Physica B xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Physica B

journal homepage: www.elsevier.com/locate/physb

Admittance spectroscopy or deep level transient spectroscopy: A contrasting juxtaposition

Joachim Bollmann[a,*], Andre Venter[b]

[a] Technische Universität Bergakademie Freiberg, Akademiestrasse 6, 09599 Freiberg, Germany
[b] Nelson Mandela Metropolitan University, University Way Port Elizabeth, South Africa

ARTICLE INFO

Keywords:
Admittance spectroscopy
Deep level transient spectroscopy
Spectroscopic resolution
SiC
Detection limit
Deep level defects

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} 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 ΔE 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 $f(t \to \infty) = f_0 = n_t(x)/N_t$ where, N_t is the trap density and n_t, the number of statistically occupied traps. It follows that

* Corresponding author.
E-mail address: joachim.bollmann@esm.tu-freiberg.de (J. Bollmann).

http://dx.doi.org/10.1016/j.physb.2017.07.048
Received 21 April 2017; Received in revised form 20 July 2017; Accepted 21 July 2017

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

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 widow, using a box-car or a lock-in amplifier.

The time constant τ of the observable capacitance transient $C(t) = C_p exp(-e_n t)$ is related to the relaxation time constant τ 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.

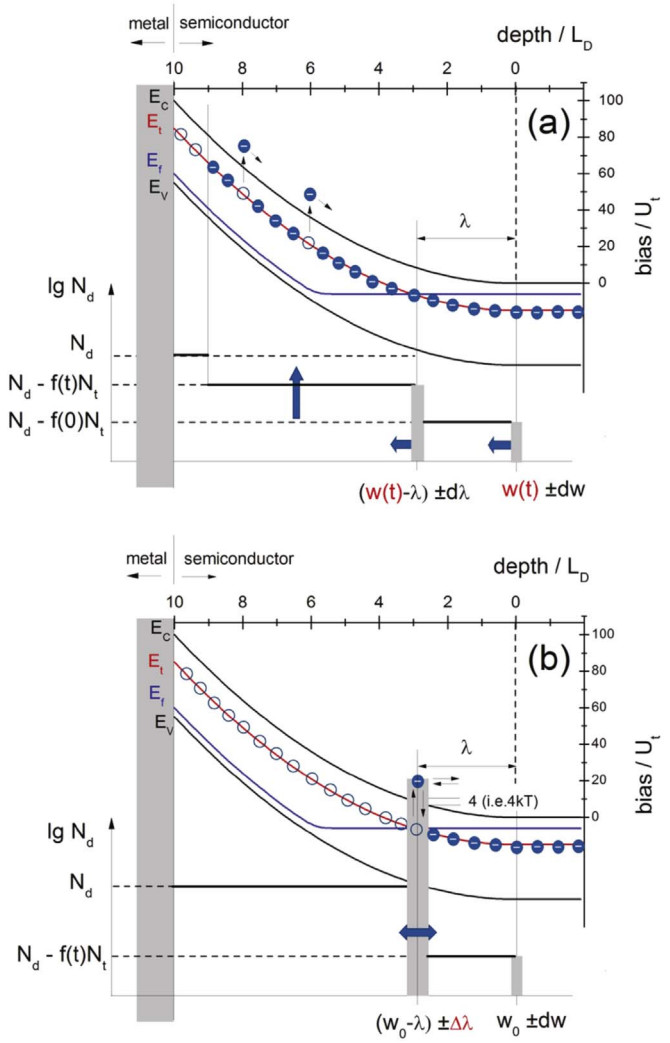

Fig. 1. Band bending in a reverse biased Schottky barrier diode containing traps in the depletion region: (a) Exponential relaxation of trap occupation to steady state due to thermal emission (DLTS mode), and (b) continuous charge trapping and emission from a defect level at and near w_0-λ (AS mode).

The applied dc bias defines the position of the λ-point (Fig. 1), while any superimposed ac bias $\widetilde{V}(t) = Vsin(\omega t)$ 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 $E_f(t) = q\widetilde{V}$ around $E_f(t) = E_t$. Under these conditions, a single defect has an elementary capacitance C_e of $6{\cdot}10^{-18}$ Farad at 300 K (f=0.5).

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

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 ΔC 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 λ 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:

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

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 DLC 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-λ (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 λ depends on temperature, doping density and trap