ARTICLE IN PRESS

Physica B xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Physica B

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

Capacitance spectroscopy on *n*-type GaNAs/GaAs embedded quantum structure solar cells

Danielle Venter[a,*], Joachim Bollmann[b], Martin Elborg[c], J.R. Botha[a], André Venter[a]

[a] Nelson Mandela Metropolitan University, 6506 Port Elizabeth, South Africa
[b] Technische Universität Bergakademie Freiberg, 50937 Freiberg, Germany
[c] National Institute for Materials Science, 305-0047 Tsukuba, Japan

ARTICLE INFO

Keywords:
GaNAs/GaAs
Deep level transient spectroscopy
Admittance spectroscopy
Quantum wells

ABSTRACT

In this study, both deep level transient spectroscopy (DLTS) and admittance spectroscopy (AS) have been used to study the properties of electrically active deep level centers present in GaNAs/GaAs quantum wells (QWs) embedded in *p-i-n* solar cells. The structures were grown by molecular beam epitaxy (MBE). In particular, the electrical properties of samples with Si (*n*-type) doping of the QWs were investigated. DLTS revealed four deep level centers in the material, whereas only three were detected by AS. NextNano++ simulation software was used to model the sample band-diagrams to provide reasoning for the origin of the signals produced by both techniques.

1. Introduction

Quantum structures for low dimensional electron confinement in semiconductors offer significant potential for the development of unique optoelectronic devices. In particular, nitrogen containing alloys such as GaNAs and GaInNAs are interesting for fundamental research as well as for the potential development of long wavelength optoelectronics, vertical-cavity surface-emitting laser diodes and intermediate-band solar cells [1–3]. It is well known that the bandgap of GaNAs is inversely correlated with the nitrogen concentration through the lowering of the conduction band minimum. For samples with low nitrogen concentration (x < 1%), a negligible valence band offset is anticipated [4,5]. This results in strong confinement of electrons in GaN_xAs_{1-x}/GaAs quantum well (QW) structures with unobstructed hole transport which allows for fast carrier separation and thus a reduction in electron-hole recombination rates, a vital requirement for the enhancement of solar cell efficiency. The purpose of this paper is to investigate the application of capacitance spectroscopy in characterizing electrically active energy states present in this material system.

2. Theory

Admittance spectroscopy (AS) and deep level transient spectroscopy (DLTS) were used to examine the electronic properties of deep levels present in the GaNAs/GaAs QWs. In AS, the conductance G of a diode under a small AC test bias is given by:

$$\frac{G}{\omega} = C_0\left(\frac{\omega\tau}{1+(\omega\tau)^2}\right), \tag{1}$$

where $\omega = 2\pi f$ is the angular frequency and τ is the defect relaxation time. Peak AS values appear when $\tau\omega = 1$ (with $\tau^{-1} = 2e_n$ where e_n is the emission rate). This enables the formulation of an Arrhenius plot from which the thermal activation energy of the related levels can be estimated. In this case C_0 , is related to the trap density [6].

As a first estimation, in DLTS, the trap density N_T is related to the amplitude of the capacitance transient:

$$\frac{N_T}{N_D} = \frac{2\Delta C\,(0)}{C}, \tag{2}$$

where N_D is the donor concentration, ΔC is the change in capacitance at $t = 0$, due to a saturating filling pulse, and C is the capacitance of the diode under quiescent reverse bias conditions. The temperature dependent defect emission rate was obtained from the difference spectra by Laplace DLTS while the defect signatures were extracted from Arrhenius plots in the conventional manner using:

$$e_n = \sigma_{na}\gamma_n T^2 \exp\left(-\frac{E_c - E_T}{kT}\right).$$

Here, e_n is the electron emission rate at a given temperature T, σ_{na} the apparent capture cross section of the defect, k is the Boltzmann constant and γ_n is equal to $(N_c\langle v_n\rangle/T^2)(g_0/g_1)$. N_c is the effective density of states in the conduction band, $\langle v_n\rangle$ the average thermal velocity of the

* Corresponding author.
E-mail address: s212244450@nmmu.ac.za (D. Venter).

http://dx.doi.org/10.1016/j.physb.2017.07.036
Received 21 April 2017; Received in revised form 17 July 2017; Accepted 18 July 2017
0921-4526/

Please cite this article as: Venter, D., Physica B (2017), http://dx.doi.org/10.1016/j.physb.2017.07.036

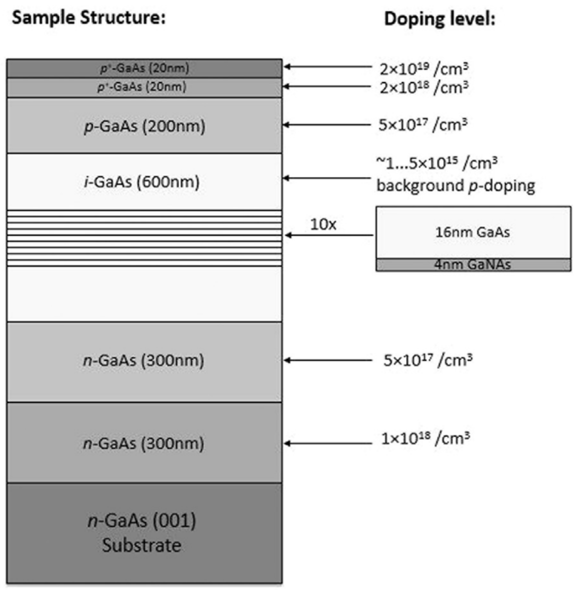

Fig. 1. Schematic of the *n*-type GaNAs/GaAs QW *p-i-n* diode depicting the layer thicknesses and doping concentrations.

electrons and g_0 and g_1 are degeneracy terms related to the defect state before and after electron emission [7]. It is evident that linearization of equation (3) allows the extraction of the activation enthalpy and the apparent capture cross section of a deep level.

3. Material and methods

Samples used in this study were grown by molecular beam epitaxy (MBE) on *n*-type GaAs (001) substrate. The *p-i-n* GaAs solar cells contained ten periodically spaced *n*-type (Si-doped) QWs embedded in the intrinsic region as shown schematically in Fig. 1.

Standard current-voltage (*I-V*) measurements were employed to determine the diode quality while doping profiles were obtained by means of capacitance-voltage (*C-V*) measurements. Admittance measurements were undertaken using a HP-4284A LCR meter. The measurements were performed using a 35 mV test signal at probing frequencies ranging between 318 Hz and 1 MHz. The conductance of the sample was measured while applying a reverse bias of −1 V. Conventional DLTS spectra were recorded at a scan rate of 4 K/min using a rate window of $10^4 Hz$. Unless stated otherwise the reverse bias and filling pulse were −1 V and 1.5 V respectively. The pulse width, in all cases, was 1 ms. The activation enthalpy ΔE, was determined from the slope of the $log\,(1/e_n\,)$ versus $(1000/T)$ Arrhenius plot. Laplace DLTS was used to resolve defects with narrowly spaced emission rates. All AS and DLTS, measurements were performed in the 20–320 K temperature range using a closed cycle liquid helium cryostat. Nextnano++[8], a simulation software program, developed to study physical properties of electronic and optoelectronic devices, was employed to model the electronic structure for the investigated sample structures.

4. Results and discussion

I-V measurements, performed on the *p-i-n* diodes, showed rectification of around 3 orders of magnitude at ± 1 V with a reverse current below 10 nA at −4 V. Fig. 2 depicts AS spectra, obtained from the *n*-type GaNAs/GaAs QW *p-i-n* diode. A set of preselected test signal frequencies at a reverse bias of −1 V where used for these measurements. Evidently, three levels are detected.

Fig. 3 depicts Arrhenius plots for the three defect levels observed in Fig. 2. The energies obtained from these plots are 201 ± 1 meV, 283 ± 3 meV and ~194 ± 15 meV, respectively. Notably, non-linearity is observed in the Arrhenius curve of level 3. The same experiment was conducted on a reference GaAs *p-i-n* structure, which contained no embedded QWs (not shown here). In the admittance spectra of the reference sample only one defect level, resembling level 3 in the embedded QWs sample, was present. It is therefore reasonable to assume that levels 1 and 2 are attributed to the introduction of the QWs into the sample.

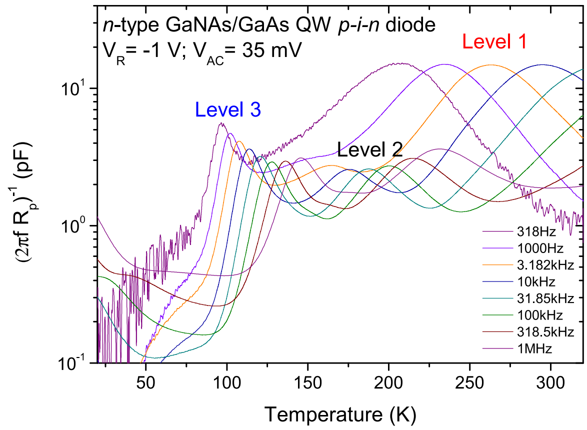

Fig. 2. Admittance spectrum for the *n*-type GaNAs/GaAs QW *p-i-n* diode depicting the presence of three deep level centers. Pulse conditions were set to have a reverse bias of −1 V with a superimposed AC bias of 35 mV.

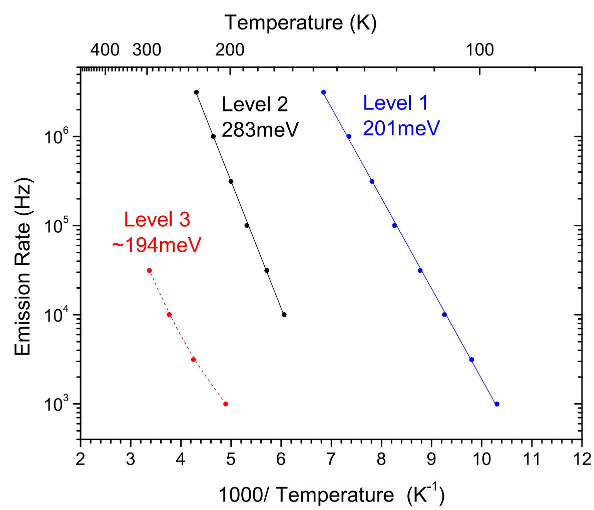

Fig. 3. Associated Arrhenius plots for the defects observed by AS in Fig. 2. The activation energies are 201 ± 1 meV, 283 ± 3 meV and ~194 ± 15 meV, respectively.

Subsequently, Nextnano++ was used to model the electronic structure for the investigated sample. The simulations yielded the valence and conduction bands of the sample as well as the electron and hole Fermi levels. Deep levels, observed experimentally at 201 meV and 283 meV (labeled as level 1 and 2 respectively), were deliberately introduced into the modeled structure with the intention to confirm the origin of a cross-over point at these energies, as is needed for admittance spectroscopy.

Fig. 4. Depicts the NextNano++ simulation of the *n*-type GaNAs/GaAs QW *p-i-n* diode. It is clear from the simulation that both the electron and hole Fermi levels produce "cross-over points" with the proposed deep level centers. It is instructive to note that the AS signal originates from the edge of the depletion region which, in this case, extends to ~593 nm at −1 V reverse bias. Thus, the 35 mV superimposed AC signal will consequently fill and empty levels around this point, resulting in a variation in the admittance signal of the sample. Since cross-over points between the electron Fermi level and the proposed deep level center located at 201 meV and 283 meV occur at