DEEP LEVEL TRANSIENT SPECTROSCOPY

Impurity doping is important in semiconductor manufacturing, since it is indispensable for controlling the conductivity type and the carrier density in semiconductors. Typical dopants in silicon (Si) are phosphorus (P) and boron (B), which act as a donor and an acceptor, respectively. Their ionization energy is several tens of meV, and thus B and P are almost fully ionized at room temperature. In an energy band diagram, such an impurity level is located in the close vicinity of either the conduction-band or the valence-band edge. Foreign atoms other than such dopants, as well as lattice defects, can be unintentionally incorporated in semiconductors in virtually every step during the processing of semiconductor devices. Most lattice defects and transition metal impurities give rise to electronic states within the energy bandgap of semiconductors, and their energy positions are usually *deep*—that is, at least several times kT (approximately 100 meV at room temperature) from both band edges. Therefore, an unintentionally introduced defect or contaminant is generally called a *deep level* or a trap level. The evaluation of deep levels is a key issue in semiconductor manufacturing as well as the development of new semiconductor materials and devices, since trapping, generation, and recombination of electrons and holes at deep levels significantly affect the performance and reliability of the devices.

Deep-level transient spectroscopy, invented by D. V. Lang of Bell Laboratories in 1974, is one of the most powerful tools for high-sensitivity detection of trap levels in a semiconductor. This technique is capable of determining the concentration, the energy level, and the capture cross section of the trap levels in the semiconductor junction regions. It has now become a standard technique, usually referred to by its abbreviation "DLTS," to evaluate the purity of semiconductor crystals, the quality of device fabrication processes, and the reliability of devices.

The main features of DLTS are its sensitivity, measurement speed, and spectroscopic nature. DLTS is sensitive to trap concentrations as low as about 10^{-5} times the doping concentration. In characterizing trap levels in a semiconductor doped with, for example, 10^{15} cm^{-3} of donors or acceptors, concentrations of 10^{10} cm^{-3} of defects [on the order of parts per trillion (ppt) with respect to the host atoms] can be detected by using this technique.

In this method, the temperature of the diode, such as a *pn* junction, a Schottky barrier junction, or a metal–insulator–semiconductor (MIS) structure, is slowly scanned while the bias voltage is changed in increments. The depletion-layer capacitance transient due to carrier emission from the trap level is sampled at two successive delayed gate times. The difference between two sampled values constitutes the spectrum, which has a peak at a certain temperature. Information about trap concentrations and energy levels can be extracted straightforwardly from it: the height and the position of the peaks directly correspond to the concentration and the energy level, respectively. The sign of each peak indicates whether the observed defect acts as a trap for minority or majority carriers.

PRINCIPLE OF THE DLTS TECHNIQUE: RATE WINDOW CONCEPT

The basic idea of DLTS is the rate window concept. Consider exponential transients with a time constant τ as a physical system approaches a steady state following the application of a stepwise disturbance at $t = 0$. The following signal analysis can be expected for any physical system governed by Boltzmann statistics. In the standard DLTS measurements, the space charge density in the junctions varies with time due to thermal emission of the trapped carriers as the bias voltage is switched between two values. Since such carrier emission is a thermally activated process, the transient time constant τ (i.e., the reciprocal of the carrier emission rate) decreases as the temperature is increased. The left-hand side of Fig. 1 schematically shows a series of exponential transients at various temperatures. In the first-order approximation, the time constant of the thermally activated transient varies exponentially with $1/T$. The transient is very slow at low temperatures and becomes very rapid with increasing temperature. Let us now take the difference between the transient amplitude sampled at two fixed times t_1 and t_2 after the application of a stepwise disturbance. This is a DLTS signal, and its normalized form $S(T)$ is given by

$$S(T) = \exp\left(-\frac{t_1}{\tau}\right) - \exp\left(-\frac{t_2}{\tau}\right) \tag{1}$$

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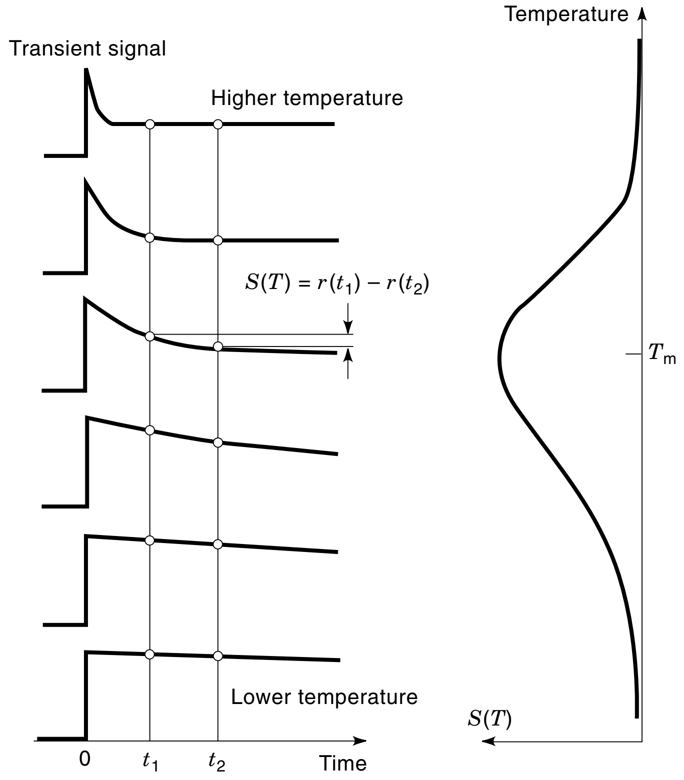


Figure 1. The principle of the DLTS technique. The left-hand side shows schematic exponential transients with a time constant τ that is thermally activated. The difference between the transient amplitude sampled at two fixed times t_1 and t_2 passes through a maximum as a function of temperature. The time constant at temperature T_m is equal to the rate window $\tau_m = (t_2 - t_1)/\ln(t_2/t_1)$.

Such a difference signal is almost zero at either low or high temperature, since the transient is too slow or too rapid, respectively, for the sampling times. However, in the midrange of temperatures where the transient time constant is on the order of the sampling delay times, the difference signal appears and passes through a maximum as a function of temperature. Thus, $S(T)$ has a peak. If the physical system contains more than one independent transient process, the resultant DLTS signal has a multipeaked structure. At the temperature of each response peak T_m, the time constant is equal to the *rate window* τ_m derived simply by differentiating Eq. (1) with respect to τ and setting the result equal to zero:

$$\tau_m = \frac{t_2 - t_1}{\ln(t_2/t_1)} \tag{2}$$

The activation energy can be determined by making an Arrhenius plot of log τ_m versus $1/T_m$, if the DLTS spectra are measured by choosing a series (five or more) of rate windows. Different rate windows can be obtained by choosing a convenient sequence of values of t_1/t_2.

Equation (1) is a kind of linear filtering operation in an integral transformation; in this particular case the weighting function is $\delta(t - t_1) - \delta(t - t_2)$. Such an operation is well known as the matched filter in the field of communication systems, which means that the optimum weighting function has the form of the noise-free signal itself, and therefore the optimum weighting function is a decaying exponential.

Another way to obtain a higher-S/N DLTS signal with a standard instrument is the use of a lock-in amplifier that has square-well bipolar gates.

DETECTION OF TRAPPED CHARGES BY JUNCTION CAPACITANCE

In a standard DLTS technique, the time variation of the trapped charge in the depletion layer is measured by means of the transient of the high-frequency (typically 1 MHz) junction capacitance. The junction capacitance C is related to the depletion-layer width W as

$$C = \epsilon_S \frac{A}{W} \tag{3}$$

where ϵ_S is the dielectric constant of the semiconductor and A the junction area. This equation is the same as the standard expression for a parallel-plate capacitor where the spacing between the two plates represents the depletion-layer width. Now, let us consider the depletion layer of either a p^+n or a metal–n (Schottky) junction, where the n-type region is uniformly doped with a shallow donor. Hereafter, we will consider trap levels in the n-type region for simplicity if not otherwise stated. For such a one-sided junction, the depletion layer width is given by

$$W = \sqrt{\frac{2\epsilon_S(V_{bi} - V)}{q(N_D \pm N_T)}} \tag{4}$$

where V_{bi} is the built-in voltage, V the applied bias voltage, q the electronic charge, and N_D and N_T the concentrations of the shallow donor and the trap level, respectively. The sign in the denominator is positive or negative for donor-type or acceptor-type traps.

Equations (3) and (4) mean that the depletion layer width under quiescent bias is reduced as the density of the positive charges in the depletion layer increases, and hence the resultant junction capacitance increases. Positive ionization of the trap level takes place by either electron emission or hole capture at the level. Consequently, electron emission from a trap level in the n-side depletion layer (i.e., majority carrier emission) induces an increasing transient of the junction capacitance. Likewise minority carrier emission gives rise to a decaying capacitance transient.

When the trap concentration is much smaller than the shallow dopant concentration ($N_T \ll N_D$), a simple linear relationship between the trap-level concentration and the induced capacitance change ΔC is derived from Eqs. (3) and (4) as

$$\frac{N_T}{N_D} \approx 2\frac{\Delta C}{C_0} \tag{5}$$

where C_0 is the total capacitance under quiescent bias voltage. In the limit of small trap concentration, the measured junction capacitance shows exponential transients that are directly related to the rate equations for the electron occupation of the trap levels, which will be discussed later. In general, the trap level and the doped impurity are not uniformly distributed in space. Therefore, it will be useful to find the capacitance change δC induced by the ionized traps in the interval between x and $x + \delta x$, where x is the position within the n-side of the depletion layer. By solving the Poisson equation, just as in the depletion layer analysis in standard semiconductor textbooks, the relative capacitance change is seen to be given by

$$\left.\frac{\delta C}{C_0}\right|_x = -\frac{N_T(x)x\,\delta x}{W^2 N_D(W)} \tag{6}$$

where $N_D(W)$ is the donor concentration at the depletion layer edge W. It is known from this result that the junction capacitance has maximum sensitivity to a trap at the depletion-layer edge, but is insensitive to one at the junction plane.

Integrating Eq. (6) with respect to x from 0 to W gives the same result as Eq. (5) for a uniform distribution of N_T and N_D, as one would expect.

CHANGE IN ELECTRON OCCUPATION AT TRAP LEVELS

Shockley–Read–Hall Statistics and Rate Equation

The kinetics of trapping, recombination, and generation at a single energy level in the semiconductor bandgap were first considered by Shockley, Read, and Hall. Hence, the following treatment is usually called the SRH statistics. Figure 2 shows four processes of electron and hole capture and emission by a single-energy-trap level. The four elementary processes are:

(a) Electron capture from the conduction band to an unoccupied trap level. The capture rate is given by the product of the conduction electron density n and the capture coefficient, nC_n. The capture coefficient is given by $C_n = \sigma_n v_{\mathrm{th},n}$, where σ_n is the capture cross section for electrons, and $v_{\mathrm{th},n}$ the electron thermal velocity.

(b) Electron emission from an occupied level to the conduction band, with an emission rate e_n.

(c) Hole capture from the valence band to an occupied level, with a capture rate pC_p, where the symbols are defined similarly to those in (a). In the figure, the direction of the arrow indicates the equivalent electron transition.

(d) Hole emission from an unoccupied level to the valence band, with an emission rate e_p.

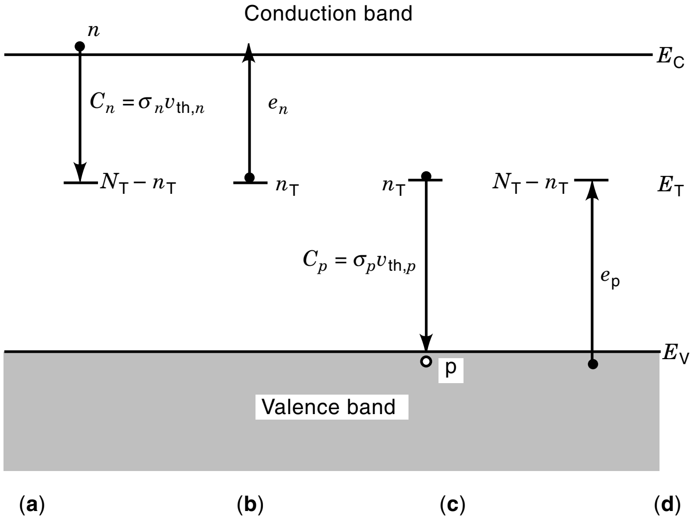


Figure 2. The four processes of electron and hole capture and emission by a single-energy-trap level.

The emission rate and the capture coefficient are not independent on each other. The principle of detailed balance yields the relationship between the two quantities. For example, the electron emission rate is given by

$$e_n = \frac{\sigma_n v_{\mathrm{th},n} N_C}{g} \exp\left(-\frac{E_C - E_T}{kT}\right) \tag{7}$$

where N_C is the effective density of states of the conduction band, g the degeneracy of the trap level, and $E_C - E_T$ the energy level. The hole emission rate is given in a similar form. When the semiconductor is illuminated with light, optical emission of electrons and/or holes may take place. The electron and hole transitions are expressed in the same form as (b) and (d), respectively, in the SRH process shown in Fig. 2. The optical emission rates are given by $\Phi\sigma_n^0$ and $\Phi\sigma_p^0$ for electrons and holes, respectively, where Φ is the incident photon flux and $\sigma_{n,p}^0$ the photoionization cross section.

The time variation of the trapped electron density n_T is determined by the rate equation with the above rate constants:

$$\begin{aligned}\frac{dn_T}{dt} &= nC_n(N_T - n_T) - (e_n + \Phi\sigma_n^0)n_T - pC_p n_T \\ &\quad + (e_p + \Phi\sigma_p^0)(N_T - n_T)\end{aligned} \tag{8}$$

From this rate equation, we may solve for n_T under a given initial condition. If we define the electron occupation function as $f_T \equiv n_T/N_T$, the concentration of positively charged levels for a donor-type defect is given by $N_T(1 - f_T)$. The solution includes an exponential with a transient time constant

$$\tau = \frac{1}{nC_n + e_n + \Phi\sigma_n^0 + pC_p + e_p + \Phi\sigma_p^0} \tag{9}$$

In the steady-state condition, the electron occupation of the trap level becomes

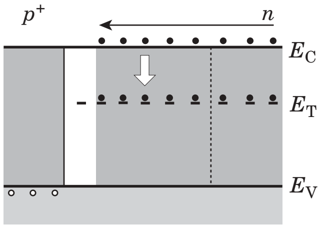
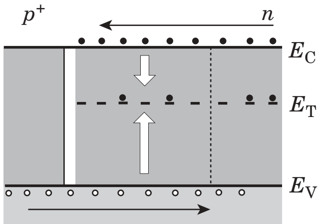
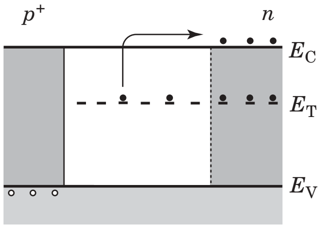
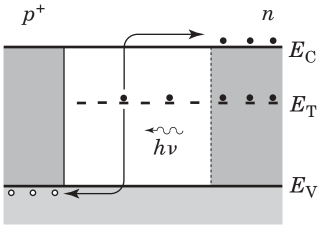
$$\overline{f_T} \equiv \frac{\overline{n}_T}{N_T} = \frac{nC_n + e_p + \Phi\sigma_p^0}{nC_n + e_n + \Phi\sigma_n^0 + pC_p + e_p + \Phi\sigma_p^0} \tag{10}$$

How to Control the Electron Occupation of the Trap Level

DLTS and its related techniques rely on the transition between two steady states of the electron occupation at the trap level, to which the junction is switched alternately by changing the bias voltage. Instead of using a pulsed bias, optical illumination may be applicable. In Table 1, typical conditions used for the actual experiments are summarized in relation to Eqs. (9) and (10). Again, we will consider trap levels in the n-side of the p^+n junction.

(i) *Reduction of the Applied Reverse Bias in the Dark.* In this condition, majority carriers enter the

Table 1. Summary of the Behavior of Trap Levels in the n-Side Depletion Layer of the p^+n Junction

Experimental Condition	Schematic Illustration of the Depletion Layer	Transient Time Constant τ	Steady-State Electron Occupation $\overline{f}_T$
(i) Reverse-bias reduction, majority carrier filling pulse		$\frac{1}{nC_n} = \frac{1}{n\sigma_n v_{th,n}}$	1
(ii) Forward-bias application, minority carrier injection pulse		$\frac{1}{nC_n + pC_p}$	$\frac{nC_n}{nC_n + pC_p}$
(iii) Reverse-bias application, thermal emission of carriers		$\frac{1}{e_n}$	0
(iv) Illumination at LT, optical injection pulse		$\frac{1}{\Phi(\sigma_n^o + \sigma_p^o)}$	$\frac{\sigma_p^o}{\sigma_n^o + \sigma_p^o}$

observed region. Since a typical rate window used for DLTS measurements ranges from milliseconds to several seconds, the detectable thermal emission rate is below about 10^3 s^{-1}. If we assume $n = 10^{16}$ cm^{-3}, $\sigma_n = 10^{-16}$ cm^2, and $v_{th,n} = 10^7$ cm/s, all of which are in the typical orders of magnitude for these parameters, then the capture rate will be 10^7 s^{-1}, much larger than the electron emission rate ($nC_n \gg e_n$). No hole injection under a reverse- or zero-bias condition guarantees $nC_n \gg pC_p$, and hence the dominant rate coefficient can be nC_n. Thus, the transient time constant τ and the steady-state electron occupation function $\overline{f_T}$ become

$$\tau = \frac{1}{nC_n} = \frac{1}{n\sigma_n v_{th,n}}, \qquad \overline{f_T} \approx \frac{nC_n}{nC_n} = 1 \tag{11}$$

This type of bias pulse is called a *filling pulse*; it momentarily reduces the diode bias and introduces only majority carriers into the region of observation.

(ii) *Application of the Forward Bias in the Dark.* In this case, both majority and minority carriers enter the observed region. Then τ and $\overline{f_T}$ are

$$\begin{aligned} \tau &= \frac{1}{nC_n + pC_p} = \frac{1}{n\sigma_n v_{th,n} + p\sigma_p v_{th,p}}, \\ 0 &\le \overline{f_T} \approx \frac{nC_n}{nC_n + pC_p} \le 1 \end{aligned} \tag{12}$$

This type of bias pulse is called an *injection pulse.* If we use a p^+n junction, a high hole injection efficiency enables us to make $\tau \approx (p\sigma_p v_{th,p})^{-1}$ and $\overline{f_T} \approx 0$ for the trap level with $C_p \gg C_n$. The trap level is filled with holes (minority carriers).

(iii) *Application of the Reverse Bias in the Dark.* Since the concentration of neither electrons nor holes becomes negligibly small in the observed region, the capture rates, nC_n and pC_p, are much smaller than the thermal emission rates at temperatures where the rate window is comparable to the emission rate. Furthermore, the built-in field in the depletion layer can sweep the emitted carriers out of the observed region, and hence carrier recapture can be neglected. If the trap level is closer to the conduction band than to the valence band, it is a natural consequence that the electron emission rate is much larger that the hole emission rate ($e_n \gg e_p$). For such an electron trap, the dominant rate coefficient becomes e_n. In the steady state, the electron occupation function at the trap level will be zero:

$$\tau = \frac{1}{e_n} = \frac{g}{\sigma_n v_{\mathrm{th},n} N_\mathrm{C}} \exp\left(\frac{E_\mathrm{C} - E_\mathrm{T}}{kT}\right), \qquad \overline{f_\mathrm{T}} \approx \frac{1}{e_n} = 0 \tag{13}$$

The above time constant (i.e., emission time constant) as a function of temperature is the major quantity to be determined by a standard DLTS measurement. For this purpose, a series of rate windows are chosen as mentioned before.

(iv) *Optical Illumination.* If measurements are carried out at low temperatures or under strong illumination, the dominant rate coefficients can only be optical terms in the depletion layer. Then

$$\tau = \frac{1}{\Phi(\sigma_n^0 + \sigma_p^0)}, \qquad 0 \le \overline{f_\mathrm{T}} \approx \frac{\sigma_p^0}{\sigma_n^0 + \sigma_p^0} \le 1 \tag{14}$$

When we illuminate a trap level closer to the conduction band than to the valence band with photons ($E_\mathrm{C} - E_\mathrm{T} < h\nu < E_\mathrm{T} - E_\mathrm{V}$), σ_p^0 can be zero. Therefore, the defect level becomes completely unoccupied with electrons ($\overline{f}_\mathrm{T} = 0$). The basic idea of photocapacitance spectroscopy relies on this transition and the accompanying capacitance transient. Optical illumination is also useful for detection of minority carrier traps in Schottky diodes (metal–semiconductor junctions) where minority carrier injection by applying forward bias voltage is impossible. The trap level can be partially filled with minority carriers by using an optical pulse.

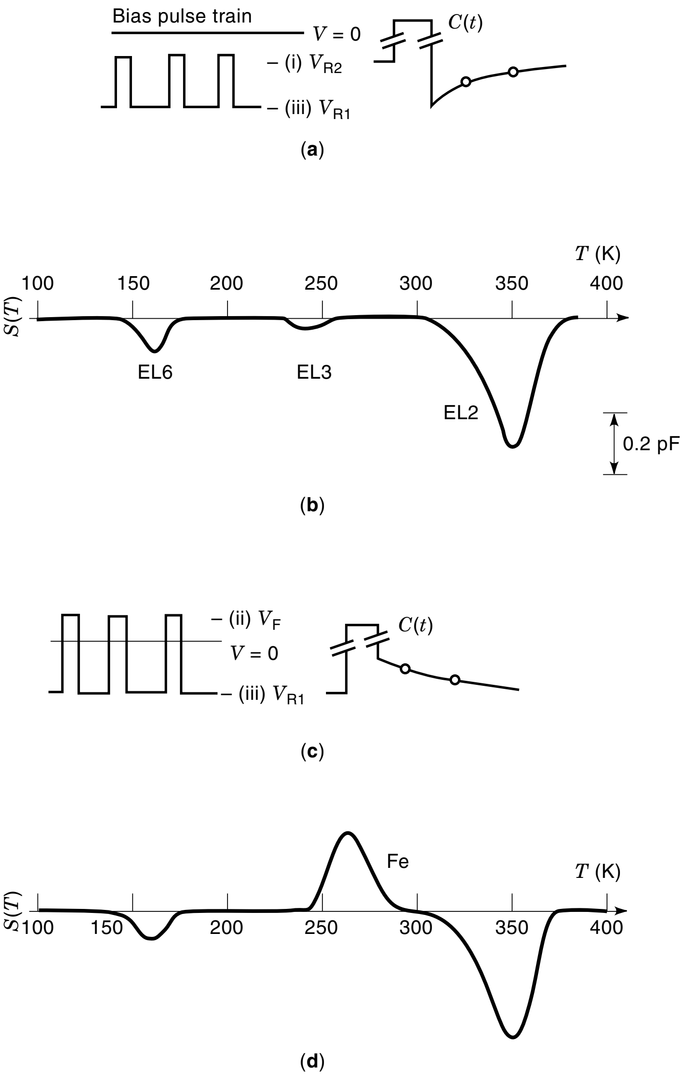


Figure 3. DLTS spectra for (a) electron traps in a GaAs p^+n diode applied by majority-carrier filling pulses and (b) electron traps and one hole trap in the same diode applied by injection pulses.

DEEP-LEVEL CHARACTERIZATION WITH JUNCTION CAPACITANCE TRANSIENTS

Carrier Emission Spectra

From the carrier emission process, we can determine the energy level and the concentration of the trap level [see condition (iii) in Table 1]. This is the most common mode of DLTS measurements. Figure 3 shows an example of DLTS spectra measured with GaAs p^+n diodes, in which the observed region is in the n-side of the depletion layer. For the characterization of majority carrier (electron) traps, the applied bias is changed between lower and higher reverse voltages [Fig. 3(a)]. If the duration of the reduced reverse bias (filling pulse) is sufficiently long compared with the capture time constant $(n\sigma_n v_{\mathrm{th},n})^{-1}$, the trap levels are completely filled with electrons [see condition (i) in Table 1]. Under the higher reverse bias, the positive space charge density increases due to the electron emission from the trap levels, and hence it can be easily understood from Eqs. (3) and (4) that the junction capacitance increases with time. Therefore, negative peaks are observed in the resultant DLTS spectrum. For small trap concentrations, the peak heights are simply proportional to the concentrations. In general, the higher the peak temperature, the deeper the energy level. Hence, the measured spectrum is a straightforward way to analyze unknown traps or to routinely monitor known traps in several samples.

For the characterization of minority carrier traps, the applied voltage is swung into the forward bias region. Under such an injection pulse, both electrons (in this particular example, majority carriers) and holes (minority carriers) exist in the observed region and are captured by the trap levels [see condition (ii) in Table 1]. The steady-state electron occupation will be between zero and unity. After the bias voltage returns to the quiescent reverse bias, the trap level, if it is closer to the valence band than to the conduction band, emits holes. In this case, the junction capacitance transient becomes a decaying exponential as shown in Fig. 3(b). Therefore, the difference signal as a function of temperature yields a positive

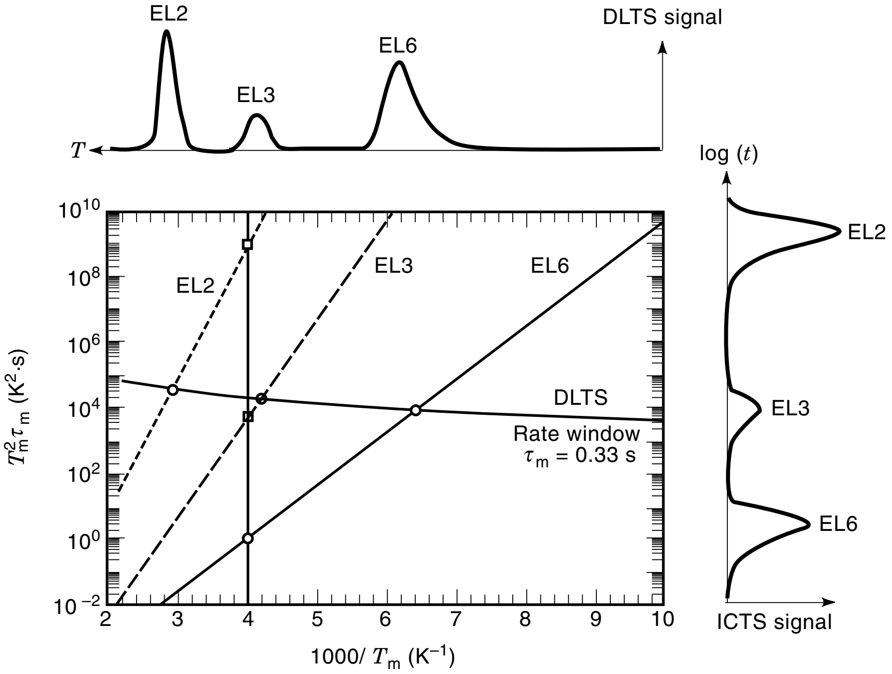


Figure 4. A schematic Arrhenius plot for three electron traps in GaAs, EL2, EL3, and EL6. The DLTS signal gives peaks at temperatures where each emission time constant becomes the rate window. The figure also shows a schematic isothermal capacitance spectrum (ICTS) at 250 K.

peak when a sample contains a minority carrier trap. It should be noted that the trap concentration is underestimated with the observed peak height because the initial hole occupation is always less than unity. In order to obtain the exact value of the concentration, we have to know the injected carrier density and the capture cross sections for both electrons and holes.

An alternative way for the trap level to be filled with minority carriers is optical pulses [condition (iv) in Table 1]. If we use a light source in the proper range of photon energy, both electron and hole emissions take place due to photoionization and then the trap level will be partially filled with holes. Even in the injection pulse mode, majority carrier traps can be also detected, but, for the same reason as with minority carrier traps, the observed peak height will be reduced from that measured in the majority-carrier filling mode. If some electron traps also act as an effective lifetime killers or recombination centers under minority carrier injection, their peak heights can be dramatically reduced by using minority carrier injection pulses.

Arrhenius Plots

The energy level can be derived from an Arrhenius plot of the logarithm of the emission time constant. Because the thermal velocity of carriers and the effective density of states of the bands are proportional to $T^{1/2}$ and $T^{3/2}$, respectively, we usually plot the product of the rate window and the square of the peak temperature as a function of the reciprocal of the peak temperature, namely, $\log(T_m^2\tau_m)$ versus $1000/T_m$. A series of DLTS spectra were obtained using different rate windows. Figure 4 shows the relationship between such an Arrhenius plot for several trap levels and a certain rate window. It is noted that the activation energy does not always mean the energy position of the trap level. In general, the capture cross section depends on temperature. For example, a carrier-capturing process with the emission of multiple phonons is thermally activated with an energy barrier of ΔE, as is well known for many trap levels in III–V compound semiconductors. In this case, the capture cross section is expressed as

$$\sigma_n = \sigma_\infty \exp\left(-\frac{\Delta E}{kT}\right) \tag{15}$$

where σ_∞ is the capture cross section at infinite temperature. Hence, the slope of the Arrhenius plot gives $(E_C - E_T) + \Delta E$. By extrapolating the Arrhenius plot to the vertical axis we can determine the preexponential factor of Eq. (13). Since the values of $v_{th,n}$ and N_C are known, the value of g/σ_∞ can be derived, but cannot be separated into its components. If we can independently measure the temperature dependence of capture cross sections of the form (15), both the energy level and the degeneracy factor of the trap can be determined.

Isothermal Capacitance Transient Spectroscopy

An equivalent spectrum to DLTS can be obtained by analyzing an isothermal transient signal as follows. First, consider the function

$$f(t) = t\exp\left(-\frac{t}{\tau}\right) \tag{16}$$

which has a maximum value at $t = \tau$. When $f(t)$ is plotted as a function of the logarithm of t, we can obtain an equivalent shape to the DLTS spectrum. For the transient of the junction capacitance due to trap levels, Eqs. (3) and (4) imply that the *isothermal capacitance transient spectrum* (ICTS) is given by

$$S(t) = t\frac{dC^2}{dt} \tag{17}$$

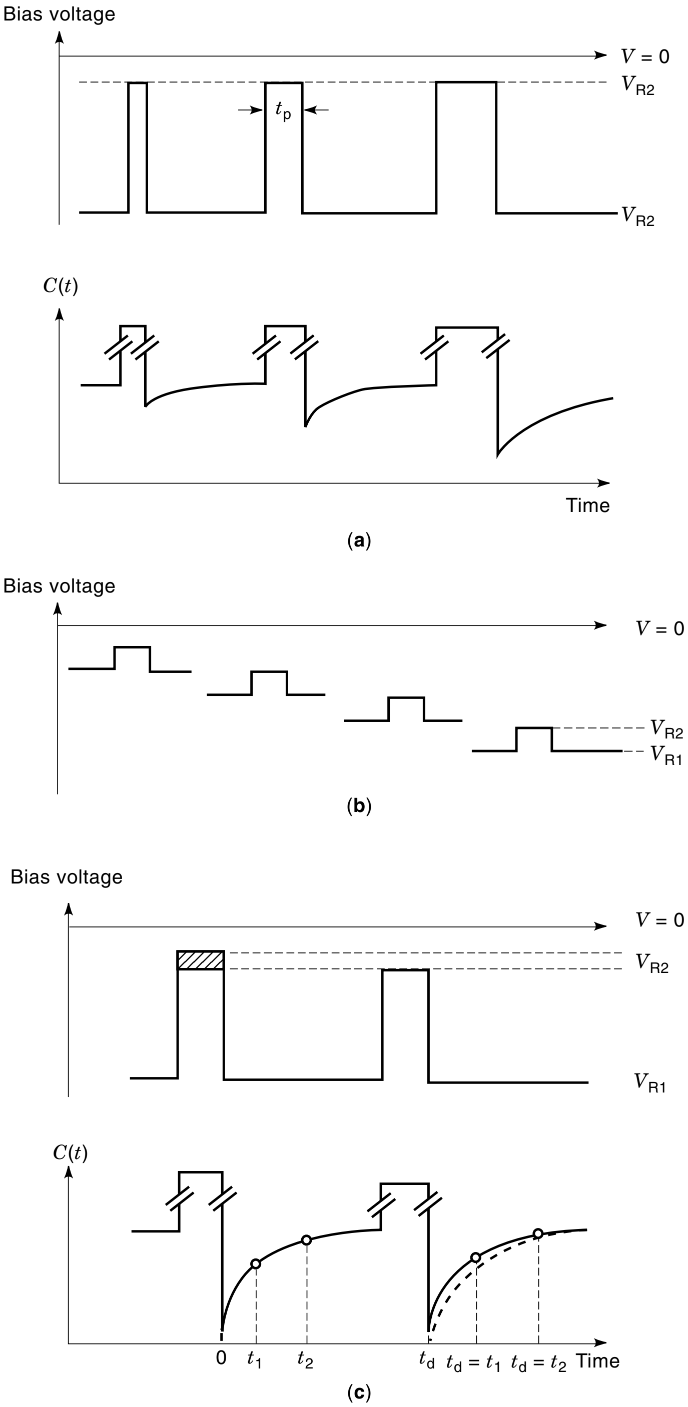


Figure 5. Diagrams of pulse sequence showing how to measure (a) capture cross sections (fast pulse), (b) trap concentration profiles (small pulse), and (c) electric field dependence of carrier emission rates (double DLTS).

where the first derivative is taken so as to eliminate the baseline component of the junction capacitance due to shallow dopants. Figure 4 also shows a schematic ICTS spectrum in relation to the Arrhenius plot, as well as the corresponding DLTS spectrum. Practically, we cannot obtain such a wide spectrum; shorter and longer time constants are not realistic due to the response time of capacitance meters and the limits on experimental time, respectively.

Determination of Capture Cross Section

In condition (ii) of Table 1, the time evolution of the electron occupation of the trap level is given by

$$\frac{n_{\mathrm{T}}(t)}{N_{\mathrm{T}}} = 1 - \exp(-n\sigma_n v_{\mathrm{th},n} t) \tag{18}$$

Since this capturing process occurs not in a depletion region but in a neutral region induced by reducing the applied reverse bias, we cannot monitor it in real time with the capacitance transient. Therefore, we use a series of short carrier-filling pulses as shown in Fig. 5(a), the minimum width of which is shorter than the capture time constant $(n\sigma_n v_{\mathrm{th},n})^{-1}$. Then, we monitor emission spectra for the partially filled trap levels after returning to the quiescent bias. The longer the filling-pulse width, the higher the resultant DLTS peak. Again, if the trap concentration is small enough compared with the shallow dopants, the measured DLTS peak is proportional to $n_{\mathrm{T}}(t_{\mathrm{p}})$, where t_{p} is the filling-pulse width, and hence we can determine the capture cross section at T_{m} from the t_{p} dependence of the peak height.

Other Pulse Sequences for Advanced Characterization

The sequence of filling pulses shown in Fig. 5(b) is useful in determining the spatial profile of trap concentrations. By using majority carrier pulses with an amplitude small compared to the steady-state bias voltage, the region observed by the capacitance transient can be restricted to a small region in the vicinity of the junction edge. Equation (6) can be applied to the calculation of the trap concentration in conjunction with the standard C–V profile measurement of shallow dopants $N_{\mathrm{D}}(W)$.

Figure 5(c) shows the method termed *double DLTS* (DDLTS), which consists in alternating filling pulses with two different amplitudes. The sampled capacitance data $C(t_1)$, $C(t_2)$, $C(t_1 + t_{\mathrm{d}})$, $C(t_2 + t_{\mathrm{d}})$ are processed as

$$S_{\mathrm{DDLTS}} = [C(t_1) - C(t_2)] - [C(t_1 + t_{\mathrm{d}}) - C(t_2 + t_{\mathrm{d}})] \tag{19}$$

where t_{d} is the separation between two different filling pulses. The resultant DLTS signal can be attributed to a narrow region in the interior of the depletion layer, where the electric field varies in space. Therefore, this method is capable of detecting the carrier emission from the trap levels within a narrow region, and determining the electric field dependence of the thermal emission rate. This provides important information on the charge state of the trap level. If a trap level is a donor type, where its charge state becomes positive after electron emission, the emission rate is enhanced under higher electric fields due to the so-called Poole–Frenkel effect.

DLTS is also capable of characterizing continuous energy levels, such as interface states in MIS or metal–oxide–semiconductor (MOS) structures. For this purpose, various pulse sequences and analytical methods have been proposed in order to deconvolve the energy dependence of the density of states from the measured broad spectra.

BIBLIOGRAPHY

Standard Test Method for Characterizing Semiconductor Deep Levels by Transient Capacitance Techniques, ASTM F978-90, Philadelphia: ASTM, 1990.

P. Bräunlich (ed.), *Thermally Stimulated Relaxation in Solids,* Berlin: Springer-Verlag, 1979.

J. E. Carroll, *Rate Equations in Semiconductor Electronics,* London: Cambridge University Press, 1985.

D. V. Lang, Deep-level transient spectroscopy: A new method to characterize traps in semiconductors, *J. Appl. Phys.,* **45**: 3023–3032, 1974.

D. C. Look, *Electrical Characterization of GaAs Materials and Devices,* New York: Wiley, 1989.

G. L. Miller, J. V. Ramirez, and D. A. H. Robinson, A correlation method for semiconductor transient signal measurements, *J. Appl. Phys.,* **46**, 2638–2644, 1975.

A. G. Milnes, *Deep Impurities in Semiconductors,* New York: Wiley, 1973.

H. Okushi and Y. Tokumaru, Isothermal capacitance transient spectroscopy, *Jpn. J. Appl. Phys.,* **20**: supplement 20-1, 1981.

S. T. Pantelides (ed.), *Deep Centers in Semiconductors,* 2nd ed., Philadelphia: Gordon and Breach Science, 1992.

S. M. Sze, *Physics of Semiconductor Devices,* 2nd ed., New York: Wiley, 1981.

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DEEP LEVEL TRANSIENT SPECTROSCOPY. See ACTIVATION ENERGY.