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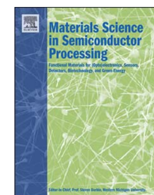

# DLTS study of InGaAs and GaAsN structures with different indium and nitrogen compositions

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ABSTRACT

In this article Deep Level Transient Fourier Spectroscopy experiments and various evaluation procedures were used to study emission and capture processes of deep energy levels in intentionally undoped InGaAs and GaAsN semiconductor structures. The examined samples, grown by Atmospheric Pressure Metal Organic Vapour Phase Epitaxy on GaAs substrates, were analyzed at various indium and nitrogen concentrations. Main attention was focused on differences in defect distributions, relations in possible composition and growth condition sensitive defect states. Valuable characteristics of particular In/N contents capable to eliminate or reduce specific impurities are discussed. A possible indium dependent dual state InGaAs complex and a nitrogen and growth condition dependent dual type GaAsN complex was introduced/confirmed. The most balanced samples for further utilizations were achieved for In = 8.9% and N = 1%.

## 1. Introduction

III-V group semiconductor materials such as dilute nitrides are frequently studied due to their unique characteristics in many areas of semiconductor research. Actual effort is devoted to promising semiconductor compounds lattice matched to GaAs such as InGaAsN as candidate materials for device applications in fibre-optic telecommunication systems, bipolar transistors, multi-junction solar cells and multi quantum well structures [1–3]. Solar energy is one of the most important environmental friendly alternative energy sources harnessed by humanity. Different materials and structures are continuously studied to achieve higher and higher efficiencies. Record efficiency of 43.5% has been achieved using multi-junction solar cells based on GaInNAsSb junctions [4]. New approaches for InGaAsN based structures are still under consideration to obtain efficiency around 50% by 4- or 5- junction solar cells [5]. One way to increase the efficiency is to split the solar spectrum by the application of different semiconductor layers, meaning different band gaps absorbing photons with different energies [6]. In case of InGaAsN various band gap widths are obtained by different In and N compositions, where discontinuity in the valence band and the conductivity band exists which can improve the carrier collection of the solar cell.

Increasing requirements on quality and efficiency of solar cells needs to be supported by various characterization procedures. Successful application requires the understanding of generated electrically active defects affecting efficiency, which must be correlated with the growth process in order to develop the fabrication. To determine proper material compositions is rather complicated, especially in the case of InGaAsN where defect states are associated with the indium and nitrogen content [7–10]. It is necessary to analyze InGaAs and GaAsN semiconductor structures with various compositions.

Deep Level Transient Fourier Spectroscopy (DLTFS) has a key role in defect characterization and it satisfies basic requirements of diagnosis such as: accuracy, non-destructivity and sensitivity [11–13]. This method is able to measure deep energy level charge carrier emission or capture as a dependency of temperature by processing capacitance transient signals. The exponentially changing capacitance in time ensured by electrical excitation enables us to calculate Arrhenius curves at different emission rates, which leads to the definition of trap parameters (activation energy $\Delta E_T$, capture cross section $\sigma_T$ and trap concentration $N_T$) [14].

The aim of the presented study is to investigate emission and capture processes in InGaAs and GaAsN samples at various compositions by DLTFS method and to support the InGaAsN solar cell research.

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## 2. Sample preparation

The investigated intentionally undoped InGaAs "i" and GaAsN "i" samples were grown by Atmospheric Pressure Metal Organic Vapour Phase Epitaxy (AP-MOVPE) using AIX 200 R&D horizontal reactor on n-type GaAs (Si doped with concentration $1 \div 2 \times 10^{18}\ cm^{-3}$) substrates at the Wroclaw University of Science and Technology. High purity hydrogen was employed as carrier gas (99.9999%). Trimethylgallium (TMGa, ($Ga(CH_3)_3$)), trimethylindium (TMIn – $In(CH_3)_3$), tertiarybutylhydrazine (TBHy – ($C_4H_9)HN_2H_2$)) and arsine ($AsH_3$: 10% mixture in $H_2$) were applied as growth precursors [15–17]. Each InGaAs and GaAsN layer was deposited on a 450 nm width undoped i GaAs buffer layer grown at following process conditions: growth temperature $T_g = 670$, flow rate of hydrogen through the bubbler with TMGa $V_{H2/TMGa} = 10\text{ml/min}$ and flow rate of arsenic source $V_{AsH3} = 300\text{ml/min}$. Four InGaAs samples with In concentrations 3.4%, 8.9%, 10.5% and 12.8% and five GaAsN structures with N concentrations 0.9%, 1.15%, 1.5%, 1.6% and 1.85% were investigated. The compositions of the mentioned ternary alloys were determined using high resolution X-ray diffraction. The In concentration was varied by changing a flow rate of hydrogen through the bubbler with TMIn ($V_{H2/TMIn} = 5 \div 35\text{ml/min}$), while the N content difference was achieved at distinct growth temperatures $T_g = 565 \div 605°C$ (Tables 1 and 2). Ring shaped Schottky contacts were prepared by Au deposition. Square shaped cut samples were glued on sockets to ensure a more applicable preparation for DLTFS experiments (Fig. 1).

## 3. Experiment

All DLTFS experiments of this study took place at the Slovak University of Technology, Faculty of Electrical Engineering and Information Technology, Institute of Electronics and Photonics using DLTFS measurement system BIORAD DL8000. DLTFS spectra were measured in temperature range 85–500 K with electrical excitation proposed according to measured IV and CV curves with a filling voltage lower as the threshold ($U_P = 0.05\text{V}$) and reverse voltage ($U_R = -0.5\text{V}$) at the possible lowest saturation current. The electrical excitation time () was typically chosen in a millisecond order. Capacitance transient signals induced by charge carrier emission or capture were measured at different sets of period widths. In each case similar spectra were observed, results at highest spectral amplitudes are shown ($T_W = 15\text{ms}$) (Figs. 2 and 3).

In order to precisely state and evaluate In/N induced defects all the spectra were compared and analyzed (Figs. 2 and 3). Such comparison is particularly interesting since we are able to monitor and confirm identical defects at different band gaps, hence different indium and nitrogen concentrations. Moreover trends in trap concentration changes and activity are also observable, however these are hard to conclude, since peak amplitudes are directly influenced by defect concentrations, locally distributed defects, and investigated sample's contact area. It should be also noticed that referent samples were undoped, therefore the conduction type of defects was not clearly definable. Deep energy level parameters were calculated for both p and n type in all cases and more probable defect origins taken into account.

**Table 1**
Growth conditions and Indium composition of investigated undoped InGaAs "i" referent solar cell samples.

| Sample | $H_2$ flow rate through the bubbler with TMIn $V_{H2/TMIn}$ (ml/min) | Growth temp. $T_g$ (°C) | "i" $In_yGa_{1-y}As$ | |
|---|---|---|---|---|
| | | | $d$ (nm) | $y$ (%) |
| InGaAs "i" I | 5 | 585 | ~ 110 | 3.4 |
| InGaAs "i" II | 20 | 585 | ~ 110 | 8.9 |
| InGaAs "i" III | 32 | 585 | ~ 120 | 10.5 |
| InGaAs "i" IV | 35 | 585 | ~ 110 | 12.8 |

**Table 2**
Growth conditions and Nitrogen composition of investigated undoped GaAsN "i" referent solar cell samples.

| Sample | $H_2$ flow rate through the bubbler with TBHy $V_{H2/TBHy}$ (ml/min) | Growth temp. $T_g$ (°C) | "i" $GaAs_{1-x}N_x$ | |
|---|---|---|---|---|
| | | | $d$ (nm) | $x$ (%) |
| GaAsN "i" I | 1500 | 585 | ~ 65 | 0.90 |
| GaAsN "i" II | 1500 | 605 | ~ 100 | 1.15 |
| GaAsN "i" III | 1500 | 595 | ~ 126 | 1.50 |
| GaAsN "i" IV | 1500 | 565 | ~ 100 | 1.60 |
| GaAsN "i" V | 1500 | 575 | ~ 130 | 1.85 |

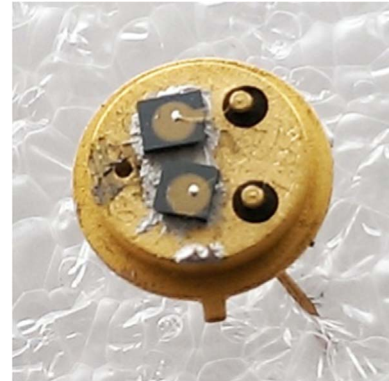

**Fig. 1.** Samples prepared for DLTFS experiments.

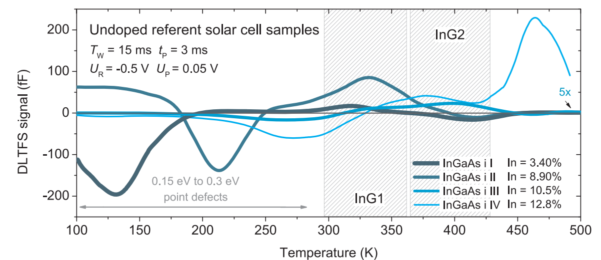


**Fig. 2.** DLTFS spectra of InGaAs structures at different indium concentrations.

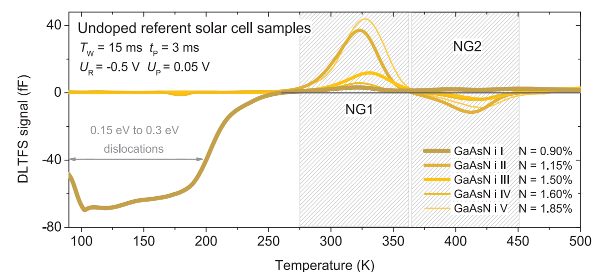


**Fig. 3.** DLTFS spectra of GaAsN structures at different nitrogen concentrations.

## 4. Results and discussions

As Figs. 2 and 3 show, in both cases high trap concentration broad peaks with complex activation energies in the range of 0.15–0.3 eV were obviously dominating at lower temperatures of samples with low In and N contents. MBE grown GaAs and InGaAs samples were extensively studied in the past, and it is well known that these samples more consistently exhibit deep energy levels labelled as M1 – M5 [21].

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