

Deep Level Characterization Improved by Laplace Charge Transient Spectroscopy

Shumpei Koike, Kazuo Uchida, Shinji Nozaki

Abstract— Deep-level transient spectroscopy (DLTS) has been widely used to electrically characterize the defects in semiconductors. The DLTS spectrum obtained by the rate-window analysis often shows a peak resulting from a transient signal made of two or more exponential signals. In such a case, the energies of the defects responsible for the transient are closely spaced together. The analysis of the transient signal by the inverse Laplace transform is able to resolve a single energy obtained by the rate-window analysis into multiple energies. The charge transient signal is more favored for the inverse Laplace transform than for the capacitance transient signal because the data can be immediately obtained after the pulse by the charge transient spectroscopy (QTS). Using a simulation, the Laplace charge transient spectroscopy has been shown to improve the deep level characterization.

Index Terms— charge transient spectroscopy, deep-level transient spectroscopy, inverse Laplace transform.

I. INTRODUCTION

Signals with exponential decays are frequently observed in physical phenomena such as radioactive decay [1], heat transfer [2], chemical reactions [3] and vibrations [4]. Such signals often convolute multiple exponentials. The time constant of each exponential is an important physical parameter but difficult to extract from the multi-exponentials. In this paper, we propose a novel technique to extract the time constants from a multi-exponential signal and apply it to the characterization of deep-level impurities in semiconductors, which often degrade the device's performance. Many have proposed methods to characterize the deep-level impurities. Among them, deep-level transient spectroscopy, known as DLTS [5], has been the most widely accepted to electrically measure the energy levels, capture cross-sections and concentrations of the deep-level defects or impurities. In the DLTS, the transient capacitance is typically measured after applying a pulsed voltage to the diode. In the case of the majority-carrier DLTS, the reverse bias of the diode is momentarily reduced by a voltage pulse, and the deep-level traps, which have been unoccupied, capture the majority carriers. After the bias voltage returns to the quiescent reverse bias voltage, the trapped charges are thermally emitted and the depletion width decreases to the steady-state value with time. As a result, the capacitance transient, the current transient or the charge transient is observed. Taking

advantage of the charge transient, we propose Laplace charge transient spectroscopy as an improved characterization technique for deep-level impurities in semiconductors.

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II. CHARGE TRANSIENT SPECTROSCOPY

Most capacitance meters cannot measure the values immediately after pulsing the diode directly by connecting a pulse generator with a capacitance meter, and require a substantial time, typically about 100-200 μs before being able to make stable measurements [6]. Instead of capacitance transient spectroscopy, current transient spectroscopy (CTS) [7] was proposed. However, a conventional current meter also becomes unstable immediately after pulsing the diode and needs some time for integration over time to reduce the noise. Charge transient spectroscopy (QTS) [8] was also proposed to measure the integrated current in real time using a simple current integrating circuit made of a fast-response op-amp, resistor and capacitor, as shown in Fig. 1.

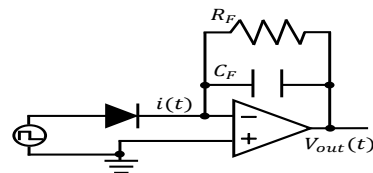


FIG. 1. QTS circuit consisting of an op-amp, resistor and capacitor.

There are three main advantages for using the QTS. The first is the simplicity of the measurement apparatus. The QTS circuit is much less expensive than capacitance and current meters. The second is the high-speed response. The charge transient can be measured immediately after pulsing the diode and it does not lose any transient signal data points because of a high-speed response of the op-amp such as LF357 [9]. The third is the noise immunity. The integrating circuit plays the role of a low-pass filter. Because of this feature, the QTS is more immune to noise than the CTS. The second point was confirmed by measurement of the capacitance and charge transients of a semiconductor with deep-level defects, as shown in Fig. 2.

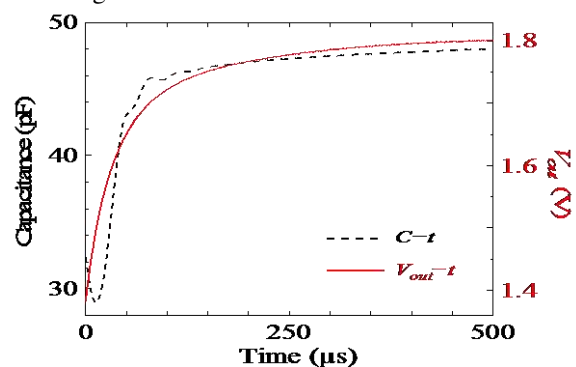


FIG. 2. Capacitance and charge transients measured after applying a voltage pulse to a semiconductor with deep-level defects.

Fig. 2 shows the capacitance and QTS output voltage over the time period of 0-500 μs . The capacitance transient was

measured using a Boonton 7200. As mentioned in the introduction, the transient measured by the capacitance meter shows a ringing immediately after the pulse with a high slew rate is directly applied to the meter from an external source, and the data for times up to 200 μ s seem to be invalid in the figure. In contrast to the capacitance transient, the QTS output voltage is not disturbed by the sudden change in the diode voltage, and the QTS circuit can measure the transient signal immediately after pulsing the diode. The data acquired immediately after the pulse are also important as discussed in the following sections.

The charge transient signal is measured as an output voltage of the QTS circuit in Fig. 1. It is determined by integrating the transient current expressed by

$$i(t) = \frac{AqWN_T}{2\tau} \exp\left(-\frac{t}{\tau}\right), \quad (1)$$

where A is the area of the diode, q is the elementary charge, W is the width of the depletion region, N_T is the density of the defect, τ is a time constant, and t is the time. The output voltage of the QTS circuit with Eq. (1) as an input is given by

$$V_{out}(t) = \frac{AqWN_T R_F}{2(R_F C_F - \tau)} \left\{ \exp\left(-\frac{t}{R_F C_F}\right) - \exp\left(-\frac{t}{\tau}\right) \right\}, \quad (2)$$

where R_F is the feedback resistance and C_F is the feedback capacitance of the QTS circuit shown in Fig. 1.

For $\tau \ll R_F C_F$, eq. (2) becomes

$$V_{out}(t) = \frac{AqWN_T}{2C_F} \left\{ 1 - \exp\left(-\frac{t}{\tau}\right) \right\}. \quad (3)$$

As a result, the charge transient signal is given by

$$Q(t) = \int_0^t i(t') dt' = C_F V_{out}(t) = \frac{AqWN_T}{2} \left\{ 1 - \exp\left(-\frac{t}{\tau}\right) \right\}. \quad (4)$$

By comparison of Eqs. (3) and (4), the output voltage $V_{out}(t)$ is proportional to the charge transient signal $Q(t)$. The above equations were extensively derived by Farmer et al [8].

III. RATE-WINDOW ANALYSIS

In the DLTS, the transient signal is often analyzed using the rate-window concept, where the DLTS signal is obtained as the difference between the transient amplitudes sampled at two times, t_1 and t_2 , after the voltage pulse [5]. The rate window can be expressed in terms of the transient-time constant giving rise to the maximum DLTS signal,

$$\tau_{\max} = \frac{t_1 - t_2}{\ln \frac{t_1}{t_2}}. \quad (5)$$

Let us illustrate the QTS with the rate-window analysis using the hypothetical defects shown in Table I.

TABLE I. Hypothetical defects in a semiconductor.

	Activation Energy (eV)	$AqWN_T/(2C_F)$ (V)	capture cross section (cm^2)
Defect D ₁	0.25	0.6	1×10^{-15}
Defect D ₂	0.30	0.4	1×10^{-14}

The emission rate of the deep levels are obtained from the following equation [5]:

$$e = \frac{S \langle v_n \rangle N_c}{g} \exp\left\{ - (E_C - E_T) / kT \right\}, \quad (6)$$

where S is the capture cross section of electrons, e is the emission rate of electrons, g is the degeneracy factor for the deep level, $\langle v_n \rangle$ is the average thermal velocity of electrons, N_c is the effective density of states for electrons in the conduction band, $E_C - E_T$ is the activation energy of a deep level, k is the Boltzmann constant, and T is the absolute temperature. The emission rate was calculated using Eq. (6) for the parameters listed in Table II and is shown as a function of temperature in Fig. 3.

TABLE II. Physical parameters of a hypothetical semiconductor.

v_n (cm/s)	N_c (cm^{-3})	g
$8.66 \times 10^5 \times T^{\frac{1}{2}}$	$1.73 \times 10^{16} \times T^{\frac{3}{2}}$	1

The transient signals of the voltage output of the QTS circuit were generated from the emission rates of Defects D₁ and D₂ at 170 K in Fig. 3 and shown for only D₁, only D₂ and for both D₁ and D₂ in Fig. 4. The transients for only D₁ and only D₂ are single exponentials, while that for both D₁ and D₂ is a double exponential.

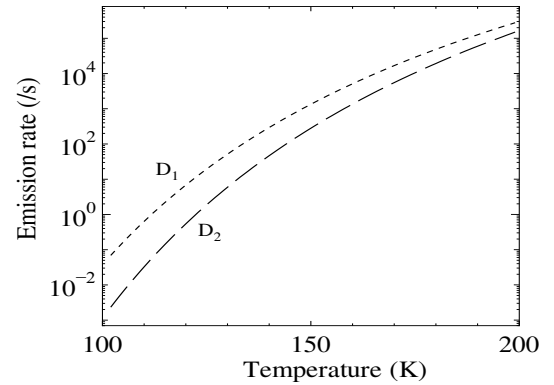


FIG. 3. Temperature vs. emission rate plot calculated by Eq. (6) using the parameters listed in Tables I and II.

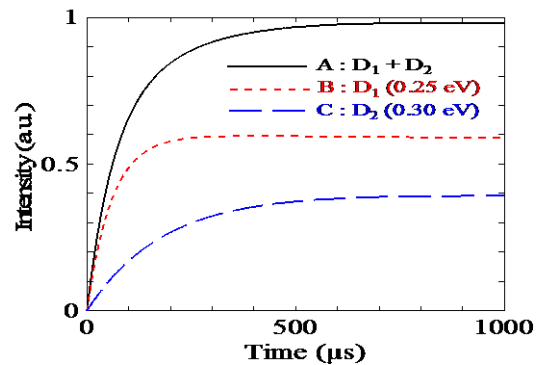


FIG. 4. The simulated transient signals at 170 K. A is the combined signals by B and C. B and C are transient signals of defects D₁ and D₂, respectively.

The DLTS spectra with the rate-window analysis using the charge transient signals were obtained using the emission rates in Fig. 3 and shown in Fig. 5. In the figure, the DLTS spectra in black are for $t_1 = 50 \mu$ s and $t_2 = 250 \mu$ s, corresponding to a time constant of 124 μ s at the peak temperature. In the case of the capacitance transient, t_1 should be longer than 200 μ s due to the slower response of the capacitance meter. By keeping the difference between t_2 and t_1 the same as that of the QTS signal, t_1 and t_2 were set at 200

and 400 μs , respectively, for the hypothetical QTS spectrum D_2' obtained for only D_2 to simulate the output of a capacitance meter with a slower response.

Note that the peak temperature of the spectrum for D_1 and D_2 is not the same as that for only D_1 or only D_2 . If a semiconductor has both deep-level defects, D_1 and D_2 , the peak needs to be deconvoluted to two peaks in order to estimate the activation energies of D_1 and D_2 . The deconvolution may lead to inaccurate activation energies, in particular, if the energies are very close to each other. The Laplace QTS is a powerful technique to resolve the activation energies in the multi-exponential transient decay signal, as discussed in the next section.

In Fig. 5, the peak height of the DLTS spectrum D_2 for only D_2 obtained from the charge transient is much larger than the DLTS spectrum D_2' from the capacitance transient with a slower response. It suggests that the DLTS spectrum obtained from the charge transient is more immune to noise.

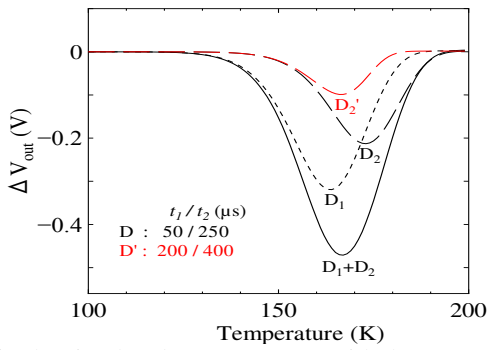


FIG. 5. The simulated DLTS spectra with the rate-window analysis are for $t_1 = 50 \mu\text{s}$ and $t_2 = 250 \mu\text{s}$ about defects D_1 and D_2 . D_2' is the hypothetical DLTS spectrum obtained for only D_2 with $t_1 = 200 \mu\text{s}$ and $t_2 = 400 \mu\text{s}$ to simulate the output of a capacitance meter with a slower response.

IV. LAPLACE CHARGE TRANSIENT SPECTROSCOPY

As briefly mentioned in the last section, the rate-window analysis of the charge or capacitance transient suffers from resolution of the closely spaced energy levels. The analysis by the inverse Laplace transform of the multi-exponential transient was found to be able to resolve the energy level of a defect responsible for each peak of the DLTS spectrum into two or more energy levels of defects. Peaker et al. referred to such an analysis of the capacitance transient signal as the Laplace DLTS (LDLTS) [10], [11]. In this section, we will show that the charge transient is more suitable for the analysis by the Laplace transform than the capacitance transient. We refer to the charge transient spectroscopy with the Laplace transform analysis as Laplace charge transient spectroscopy, namely Laplace-QTS.

Before discussing the advantage for using the Laplace charge transient spectroscopy over the Laplace DLTS using the capacitance transient, let us explain why the Laplace QTS is able to resolve the closely-spaced energies of the deep-level defects. We consider the n defects with activation energies close to each other. The charge transient in Eq. (4) then becomes

$$Q(t) = \frac{AqW}{2} \sum_{i=1}^n N_{Ti} \{1 - \exp(-e_i t)\}, \quad (7)$$

where e_i is the emission rate of electrons that is the reciprocal of the time constant τ_i , and subscript i denotes defect i ($i =$

$1, \dots, n$). Although Eq. (7) also describes the charge transient of holes in the p-type semiconductor, we consider only the electrons in this paper. Using the inverse Laplace transform, the sum of the exponential function in Eq. (7) is transformed into the sum of the delta function [12],

$$L^{-1} \left\{ \sum_{i=1}^n N_{Ti} \exp(-e_i t) \right\} = \sum_{i=1}^n N_{Ti} \delta(s - e_i) \quad (8)$$

As seen on the right hand side of Eq. (8), the emission rates are easily resolved. Similarly, we obtain the emission rates at other temperatures. An Arrhenius plot can be made from the emission rate as a function of the temperature for defect i in a manner similar to the rate window analysis, and enables calculation of the activation energy of defect i [11].

As mentioned in the last section, the transient measured by the capacitance meter produces a ringing immediately after the pulse with a high slew rate is directly applied to the meter from an external source, and the data for times up to 200 μs seem to be invalid. In contrast to the capacitance transient, the QTS output voltage is not disturbed by the sudden change in the diode voltage, and the QTS circuit can measure the transient signal immediately after pulsing the diode. The data acquired immediately after the pulse are also important in order to extract the emission rates of all the defects in the temperature range by the inverse Laplace transform. This is confirmed by the following example.

Suppose the transient signal consists of three exponential signals with time constants of 1, 0.1 and 0.01 ms, as illustrated in Fig. 6. The sum of the exponentials is normalized by dividing by 3. Suppose that the data for the first 200 μs may not be valid due to the slower response of the capacitance meter when a pulse with a high slew rate is directly applied to the meter from an external source, and The data were acquired 200 μs after the pulse was fed into the CONTIN program [13]-[15] to perform the inverse Laplace transform, because any data obtained before 200 μs were considered invalid.

The result is shown in Fig. 7 (a). In contrast to the result for the whole transient signal acquired immediately after the pulse shown in Fig. 7 (b), the component with the highest emission rate, 10^5 s^{-1} , is missing in the emission-rate plot, where each delta function corresponds to the inverse Laplace transform of an exponential function, as shown in Eq. (8). The emission rate is obtained from the value on the horizontal axis. A cause for missing the fastest component is easily understood because the exponential with the highest emission rate significantly affects the early part, but not the last part of the transient signal. In other words, the transient signal without the fastest component is significantly different from that with three exponentials. This example illustrates how important it is to acquire the whole transient immediately after the pulse in order to extract all the emission rates by the inverse Laplace transform.

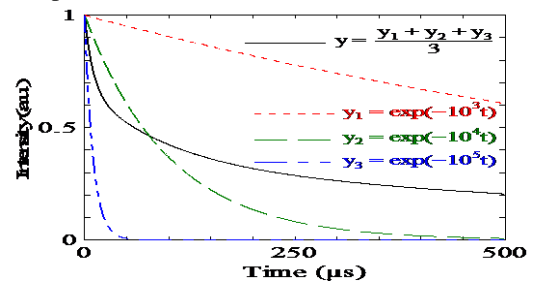


FIG. 6. Hypothetical transient signal made of three exponentials.

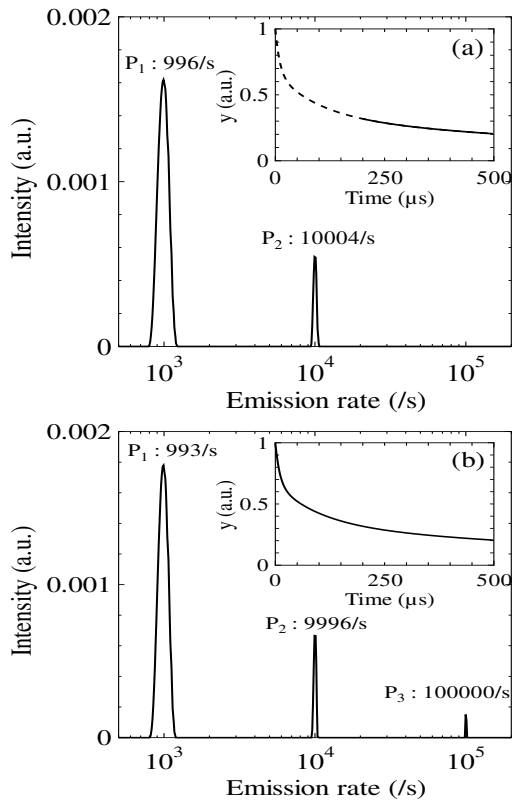


FIG. 7. Emission plot obtained from the inverse Laplace transform: (a) for the transient signal acquired only 200 μ s after the pulse and (b) for the transient signal acquired immediately after the pulse.

V. CONCLUSION

Laplace charge transient spectroscopy was proposed to improve the electrical characterization of deep-level defects in a semiconductor. Unlike capacitance transient spectroscopy, the data can be acquired by the charge transient spectroscopy immediately after the pulse. We have successfully demonstrated the importance of acquisition of the whole transient even in the well-established DLTS with the rate-window analysis. If the shortest sampling time is limited to 200 μ s, the DLTS peak height becomes low and more subject to noise. The DLTS with the rate-window analysis has a weakness in resolution of the closely spaced energies of the deep-level defects. Laplace DLTS has been proven to resolve a single energy obtained by the rate-window analysis into multiple energies. However, the highest emission rate was missing in the emission plot for the hypothetical multiple exponential transient if the transient data were acquired only from 200 μ s after the pulse. Therefore, the QTS is more suitably combined with the analysis using the inverse Laplace transform. The charge transient signal is more preferred for the inverse Laplace transform than the capacitance transient signal because the data can be obtained immediately after the pulse by the charge transient spectroscopy (QTS).

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