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NEW EXPERIMENTAL AND ANALYSIS METHODS IN I-DLTS*

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New experimental and analysis methods in I-DLTS

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Abstract:

A new experimental apparatus to perform I-DLTS measurements is presented. The method is shown to be faster and more sensitive than traditional double boxcar I-DLTS systems. A novel analysis technique utilising multiple exponential fits to the I-DLTS signal from a highly neutron irradiated silicon sample is presented with a discussion of the results. It is shown that the new method has better resolution and can deconvolute overlapping peaks more accurately than previous methods.

1. Introduction

Microscopic defect analysis techniques are widely used in the study of deep level defects in semiconductors. Traditional Capacitance Deep Level Transient Spectroscopy (C-DLTS) was developed by Lang [1] and is a sensitive and straightforward to analyze temperature dependant spectroscopic technique to determine concentrations, energy levels, and capture rates of traps. Recently I-DLTS (current-DLTS) [2] has been shown to be promising method to analyze high resistivity silicon and to identify and correlate radiation induced deep levels with other properties of the semiconductor under study. This paper presents a new apparatus that increases the speed with which the I-DLTS signal is extracted over traditional methods. It will demonstrate a new analysis technique to increase the resolving power of the method.

2. Experimental Method and Results

Details of the BNL I-DLTS double boxcar system have been described in ref [2]. The new addition to the system is a digital oscilloscope (TDS 540) to record the current transient. The sample (Si. Pol. Oxygen 3 10^{15} O/cm^3; RTA 3.8m; ETA 5hr) used in this study was a high resistivity $p^+/n/n^+$ diode irradiated to 1.03 10^{14} n/cm^{-2}. A thermal scan of the sample was made and the I-DLTS transients at each temperature were recorded for further analysis. This allows one to compare the old double boxcar and new multi-exponential method as well as point out the future possibilities of this new experimental system.

The DLTS transient, typically an exponential in time, is usually fed into a dual-gate signal averager (double boxcar) which selects the emission rate window and improves the signal to noise ratio by averaging many transients allowing the detection of low concentration traps. The idea is to fully characterize the transient by sampling it at two discrete points in time along the exponential as seen in Figure 1. Notice that the transient is obviously non-exponential and is better characterized by two exponentials. The double boxcar I-DLTS signal in Figure 1 is equal to V(t1)-V(t2), where t1-t2 is typically referred to as the rate window, and the I-DLTS spectrum is generated by plotting this voltage difference versus temperature as seen in Figure 2. In Figure 2 we show the I-DLTS spectrum generated by fitting single and double exponentials to the transients. As seen there is a significant difference between the two since single exponentials do not well characterize the transient. By varying t1 in Figure 1 and determining the positions of the peaks in the I-DLTS spectrum in Figure 2 Arrhenius plots are generated to determine the energy and cross-sections of traps. The implicit assumption made when analyzing I-DLTS spectrums for energies and cross-sections is that the transient is exponential, an assumption which Figure 1 shows to be not always valid.

Replacing the double boxcar with a digital oscilloscope allows one to characterize the full transient (important in the presence of non-exponential signals arising from closely spaced traps or broad activation energies for emission) at no cost in time for acquiring the DLTS spectrum. The transient can than be analyzed for be presence of multiple exponentials and I-DLTS signals can be generated for each of the multiple exponentials. The time scale for a measurement is set by the wait for thermal equilibrium at each temperature step.

Access to all the points on the transient as opposed to two reduces the errors on the DLTS signal for the same data set as seen in Figure 3. The new method allows one to fit the transient at each temperature step to fully characterize it thus decreasing the errors on determining the level of the transient at a particular time with respect to the old method. With the new method only one temperature scan is necessary to fully characterize a sample as different rate windows are trivially generated once all the transients are fit as seen in Figure 4 giving the user a quick 3D graphical representation of the Arrhenius curves. Code to extract the energies and cross-sections of the traps seen in Figure 4 is straightforward. The method used is this paper is to look at the projections of Figure 4 in the temperature-time plane and fit the resulting curves as seen in Figure 5. The energy and cross-sections of the traps in Figure 5 are determined by the following equations:

$$\begin{cases} E_c - E_t \text{ (or } E_t - E_v) = \dfrac{\text{Slope}}{5.03} \quad \text{(eV)} \\ \sigma_n = 6.10 \times 10^{-22} \cdot \alpha \cdot 10^{-I} \end{cases}$$

where E_c- E_t is the energy of the trap, σ_n is the cross-section in cm^2, α is a constant which depends on the value of t1 and t2 used in Figure 1 (1.12 for t2=4t1), and I is the intercept of the curves in Figure 5. It should be noted that the curves in Figure 5 would be better fit should the points span a greater range. This just corresponds to reading out more of the transient with ones oscilloscope. In principle one can also extrapolate the transients to areas not measured but with high uncertainty. Error propagation of the results is trivial as one has access to all the errors on the fits. Further the viability of ones model (one versus two exponential fits) can easily be tested by plotting the ratios of the various χ^2 of the fits as a function of temperature as seen in Figure 6. Figure 6 also shows in which areas one-dimensional exponential fits are acceptable.

3. Discussion

Some traps are in reality two traps close together and result in an I-DLTS transient that is a sum of two exponentials. One can fit multiple exponentials to the transients to deconvolute the I-DLTS signal and plot the resulting I-DLTS spectra from each exponential. Deconvolutions are better done at the transient level where one has direct access to the shape of the transients. In the double boxcar method the transient is processed through a rate window that acts as a smearing function and also limits the amount of information passed about the transient to two points. It is difficult to deconvolute two exponentials from a waveform by sampling it at only two points.

An I-DLTS spectrum from fitting a double exponential to the data are shown in Figure 7 together with the I-DLTS spectrum from each of the exponentials individually. All fits had reasonable chi-squares per degree of freedom. As seen there is a shoulder in the combined double exponential spectrum around T=90K. This shoulder is resolved into two peaks when one looks at the first and second exponential spectrums. Interesting substructure is seen in the T>175K region and will be explored in future papers. Further around T=160K where it was not obvious from the combined double exponential that there are two peaks this method picks them out. A blowup of this region is shown in Figure 8. Some peaks are artifacts of the fitting process but can be quickly eliminated them as they are quickly die away at different rate windows and seen to be unphysical.

Note that the traces from the individual exponential fits never go to zero but, for example around T=200K, are actually very close to each other in the position of the peak. There appears to be some spectral leakage between the two exponentials. This probably arises since while there is only one trap, the trap is broad in activation energy and so has exponential slopes close to each other. A more general and precise method is necessary.

In general one should do a Laplace transform of the transient to determine the magnitude and slopes of all the exponential which make up the transient [3,4].

$$f(t)=\int_0^\infty F(s)\, e^{-st} ds$$

The term F(s) in the Laplace transform and gives one the density of the different exponentials that make up the DLTS transient, equivalent to Fourier coefficients which tell one the density of periodic functions which make up a waveform. It is equivalent to fitting an infinite number of exponentials to the data and determining which ones contribute. However, Laplace transforms are notoriously numerically unstable and while various numerical techniques exist in the literature none have been found by us to be stable to noisy data. We feel fitting multiple exponentials to the transient is a particularly simple method to extract the necessary information. One does not know a priori whether two or twenty exponentials are contributing to the transient. Our method involves fitting one, two, three, and four exponentials to the same transient. Than one can compare the chi-squares of the four different fits as seen in Figure 6. When the division of the chi-squares from n and n+1 exponentials (n = # of exponentials) is greater than 1 this indicates than n+1 exponentials should be used to characterize the transient. As seen there is no difference between fitting three and four exponentials and indeed the coefficients of the fourth exponential lead to a zero fourth term. In general it appears that fitting three exponentials best characterizes the data and fitting one exponential is not very good. However, two exponential fits are a good first effort at increasing accuracy and deconvolution peaks. While this method can not map the spread in activation energies of broad traps which a Laplace transform would provide it does provide a good deconvolution technique increasing the sensitivity of I-DLTS measurements.

4. Conclusion

A new fast, sensitive, and well-resolved I-DLTS technique has been demonstrated. It increases the resolving power of I-DLTS measurements and is relatively straightforward to implement in systems that use traditional double boxcar systems.

Acknowledgements:

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Reference:

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[3] L. Dobaczewski et al, Journal of Applied Physics, Vol. 76, Num. 1, July 1994.
[4] D.D. Nolte et al, Journal of Applied Physics, Vol. 62, Num. 3, August 1987.

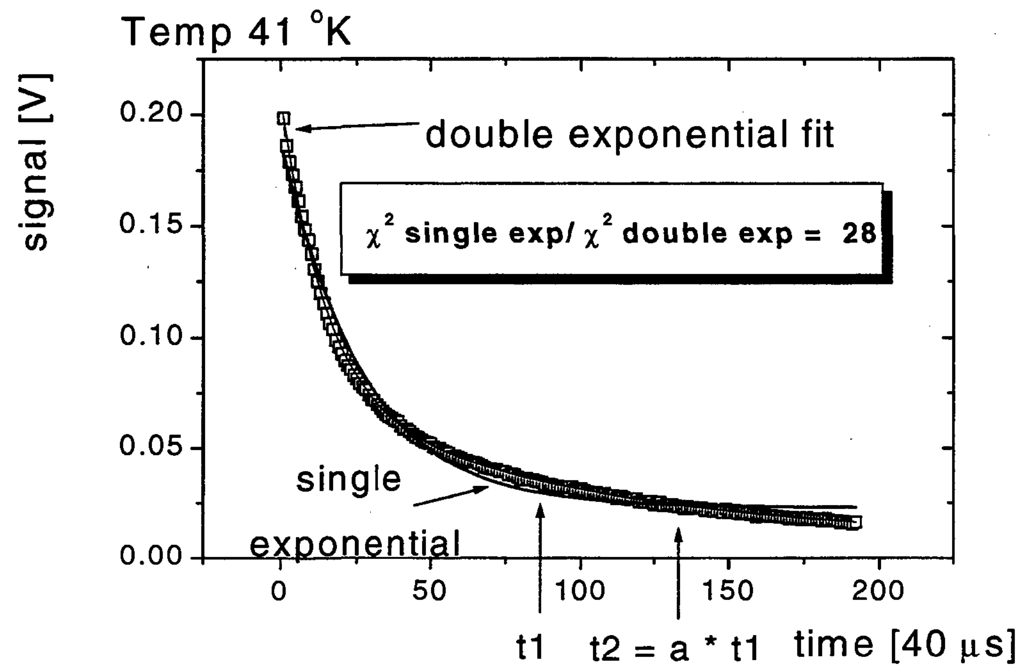

Figure 1: The I-DLTS transient with single and double exponential fits. Note that a single exponential fit does not well characterise the transient.

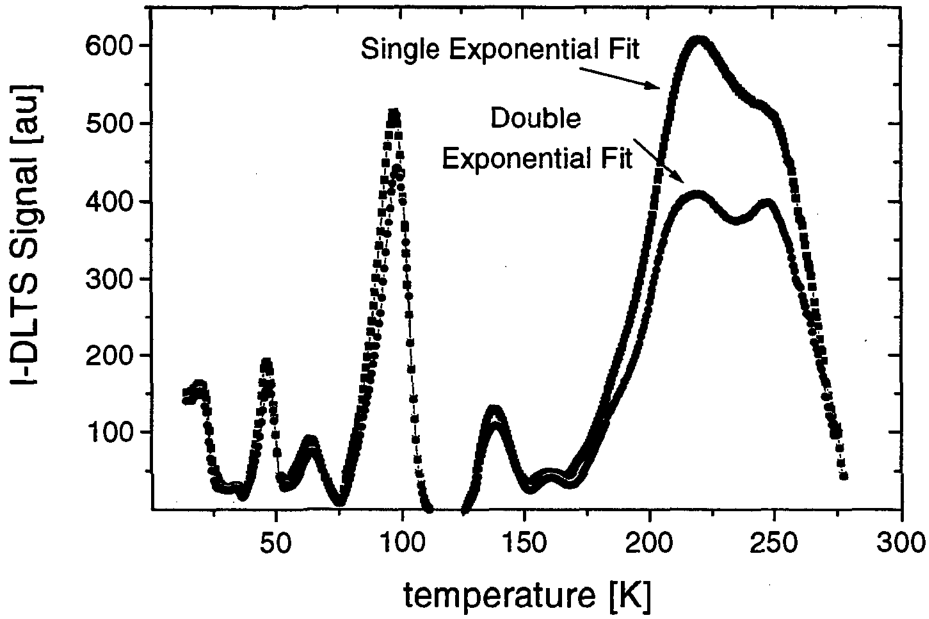

Figure 2: I-DLTS spectrum generated from single and double exponential fits to the I-DLTS transient. Double exponential fits better characterise the transient.

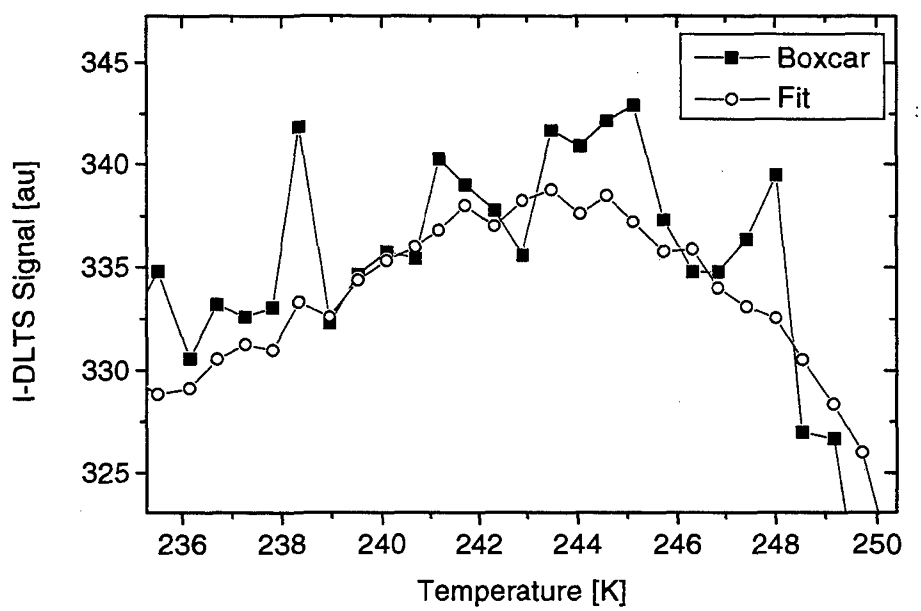

Figure 3: I-DLTS spectrum generated from the double boxcar method and the new multi-exponential fit method. Note that fluctuations in the fit spectrum are smaller. The transients were averaged an identical number of times in both methods.

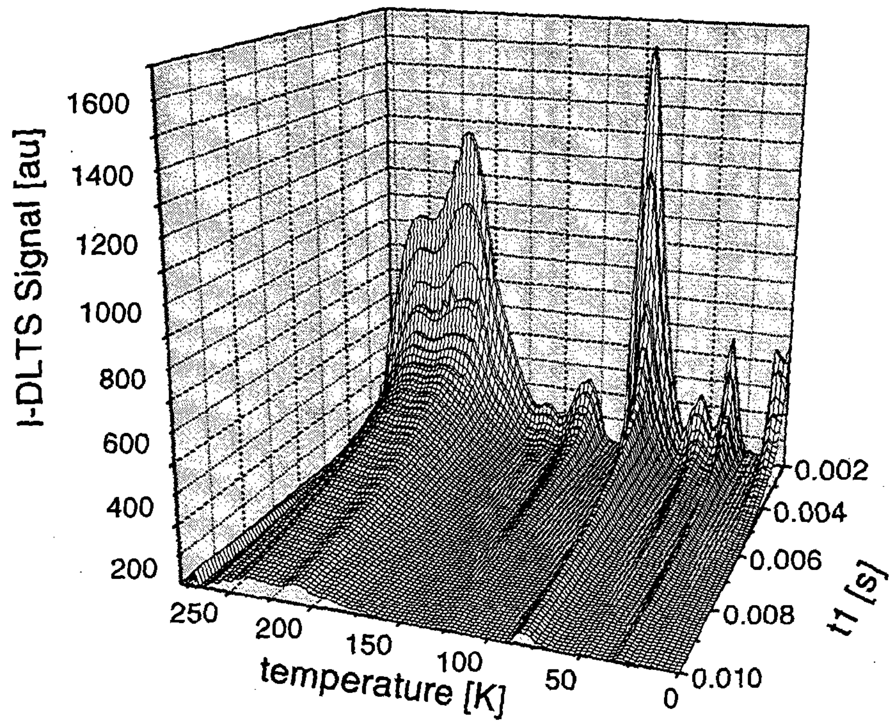

Figure 4: I-DLTS spectrum generated with one temperature scan with the new method. The Arrhenius curves are clearly visible.

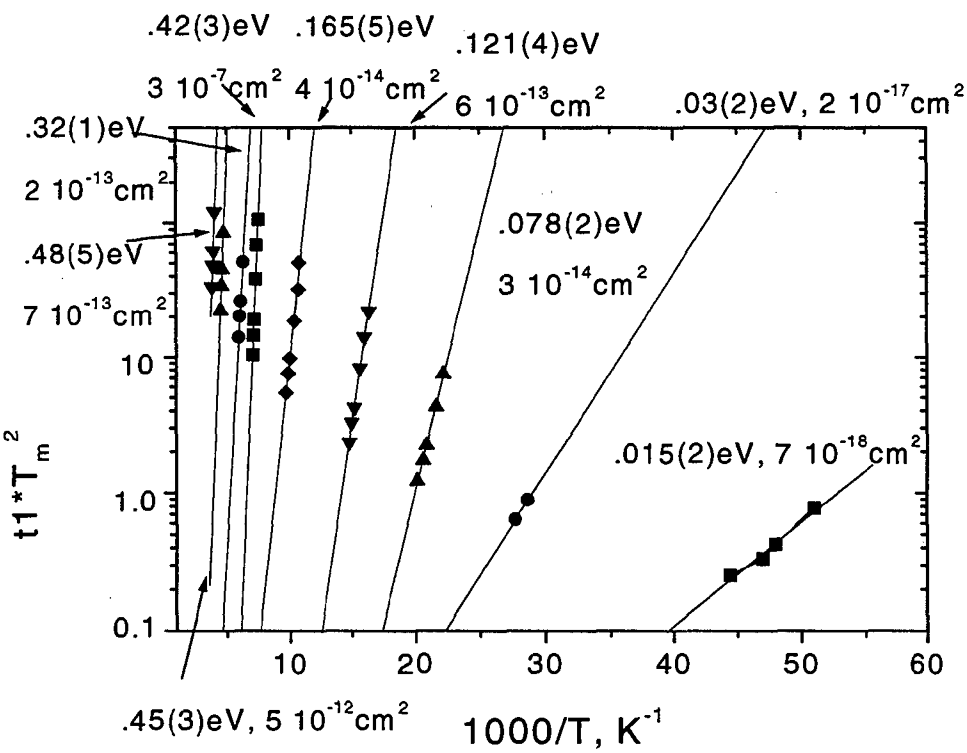

Figure5: Arrhenius plots generated from Figure 4. Also shown are the calculated energies and cross-sections.

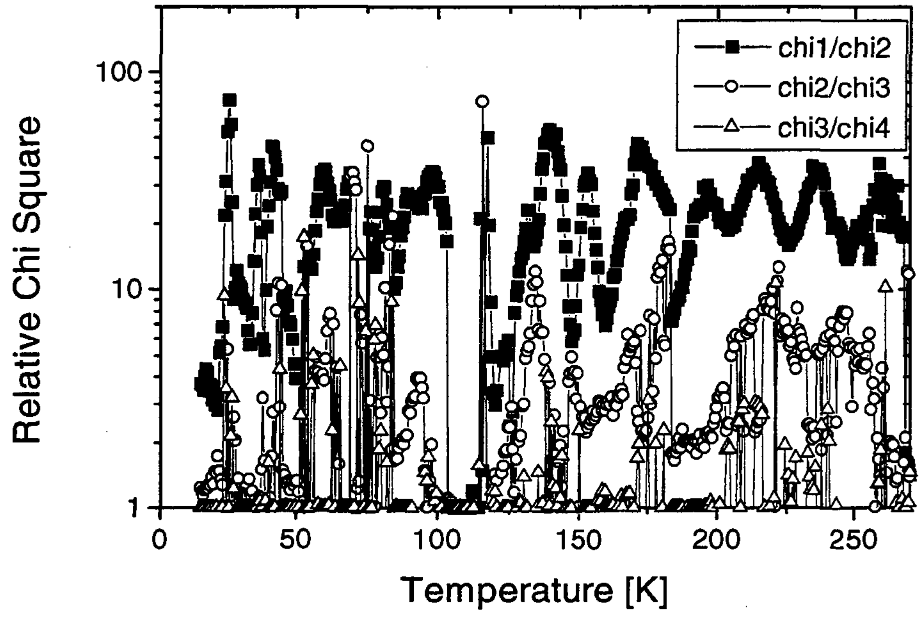

Figure 6: By comparing the ratios of chi-squares from fits with different number of exponentials one can evaluate how many exponentials to fit to the DLTS transient in different temperature regions.

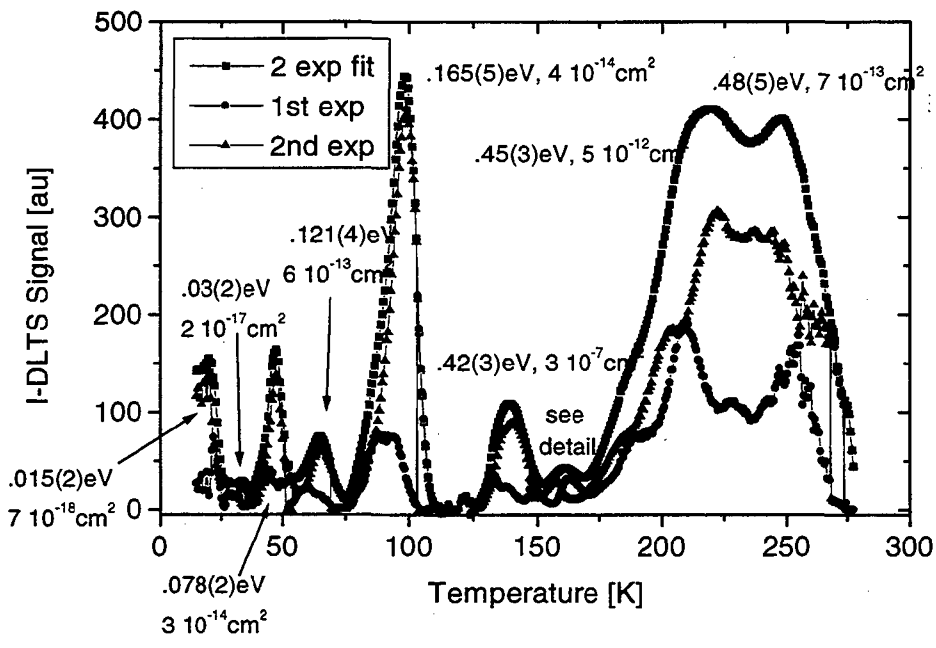

Figure 7: I-DLTS spectra should be generated from the two exponentials that make up the double exponential fit. Notice the shoulder at T=90K is well resolved and a broad peak at T=160K is deconvoluted.

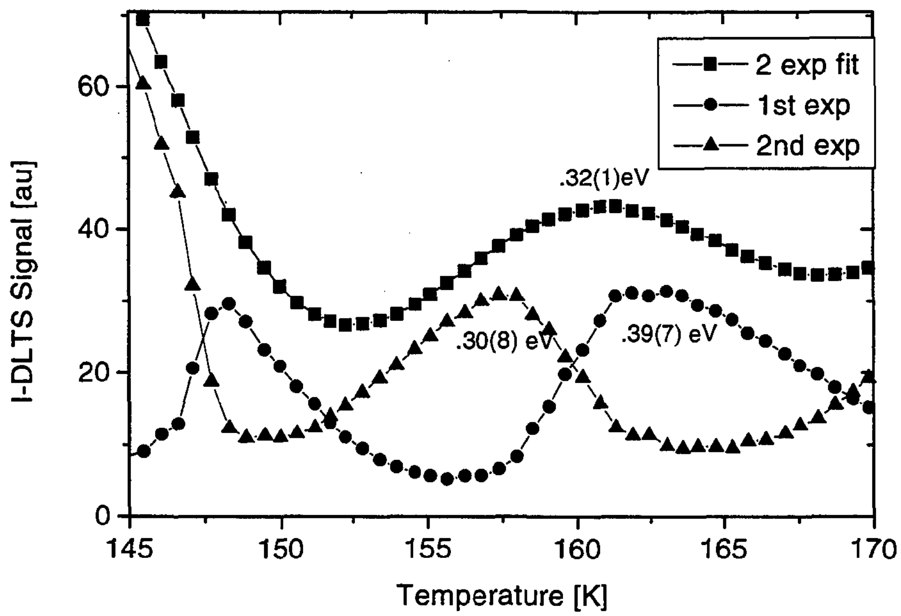

Figure 8:Detail of Figure 7. Unphysical peaks quickly die away at different rate windows and are easily eliminated.

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