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Frequency-scanned deep-level transient spectroscopy

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The output signal in a deep-level transient spectroscopy experiment is a function of both the rate-window settings and sample temperature. Usually, the rate window is held fixed and the temperature scanned to produce the deep-level spectrum. We will demonstrate that a deep-level spectrum can also be obtained by fixing the temperature and scanning the rate window.

Deep-level transient spectroscopy[1] (DLTS) has become extremely useful in determining the thermal emission properties of deep levels of impurities and defects in semiconductors. The energy levels and carrier capture cross sections of these centers are obtained by measuring the junction capacitance,[1] current,[2] or charge[3] transient of a reverse-biased diode following a shorting or injecting pulse which temporarily populates the deep levels in the normally depleted region of the diode. In fact, these transient techniques have recently been extended to obtain the symmetry of several centers responsible for deep levels by applying uniaxial stress to diodes fabricated on samples of different crystallographic orientations.[4,5]

In the usual DLTS experiment, the time constant, τ, of the junction transient following the bias pulse, is compared to an electronically established rate window which is determined using gating electronics synchronized with the bias pulse. This time constant which, for majority carriers in n-type material, is given by

$$\tau^{-1} = N_c\, \sigma_n \langle v_n \rangle \exp[\,-(E_C - E_T)/kT\,], \qquad (1)$$

is varied experimentally by scanning the diode temperature while the rate window is held fixed in order to produce a DLTS spectrum. Analysis of this spectrum yields the depth of the energy level, the center's carrier capture cross section, and the concentration of centers. The symbols in Eq. (1) have the usual meaning.[1] We will show that an alternate approach, which also produces a DLTS spectrum, is to hold the sample temperature constant and scan the rate-window parameters. Although the practical application of this technique is somewhat restricted because of the limitations of the electronic circuits normally used to establish rate windows, we have been able to demonstrate this concept experimentally and will discuss a few applications of this new DLTS method.

The diode junction transient, following a repetitive bias pulse of period P, produces exponential changes in the junction capacitance, current, or charge which are amplified by detection circuits to produce a periodic analog output signal $e_s(t,\tau)$ of the general form for a single period of

$$e_s(t,\tau) = Ae^{-t/\tau} + B, \qquad (2)$$

where τ is given by Eq. (1) and the parameters A and B are either constants or temperature-dependent functions independent of time. This signal is periodic in that $e_s(t) = e_s(t+P)$. The junction signal e_s is converted into a DLTS output signal e_0 by multiplying by another periodic reference or weighting signal $e_r(t,P)$, which established the rate windows, and is then electronically averaged over the bias pulse period, i.e.,

$$e_0(P,\tau) = \frac{1}{P}\int_0^P e_s(t,\tau) e_r(t,P)\, dt. \qquad (3)$$

The integration represents the correlation between the junction relaxation time constant τ and the electronic rate window which is simply related to the period or frequency of the bias pulse. Since $e_0(P,\tau)$ can be varied by varying either τ or P, the possibility exists, using a suitable weighting function, for the output function to have a maximum as the temperature is held fixed and the period or frequency of the bias pulse varied. This is the essence of frequency-scanned DLTS.

As a particular example, we will calculate the output signal function e_0 when the reference function is a square wave obtained using a lock-in amplifier operating in the broadband mode. Then $e_r(t,P) = +1$ for $0<t<P/2$ and -1 for $P/2<t<P$, where $t=0$ is the end of the bias pulse which we will assume for simplicity to have a negligible pulse width compared to the period P between bias pulses. Under these conditions, and using Eqs. (2) and (3), we obtain[6]

$$e_0(\tau,P) = \frac{A\tau}{P}(1 - e^{-P/2\tau})^2. \qquad (4)$$

For a fixed value of P, this function has a maximum at the DLTS peak as the temperature and τ are scanned. This maximum is found numerically from the partial derivative $\partial e_0/\partial T\,|_P = 0$ to be

$$\tau_{\max} = 0.398P = 0.398/f, \qquad (5)$$

where P is the period of the bias pulse and f the frequency. This is the usual DLTS method for obtaining the values of τ at the DLTS peak temperature for use in an Arrhenius plot. In fact, $\tau_{\max}$ is the same for each DLTS peak and is determined solely by the rate-window setting P.

Note, however, that Eq. (4) also has a maximum if the period or frequency is varied and the temperature and τ held constant. In this case, from $\partial e_0/\partial P\,|_\tau = 0$, we likewise obtain

$$f_{\max} = P_{\max}^{-1} = 0.3894/\tau, \qquad (6)$$

i.e., when scanning the frequency of the bias pulse, the frequency at which a DLTS peak occurs is determined by the value of τ which is held fixed using a fixed temperature. This

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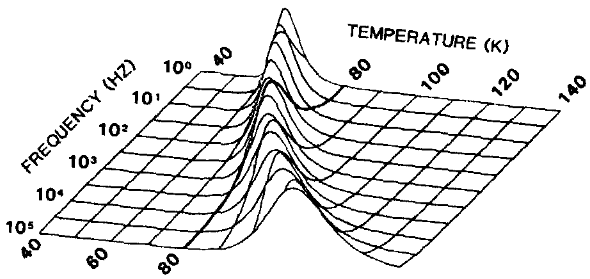

FIG. 1. Plot of the output signal $e_0(f,T)$ from a DLTS experiment as a function of temperature and frequency. A frequency-scanned constant-temperature spectrum (heavy solid line) is constructed from various isofrequency (fixed-rate-window) spectra.

frequency-scanning concept is demonstrated in Fig. 1 where a plot of e_0 from Eq. (4) is shown as a function of T and $f = P^{-1}$. Clearly, the DLTS spectrum for a single level is really a peak in the three-dimensional space of (e_0, T, f).

Figure 2(a) shows experimental DLTS spectra for n-type neutron-irradiated silicon taken with a lock-in amplifier operated in broadband so that Eq. (4) can be used to analyze the data. The spectra for four different frequencies (or periods) are shown. Figure 2(b) shows the frequency-scanned DLTS spectra calculated from Eq. (4) for three fixed temperatures and for the same defects shown at the top of this figure. Although the ordering of the peaks is reversed, both sets of spectra contain the same information, and identical Arrhenius plots can be obtained using Eq. (5) for normal DLTS or Eq. (6) for frequency-scanned DLTS. It is apparent from Fig. 2(b) that a practical limitation exists with frequency-scanned DLTS in that a very wide range of frequencies is required to cover the same range of energy levels that temperature-scanned DLTS covers. This limitation restricts frequency-scanned DLTS to the investigation of single peaks or closely spaced peaks with the electronic instruments currently available. We have, nevertheless, been able to find several useful applications of this technique.

As a demonstration of frequency-scanned DLTS, we have investigated the DLTS level of the oxygen thermal donor in Czochralski silicon, which is produced by annealing oxygen containing material to 450 °C.[7] We observe an energy level at 0.105 ± 0.023 eV below the conduction band with a capture cross section of about 10^{-14} cm^2 for a 6-V reverse bias. This ionization energy shifts as a function of junction electric field, in agreement with previous work.[7] We have used charge transient spectroscopy[4] in order to obtain as wide a frequency range as possible for this experiment.

Figure 3 shows a frequency-scanned DLTS spectrum of this level taken at a fixed temperature of 70.4 K (solid circles). Data were obtained manually by adjusting the period between bias pulses and measuring the lock-in dc output. The period was scanned over a frequency range of 10^1 to 10^5 Hz, which is sufficient to cover the entire frequency-scanned DLTS peak. It should be noted that a second peak at about 5.5×10^4 Hz is observed. This peak is due to an approximately exponential transient of the sample-and-hold amplifier following the bias pulse, which was clearly seen on the oscil-

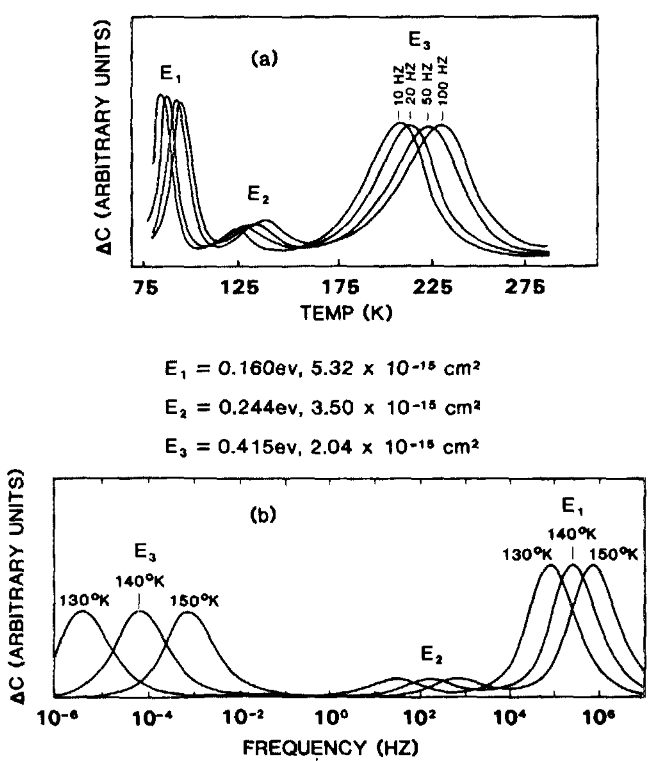

FIG. 2. (a) Typical temperature-scanned DLTS spectra for n-type neutron-irradiated silicon taken for various bias pulse frequencies using a broadband lock-in technique; (b) calculated frequency-scanned DLTS spectra using the same detection technique.

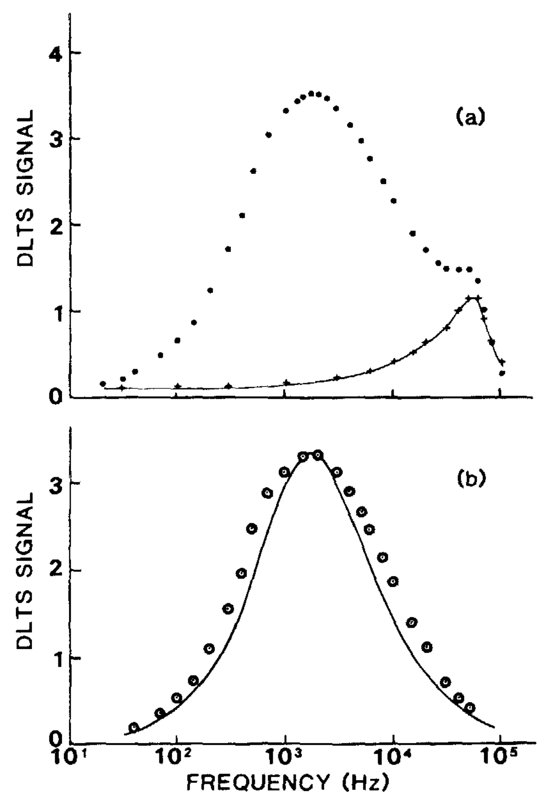

FIG. 3. (a) Frequency-scanned DLTS spectrum of the thermal donor level obtained using broadband lock-in detection as described in the text (solid circles) taken at 70.4 K. An instrument transient is obtained at 23.5 K (crosses). (b) Corrected DLTS spectrum is shown by open circles while the theoretical line shape is shown as a solid line.

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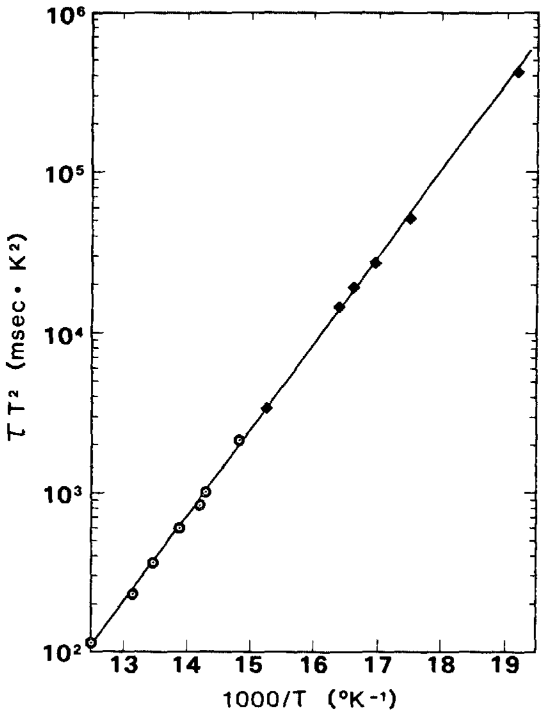

FIG. 4. Arrhenius plot for the thermal donor level. Open circles are obtained for frequency-scanned DLTS while solid circles are for temperature scanned DLTS.

loscope trace. Using Eq. (6), we estimate that this smaller peak corresponds to an instrument transient of 7.1 μsec, in good agreement with our estimate from the oscilloscope traces. This instrument peak does not move with respect to frequency as the sample temperature is changed. We have made use of this fact to obtain a correction curve for the instrument response shown in Fig. 3 by the crosses. To obtain this curve, the sample temperature was lowered to 23.5 K so as to move the DLTS energy level to frequencies below 10 Hz. The open circles represent the experimental DLTS level for the thermal donor after correcting for instrument response time. These data are in good agreement with theoretical line shape calculated from Eq. (4) and shown in Fig. 4 as a solid line. Although we note that the experimental peak is slightly broadened relative to the calculated line shape, we have also observed similar broadening for most normal DLTS peaks.

We have made frequency-scanned DLTS spectra at seven fixed temperatures ranging from 68 to 80 K in order to obtain an Arrhenius plot. These data are shown in Fig. 4 as the open data points. The solid data points in Fig. 4 were obtained using normal (temperature-scanned) DLTS. The agreement between the two sets of data is excellent.

This new DLTS technique of varying the rate window while holding the sample at fixed temperature is not limited to lock-in amplifiers. If we consider a double boxcar, for example, the output signal is given by

$$e_0(t_1, \tau) = A\,(e^{-t_1/\tau} - e^{-\alpha t_1/\tau}), \tag{7}$$

where t_1 is the time of the first gate and $\alpha = t_2/t_1$ is usually held fixed, where t_2 is the time of the second gate.[1] For normal temperature-scanned DLTS we obtain from $\partial e_0/\partial \tau|_t = 0$,

$$\tau_{\max} = \frac{t_2 - t_1}{\ln(t_2/t_1)} = \frac{t_1(\alpha - 1)}{\ln\alpha}, \tag{8}$$

while for rate-window scanning at fixed temperature and fixed α, we obtain from $\partial e_0/\partial t_1|_\tau = 0$,

$$t_{1_{\max}} = \frac{\tau \ln\alpha}{\alpha - 1}. \tag{9}$$

It can also be shown that rate-window scanning is possible for a number of DLTS variations.

We have seen that frequency-scanned DLTS, although limited in practical application by the very wide frequency range required to cover the whole spectrum, can be used to investigate transients inherent in the DLTS electronics. In addition to the sample-and-hold transient described here, we have also observed peaks for a capacitance-meter transient. These electronic transients are fixed in frequency for various sample temperatures and easily identified. A second application of the technique is the investigation of radiation-damage defects which have specific annealing temperatures. It is possible in some cases to obtain a frequency-scanned DLTS spectrum while holding the sample temperature below the annealing temperature. The usefulness of this new DLTS technique is mainly limited by the ability to extend present techniques to much higher frequencies.

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