An Efficient Technique for Analyzing Deep Level Transient Spectroscopy Data

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A novel Deep Level Transient Spectroscopy (DLTS) method is introduced. The technique uses two data points taken from a DLTS capacitive transient to make a direct calculation for the emission rate. The method is valid for all points of a thermal scan, as opposed to Lang’s original DLTS, which can only calculate the emission rate at the DLTS peaks. A complete Arrhenius plot can be constructed using one to four temperature scans. The method is additionally applied to simulated noise. Electron traps in Silicon are investigated with the new technique, using laboratory data. A comparison is made between this new method, the original DLTS of Lang, and recent developments made by other authors.

Key words: DLTS, capacitance, Si

INTRODUCTION

Since its inception by D. V. Lang,1 Deep Level Transient Spectroscopy, or DLTS, has become a popular method for characterizing and identifying deep level defects in semiconducting materials. In Lang’s original DLTS, the capacitive transient is recorded at two discrete points during the exponential decay. The method then defines a normalized signal equal to the difference between the two points:

\[ S(T) = \frac{[C(t_1) - C(t_2)]}{\Delta C(0)} \]

using \( \Delta C(0) \) to be the magnitude of the capacitive transient. Because the decay is assumed to be exponential in form, the equation can subsequently be written as:

\[ S(T) = \left(\exp(-\alpha t_1)\right) - \left(\exp(\alpha t_2)\right) \]

Carrier emission out of the filled traps is thermally activated, and the emission rate \( \alpha \) is given by

\[ \alpha = \frac{e_1}{\sigma_1 v_0 n_1 / g \exp(-\Delta E/kT)} \]

where \( \sigma_1 \) is the minority carrier capture cross section in \( \text{cm}^2 \), \( v_0 \) is the thermal velocity in \( \text{cm/s} \), \( n_1 \) is the effective density of states, \( g \) is the degeneracy of the trap, and \( \Delta E \) is the energy separation between the trap and the minority carrier band edge. A thermal scan of \( S(T) \) will result in a peak value at a particular temperature. Lang determines the value of the emission rate at the peak by taking the temperature derivative of \( S(T) \), setting it equal to zero, and then calculating the emission rate. This results in:

\[ e_1 = \ln(t_1/t_2)/(t_1 - t_2) \]

The choices of \( t_1 \) and \( t_2 \) will therefore determine the emission rate that will exist at the peak value. Since the emission rates are thermally activated, multiple thermal scans using different values of \( t_1 \) and \( t_2 \) will yield a variety of calculated emission rates, matched with the temperature values of the peaks. Using these emission rates and temperature values an Arrhenius plot can be constructed which provides the deep level energy in its slope, using the given equation for the emission rate.

This method has become popular for studying the deep level defects in semiconductors. However, one of the major drawbacks has been the need to use a large number of thermal scans to create an Arrhenius plot with an appreciable number of points. Several authors have attempted to remedy this situation, using the original signal \( S(T) \) supplied by Lang.

Hjalmarson et al.2 have developed a unique method of plotting the signal \( S(T) \) so that the deep level energy is given in the slope. The method only works for data points on the lower temperature side of the DLTS peak. The use of different \( t_1 \) and \( t_2 \) values caused the plotted values to shift on the \( 1000/T \) axis, but the slope remained the same.

Le Bloa et al.3 and Goto et al.4 have used the width of the normalized DLTS signal to determine the deep level energy. Based upon the magnitude of the signal \( S(T) \) to the right and left sides of the peak, they report that it is possible to determine the deep level energy employing a single thermal scan.

R. Langfeld5 has also developed a method employing a single thermal scan. Iterative values of \( C(0) \), deep level trap energies, and capture cross sections are used to duplicate the thermal scan. Once a proper fit has been found, the iteration is stopped and the final values are obtained.

Kim, Schlesinger, and Milnes have developed a new technique that uses eight data points taken from the exponential transient.6 Using four data points for each deep level, the emission rates from two overlapping peaks were found. The authors re-
ported that the method worked in computing the emission rates from the two deep levels provided that the peaks were not too close together. The analysis became more sensitive to noise as the separation of the peaks was reduced.

In this paper, a new method of calculating the emission rate is presented. The new method uses the same data points as Lang's original technique, and can be used to create a typical Arrhenius plot. Only 2–4 thermal scans are needed in the presence of noise to characterize a deep level defect, and if the data is relatively noise-free, only a single thermal scan is necessary.

**THE DIVISOR METHOD**

The capacitive signal in Deep Level Transient Spectroscopy has two terms. The first of these is a static offset capacitance, which is accounted for in the junction capacitance and in the capacitance of the leads to the sample. This will be referred to as the offset capacitance, $C_{ss}$. The second is the exponential term described previously, with a transient magnitude of $\Delta C(0)$. The capacitive transient can be expressed at times $t_1$ and $t_2$ as follows:

$$C(t_1) = C_{ss} - \Delta C(0) \exp(-e_1 t_1)$$
$$C(t_2) = C_{ss} - \Delta C(0) \exp(-e_1 t_2)$$

Subtracting the offset capacitance from both sides and dividing, the equations become:

$$\frac{C(t_1) - C_{ss}}{C(t_2) - C_{ss}} = \frac{\Delta C(0) \exp(-e_1 t_1)}{\Delta C(0) \exp(-e_1 t_2)}$$

Then, by dividing out the $\Delta C(0)$ term and lumping the exponential terms together, emission rate $e_1$ is found to be:

$$e_1 = \frac{\ln\{|C(t_1) - C_{ss}|/[C(t_2) - C_{ss}]\}}{t_2 - t_1}$$

By knowing the capacitive transient values at $t_1$ and $t_2$, it is therefore possible to directly calculate the emission rate at all points in the DLTS scan; the calculation is not limited to the peak. Since the emission rate computation employs the division of the capacitive values, it is referred to as the divisor technique.

In order to make the emission rate calculation just given, the offset capacitance $C_{ss}$ must first be known, so that it can be subtracted. To make a determination of it, a comparison to Lang's derivation is used at the peak:

$$e_1 = \frac{\ln\{|C(t_1) - C_{ss}|/[C(t_2) - C_{ss}]\}}{t_2 - t_1} = \ln(t_2/t_1)/(t_2 - t_1)$$

It is then found that at the peak, the following must be true:

$$|C(t_1) - C_{ss}|/[C(t_2) - C_{ss}] = t_2/t_1$$

Using the measured values of $C(t_1)$ and $C(t_2)$ at the peak, the only unknown is $C_{ss}$, which is then easily solved for.

In a DLTS application where double-correlation is used, the DLTS signal will not have an offset term, since it will cancel out. In that case, the emission rate computation reduces to:

$$e_1 = \frac{\ln\{|C(t_1)/C(t_2)|\}}{t_2 - t_1}$$

This eliminates the need to determine the offset capacitance.

The magnitude of the transient, $\Delta C(0)$, can be found as well, by extrapolating the signal back to the origin:

$$\Delta C(0) = C(t_1)/\exp(-e_1 t_1)$$

The magnitude can then be used in the traditional manner to find the trap density relative to the doping density of the majority carriers.

In order to apply this technique to both simulated and actual data, a computer program was written in BASIC. The program calculates the emission rate at each temperature value and then outputs the values in an ASCII file. The file can be read by a graphics program to create an Arrhenius plot. If the capture cross section of the trap is also known prior to the analysis, the program can compute the deep level energy at each temperature point by using the temperature and emission rate values. If the capture cross section is not known prior to analysis, it can be determined after the deep level energy has been found from the slope of the Arrhenius plot. The analysis can then be repeated, and the deep level energy values can be determined at each temperature point. The program also outputs the trap density, transient magnitude, and the average values of the point-by-point deep level values for the DLTS scan.

Several simulations were run using theoretical data with the divisor method program. The first simulation used noise-free, ideal data. A deep level electron trap of $E_c - 0.5$ eV was modeled in GaAs using sampling times of $t_1 = 0.001$ sec and $t_2 = 0.006$ sec. The DLTS peak is shown in Fig. 1.

![Fig. 1 — Simulated DLTS thermal scan of $E_c - 0.5$ eV deep level trap in GaAs. Transient magnitude is 10 pF.](image-url)