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# A novel method to detect nonexponential transients in deep level transient spectroscopy

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In conventional Deep Level Transient Spectroscopy (DLTS) measurements, the analysis of the results is based upon the assumption of an exponential current or capacitance transient. We present experimental and computational results on a novel experimental method for determining when the assumption of exponentiality is not satisfied by the sample under study. The measurement may be performed without any changes in the conventional double-boxcar DLTS system.

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## INTRODUCTION

Deep Level Transient Spectroscopy (DLTS) has emerged as a very useful method for determining the parameters of deep impurity levels in semiconductors. In his original paper on the technique, Lang<sup>1</sup> pointed out that the procedure was strictly valid only for exponential transients. However, parameters are often derived from experimental capacitance transients without testing for their exponentiality. It follows that erroneous values for activation energies and cross sections may be reported when the standard analysis, correct only for exponential transients, is used.

There are several ways that one can obtain a nonexponential current or capacitance transient, each of them with a different underlying cause. The most obvious is the case where more than one defect contributes to the transient and each defect has its own exponential decay with different decay parameters. A single defect with a multiple-step decay process, such as a negative-U defect<sup>2</sup> under photoexcitation, can also give a nonexponential transient. The fact that the change in free carrier density at the edge of the depletion region is not sharp gives rise to a distribution of transients<sup>3,4</sup> from the transition region at the depletion layer-neutral semiconductor interface. If the density of deep levels is comparable with the dopant density, the capacitance transient no longer has an exponential form.<sup>5</sup> Also, the emission rate may depend on electric field which results in a continuous distribution of time constants coming from different depths of the depletion region. Finally, charging the traps in only part of the depletion region (a transient capacitance in series with a constant capacitance) will also yield nonexponential transients.

We have excluded from consideration instrumental artifacts such as system response times<sup>6</sup> which could produce nonexponential transients, but could do so independent of the actual sample under study. Also, we have excluded effects of large sample resistance, either bulk or contact, which could give a circuit time constant that, when combined with the emission time constant, would produce a nonexponential output.

In the case of an isothermal spectroscopic method, one could simply measure the transient directly and then test that transient for exponentiality.<sup>7</sup> From a survey of the literature, it appears that most DLTS systems are not designed

for isothermal measurements. For the transients normally examined in a DLTS experiment, a fast transient recording system with high precision would also be required. Consequently, we have investigated a relatively simple test which can be performed by varying the gate delay times on a conventional double-boxcar DLTS system. Elaborate temperature control is not required, only run-to-run reproducibility.

## ANALYSIS

In the following analysis of a capacitance transient by the double-boxcar procedure, the electron emission rate,  $e_n$ , is given by

$$e_n = v_{th} \sigma_n N_c \exp(-\Delta E_n/kT),$$

where  $v_{th}$  is the electron thermal velocity,  $\sigma_n$  is the capture cross section for electrons,  $N_c$  is the density of states in the conduction band,  $\Delta E_n$  is the energy separation from the conduction band of the deep level in question,  $k$  is the Boltzmann constant, and  $T$  is the absolute temperature. An analogous equation holds for holes.

The capacitance transient of interest arises from the emission of trapped electrons from the deep level when the reverse bias is reestablished after a charging pulse. The transient can be modeled by

$$C(t, T) = [C_f - (C_f - C_i) \exp(-e_n t)]_T,$$

where  $C(t, T)$  is the measured capacitance as a function of time,  $t$ , at the essentially constant temperature,  $T$ , and  $C_i$  and  $C_f$  are the initial and final capacitance of the transient response. The double boxcar determines the difference in capacitance at gate delay times of  $t_1$  and  $t_2$ . The output signal is

$$\begin{aligned} \Delta C &= C(t_1, T) - C(t_2, T) \\ &= [(C_i - C_f) [\exp(-e_n t_1) - \exp(-e_n t_2)]]_T. \end{aligned}$$

A peak in this signal as a function of temperature occurs when<sup>1</sup>

$$e_n = \frac{\ln(t_1/t_2)}{t_1 - t_2}.$$

It is more convenient to use this relationship in its reciprocal form, which is

$$\tau_{\max} = \frac{1}{e_n} = \frac{t_1 - t_2}{\ln(t_1/t_2)},$$

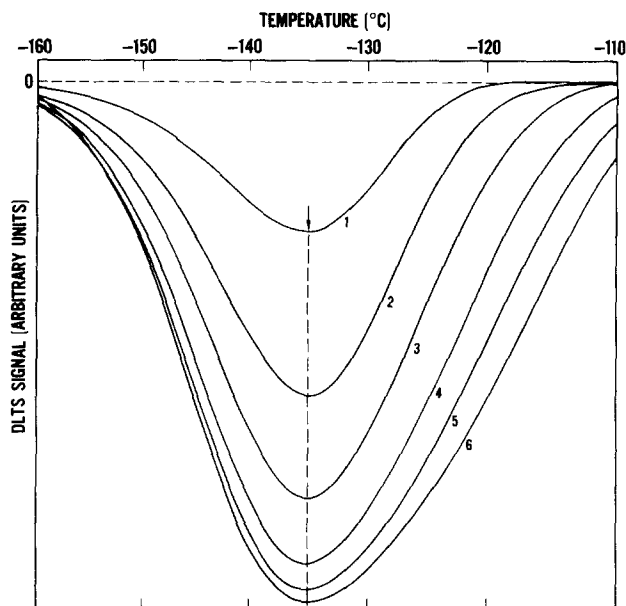


FIG. 1. DLTS curves for a  $p^+n$  diode on wafer 93A with a bias sequence of  $-5, 0, -5$  V. The  $t_1$  and  $t_2$  values are given in Table II. The curve with the smallest ratio of  $t_2/t_1$  is at the top and the one with the largest ratio is at the bottom. Note that the peak temperature is the same for all curves. A negative DLTS peak corresponds to majority carrier (electron) emission.

where  $\tau_{\max}$  is the time constant of the DLTS transient at the temperature where the signal is a maximum;  $1/\tau_{\max}$  is often called the rate window.

If the transient measured is exponential, then the individual values of  $t_1$  and  $t_2$  which produce a given  $\tau_{\max}$  are unimportant for the analysis of the data. In fact, many papers give only the rate window and not the individual gate times. A given value of  $\tau_{\max}$  can, however, be obtained by widely differing pairs of  $t_1$  and  $t_2$  values. We have attempted to use this property of  $\tau_{\max}$  to test the exponential nature of selected samples measured in a conventional double-boxcar DLTS apparatus. We have examined samples in which the transient is known to be a good exponential; where incomplete collapse of the depletion region produces a nonexponential transient; where high doping effects distort the transient; and where emission from more than one defect level is contributing to the transient. In each of the nonexponential cases, the temperature of the DLTS peak was found to depend on the values of  $t_1$  and  $t_2$ , even though  $\tau_{\max}$  was unchanged.

## RESULTS

All of the measurements reported in this paper have been performed on wafers using a variable temperature wa-

fer chuck with a temperature range from  $-195^\circ\text{C}$  to  $350^\circ\text{C}$ .<sup>8</sup> Thermal scan rates were typically  $0.1^\circ\text{C/s}$  in the heating direction only. The capacitance bridge is a specially designed variable frequency type with rf phase sensitive detection performed using a balanced mixer.<sup>9</sup> For the measurements described in this work, the bridge was operated at 20 MHz. The pulse generator used for the bias sequence, the counter used to measure the gate delay times, and the double gate boxcar for sampling the transient were commercial items. Temperatures were measured with a chromel-alumel thermocouple mounted in the wafer chuck, and the thermocouple output was also used to drive the temperature axis of the x-y recorder.

Figure 1 shows a family of DLTS curves obtained on a  $p^+n$  diode fabricated on platinum-doped,  $n$ -type silicon (wafer 93A). The peak of all of the curves occurs at the same temperature suggesting that the capacitance transient has a single exponential decay. Indeed, this conclusion is supported by careful examination of a complete transient recorded under isothermal conditions. The parameters of the wafers used in this investigation are given in Table I, and for wafer 93A, the deep impurity density is only 10% of the shallow impurity density; consequently, a good exponential would be expected. The curves were made with  $t_1$  and  $t_2$  settings which gave  $\tau_{\max} = 500\mu\text{s}$ . The individual  $t_1$  and  $t_2$  values are listed in Table II. Experimentally, one usually finds that there is a minimum value of  $t_1$  that is feasible, which depends upon the recovery time of the system from the reverse bias transient. Very large values of  $t_2$  are normally impractical as these would then limit the duty cycle and thus necessitate slow thermal scan rates to obtain reasonable signal-to-noise ratios. Consequently,  $t_2/t_1$  ratios of greater than 50 are usually not feasible. At the other extreme,  $t_2/t_1$  ratios of less than two result in an output signal which is too low for satisfactory operation. The duration of the sampling gates was  $5\mu\text{s}$ , and one half of this, or  $2.5\mu\text{s}$ , is included in the listed  $t_1$  and  $t_2$  values. To be certain that this gate duration had no effect on the conclusion, scans were made with a duration of  $0.5\mu\text{s}$  and no change was seen in the DLTS peak positions. The wider gates give better signal-to-noise ratios and are preferred for this reason. To show the sensitivity of  $\tau_{\max}$  to the individual  $t_1$  and  $t_2$  values, Table II gives changes in these values ( $\delta t_1, \delta t_2$ ) which would produce a 5% change in  $\tau_{\max}$  corresponding to a shift of  $0.35^\circ\text{C}$  in the position for the DLTS peaks in Fig. 1. This shift is about equal to the repeatability of the curves shown.

The bias-voltage sequence used for the curves in Fig. 1 was  $-5, 0, -5$  V which resulted in essentially complete collapse of the depletion region during the 0-V charging pulse, as is conventional for this type of DLTS. However, there are

TABLE I. Parameters of the wafers used for this work.

Fig. no.	Wafer no.	Shallow impurity		Deep impurity	
		Species	Density	Species	Density
1,2	93A	Phosphorus	$1.2 \times 10^{15}$	Platinum	$1.5 \times 10^{14}$
3	94C	Boron	$3.5 \times 10^{15}$	Platinum	$3.2 \times 10^{15}$
4	R32NB	Phosphorus	$6 \times 10^{13}$	?	$5 \times 10^{10}$

TABLE II. Gate delay times in microseconds used for the DLTS curves in Figs. 1-3 ( $\tau_{\max} = 500 \mu\text{s}$  for all pairs) and change in  $t_1$  and  $t_2$  which separately would produce a 5% change in  $\tau_{\max}$  (to  $475 \mu\text{s}$ ).

Curve no.	$t_1$	$t_2$	$t_2/t_1$	$\delta t_1$	$\delta t_2$
1	342.3	700	2.0	-38.0	-61.8
2	203.2	1000	4.9	-26.5	-78.9
3	123.6	1300	10.5	-18.6	-94.6
4	75.9	1600	21.1	-13.0	-110.0
5	54.9	1800	32.8	-10.2	-120.2
6	39.9	2000	50.4	-8.0	-130.6

applications, such as depth profiling, where the depletion region is only partially collapsed during the charging pulse to obtain the defect density in a narrow spatial region. This gives a fixed capacitance in series with that due to the region of defect emission, and the resultant transient is no longer truly exponential. When this series capacitance is large compared to the capacitance of the transient, the perturbation is insignificant, but when this is not true, the resultant transient is nonexponential. Also, with incomplete charging, emission from the edge of the depletion region is relatively more important, and this is a source of additional nonexponentiality. To investigate these effects, a family of DLTS curves was obtained for the above wafer using a bias sequence of  $-5, -4, -5 \text{ V}$ . The results in Fig. 2 show that the DLTS peak position varies by almost  $2^\circ\text{C}$  depending systematically on the values of  $t_1$  and  $t_2$ , even though all pairs have the same  $\tau_{\max}$ . As the spread between  $t_1$  and  $t_2$  is reduced, the DLTS peak shifts successively less. This is expected since the pairs are converging on a measurement of the tangent to the transient at  $t = \tau_{\max}$ . This case was also examined by careful isothermal measurements with the result that

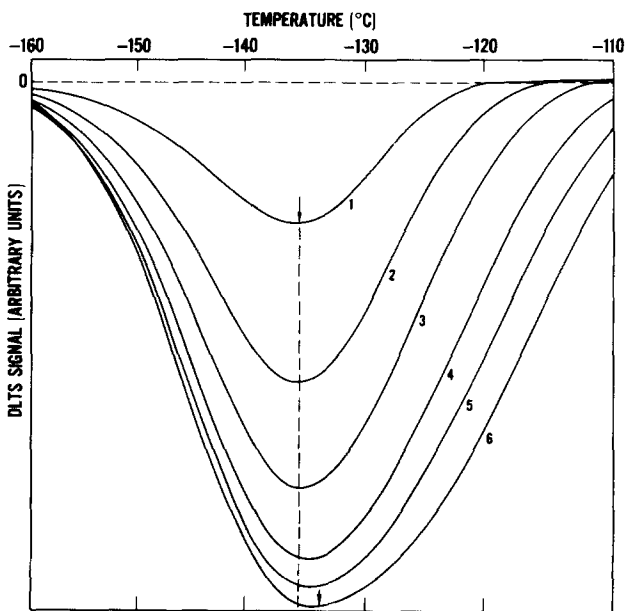


FIG. 2. DLTS curves for the same diode and gate times as Fig. 1, but with a bias sequence of  $-5, -4, -5 \text{ V}$ . The DLTS peak shift of  $2^\circ\text{C}$  is due to the nonexponentiality introduced by the relatively large contribution from the depletion edge region and by the fixed capacitance in series with that of the active region.

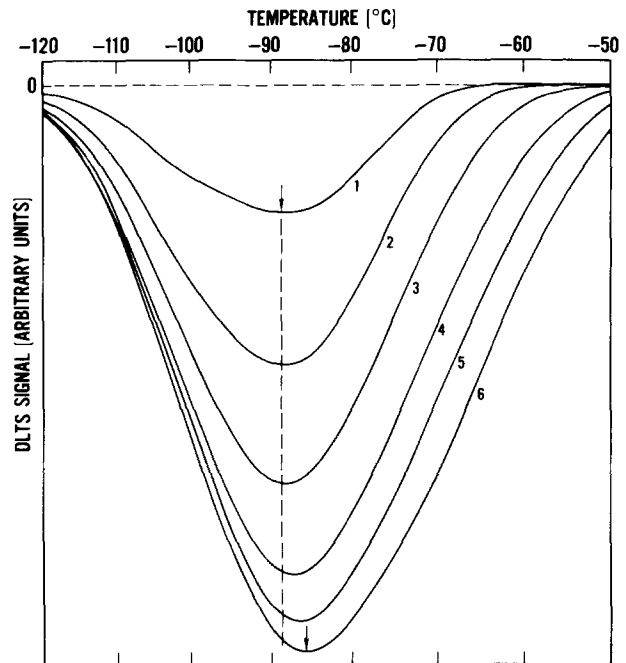


FIG. 3. DLTS curves for an  $n^+p$  diode on wafer 94C with a bias sequence of  $+5, 0, +5 \text{ V}$ . The gate delay times are given in Table II. The peak shifts  $3^\circ\text{C}$  because the transient is nonexponential due to the non-negligible deep-level density compared to the shallow boron density.

the time constant at the beginning of the transient was 11% shorter than it was after one time constant. Although these isothermal measurements are made at substantially lower temperatures and consequently longer decay times than the DLTS measurements, the underlying cause of the nonexponential behavior is the same for both cases. We are thus justified in comparing these results.

In Fig. 3 the nonexponentiality introduced by heavy doping is examined by this method using wafer 94C which was diffused with platinum at  $1000^\circ\text{C}$ . The ratio of deep levels to shallow levels was determined to be about 0.9 from a fit of low temperature capacitance-voltage measurements to the Sah-Reddi model.<sup>10</sup> With a ratio this large, the capacitance transient should not be exponential in form. The results in Fig. 3 confirm this expectation as the DLTS peak shifts a total of  $3^\circ\text{C}$  for the scans obtained with the  $t_1$  and  $t_2$  pairs used in the measurement (see Table II). The presence of considerable nonexponentiality was also seen in isothermal measurements from which the time constant was found to be initially 9% shorter than after one time constant and 31% shorter than after two time constants.

Another common cause of nonexponential transients is the overlap of transients from two (or more) different centers. Figure 4 shows DLTS curves obtained on wafer R32NB, a commercial power rectifier wafer containing trace amounts of unknown impurities. The curves were made with a  $\tau_{\max}$  of 5 ms; thus the  $t_1$  and  $t_2$  values are 10 times those given in Table II. With the larger  $\tau_{\max}$ , the peaks occur at lower temperatures and are consequently better resolved. For large ratios of  $t_2/t_1$ , there is little obvious evidence of two peaks in Fig. 4. However, for small  $t_2/t_1$  ratios, two peaks are clearly seen as analysis would predict.<sup>11</sup> From

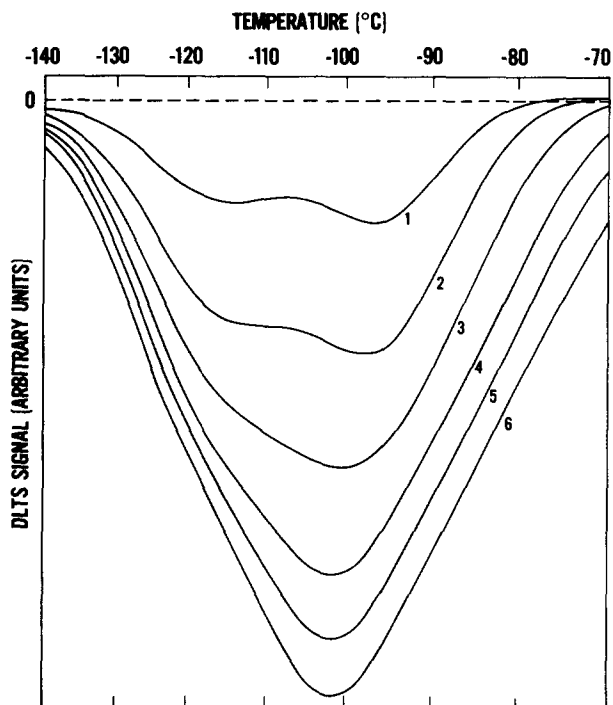


FIG. 4. DLTS curves from overlapping transients measured on a commercial  $p^+n$  power rectifier diode. The bias sequence was  $-10, 0, -10$  V and the gate times were ten times larger than those in Table II ( $\tau_m = 5$  ms for all curves). The smaller ratios of  $t_2/t_1$  clearly show two peaks which might go unresolved if only large ratios of  $t_2/t_1$  were used.

more extensive measurements, the two levels were found to have activation energies of 0.25 and 0.29 eV below the conduction band. Energy levels this far apart can usually be detected when curves are run with the wide range of  $\tau_{\max}$  values needed for an Arrhenius plot. However, levels somewhat closer in energy (specifically in emission rate) might go undetected unless scans are made with small ratios of  $t_2/t_1$ . Once it is established that only one level is contributing to the emission peak, scans can be made with a larger ratio for increased DLTS signal.

## CONCLUSION

We have shown that a simple experiment can be performed which tests an underlying assumption in every DLTS experiment, that of exponentiality of the transients. The test is sufficiently sensitive to examine typical cases of interest and relies only on the reproducibility of the instrumentation, not on its absolute accuracy. When the method is used routinely to check for exponentiality, only two or three curves, at widely spaced ratios of  $t_2/t_1$ , are needed.

We expect that the use of this technique (or other related methods) may significantly improve the interlaboratory agreement on the parameters of a given defect.<sup>12</sup> In this way, DLTS may more closely approach its early promise as a means for analysis of unknown trace impurities in semiconductors.

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