Activation energies of the In$_{Si}$-Si$_i$ defect transitions obtained by carrier lifetime measurements

Kevin Lauer*,1, Christian Möller1, Christopher Teßmann1,2, Dirk Schulze2, and Nikolay V. Abrosimov3

1 CiS Forschungsinstitut für Mikrosensorik GmbH, Konrad-Zuse-Str. 14, 99099 Erfurt, Germany
2 TU Ilmenau, Institut für Physik, Weimarer Str. 32, 98693 Ilmenau, Germany
3 Leibniz-Institut für Kristallzüchtung, Max-Born-Str. 2, 12489 Berlin, Germany

Received 29 April 2016, accepted 1 February 2017
Published online 21 February 2017

Keywords carrier lifetime, light-induced degradation, silicon

* Corresponding author: e-mail: klauer@cismst.de, Phone: +49 361 663 1211, Fax: +49 361 663 1413

Light-induced degradation (LID) is investigated in indium doped silicon by time and temperature dependent carrier lifetime measurements. Different transitions rates and activation energies were measured and interpreted within the A$_{Si}$-Si$_i$ defect model. The case of indium acceptors is compared to the case of boron. Results are discussed within the frame of a comparison between A$_{Si}$-Si$_i$ and A$_{Si}$-Fe$_i$ defects. It was found that reported dependencies of the transitions rates of the A$_{Si}$-Si$_i$ defect on the hole density support defect models which are based on defect configuration changes. An in-depth explanation of the A$_{Si}$-Si$_i$ defect model is given and possible errors related to the measurement of transition rates are discussed.

1 Introduction

The phenomenon of light-induced degradation (LID) [1], which occurs in boron-doped silicon, was found to occur in indium doped silicon as well [2, 3]. For the case of boron, it was proposed that oxygen trimers [4] or dimers [5] are located in the vicinity of this acceptor atom and are responsible for the LID phenomenon. Considering ab initio simulations of one acceptor and one silicon atom sharing one lattice position in silicon [6–9], an A$_{Si}$-Si$_i$ defect was proposed as an alternative origin for LID [2] and a defect model was developed [10]. This defect model can also explain the kinetics of a photoluminescence peak in indium doped silicon called P line [10]. Existing experimental data with respect to the boron interstitial defect and oxygen clustering during crystal cooling are in agreement with the assumption of an A$_{Si}$-Si$_i$ defect [11]. Hence, the defect underlying the LID phenomenon is denoted by A$_{Si}$-Si$_i$ defect throughout this work. Our A$_{Si}$-Si$_i$ defect is modeled throughout the manuscript by a configurational-coordinate (cc) energy diagram to interpret the kinetics of the LID phenomena.

In this contribution, we further investigate the case of indium. We report on the activation energies of the different transitions within the A$_{Si}$-Si$_i$ defect model. The activation energies are obtained by time- and temperature-dependent charge carrier lifetime measurements on one indium doped silicon sample.

2 Defect model

2.1 Level scheme

The A$_{Si}$-Si$_i$ defect model, which was developed in Ref. [10], is extended by a third configuration to include a more likely mechanism for the generation of the fast recombination center (see Fig. 1). The shape of the total energy curves is deduced from ab initio simulations of the silicon interstitial [12]. It is presumed that a possible A$_{Si}$-Si$_i$ defect inherits the properties of a free silicon interstitial atom. The cc diagram reported in this contribution is a suggestion, which is used to exemplify the explanation of the LID phenomenon using those diagrams. There are seven possible states of the defect within this model, which are denoted by numbers. The total energy, which includes the elastic and electronic energy, is plotted for each charge state as a function of the defect configuration coordinate. An introduction to the application of cc diagrams can be found, e.g., in Refs. [13, 14].

The electronic energy is indicated with respect to the interaction of the defect with the valence band. This is sufficient to explain the kinetics of the LID phenomenon in p-type silicon. If a hole is emitted into the valence band...
charge state (state 3, 4, and 6) lie at different configuration coordinates compared to the respective energy minima in the neutral charge state (state 2, 5, and 7). This means that during the electron hole recombination events slight configuration changes take place. In case of such processes one of the simplifying assumptions made in the standard SRH statistics is invalid. In standard SRH statistics, it is assumed that the energy position of the defect level is stable and does not depend on the charge state of the defect. If configuration changes of the defect appear during a recombination event the activation energy of the electron emission (e.g., from state 6) and the activation energy of the hole emission (e.g., from state 7) cannot be described with only one energy level within the band gap. It could be possible, that in such a case an appropriate fit of measured carrier lifetimes using the standard SRH formula requires two standard SRH defect levels.

A detailed description of the statistics which could describe electron hole recombination via such recombination channels is beyond the scope of the present contribution. Irrespective of the exact recombination statistics the recombination rate must be a linear function of the defect density. For simplicity the recombination channels within the $A_{Si-Si}$ defect model are approximated by the standard SRH statistics in the following.

The LID phenomenon exhibits two main recombination channels, which can be separated by the timescale of their appearance and are denoted by the fast recombination center (FRC) and the slow recombination center (SRC). Within the $A_{Si-Si}$ defect model, the FRC is the recombination channel related to the transition between the states 4 and 5 and the SRC is related to the transition between the states 6 and 7. The other two recombination channels in the $A_{Si-Si}$ defect model (transitions 1 to 2 and 2 to 3) are assumed to have recombination parameters which result in a negligible recombination activity. This assumption can be made since the initial state of the LID phenomenon after annealing was found to be less recombination active.

An electron trap, which is related to the defect underlying the LID phenomenon, was observed by minority carrier transient spectroscopy (MCTS) with an electron emission activation energy of $E_C - E_i = (0.41 \pm 0.01)$ eV. An electron capture cross section of $\sigma_e \sim 10^{-17}$ cm$^{-2}$ was found [16]. $E_C - E_i$ denotes the distance of the level from the conduction band. Within the frame of the $A_{Si-Si}$ defect model, this activation energy can be identified with the electron emission from state 6 to 7.

The energy level at $E_C - E_i = (0.41 \pm 0.04)$ eV and the electron/hole capture cross section ratio of $\sigma_n/\sigma_p = 9.5$, which are determined from temperature- and injection-dependent lifetime spectroscopy (TIDLS) using standard SRH statistics [17], are associated in the $A_{Si-Si}$ defect model with the transition from state 6 to 7.

### 2.2 Defect kinetic

The kinetic of the LID phenomenon is explained within the frame of the $A_{Si-Si}$ defect model by charge state change induced configuration changes. The
The temporal evolution of the defect density \([Z_6](t)\) can be measured by the time dependent charge carrier lifetime as explained in the following. The carrier lifetime is the average time interval an excess charge carrier spends in the valence or conduction band before an electron hole recombination event.

In the SRH statistics the inverse carrier lifetime, which can be calculated for a specific defect with given energy level and capture cross sections for electrons and holes, is proportional to the density of the defect. In case of the transitions between states 6 and 7, the SRH carrier lifetime \(\tau_{6\rightarrow7}\) and the time dependent defect density in state 6 \([Z_6](t)\) are related via:

\[
\frac{1}{\tau_{6\rightarrow7}(t)} = C_{6\rightarrow7}[Z_6](t).
\]

\(C_{6\rightarrow7}\) is the SRH prefactor, which depends in the standard SRH statistics on the position of the energy level and the capture cross sections. A similar equation holds for the SRH carrier lifetime \(\tau_{4\rightarrow5}\), which is caused by the transition between the states 4 and 5. The measured carrier lifetime \(\tau_m\) is the sum of all recombination channels:

\[
\frac{1}{\tau_m(t)} = \frac{1}{\tau_{6\rightarrow7}(t)} + \frac{1}{\tau_{4\rightarrow5}(t)} + \frac{1}{\tau_{\text{other}}},
\]

with \(\tau_{\text{other}}\) being the carrier lifetime due to all other recombination channels. If the inverse lifetime measured at \(t=0\) is subtracted from Eq. (5), it follows with Eq. (3):

\[
\frac{1}{\tau_m(t)} - \frac{1}{\tau_m(t=0)} = (C_{6\rightarrow7} - C_{4\rightarrow5})[Z_6](t).
\]

If the carrier lifetime \(\tau_m\) is measured as a function of time (see Fig. 2 or Fig. 3), the function \([Z_6](t)\), which is associated with the generation of the SRC, can be obtained. An exponential fit of the inverse carrier lifetime then reveals the generation rate of the SRC, which is denoted by \(k_{46}\) and is plotted as a function of temperature in Fig. 4. The energy

![Figure 2](image-url)  
**Figure 2** Carrier lifetime as a function of time during transitions 3 to 4 and 4 to 6.
Figure 3 Inverse carrier lifetime as a function of illumination and annealing time during a complete In$_{Si}$-Si$_{Si}$ defect cycle. The exponential fits and the transition rates for the transitions 3 to 4, 4 to 6, and 7 to 5 are given.

Figure 4 Arrhenius plot of the In$_{Si}$-Si$_{Si}$ defect transition rates. The activation energies for each transition are denoted as well.

The activation energies for each transition are denoted as well. $k_i$ are the rates of all possible transitions (see Fig. 1). For example, the solution of this rate equation system for $Z_i(t)$ and $Z_j(t)$ would describe the defect density $N_{i,SRC}(t) = [Z_i](t) + [Z_j](t)$, which is used in the standard SRH approach and is a linear function of the measured inverse carrier lifetime.

The decision to explain the generation of FRC by a thermally activated configuration change is discussed in the following. In the first $A_{Si}$-$Si$ defect model proposed in Ref. [10], the generation of the FRC was an electron capture process. One physical mechanism to release the energy of the electron is by emission of multiple phonons ([18] and references therein). The temperature dependence of the rate of this process can be described by an Arrhenius law (see Eq. (1)) as well. If the electron capture process would be responsible for the generation of the FRC, it is necessary to assume a capture cross section for electrons in the range of $\sigma_r = k_{34}/(v_{th} n) \sim 10^{-25}$ cm$^2$. $v_{th}$ is the thermal velocity of electrons and $n$ is the electron density caused by illumination. As this capture cross section is several orders of magnitude below reported capture cross sections for defects in silicon [18] this process seems to be unlikely.

On the other hand transition rates for configuration changes depend on the ratio between the partition function in the transition state and the partition function in the initial state (see in Ref. [19]). To calculate a transition rate, for example for the FRC (transition 3 to 4 in Fig. 1) the partition function of state 3 and of the transition state must be known. The transition state in case of the FRC is the defect configuration at the maximum total energy between states 3 and 4. These partition functions can be described classically but can contain quantum mechanical processes like tunneling as well [19].

In the classical picture, the transition state between states 3 and 4 would be a state where the acceptor atom, the silicon atom of the $A_{Si}$-$Si$ defect and the surrounding silicon atoms of the lattice all have a defined position, velocity and direction of the velocity. Depending on the probability of the occupancy of this transition state, the transition rate may vary over orders of magnitude. Hence, an explanation of the FRC generation via a thermally activated configuration change seems to be more likely compared to the capture of electrons. It has to be noted that a measured transition rate also depends on the occupancy probability [20] of the initial state [21].

To enable thermally activated configuration changes for the FRC transition it is necessary to introduce two new electronic levels in comparison to the previous model. Two consecutive electron captures from state 1 change the charge state of $A_{Si}$-$Si$ defect to negative. After these electron captures configuration changes in the negative charge state take place. A second reason, which has led to the introduction of the two levels, is the reported cc diagram of two silicon atoms sharing one lattice position [20]. Within this cc diagram three stable configurations are reported.

The exact shape of the cc diagram for each type of $A_{Si}$-$Si$ defect, e.g., the $B_{Si}$-$Si$ defect is not reported in the
literature. To suggest the $A_{Si-Si_i}$ defect model depicted in Fig. 1, we followed as a first estimate the reported configuration for the $B_{Si-Si_i}$ defect with lowest total energy in the negative charge state [6] is indeed similar to corresponding configuration of two silicon atoms sharing one lattice position, which is the split interstitial configuration [12].

### 3 Experimental

The samples used for this study were cut from an intentional indium-doped 2 inch $<100>$ Czochralski crystal, which was grown at Leibniz-Institut für Kristallzüchtung (IKZ). The sample used for the carrier lifetime measurements was etched with potassium hydroxide to remove the saw damage, standard RCA cleaned and surface passivated by a PECVD silicon nitride layer [22].

A shiny etched sample of 2 mm thickness was used for FTIR measurements. Details of the FTIR setup can be found in Ref. [23]. Interstitial oxygen concentration was $[O_i] = 7.8 \times 10^{17}$ cm$^{-3}$ [24]. Low temperature FTIR measurements revealed a boron concentration of $[B_i] = 1.9 \times 10^{14}$ cm$^{-3}$ and $[B_i] = 2.2 \times 10^{14}$ cm$^{-3}$ using the calibration factors of Refs. [25, 26], respectively. The indium concentration is $[In_i] = 1.1 \times 10^{16}$ cm$^{-3}$ and $[In_i] = 2.9 \times 10^{15}$ cm$^{-3}$ with the calibration factors of Refs. [26, 27], respectively. The measurements were carried out under bias illumination to remove the compensation effect of the thermal donors.

The specific resistivity of $\rho = (3.8 \pm 0.2) \ \Omega$cm (p-type) was measured by a 4-point-probe setup [24]. The specific resistivity increased unexpectedly to $\rho = (11.4 \pm 1.2) \ \Omega$cm after the thermal donor anneal of 600°C for 20 min. Carrier lifetime measurements were done on a sample without thermal donor anneal.

The microwave-detected photoconductance decay (MWPCD) after laser excitation was measured using the Semilab WT-2000 device. To extract the carrier lifetime at a fixed excess carrier density of $\Delta n = 5 \times 10^{14}$ cm$^{-3}$ the photoconductance decay was evaluated after the method described in Ref. [28]. A temperature controlled hot plate was used to investigate the carrier lifetime change during the defect reactions at different temperatures.

The defect transitions within the $A_{Si-Si_i}$ defect model from state 3 to 4, 4 to 6, and 5 to 2 were monitored while the sample was stored on the hotplate, which was placed in the MWPCD device. For the transition from state 7 to 5, an external hot plate was used. The illumination during the transitions 3 to 4 and 4 to 6 was done with the MWPCD excitation laser, which has an average intensity of $I_{av} = 8.5 \text{kW m}^{-2}$.

The error of the carrier lifetime is estimated by calculating the standard deviation of the carrier lifetime during the LID experiment of the gallium doped sample in Ref. [2]. The standard deviation from the mean value during this LID experiment is found to be 0.2%. For the measurements of the transition from state 7 to 5, the sample was taken out of the device. Despite careful positioning of the sample small lateral variations of the measurement position may occur. These variations may lead to an additional error as the carrier lifetime varies laterally, as well.

An example of the evolution of the carrier lifetime during the transitions 3 to 4 (generation of FRC) and 4 to 6 (generation of SRC) is shown in Fig. 2. The measurements under illumination started after annealing the samples at 200°C for 10 min to adjust state 1. For the carrier lifetime measurement during transition 5 to 2 (annihilation of FRC) the illumination was turned off after completion of transition 3 to 4. For the LID experiment plotted in Fig. 3, transition from state 3 to 4 is assumed to be completed after 1800 s. Transition 7 to 5 was monitored after illumination for about 1 d at 50°C. A complete $In_{Si-Si_i}$ defect cycle is shown in Fig. 3. Reported transition rates are the inverse time constants of a monoexponential fit to the time dependent inverse lifetimes.

The measured rates of the different $In_{Si-Si_i}$ defect transitions as a function of the inverse temperature are depicted in Fig. 4. Activation energies are obtained from a linear fit to the Arrhenius plot of the transition rates. The error bars of the transition rates represent the standard errors from the least squares fitting method. An accuracy of the temperature measurement of $\pm 1$ K is assumed. The activation energies for the different transitions are summarized and compared to the boron case in Table 1.

### 4 Discussion

In Table 1, the activation energies for the generation and annihilation of the FRC and the SRC are given, respectively. The denotation follows the $A_{Si-Si_i}$ defect model with transition from state 3 to 4 and 5 to 2

<table>
<thead>
<tr>
<th>transition</th>
<th>$In_{Si-Si_i}$ (LID) $E_A$ (eV)</th>
<th>$In_{Si-Si_i}$ (Pline) $E_A$ (eV)</th>
<th>$B_{Si-Si_i}$ (LID) $E_A$ (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 to 4</td>
<td>$0.37 \pm 0.03$</td>
<td>$0.46 \pm 0.07^a$</td>
<td>$0.23 \pm 0.02^b$</td>
</tr>
<tr>
<td>5 to 2</td>
<td>$0.60 \pm 0.17$</td>
<td>$0.41 \pm 0.03^c$</td>
<td>$0.41 \pm 0.03^c$</td>
</tr>
<tr>
<td>4 to 6</td>
<td>$0.50 \pm 0.05$</td>
<td>$0.475 \pm 0.035^b$</td>
<td>$1.36 \pm 0.06^d$</td>
</tr>
<tr>
<td>7 to 5</td>
<td>$1.36 \pm 0.07$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$^a$Ref. [11].
$^b$Ref. [40].
$^c$Ref. [10].
$^d$Ref. [41].
associated with generation and annihilation of the FRC and transition 4 to 6 and 7 to 5 associated with generation and annihilation of the SRC. The activation energies, which are obtained in this work for the case of indium, are compared to the literature data in Table 1 for the case of boron. Additionally, one activation energy, which was measured by low temperature photoluminescence spectroscopy, is included as well. For the transitions from state 3 to 4 and 5 to 2, a difference between the cases boron and indium is observed. For the transitions from state 4 to 6 and 7 to 5, the activation energies are comparable within the error. For the SRC, this is a similar situation as in the case of the AlSi-Fe\textsubscript{i} defects [29]. The common understanding for the association reaction of the AlSi-Fe\textsubscript{i} defects is that this activation energy is a measure for the diffusion barrier of positively charged interstitial iron.

The close relation between the LID phenomenon and the AlSi-Fe\textsubscript{i} defects becomes also apparent in existing models for the LID phenomenon [30], as similar defect reaction models as well as energy diagrams [31, 32] were proposed. Both suggested models are based on a pairing process including a long-range migration and three characteristic energies, which are the dissociation energy, the binding energy and the migration energy. The migration energy is in each case related to a fast diffusing component of the respective defect complex. In Ref. [30], the fast diffusing component was proposed to be the oxygen dimer. This close relation between the LID phenomenon and the AlSi-Fe\textsubscript{i} defects is discussed in the following.

The AlSi-Fe\textsubscript{i} defects were comprehensively investigated [31] and there are experiments, which indicate that a dissociation process indeed occurs [33, 34]. In that case, the substitutional acceptor and the iron are fully separated. It is known, that the AlSi-Fe\textsubscript{i} defect itself can be metastable [31]. Such a behavior was reported, e.g., for the AlSi-Fe\textsubscript{i} defect [35] but not for the BSi-Fe\textsubscript{i} defect [30]. In case of the AlSi-Fe\textsubscript{i} defect for each stable configuration, the defect parameters for carrier recombination are different. This means that a configuration change of the AlSi-Fe\textsubscript{i} defect would induce a change in the carrier lifetime. The dissociation of the iron from the aluminum would then lead to a further change of the carrier lifetime. The recombination center after dissociation is the free interstitial iron atom. A defect with such properties could explain the two-step properties of the LID phenomenon. This would mean that the LID phenomenon is partly caused by a long-range migration process rather than by configuration changes as assumed in the present AlSi-Si\textsubscript{i} defect model. This possibility is discussed in the following.

On the basis of current experimental data such a mechanism for the AlSi-Si\textsubscript{i} defect is still possible. Illumination would first induce a defect configuration change. After that the acceptor and the silicon interstitial dissociate as the Coulomb attraction vanishes due to the electron capture. Annealing in darkness would then lead to an association of the acceptor and the silicon interstitial caused by the Coulomb attraction. The silicon interstitial is similarly to the interstitial iron positively charged in p-type silicon [36]. The wide range of reported data on the diffusivity of the silicon interstitial [37] does not allow to rule out such a mechanism.

Within this idea it could be possible that after the dissociation process the silicon interstitial moves to other sinks like substitutional carbon C\textsubscript{s}, interstitial oxygen O\textsubscript{i} [38], di-oxygen vacancy complex VO\textsubscript{2}, or an oxygen dimer O\textsubscript{2} [39]. In these cases, the transition rate from state 4 to 6 (generation rate of SRC) must depend on the density of the sink itself, as the rate would be sensitive to the diffusion distance. In case of carbon, no reports of the dependency of the rate on the carbon concentration are known to the authors. In case of interstitial oxygen, it was found that the generation rate of the slow LID component does not depend on the interstitial oxygen concentration [40]. Hence, interstitial oxygen is unlikely as a sink for interstitial silicon or for interstitial boron, as proposed in Ref. [38]. The same holds for the possibility that the oxygen dimer is the sink, as its concentration depends on the interstitial oxygen concentration as well.

The basic question is: Is the observed LID phenomenon due to a configuration change of a defect as proposed in Refs. [4, 10] or does a long-range migration occur similar to the AlSi-Fe\textsubscript{i} defects at least for one component? One criterion would be, how the annihilation rate of the SRC (transition 7 to 5) depends on the acceptor density. If a long-range motion of the silicon interstitial away from the substitutional boron during defect generation would occur, the annihilation rate should increase linearly with the acceptor density [42]. This feature is used in case of the AlSi-Fe\textsubscript{i} defects to measure the acceptor density in compensated silicon [34]. For the LID, however, a decrease of the annihilation rate with increasing hole density is observed [41]. It was shown, that the annihilation rate is not related to the acceptor density. This finding supports defect models, which associate the annihilation of LID with configuration changes. If a long-range migration would occur, the annihilation rate in uncompensated and compensated silicon in similarity to the AlSi-Fe\textsubscript{i} defects should depend on the acceptor density.

The interpretation of the various dependencies of the measured defect transition rates on parameters like electron and hole density, etc. [43] is a complex problem. In case of a two-state system, as assumed for the AlSi-Fe\textsubscript{i} defects [29], the reaction rates of the equilibrium reaction can be extracted by solving the rate equations Eq. (7) for \((i = 1, \ldots , 2)\) and fitting the analytical solution to the measured data. In that way, the association and dissociation reaction rates \(k_{1,2}\) and \(k_{2,1}\), respectively, for the AlSi-Fe\textsubscript{i} defects could be separated [29]. In case of the AlSi-Si\textsubscript{i} defect, there are 7 states with 16 possible reaction rates (see Fig. 1). An analytical solution of Eq. (7) for \((i = 1, \ldots , 7)\) does not exist. Hence, a separation of a measured transition rate into the different reaction paths of the AlSi-Si\textsubscript{i} defect model, which occur in an experimental setup, is hardly possible. It is necessary to make assumptions as indicated in the theory section, which are responsible for a systematic error in the obtained results.

Such a systematic error was found for the case of AlSi-Fe\textsubscript{i} defects [29]. In that case, the acceptor iron association reaction
was monitored by carrier lifetime measurements starting from the fully dissociated state. Then the activation energies were obtained under two assumptions. First, only the association reaction was assumed to be present, which means that the rate equation system Eq. (7) was solved for \( i = 1 \). Second, the association as well as dissociation reaction was assumed to be present during the measurement, which means that the rate equation system Eq. (7) is solved for \( i = 1, 2 \). Both solutions were fitted to the same measured data and the activation energies were obtained. It was found that the activation energy for the association reaction is different in both cases. This systematic error is due to the different assumptions made for the extraction of the transition rates.

In case of the LID phenomenon, it was found that generation as well as annihilation of the SRC occurs simultaneously [44]. This means that a similar systematic error as observed in case of \( \text{As}_{25}-\text{Fe} \) defects may occur for the case of \( \text{As}_{25}-\text{Si} \) defects. Such a systematic error must be taken into account, if the measured activation energies are compared to energy barriers, which could be obtained by \textit{ab initio} simulations. A detailed analysis of the systematic error due to the assumptions made for the evaluation of the measured data is beyond the scope of the present investigation. A comparison of the activation energies obtained in this work with activation energies reported in the literature is possible as the assumptions made to solve Eq. (7), which are made in this work and which are used in the literature [40, 41, 45], are the same.

In our sample, the defect density parameter \( N_i \) is about a factor 5 larger than expected if the sample would contain no indium [40, 46]. This means that the small amount of boron, which is present in the sample, has only a small impact on the observed LID phenomenon. But this impact may lead to a small error in the reported activation energies as well.

The consequence of the occurrence of all possible transitions in Eq. (7) during an LID experiment is that the measured generation rate of the SRC is in principle influenced by all possible transition rates \( k_{ji} \) of the \( \text{As}_{25}-\text{Si} \) defect model (see Fig. 1). The following questions exist: How does the solution of the rate equation system Eq. (7) changes if a parameter like, e.g., the hole density is changed? Which change in a transition rate due to variation of a parameter (e.g., hole density) is the reason for the change in the measured transition rate?

Experimentally, it is found that the measured generation rate of the SRC and the defect density, which is correlated to the equilibrium population of states 6 and 7, depends on the hole density [47]. It is possible that the transition from state 6 to 7, which is indeed a hole capture, has a large impact on the solution of the rate equation system and hence on the measured generation rate and on the measured defect density. With increasing hole density the transition 6 to 7 becomes more likely and state 6 is depopulated. This has an impact on the equilibrium reaction between states 4 and 6 and could in consequence increase the measured transition rate as well as the number of defects which are in state 6 or 7.

In Ref. [44], a defect activation due to a charge state change as proposed in Ref. [2, 4, 10] was explicitly ruled out. The experiments carried out in Ref. [44] are based on the assumption that the charge state of a defect under non-equilibrium conditions is exclusively controlled by the quasi-Fermi levels. This assumption is wrong. It is necessary to take into account the capture cross sections for electrons and holes of a defect [20]. It is possible that the observed temperature dependence of the \( V_{50} \) value is caused by the temperature dependence of the capture cross sections of the defect. Hence, the reported experimental results [44] are not sufficient to exclude a possible defect activation by changing the charge state of the defect.

Bothe et al. [48] built-up a sophisticated experiment to measure the \( V_{50} \) value. A forward voltage was applied to degrade \textit{n-in-p} CZ silicon solar cells until a steady state is reached. The applied forward voltage generates electrons in the p-type base, which induce the LID phenomenon. A similar experiment was carried out for the case of \( \text{As}_{25}-\text{Fe} \) defects [49]. In that case, it was necessary to shift the steady state of the \( \text{As}_{25}-\text{Fe} \) defects by illumination. The \( V_{50} \) value defines the applied forward voltage and in consequence the electron density for a steady state of 50% of the maximal defect density. Within the frame of the \( \text{As}_{25}-\text{Si} \) defect model this situation occurs for example for the SRC if the rate \( k_{46} \) equals the rate \( k_{75} \).

5 Conclusions The activation energies of the different defect transitions of the \( \text{In}_{25}-\text{Si} \) defect were determined by time and temperature dependent carrier lifetime measurements. It was found that the energies of transitions 3 to 4 and 5 to 2 are different compared to the \( \text{B}_{25}-\text{Si} \) case. But for the transitions 4 to 6 and 7 to 5 the activation energies are within the error the same for the \( \text{In}_{25}-\text{Si} \) and for the \( \text{B}_{25}-\text{Si} \) defect. These results were discussed by comparing the properties of \( \text{As}_{25}-\text{Si} \) and \( \text{As}_{25}-\text{Fe} \) defects. It was found that the dependencies of the transition rates for the \( \text{As}_{25}-\text{Si} \) defects on parameters like the acceptor or hole density support a defect model, which is based on defect configuration changes and not on long-range migration processes. An in-depth explanation of the \( \text{As}_{25}-\text{Si} \) defect model is given and it is shown that in general a rate equation system needs to be solved to explain the LID phenomenon. Depending on the assumptions made to solve the equation system a systematic error occurs if measured reaction rates are identified with transition rates within the \( \text{As}_{25}-\text{Si} \) defect model.

Acknowledgements Jan Schmidt and Alexander Lawerenz are acknowledged for fruitful discussions. The funding of this work by Bundesministerium für Wirtschaft und Energie under contract number VF140015 is acknowledged.

References
