1. Physical basics

Deep Level Transient Spectroscopy (DLTS) was developed in 1974 by D.V. Lang [1] to investigate energetically "deep" charge trapping levels in semiconductor space charge structures, which may be either pn junctions or Schottky barriers. It utilizes the fact that the rf capacitance of the sample (usually measured at 1 MHz under reverse bias) depends on the charge state of deep levels in the space charge region (SCR). In total depletion approximation, the rf capacitance of a sample having a homogeneous doping concentration is:

$$C_0 = A \sqrt{\frac{\varepsilon_0 \varepsilon_r (N_D - N_A)}{2(V_r + V_d)}}$$

(1)

Here, A is the sample area, $N_D - N_A$ is the total net charge density in the SCR, $V_r$ is the reverse bias, $\varepsilon_0 \varepsilon_r$ is the permittivity of the semiconductor material, and $e$ is the electron charge. If the sample is a pn junction, $N_D - N_A$ refers to the lower doped side of the junction. $V_d$ is the built-in diffusion voltage of the SCR. $V_r$ and $N_D - N_A$ can be determined e.g. by CV measurements [2,3], where $V_d$ is the crossing point of the extrapolated $1/C^2$ plot vs. $V_r$ with the $V_r$-axis, and $N_D - N_A$ is calculated from eq. (1).

If charged trapping levels are existent in the SCR, their space charge has to be added to $N_D - N_A$. Assuming a donor-like trap level of concentration $N_t$ in a n-type sample under a reverse bias $V_r$, the capacitance change by recharging these levels is:

$$\Delta C = A \sqrt{\frac{\varepsilon_0 \varepsilon_r (N_D - N_A)}{2(V_r + V_d)}} - A \sqrt{\frac{\varepsilon_0 \varepsilon_r (N_D - N_A + N_t)}{2(V_r + V_d)}}$$

$$\cong C_0 \frac{N_t}{2(N_D - N_A)}$$

(2)

The last identity holds approximately if $N_t \ll N_D - N_A$ holds. Then the trap concentration $N_t$ is calculated from the capacitance change $\Delta C$ as:

$$N_t = \frac{2 \Delta C}{C_0} (N_D - N_A)$$

(3)

2. Experimental procedure

Fig. 1 shows the basic experimental procedure of DLTS. The capacitance of the sample is measured under reverse bias $V_r$. For performing the DLTS routine, bias pulses are periodically applied to the sample, hence $V_r$ is reduced or even reversed for a certain filling pulse width $t_{imp}$, leading to a periodic recharging of the levels in the SCR. During these pulses the rf capacitance increases, which, however, is not regarded in DLTS. Immediately after each pulse the rf capacitance changes by $\Delta C$, whereby $\Delta C$ is negative for majority carrier traps (shown in Fig. 1) and positive for minority carrier traps. If a Schottky diode is used, or if in a pn junction the reverse bias is only reduced by a pulse bias $V_{pulse} \leq V_r$, only majority carrier traps are recharged. If during the pulse a pn junction is forward-biased into injection, also minority carriers may be recharged.

The degree of trap filling depends on $t_{imp}$ and on the capture coefficient of the traps $c_n$ (for electrons) or $c_p$ (for holes) by:

$$c_n = \frac{n}{t_{capt}}; \quad c_p = \frac{p}{t_{capt}}$$

(4)

$n$ and $p$ are the free carrier concentrations of electrons and holes, respectively, during the capture process. Note that (3) and (4) only hold if $\Delta V$ is large compared to $V_d$ and close to $V_r$. For $\Delta V < V_r$, the trap concentration for saturation pulses and homogeneous trap incorporation is calculated as:

$$N_t = \frac{2 \Delta C V_r}{C_0 \Delta V} (N_D - N_A)$$

(5)

Hence, for homogeneous trap distribution the DLTS peak height $\Delta C$ is expected to be proportional to the filling pulse height $\Delta V$, and $N_t$ can be calculated if $N_D - N_A$ is known.
3. Evaluating DLTS signals

The equilibrium degree of trap filling in the SCR under reverse bias is zero, hence the levels are ionized. If after a filling pulse traps are filled and the reverse bias is re-established, the system is in thermal non-equilibrium and relaxes by thermally emitting the trapped charges into the corresponding bands, where they are swept away by the electric field. For isolated point defects this relaxation is exponential in time, but for extended defects like dislocations, precipitates, and interface layers the emission transient (just as the trap filling process) may be non-exponential. Therefore, all relations above strictly hold only for point defects.

The relaxation is connected with a capacitance transient, which is converted into a measurable transient signal by a capacitance meter. The time constant $\tau_e$ of the thermal emission is governed by the thermal emission rate $e_{n,p}$ which depends on the trap energy $E_t$ and on the temperature $T$:

$$e_{n,p} = \frac{1}{\tau_e} \frac{N_{cv} c_{np}}{g} \exp\left(-\frac{E_t}{kT}\right)$$  \hspace{1cm} (6)

Here, $N_{cv}$ is the effective density of states in the conduction band (for electron emission) or the valence band (for hole emission), $g$ is the degeneracy factor of the level, usually assumed to be unity, and $kT$ is the thermal energy. The exponential dependence of the emission rate on $1/T$ (the so-called Arrhenius plot), with the trap energy $E_t$ determining its slope and the capture coefficient $c_{np}$ determining its prefactor, is the signature of each trap, which is used for their identification.

In DLTS filling pulses are applied periodically to the sample, leading to periodical capacitance transients (see Fig. 1). The basic idea of DLTS is to convert the capacitance transients into the DLTS-signal by "correlating" them on-line. The simplest kind of DLTS correlation is the 2-point correlation (boxcar method), where the capacitance is measured at two times $t_1$ and $t_2$ after the end of each filling pulse, and the difference $D$ between these two values is displayed:

$$D = C(t_1) - C(t_2)$$ \hspace{1cm} (7)

Hence, the DLTS signal is scaled in units of capacitance (usually pF). Other kinds of correlation are providing an especially good signal-to-noise ratio (exponential correlation) or a better energy resolution than 2-point correlation [3].

Usually the DLTS measurement starts at low temperature, the temperature is slowly ramped up, and the DLTS signal $D$ is recorded. During the T-ramp the relaxation time constants of all levels in the sample are gradually increasing from very large values to very low ones according to eq. (6). As long as $T$ is too low for significant thermal emission until $t_2$, the difference $D$ is zero. If $T$ is so high that the relaxation is already over at $t_1$, $D$ is also zero. Only if $e_{n,p}$ (or $\tau_e$, respectively) of a level falls into the so-called "rate window" given by the selection of $t_1$ and $t_2$, a DLTS peak appears, see Fig. 2.

![Fig. 2: The maximum DLTS signal is recorded at a Temperature correlated to the emission rate $e_{n,p}$. An arrhenius plot of ln $e_{n,p}$ over 1/T yields the trap energy (in case of ideal point defects).](image)

For 2-point correlation we obtain the following condition for the DLTS peak maximum:

$$e_{n,p} = \frac{\ln(t_2/t_1)}{t_2 - t_1}$$ \hspace{1cm} (8)

The "rate window" $e_{n,p}$ has the unit of s$^{-1}$. For 2-point correlation, the corresponding time constant $\tau_e$ is always lying between $t_1$ and $t_2$. The maximum signal shifts to other temperatures if $t_1$ and $t_2$ are varied; as long as the ratio $t_1/t_2$ is kept constant, the line shape of the DLTS signal is preserved.

A sample DLTS plot is shown in Fig. 3. Set-up techniques, sample measurements and applications are discussed in the lecture (see sheets).

![Fig. 3: DLTS analysis of conducting GaAs [4].](image)

Literature:

[2] M. Bickermann et al., Kapazitätsspannungsmessungen an MIS-Kondensatorstrukturen zur Ermittlung von Halbleiter-


Fortgeschrittenenpraktikum/fp/dlts.pdf