SLOVAK UNIVERSITY
OF TECHNOLOGY IN BRATISLAVA
FACULTY OF ELECTRICAL ENGINEERING
AND INFORMATION TECHNOLOGY

Ing. Arpád Kósa

Author's report on the dissertation thesis

DEEP LEVEL TRANSIENT SPECTROSCOPY STUDY OF EMISSION AND CAPTURE PROCESSES IN MULTILAYER SEMICONDUCTOR STRUCTURES

for the acquisition of: academic title philosophiae doctor, PhD.

in study programme: **Electronics and Photonics**
and study field: 5.2.13 Electronics

Date and place: In Bratislava, July 2016

SLOVAK UNIVERSITY OF TECHNOLOGY
IN BRATISLAVA
FACULTY OF ELECTRICAL ENGINEERING
AND INFORMATION TECHNOLOGY

Ing. Arpád Kósa

Author's report on the dissertation thesis

DEEP LEVEL TRANSIENT SPECTROSCOPY STUDY OF EMISSION AND CAPTURE PROCESSES IN MULTILAYER SEMICONDUCTOR STRUCTURES

for the acquisition of: academic title philosophiae doctor, PhD.

in study programme: **Electronics and Photonics**
and study field: 5.2.13 Electronics

Date and place: In Bratislava, July 2016

The dissertation thesis was prepared in full time attendance form

at the Institute of Electronics and Photonics, Slovak University of Technology in Bratislava, Faculty of Electrical Engineering and Information Technology

Submitter: **Ing. Arpád Kósa**
Institute of Electronics and Photonics, Slovak University of Technology in Bratislava, Faculty of Electrical Engineering and Information Technology
Ilkovičova 3, 812 19 Bratislava, Slovak republic

Supervisor: **prof. Ing. Ľubica Stuchlíková, PhD.**
Institute of Electronics and Photonics, Slovak University of Technology in Bratislava, Faculty of Electrical Engineering and Information Technology
Ilkovičova 3, 812 19 Bratislava, Slovak republic

Opponents: **Ing. Jozef Osvald, DrSc.**
Slovak Academy of Sciences
Dúbravská cesta 9, 841 04 Bratislava, Slovak republic

doc. Ing. Igor Jamnický, Csc.
Faculty of Electrical Engineering, University of Žilina
Univerzitná 1, 010 26 Žilina, Slovak republic

Author's report sent on: .....

Date of dissertation thesis defence: .....

at Slovak University of Technology in Bratislava, Faculty of Electrical Engineering and Information Technology**,** Ilkovičova 3, 812 19 Bratislava, Slovak republic

prof. Dr. Ing. Miloš Oravec
Dean

Contents

1. Introduction, current state of research

Development and production of high quality semiconductor materials are crucial steps of technical advancement. Concentrated effort is focused on the fabrication of perfect crystal structures, despite the fact that it is very hard to ensure precise growth conditions such as temperature, pressure and high component purity. During growth processes different types of impurities are formed, which can highly affect the function and electrical properties of final structures. Electrically active defects also called as deep energy levels from energetic point of view are allowed states localized in the band gap of the semiconductor material. By capturing charge carriers these are directly influencing generation and recombination processes, usually with non beneficial effects.

In order to identify inadequacies of growth technologies, the manufacture of high quality semiconductor materials has to be supported by appropriate diagnostic approaches. One of the most important methods of electrically active defect investigation is Deep Level Transient Spectroscopy (DLTS). The standard DLTS method was founded by David Vern Lang in 1974 with the objective of semiconductor material characterization [1]. During the following decades many variations of the standard method were developed like Deep Level Transient Fourier Spectroscopy - DLTFS, which processes measured data by Fourier analysis [2] - [6]. DLTS has a key role in defect characterization satisfying basic requirements of diagnosis, especially accuracy, non-destructivity and sensitivity [7], however in certain cases reliability of evaluated data is highly affected by the presence of mutually interacting complex impurities. It is difficult to effectively separate these responses therefore calculated parameters are obtained with reduced precision. Investigation of complicated multilayer semiconductor structures also induces difficulties, since different materials and several semiconductor junctions are involved. Various experimental and analytical evaluation methods are needed to be carried out and compared to establish a complex evaluation and defect investigation.

Actual research is focused on multilayer structures utilized in photovoltaic applications, since solar energy as a renewable energy source is more and more important in everyday life. It is an efficient and pollution free method of electricity generation, rapidly grown with high importance in the last decade. Attention is devoted to promising semiconductor compounds on GaAs basis, such as InGaAs, GaAsN and InGaAsN alloys. These materials, due to their unique physical properties are suitable candidates for multi junction solar cells and other semiconductor and photovoltaic applications. Dilute-nitride InGaAsN based solar cells lattice matched to GaAs were demonstrated as working prototypes since 1998 [8]. Sub cells with adequate performances for 3 junction cells were reported in 2007 [9]. World record efficiency 43.5% has been achieved by multi-junction solar cells employing GaInNAsSb junctions [10]. New approaches for InGaAsN based structures are continuously studied to realize 50% efficiency by 4- or 5- junction solar cells lattice matched to GaAs and Ge substrates [11]. Increasing requirements on quality and efficiency of solar cells, not only in space technology but also in terrestrial utilizations, needs to be supported by various experiments and characterization procedures. Successful application requires the understanding of generated electrically active defects. Investigation must be correlated with the growth process in order to develop the fabrication, since it is hard to determine proper material compositions, especially in the case of InGaAsN where defect states are associated with the indium and nitrogen content [12], [13].

One of the most difficult parts of the DLTFS investigation is the interpretation of experimental results. Different factors are needed to be taken into account in order to establish a reliable evaluation procedure. On one hand we can have a comprehensive result, although on the other a non evaluable experiment. In some cases the opposite is true, deep energy level parameters are obtained with high reliability, but structural and geometrical properties are indicating a questionable investigation [14] - [16]. The accuracy of the method is mainly affected by complex situations, in which different defect states are interacting, while a more complicated situation rises, when the object of the investigation is a multilayer structure, containing several p-n or p-i-n junctions not only in homogenous but also heterogeneous compositions [17], [18]. To state the layer origin of such a DLTFS spectrum is rather difficult. Without knowing the exact layer and material type where the defect is localized, the investigation loses its point. There is no 100% proven approach for the DLTFS evaluation of multilayer structures, therefore application of referent structures and different evaluation and experimental methods is essential.

The dissertation thesis deals with proposition of an effective approach of high reliability and complex deep energy level parameter investigation in complicated multilayer structures by the DLTS method. Main attention is focused on InGaAsN based tandem solar cells and selected referent samples to solve challenges of analysis, such as limiting factors of evaluation: involvement of undoped semiconductor layers, different material compositions and structural properties, composition and growth parameter defect dependencies.

This work was supported by the Scientific Grant Agency of Slovak Republic Education Ministry (projects VEGA 1/0377/13, VEGA 1/0439/13, VEGA 1/0712/12, VEGA 1/0739/16, SOLAR 115721, SOLAR2 115721), co-financed by Polish Ministry of Science and Higher Education under the grant no. N N515 607539, further on by the European Union within European Regional Development Fund through grant Innovative Economy (POIG.01.01.02-00-008/08-05), by Wroclaw University of Science and Technology statutory grant S20010, B20011 and Slovak-Polish International Cooperation Program no. SK-PL-0017-09 & 0005-12. All experiments took place at the Slovak University of Technology, Faculty of Electrical Engineering and Information Technology, Institute of Electronics and Photonics using DLTS measurement system BIORAD DL8000.

2. Goals of the dissertation thesis

Quality of multilayer semiconductor structures based on A3B5 utilized in photovoltaic applications, and also investigation of their emission-capture processes dependent electrical properties are constantly at the center of basic research. Following goals of the dissertation thesis have been established:

- To analyse basics of the DLTS method and according to this knowledge to propose an effective approach of high reliability and complex deep energy levels parameters investigation in complicated multilayer structures.
- To investigate emission and capture processes in multilayer structures with several homogeneous and heterogeneous semiconductor junctions (p-n, n-p, p-i-n) by DLTFS method and its modifications. Focus of attention on defect distribution in multilayer (tandem) solar cell structures based on InGaAsN/GaAs.
- To analyse structure composition and growth process dependent defect states (different material concentrations - different band gaps, undoped semiconductor layers, defect complexes) affecting the trap parameter calculation, defect type identification and origin determination.

3. Experiments and sample preparation

The investigated InGaAsN tandem solar cell samples, including the referent structures were grown by Atmospheric Metal Organic Vapour Phase Epitaxy (AP-MOVPE) using AIX 200 R&D horizontal reactor on a n-type GaAs (Si doped) substrate at the Wroclaw University of Science and Technology. As dopant sources silane (SiH_4 in H_2) and diethylzinc (DEZn - $Zn(C_2H_5)_2$) were used for n-type and p-type dopants respectively. 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. Fabricated structures were prepared in two metallization configurations. In the first case as a typical detector ring structure with an inner diameter $\emptyset = 150$ µm (circle shaped active area), where the metallic

p-type (Pt/Ti/Pt/Au) and n-type (AuGe/Ni/Au) contacts were deposited under vacuum conditions on the top and around the mesa, respectively. The second configuration was prepared with p-type AuBe transparent and n-type AuGeNi standard metallization by deposition on the top and bottom side of the structure (Fig.). The transparency was determined as 40 % [19].

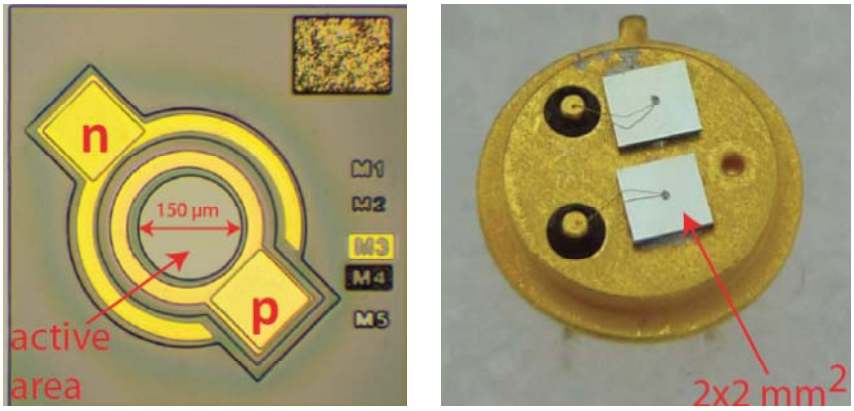

Fig. 3.1 Images of the fabricated, test solar cell structures. Typical detector configuration with circle shape active area (left) and structures with transparent top electrodes (right).

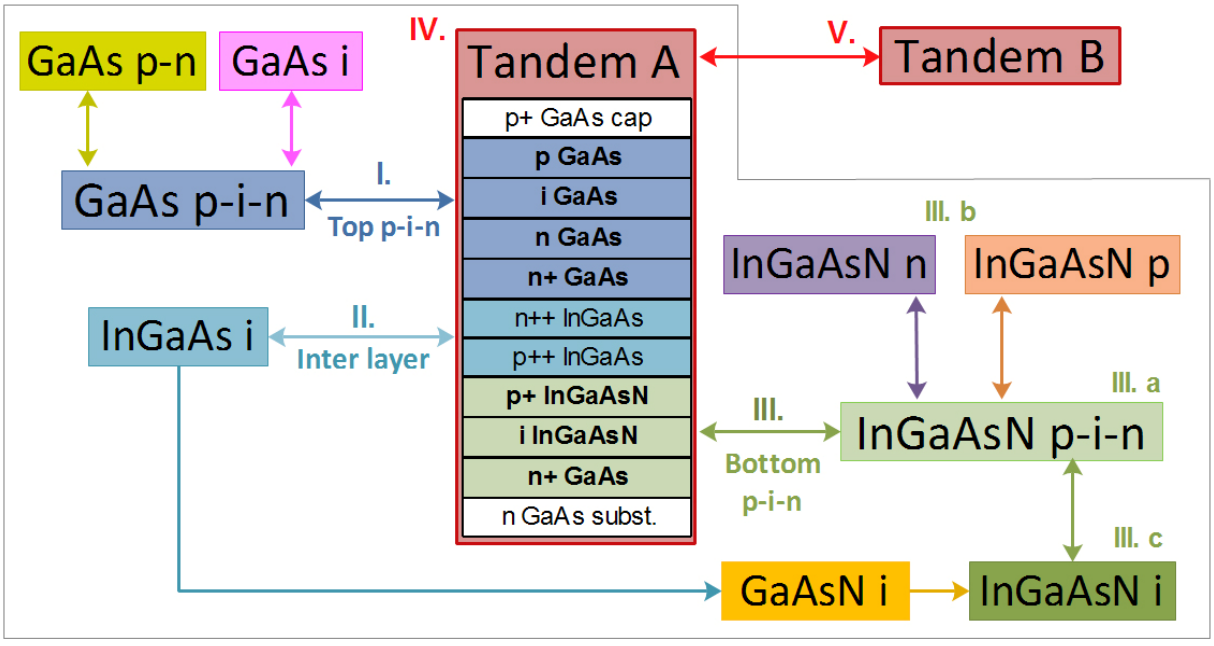

Fig. 3.2 Mind-map of DLTS analysis, plan of the tandem solar cell evaluation.

The examined tandem solar cell sample consisted of three sub-junctions: GaAs top p-i-n InGaAs n-p interlayer and InGaAsN bottom p-i-n. In order to establish a complex defect investigation, each sub solar cell junction (top p-i-n, bottom p-i-n and the InGaAs n-p interlayer) should be investigated and compared by referent structures prepared in the same aperture with the same technology. According to available referent samples and the structure scheme the first tool of complex investigations, an evaluation diagram was created, simply to define the basic tasks of analysis (Fig. 3.2). The following steps are relevant:

I. Examination of the top GaAs p-i-n solar cell (**Chyba! Nenašiel sa žiaden zdroj odkazov.**, blue), by comparison with referent GaAs p-i-n, p-n and i structures. Attention devoted to intrinsic layer induced trap levels, reliability and defect type statement, addressing the problem of intrinsic layer involvement in DLTFS analysis.

II. Analysis of In concentration influences on DLTFS responses in InGaAs referent samples to precisely identify In trap origins for the InGaAs tunnel junction (Fig. 3.2, turquoise).

III. Evaluation of the bottom InGaAsN p-i-n structure (Fig. 3.2, green):

   a. DLTFS experiment and analysis of emission and capture processes in the InGaAsN p-i-n bottom solar cell referent sample.

   b. Evaluation of correlations between InGaAsN p and n type referent samples and the InGaAsN p-i-n structure, to state the conduction type of defects (p, n).

   c. Comparison of InGaAsN intrinsic referent sample with the bottom p-i-n structure to locate the intrinsic layer response, overall comparison of undoped referent structures GaAs i, InGaAs i at different percentages of In, GaAsN i at different contents of N and InGaAsN i to state and distinguish between defect level origins (GaAs, In or N induced). Assessment of result in accordance with the InGaAsN p-i-n referent sample.

IV. DLTFS analysis of the InGaAsN tandem solar cell structure Tandem A by referent sample comparison (each sub-junction I, II, III). Identification of probable defect origins and generation conditions.

V. DLTFS evaluation of Tandem A and Tandem B multilayer InGaAsN samples with different growth conditions to identify dependent electrically active defect states. Investigation of relations between these two samples and generated defect states.

VI. Overall InGaAsN tandem solar cell DLTFS evaluation and conclusion. Discussion about identified defect states, possible origins and conditions of elimination or reduction. Specification of a more suitable structure for a high efficient solar cell.

4. Results and discussion

Main achievement of the thesis is a complex DLTFS investigation of emission and capture processes in multilayer InGaAsN solar cells, proposing an effective way of defect recognition in complicated semiconductor structures. This adequate electrically active defect study is particularly important, since it supports the up to date DLTFS and InGaAsN solar cell research. Stated results represent essential information for future DLTFS investigations and the InGaAsN solar cell growth process optimization. Outcome of the analysis should assist the growth of InGaAsN solar cells with higher efficiencies. All the results of the present work

can be summarized according to the stated sub tasks of the InGaAsN tandem solar cell investigation (Fig. 3.2).

I.

DLTFS analysis of the top GaAs p-i-n sub-junction of the multilayer solar cell structure in terms of reliability improvement, addressing the problematic of a dual type majority/minority carrier defect complex and the intrinsic layer induced defect conduction type statement difficulty (Fig. 4.1). This type of trap state, typical for undoped structures, highly influences the reliability of standard DLTFS evaluations. A unique analytical approach of data sorting was proposed, capable to overcome standard DLTFS evaluation limitations thereby ensuring a high precision defect parameter calculation. Based on the definitions of transition areas (Fig. 4.1 right shaded areas) low classified spectral points were filtered out and defect parameters were recalculated (Fig. 4.1 right). This chapter includes a detailed discussion of many available analytical and experimental techniques and their limitations in connection with such a complex defect state.

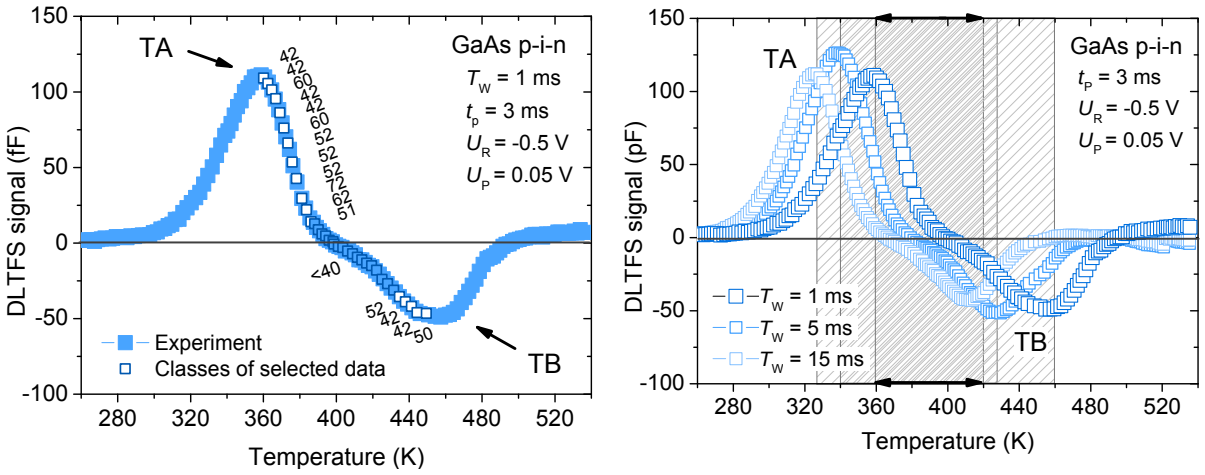

Fig. 4.1 Transient classifications of the GaAs p-i-n measured DLTFS curve (left) and defined curve transition areas (right).

The approach was confirmed by all the available experimental methods such as: DLTFS experimental parameter variations, Isothermal Transient Spectroscopy, Minority carrier DLTFS, DLTFS spectrum simulations, comparison by referent samples and literature. It should be highlighted, that the Minority carrier DLTFS an important part of the experiment capable to filter out majority carrier responses (Fig. 4.2), was the first time utilized and optimized for the DLTFS measurement system DL8000. Standard procedures of these optical experiments and sample contacting were specified assessed and are used since then. Spectral results confirmed the validity of the proposed analytical approach, and the presence of the interacting defect complex. Probable defect and intrinsic layer conduction types were stated, in addition insufficiencies of the GaAs top p-i-n solar cell were discussed in detail. The realized high precision defect investigation showed two dominative defect states of the dual type complex: a nickel related electron type defect (0.48 eV [20], [21]) and a possible hole

like oxygen associated meta-stable state of the arsenic antisite EL2 (0.63 eV [22]). Both the presence of oxygen and Ni were connected to a possible growth process source.

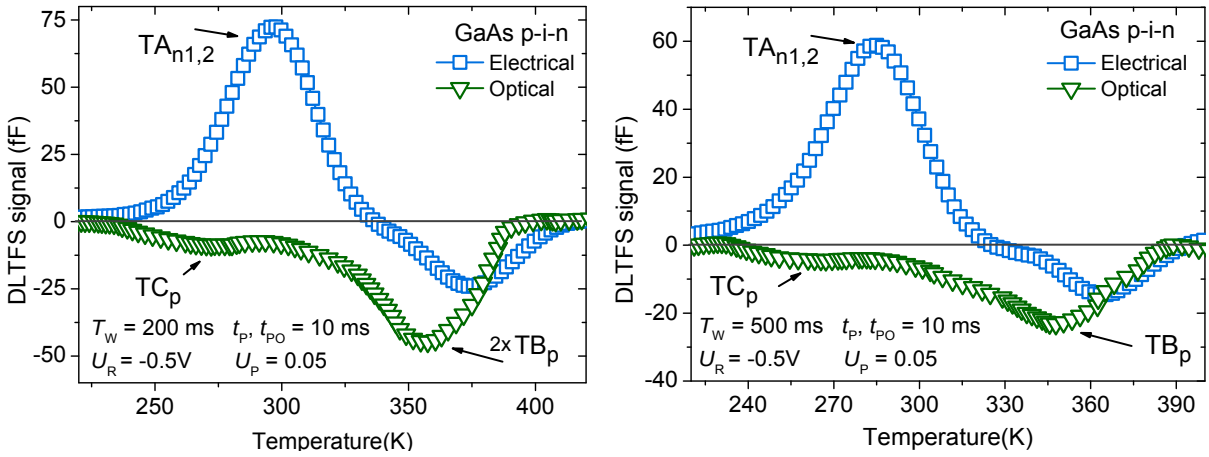

Fig. 4.2 Comparison of standard DLTFS and MCDLTFS measurements of GaAs p-i-n at two set of parameters. Optical excitation of the minority response.

II.

DLTFS analysis of InGaAs based referent structures at various In concentrations supporting the InGaAs n-p tunnel junction investigation of the multilayer InGaAsN solar cell, regarding In dependent defect states (Fig. 4.3). The most important achievement of this chapter is the definition of proper indium concentrations for InGaAs as a high purity sample. Four referent structures with In concentrations 3.4 %, 8.9 %, 10.5 % and 12.8 % were investigated addressing the gradient composition DLTFS question of activation energy calculation. Three significant affects of the In composition were concluded: shifting DLTFS spectrum peaks, hence fluctuating activation energies at different band gaps of the associated In content (Fig. 4.4), higher In concentration around 10.5 % reducing low temperature point defects (Fig. 4.3), presence of a more substantial In dependent dual state defect confirmed experimentally and by calculations (Fig. 4.4).

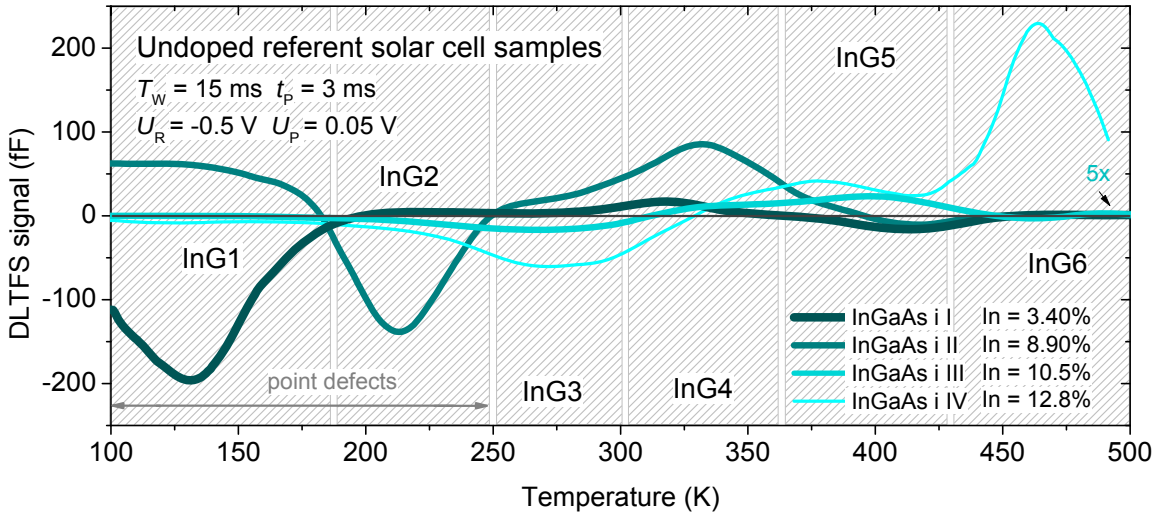

Fig. 4.3 DLTFS spectra of InGaAs undoped referent samples at different In concentrations.

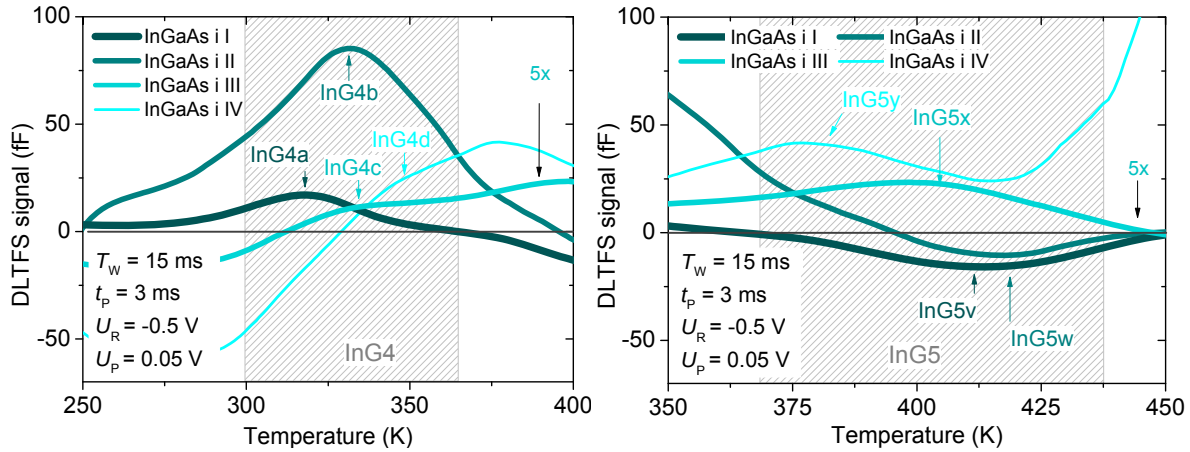

Fig. 4.4 Detailed DLTFS of trap group InG4 (left) and InG5 (right).

DLTFS experiments ensured the identification of two significant deep energy levels InG4 as a Cu(~0.48 eV [23]) related hole trap visible in all samples (Fig. 4.4 left) and InG5 as EL2 (~0.77 eV [24]) and its meta stable double donor state EL^{22+} (~0.57 eV [25]). According to these results there is a high possibility that the discussed formation of the identified EL2 and its meta-stable state is connected to the In concentration, since a clear transition was experimentally supported by examined DLTFS spectra (Fig. 4.4 right). As far as the study of research information is correct and up to date, the double donor state defect transition of EL2 was not related to indium content until now. By the observed number and concentration of trap states, sample with 10.5 % of In was stated as the purest, nevertheless a hypothetical value of 9.5 % was assumed, high enough to eliminate or reduce point defects, further on to ensure an equilibrium of the dual state deep energy level.

III.

DLTFS analysis of InGaAsN based p-i-n referent sample a structural equivalent of the bottom p-i-n multilayer solar cell sub-junction. The most important achievement of this chapter is the definition of proper nitrogen concentrations for GaAsN as a high purity sample. Five referent structures with N concentrations 0.9 %, 1.15 %, 1.5 %, 1.6 % and 1.85 % were investigated addressing the gradient composition DLTFS question, and growth condition dependence of electrically active deep energy levels, since each sample was grown at different temperatures (585 °C, 605 °C, 595 °C, 565 °C, 575 °C - GaAsN i I - V). These experiments together including task II were carried out in order to support the InGaAsN p-i-n analysis, since different In and N gradient concentrations were involved. Three significant affects of the N composition and growth temperature parameter pair were concluded: shifting DLTFS spectrum peaks, meaning fluctuating activation energies at different band gaps of the associated N content (Fig. 4.6), higher N concentration around 1.0 % eliminating low temperature dislocations (Fig. 4.5), probable presence of more substantial N concentration and growth temperature dependent defect complex confirmed experimentally (Fig. 4.6).

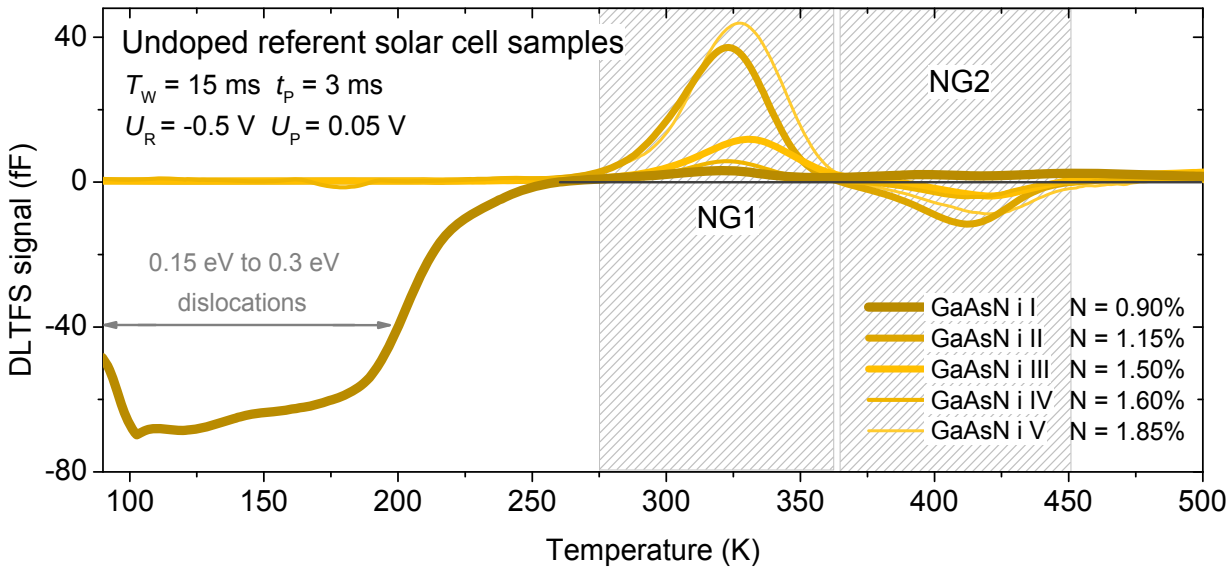

Fig. 4.5 DLTFS spectra of GaAsN undoped referent samples at different N concentrations.

DLTFS experiments ensured the identification of two significant defect complexes NG1 and NG2, possibly containing a nitrogen and GaAs related state in both cases: NG1 was identified as a complex of a hole like GaAs trap (NG1* ≅ 0.46 eV [23]) together with a nitrogen induced defect (NG2** ≅ 0.54 eV [26]), while NG2 as an opposite type trap complex including a possible nitrogen related electron like negative signal (NG2 ≅ 0.66 eV [27]) with a GaAs assumed hole like positive one (NG2 ≅ 0.71 eV [28]). Each complex was significant at specific growth conditions.

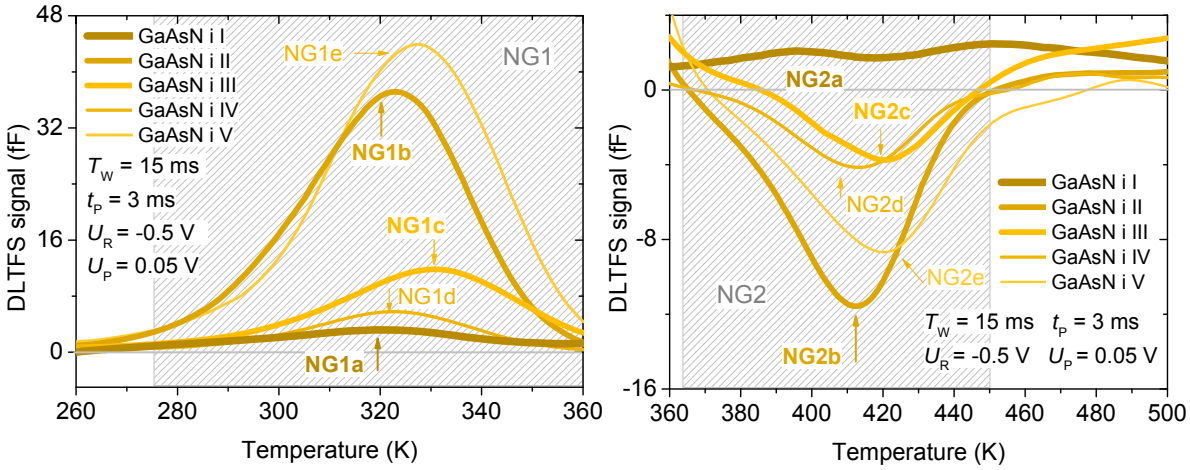

Fig. 4.6 Detailed DLTFS of trap group NG1 (left) and NG2 (right).

As concluded, NG1 defect concentration was increased by both growth factors (temperature, N content Fig. 4.6 left), while the temperature sensitive positive signal of NG2 interacting with the N content dependent negative spectrum showed dominant behaviours as follows: low N content and high temperature was favourable for GaAs related NG2 (Fig. 4.6 right NG2a) and high N content lower temperatures for the negative N related NG2 (Fig. 4.6 right NG2b). Referent sample with 1.60 % at 565 °C (GaAsN i IV) could be considered as the most balanced structure where NG1 and NG2 were the lowest and at the same time dislocations

were suppressed. An optimized growth temperature lower as 585 °C was proposed for a high purity sample avoiding the generation of growth temperature sensitive GaAs defects, if possible with N content around 1 % efficient enough to ensure a suitable nitrogen concentration eliminating dislocations.

IV.

Assessment of tasks I - III for the tandem solar cell defect distribution investigation. All the previous achievements were processed to analyse the Tandem A solar cell structure. DLTFS spectrum origin was localized as the intrinsic layer of the bottom InGaAsN p-i-n sub-junction, and an adequate defect investigation was carried out accordingly (Fig. 4.7). Experimentally obtained DLTFS spectrum of the investigated multilayer solar cell structure was compared step by step with all of the examined referent solar cell structures, which made possible to precisely identify relevant defect states.

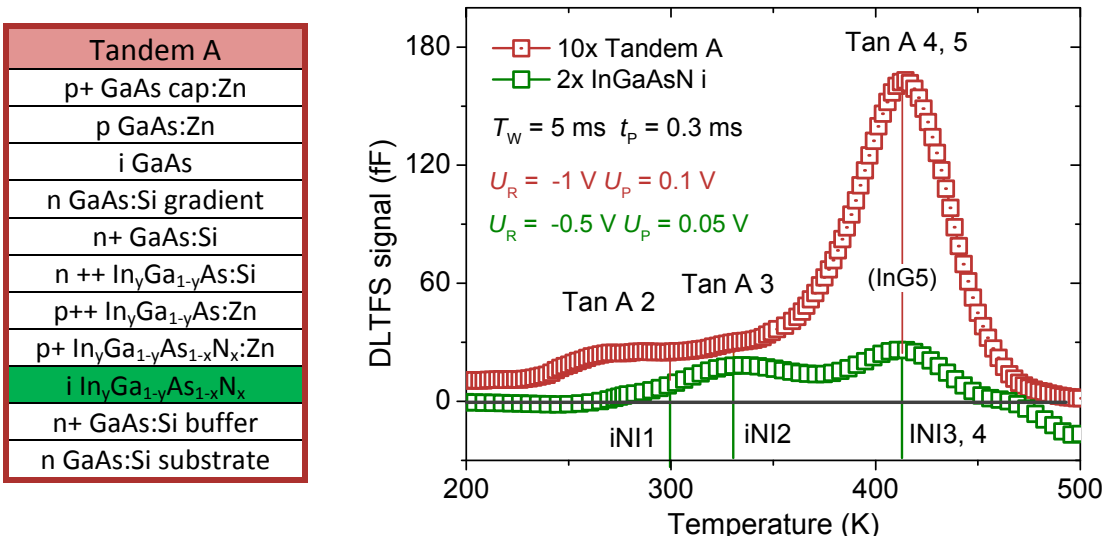

Fig. 4.7 Schematic description of the Tandem A InGaAsN multilayer solar cell with marked InGaAsN i reference of the bottom p-i-n sub junction (left) with compared DLTFS spectrums (right).

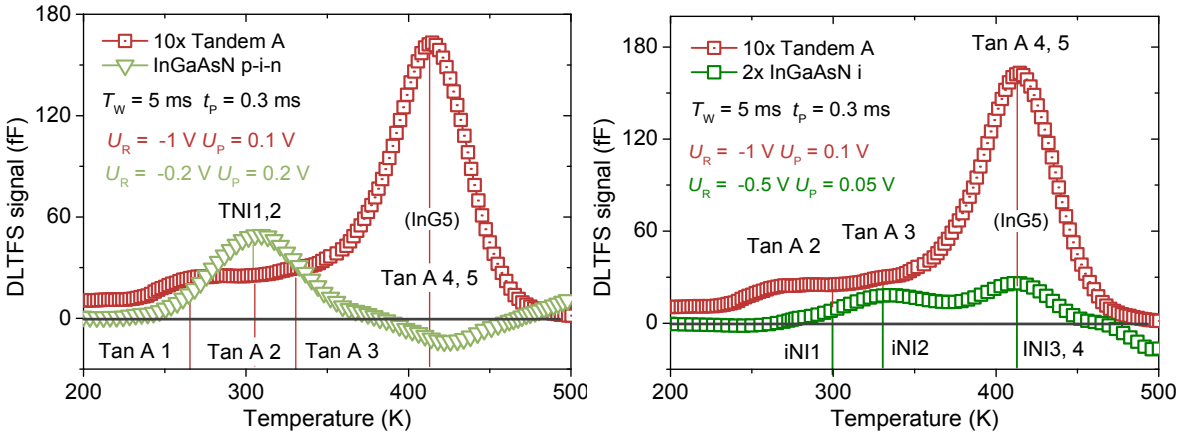

Fig. 4.8 DLTFS comparison of InGaAsN p-i-n, i and Tandem A solar cell samples.

Electrically active defect differences in the InGaAsN intrinsic referent, InGaAsN bottom p-i-n referent and the tandem experiment were observed (Fig. 4.8). These deviations were attributed to the In sensitive dual defect state of InG5 (chapter II.) indicating an another growth condition dependence (the only difference in these samples), thus the hydrogen flow rate of the AP-MOVPE gallium source (TMGa). In the light of discussed achievements, for comparison purposes another tandem solar cell structure Tandem B was examined, in the light of TMGa growth condition correspondences: Tandem A with InGaAsN intrinsic referent sample (7 mil/min) and Tandem B with InGaAsN bottom p-i-n referent structure (10 mil/min). Further growth condition dependent defect state investigations were carried out by the next chapter of the dissertation thesis.

V.

Analysis of growth dependent deep energy levels in tandem solar cell structures. Significant achievement of the Tandem A and Tandem B comparison (Fig. 4.9) is the evidence of InG5 dual defect state and its growth condition dependence probably capable to change the conduction type of the bottom InGaAsN p-i-n intrinsic layer. Identical but inverse DLTFS spectra were measured for Tandem B (Fig. 4.9 right).

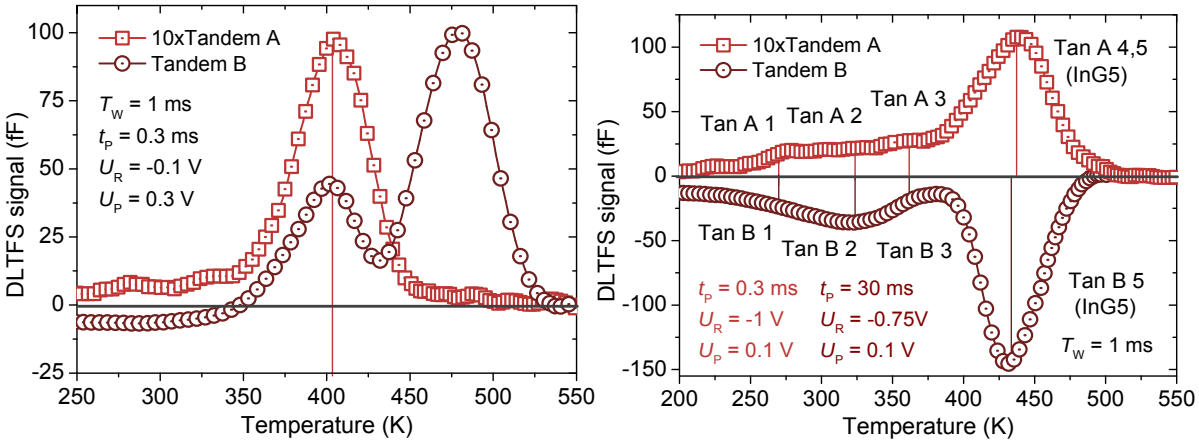

Fig. 4.9 DLTFS spectra comparison of Tandem A and Tandem B InGaAsN multilayer solar cell structures at different experimental conditions.

Several DLTFS experimental outputs and analysis of spectral simulations confirmed the conduction type change tendency of InG5. According to the observed relations the 7 mil/min TMGa flow rate assists the concentration of the p type trap state (InG5 at 0.57 eV of Tandem A Fig. 4.9 right, light red), which can become significant enough to result a p type conduction. On other hand the 10 mil/min TMGa flow rate increases the n-type InG5 concentration, becoming high enough to induce the conduction type change, hence the undoped layer of Tandem B acts as n type (Fig. 4.9 right, dark red). InG5 can co-exist in both forms due to the indium sensitive property (chapter II.) and gradient concentration of InGaAsN layers. This trap state was observed at different DLTFS conditions both in Tandem A and Tandem B samples (Fig. 4.9).

VI.

Specification of a more suitable structure for a high efficient solar cell. Comparison of Tandem A with 7 mil/min and Tandem B with 10 mil/min resulted the assumption of the InGaAsN bottom p-i-n conduction type change and increased concentration about 10 times higher (Fig. 4.9). According to all the evaluated relations Tandem A sample is a more proper candidate for higher multilayer solar cell efficiencies, nevertheless all the proposed In/N factors (tasks II and III) should ensure a multilayer sample of a higher quality. In means of a pure growth process, provision of an oxygen gas purifier should be applied, able to eliminate the oxygen defect relation of the top GaAs p-i-n active layer (task I).

5. Achievements of the dissertation thesis

Main achievements of the dissertation thesis can be summarized as follows:

- proposal of a new Deep Level Transient Spectroscopy evaluation approach of emission and capture processes in multilayer semiconductor structures to increase the effectiveness and reliability of standard DLTFS analysis,
  - implementation of the proposed Arrhenius data sorting method in the evaluation process of a complex dual conduction type defect state typically observed in multilayer semiconductor referent structures,
  - calculation of deep energy level parameters with higher reliability and reproducibility by the utilization of proper DLTFS methods and evaluation procedures (DLTFS with electrical and optical excitation, Isothermal transient spectroscopy, DLTFS experimental parameter variation and optimization, direct and indirect evaluation methods),
- verification of the proposed approach by DLTFS evaluation of emission and capture processes in selected semiconductor structures based on GaAs, InGaAs, GaAsN, InGaAsN,
- implementation and optimization of Minority carrier DLTFS for the DLTFS measurement system DL8000 workplace, extension of InGaAsN minority carrier defect analysis,
- acquirement of new knowledge about emission and capture processes and related defect states in multilayer solar cell structures based on InGaAsN in order to support the growth process,
  - more than 20 deep energy levels were identified in referent structures, many of these corresponding with the tandem solar cell experiment,
  - based on spectral comparison and analysis probable type and origin of identified undoped layer defect states were stated,
- specification of structural properties and growth conditions to achieve higher solar cell efficiencies of fabricated multilayer structures,
  - 10.5 % of indium in InGaAs samples decreases/eliminates low temperature point defects

- 1.6 % of nitrogen at growth temperature 565 °C of GaAsN samples suppresses dislocations and reduces GaAs/N complex defect amplitudes,
- indium content and growth condition dependence of a dual type complex (EL2/EL2^{2+}) was confirmed experimentally and by calculations,
- nitrogen content related and growth temperature dependent GaAs defect complexes were evaluated,
- according to the analysis and defect distributions in tandem solar cell samples the gallium dopant source with 7mil/min flow rate, indium around 9.5 % and nitrogen with 1 % at growth temperature lower as 585 °C were stated as preferable,

6. Conclusion

Development of high quality semiconductor materials is an important factor in the technical advancement of semiconductor structures. The production has to be supported by appropriate diagnostic methods, in which Deep Level Transient Fourier Spectroscopy has a key role. Although DLTFS satisfies basic requirements of diagnostics like other techniques it has its limitations. The most difficult parts of the DLTFS investigation is the interpretation of experimental results. The reliability of the method is mainly affected by complex situations, like the involvement of multilayer structures. Utilization of various DLTFS defect recognition techniques, as well as analytical approaches and referent structures is crucial in complicated structure analysis.

Objects of this study, InGaAsN based tandem solar cells were chosen fulfilling all the structural properties, which require complex evaluations. These are: involvement of several semiconductor junctions (p-n, n-p, p-i-n) in homogeneous and heterogeneous compositions complicating the localization of DLTFS response origins, layers of different doped and undoped materials (GaAs, InGaAs, GaAsN, InGaAsN) questioning the defect type determination, gradient compositions (different In and N concentrations - different band gaps) affecting the trap parameter calculation, and last but not least the growth condition dependence having the potential to generate different defect complexes.

As this study shows, the defect distribution DLTFS investigation of complicated semiconductor structures is essential to reveal defect behaviours of composition, and growth condition sensitive meta-stable and complex deep energy levels. It has the potential to support the growth process and the understanding of generated defects. Comprehensive analysis is crucial, since the standard DLTFS evaluation is not sufficient and adequate enough to observe reliable results. Several analytical and experimental methods are needed to be exploited and processed to ensure a reliable defect parameter calculation. Special demands of multilayer samples need an effective DLTFS guide of electrically active trap investigations to ensure a pure technological process and mass utilization in praxes.

7. Resumé

Vývoj vysoko kvalitných polovodičových materiálov je dôležitým faktorom pre dosiahnutie technického pokroku v oblasti polovodičových štruktúr. Výroba musí byť podporovaná vhodnými diagnostickými metódami na skúmanie kvality, medzi ktoré patrí spektroskopia hlbokých hladín (DLTS), univerzálna metóda na identifikáciu parametrov elektricky aktívnych porúch v polovodičových bariérových štruktúrach. Táto dizertačná práca sa zaoberá návrhom efektívneho skúmania emisno-záchytných procesov vo viacvrstvových polovodičových štruktúrach. Komplikované štruktúry obsahujúce nielen rôzne materiály ale aj viaceré homogénne a heterogénne polovodičové prechody (n-p, p-n, p-i-n) sú príčinou nejednoznačných výsledkov DLTS experimentov a následne náročnej interpretácie elektricky aktívnych porúch. Tieto defekty môžu byť nielen kompozične ale aj technologicky závislé, čo znamená, že rôzne koncentrácie prvkov zlúčenín, ale aj rôzne rastové podmienky, ako je napr. teplota, môžu byť pôvodom generovaných komplexných porúch. Fourierova spektroskopia hlbokých energetických hladín (DLTFS), digitálna modifikácia štandardnej DLTS, je v súčasnosti jedna z najvyužívanejších metód DLTS diagnostiky, ktorá sa vyznačuje vysokou citlivosťou, nedeštruktívnym charakterom a adaptabilitou pre rôzne materiály. Z analytických a experimentálnych výstupov metódy DLTFS je možné určiť pôvod a základné parametre identifikovaných defektov. DLTFS rovnako ako ostatné experimentálne metódy, má ale svoje obmedzenia.

Cieľom výskumu prezentovaného v tejto práci bolo riešiť jednotlivé výzvy DLTFS metódy súvisiace s viacvrstvovými polovodičovými štruktúrami ako sú: skúmanie presnosti danej metodiky z hľadiska vyhodnotenia vplyvu nedopovaných štruktúr pre určenie typu vodivosti defektov, analýza kompozične závislých hlbokých energetických hladín rôznych materiálov (rôzne šírky zakázaného pásma) a vyšetrenie vplyvu rastových podmienok, ktoré majú priamy dosah na presnosť výpočtu parametrov porúch.

Súčasný výskum sa orientuje na vývoj vysokoúčinných viacvrstvových solárnych článkov, v ktorých InGaAsN predstavuje perspektívny materiál. Pridávaním malého množstva india alebo dusíka do tejto zlúčeniny je možné dosiahnuť výhodné vlastnosti, ako sú napríklad rôzne šírky zakázaného pásma optimalizované pre rôzne vlnové dĺžky slnečného žiarenia. S cieľom dosiahnuť vysokú účinnosť, sú z tohto materiálu vytvorené takzvané tandem solárne články obsahujúce viaceré aktívne vrstvy teda aj polovodičové prechody a heteroprechody. Skúmanie týchto štruktúr má potenciál vyriešiť jednotlivé DLTFS výzvy, preto predmetom predloženej práce bolo vykonanie komplexnej diagnostiky InGaAsN tandemových solárnych článkov s viacerými polovodičovými štruktúrami vytvorených pri rôznych rastových podmienkach.

Výsledky dizertačnej práce a jednotlivé prínosy boli roztriedené do šiestich bodov podľa plánu analýz, dostupných referenčných vzoriek a štrukturálnych vlastností InGaAsN tandemových článkov pozostávajúcich z troch štruktúr: hornej GaAs p-i-n diódy, InGaAs n-p tunelovacej diódy a dolnej InGaAsN p-i-n diódy. Veľká pozornosť bola venovaná presnosti

vyhodnotenia nedopovaných vrstiev, rôznych kompozícií a rastových podmienok referenčných štruktúr.

I.

DLTFS analýza hornej GaAs p-i-n štruktúry z hľadiska zvýšenia presnosti štandardného výpočtu parametrov hlbokých energetických hladín, a to hlavne v prípade komplexného defektu s duálnym vodivostným typom (majoritné/minoritné) v nedopovanej polovodičovej vrstve. Tieto špecifické podmienky majú za následok nejednoznačnosť výsledkov analýzy a určenia typu a pôvodu porúch. V nameraných DLTFS spektrách je často pozorovaný prudký pokles spojený so zmenou z kladného na záporný signál (Fig. 4.1). Bol navrhnutý unikátny analytický prístup na triedenie spektrálnych dát (Fig. 4.1), ktorý je schopný prekonať obmedzenia DLTFS štandardného vyhodnotenia a zabezpečiť presnejšie určenie poruchových stavov. Na potvrdenie správnosti navrhnutej metodiky a adekvátnosť získaných výsledkov boli využité relevantné experimentálne metódy: variácia experimentálnych meracích parametrov, Izotermálna spektroskopia hlbokých energetických hladín, DLTFS s optickou excitáciou (MCDLTFS), komparácia s referenčnými štruktúrami a simulácie DLTFS spektier. Je potrebné vyzdvihnúť, že dôležitá časť experimentu, teda využitie DLTFS metódy s optickou excitáciou vhodnej na skúmanie minoritných porúch bolo na meracom pracovisku DL8000 implementované prvýkrát (Fig. 4.2). Boli špecifikované a zaznamenané optimalizované postupy DLTFS experimentov s optickou excitáciou, ako je nakontaktovanie a umiestnenie štruktúr, nastavenie optického zdroja (optický zdroj: GaAs laserová dióda s vlnovou dĺžkou $\lambda = 850$ nm) a vhodných meracích podmienok. Stali sa základom bežných DLTFS experimentov. S vysokou pravdepodobnosťou bol identifikovaný pôvod a vodivostný typ porúch v intrinzickej GaAs vrstve. Vyhodnotenia realizované so zvýšenou presnosťou potvrdili prítomnosť dominantných defektov duálneho komplexu, a to prítomnosť niklu (0.48 eV [20], [21]) elektrónového typu a pravdepodobne dierového meta-stabilného stavu známeho GaAs defektu EL2 (0.63 [22]) súvisiaceho s kyslíkom. Bolo stanovené, že vznik týchto porúch bol priamym následkom rastového procesu.

II.

Vyhodnotenie priameho vplyvu veľkosti koncentrácie india na generáciu alebo zánik elektricky aktívnych porúch v InGaAs štruktúrach na podporu optimalizácie tunelovej InGaAs medzivrstvy tandemového solárneho článku (Fig. 4.3). Hlavným prínosom tejto časti práce je zadefinovanie vhodnej koncentrácie india na dosiahnutie štruktúry s najnižšou aktivitou porúch. Skúmané boli štyri referenčné vzorky s koncentráciami 3,4 %, 8,9 %, 10,5 % a 12,8 %. Zistené boli tri významné vplyvy veľkosti koncentrácie india: posunutie DLTFS píkov a spektier prisudzované rozdielom v šírke zakázaných pásiem spôsobených rôznou veľkosťou koncentrácie In, zníženie koncentrácie bodových porúch pri vyšších obsahoch India okolo 10,5 % (Fig. 4.3), experimentálne ale aj výpočtom potvrdená prítomnosť závažnej komplexnej poruchy s duálnym stavom (Fig. 4.4). Boli určené dve významné hlboké energetické hladiny, a to InG4 ako Cu (0,48 eV [23]) dierového typu prítomná vo všetkých vzorkách (Fig. 4.4 vľavo) a InG5 ako komplex s duálnym stavom

(Fig. 4.4 vpravo) elektrónového typu EL2 (0,77 eV [24]) spolu s dierovým meta-stabilným komplexom $EL2^{2+}$ (0,57 eV [25]). Zo získaných výsledkov vyplýva, že s veľkou pravdepodobnosťou je prechod tejto poruchy medzi dvoma stavmi priamo spojený s koncentráciou India. Pokiaľ sú informácie výskumných štúdií adekvátne, meta-stabilný charakter poruchy EL2 nebol doteraz zaznamenaný v súvislosti s indiom, avšak diskutovaný prechodový jav bol jednoznačne potvrdený DLTFS experimentálnymi výsledkami. Na základe počtu a koncentrácie porúch bola určená ako najčistejšia vzorka s 10,5 % india. Tiež bola stanovená hypotetická hodnota 9.5 % ako postačujúca na elimináciu bodových defektov, pri ktorej je InG5 duálny komplex pravdepodobne v rovnováhe.

III.

Podrobná analýza dolnej InGaAsN p-i-n referenčnej štruktúry tandemového solárneho článku. Najdôležitejším prínosom tejto časti je vyhodnotenie priameho vplyvu koncentrácie dusíka na generáciu alebo zánik elektricky aktívnych porúch v GaAsN štruktúrach. Získané výsledky spolu s InGaAs experimentmi (bod II) sú nevyhnutné na podporu DLTFS vyhodnotenia dolnej InGaAsN p-i-n štruktúry. Bolo skúmaných päť referenčných vzoriek s koncentráciami dusíka 0,9 %, 1,15 %, 1,5 %, 1,6 % a 1,85 %, čo umožnilo vyšetriť otázku DLTFS problematiky gradientných kompozícií a závislosti defektov od rastových podmienok. Každá vzorka bola narastená pri inej teplote, aby bola dosiahnutá iná koncentrácia dusíka (585 °C, 605 °C, 595 °C, 565 °C, 575 °C). Boli určené tri významné vplyvy dusíka a rastovej teploty: posunutie DLTFS píkov (Fig. 4.6), teda fluktuácia aktivačných energií vyvolaná rôznymi koncentráciami dusíka t.j. rôznymi šírkami zakázaných pásem GaAsN, zníženie koncentrácie dislokačných defektov pri vyšších obsahoch dusíka okolo 1 % (Fig. 4.5), pravdepodobná prítomnosť poruchového komplexu čiastočne závislého od N koncentrácie ale aj rastovej teploty. Pomocou DLTFS experimentov a analýz boli určené dva komplexy NG1 and NG2 s interagujúcimi poruchami GaAs a N pôvodu, ktoré je možné interpretovať nasledovne: NG1 bola identifikovaná ako komplex dvoch dierových porúch, a to GaAs typu Cu (NG1* ≅ 0.46 eV [23]) spolu s dusíkom indukovaným defektom (NG1** ≅ 0,54 eV [26]). Ďalej NG2 ako komplex s duálnym vodivostným typom s komplexnými členmi elektrónového dusíkového (NG2 ≅ 0,66 eV [27]) a dierového GaAs typu (NG2 ≅ 0,71 eV [28]). Toto tvrdenie bolo stanovené podľa charakteru DLTFS spektier a píkov NG1/NG2, ktoré mali nelineárne vlastnosti, teda v prípade NG1 maximálna amplitúda bola pozorovaná nielen pri najvyššej koncentrácii dusíka, ale aj pre najvyššiu rastovú teplotu rôznych vzoriek. Podľa toho je možné predpokladať, že s veľkou pravdepodobnosťou každý komplexný člen má svoj dominantný charakter pre daný štrukturálny/rastový parameter. Znamená to, že pri vyššej rastovej teplote GaAs porucha sa stáva dominantnou, zatiaľ čo vyššia koncentrácia N je priaznivá pre dusíkom indukované poruchové stavy (Fig. 4.6). Referenčná vzorka s parametrami N = 1,60 % pri 565 °C bola najvhodnejšia z hľadiska vyváženosti elektricky aktívnych porúch, pri ktorom amplitúdy komplexov NG1 a NG2 boli najnižšie a v rovnakom prípade boli odstránené elektricky aktívne dislokácie. Technológom bola na zváženie navrhnutá optimalizovaná rastová teplota nižšia ako 585 °C, ktorá by mohla zabrániť vzniku

teplotne senzitívnych GaAs porúch. Pokiaľ by bola vzorka narastená s koncentráciou okolo N = 1 % je predpoklad, že bude zabezpečená eliminácia dislokácií.

IV.

Zhrnutie výsledkov I až III s účelom vykonať relevantné a detailné skúmanie poruchových stavov viacvrstvového tandemového solárneho článku na základe systematického porovnávania referenčných experimentov. Na základe získaných výsledkov bola lokalizovaná DLTFS odozva viacvrstvového solárneho článku, ktorej pôvod je pravdepodobne z InGaAsN nedopovanej vrstvy dolnej p-i-n štruktúry (Fig. 4.7). Zároveň boli pozorované závažné rozdielne elektricky aktívne poruchové stavy referenčných vzoriek InGaAsN i a InGaAsN p-i-n v porovnaní s tandemovou štruktúrou (Tandem A, Fig. 4.8). Rozdiely boli preskúmané v súvislosti s InG5 komplexom duálneho stavu (bod II) indukujúcim ďalší možný faktor ovplyvňujúci meta-stabilný stav tohto defektu. Jediný rozdiel medzi týmito vzorkami okrem In/N gradientu bol jeden z APMOVPE technologických parametrov, teda pomer toku vodíka gálium zdroja (TMGa). Na základe týchto skutočností bola zahrnutá do ďalšieho výskumu druhá viacvrstvová štruktúra (Tandem B) s identickými rastovými podmienkami ako InGaAsN p-i-n referenčná vzorka. Podľa korešpondujúcich TMGa parametrov boli vykonané nasledovné porovnávania: Tandem A s InGaAsN intrinsickou referenčnou vzorkou (TMGa = 7 mil/min) a Tandem B s InGaAsN dolnou p-i-n referenčnou štruktúrou (TMGa = 10 mil/min). Podrobné vyhodnotenie bolo vykonané ako hlavná úloha ďalšej kapitoly dizertačnej práce.

V.

DLTFS analýza vplyvu rastových podmienok na hlboké energetické hladiny tandemového solárneho článku. Najdôležitejším výstupom porovnania Tandemu A a Tandemu B je dôkaz prítomnosti poruchy InG5 duálneho komplexu, ktorá je schopná pri daných rastových podmienok zmeniť typ vodivosti nedopovanej vrstvy InGaAsN dolnej p-i-n štruktúry (Fig. 4.9). Viaceré experimentálne, analytické ale aj simulačné výsledky podporili túto hypotézu a ukázalo sa, že pomer toku gália TMGa = 7 mil/min vyvolá výraznejšiu koncentráciu dierového stavu duálneho komplexu (InG5 = 0.57 eV), pričom TMGa = 10 mil/min zvyšuje prítomnosť InG5 defektov opačného, elektrónového typu (Fig. 4.9 vpravo). Pravdepodobne v oboch prípadoch rastovo indukovaná koncentrácia porúch sa stáva takou výraznou, že dokáže zmeniť vodivosť. InG5 môže koexistovať v oboch stavoch vzhľadom na In citlivosť (bod II) a gradientnú kompozíciu InGaAsN vrstiev, teda bolo možné pozorovať prítomnosť týchto energií pri rôznych DLTFS meracích podmienkach.

VI.

Špecifikácia najvhodnejšej viacvrstvovej štruktúry solárneho článku na dosiahnutie vyššej účinnosti a návrh faktorov pre vylepšenie štrukturálnych vlastností. Porovnanie výsledkov získaných z DLTFS spektier nameraných na tandemových solárnych článkoch Tandem A (TMGa = 7 mil/min) a Tandem B (TMGa = 10 mil/min) umožnilo stanoviť rôzne poruchové stavy závislé nielen na kompozičné vlastnosti ale aj rastové podmienky. Vo vzorke Tandem B bola pozorovaná zmena vodivostného typu aktívnej vrstvy dolnej p-i-n InGaAsN štruktúry

a približne desať násobné zvýšenie koncentrácie porúch (Fig. 4.9). Na základe dosiahnutých výsledkov vzorka Tandem A je viac vyhovujúca pre vyššie účinnosti, avšak navrhnuté štrukturálne zmeny podľa In/N faktorov porúch (body II, III) by mali zabezpečiť solárny článok s vylepšenými vlastnosťami. Z hľadiska zvýšenia čistoty technologického procesu, by bolo žiaduce zavedenie vysoko kvalitného čistiaceho modulu kyslíka na elimináciu poruchových stavov súvisiacich s kyslíkom aktívnej vrstvy hornej GaAs p-i-n štruktúry.

Prínosy a výstupy dizertačnej práce poukázali na nevyhnutnosť skúmania distribúcie poruchových stavov metódou DLTFS vo viacvrstvových komplikovaných polovodičových štruktúrach. Aby bolo možné identifikovať rastovo ale aj kompozične závislé meta-stabilné a komplexné poruchové stavy je dôležité využiť rôzne experimentálne, ale aj analytické metódy, ktoré sú schopné prekonať limitujúce faktory a nedostatky presnosti štandardného DLTFS vyhodnotenia, a to hlavne pre špecifické prípady nedopovaných vrstiev. Vysoké požiadavky na kvalitu viacvrstvových štruktúr vytvárajú potrebu efektívneho vyhodnotenia elektricky aktívnych porúch na podporu čo najčistejšieho technologického procesu a možnosti širšieho zavedenia výsledných viacvrstvových polovodičových prvkov do praxe.

Hlavné prínosy dizertačnej práce sú zhrnuté v nasledujúcich bodoch:

- navrhnutie nového prístupu na vyhodnocovanie emisných a záchytných procesov spektroskopiou hlbokých energetických hladín vo viacvrstvových polovodičových štruktúrach s cieľom zvýšiť efektívnosť a spoľahlivosť DLTFS analýz,
  - návrh analytického riešenia na triedenie Arrheniových dát za účelom implementácie do štandardného DLTFS vyhodnotenia v prípade komplexného defektu s duálnym vodivostným typom typickým pre viacvrstvové štruktúry,
  - zvýšenie spoľahlivosti a reprodukovateľnosti vypočítaných parametrov identifikovaných hladín využitím vhodnej kombinácie modifikácií DLTFS metód a vyhodnocovacích techník (DLTFS s elektrickou a optickou excitáciou, Izotermálna spektroskopia hlbokých energetických hladín, optimalizácia vstupných meracích parametrov, priama a nepriama evaluácia...),
- verifikácia návrhu prístupu vyhodnocovania emisných a záchytných procesov metódou DLTFS vo vybraných polovodičových štruktúrach na báze GaAs (InGaAs, InGaAsN a GaAsN),
- implementácia a optimalizácia metodiky DLTFS s optickou excitáciou (MCDLTFS) na meracom pracovisku DL8000, rozšírenie možností identifikácie minoritných porúch v InGaAsN,
- získanie nových poznatkov o emisných a záchytných procesoch vo viacvrstvových polovodičových solárnych článkoch na báze InGaAsN spektroskopiou hlbokých energetických hladín s cieľom optimalizácie výrobného procesu,

- identifikovali sme v referenčných štruktúrach viac ako 20 porúch, z ktorých viaceré korešpondovali s poruchami v skúmanom tandemovom solárnom článku,
- na základe porovnania sme určili pravdepodobný charakter a pôvod porúch v intrinzických vrstvách,

• špecifikácia štrukturálnych vlastností a rastových podmienok pre dosiahnutie vyššej účinnosti viacvrstvových solárnych článkov,

- pri koncentrácii india 10,5 % v InGaAs štruktúrach dochádza k zníženiu koncentrácie a eliminácii bodových porúch,
- v GaAsN štruktúre s koncentráciou dusíka 1,60 % rastené pri 585 °C bola zistená eliminácia dislokácií, zníženie amplitúd GaAs/N komplexov v nameraných DLTFS spektrách,
- experimentálne a výpočtom bola potvrdená závislosť poruchového komplexu s duálnym stavom (EL2/$EL2^{2+}$) od rastových podmienok a od veľkosti koncentrácie india,
- bola vyhodnotená závislosť poruchových komplexov od koncentrácie dusíka a rastovej teploty,
- z analýzy distribúcie porúch v tandemových štruktúrach bol ako výhodnejší stanovený prietok gália zo zdroja v rámci rastového procesu 7 mil/min, s koncentráciou india okolo 9,8 % a dusíka 1 % pri rastovej teplote nižšej ako 585 °C.

References

[1] LANG, D. V. Deep-level transient spectroscopy: A new method to characterize traps in semiconductors. *Journal of Applied Physics*, 1974, 45.7: 3023-3032.

[2] WEISS, Sieghard. *Semiconductor Investigations with the DLTFS method*, 1991. PhD Thesis, Department of Physics Gesamthochschule Kassel University of the Country of Hessen.

[3] WEISS, S.; KASSING, R. Deep Level Transient Fourier Spectroscopy (DLTFS)—A technique for the analysis of deep level properties. *Solid-State Electronics*, 1988, 31.12: 1733-1742.

[4] PhysTech, Deep-Level Transient Spectroscopy System, Theory Manual, 2010, online at: http://www.phystech.de/products/dlts/dltstheo.htm

[5] PhysTech, Deep-Level Transient Spectroscopy System, Software Manual, 2010, online at: http://www.phystech.de/products/dlts/dlsoftw.htm

[6] PhysTech, Deep-Level Transient Spectroscopy System, Software Basics, 2010, online at: http://www.phystech.de/products/dlts/dlsoftw.htm

[7] MILLER, G. L.; LANG, D. V.; KIMERLING, L. C. Capacitance transient spectroscopy. *Annual Review of Materials Science*, 1977, 7.1: 377-448.

[8] FRIEDMAN, D. J., et al. 1-eV solar cells with GaInNAs active layer. *Journal of Crystal Growth*, 1998, 195.1: 409-415.

[9] JACKREL, David, et al. GaInNAsSb solar cells grown by molecular beam epitaxy. In: *2006 IEEE 4th World Conference on Photovoltaic Energy Conference*. IEEE, 2006. p. 783-786.

[10] SABNIS, Vijit; YUEN, Homan; WIEMER, Mike. High-efficiency multijunction solar cells employing dilute nitrides. In: *8th International conference on concentrating photovoltaic systems: CPV-8*. AIP Publishing, 2012. p. 14-19.

[11] YAMAGUCHI. M, et. al. Intermediate-Band Solar Cells Using In-Plane Ultrahigh Density InAs/GaAsSb Quantum Dot, Sheets In: *Photovoltaic Specialists Conference (PVSC)*, 2012.

[12] STUCHLÍKOVÁ, Ľ., et. al. DLTFS Study of p-i-n Diode Based on InGaAsN/GaAs Multi-Quantum Well Structure. In: *APCOM 2013. Applied Physics of Condensed Matter: Proceedings of the 19th International Conference*. 2013, 293-296.

[13] STUCHLÍKOVÁ, Ľ., et. al. The impact of indium and nitrogen concentration on the quality of the InGaAsN/GaAs heterostructures. In: *APCOM 2014. Applied Physics of Condensed Matter : Proceedings of the 20th International Conference*, 2014, 67-70.

[14] KÓSA, A.; STUCHLÍKOVÁ, Ľ. Analysis and processing of DLTFS spectrums, In: *Student scientific and professional activity 2011*, Proceedings of selected works. Bratislava, Slovak, 2011, 175-180.

[15] KÓSA, A.; RYBAR, J.; STUCHLÍKOVÁ, Ľ. Characterization of InGaAsN/GaAs heterostructures by DLTS method, In: *Student scientific and professional activity 2012*, Proceedings of selected works, Bratislava, 2012, 307-312.

[16] KÓSA, A., et al. Deep Level Investigation on AlGaN/GaN Structures by DLTS Method, In: *Student scientific and professional activity 2013,* Proceedings of selected works, Bratislava, 2013.

[17] Solar cells operational principles, University of Illinois - College engineering, online lecture, 2011, online at: https://wiki.engr.illinois.edu

[18] LUND, H., et al. Solar cells, Norwegian University of Science and Technology, Online course, 2008, online at: http://org.ntnu.no/solarcells/index.php

[19] DAWIDOWSKI, Wojciech, et al. AP-MOVPE technology and characterization of InGaAsN pin subcell for InGaAsN/GaAs tandem solar cell. *International Journal of Electronics and Telecommunications*, 2014, 60.2: 151-156.

[20] PARTIN, D. L., et al. Deep-level transient spectroscopy studies of Ni-and Zn-diffused vapor-phase-epitaxy n-GaAs. *Journal of Applied Physics*, 1979, 50.11: 6845-6859.

[21] BABIŃSKI, A.; BAJ, M.; HENNEL, A. M. The Pressure Dependence of Transition Metal-Related Levels in GaAs. *Acta Physica Polonica A*, 1991, 79.2-3: 323-327.

[22] RYAN, J. M., et al. The effects of temperature and oxygen concentration on the photoluminescence of epitaxial metalorganic vapor-phase epitaxy GaAs: O. *Journal of applied physics*, 1994, 76.2: 1175-1179.

[23] BREHME, S.; KRISPIN, P.; LUBYSHEV, D. I. Hole traps in indium-doped and indium-free GaAs grown by molecular beam epitaxy. *Semiconductor science and technology*, 1992, 7.4: 467.

[24] MAEDA, K., et al. STM nanospectroscopic studies of individual As-antisite defects in GaAs. *Materials Science in Semiconductor Processing*, 2003, 6.5: 253-256.

[25] NAZ, Nazir A., et al. Doubly charged state of EL2 defect in MOCVD-grown GaAs. *Physica B: Condensed Matter*, 2007, 401: 250-253.

[26] CHEN, K. M., et al. Deep levels in nitrogen-implanted n-type GaAs. *Journal of applied physics*, 1995, 78.6: 4261-4263.

[27] YAMAGUCHI, Masafumi, et al. Analysis of defects and impurities in new (In) GaAsN materials for concentrator multi-junction solar cells. In: *Photovoltaic Specialists Conference (PVSC), 2009 34th IEEE*. IEEE, 2009. p. 002332-002335.

[28] MADELUNG, Otfried (ed.). *Semiconductors: group IV elements and III-V compounds*. Springer Science & Business Media, 2012.

List of personal publications

ADC Scientific publications in foreign current content papers

ADC01 **KÓSA, Arpád** - STUCHLÍKOVÁ, Ľubica - HARMATHA, Ladislav - MIKOLÁŠEK, Miroslav - KOVÁČ, Jaroslav - SCIANA, Beata - DAWIDOWSKI, Wojciech - RADZIEWICZ, Damian - TLACZALA, Marek. Defect distribution in InGaAsN/GaAs multilayer solar cells. In *Solar Energy*. Vol. 132, (2016), s. 587-590. ISSN 0038-092X.

ADC02 STUCHLÍKOVÁ, Ľubica - HARMATHA, Ladislav - PETRUS, Miroslav - RYBÁR, Jakub - ŠEBOK, Ján - SCIANA, Beata - RADZIEWICZ, Damian - PUCICKI, Damian - TLACZALA, Marek - **KÓSA, Arpád** - BENKO, Peter - KOVÁČ, Jaroslav - JUHÁSZ, Peter. Electrical Characterization of the AIIIBV-N Heterostructures by Capacitance Methods. In *Applied Surface Science*. Vol. 269 (2013), s.175-179. ISSN 0169-4332.

ADC03 STUCHLÍKOVÁ, Ľubica - WEIS, Martin - JUHÁSZ, Peter - **KÓSA, Arpád** - HARMATHA, Ladislav - JAKABOVIČ, Ján. Defect Analysis of Pentacene Diode. In *Acta Physica Polonica A: International Conference on Defects Recognition, Imaging and Physics in Semiconductors, Warsaw, Poland, 15-19 Sept. 2013*. Vol. 125, iss. 4 (2014), s. 1038-1041. ISSN 0587-4246.

ADE Scientific publications in other foreign papers

ADE01 GOGOLA, Roman - **KÓSA, Arpád**. Electronic Control of Fuel Mixture Preparation and Injection in Internal Combustion Engines. In *American Journal of Mechanical Engineering [online]*. Vol. 2, no. 7 (2014), online, p. 231-238. ISSN 2328-4110.

ADE02 **KÓSA, Arpád** - RYBÁR, Jakub - STUCHLÍKOVÁ, Ľubica. Numerical Approach to the Problem of Digital DLTS Measurements Signal Analysis. In *ElectroScope [online]*. vol. 2013, n. 5 (2013), s.online [5] s. ISSN 1802-4564.

ADN Scientific papers in domestic journals registered in Web of Science or SCOPUS

ADN01 HARMATHA, Ladislav - MIKOLÁŠEK, Miroslav - STUCHLÍKOVÁ, Ľubica - **KÓSA, Arpád** - ŽIŠKA, Milan - HRUBČÍN, Ladislav - SKURATOV, Vladimir A.. Electrically active defects in solar cells based on amorphous silicon/crystalline silicon heterojunction after irradiation by heavy Xe ions. In *Journal of Electrical Engineering*. Vol. 66, No. 6 (2015), s. 323-328. ISSN 1335-3632. V databáze: WOS: 000368358400004.

ADN02 **KÓSA, Arpád** - STUCHLÍKOVÁ, Ľubica - DAWIDOVSKI, Wojciech - JAKUŠ, Juraj - SCIANA, Beata - RADZIEWICZ, Damian - PUCICKI, Damian - HARMATHA, Ladislav - KOVÁČ, Jaroslav - TLACZALA, Marek. DLTFS investigation of InGaAsN/GaAs tandem solar cell. In *Journal of Electrical Engineering*. Vol. 65, No. 5 (2014), s. 271-276. ISSN 1335-3632.

AFB Published invited contributions from domestic scientific conferences

AFB01 STUCHLÍKOVÁ, Ľubica - DONOVAL, Daniel - **KÓSA, Arpád** - BENKO, Peter - ONDRÁSOVÁ, Iveta - HRBÁČEK, Jiří. Through ICT and new pedagogical approaches to skills for key enabling technologies. In *ICETA 2015: 13th IEEE international conference on emerging eLearning technologies and applications. Starý Smokovec, Slovakia. November 26 - 27, 2015*. Danvers: IEEE, 2015, S. 349-355. ISBN 978-1-4673-8534-3. V databáze: IEEE.

AFB02 STUCHLÍKOVÁ, Ľubica - **KÓSA, Arpád**. Massive Open Online Courses - Challenges and Solutions in Engineering Education. In *ICETA 2013 [online]: 11th IEEE International Conference on Emerging eLearning Technologies and Applications. October 24-25, 2013 Stary Smokovec, Slovakia*. [S. l.]: IEEE, 2013, s.CD ROM, p. 359-360. ISBN 978-1-4799-2161-4.

AFC Published contributions from international scientific conferences

AFC01 STUCHLÍKOVÁ, Ľubica - **KÓSA, Arpád** - BENKO, Peter - MAREK, Juraj - CHVÁLA, Aleš - DONOVAL, Daniel. How to prepare university graduates as highly skilled key enabling technologies professionals?. In *EWME 2016. 11th European Workshop on Microelectronics Education: Proceedings; Southampton; Great Britain; May 11-13, 2016*. IEEE catalog number CFP1656Y-USB, ISBN 978-1-4673-8583-1.

AFC02 CHVÁLA, Aleš - MAREK, Juraj - **KÓSA, Arpád** - PRÍBITNÝ, Patrik - STUCHLÍKOVÁ, Ľubica - DONOVAL, Daniel. 2/3-D Device simulations as an effective tool in microelectronics education. In *EWME 2016. 11th European Workshop on Microelectronics Education: Proceedings; Southampton; Great Britain; May 11-13, 2016*. IEEE catalog number CFP1656Y-USB, ISBN 978-1-4673-8583-1.

AFC03 MAREK, Juraj - BENKO, Peter - CHVÁLA, Aleš - **KÓSA, Arpád** - PRÍBITNÝ, Patrik - STUCHLÍKOVÁ, Ľubica - DONOVAL, Daniel. The secret of successful student team project. In *EWME 2016. 11th European Workshop on Microelectronics Education: Proceedings; Southampton; Great Britain; May 11-13, 2016*. IEEE catalog number CFP1656Y-USB, ISBN 978-1-4673-8583-1.

AFC04 **KÓSA, Arpád** - STUCHLÍKOVÁ, Ľubica - BENKO, Peter. Blended learning in practice. In *Distance learning, simulation and communication 2015: International conference. Brno, Czech Republic. May 19-21, 2015*. Brno: University of Defence, 2015, S. 73-78. ISBN 978-80-7231-992-3, 978-80-7231-993-0 (CD-ROM).

AFC05 STUCHLÍKOVÁ, Ľubica - **KÓSA, Arpád** - BENKOVSKÁ, Jana. From a teaching machine to MOOC. In *Distance learning, simulation and communication 2015: International conference. Brno, Czech Republic. May 19-21, 2015*. Brno: University of Defence, 2015, CD-ROM, [6] s. ISBN 978-80-7231-992-3, 978-80-7231-993-0 (CD-ROM).

AFC06 STUCHLÍKOVÁ, Ľubica - **KÓSA, Arpád** - JAKUŠ, Juraj - ŠUŠOLIAK, Michal - DONOVAL, Daniel - HRBÁČEK, Jiří. Interactive animation as a motivation tool. In *EWME 2014. 10th European Workshop on Microelectronics Education: Proceedings; Tallinn; Estonia; May 14-16, 2014*. Danvers: IEEE, 2014, s. 116-119. ISBN 978-147994016-5.

AFC07 STUCHLÍKOVÁ, Ľubica - **KÓSA, Arpád** - BENKO, Peter - DONOVAL, Daniel. Massive Open Online Courses in Microelectronics education. In *EWME 2014. 10th European Workshop on Microelectronics Education: Proceedings; Tallinn; Estonia; May 14-16, 2014*. Danvers: IEEE, 2014, s. 31-36. ISBN 978-147994016-5.

AFC08 STUCHLÍKOVÁ, Ľubica - BENKOVSKÁ, Jana - NEMEC, Michal - **KÓSA, Arpád** - JUHÁSZ, Peter - JAKUŠ, Juraj - BENKO, Peter. E-Learning in Engineering Education. In *New technologies in education [online]: 6th international conference. Proceedings of abstracts. Brno, 15. 11. 2012*. Brno: University of Masaryk, 2013, s.CD-ROM, [5] s. ISBN 978-80-210-6402-7.

AFC09 STUCHLÍKOVÁ, Ľubica - BENKOVSKÁ, Jana - JAKUŠ, Juraj - HARMATHA, Ladislav - NEMEC, Michal - BENKO, Peter - **KÓSA, Arpád** - JUHÁSZ, Peter. DLTFS Study of Deep Traps in Schottky Diodes Based on AlGaN/GaN Heterostructure. In *EDS´13. Electronic Devices and Systems IMAPS CS International Conference 2013: Proceedings; Brno, Czech Republic, 26-27 June 2013*. Brno: Brno University of Technology, 2013, s.98-103. ISBN 978-80-214-4754-7.

AFD Published contributions from domestic scientific conferences

AFD01 **KÓSA, Arpád** - CSIBA, Michal - POHORELEC, Ondrej - STUCHLÍKOVÁ, Ľubica - HARMATHA, Ladislav - KOVÁČ, Jaroslav - SCIANA, Beata - DAWIDOWSKI, Wojciech - TLACZALA, Marek. Indium and nitrogen composition dependent InGaAsN electrical active defects. In *ADEPT 2016: 4th international conference on advances in electronic and photonic technologies. Tatranská Lomnica, High Tatras, Slovakia. June 20-23, 2016*. ISBN 978-80-554-1226-9.

AFD02 **KÓSA, Arpád** - ŽIŠKA, Milan - STUCHLÍKOVÁ, Ľubica - HARMATHA, Ladislav. Accuracy improvement of Deep-Level Transient Fourier Spectroscopy by analytical approaches. In *ADEPT 2016: 4th international conference on advances in electronic and photonic technologies. Tatranská Lomnica, High Tatras, Slovakia. June 20-23, 2016*. ISBN 978-80-554-1226-9.

AFD03 PETRUS, Miroslav - SZOBOLOVSKÝ, Robert - STUCHLÍKOVÁ, Ľubica - **KÓSA, Arpád** - HARMATHA, Ladislav - KOVÁČ, Jaroslav. Deep Level Transient Fourier Spectroscopy with optical excitation for ALGaN/GaN HEMT structure investigation. In *ADEPT 2016: 4th international conference on advances in electronic and photonic technologies. Tatranská Lomnica, High Tatras, Slovakia. June 20-23, 2016*. ISBN 978-80-554-1226-9.

AFD04 PETRUS, Miroslav - SZOBOLOVSKÝ, Robert - HARMATHA, Ladislav - **KÓSA, Arpád** - STUCHLÍKOVÁ, Ľubica - KOVÁČ, Jaroslav. Characterization of AlGaN/GaN hemt structures by deep level transient fourier spectroscopy with optical excitation. In *APCOM 2016: Proceedings of 22nd international conference on applied physics of condensed matter. Štrbské Pleso, Slovak Republic. June 22-24, 2016*. ISBN 978-80-227-4572-7.

AFD05 PETRUS, Miroslav - SZOBOLOVSKÝ, Robert- **KÓSA, Arpád.** Deep Level Transient Fourier spectroscopy with optical excitation – powerful tool for defect characterization in wide bandgap semiconductors. In *ELITECH 2016 : Proceedings of 18th conference of PhD. students. FEI STU Bratislava. June 8, 2016.* ISBN 978-80-227-4561-1.

AFD06 **KÓSA, Arpád** - STUCHLÍKOVÁ, Ľubica- HARMATHA, Ladislav - MIKOLÁŠEK, Miroslav - KOVÁČ, Jaroslav - SCIANA, Beata - DAWIDOWSKI, Wojciech - TLACZALA, Marek. Characterization of InGaAsN/GaAs multilayer solar cells. In *OZE 2016*, *6th International Scientific Conference on Renewable Energy Sources. Tatranské Matliare, Slovak Republic. May 31- June 2, 2016*. ISBN 978-80-89402-81-6.

AFD07 **KÓSA, Arpád** - MIKOLÁŠEK, Miroslav - STUCHLÍKOVÁ, Ľubica - ŽIŠKA, Milan - HARMATHA, Ladislav - KOVÁČ, Jaroslav Jr. - SCIANA, Beata - DAWIDOWSKI, Wojciech - TLACZALA, Marek. Electrophysical properties of GaAs concentrator solar cell. In *OZE 2016*, *6th International Scientific Conference on Renewable Energy Sources. Tatranské Matliare, Slovak Republic. May 31- June 2, 2016*. ISBN 978-80-89402-81-6.

AFD08 **KÓSA, Arpád** - STUCHLÍKOVÁ, Ľubica - HARMATHA, Ladislav - KOVÁČ, Jaroslav - SCIANA, Beata - DAWIDOWSKI, Wojciech - RADZIEWICZ, Damian - TLACZALA, Marek. Complex defect investigation by DLTFS method. In *ADEPT 2015: 3rd international conference on advances in electronic and photonic technologies. Štrbské Pleso, High Tatras, Slovakia. June 1-4, 2015*. 1. pub. Žilina: University of Žilina, 2015, S. 198-201. ISBN 978-80-554-1033-3.

AFD09 STUCHLÍKOVÁ, Ľubica - **KÓSA, Arpád** - HARMATHA, Ladislav - JUHÁSZ, Peter - KOVÁČ, Jaroslav - SCIANA, Beata - DAWIDOWSKI, Wojciech - PUCICKI, Damian - TLACZALA, Marek. The influence of growth parameters on Emission and capture processes in InGaAsN structures. In *ADEPT 2015: 3rd international conference on advances in electronic and photonic technologies. Štrbské Pleso, High Tatras, Slovakia. June 1-4, 2015*. 1. pub. Žilina: University of Žilina, 2015, S. 316-319. ISBN 978-80-554-1033-3.

AFD10 HARMATHA, Ladislav - ŽIŠKA, Milan - STUCHLÍKOVÁ, Ľubica - **KÓSA, Arpád** - MIKOLÁŠEK, Miroslav - HRUBČÍN, Ladislav - SKURATOV, Vladimir A.. Electrically active defects in the amorphous silicon/crystalline silicon heterojunction solar cell after heavy Xe ions irradiation. In *APCOM 2015: Proceedings of 21st international conference on applied physics of condensed matter. Štrbské Pleso, Slovak Republic. June 24-26, 2015*. 1. pub. Bratislava: STU Publishing, 2015, S. 93-96. ISBN 978-80-227-4373-0.

AFD11 HANIC, Michal - **KÓSA, Arpád** - KOVÁČOVÁ, Soňa - BENKO, Peter - HAGARA, Miroslav - KUBINEC, Peter - KOVÁČ, Jaroslav Jr. - FLOROVIČ, Martin - MARTON, Marián - VOJS, Marian - POHORELEC, Ondrej - HRBÁČEK, Jiří - STUCHLÍKOVÁ, Ľubica. Interactive forms of technical education support in primary and secondary schools. In *ICETA 2015: 13th IEEE international conference on emerging eLearning technologies and applications. Starý Smokovec, Slovakia. November 26 - 27, 2015*. Danvers: IEEE, 2015, S. 91-97. ISBN 978-1-4673-8534-3.

AFD12 KOVÁČ, Jaroslav Jr. - SZOBOLOVSKÝ, Robert - **KÓSA, Arpád** - STUCHLÍKOVÁ, Ľubica - KOVÁČ, Jaroslav. Transfer of knowledge from scientific research projects towards middle school scholars. In *ICETA 2015: 13th IEEE international conference on emerging eLearning technologies and applications. Starý Smokovec, Slovakia. November 26 - 27, 2015*. Danvers: IEEE, 2015, S. 201-206. ISBN 978-1-4673-8534-3.

AFD13 MATUŠKA, Michal - STUCHLÍKOVÁ, Ľubica - **KÓSA, Arpád**. Affects of AlGaN layer etching on emission processes of AlGaN/GaN HEMT structures. In *ŠVOČ 2014 [online]: Proceedings of selected works 2014, Bratislava, 29. April 2014*. 1. pub. Bratislava: FEI STU, 2014, CD-ROM, s. 193-198. ISBN 978-80-227-5154-5.

AFD14 **KÓSA, Arpád** - STUCHLÍKOVÁ, Ľubica - DAWIDOWSKI, Wojciech - JAKUŠ, Juraj - SCIANA, Beata - RADZIEWICZ, Damian - PUCICKI, Damian - HARMATHA, Ladislav - KOVÁČ, Jaroslav - TLACZALA, Marek. Investigation of emission and capture processes in InGaAsN/GaAs tandem solar cell structures. In *ADEPT 2014: 2nd International Conference on Advances in Electronic and Photonic Technologies; Tatranská Lomnica, Slovakia; June 1-4, 2014*. 1. pub. Žilina: University of Žilina, 2014, s. 79-82. ISBN 978-80-554-0881-1.

AFD15 JAKUŠ, Juraj - STUCHLÍKOVÁ, Ľubica - **KÓSA, Arpád** - HARMATHA, Ladislav - KOVÁČ, Jaroslav - SCIANA, Beata - DAWIDOWSKI, Wojciech - RADZIEWICZ, Damian - PUCICKI, Damian - TLACZALA, Marek. Investigation of the charge carrier emission from quantum wells in triple quantum well. In *ADEPT 2014: 2nd International Conference on Advances in Electronic and Photonic Technologies; Tatranská Lomnica, Slovakia; June 1-4, 2014*. 1. pub. Žilina: University of Žilina, 2014, s. 83-86. ISBN 978-80-554-0881-1.

AFD16 MATUŠKA, Michal - STUCHLÍKOVÁ, Ľubica - **KÓSA, Arpád** - BENKO, Peter - JAKUŠ, Juraj - ŠKRINIAROVÁ, Jaroslava - HARMATHA, Ladislav - KOVÁČ, Jaroslav. Influence of barrier AlGaN layer recess etching on emission and capture processes in AlGaN/GaN heterostructures. In *ADEPT 2014: 2nd International Conference on Advances in Electronic and Photonic Technologies; Tatranská Lomnica, Slovakia; June 1-4, 2014*. 1. pub. Žilina: University of Žilina, 2014, s. 184-187. ISBN 978-80-554-0881-1.

AFD17 HARMATHA, Ladislav - STUCHLÍKOVÁ, Ľubica - MIKOLÁŠEK, Miroslav - **KÓSA, Arpád**. DLTS study of inversion at the amorphous - crystalline silicon heterojunction passivated by different thicknesses of i-layer. In *ADEPT 2014: 2nd International Conference on Advances in Electronic and Photonic Technologies; Tatranská Lomnica, Slovakia; June 1-4, 2014*. 1. pub. Žilina: University of Žilina, 2014, s. 188-191. ISBN 978-80-554-0881-1.

AFD18 STUCHLÍKOVÁ, Ľubica - JAKUŠ, Juraj - **KÓSA, Arpád** - HARMATHA, Ladislav - KOVÁČ, Jaroslav - SCIANA, Beata - RADZIEWICZ, Damian - PUCICKI, Damian - DAWIDOVSKI, Wojciech - TLACZALA, Marek. The impact of indium and nitrogen concentration on the quality of the InGaAsN/GaAs heterostructures. In *APCOM 2014. Applied Physics of Condensed Matter: Proceedings of the 20th International Conference; Štrbské Pleso, Slovakia; 25-27 June 2014*. 1. pub. Bratislava: Publishing STU, 2014, s. 67-70. ISBN 978-80-227-4179-8.

AFD19 **KÓSA, Arpád** - STUCHLÍKOVÁ, Ľubica - BENKO, Peter - JAKUŠ, Juraj - HARMATHA, Ladislav - KOVÁČ, Jaroslav - SCIANA, Beata - DAWIDOWSKI, Wojciech - RADZIEWICZ, Damian - PUCICKI, Damian - TLACZALA, Marek. DLTS Study of Electrically Active Defects in Triple Quantum Well InGaAsN/GaAs Heterostructures. In *ASDAM 2014: The 10th International Conference on Advanced Semiconductor Devices and Microsystems. Smolenice Castle, Slovak Republic, October 20-22, 2014*. 1. pub. Danvers: IEEE, 2014, s. 193-196. ISBN 978-1-4799-5474-2.

AFD20 **KÓSA, Arpád** - BENKOVSKÁ, Jana - STUCHLÍKOVÁ, Ľubica - BÚC, Dalibor - DUBECKÝ, František - HARMATHA, Ladislav. Radiation Hardness of 4H-SiC Structures. In *ASDAM 2014: The 10th International Conference on Advanced Semiconductor Devices and Microsystems. Smolenice Castle, Slovak Republic, October 20-22, 2014*. 1. pub. Danvers: IEEE, 2014, s. 41-44. ISBN 978-1-4799-5474-2.

AFD21 STUCHLÍKOVÁ, Ľubica - **KÓSA, Arpád** - BENKOVSKÁ, Jana - BENKO, Peter - HARMATHA, Ladislav - KOVÁČ, Jaroslav. Defects in Schottky Diodes Based on AlGaN/GaN Heterostructures. In *ASDAM 2014: The 10th International Conference on Advanced Semiconductor Devices and Microsystems. Smolenice Castle, Slovak Republic, October 20-22, 2014*. 1. pub. Danvers: IEEE, 2014, s. 189-192. ISBN 978-1-4799-5474-2.

AFD22 **KÓSA, Arpád** - JUHÁSZ, Peter - BENKOVSKÁ, Jana - STUCHLÍKOVÁ, Ľubica. Deep Level Investigation on AlGaN/GaN Structures by DLTS Method. In *ŠVOČ 2013 [online]: Proceedings of selected works, Bratislava, 23. April 2013*. 1. pub. Bratislava: FEI STU, 2013, s.CD ROM, s. 319-324. ISBN 978-80-227-3909-2.

AFD23 **KÓSA, Arpád** - BENKOVSKÁ, Jana - STUCHLÍKOVÁ, Ľubica. Investigation of Defects in 4H-SiC Detectors Before and after Neutron Radiation by DLTFS Method. In *ŠVOČ 2013 [online]: Proceedings of selected works, Bratislava, 23. April 2013*. 1. pub. Bratislava: FEI STU, 2013, s.CD ROM, s. 297-302. ISBN 978-80-227-3909-2.

AFD24 BENKOVSKÁ, Jana - **KÓSA, Arpád** - STUCHLÍKOVÁ, Ľubica - DUBECKÝ, František - HARMATHA, Ladislav. DLTS Study of Neutron Bombarded 4H-SiC Detector. In *ADEPT 2013: 1st International Conference on Advances in Electronic and Photonic Technologies. Nový Smokovec, High Tatras, Slovakia, June 2-5, 2013*. 1. pub. Žilina: University of Žilina, 2013, s.274-277. ISBN 978-80-554-0689-3.

AFD25 RYBÁR, Jakub - **KÓSA, Arpád** - STUCHLÍKOVÁ, Ľubica. Deep Level Parameters Calculation Using Fitting Evaluation Analysis in Digital DLTS Measurements. In *ADEPT 2013: 1st International Conference on Advances in Electronic and Photonic Technologies. Nový Smokovec, High Tatras, Slovakia, June 2-5, 2013*. 1. pub. Žilina: University of Žilina, 2013, s.262-265. ISBN 978-80-554-0689-3.

AFD26 **KÓSA, Arpád** - RYBÁR, Jakub - STUCHLÍKOVÁ, Ľubica. Characterization of InGaAsN/GaAs heterostructures by DLTS method. In *ŠVOČ 2012 [online]: Proceedings of selected works, Bratislava, 25. April 2012*. Bratislava: FEI STU, 2012, s.CD-ROM, s. 307-312. ISBN 978-80-227-3697-8.

AFD27 STUCHLÍKOVÁ, Ľubica - RYBÁR, Jakub - **KÓSA, Arpád** - PETRUS, Miroslav - HARMATHA, Ladislav - ŚCIANA, Beata - PUCICKI, Damian - TLACZALA, Marek - RADZIEWICZ, Damian. Investigation of InGaAsN/GaAs Heterostructures by Capacitance Methods. In *APCOM 2012. Applied Physics of Condensed Matter: Proceedings of the 18th*

International Conference. Štrbské Pleso, Slovak Republic, June 20-22, 2012. 1. pub. Bratislava: STU in Bratislava, 2012, s.357-360. ISBN 978-80-227-3720-3.

AFD28 **KÓSA, Arpád** - STUCHLÍKOVÁ, Ľubica. Analysis and processing of DLTFS spectra. In *ŠVOČ 2011: Student scientific work. Proceedings of selected works. Bratislava, Slovak Republic, 4.5.2011*. Bratislava: STU in Bratislava FEI, 2011, s.175-180. ISBN 978-80-227-3508-7.

AFD29 RYBÁR, Jakub - **KÓSA, Arpád** - DUBECKÝ, František - PETRUS, Miroslav - STUCHLÍKOVÁ, Ľubica - BENKOVSKÁ, Jana - HARMATHA, Ladislav - HRKÚT, Pavol - BAČEK, D. - KOVÁČ, Peter. DLTS Study of Neutron Bombarded Silicon Detector. In *APCOM 2011. Applied Physics of Condensed Matter: Proceedings of the 17th International Conference. Nový Smokovec, Slovak Republic, June 22-24, 2011*. Žilina: University of Žilina, 2011, s.192-195. ISBN 978-80-554-0386-1.

BEF Scientific works in domestic proceedings

BEF01 BENKO, Peter - **KÓSA, Arpád** - STUCHLÍKOVÁ, Ľubica - SOLČIANSKY, Michal - FLOROVIČ, Martin - KOVÁČ, Jaroslav. Electrical characterization of AlGaN/GaN Schottky heterostructure. In *WOCSDICE 2015: 39th workshop on compound semiconductor devices and integrated circuits. Smolenice, Slovakia. 8-10 June, 2015*. Bratislava: UEF FEI STU, 2015, S. 89-90.

BEF02 **KÓSA, Arpád** - STUCHLÍKOVÁ, Ľubica - POHORELEC, Ondrej - HARMATHA, Ladislav - KOVÁČ, Jaroslav - SCIANA, Beata - DAWIDOWSKI, Wojciech - RADZIEWICZ, Damian - PUCICKI, Damian - TLACZALA, Marek. Investigation of emission and capture processes in triple quantum well InGaAsN/GaAs heterostructures. In *WOCSDICE 2015: 39th workshop on compound semiconductor devices and integrated circuits. Smolenice, Slovakia. 8-10 June, 2015*. Bratislava: UEF FEI STU, 2015, S. 9-10.

BEF03 STUCHLÍKOVÁ, Ľubica - BENKOVSKÁ, Jana - **KÓSA, Arpád** - PETRUS, Miroslav - HARMATHA, Ladislav - ŽIŠKA, Milan - KOVÁČ, Jaroslav. DLTS study of deep traps in InAlN/GaN heterostructures. In *WOCSDICE 2015: 39th workshop on compound semiconductor devices and integrated circuits. Smolenice, Slovakia. 8-10 June, 2015*. Bratislava: UEF FEI STU, 2015, S. 101-102.

BFA Abstracts of scientific works from international conferences

BFA01 **KÓSA, Arpád** - STUCHLÍKOVÁ, Ľubica - HARMATHA, Ladislav - KOVÁČ, Jaroslav - SCIANA, Beata - DAWIDOWSKI, Wojciech - RADZIEWICZ, Damian - TLACZALA, Marek. Defect distribution in InGaAsN/GaAs tandem solar cells. In *ICDS 2015 [online]: 28th International conference on defects in semiconductors. Espoo, Finland. July 27 – 31, 2015*. Espoo: Aalto University, 2015, USB, [2] s.

GII Other publications

GII01 STUCHLÍKOVÁ, Ľubica - WEIS, Martin - JUHÁSZ, Peter - **KÓSA, Arpád** - HARMATHA, Ladislav - JAKABOVIČ, Ján. Deep Level Transient Spectroscopy Study of Pentacene Diode. In *15 th International Conference on Defects Recognition, Imaging and Physics in Semiconductors: Warsaw, Poland, September 15-19, 2013*, 2013, s.80-81.

Citations: 4 citations of 2 publications from these 2 in Web of Science, 3 in Scopus and 2 in reviewed journals