, that transients are measured under variation of the pulse width, using a constant period width  $T_w$ . The short pulses are generated with a e.g. HP 8116 pulsgenerator and an optional fast pulse interface for the DLTS electronics.

Before starting the measurement itself, the measurement parameters 'Temperature' and 'Periodwidth  $T_w$ ' have to be defined and optimized as well as the reverse bias and pulse voltage. This is done directly by measuring C/V, IV curves and single transients checking the results, changing the parameter, measuring again, and so on, till the parameter is optimized. A special measurement task 'Check measurement' makes this quite easy.

1. Reverse bias and pulse voltage ( $U_R$  and  $U_P$ )

Both voltages should have been known from former measurements (tempscan, C/V's, I/V's). An ITS measurement should be done on 'known' samples. A C/V and I/V check at the desired measurement temperature is always useful, to get the correct shallow doping (C/V) and the leakage current at that temperature.

2. Temperature

The measurement temperature should be selected that way, that the determined level does have an emission time constant of app. 1ms to 100ms. It is checked with a single transient measurement (see fig. 1). The time constant is given at the top,  $\tau(a1, b1) = 1,365$  ms in fig.1. The test measurement can be done with standard period width of 20ms or 200ms.

3. Periodwidth  $T_w$

After the temperature has been defined the period width can now be optimized. For an optimal signal, it should be 3 to 8 times of the emission time constant. The value that should be looked at is ' $\tau, ts/T_w = 0,13, 1,09$ ' (for the example in fig. 1), means  $\tau/T_w = 0,13$  and  $ts/T_w = 1,09$ .  $\tau$ =emission time constant,  $T_w$ =period width,  $ts$ =time till the measurement meets the noise level.  $\tau/T_w$  gives the relation between the emission time constant and the period width (transient measurement time) for this example one time constant is passed after 0,13 of  $T_w$  or during  $T_w$   $1/0,13 \approx 8$  timeconstants are measured.  $ts/T_w$  defines whether and how long only noise has been measured.  $ts/T_w = 1$  is the optimal. It means, that the transient has been exactly measured to the detection limit (noise level),  $ts/T_w > 1$  means the measurement has not reached the noise level,  $ts/T_w < 1$  means that the transient measurement has partly measured only noise. For the example,  $T_w$  can be enlarged by app. 10% till reaching the noise level. The quotient  $ts/T_w$  can not always be optimized to 1, specially for small emission amplitudes is this not possible. The main value for optimizing  $T_w$  should be  $\tau/T_w$ .

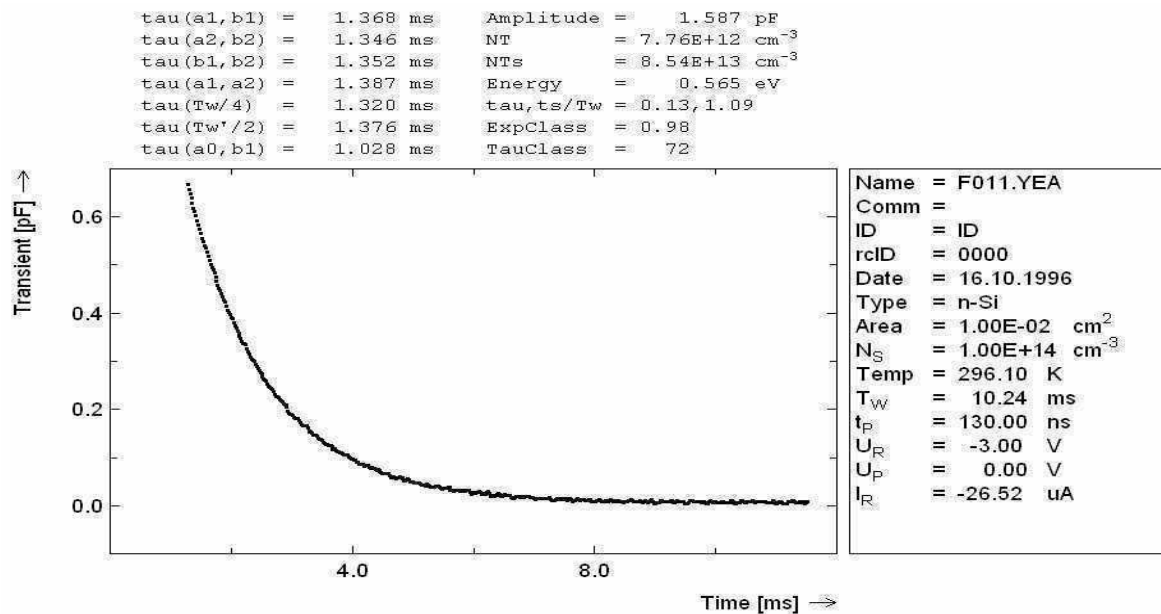


fig. 1: example for an optimized transient measurement

After the constant measurement parameters  $T$ ,  $T_w$ ,  $U_p$ ,  $U_R$  has been defined the varied ones has to be defined too, for this example, the pulsewidth. The start and end values as well as the no.'s of measurements between the limits can be set in the software. The selection of the range the parameter shall be varied depends on the physical values of the to be measured sample specific constant:

#### 1. For Trapconcentration profiles

The voltage values define the information depth (by the space charge region) in which a trapconcentration profile can be determined. The space charge region depends also drastically from the shallow doping of the sample. Therefor the information depth depend mainly from the used sample and only secondely from the usable voltage range. The effective depth can be checked using a measured  $C/V$  curve and the evaluation of the space charge region vers. bias voltage of the DLTS software. The decision which voltage, pulse voltage  $U_b$ , Reverse bias Voltage  $U_R$  or both ones with a fix difference (pulseheight  $U_R - U_b$ ) between it, shall be varied depend on the kind of profile and the trapconcentration in relation to the shallow doping. For strong profiles (more than a factor of 10 between maximum and minimum value) and high concentrations the constant pulseheight method is the best. For small profiles or small signals the variation of the pulsvoltage  $U_p$  might be the best. Only in few cases the variation of the reverse bias voltage will give the best results. The evaluation formulars should be clear before starting this measurement, (see e.g. Theory part of the manual or application note, or any semiconductor book)

#### 2. Electrical field dependance of the emission process

The argumentation follows exactly that one above, only exchanging 'information depth' by 'electrical field' at the trap.

#### 3. capture cross section determination

The measurement uses the fact, that a trap level is only partly filled, if the filling pulse width  $t_p$  is small enough compared with the capturing time constant  $\tau_c$  of this level. The concentration of the captured carriers is detected by the normal emission transient, using the amplitude or  $\Delta C$  value. The capture time constant depends mainly on the capture cross section, the desired measurement result, and the shallow doping  $N_s$  (Chpt. 1.3 DLTS Theory). For that, not every capture cross section  $\sigma_{n,p}$  can be measured in every sample because the fastest pulse is limited to 10ns. Large  $\sigma_{n,p}$  ( $\sigma_{n,p} > 1e-14 \text{ cm}^2$ ) can only be determined in low doped samples ( $N_s < 1e15 \text{ cm}^{-3}$ ). As a hint for the start value of the pulse width (for Silicon) the following approximation can be used:  $t_p(\text{start}) = 10\text{ns}/(\sigma_{n,p} * N_s)$ , with  $t_p$  minimum = 10ns better 20ns. It's an experience that smaller pulsewidths, even if the pulse generator can supply it, does not completely reach the sample through standard BNC cables. For the example below:  $\sigma_{n,p} = \text{app. } 1e-13 \text{ cm}^2$ ,  $N_s = \text{app. } 1e13 \text{ cm}^{-3}$  give  $t_p(\text{start}) = 20\text{ns}$ .

For the selection of the largest pulsewidth that should be used for this measurement, a similar argumentation as for an optimized emission transient measurement can be used. Approximate 8 timeconstants, in this case capture time constants  $\tau_c$ , should be measured to get an optimized capturing transient. A similar approximation as done for the  $t_p$  start value gives  $t_p(\text{End}) = 100\text{ns}/(\sigma_{n,p} * N_s)$ . For this estimation as a value for  $\sigma_{n,p}$  the result of an Arrhenius plot from a tempscan measurement can be used although the evaluated values for the capture cross section from an Arrhenius plot and from this direct measurement differ due to the entropic factor  $X_{n,p}$  (see DLTS theory e.g. our DLTS basic manual).

The increment values for all varied parameter is automatically calculated due to the no. of transients that the user likes to measure between these start and end values (input: no. of points). A capture cross section measurement as an example for transient measurement under varied parameter is shown in fig. 2. It shows very nicely the trick, how the normally very fast capture transient ( $\tau_c = 1\text{ns}$  to  $1000\text{ns}$ ) can be measured.

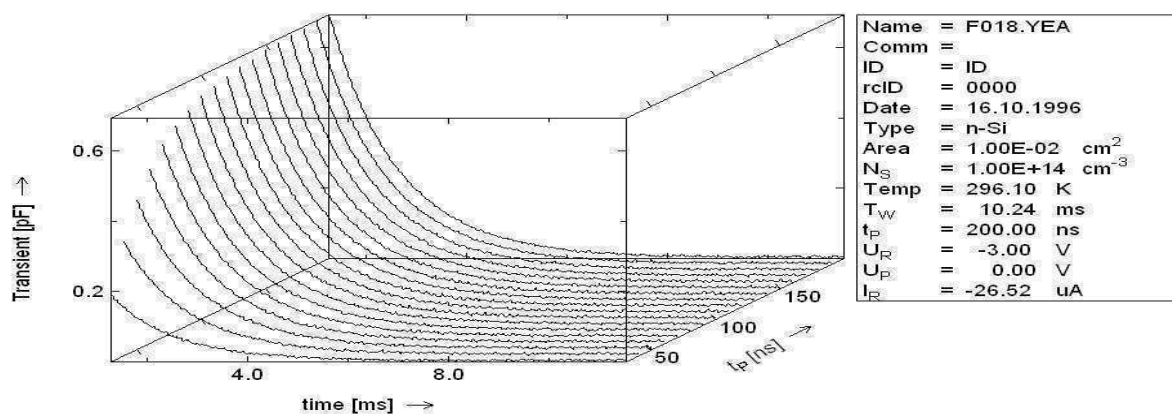


fig. 2: Set of transients with varied pulsewidth

The x/y coordinates give the measured emission transients in Capacitance ver. time. The 3rd dimension z-axis gives the varied parameter, the pulse width.

(Parameter:  $T_w=10,24\text{ms}$ ,  $t_p(\text{start}) = 30\text{ns}$ ,  $t_p(\text{end})=200\text{ns}$ , no.'s =18)

Looking at the y/z layer of this 3d plot, the capacitance transient start value (close to transient amplitude) vers. the pulse width, it can be seen, how this start value increases with increasing pulse width due to a successively enlarged filling level of the traps. This y/z layer gives directly the capture transient constructed by the measured emission transients amplitude. The measurement of the very fast capture transient has been transferred to several

measurements of quite slow emission transients. The amplitudes or coefficients vers. pulswidth is now be used for the capture cross section calculation as mentioned above.

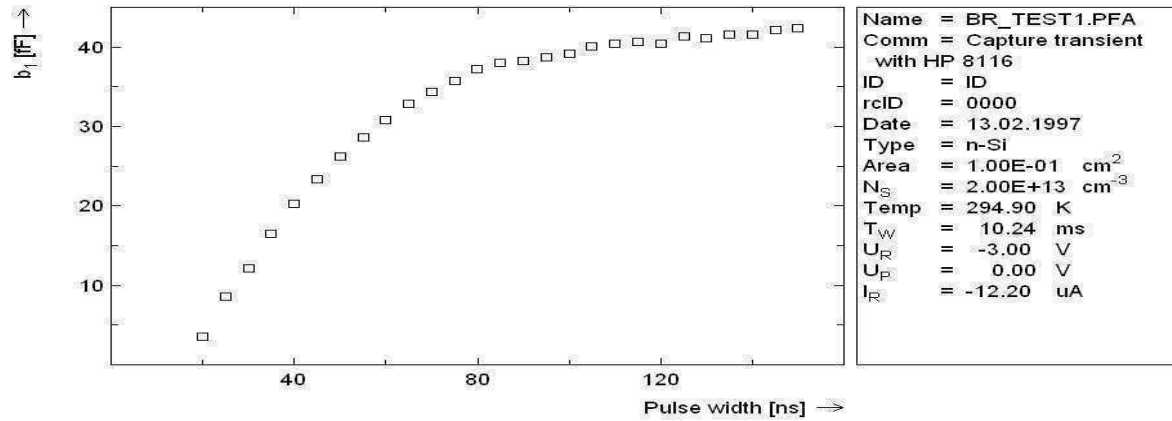


fig. 3: capture transient,  $\Delta C$  vers. pulse width

Fig. 3 gives the constructed capture transient using the  $b_1$  coefficient. The direct analysis (not shown here) gives then the vales for  $\tau_C$ ,  $A_C$  (captureing timeconstant and amplitude) from which  $\sigma_C$  and  $N_T$  are calculated. The second mode for an evaluation of these data is shown below in fig. 4. It's not using the direct Fourier analysis but the logerithimizing of the

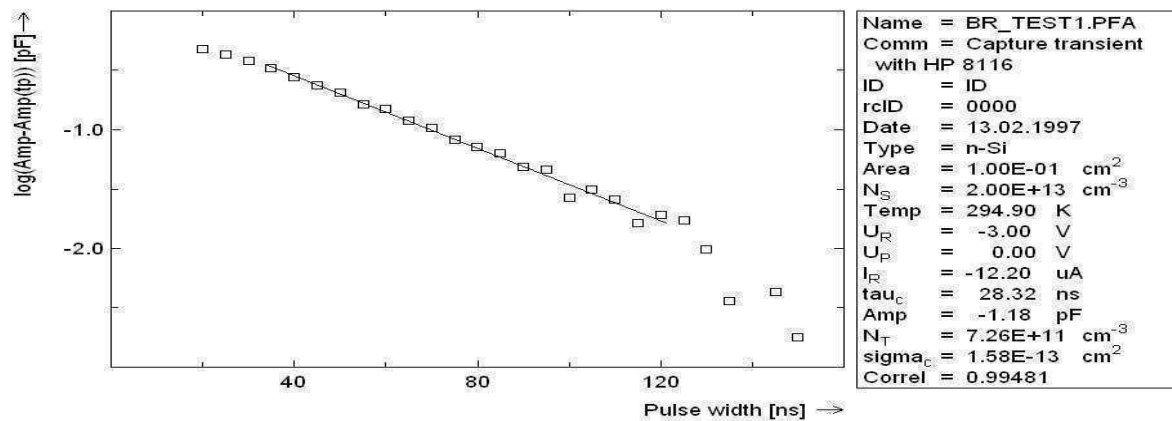


fig. 4: capture cross section evaluation plot  
logarithm of the emission amplitude vers. pulse width

transients amplitude plotted vers. the pulsewidth.. The slope of these data also gives  $\tau_C$ ,  $A_C$  and then  $\sigma_C$  and  $N_T$ .

In a similar way as shown above for the measurement and evaluation of the capture cross section the depths profile and field dependance measurements and evaluations are done. The software automatically supports only that evaluations, thats possible for the measured data. All evaluation given is standard literatures are implemented and can be selected in the software.

The **Periodwidthscan** is a special measurement mode in the isothermal transient measurement module. Similar to a tempscan gives a periodwidthscan the timeconstants of emission processes by a maximum analysis. But while in a tempscan the emission time constant is changed by temperature and measured with a constant periodwith  $T_w$  in which at the maximum the emissiontransient fits best, during a periodwidthscan the

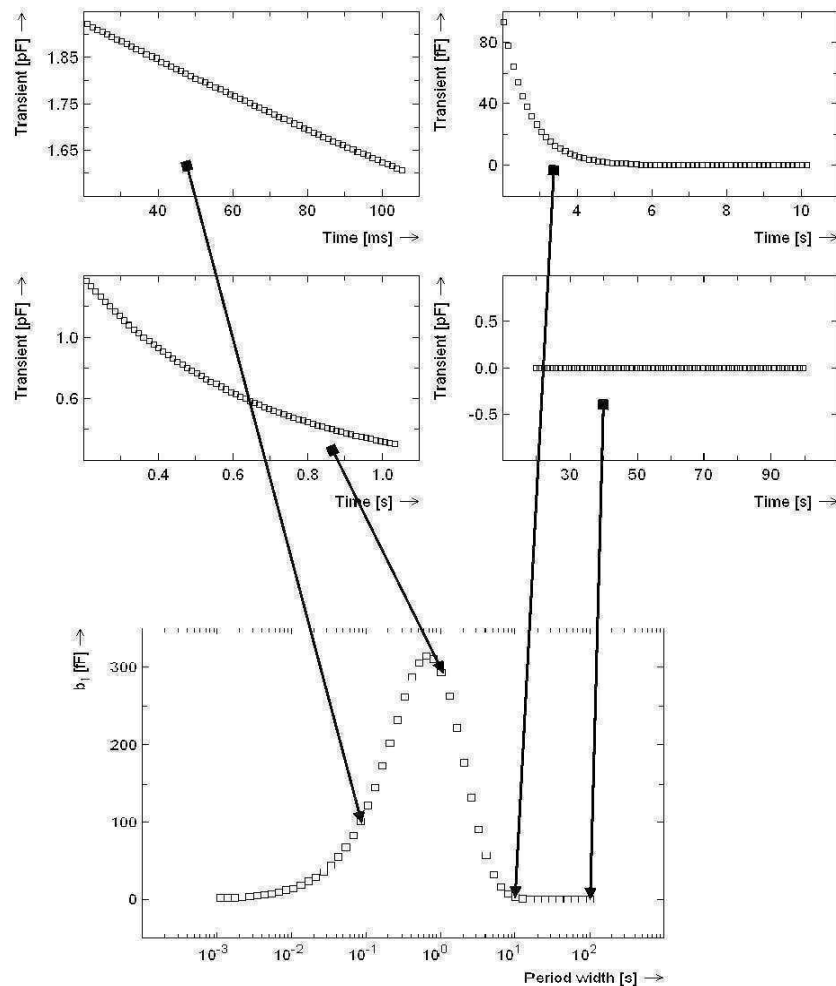
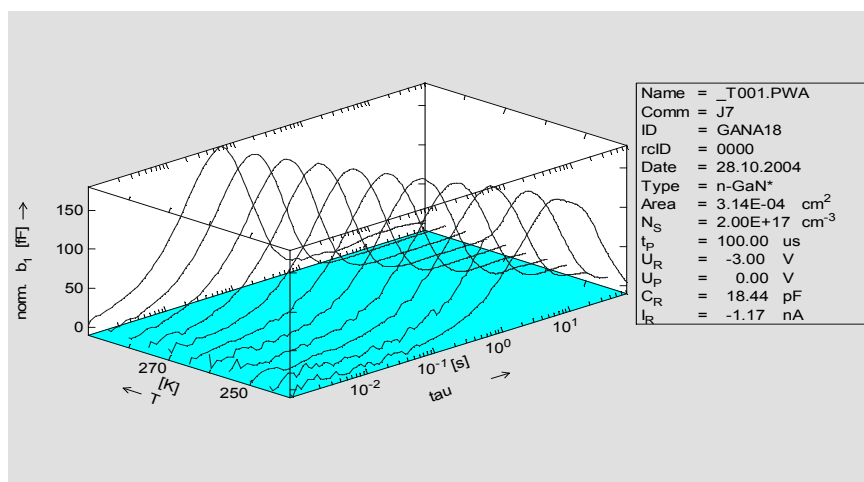
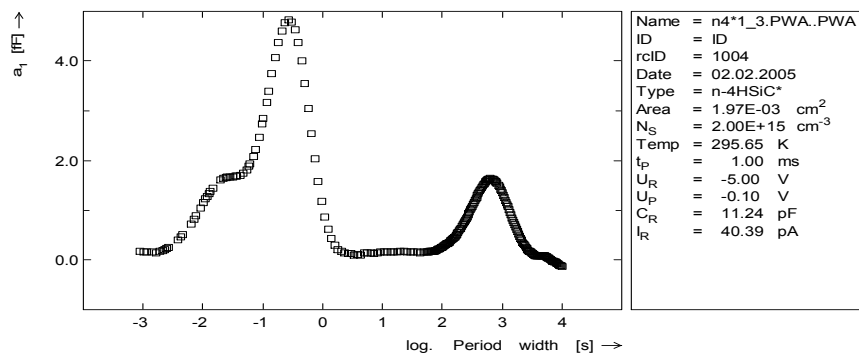
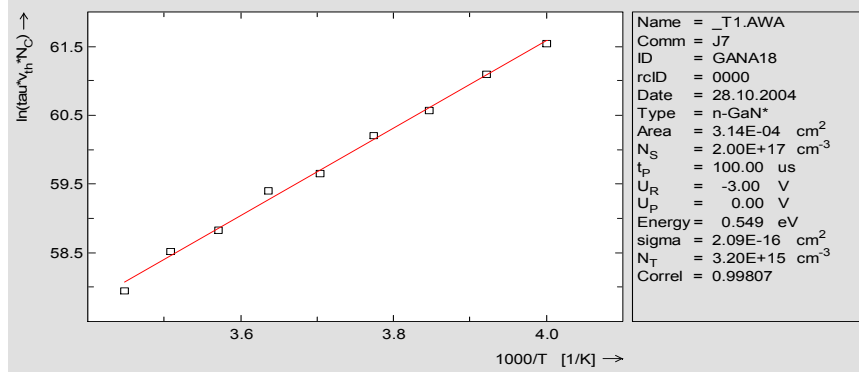


fig.5: periodwidthscan constructed by transients measured at different periodwidths

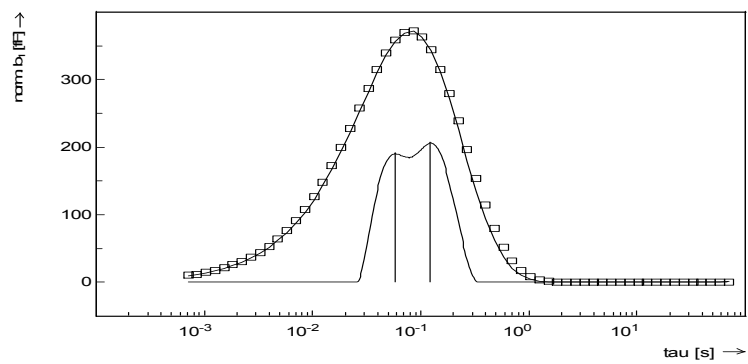
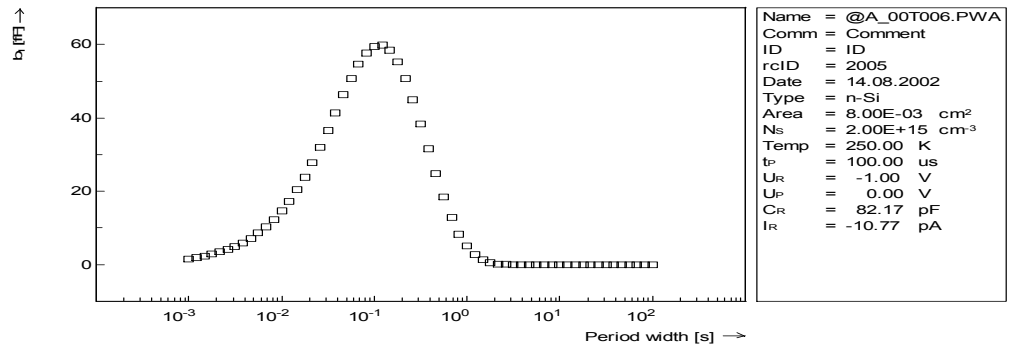
emissionprocess is kept constant and the measurement parameter  $T_w$  is automatically varied. At the maximum however the periodwidths fits best to the emissiontransient and it gives similar to the tempscan the timeconstant and concentration of the level causing the emissiontransient

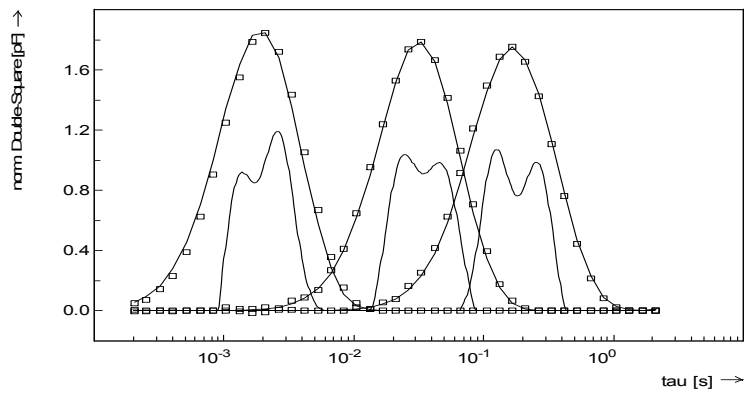
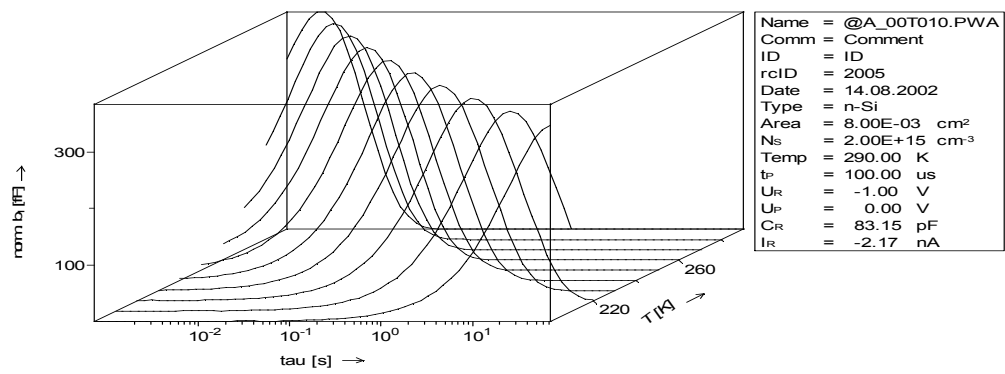


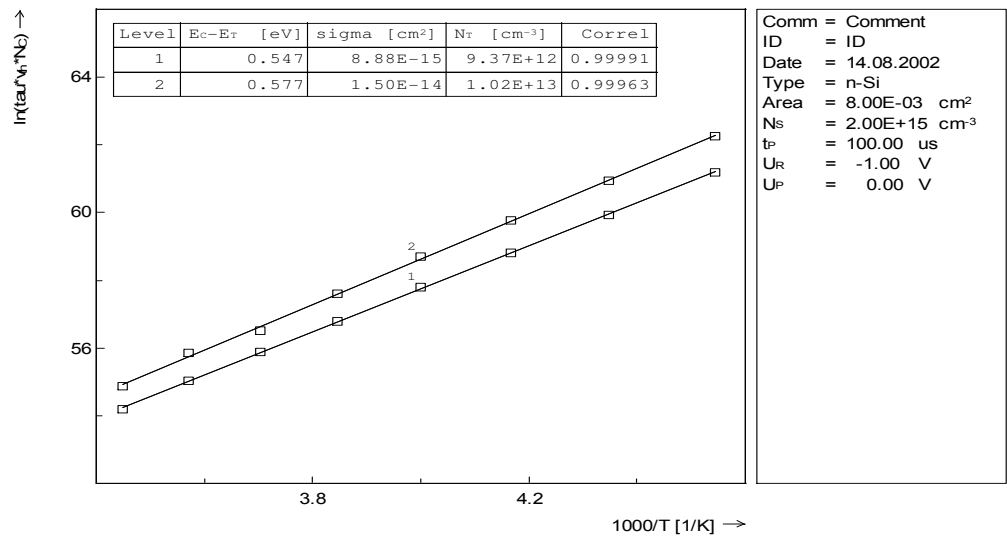




# HERA







the emission process is kept constant and the

## High Energy Resolution Analysis Deep Level Transient Spectroscopy

The High Energy Resolution Analysis (HERA) uses quite new or well known mathematic procedures as:

**Fourie** transformation, **Laplace** transformation, multi exponential **transient fit**, **ITS** (Isothermal Transient Spectra) **signal refolding**, **tempscan signal refolding**

for separating two or several overlapping emission processes. All procedures base on the exponentiality of the emission process (see DL Basics manual) shortly given for n-type material below as:

1 level ;  $n \gg p$  ;  $n \gg N_T$  (DLTS approximation, n-type )

$N_T$  = Trap level concentration;  $\Delta H_T$  = Trap level energy;

$\sigma_T$  = capture cross section;  $X_T$  = Entropic factor of the the trap level

For the number of occupied traps after filled at  $t=0$  we get:

$$1.1 \quad n_T(t) = N_T * \exp(-t/\tau)$$

with the emission time constant

$$1.2 \quad \tau = \sigma_T * X_T * \exp(-\Delta H_T/kT)$$

For characterizing the trap,  $N_T$  ;  $\Delta H_T$  ;  $\sigma_T * X_T$  is needed and evaluated by using the

Emission amplitude  $= N_T = n_T(t=0)$  and the

Arrhenius plot  $= \ln(\tau)$  vers.  $1/T$   $\longrightarrow$

slope  $= \Delta H_T$  ; intercept  $= \sigma_T * X_T$

$n_T(t)$  is observed and measured by a Schottky diode capacitance with:

$$1.3 \quad C(t) = C_0 - \Delta C * \exp(-t/\tau);$$

as capacitance transient and

$$1.4 \quad \Delta C = C_0 * N_T / 2N_S * SCR_{Corr}$$

as transients amplitude with

$$1.5 \quad C_0 = \epsilon_0 * A/w_r$$

as equilibrium capacitance.

In the software of our digital DLTS systems (FT 1030, DL8000, and the new HERA DLTS) there are two principle different evaluations implemented for evaluating the timeconstants  $\tau$  and amplitudes  $\Delta C$  from the measured  $C(t)$  transients, the Direct Analysis and the Maximum Analysis.

### 1. The Direct Analysis

directly uses the measured transient and the coefficients calculated by a Fourier transformation for directly evaluating the timeconstant  $\tau$  (see DLTS Basics manual for formulars). The amplitude is calculated by an extrapolation of the measured transient  $C(t)$  to time  $t=0$ . The values for  $\tau$  and  $\Delta C$  are always calculated for every measured transient independant of the real shape of it, but all calculation are only valid for a single exponential emission process. Any additional or different timeshapes overlayed in the measured transient causes big systematical errors in the results. Therefor we are calculating the so called tau class (0 to 75 in nonlinear steps, see DLTS basic manual) as a value for characterizing the quality of the measurement and evaluation. Only tau classes above 60 can be really accepted for direct evaluations.

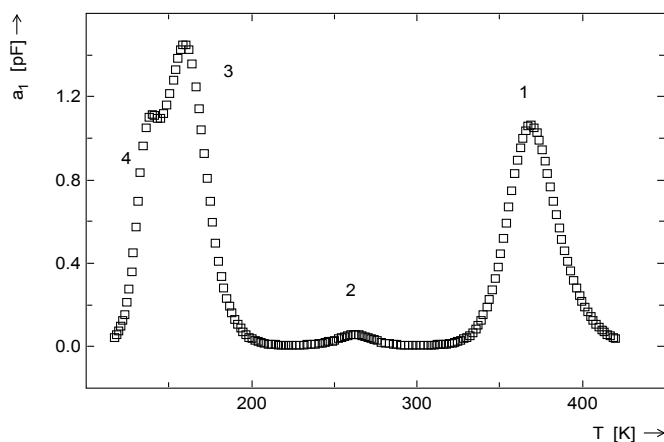
The direct analysis is available everytime if transient are measured, as a single **transient** measurement evaluation in the transient software module, in the **Isothermal Transient Spectra** module as an evaluation of transients measured under systematically changed parameters (voltages  $U_P, U_R$ , periodwidth  $T_W$ , temperature  $T$ ) and in the **Tempscan** module as a direct Arrhenius plot evaluation of transients measured as a function of the temperature.

### 2. The Maximum Analysis

uses correlation functions (28 independant ones) for calculating  $dC$  (tempscan or periodwidthscan amplitudes) values of every measured transient. These  $dC$  values are measured as a functio

n of the temperature for a tempscan or as a function of the periodwidth for a periodwidthscan. The plots  $dC$  vers.  $T$  or  $dC$  vers.  $T_W$  show a maximum that gives the timeconstant  $\tau$  and the temperature  $T$  of the observed emission process. Several

fig. H.1: Tempscan with different traps



correlation functions (of a tempscan) or several periodwidth measurements (at different temperatures) give several ( $\tau, T$ ) pairs for further evaluations by an Arrhenius plot. The Arrhenius plot gives (as for the direct analysis)  $\Delta H_T \sigma_T * X_T$  of the trap, the maxima height (averaged over that of the different correlation functions or the different periodwidthscans) gives the amplitude  $\Delta C$  and the trapconcentration  $N_T$ .

Also these maxima evaluations are only valid for single exponential emission processes. Similar to the direct analysis systematical errors appear if the exponentiality is not strictly fulfilled. That means, that several trap levels present in a semiconductor sample can only be correctly evaluated if its timeconstants differ enough to be detected as single events, and not as an overlapp of several processes. (transients will always be measured independant of having one or several overlapping processes). This is demonstrated in the diagram above, a tempscan measurement of several traps, where trap 1 and 2 are isolated and can be evaluated without any problems, and trap 3 and 4 are overlapping and the results (Arrhenius plot, max. hights) may give incorrect values. For ITS and direct evaluations the argumentation is similar. At the end, this limits the energy resolution several levels of the DLTS measurements. The High Energy Resolution Analysis DLTS now solves this limits by mathematics. We now look at the formulars above for the case of several levels (emission transients) overlapping eachother. All othr conditions are the same compared to above. We get for

2 or more levels

$$1.6 \quad n_{Ti}(t) = N_{Ti} * \exp(-t/\tau_i); \quad \tau_i = \sigma_{Ti} * X_{Ti} * \exp(-\Delta H_{Ti}/kT)$$

$$1.7 \quad C(t) = C_0 - \Delta C_1 * \exp(-t/\tau_1) - \Delta C_2 * \exp(-t/\tau_2) \dots$$

$$1.8 \quad C(t) = C_0 - \sum_{i=1}^{i=N} \Delta C_i * \exp(-t/\tau_i) \quad ; \quad N = \text{max. number of traps}$$

as an expression for the measured capacitance transient  $C(t)$  if a discrete number of overlapping processes is estimated

or we get

$$1.9 \quad C(t) = C_0 + \int_{s=0}^{s=\infty} (F(\Delta C) * \exp(-s*t) * ds) \quad ; \quad \text{substituting } s=1/\tau$$

for a continuous number of overlapping processes in the measured transient.

It's to see, that 1.8 is basically a sum of exponentials and that 1.9 gives an Integral over exponentials. The intergal is a so called Laplace transformation, (time to 1/timeconstant) correctly an inverse Laplace transformation due to the negative argument in the exponential.



For our

### 3. Direct HERA evaluation

we are now using formulars 1.8 and 1.9, or better we are using evaluation procedures using these formulars developed by some groups. One is the so called FTKAREC software from the University of Freiburg Germany, where the user (you) have to licence this software and download it from the Universities homepage or as freeware from Dr. Stephen Provencher (sp@s-provencher.com) under acceptance of his ownership of the software. The FTKAREC software only uses formular 1.9, the inverse Laplace transformation, the software from Dr. Provencher uses also this inverse Laplace transformation, but also a discrete based calculation, a multi exponential transient fit, based on formular 1.8.

The result of this inverse Laplace transformation is an amplitude destribution,an amplitude versus a time constant plot.  $F(\Delta C)$  the amplitude expression in the intergral 1.9 consists of delta functions times the amplitudes.

$$2.0 \quad F(\Delta C, s) = \delta(ds * \Delta C(s) > 0) * \Delta C(s)$$

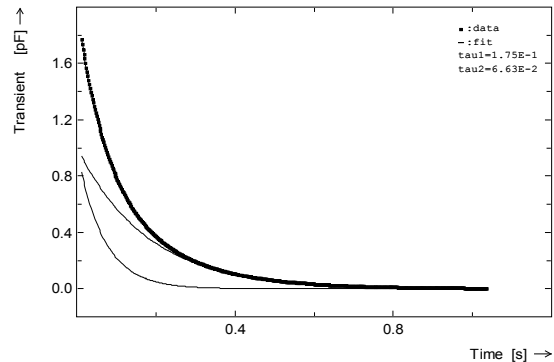
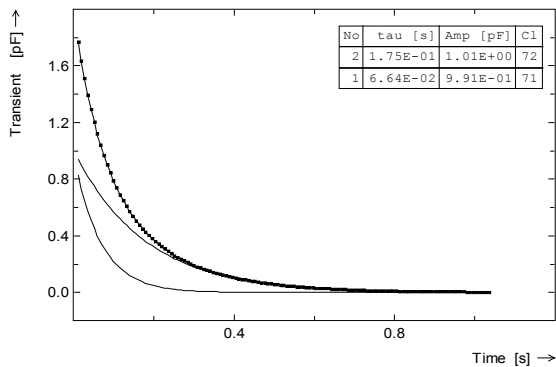
the delta function  $\delta$  becomes 1 for any valid reciprocal timeconstant  $s$  (in  $C(t)$  added emission process) and will then add the evaluated amplitude to the amplitude distribution. Even for very good signals, this  $\Delta C$  calculation is quite sensitive and can fail. Therefore we always will check and correct the different amplitudes of the found (by this Laplace transformation) emission processes (timeconstants) by fitting the measured transient  $C(t)$  under variation of these  $\Delta C(s)$  values. The corrected  $\Delta C(s)$  values and the analysed  $\tau$  values give the results of the deconvulated transients using the Laplace transformation.

Similar to this inverse Laplace transformation the multi exponential transient fit using Provenchers DISCRETE algorithm gives the timeconstants and, again after an additional transient fit, the amplitudes of the emission processes found to be part of the measured transient.

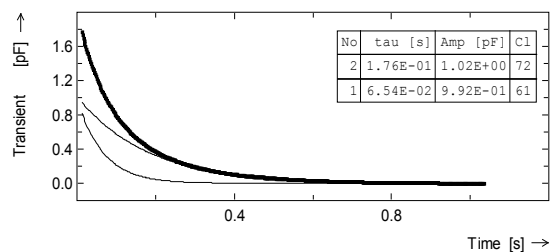
These three different deconvulation calculations are selectable in our software as an option for our direct analysis.

Direct HERA evaluation examples

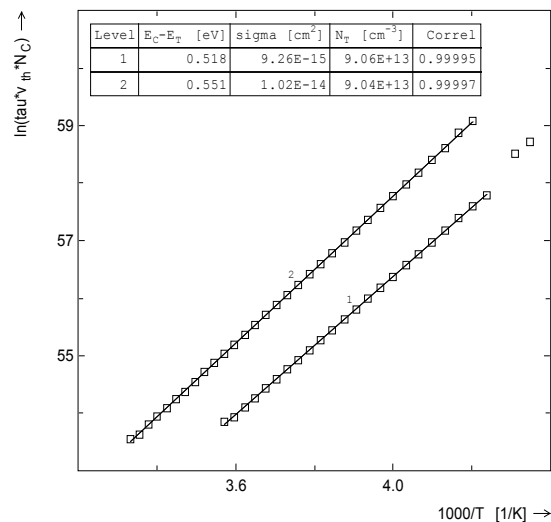
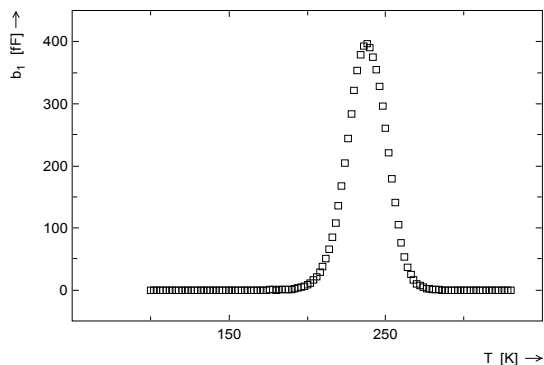
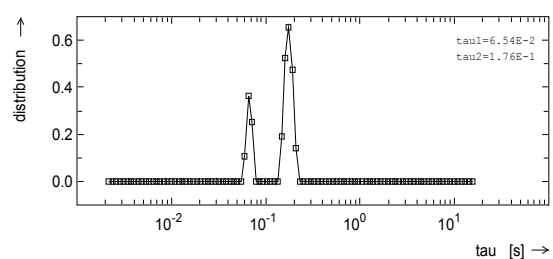
One simulated transient with 3 different evaluations. (2 levels, 1.0pF amplitudes)  
On the upper left the provencher discrete evaluation, on the upper right the 2 level fourie



fit and right the inverse Laplace transformation with the timeconstant distribution. It's to see, that the amplitudes in distribution are not correct. The given amplitudes in the transient pot are correct after fitted with the transient (as explained above).



On the bottom right the result of a Laplace transformation of a simulated tempscan (128 points of each transient are saved during a tempscan).  
On the left the tempscan signal of the direct evaluated Arrhenius plot. Not even a should is seen in the tempscan signal dC vers. T.



Parallel to our HERA evaluation of the measured transients, the direct HERA evaluation, we have developed a deconvolution software for the maximum analysis.

#### 4. Maximum HERA analysis.

The standard maximum analysis is used to calculate the timeconstants and the amplitudes of **one exponential** emission process observed by capacitance transients. It has been developed to reduce data and to get a better sensitivity. In that times (late 70's early 80's) the data reduction function, the so called correlation function, has been made by a hardware correlator, a lock-in amplifier or a box-car integrator. As explained in the 'DLTS basic' manual our digital systems (FT 1030, DL 8000 and now the HERA-DLTS) are using software correlator functions. Although the measured transients and the direct analysis will give all values for an Arrhenius plot analysis, the maximum analysis as an independant evaluation to the direct one, gives sometimes more information (due to the fact that more transients for each timeconstant has been measured) or more accepted information by the users, because the analysis has been accepted for DLTS during years. This has been a reason for s not only to use a deconvolution software for transients as Laplace DLTS ect., but also to develop a deconvolution software for this well known maxima analysis (Tempscan and Periodwidthscan). The calculation itself is done numerically, a closed analytical formular for it is not existing. It's a fact, that all used mathematic calculation will give some results, valid or not. It only should be used as a help to get information out of the measurements that without it can not (or not so easy) be used. But the results have to be checked by the physical modell. This should be done by our tempfit or periodwidthscan fit calculations. Only if the results from the deconvolution and than from the Arrhenius plot describe the measured data completely than it can be used as a measurement result in the physical view.

To explain the deconvolution (refolding) we start from the capacitance transient

$$2.1 \quad C(t) = C_0 - \Delta C * \exp(-t/\tau)$$

using a correlation function

$$2.2 \quad F_{\text{corr}}(t) = \left[ \int_0^1 f(t=0, t=Tw/2) \right] + \left[ \int_0^{-1} f(t=Tw/2, t=Tw) \right]$$

f might be (nearly) any function with max. amplitudes normalized to +/-1, Tw = the periodwidth (total measurement time for the transient) with

$$2.3 \quad \int_0^{Tw} F_{\text{corr}}(t) dt = 0$$

or in words, a correlation function is a normalized function with equal areas below the function from t=0 to t= Tw/2 and t=Tw/2 to t=Tw.

Used with a timedependant signal (as 21)

$$2.4 \quad \int_0^{Tw} C(t,T) * F_{\text{corr}}(t) dt = dC(F_{\text{corr}}, T, Tw)$$

the integral gives one so called correlated value for the time dependant signal. The time dependant signal has then be reduced to one value (dC) and a well known correlation function. Changing now the time constant  $\tau$  using the temperature (tempscan) or the periodwidth Tw (periodwidthscan), the value dC gives a maximum (**sign!** we use a maximum) that defines the time constant (at that temperature) and the amplitude. (see fig. H1)

$$C(t) = C_0 - \Delta C * \exp(-t/\tau(T))$$

$$2.5 \quad \int_0^{Tw} [C_0 - \Delta C * \exp(-t/\tau(T))] * F_{corr}(t) dt = dC(F_{corr}, T, Tw)$$

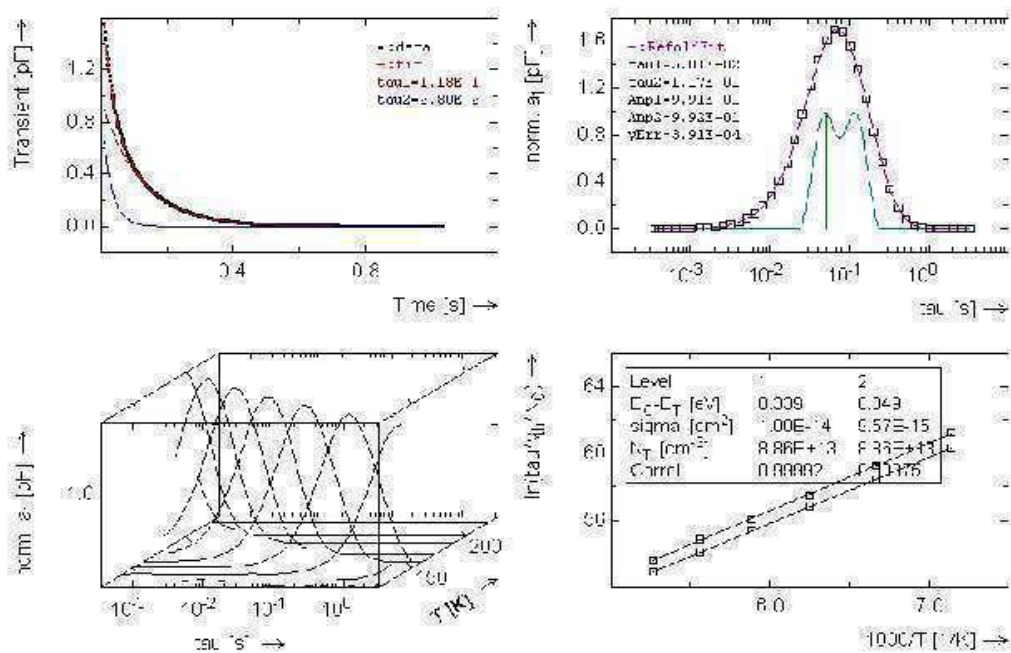
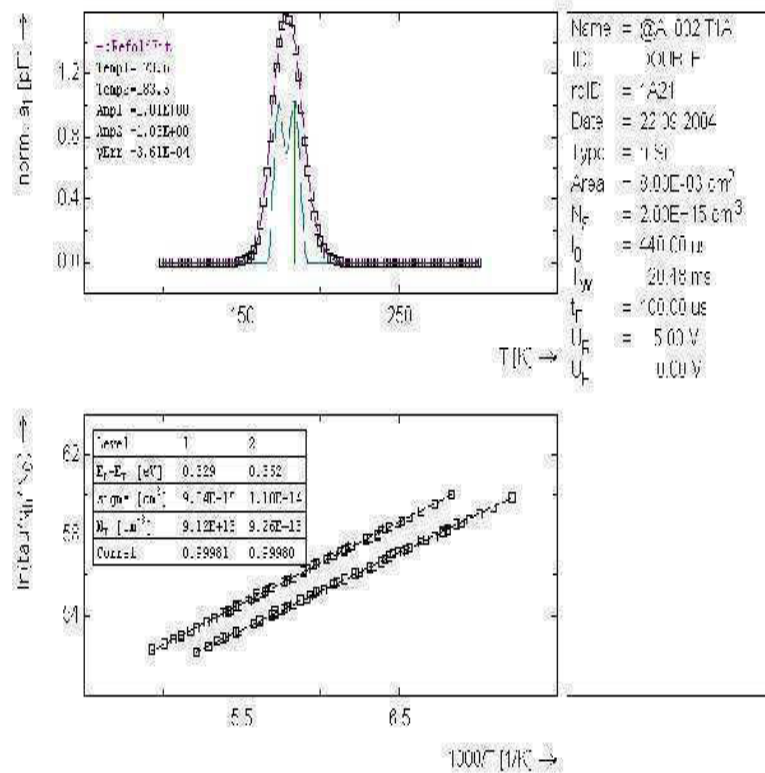
or for a number of N overlapping levels

$$2.6 \quad \int_0^{Tw} [C_0 - \sum_{i=1}^{i=N} (\Delta C_i * \exp(-t/\tau_i(T)))] * F_{corr}(t) dt = dC(F_{corr}, T, Tw)$$

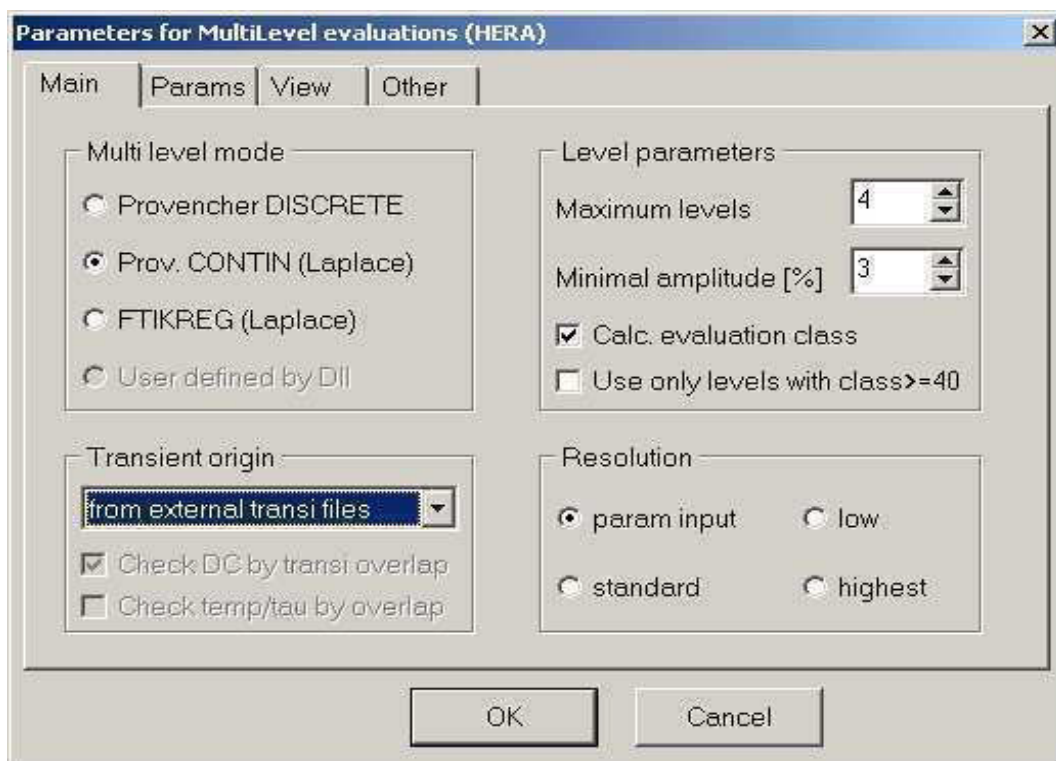
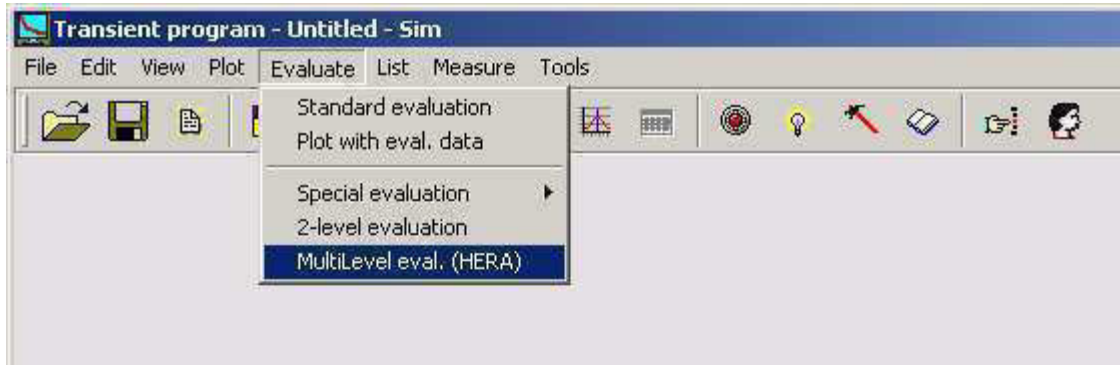
Formular 2.5 give the standard maximum analysis plots,  
for Tw = constant follows dC ver. T, the tempscan  
for T = constant follows dC vers. Tw, the periodwidthscan

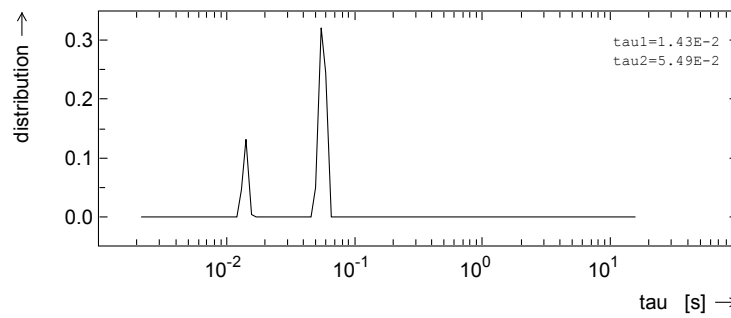
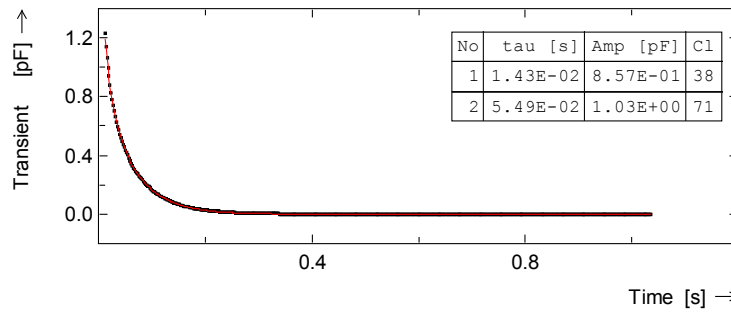
The values at the maximum, the time constant  $\tau$  and the amplitude, have to be calculated by this formula 2.5. Only for some special cases, that one used in the early days of DLTS, formula 2.5 can be solved analytically. In our software, the formular 2.5 is numerically solved to get  $\tau_{max}$  and  $\Delta C$ . For different periodwidth Tw or correlation functions Fcorr a new temscan and a new pair  $\tau_{max}$  and  $\Delta C$  for the Arrhenius plot is definened, and periodwidthscans measured at different temperatures also givenew pairs of  $\tau_{max}$  and  $\Delta C$  for an Arrhenius plot.

Maxima HERA evaluation examples.



## Direct Transient analysis





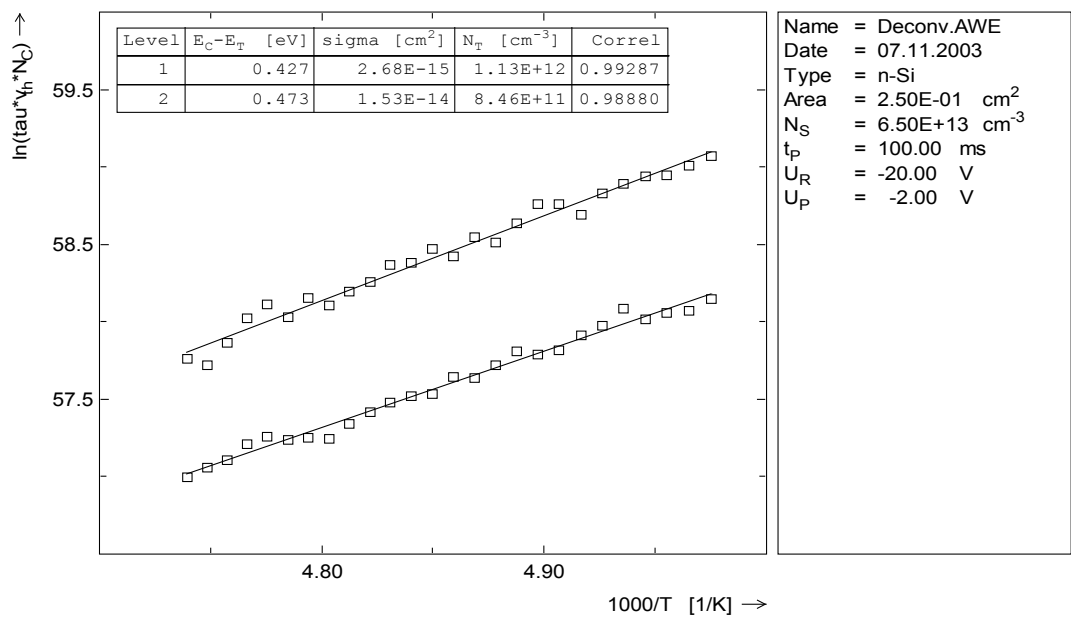
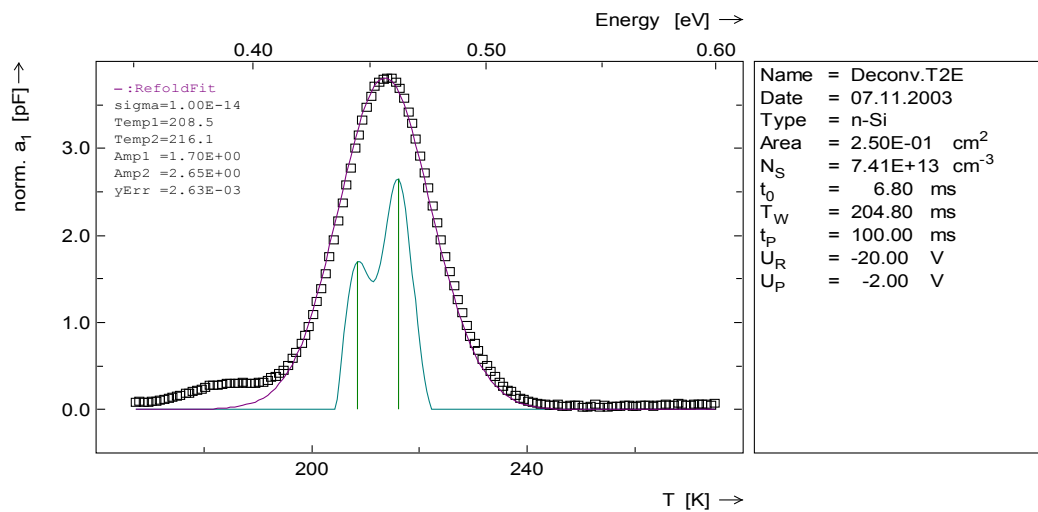
ID = ID  
Date = 23.06.2006  
Type = n-Si  
Area = 8.00E-03 cm<sup>2</sup>  
N<sub>S</sub> = 2.00E+15 cm<sup>-3</sup>  
Temp = 250.00 K  
T<sub>W</sub> = 1.02 s  
t<sub>P</sub> = 100.00 us  
U<sub>R</sub> = -5.00 V  
U<sub>P</sub> = 0.00 V  
C<sub>R</sub> = 43.92 pF  
I<sub>R</sub> = -16.02 pA

# HERA - DLTS Examples

## 1. Deconvolution of a tempscan signal (measured tempscan)

Plot 1: Tempscan signal and refolded curve with evaluated timeconstants (vertical lines)

Plot 2: Arrhenius plot using the measurement from plot 1 with different correlation functions.

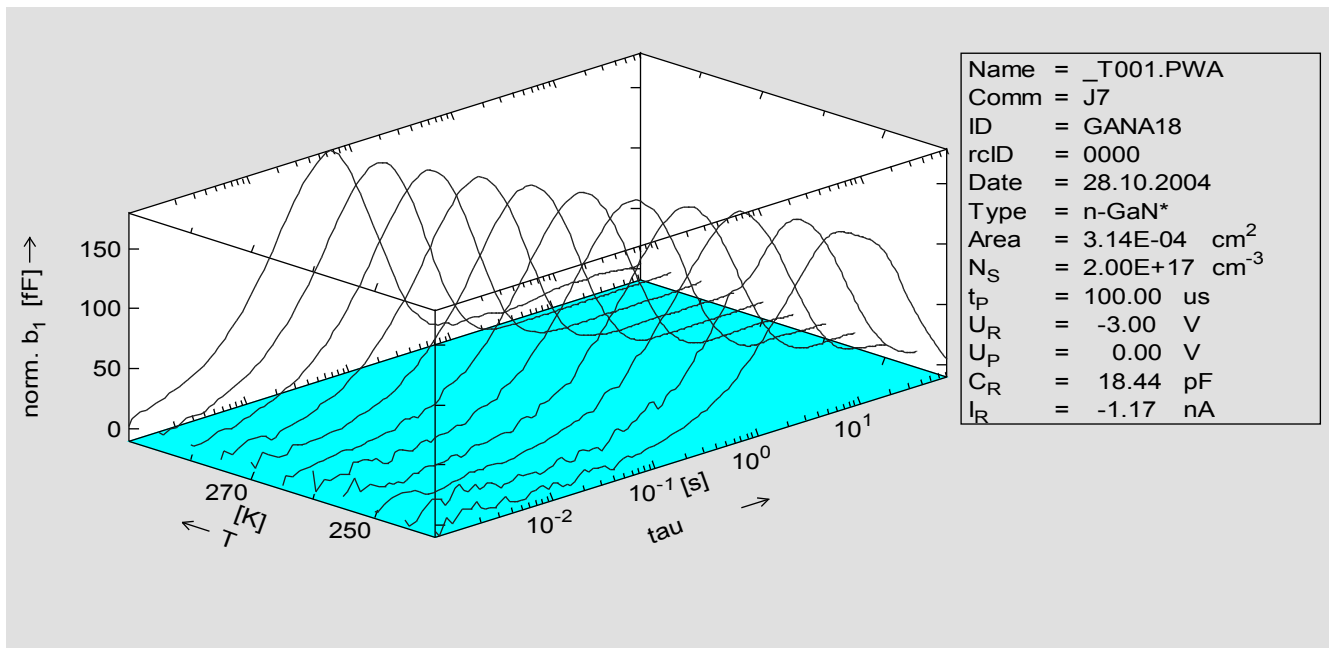




## 2. Deconvolution of periodwidthscans (similar to frequency or ratewindowscans)

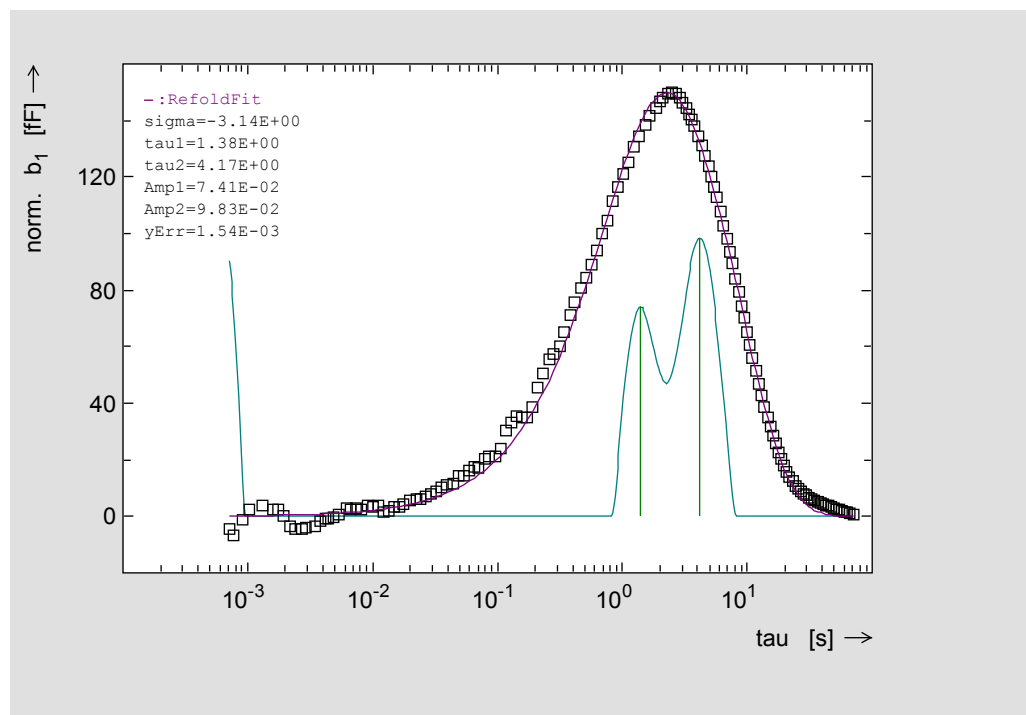
Plot 1: Periodwidthsscans at different temperatures. x-axis recalculated into emission-timeconstant  $\tau$  (measured signals)

Plot 2: One scan of plot 1 including the refold curve and evaluated timeconstants (vert. lines)



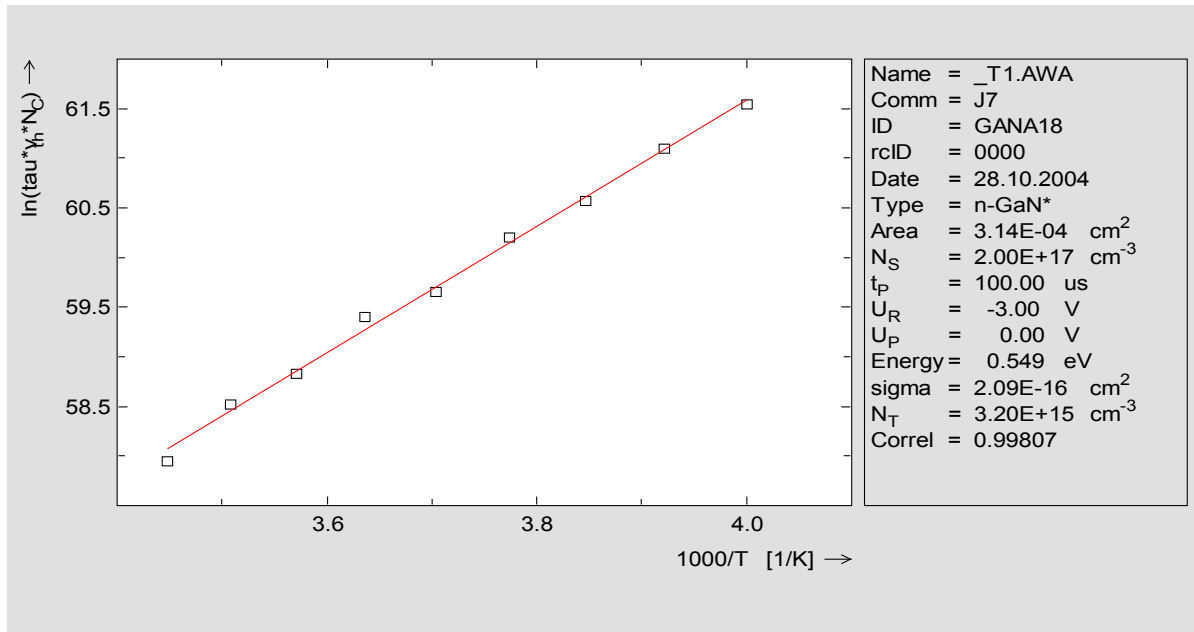
Plot 1

Plot 2



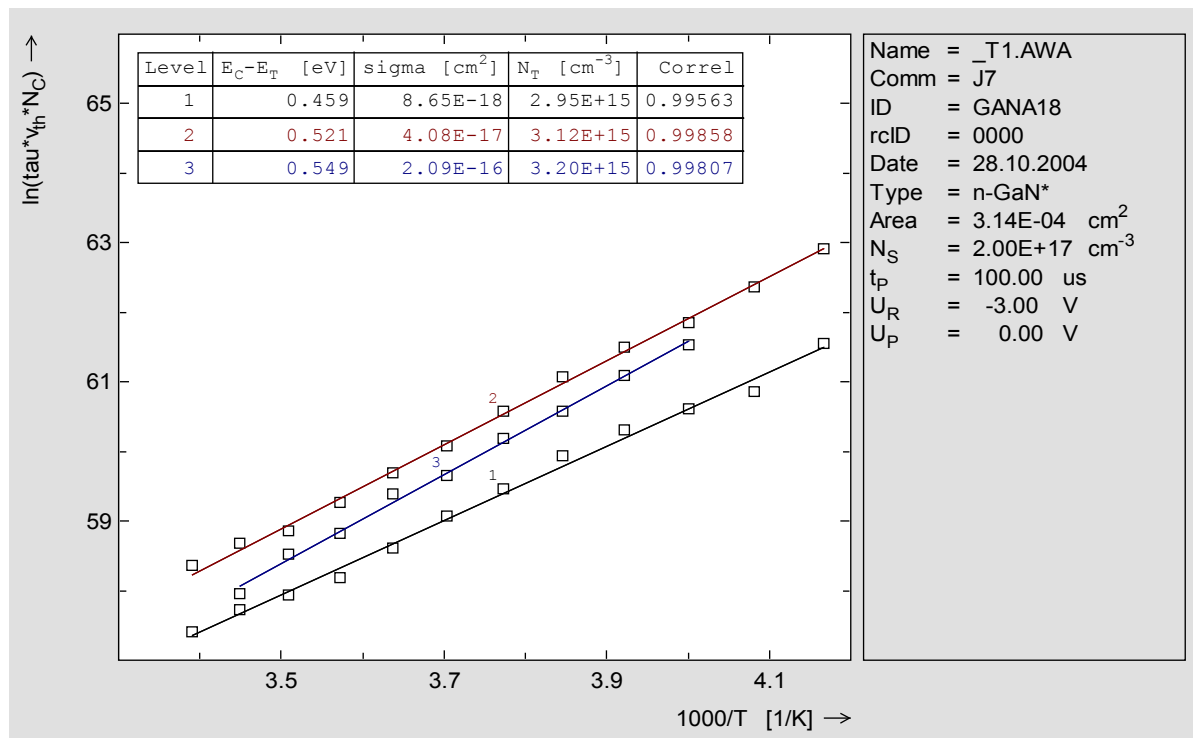
Plot 3: Arrhenius plot from plot 1 data without refolding option

Plot 4: Arrheniusplot as plot 3 but using the refolded data as shown in plot 2 (level 1 and 2)  
and compared to the data without the refolding as in plot 3.



Plot 3

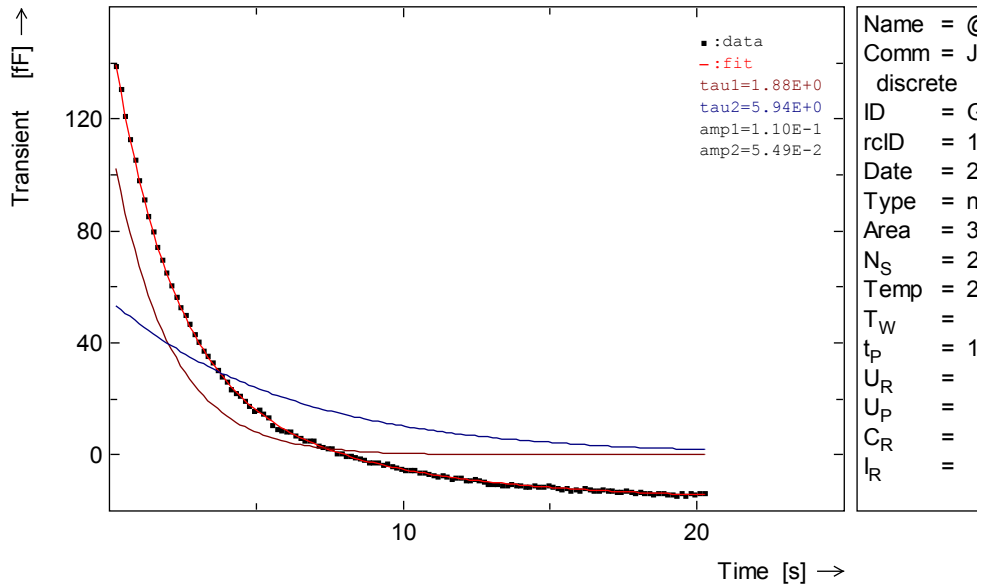
Plot 4



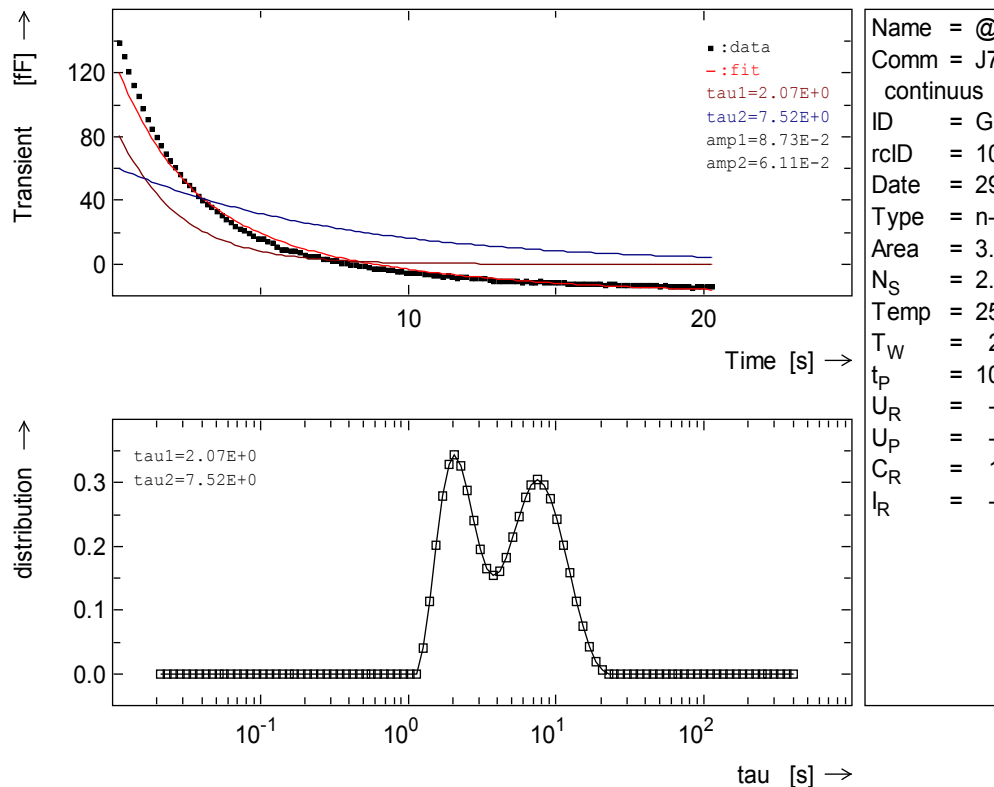
3. Deconvolution of transients by

- Plot 1: multi exponential transient fit. (very good result)
- Plot 2: Laplace transformation (not as good result for this transient),  
timeconstant distribution shown in the lower part of the plot.

Plot 1



Plot 2



#### 4. Long time (10000 seconds) periodwidthscan (alternative to a tempscan)

plot 1: as measured (up to 2 s: every datapoint = 1 transient averaged to a total time of 2 s.

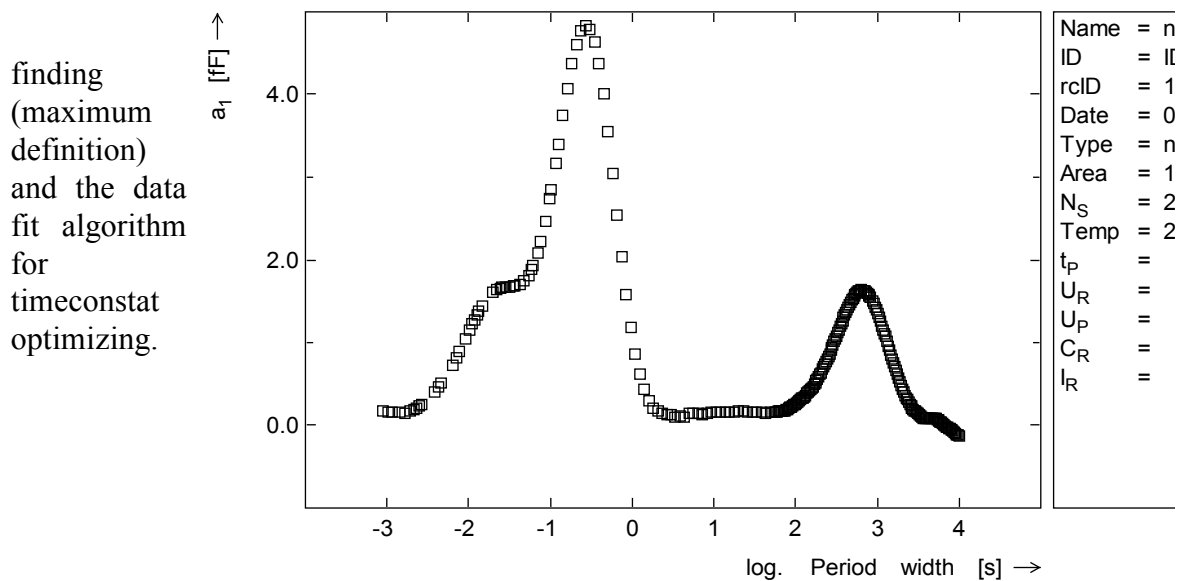
above 2 s: Only 1 transient measured with 64000 datapoints up to 10.000 seconds.

Data points for the different periodwidths selected from this transient then.

This kind of measurement reduces the measurement time to 10% of the standard

isothermal periodwidthscan measurement.

plot 2: as 1, but x-axis recalculated into timeconstant tau and the refolding used for level



Plot 1

