

# Admittance spectroscopy or deep level transient spectroscopy: A contrasting juxtaposition



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## ABSTRACT

A comprehensive understanding of defects in semiconductors remains of primary importance. In this paper the effectiveness of two of the most commonly used semiconductor defect spectroscopy techniques, viz. deep level transient spectroscopy (DLTS) and admittance spectroscopy (AS) are reviewed. The analysis of defects present in commercially available SiC diodes shows that admittance spectroscopy allows the identification of deep traps with reduced measurement effort compared to deep Level Transient Spectroscopy (DLTS). Besides the N-donor, well-studied intrinsic defects were detected in these diodes. Determination of their activation energy and defect density, using the two techniques, confirm that the sensitivity of AS is comparable to that of DLTS while, due to its well defined peak shape, the spectroscopic resolution is superior. Additionally, admittance spectroscopy can analyze faster emission processes which make the study of shallow defects more practical and even that of shallow dopant levels, possible. A comparative summary for the relevant spectroscopic features of the two capacitance methods are presented.

## 1. Introduction

The electrical and optical properties of semiconductor materials are largely controlled by impurities. Defects may be introduced unintentionally during crystal growth or by device processing. They may also be introduced intentionally because of device engineering requirements. Beside extended imperfections, point-like defects are always present. In elemental semiconductors these are mainly residual contaminants while in compounds semiconductors, intrinsic defects are of particular interest.

Defects, present in concentrations as low as  $10^{13} \text{ cm}^{-3}$  (equating to 1 in  $10^{10}$  lattice atoms), may act as trapping and/or non-radiative recombination centers, potentially modifying the electronic properties (viz. quantum efficiency and free carrier lifetime) of materials. Typically, such defects are characterized by one or more energy level located within the band gap of the semiconductor and is referred to as deep level centers (DLC). Trapped carriers may be emitted through thermal excitation. The emission probability is given by  $\exp(-\Delta E/kT)$  with  $\Delta E$  the thermal activation energy of the transition. Clearly, the capture and emission properties of these DLCs and the precise and effective determination thereof, are vitally important.

In this paper the effectiveness of two of the most commonly used defect spectroscopy techniques, deep level transient spectroscopy

(DLTS) and admittance spectroscopy (AS) are reconsidered. This is done by the analysis of defects present in commercially available SiC diodes.

## 2. Capacitance spectroscopy

Perhaps the most commonly used electrical defect spectroscopic techniques used in condensed matter physics are admittance spectroscopy and deep level transient spectroscopy [1–3].

These techniques detect the thermal emission of trapped carriers from a particular DLC. Consequently the analysis is based on the semi-empirical Shockley Read and Hall (SRH) statistical model, specifying the transition rates for the thermal emission ( $G$ ) and the capture ( $R$ ) respectively of charge carriers with  $G(T) = e_{n,p}(T)$ ,  $R_n(T, n) = c_n(T) n$  and,  $R_p(T, p) = c_p(T) p$ . Here,  $e_{n,p}$  is the emissions rate for electrons/holes, while  $c_{n,p}$  is the capture coefficient for electrons/holes.

Consider an electron trapped by a defect with energy  $E_t$ , located in the forbidden gap of in an n-type semiconductor. The energy required by the electron to emit to the conduction band is  $\Delta E = E_c - E_t$ . At a given temperature the capture and emission rates are in equilibrium and the steady state occupation of the DLC is given by  $f(t \rightarrow \infty) = f_0 = n_t(x)/N_t$  where,  $N_t$  is the trap density and  $n_t$ , the number of statistically occupied traps. It follows that

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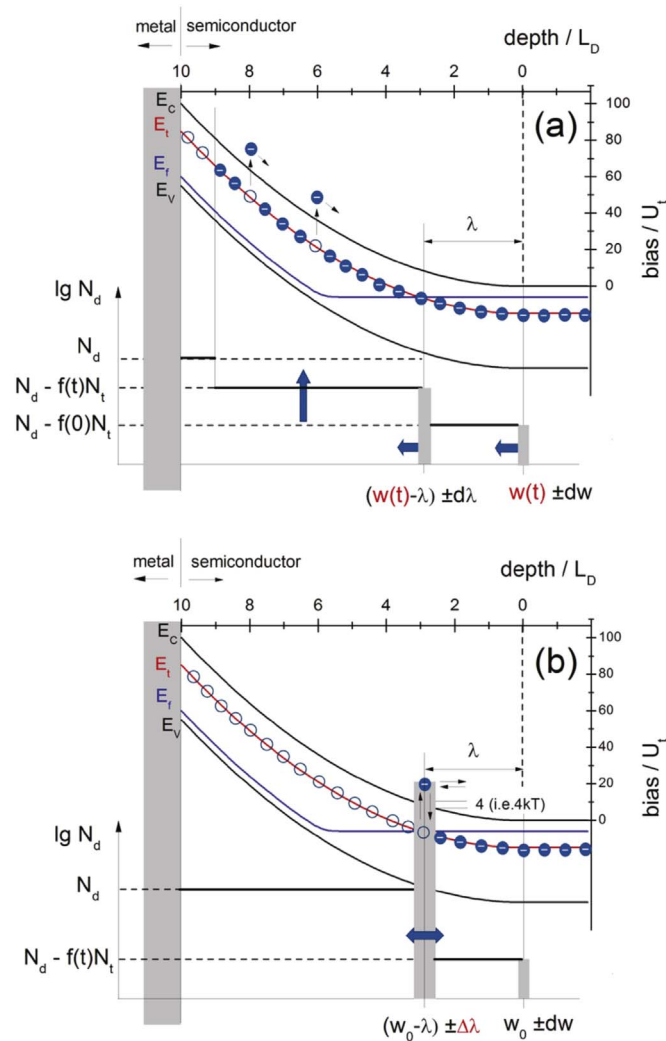
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$$c_n(1 - f_0)n(x) = e_n f_0 \Rightarrow \frac{e_n}{c_n n(x)} = \frac{1}{f_0} - 1 = \exp\left(\frac{E_f - E_t}{kT}\right) \quad (1)$$

Briefly, in DLTS a rectifying device is subjected to a reverse bias upon which a pulse of appropriate width, frequency and amplitude is superimposed. Defects in the depletion (or space charge) region may be filled and subsequently emptied, provided that sufficient energy is available for the transition. As already stated the emission rate is temperature depended. The capture and emission processes translate to changes in the device capacitance. The ensuing capacitance transient can be followed very precisely, within a pre-defined rate window, using a box-car or a lock-in amplifier.

The time constant  $\tau$  of the observable capacitance transient  $C(t) = C_p \exp(-e_n t)$  is related to the relaxation time constant  $\tau$  of the defect by  $\tau^{-1} = e_n$ .  $C_p$  is the non-equilibrium capacitance of the junction immediately after excitation. The capacitance transient amplitude is given by  $\Delta C = C_0 - C_p$  and is related to the number of thermally emitted traps.  $C_0$  is the steady state junction capacitance under the bias  $V_0$ .

In admittance spectroscopy the situation is different. Here, the occupation of the defect level at the cross-over point will resonate with the ac test signal, consequently altering the admittance of the junction (Fig. 1(b)). No traditional filling pulse is provided as in the case of DLTS.



**Fig. 1.** Band bending in a reverse biased Schottky barrier diode containing traps in the depletion region: (a) Exponential relaxation of trap occupation to steady state due to thermal emission (DLTS mode), and (b) continuous charge trapping and emission from a defect level at and near  $w_0 - \lambda$  (AS mode).

The applied dc bias defines the position of the  $\lambda$ -point (Fig. 1), while any superimposed ac bias  $\tilde{V}(t) = V \sin(\omega t)$  of appropriate frequency will stimulate the charging and discharge of traps  $dQ = qd(f(t))$  due to the variation of occupation  $f(t)$  according to  $E_f(t) = q\tilde{V}$  around  $E_t = E_f$ . Under these conditions, a single defect has an elementary capacitance  $C_e$  of  $6 \cdot 10^{-18}$  Farad at 300 K ( $f=0.5$ ).

$$C_e = \frac{dQ}{d\tilde{V}} = q \left( \frac{d\tilde{V}}{dt} \right)^{-1} \frac{df}{dE_f} \frac{dE_f}{dt} = f(1-f) \frac{q^2}{kT} \quad (2)$$

Due to the symmetry in  $f$ , electron and hole traps have the same elementary capacitance and are not distinguishable. For a given test frequency, each trap has a characteristic time constant associated with the transition from the adiabatic response (emptying and trapping of defects around the cross-over point are in phase with  $dE_f$ ) to the "frozen-in" situation (emission rate much smaller than the test frequency). It can be shown that the admittance of a junction with traps can be represented as a combination of the junction capacitance  $C_0(V_0)$  and a parallel RC-circuit with a time constant related to the relaxation time  $\tau = (e_n + c_n n)^{-1}$  of the traps [4]. With a test frequency  $\omega = 2\pi f_{test}$  the conductance is

$$\frac{1}{R_p \omega} = C_d \left( \frac{\omega \tau}{1 + (\omega \tau)^2} \right) = \frac{1}{2} \frac{C_d}{\cosh(\ln(\omega \tau))}. \quad (3)$$

with  $C_d$ , the additional capacitance due to deep level defects.

## 2.1. Trap profiling by DLTS

In a DLTS measurement, a rectifying device is subjected to a pre-defined reverse dc bias  $V_0$  upon which a pulse of appropriate width, frequency and amplitude  $V_p$  is superimposed. Based on the pulse conditions, defects in the depletion region may then be filled and subsequently emit. The emission processes from a region inside  $w_0(V_0)$  defined by  $w_p(V_p)$  results in a  $\Delta C$  related to the trap density in this region. Consider a material with a uniform doping density  $N_d$  and a homogenous trap density  $N_t$ . With the junction capacitance  $C_p(V_p)$  during the filling pulse, the space charge width  $w_0(V_0)$  from  $C_0$  and  $\lambda$  given by (7) the trap concentration relative to the doping concentration is:

$$\frac{N_t}{N_d} = \frac{2\Delta C}{C_0} \left[ 1 - \left( \frac{C_0}{C_p} \right)^2 - \frac{2\lambda}{w_0} \left( 1 - \frac{C_0}{C_p} \right) \right]^{-1} \quad (4)$$

For  $\lambda \ll w_0$  and  $C_p \gg C_0$  (filling the complete space charge region) this simplifies to:

$$\frac{N_t}{N_d} \approx \frac{2\Delta C}{C_0}. \quad (5)$$

Notably, advanced spectrometers are able to resolve  $N_t/N_d \leq 10^{-6}$ . By using a double pulse technique, spatial defect distributions within the space charge layer can be determined [5]. For filling pulses longer than  $10^5$  times the capture time constant  $(c_n n_0)^{-1}$ , the resolution of the DL depth profile improves to approximately one Debye length [6].

## 2.2. Trap profiling by AS

The peak amplitude of the conductance peak  $C_d$  is related to the trap density at the cross over point  $w_0 - \lambda$  (Fig. 1b). There are two methods to correlate  $C_d$  with the trap density  $N_t$ . One can either (i) transform the area density  $N_{\square} = C_d / C_e$ , where  $C_d$  has units  $[F/cm^2]$ , into a bulk concentration by considering the volume around the cross over point which contributes to the conduction signal or (ii) relate  $C_d$  to the background capacitance of the junction  $C_0$ , e.g. relate  $N_t$  to  $N_d$ . Because the indefinite integral over  $f(1-f)$  is one, an equivalent rectangular distribution is given by  $\pm 2kT$  around the Fermi energy. The resulting spacing  $\Delta\lambda$  at  $\lambda$  depends on temperature, doping density and trap

energy and is:

$$\Delta\lambda = 3\sqrt{2} U_T \sqrt{\frac{\epsilon_0 \epsilon_r}{N_d} \frac{1}{(E_c - E_t) + kT \ln(N_d/N_c)}} \quad (6)$$

while  $\lambda$  is given by:

$$\lambda = \sqrt{2 \left( \frac{\epsilon_0 \epsilon_r kT}{q^2 N_d} \right) \left( \frac{E_f - E_t}{kT} \right)}. \quad (7)$$

With advanced LCR meters a noise level below 10 pF/cm<sup>2</sup> may be achieved. This corresponds to  $N_{\square} \approx 3 \times 10^6 \text{ cm}^{-2}$ , meaning that for  $\Delta\lambda = 200 \text{ nm}$  a trap density of  $10^{11} \text{ cm}^{-3}$  can be detected! From the total differential capacitance  $C = C_d + C_0 = (dQ_d + dQ_0)/dU$  with  $dQ = dQ_t + dQ_c = Aq \{N_t d(w_0 - \lambda) + N_d d(w_0)\}$  and  $dU = q/\epsilon_0 \epsilon_r \{N_t (w_0 - \lambda) d(w_0 - \lambda) + N_d w_0 d(w_0)\}$  follows in case of low defect densities ( $N_t \ll N_d$  and  $dw_\lambda = dw_0$ )

$$\frac{C_d}{C_0} \cong \frac{N_t}{N_d} \left( 1 - \frac{(w_0 - \lambda)}{w_0} \right) = \frac{\lambda}{w_0} \frac{N_t}{N_d}. \quad (8)$$

Interestingly, for AS the sensitivity is  $x/w_0$  ( $x = \lambda$ ) while for DLTS the spatial sensitivity for a point  $x$  within the space charge layer is  $(1 - x/w_0)$ . Comparing with (5) it turns out that the detection threshold of AS for low reverse biases is practically the same as for DLTS.

### 2.3. Spectroscopic resolution

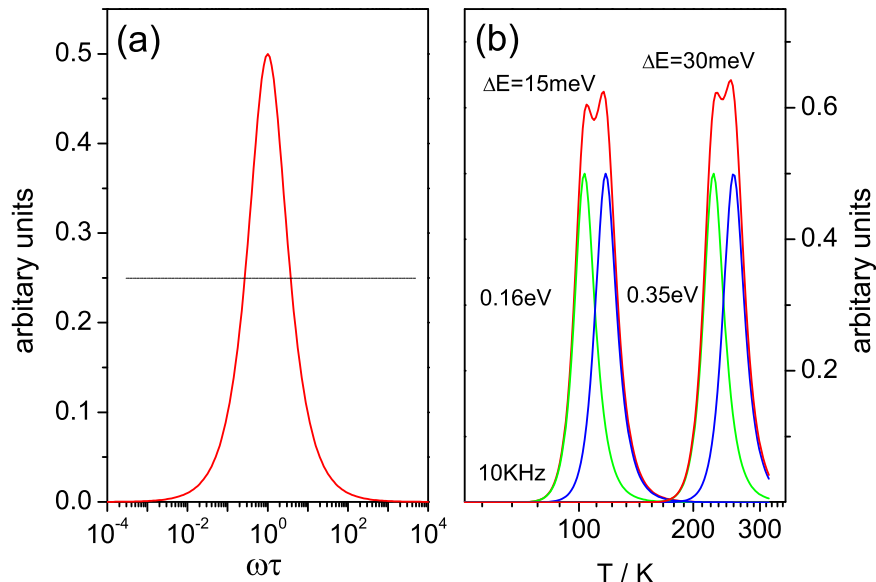
The conductance is symmetric in  $\omega$  and  $\tau$  ( $\propto e_n^{-1}$ ) and has a maximum when  $\omega\tau = 1$ . The conductance of a material can be studied by performing either temperature dependent measurements at a pre-defined test frequency  $f_{\text{test}}$  or by isothermal thermal frequency scans. In the latter case the peak shape on a logarithmic scale is symmetric as it is clear from (3) and has a half width ratio of 3.54 (Fig. 2a). Fig. 2b shows the resolution capability of AS for two traps with identical capture coefficients but with differences of 15 meV and 30 meV respectively in their activation energy in the temperature scan mode. Also note the symmetric shape of the peaks when the temperature is plotted on the logarithmic scale. In comparison, DLTS peaks from frequency scans are not symmetric and could have a significantly broader half width, with commensurately reduced resolution. In fact, corresponding spectroscopic resolution (to AS) can only be attained in DLTS in special cases by transient filtering of higher order.

### 3. Experimental results

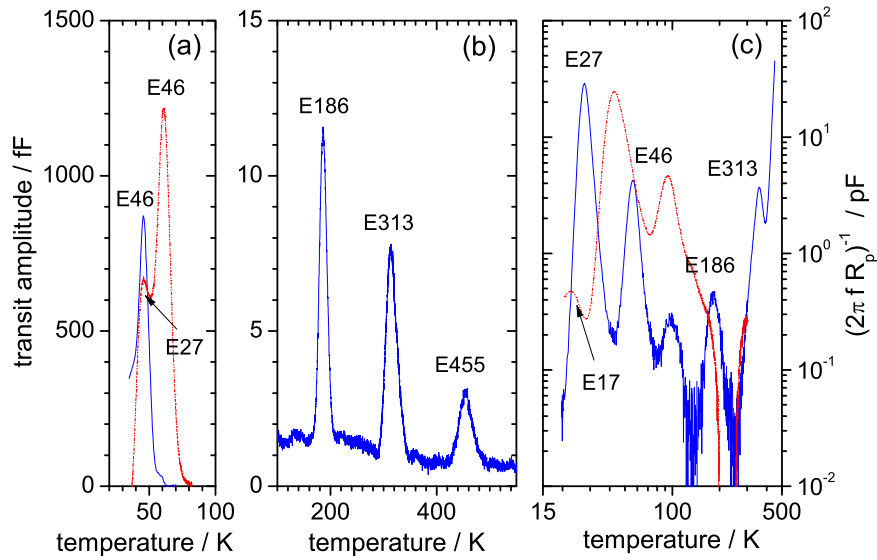
The effectiveness (advantages and disadvantages) of DLTS and AS are illustrated next by analyzing the defects in commercially available SiC Schottky barrier diode (product number: C3D02060A), sourced from Cree Inc. Fig. 3 depicts DLTS and AS spectra obtained from the SiC diode. It is clear that both methods yield comparable sensitivity and spectral resolution. Additionally, AS allows the detection of shallower defect levels (here the nitrogen donor). Table 1 summarizes the defect parameters as obtained from results from DLTS and AS. The defect densities by DLTS and AS are in excellent agreement for the defect levels E186 and E313. The variation for E27 and E46 in AS are due to the violation of the low defect approximation. Considering the limits of DLTS, the value for E46 is realistic. Clearly there are differences in the estimated activation energies beyond the measuring inaccuracy (Fig. 4). Certainly for defect densities approaching the shallow doping density ( $N_d/N_t \leq 10$ ) the relation between the test frequency and emission rate  $\tau = (e_n + c_n n)^{-1} = 2e_n$ , with  $e_n \equiv c_n n$  at the cross-over point  $\lambda$  is no longer valid. For details on the nature of the detected deep level centers refer to [7,8].

In summary,

- **Defect density:** Both methods have virtually the same sensitivity, however only DLTS can distinguish between electron and hole traps.
- **Spatial defect distribution:** In principle both methods provide precise spatial defect profiles if specific corrections are taken into account.
- **Experimentally accessible time constants:** The range of time constants span about 8 orders of magnitude. AS enables faster rate windows (60 ns to 1 ms) while DLTS uses lower rate windows (100  $\mu$ s (best 5  $\mu$ s) to 5 s) (Fig. 4).
- **Capture coefficients:** Only DLTS allows measurement of electron and hole capture coefficients in a limited temperature range because the population conditions can be controlled by the filling pulse duration [9].
- **Thermal activation energy:** Both methods are based on the same evaluation model, therefore the Arrhenius-plot should be identical. In practice deviations could occur due to a dependence of the thermal activation energy on the electrical field. AS signals originate from the low field region of the junction.



**Fig. 2.** (a) Conductance response due to a mono-energetic DLC showing the symmetry and the half-width of peaks in AS in 'frequency-scan' mode, (b) Demonstration of the resolution of AS for two traps (0.16 eV and 0.35 eV) with identical capture coefficient but a variation of 15 meV and 30 meV, respectively in activation energy in 'temperature-scan' mode.

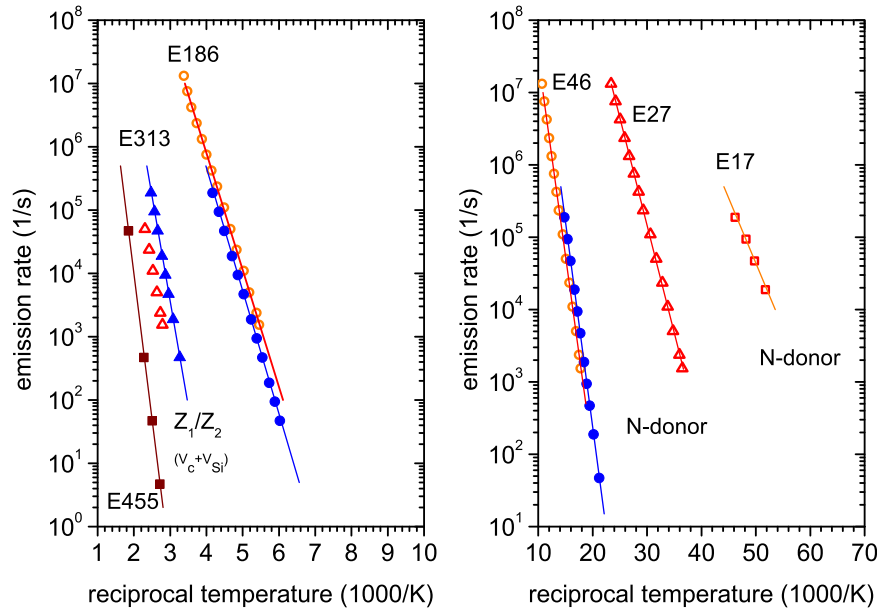


**Fig. 3.** (a), (b) DLTS spectra recorded with different measuring sensitivity and two rate windows, 970 Hz (solid) and 194 kHz (dotted) respectively. The reverse bias and pulse bias were 20 V and 10 V respectively. (c) Admittance spectra obtained under zero bias for test frequencies of 492 Hz (solid) and 4.2 MHz respectively.

**Table 1**

Summary of the defects parameters of the SiC diodes sourced from Cree Inc. as analyzed by DLTS and AS. Experimental data fitted according to  $e_n = A_0 \exp(-(E_c - E_T)/kT)$ . The defect densities were determined by AS using for  $N_{T(A)}$  Eq. (6) and for  $N_{T(B)}$  Eq. (8) respectively. The AS test frequency was 492 Hz and the rate window for DLTS 1.064 kHz.

Level	Admittance			DLTS				
	$A_0$ [THz]	$\Delta E$ [meV]	$\lambda \Delta \lambda$ [nm]	$N_{T(A)}$ [ $10^{13} \text{ cm}^{-3}$ ]	$N_{T(B)}$ [ $10^{13} \text{ cm}^{-3}$ ]	$A_0$ [THz]	$\Delta E$ [meV]	$N_T$ [ $10^{13} \text{ cm}^{-3}$ ]
E17	44.6	$36 \pm 1$				–	–	
E27	125	$59 \pm 1$	(1300) 250	1	70	–	–	
E46	9	$108 \pm 1$	210 40	52	57	50	$112 \pm 1$	410
E186	20	$366 \pm 2$	215 40	<b>3.6</b>	<b>5.3</b>	26	$384 \pm 2$	<b>4.1</b>
E313	1	$623 \pm 1$	260 65	<b>33</b>	<b>33</b>	32	$657 \pm 2$	<b>34</b>
E455	–	–	–	–	–	16.6	$914 \pm 8$	1.5



**Fig. 4.** Arrhenius plots of thermal emission rates of defects detected in SiC diodes sourced from Cree Inc. DLTS (solid symbols) and AS (open symbols).

#### 4. Conclusion

Defects in commercially available SiC power Schottky barrier diodes were analyzed to demonstrate the comparative effectiveness of DLTS and AS. Admittance spectroscopy is a cost effective but never-

theless sensitive, and easy to implement defect spectroscopic method with excellent spectroscopic resolution. Further advantages are the faster rate windows allowing the study of shallower deep level centers and the less rigorous requirements to the electronic properties of junctions under study. In more complex structures like embedded

quantum wells, Filling pulses will excite different regions while the positions of the cross-over points are usually known. The recorded temperature dependent emission rates for DLTS and AS are virtual identically for defect density below 10% of the doping density. Furthermore, in DLTS carrier emission occurs throughout the space charge region where the electric field is not constant. Here, accurate determination of activation energy is therefore subjected to precise knowledge the electric field which is not the case with AS.

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