SECOND EDITION

SEMICONDUCTOR MATERIAL AND DEVICE CHARACTERIZATION

DIETER K. SCHRODER

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DIETER K. SCHRODER
Arizona State University
Tempe, Arizona

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3–5 decades of time constants to be taken.[79] It can separate closely spaced deep levels where conventional DLTS fails.

5.6.2 Interface Trapped Charge DLTS

The instrumentation for interface trapped charge DLTS is identical to that for bulk deep-level DLTS. However, the data interpretation is different because interface traps are continuously distributed in energy through the band gap, whereas bulk traps have discrete energy levels. We illustrate the interface trapped charge majority carrier DLTS concept for the MOS capacitor (MOS-C) in Fig. 5.17(a). For a positive gate voltage, electrons are captured and most interface traps are occupied by majority electrons for n-substrates [Fig. 5.17(b)]. A negative gate voltage drives the device into deep depletion, and electrons are emitted from interface traps [Fig. 5.17(c)]. We assume negligible bulk states. The emitted electrons give rise to a charge, capacitance, or current transient. Although electrons are emitted over a broad energy spectrum, emission from interface traps in the upper half of the band gap dominates. DLTS is very sensitive, allowing interface trap density determination in the mid-10^9 cm^{-2} eV^{-1} range.

Interface trap characterization by DLTS was first implemented with MOSFETs.[80] MOSFETs, being three-terminal devices, have an advantage over MOS capacitors (MOS-Cs). By reverse biasing the source-drain and pulsing the gate, majority electrons are captured and emitted without interference from minority holes that are collected by the source-drain. This allows interface trap majority carrier characterization in the upper half of the band gap. With the source-drain forward biased, an inversion layer forms,

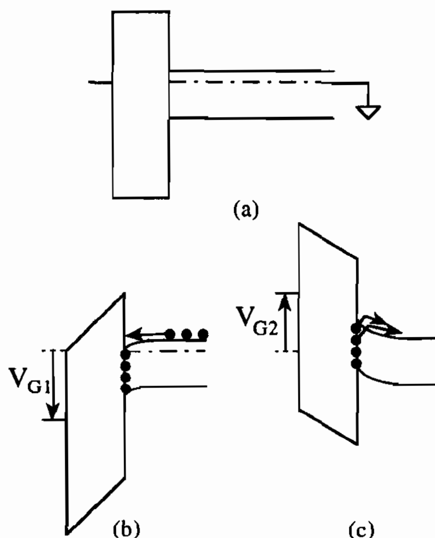

Fig. 5.17 (a) Majority carrier capture and (b) majority carrier emission from interface traps.

allowing interface traps to be filled with minority holes. Minority carrier characterization is then possible and the lower half of the band gap can be explored. This is not possible with MOS-Cs because there is no ready source of minority carriers. When an inversion layer does form through thermal ehp generation, especially at higher temperatures and at high ehp generation rates, it can interfere with majority carrier trap DLTS measurements.

MOS capacitors are frequently used for interface trap characterization.[50, 81, 82] Unlike the conductance technique discussed in Chapter 6, DLTS measurements are independent of surface potential fluctuations. The derivation of the capacitance expression is more complex for MOS-Cs than it is for diodes. We quote the main results whose derivations can be found in Johnson[51] and Yamasaki et al.[82] For $qD_{\text{it}} = C_{\text{it}} \ll C_{\text{ox}}$ and $\delta C = C_{\text{hf}}(t_1) - C_{\text{hf}}(t_2) \ll C_{\text{hf}}$,

$$\delta C = \frac{C_{\text{hf}}^3}{K_s \varepsilon_0 N_D C_{\text{ox}}} \int_{-\infty}^{\infty} D_{\text{it}} \left[\exp\left(\frac{-t_2}{\tau_e} \right) - \exp\left(\frac{-t_1}{\tau_e} \right) \right] dE_{\text{it}} \tag{5.58}$$

where

$$\tau_e = \frac{\exp[(E_C - E_{\text{it}})/kT]}{\gamma_n \sigma_n T^2} \tag{5.59}$$

Here E_{it} is the energy of the interface traps. The maximum emission time is $\tau_{e,\max} = (t_2 - t_1)/\ln(t_2/t_1)$ from Eq. (5.49). In conjunction with Eq. (5.59) where $\tau_{e,\max}$ corresponds to $E_{\text{it},\max}$, we find, when the electron capture cross section is not a strong function of energy,

$$E_{\text{it},\max} = E_C - kT \ln\left[\frac{\gamma_n \sigma_n T^2 (t_2 - t_1)}{\ln(t_2/t_1)} \right] \tag{5.60}$$

where $E_{\text{it},\max}$ is sharply peaked. If D_{it} varies slowly in the energy range of several kT around $E_{\text{it},\max}$, it can be considered reasonably constant and can be taken outside the integral of Eq. (5.58). The remaining integral becomes

$$\int_{-\infty}^{\infty} \left[\exp\left(\frac{-t_2}{\tau_e} \right) - \exp\left(\frac{-t_1}{\tau_e} \right) \right] dE_{\text{it}} = -kT \ln\left(\frac{t_2}{t_1} \right) \tag{5.61}$$

allowing Eq. (5.58) to be written as

$$\delta C \approx -\frac{C_{\text{hf}}^3}{K_s \varepsilon_0 N_D C_{\text{ox}}} kT D_{\text{it}} \ln\left(\frac{t_2}{t_1} \right) \tag{5.62}$$

From Eq. (5.62) the interface trap density is

$$D_{\text{it}} = -\frac{K_s \varepsilon_0 N_D}{kT \ln(t_2/t_1)} \frac{C_{\text{ox}}}{C_{\text{hf}}^3} \delta C \tag{5.63}$$

determined from electrons emitted from interface traps in time $(t_2 - t_1)$ in the energy interval $\Delta E = kT \ln(t_2/t_1)$ at energy $E_{\text{it, max}}$. A plot of D_{it} versus E_{it} is constructed by varying t_1 and t_2. For each t_1, t_2 combination, an E_{it} is obtained from Eq. (5.60) and a D_{it} from Eq. (5.63). If the sample contains bulk as well as interface traps, it is possible to differentiate bulk traps from interface traps by the shape and the peak temperature of the DLTS plot.[82]

For the *constant capacitance* DLTS technique an equation analogous to Eq. (5.63) is[51]

$$D_{\text{it}} = \frac{C_{\text{ox}}}{qkTA \ln(t_2/t_1)} \Delta V_G \tag{5.64}$$

where A is the device area and ΔV_G is the gate voltage change required to keep the capacitance constant. Equation (5.64) is easier to use than (5.63) because neither the high-frequency capacitance nor the doping density need be known. Figure 5.18 shows the interface trap distribution for an n-type substrate, with D_{it} measured by the quasistatic and the CC-DLTS technique.[83] The discrepancy between the two curves may be due to the assumption of constant capture cross sections in the DLTS analysis.

MOS capacitors can also be measured by the current DLTS method. Using the small pulse method,[84] in which pulses of tens of millivolts are used, both interface trap density and capture cross sections can be measured.[85]

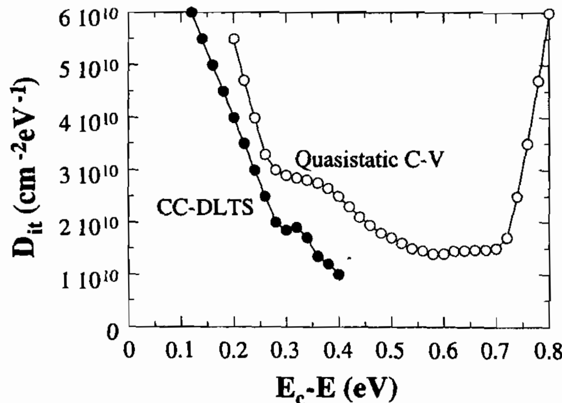

Fig. 5.18 Interface trapped charge density for n-Si measured by the CC-DLTS and quasistatic methods. Reprinted with permission after Johnson et al., Ref. 83.

Small filling pulses are applied as the quiescent bias is scanned at constant temperature and constant rate window. As the Fermi level scans the band gap, a DLTS peak is observed when τ_e in a small energy region around the Fermi level matches the rate window. Varying the rate window or the temperature gives the interface trap distribution.

5.6.3 Optical and Scanning DLTS

Optical DLTS comes in various implementations. Light can be used (1) to determine optical properties of G-R centers, such as optical capture cross sections, (2) to create electron-hole pairs for minority carrier injection, and (3) to create ehps in semi-insulating materials, where electrical injection is difficult. Light does two basic things: it imparts energy to a trapped carrier, causing its emission from a G-R center to the conduction or to the valence band, and it changes n and/or p by creating ehps, thereby changing the capture properties of the center. An electron beam in a scanning electron microscope also creates ehps and can be used for DLTS measurements. We will consider the boxcar data acquisition method here. Other methods follow similar arguments.

Optical Emission. Consider the conventional majority carrier emission process discussed earlier. A Schottky diode on an n-type substrate is zero biased and traps are filled with electrons at low temperatures. Instead of raising the temperature and detecting the capacitance or current transient due to thermal emission, the sample is held at a sufficiently low temperature for thermal emission to be negligible but optical emission takes place. Light is shone on the sample provided with a transparent or semitransparent contact. For $h\nu < (E_c - E_T)$, there is no band gap optical absorption. For $h\nu > E_c - E_T$, photons excite electrons from the traps into the conduction band. Equation (5.8) holds, but the emission rate e_n becomes $e_n + e_n^o$, where e_n^o is the *optical emission rate* $e_n^o = \sigma_n^o \Phi$, with σ_n^o the *optical* capture cross section and Φ the photon flux density. The trap density is obtained from the capacitance step just as it is during thermal emission measurements. Optical emission measurements were used very early during capacitance transient experiments.[5] The light is used in these experiments to determine optical properties of the trap, such as the optical cross section, using either capacitance or current transients.[30, 86-88]

It is possible to determine the multiplicity of charge states by varying the energy of the incident light. For a center with two donor levels, for example, one increases the light energy to excite electrons from the upper level into the conduction band, detected by a capacitance change. Increasing the energy further leaves the capacitance unchanged, provided all electrons have been excited out of that level, until the energy is sufficient to excite electrons from the second level into the conduction band. A second capacitance rise is