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The influence of high temperatures on radiation damage of $GaInP_2$/GaAs/Ge triple junction cells

Christian Brandt, Carsten Baur, Antonio Caon, Peter Müller-Buschbaum, Claus Zimmermann, and Thomas Andreev

Abstract— We report on the isothermal annealing behavior of 1 MeV electron irradiated component cells of a $GaInP_2$/GaAs/Ge triple-junction solar cell. Based on in-situ measured short circuit currents and open circuit voltages the relative defect concentration as a function of annealing time and temperature are derived. The time dependent behavior suggests the presence of (partly overlapping) exponential decays in defect concentration which in turn suggest the annealing of more than one defect having different activation energies.

***Index Terms*—Solar cells, space missions, particle irradiation**

I. Introduction

Nowadays, high temperature space missions close to the sun and its inner planetary system are of special interest. There, temperatures on the solar array can reach 200 °C even under off-pointed conditions [1,2]. With respect to particle irradiation the solar arrays are typically exposed to equivalent 1 MeV electron doses comparable to those of standard geostationary (GEO) missions (in the order of $1{\cdot}10^{15}/cm^2$). Thus, the expected degradation due to particle irradiation for lattice matched $GaInP_2$/GaAs/Ge triple junction cells is about 15%. However, in contrast to GEO missions the high temperatures during near sun missions can cause non-negligible annealing of the irradiation induced defects studied for n-Ge in Ref. [3] for GaAs in Ref. [4-6], for n-GaAs in Ref. [7-8], for GaP in Ref. [9], for p-InGaP in Ref [10], for np-InGaP diodes and solar cells in Ref. [11-13].

The objective of this study is to investigate and quantify the possible annealing effect for a $GaInP_2$/GaAs/Ge triple junction cell by a model which further allows for using the results also for life time predictions.

For this purpose, component cells of the $GaInP_2$/GaAs/Ge triple junction cell have been irradiated and isothermally stepwise annealed. During the annealing process, the electrical performance of these cells has been monitored by periodically recording their I/V-curves.

Other groups have performed isochronal annealing in combination with defect level transient spectroscopy (DLTS) measurements [4-7,9,10,12,14] and also sometimes post characterization at lower temperatures. The combination of these methods is directly linked to the activation energies, but with the disadvantage that more than one cell is needed, intermediate characterization is difficult and the experimental setups are complicated. Isothermal annealing studies found in literature also rely on post characterization at room temperature and are most of the time linked to isochronal studies [4,8]. The method of isothermal annealing applied in this study, however, not only allowed for in-situ measurements but also offered the possibility to characterize the solar cells with different methods up to the annealing temperature after each annealing step.

II. Experimental

The solar cells investigated in this study are 40.00 mm x 37.72 mm $GaInP_2$/GaAs/Ge triple junction cells and related top- and middle- component cells. Component cells are understood as single-junction cells having the same electrical and optical properties as the corresponding sub cell in the triple junction cell stack [15,16]. Details on the structure of the triple junction solar cell studied are given in reference [17]. All cells have a 100 µm thick CMX cover glass comprising a MgF_2 antireflection coating, an ultraviolet cut-off at 350 nm and a density of 2.605g/cm³ [18].

The cells were characterized at room temperature before and after irradiation with $1{\cdot}10^{15}/cm^2$ 1 MeV electrons. Subsequent isothermal annealing has been performed in air under 1AM0 conditions using a three source steady state solar simulator keeping the cells in open circuit conditions. During annealing the cell performance was monitored by periodically measuring the I/V-characteristics. Annealing has been performed until no further changes of the electrical cell parameters were found in an adequate time. After each isothermal temperature step (24 h at 50°C, 24 h at 100°C, 24 h at 150°C, 390 h at 180°C, and 596 h at 230°C) a characterization has been performed by measuring the spectral response, dark- and light- (1 AM0 and 8 AM0) I/V-measurements between room temperature up to the current annealing step temperature and finally angle

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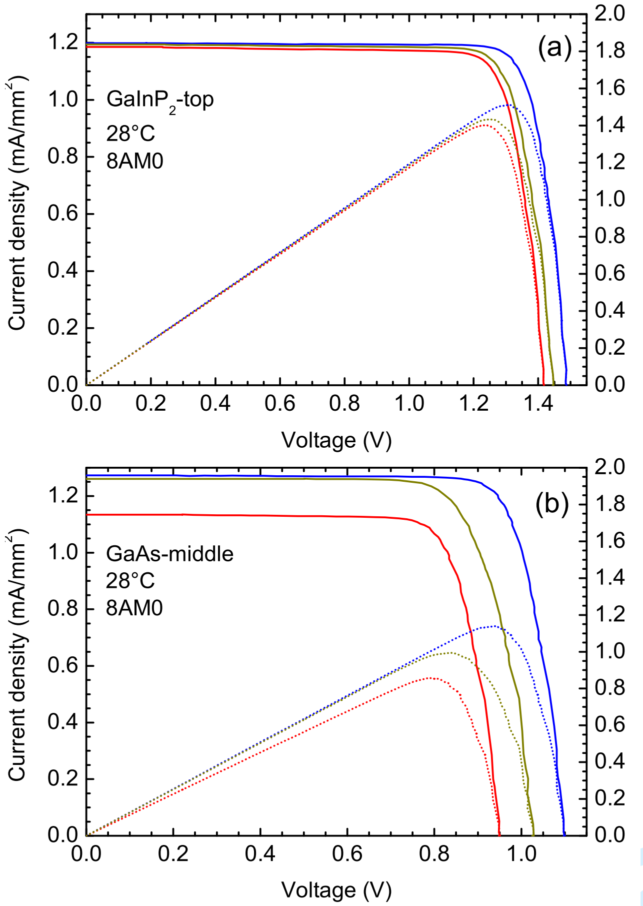

Fig. 1. I/V- and P/V-measurements of the (a) $GaInP_2$ top and (b) GaAs middle component cell before (blue) and after (red) electron irradiation, and after (dark yellow) annealing steps at 50°C, 100°C, 150°C and 180°C. The measurements have been carried out at 8AM0 and 28°C.

dependent I/V-characterization measurements which can be found elsewhere [1]. I/V-measurements at 8AM0 have been carried out with a pulsed solar simulator from Berger Lichttechnik.

III. Results

Figure 1 shows I/V-measurements performed at 28°C and 8AM0 for $GaInP_2$- and GaAs-component cells before and after irradiation with $1\cdot10^{15}/cm^2$ 1MeV electrons and after annealing at T=180°C for 390 h plus the accumulated isothermal annealing from the previous annealing steps performed at lower temperatures (50°C, 100°C, 150°C with times shown in figure 2). After irradiation (before annealing) the higher radiation hardness of the $GaInP_2$ cell is visible as its current seems to be unaffected and the voltage is degrading much less compared to the GaAs cell that shows for all cell parameters a significant drop. These results are well known from literature [19-21]. On the other hand, after annealing the cell parameters recover significantly for the GaAs cell that shows a full recovery in current and almost half in open circuit voltage while the recovery of the $GaInP_2$ component cell is less pronounced.

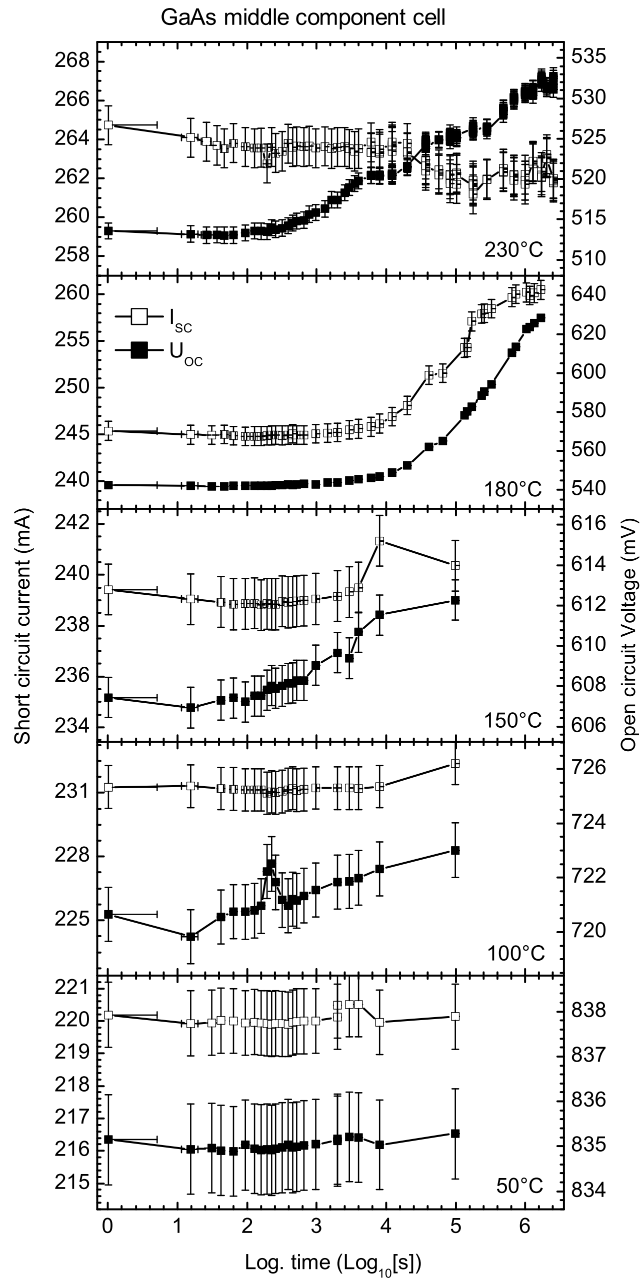

Fig. 2. In situ open circuit voltages (open circles right axis) and short circuit currents (filled squares, left axis) as measured during the isothermal annealing for the GaAs middle cell. The temperatures are indicated in each figure. Voc and Isc values before irradiation are: $I_{sc}^{0}(28°C) = 237\ mA$ with $dI_{sc}^{0}/dT = 0.258\ mA/K$ and $V_{oc}^{0}(28°C) = 1019\ mV$ with $dV_{oc}^{0}/dT = 1.939\ mV/K$.

During isothermal annealing of the irradiated cell I/V-curves have been measured in situ. Figure 2 shows the related I_{sc} and V_{oc} values as a function of time for the example of the GaAs-middle component cell. At low annealing temperatures corresponding to GEO-mission temperatures, e.g. 50°C and 100°C the annealing effect is rather small and within the error bar of the experiment. However, at 150°C already after an annealing time of 24 hours a recovery in the order of 0.7 % is found for the open circuit voltage and current values are also

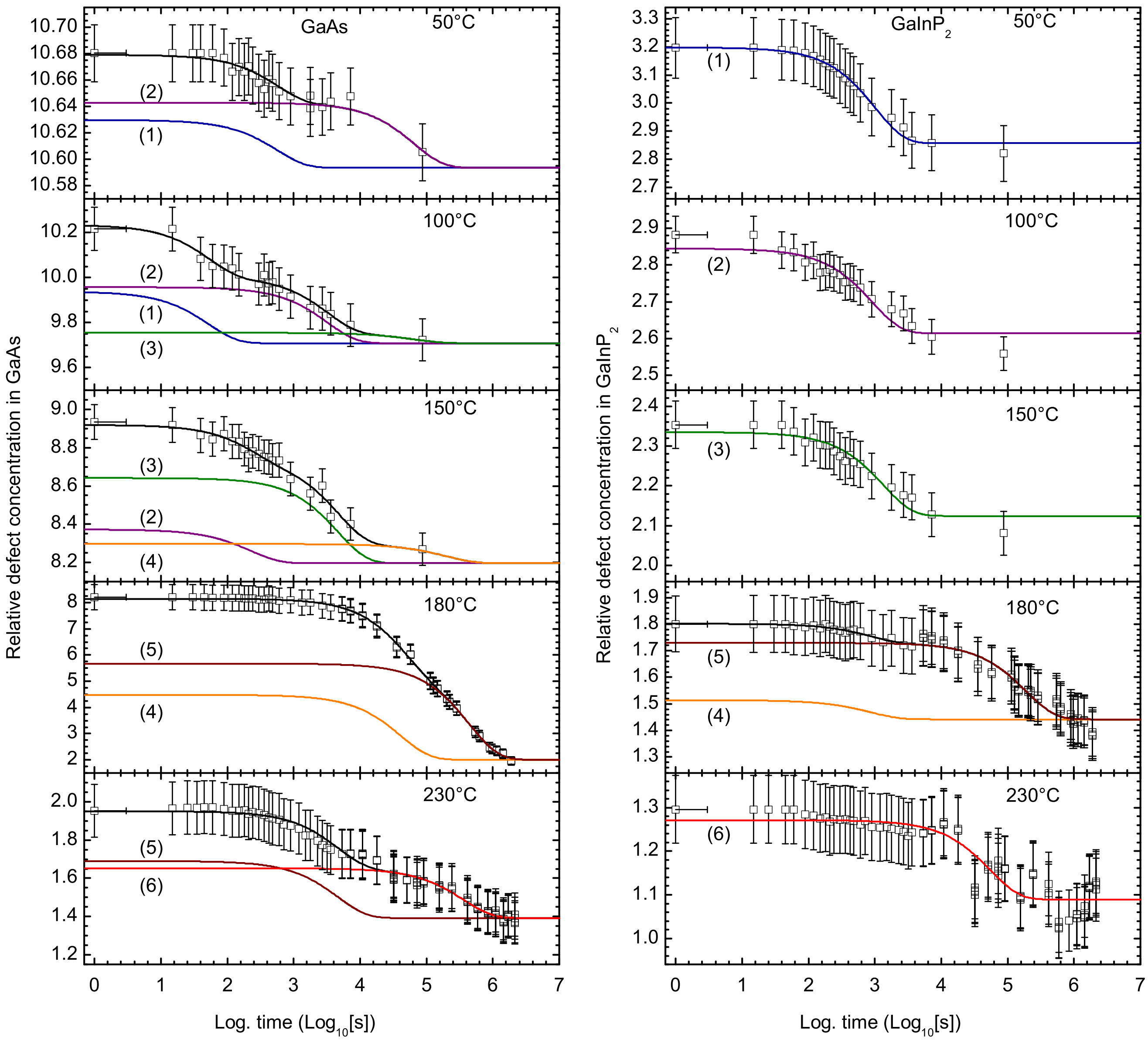

Fig. 3. Time dependent evolution of the relative defect concentration in GaAs and $GaInP_2$ component cells during the isothermal step annealing approach. The open squares show the post processed open circuit voltage and short circuit current values from figure 2 (see text). The black solid lines are the exponential decaying fits. Colored solid lines correspond to the decay of individual activation energies marked by the number in brackets in addition. The annealing temperature is given in each sub-figure.

positively affected by this tempering. In the next temperature step (180°C) a strong recovery takes place with a full recovery of the short circuit current after 140 h. The open circuit voltage also recovers strongly by another 16 % with respect to the status after annealing at 150°C. Increasing the temperature even further up to 230°C yields another improvement of the open circuit voltage so that the cell voltage is only 4 % less compared to its initial value before irradiation. At present it is not clear if this slight difference is caused by residual crystalline defects in the cell or from experimentally caused cell damages.

Additional measurements performed after each annealing step such as spectral response, dark- and light I/V confirm the above statement of an almost full recovery of the cell performance. Thus, there are additional indications that the damage caused by the irradiation induced defects may be fully reversible.

In the following, a method of a quantitative description of the defect relaxation is introduced. The one diode equation serves as a starting point [22]:

$$U_{oc} = \frac{AkT}{e}\log\left(\frac{I_{sc}}{I_0}+1\right) \qquad (1)$$

	E_A^1 (eV)	E_A^2 (eV)	E_A^3 (eV)	E_A^4 (eV)	E_A^5 (eV)	E_A^6 (eV)
$GaInP_2$	$0.52^{+0.06}_{-0.06}$	$0.60^{+0.06}_{-0.07}$	$0.69^{+0.07}_{-0.08}$	$0.72^{+0.08}_{-0.08}$	$0.93^{+0.07}_{-0.08}$	$0.98^{+0.08}_{-0.09}$
GaAs	$0.51^{+0.06}_{-0.06}$	$0.63^{+0.06}_{-0.07}$	$0.74^{+0.07}_{-0.08}$	$0.87^{+0.07}_{-0.08}$	$0.97^{+0.07}_{-0.08}$	$1.07^{+0.08}_{-0.09}$
	c_1	c_2	c_3	c_4	c_5	c_6
$GaInP_2$	0.34 ± 0.01	0.23 ± 0.02	0.21 ± 0.01	0.07 ± 0.01	0.29 ± 0.01	0.18 ± 0.01
GaAs	0.27 ± 0.03	0.44 ± 0.06	0.47 ± 0.04	2.77 ± 0.07	3.67 ± 0.05	0.26 ± 0.01
	Literature values for activation energies (e^- and p^+)			References		
$GaInP_2$ materials	Current annealing	0.42 eV to 0.55 eV		[10,11,27,28]		
	Thermal annealing	1.10 eV to 1.83 eV		[11,27,28]		
GaAs materials	Current annealing	0.10 eV to 1.08 eV		[5,9]		
	Thermal annealing	0.40 eV to 1.90 eV		[4,6,7,8]		

Tab. 1. Found activation energies and relative defect concentrations for the $GaInP_2$ and GaAs component cells. The table also provides results in literature for related semiconductor materials.

In this equation A is the ideality factor, e the elementary charge, k the Boltzmann constant and I_0 the diode saturation current. In order to correlate the number of defects N in the crystal (or what is equivalent the electrically active recombination centers) to this equation the following substitution can be performed [23]:

$$I_0 = a(T)N \quad \text{with} \quad a(T) = \frac{n_i \pi k T \sigma \upsilon_{th}}{|F_{max}|}$$

All parameters in $a(T)$ are assumed to be unaffected by particle irradiation (n_i intrinsic concentration of carriers $|F_{max}|$ the maximum electric field in the space charge region; σ the capture cross section; υ_{th} average thermal velocity).
The number of defects in the non-radiated case (index "0") can be predicted by introducing the pair $(I_{sc}^0(T), U_{oc}^0(T))$ in equation (1):

$$U_{oc}^0 = \frac{AkT}{e}\log\left(\frac{I_{sc}^0}{a(T)N_{eq}}\right) \qquad (2)$$

Accordingly for the pair $I_{sc}^*(T), U_{oc}^*(T)$ of a radiated cell, which has been annealed and measured at a temperature T up to a time t:

$$U_{oc}^* = \frac{AkT}{e}\log\left(\frac{I_{sc}^*}{a(T)(N_{eq}+N(t))}\right) \qquad (3)$$

with N_{eq} being the number of defects before irradiation and $N(t)$ the number of defects which are introduced in addition by radiation. Subtracting equation (3) from (2) yields to:

$$\frac{N(t)}{N_{eq}} = \frac{I_{sc}^*(t)}{I_{sc}^0}\exp\left(\frac{e\left(U_{oc}^0 - U_{oc}^*(t)\right)}{AkT}\right) - 1 \qquad (4)$$

A similar approach was performed by Rau and coworkers in reference [14] for Cu(In,Ga)Se_2 solar cells. Whereas in that system the number of defects was measured directly by DLTS, V_{oc} was measured always at room temperature and no changes of I_{sc} were taken into account, but for the GaAs cell in the present investigation it is of importance. It is worth mentioning that for this prediction the solar cell ideality factor A has been fixed to a constant value of 2 over the whole irradiation/annealing campaign as performed also in reference [14]. Different ideality factors would have an influence on the absolute value of the relative defect concentration, but have only a minor influence on defect relaxation activation energies and relaxation times found later on. The approach described above has been applied to all V_{oc} and I_{sc} pairs recorded for $GaInP_2$ and GaAs (cp. figure 2) for each annealing temperature to derive the relative defect concentrations according to Eq. (4). The results of this post-processing step are shown figure 5. Presenting the data in this form suggests the appearance of overlapping exponential recoveries, also indicating different activation energies. At a given annealing temperature T the annealing curve represented by the relative defect concentration can be modeled by:

$$\frac{N(t)}{N_{eq}} = c_0 + \sum_{i=1}^{m} c_i \exp\left(-\frac{t}{\tau_i}\right) \qquad (5)$$

with c_0 the number of not relaxed defects at temperature T, and c_i the number of defects with relaxation time τ_i. Using the Arrhenius equation (6) as applied by previous authors

$$E_A^i = kT\ln(\tau_i/\tau_0) \qquad (6)$$

the activation energies can be approached by the simultaneous fits of equation (5) and (6).
The measurement of τ_0,which is the inverse lattice frequency, has been performed in literature by a comparison of isothermal with isochronal annealing results as found in ref. [24-26] for transistor structures but is generally problematic [24]. Nevertheless, results in figure 3 for the GaAs component cell show that for some defect types the defects are only partly relaxed at a given temperature and annealing time: at 50°C and 100°C for activation energies (1) and (2), at 100°C and 150°C for activation energy (3), at 150°C and 180°C for activation energy (4) and at for 180°C and 230°C activation energy (5). By correlating the relaxation times $E_A(\tau_1, T_1) = E_A(\tau_2, T_2)$ for defect types of a certain activation energy that contributed to the annealing at two different temperatures, τ_0 can be derived directly from:

$$\tau_2 = \tau_0 \left(\frac{\tau_1}{\tau_0} \right)^{\left(\frac{\tau_1}{\tau_2} \right)} \qquad (7)$$

By comparing the relaxation times of all combinations in figure 3, τ_0 has been found to be $(7.71+60.0/-6.54)\cdot 10^{-6}$s.

Although this error bar is rather high in the upper direction its impact is suppressed by the logarithmic term in equation (6) so that the influence on further calculations is small. Because of the generally low sensitivity the same value has been applied also to $GaInP_2$. Finally, in an iterative approach the relaxation times can be again fitted with the τ_0 value to the relative defect concentrations with the activation energies found beforehand. Table 1 provides a summary of these results together with the relative concentration of each defect type. The table shows that results in literature are in good agreement with activation energies found by this approach, especially when taking into account that the cells were illuminated in open circuit conditions.

Finally it is worth mentioning that a $GaInP_2$/GaAs/Ge triple junction cell related to the studied component cells has been submitted to the annealing campaign. Also for this triple cell a recovery has been observed in the same order. However, in order to analyze the annealing behavior in the same way as described here the current limitation of the sub-cells would have to be considered.

IV. Conclusion

In summary it has been demonstrated that 1 MeV electron irradiated $GaInP_2$- and GaAs-triple junction component cells tend to heal out defects responsible for performance loss at elevated temperatures. A model has been described that allows to determine the relative defect concentrations from open circuit voltages and short circuit currents by an experimentally simple isothermal annealing campaign with in-situ measurements. Different activation energies have been found which are comparable to results in literature established by other methods. As a potential application of the found results it is expected that long term degradation behavior in space and competing annealing can be better modeled especially for missions where the solar cells are operating under high temperatures of more than 100°C. However, to validate such a model more investigations are needed especially annealing tests performed on solar cells irradiated with protons. This is on-going work at Astrium.

Acknowledgment

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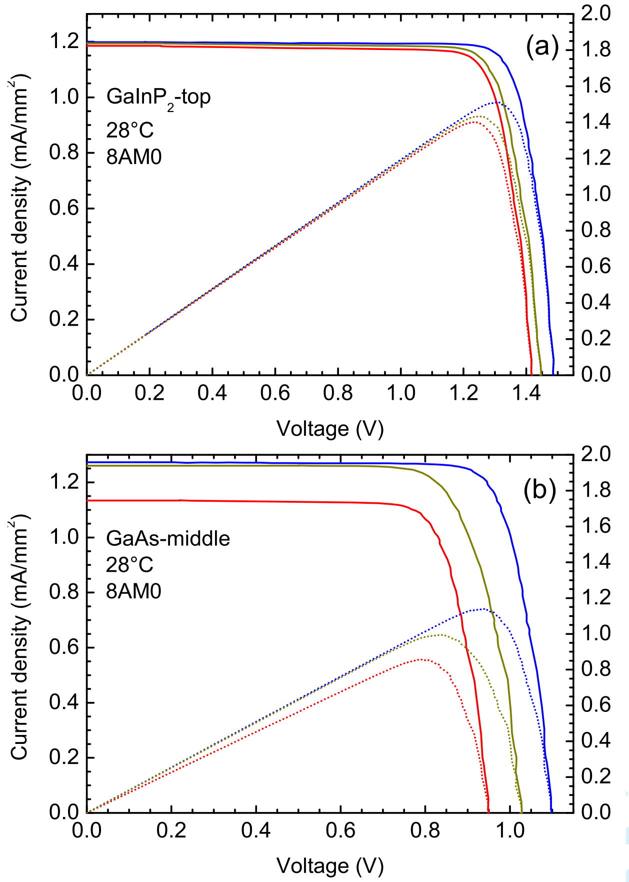

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annealing step temperature and finally angle dependent I/V-characterization measurements which can be found elsewhere [1]. I/V-measurements at 8AM0 have been carried out with a pulsed solar simulator from Berger Lichttechnik.

III. Results

Figure 1 shows I/V-measurements performed at 28°C and 8AM0 for $GaInP_2$- and GaAs-component cells before and after irradiation with $1\cdot10^{15}/cm^2$ 1MeV electrons and after annealing at T=180°C for 390 h plus the accumulated isothermal annealing from the previous annealing steps performed at lower temperatures (50°C, 100°C, 150°C with times shown in figure 2). After irradiation (before annealing) the higher radiation hardness of the $GaInP_2$ cell is visible as its current seems to be unaffected and the voltage is degrading much less compared to the GaAs cell that shows for all cell parameters a significant drop. These results are well known from literature [19-21]. On the other hand, after annealing the cell parameters recover significantly for the GaAs cell that shows a full recovery in current and almost half in open circuit voltage while the recovery of the $GaInP_2$ component cell is less pronounced.

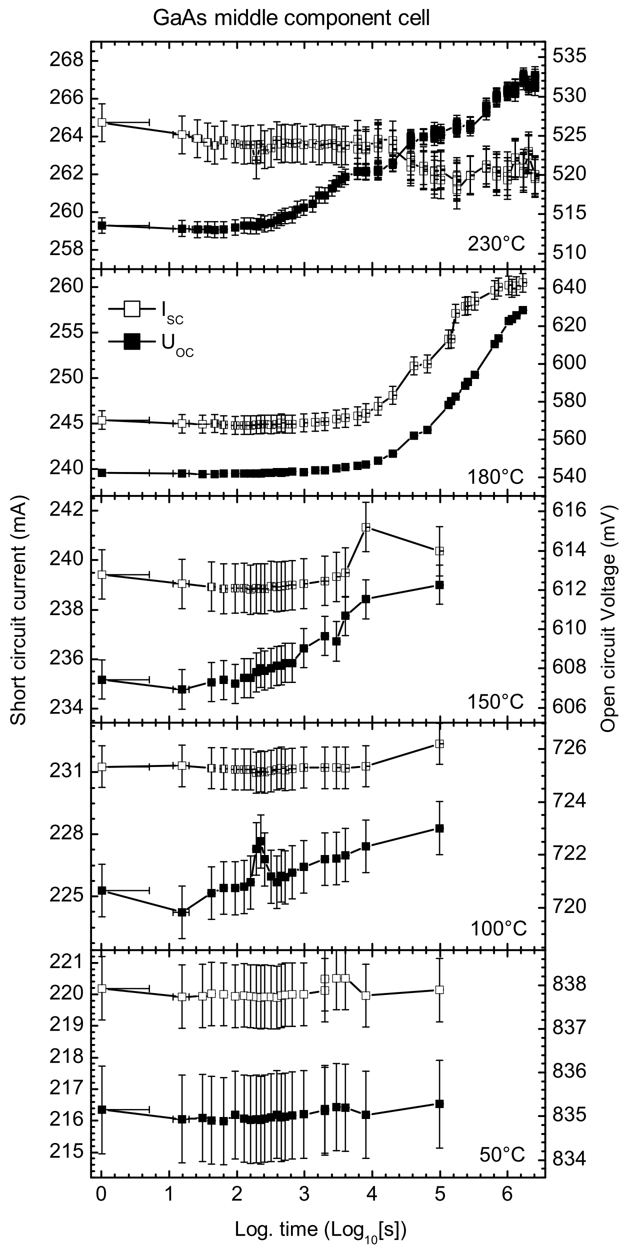

Fig. 2. In situ open circuit voltages (open circles right axis) and short circuit currents (filled squares, left axis) as measured during the isothermal annealing for the GaAs middle cell. The temperatures are indicated in each figure. Voc and Isc values before irradiation are: $I_{sc}^0(28\,°C) = 237$ mA with $dI_{sc}^0/dT = 0.258$ mA/K and $V_{oc}^0(28\,°C) = 1019$ mV with $dV_{oc}^0/dT = 1.939$ mV/K.

During isothermal annealing of the irradiated cell I/V-curves have been measured in situ. Figure 2 shows the related I_{sc} and V_{oc} values as a function of time for the example of the GaAs-middle component cell. At low annealing temperatures corresponding to GEO-mission temperatures, e.g. 50°C and 100°C the annealing effect is rather small and within the error bar of the experiment. However, at 150°C already after an annealing time of 24 hours a recovery in the order of 0.7 % is found for the open circuit voltage and current values are also

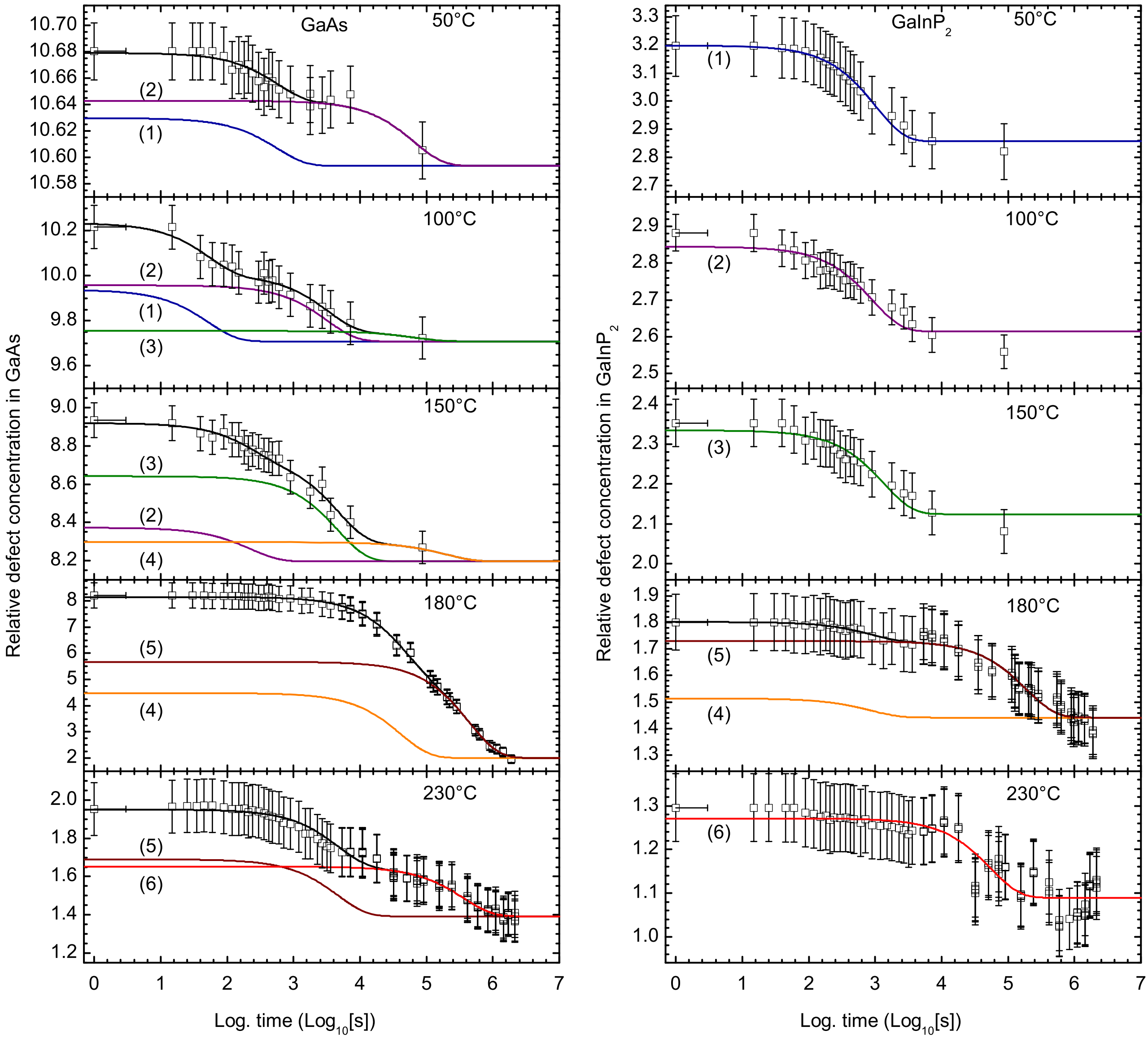

Fig. 3. Time dependent evolution of the relative defect concentration in GaAs and $GaInP_2$ component cells during the isothermal step annealing approach. The open squares show the post processed open circuit voltage and short circuit current values from figure 2 (see text). The black solid lines are the exponential decaying fits. Colored solid lines correspond to the decay of individual activation energies marked by the number in brackets in addition. The annealing temperature is given in each sub-figure.

positively affected by this tempering. In the next temperature step (180°C) a strong recovery takes place with a full recovery of the short circuit current after 140 h. The open circuit voltage also recovers strongly by another 16 % with respect to the status after annealing at 150°C. Increasing the temperature even further up to 230°C yields another improvement of the open circuit voltage so that the cell voltage is only 4 % less compared to its initial value before irradiation. At present it is not clear if this slight difference is caused by residual crystalline defects in the cell or from experimentally caused cell damages.

Additional measurements performed after each annealing step such as spectral response, dark- and light I/V confirm the above statement of an almost full recovery of the cell performance. Thus, there are additional indications that the damage caused by the irradiation induced defects may be fully reversible.

In the following, a method of a quantitative description of the defect relaxation is introduced. The one diode equation serves as a starting point [22]:

$$U_{oc} = \frac{AkT}{e}\log\left(\frac{I_{sc}}{I_0}+1\right) \qquad (1)$$

	E_A^1 (eV)	E_A^2 (eV)	E_A^3 (eV)	E_A^4 (eV)	E_A^5 (eV)	E_A^6 (eV)
$GaInP_2$	$0.52^{+0.06}_{-0.06}$	$0.60^{+0.06}_{-0.07}$	$0.69^{+0.07}_{-0.08}$	$0.72^{+0.08}_{-0.08}$	$0.93^{+0.07}_{-0.08}$	$0.98^{+0.08}_{-0.09}$
GaAs	$0.51^{+0.06}_{-0.06}$	$0.63^{+0.06}_{-0.07}$	$0.74^{+0.07}_{-0.08}$	$0.87^{+0.07}_{-0.08}$	$0.97^{+0.07}_{-0.08}$	$1.07^{+0.08}_{-0.09}$
	c_1	c_2	c_3	c_4	c_5	c_6
$GaInP_2$	0.34 ± 0.01	0.23 ± 0.02	0.21 ± 0.01	0.07 ± 0.01	0.29 ± 0.01	0.18 ± 0.01
GaAs	0.27 ± 0.03	0.44 ± 0.06	0.47 ± 0.04	2.77 ± 0.07	3.67 ± 0.05	0.26 ± 0.01
	Literature values for activation energies (e^- and p^+)				References	
$GaInP_2$ materials	Current annealing		0.42 eV to 0.55 eV		[10,11,27,28]	
	Thermal annealing		1.10 eV to 1.83 eV		[11,27,28]	
GaAs materials	Current annealing		0.10 eV to 1.08 eV		[5,9]	
	Thermal annealing		0.40 eV to 1.90 eV		[4,6,7,8]	

Tab. 1. Found activation energies and relative defect concentrations for the $GaInP_2$ and GaAs component cells. The table also provides results in literature for related semiconductor materials.

In this equation A is the ideality factor, e the elementary charge, k the Boltzmann constant and I_0 the diode saturation current. In order to correlate the number of defects N in the crystal (or what is equivalent the electrically active recombination centers) to this equation the following substitution can be performed [23]:

$$I_0 = a(T)N \quad \text{with} \quad a(T) = \frac{n_i \pi k T \sigma \upsilon_{th}}{|F_{max}|}$$

All parameters in $a(T)$ are assumed to be unaffected by particle irradiation (n_i intrinsic concentration of carriers $|F_{max}|$ the maximum electric field in the space charge region; σ the capture cross section; υ_{th} average thermal velocity).

The number of defects in the non-radiated case (index "0") can be predicted by introducing the pair ($I^0_{sc}(T), U^0_{oc}(T)$) in equation (1):

$$U^0_{oc} = \frac{AkT}{e}\log\left(\frac{I^0_{sc}}{a(T)N_{eq}}\right) \qquad (2)$$

Accordingly for the pair $I^*_{sc}(T), U^*_{oc}(T)$ of a radiated cell, which has been annealed and measured at a temperature T up to a time t:

$$U^*_{oc} = \frac{AkT}{e}\log\left(\frac{I^*_{sc}}{a(T)(N_{eq}+N(t))}\right) \qquad (3)$$

with N_{eq} being the number of defects before irradiation and $N(t)$ the number of defects which are introduced in addition by radiation. Subtracting equation (3) from (2) yields to:

$$\frac{N(t)}{N_{eq}} = \frac{I^*_{sc}(t)}{I^0_{sc}}\exp\left(\frac{e\left(U^0_{oc} - U^*_{oc}(t)\right)}{AkT}\right) - 1 \qquad (4)$$

A similar approach was performed by Rau and coworkers in reference [14] for $Cu(In,Ga)Se_2$ solar cells. Whereas in that system the number of defects was measured directly by DLTS, V_{oc} was measured always at room temperature and no changes of I_{sc} were taken into account, but for the GaAs cell in the present investigation it is of importance. It is worth mentioning that for this prediction the solar cell ideality factor A has been fixed to a constant value of 2 over the whole irradiation/annealing campaign as performed also in reference [14]. Different ideality factors would have an influence on the absolute value of the relative defect concentration, but have only a minor influence on defect relaxation activation energies and relaxation times found later on. The approach described above has been applied to all V_{oc} and I_{sc} pairs recorded for $GaInP_2$ and GaAs (cp. figure 2) for each annealing temperature to derive the relative defect concentrations according to Eq. (4). The results of this post-processing step are shown figure 5. Presenting the data in this form suggests the appearance of overlapping exponential recoveries, also indicating different activation energies. At a given annealing temperature T the annealing curve represented by the relative defect concentration can be modeled by:

$$\frac{N(t)}{N_{eq}} = c_0 + \sum_{i=1}^{m} c_i \exp\left(-\frac{t}{\tau_i}\right) \qquad (5)$$

with c_0 the number of not relaxed defects at temperature T, and c_i the number of defects with relaxation time τ_i. Using the Arrhenius equation (6) as applied by previous authors

$$E^i_A = kT\ln(\tau_i/\tau_0) \qquad (6)$$

the activation energies can be approached by the simultaneous fits of equation (5) and (6).

The measurement of τ_0, which is the inverse lattice frequency, has been performed in literature by a comparison of isothermal with isochronal annealing results as found in ref. [24-26] for transistor structures but is generally problematic [24]. Nevertheless, results in figure 3 for the GaAs component cell show that for some defect types the defects are only partly relaxed at a given temperature and annealing time: at 50°C and 100°C for activation energies (1) and (2), at 100°C and 150°C for activation energy (3), at 150°C and 180°C for activation energy (4) and at for 180°C and 230°C activation energy (5). By correlating the relaxation times $E_A(\tau_1, T_1) = E_A(\tau_2, T_2)$ for defect types of a certain activation energy that contributed to the annealing at two different temperatures, τ_0 can be derived directly from:

$$\tau_2 = \tau_0 \left(\frac{\tau_1}{\tau_0} \right)^{\left(\frac{T_1}{T_2} \right)} \quad (7)$$

By comparing the relaxation times of all combinations in figure 3, τ_0 has been found to be $(7.71+60.0/-6.54)\cdot 10^{-6}$s.

Although this error bar is rather high in the upper direction its impact is suppressed by the logarithmic term in equation (6) so that the influence on further calculations is small. Because of the generally low sensitivity the same value has been applied also to $GaInP_2$. Finally, in an iterative approach the relaxation times can be again fitted with the τ_0 value to the relative defect concentrations with the activation energies found beforehand. Table 1 provides a summary of these results together with the relative concentration of each defect type. The table shows that results in literature are in good agreement with activation energies found by this approach, especially when taking into account that the cells were illuminated in open circuit conditions.

Finally it is worth mentioning that a $GaInP_2$/GaAs/Ge triple junction cell related to the studied component cells has been submitted to the annealing campaign. Also for this triple cell a recovery has been observed in the same order. However, in order to analyze the annealing behavior in the same way as described here the current limitation of the sub-cells would have to be considered.

IV. Conclusion

In summary it has been demonstrated that 1 MeV electron irradiated $GaInP_2$- and GaAs-triple junction component cells tend to heal out defects responsible for performance loss at elevated temperatures. A model has been described that allows to determine the relative defect concentrations from open circuit voltages and short circuit currents by an experimentally simple isothermal annealing campaign with in-situ measurements. Different activation energies have been found which are comparable to results in literature established by other methods. As a potential application of the found results it is expected that long term degradation behavior in space and competing annealing can be better modeled especially for missions where the solar cells are operating under high temperatures of more than 100°C. However, to validate such a model more investigations are needed especially annealing tests performed on solar cells irradiated with protons. This is on-going work at Astrium.

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