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ELECTROPHYSICAL PROPERTIES OF GaAs P–I–N STRUCTURES FOR CONCENTRATOR SOLAR CELL APPLICATIONS

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This paper is dedicated to electro-physical characterisation of a GaAs p-i-n structure grown for solar cell applications, which was carried out by light and dark current-voltage (I–V) and Deep Level Transient Fourier Spectroscopy (DLTFS) methods. The conversion efficiency and open-circuit voltage were determined from I–V measurement at 1 and 20× sun light concentrations. Three electron like defects TA_{n1}, TA_{n2}, TD_n and one hole like defect TBp obtained by DLTFS measurements were confirmed. The origin of these defect states was stated as native GaAs impurities.

K e y w o r d s: solar cell, GaAs concentrator solar cell, I–V measurement, DLTFS, defects

1 INTRODUCTION

Solar energy is one of the many energy forms harnessed by humanity in order to produce electricity in an environmental friendly and efficient way. Among the various solar cell technologies [1–3], GaAs concentrator solar cells have the potential to achieve higher conversion efficiencies and are promising for space and terrestrial applications [4, 5]. These solar cell structures are optimized for specific applications — such as satellites, photovoltaic concentrator systems and laser power beaming. The record efficiency 28.8 %, GaAs solar cell had achieved in 2011 [5]. Due to their good properties such as high quantum efficiency and good irradiation tolerance, they are the ideal choices for space applications [7, 8]. In comparison with Si space solar cells, the radiation reliability of GaAs solar cells is over 20 % higher and the efficiency of energy conversion is 20–25 % and above. The lifetime in orbits of GaAs solar cells is 40–60 % over the one of Si solar cells [9, 10].

Key factor of development is to understand recombination dynamics in GaAs solar cell structures. Valuable feedback for the technology process is provided by the Deep Level Transient Fourier Spectroscopy (DLTFS) method, which represents a unique technique of electrically active defect and recombination centre investigation.

The aim of this paper is to introduce and discuss results of DLTFS defect investigations of the GaAs concentrator solar cell grown by Atmospheric Pressure Metal Organic Vapour Phase Epitaxy (AP-MOVPE).

In addition, temperature dependent dark and light current voltage characteristics at two light concentrations were carried out to gain further insight on the structure operation and performance.

2 EXPERIMENTAL

2.1 Device processing

The investigated p GaAs:Zn/i GaAs/n GaAs: Si solar cell was grown by AP-MOVPE on a n-type GaAs (Si doped) substrate at the Wroclaw University of Science and Technology. The GaAs p-i-n junction was sandwiched between a Si doped GaAs substrate with $n = 1 \div 2 \times 10^{18}\text{cm}^{-3}$ and a 50 nm thick Zn doped $\text{p}^+ = 1 \div 3 \times 10^{19}\text{cm}^{-3}$ cap layer. GaAs p-i-n with thicknesses of 200/800/200 nm was connected with the substrate by a n type GaAs 200 nm thick buffer layer with $n = 2 \div 3 \times 10^{18}\text{cm}^{-3}$.

Doping concentrations of the p-i-n region was as follows: p layer $p = 2 \div 3 \times 10^{18}\text{cm}^{-3}$ and n layer as a gradient $n = 2 \div 3 \times 10^{18}\text{cm}^{-3}$ to $n = 1 \div 2 \times 10^{17}\text{cm}^{-3}$, Fig. 1.

Type	Thickness	n, p (cm^{-3})
p GaAs cap:Zn	~ 50 nm	$1{\div}3{\times}10^{18}$
p GaAS:Zn	~ 200 nm	$2{\div}3{\times}10^{18}$
i GaAS	~ 200 nm	-
n GaAs:Si	~ 800 nm	gradient $1{\div}2{\times}10^{17}$ to $2{\div}3{\times}10^{18}$
n+ GaAs:Si buffer	~ 200 nm	$2{\div}3{\times}10^{18}$
n GaAs:Si substrate	~ 350 nm	$2{\div}3{\times}10^{18}$

Fig. 1. Material compositions and layer properties of the investigated p-i-n sample

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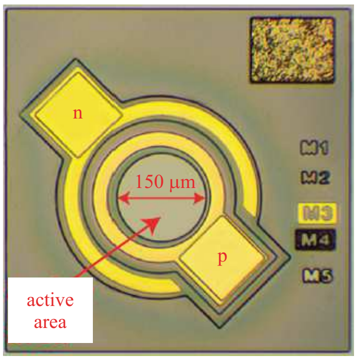

Fig. 2. Image of the fabricated metallization of test solar cell structure — typical detector configuration with the circle shape active area

The metallization was prepared as a typical detector ring structure with an inner diameter 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, Fig. 2.

2.2 Experiment

Fabricated GaAs p-i-n solar structure was investigated by current-voltage (I–V) and DLTFS measurements [11]. Light and dark I–V measurements were carried out using a source-meter unit Keithley 2612A in temperature range from 100 K to 400 K. Solar simulator 16S-002-300 with spectrum AM1.5 was used as a source of illumination. The nitrogen cryostat system with quartz glass window was used for temperature control during the measurements. The optical loses due to the glass window are around 10 %. The light I–V measurements were carried out under 1× sunlight intensity (100 mW/cm^2) and under 20× sunlight intensity (2000 mW/cm^2) achieved by focusing the light with Fresnel lens.

Electrically active defects (deep energy levels) were investigated by the DLTFS BIORAD DL8000 measuring system in temperature range from 85 K to 550 K. Measured capacitance transients were evaluated by Fourier transform analysis. This method is based on measurements of capacitance differences caused by excited emission and capture processes of deep energy levels in semiconductor materials [12]. The obtained DLTFS spectra were evaluated using the Fourier transform analysis by "Direct auto Arrhenius single level evaluation". The values of activation energies ΔE_T and cross sections σ_T of deep energy levels were determined from an Arrhenius diagram using known equations [11, 12].

3 RESULTS AND DISCUSSION

Figures 3(a)–(c) show temperature dependent I–V characteristics of the investigated GaAs p-i-n structure measured in the dark and under sun simulator with 1× sun and 20× sunlight concentrations.

Light I–V measurements allowed us to determine basic output photovoltaic parameters: open circuit voltage $V_{\rm OC}$, short circuit current density $J_{\rm SC}$, fill factor FF, and conversion efficiency η_f, which are summarized for $T = 300$ K in Tab. 1. Temperature dependent output parameters for 1× sun and 20× sun light concentration are shown in Figs. 4(a)–(d).

Table 1. Solar cell output parameters extracted from light I–V characteristics of the GaAs p-i-n structure at $T = 300$ K

$V_{\rm oc}$ (V)	$J_{\rm sc}$ (A/cm^2)	$V_{\max}$ (V)	$J_{\max}$ (A/cm^2)	FF (%)	$\eta_{\rm f}$ (%)	Intensity
0.74	0.02	0.62	0.015	74.7	9.09	1 × sun
0.87	0.35	0.73	0.323	76.6	11.70	20 × sun

Figure 4(a) shows a negligible change of $J_{\rm SC}$ with T for both 1× sun and 20× sun light concentrations. More significant temperature dependencies are observed for $V_{\rm OC}$, FF which are consequently reflected also in $\eta_{\rm f}$, Fig. 4(b)–(d). The decrease of the $V_{\rm OC}$ upon the temperature has a physical origin and it can be explained by considering the following equation

$$V_{\rm OC} = \frac{AkT}{q} \ln \frac{J_{\rm SC}}{J_{\rm Sat}}\,, \tag{1}$$

where A is the ideality factor, $J_{\rm Sat}$ is the saturation current density and $J_{\rm SC}$ is the short-circuit current density. $J_{\rm Sat}$ is strongly related with intrinsic carrier concentration of the GaAs, which increases upon the increase of temperature resulting into the increase of $J_{\rm Sat}$. While the $V_{\rm OC}$ is reciprocally proportional to the saturation current, the $V_{\rm OC}$ increases with the decrease of T, Fig. 4(b).

Both $V_{\rm OC}$ and FF have downward trends with the T and determine the temperature behaviour of $\eta_{\rm f}$. The temperature dependent $\eta_{\rm f}$ allowed us to determine temperature coefficients of efficiency $\eta_{\rm TKR}$ (in the linear temperature region 200–400 K) with values of −0.37 and −0.31 %/ °C for light concentrations 1× sun and 20× sun, respectively. Such a coefficient describes the relative decrease of the efficiency with the increase of T.

Considering (1) it is obvious that high $J_{\rm sat}$ has a detrimental effect on the $V_{\rm OC}$ and thus on the output photovoltaic performance. High quality materials with low concentration of defects are required to keep the $J_{\rm sat}$ low. The investigation of electrically active recombination centres is therefore crucial for optimization of solar cells. Using the DLTFS method, four deep energy levels were detected (Figs. 5, 6) in the investigated structure. Three of them, labelled by us as $\rm TA_{n1,2}$, and $\rm TD_n$, are linked to majority traps and one labelled as $\rm TB_p$ to a minority trap. We have produced several DLTFS spectra sets by experiments with different initial measurement conditions filling (U_P) and reverse (U_R) voltages, capacitance transient period width - time period (T_w) and filling pulse length (t_P). Typical DLTFS spectra measured on the GaAs p-i-n solar structure are displayed in Fig. 5.

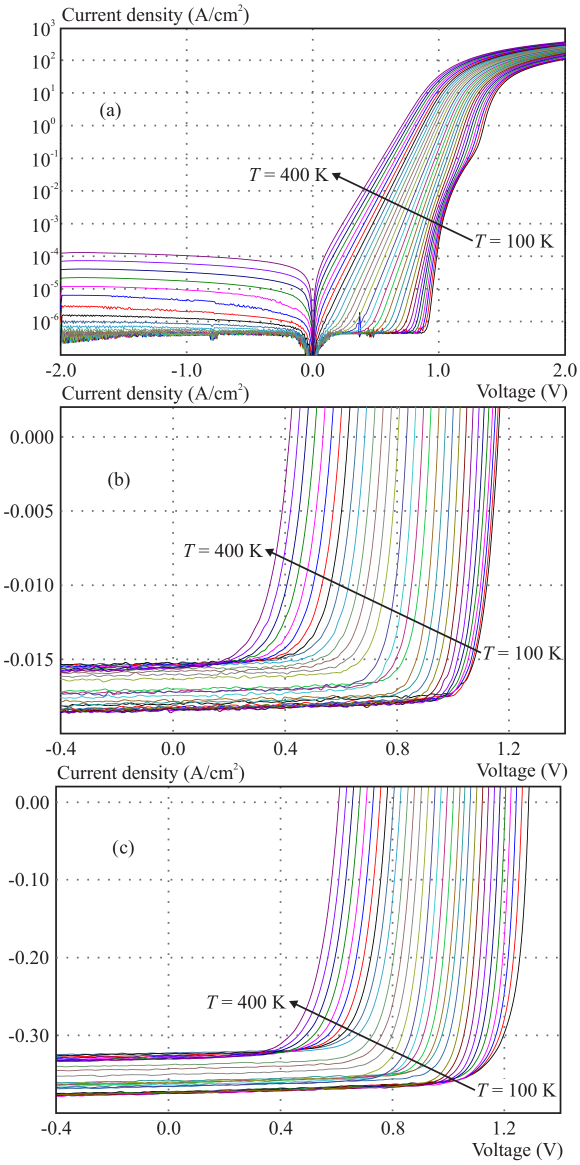

Fig. 3. Temperature dependent current-voltage characteristics of the GaAs p-i-n structure measured in the dark (a) — and under solar simulator with (b) — 1× sun, and (c) — 20× sun concentrated light

Table 2. Calculated and compared deep energy level parameters of TA_{n1}, TA_{n2} and TB_p before and after data selection with various evaluation procedures

Trap	ΔE_T (eV)	$\sigma_T(\text{cm}^2)$	ΔE_{Tref} (eV)	$\sigma_{Tref}(\text{cm}^2)$	Origin
TA_{n1}	0.486	5.11×10^{-16}	0.48 eV EC2	3.8×10^{-16}	Ni [12]
TA_{n2}	0.400	1.57×10^{-17}	0.37 eV EL16	4.0×10^{-18}	[13]
TB_p	0.691	2.34×10^{-16}	0.63 eV HC1	4.0×10^{-17}	Zn/Ni [12]
TD_n	0.747	2.95×10^{-15}	0.73 eV EX2	1.3×10^{-14}	As_{Ga} [15]

The reverse and filling voltage variation allowed us to estimate the type and layer origin of these specific responses. Since in the case of a p-i-n structure the depletion region is located at the i-layer, the active layer of the solar cell, the presence of these defect states can greatly affect the efficiency.

Figure 4(b) shows higher V_{OC} for 20× sun compared to 1× sun light concentration. This phenomenon could be explained by considering (1). While the J_{Sat} is not dependent on light, the V_{OC} increases with the increase of J_{SC} at the higher light concentration.

The *FF* exhibits initial increase upon the decrease of T, which is followed by saturation in the temperature region of 200-100 K. The *FF* is a very complex parameter, which describes the current transport, recombination of carriers and contact properties in the structure.

At slightly forward biased conditions hole injection to the i layer is ensured thereby the DLTFS curve should include also results from minority carrier traps. Higher filling voltages should increase the injection thereby amplifying initial or reveal additional minority traps. This procedure is visible in Fig. 5(a), where in the first case at higher U_P value (0.3 V) the minority trap TB_p indicated increasing tendencies, while in the second at a very low value of reverse voltage $U_R = -2$ V the minority response disappeared revealing an additional majority trap TD_n, Fig. 5(b). Figure 6 shows the obtained Arrhenius curves where $TA_{n1,2}$ and TB_p were calculated at U_R = -0.1 V U_P = 0.3 V T_W = 0.3, 1, 3 ms and t_P = 0.3 ms, while TD_n was identified at $U_R = -2$ V, U_P = 0.05 V, T_W = 2.5 s and t_P = 0.8 ms. At $U_R = -0.1$ V, U_P = 0.3 V not only the peak amplitude of TB_p but also $TA_{n1,2}$ was increased. This fact indicated that one of the $TA_{n1,2}$ complex (EC2 or EL16) has a more significant concentration at the i/n interface. Also higher hole injection (U_P = 0.3 V, increased peak of TB_p) made possible to more precisely detect the TB_p level. TD_n was identified as EL2 (EX2) a frequently described and discussed arsenic antisite defect of GaAs, by lowering the reverse voltage to -2 V.

At these measurement parameters of the $TA_{n1,2}$ level was also evidently present, but unfortunately it was no separable by the deconvolution method, Fig. 5(b). Only the presence of TA_{n1} was confirmed more strongly suggesting that TA_{n2} is located near the i/n interface.

Table 2 lists the evaluated deep energy levels with their parameters (activation energy ΔE_T, capture cross-section σ_T) and the probable origin of the deep energy level. All energy levels that were evaluated were identified as well-known material defects of GaAs. Electron energy level TA_{n1} was identified as EC2 (0.48 eV, $3.8 \times 10^{-16}\text{cm}^2$) and was originated from a Ni_{Ga} complex [13]. It is highly probable that this defect state was introduced by the growth process. The second electron energy level TA_{n2} was identified as EL16 (0.375 eV, $4.0 \times 10^{-18}\text{cm}^2$) [14]. Not many reports were published about this defect state, therefore the possible origin of a complex defect state between EC2 and EL16 is thereby not clearly understood. In our interpretation the $TA_{n,2}$ level (EL16) could be introduced by the GaAsi-n interface of the GaAs p-i-n sample, which together with the

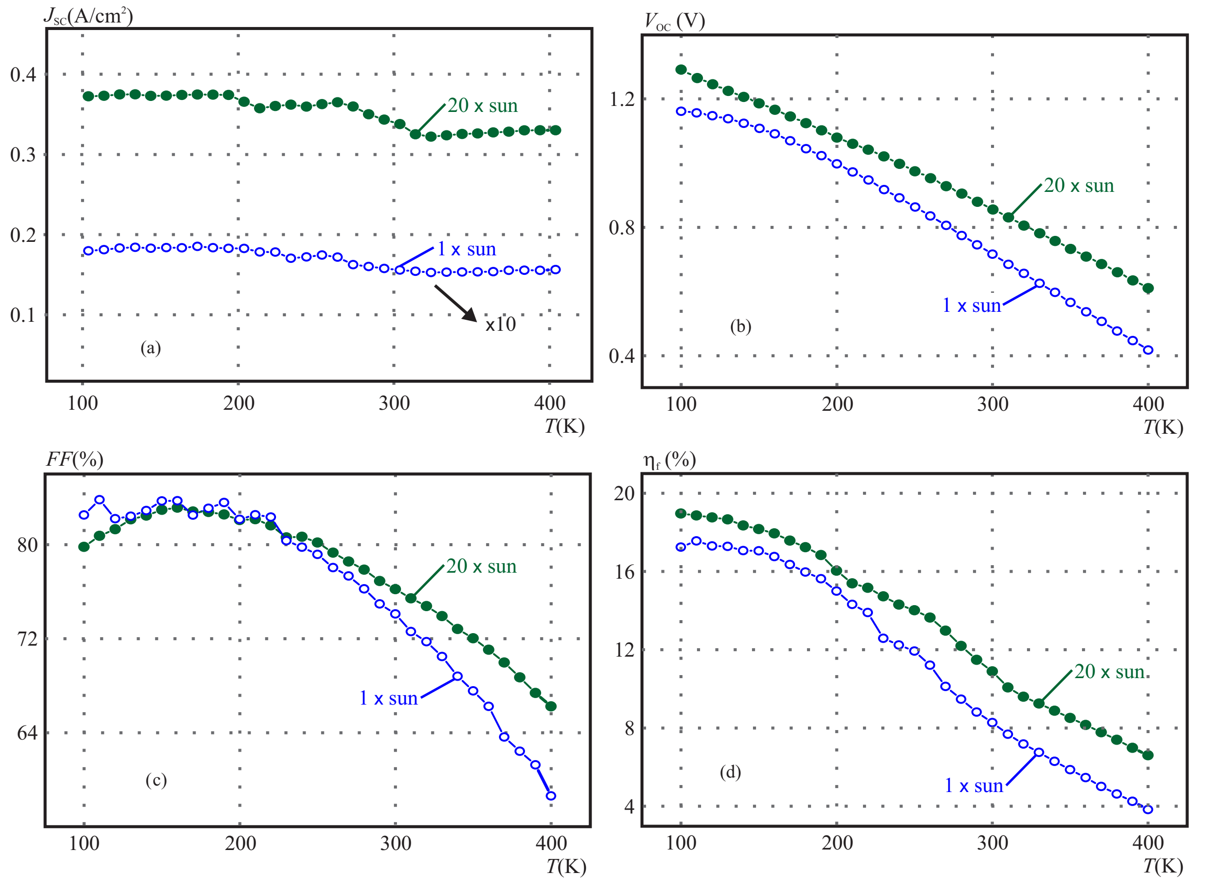

Fig. 4. Extracted (a) — J_{SC}, (b) — V_{OC}, (c) — FF, and (d) — η_f as a function of temperature at 1× sun and 20× sun light concentration

EC2 response produces a complex DLTFS peak in the spectrum.

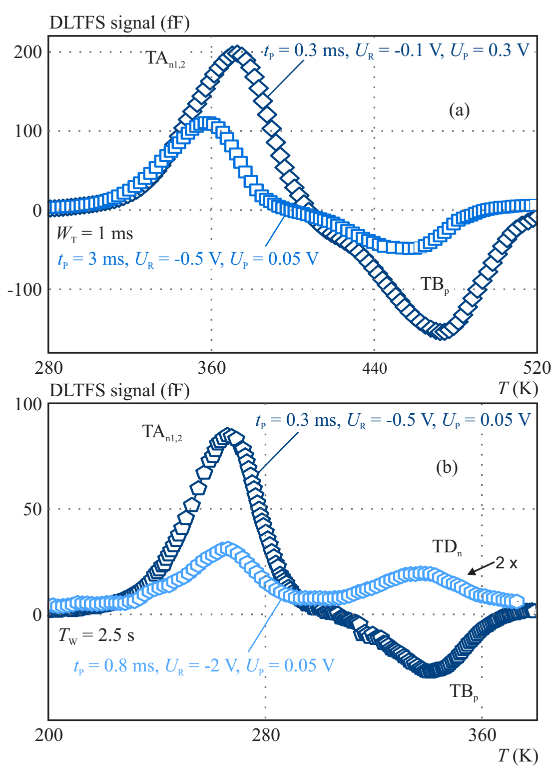

Fig. 5. DLTFS measurements of the GaAs p-i-n sample at different reverse (U_R) and filling voltage (U_P) conditions

Our investigation showed, that the deep energy level TB_p highly corresponds with a single p type deep energy level HC1 (0.63 eV, 4.0×10^{-17}cm^2). According to the literature HC1 was observed in VPE samples diffused with Zn (Ni, Zn), which were used to study hole traps [13]. Zn creates a shallow p type donor level at 0.024 eV so it was ruled out.

Definite origin of HC1 was not stated however a minority character trap caused by majority carrier capture (electron) was described. A further example of this energy state showed a hole trap population including the energy 0.63 eV where oxygen was also discussed possibly accommodating certain charge states [15]. Presence of oxygen in MOVPE grown samples are frequently observed, therefore we can not entirely rule out this consideration. The electron trap TD_n probably corresponds with defects EX2 or EL2. EL2 is a mid-gap defect level of GaAs, more precisely an arsenic antisite defect. EX2 is a formation of EL2 identified in annealed GaAs samples by rapid thermal annealing process [16].

It was suggested that EX2 is a complex of two vacancies and an antisite without interstitial arsenic atoms (V_{As}, V_{Ga}, As_{Ga}). To ensure a more pure growth process further investigations are needed in connection with all possible relations of the observed defects and the growth technology.

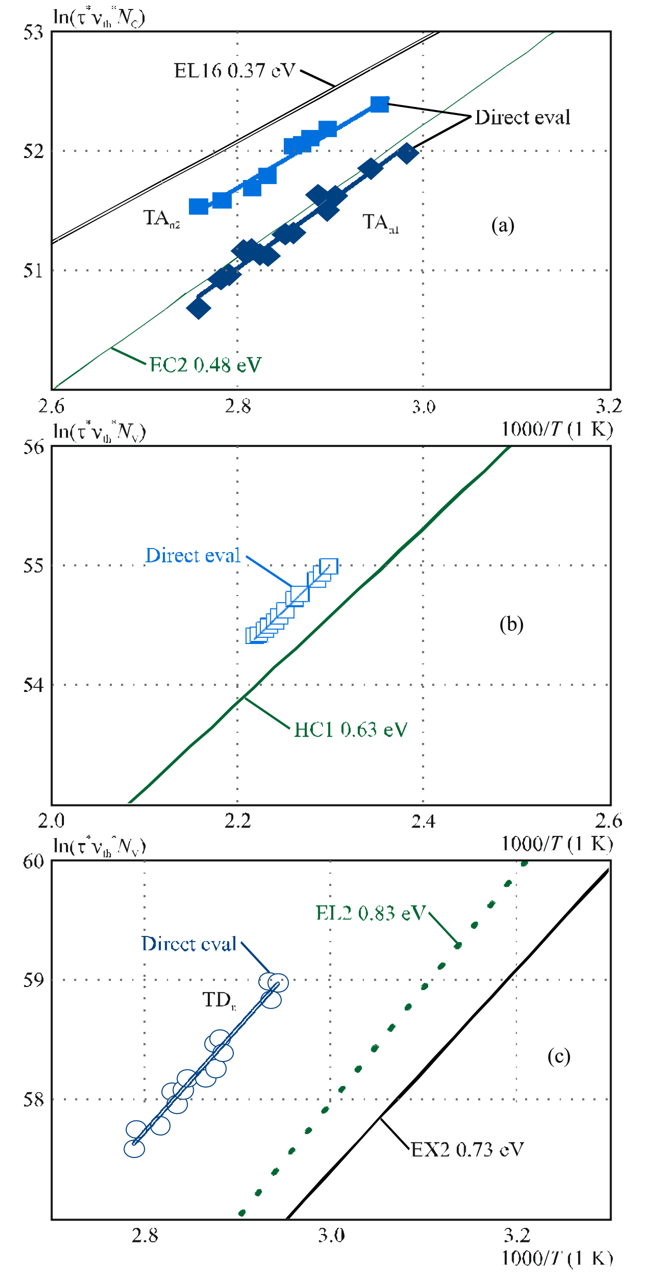

Fig. 6. Arrhenius curves of the GaAs p-i-n sample after DLTFS parameter variations. Arrhenius curves (a) – of the complex defect state $TA_{n1,2}$ with defined reference data (EC2+EL16), (b) – of the defect state TB_p with reference data HC1, (c) – of the defect state TD_n with reference data EL2 and EX2

4 CONCLUSION

This paper summarises the results of temperature dependent light and dark *I–V* measurements and DLTFS study of a GaAs p-i-n solar cell structure. Comparing output performance at different light conditions, the higher conversion efficiency as well as better temperature coefficient of efficiency measured at 20× sun light intensity indicated a good applicability of developed structures for concentrator applications. Four electrically active defects were confirmed by means of DLTFS. These were identified with high probability in connection with the growth process as well-known material defects of GaAs originated from a Ni_{Ga} complex, Oxygen and the arsenic antisite defect EL2. To achieve an increased efficiency, improved GaAs quality and the optimization of the solar cell design decreased concentration of recombination centres are needed.

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