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# Light Induced Degradation Quantification by Monitoring the $V_{OC}$ Output of Silicon Solar Cell Using Low-Cost Real-Time Virtual Instrumentation

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**Abstract**

Silicon-based solar cells under operating conditions suffer from light-induced degradation (LID), which can cause up to a 10% loss in efficiency. Impurities, such as boron, iron, and oxygen, are common at different concentrations in these solar cells. They form active recombination defects in boron-doped mono-crystalline (Cz-Si) and multi-crystalline (mc-Si) solar cells during illumination. For the solar industry, this will lead to serious financial loss, hence the importance of inspecting and controlling the LID level accurately. Seeking to minimize the human factor and the inaccuracy that comes with it, we have proposed in this research a low-cost virtual instrumentation solution to provide a new real-time instrumentation technique for solar cell characteristics such as open circuit voltage ($V_{OC}$). The virtual data acquisition system (VDAS) design is based on a low-cost Arduino board associated with MATLAB/Simulink software. Moreover, this system can collect the values of solar cell outputs under prolonged illumination and at different temperatures of the LID test in real time with an acquisition period interval of one second (1 s). Further, kinetic modeling of the solar cell output $V_{OC}$ variation as a function of light soak duration, shows the predominance of one type metastable defect over the LID test of c-Si solar cells. In addition, degradation mechanism in mc-Si solar cells involve more than one metastable defect and are more complexes due to the mc-Si substrate elaboration technique compared to c-Si substrate. Furthermore, the thermal defect activation energy of $E_{act}$ = 0.45 eV was extracted from the experimental $V_{OC}$ measurements obtained with the VDAS. Finally, the system minimizes the test period and errors for solar cell characterization compared to traditional approaches.

## 1. Introduction

One of the most pressing challenges facing humanity today is the urgent need to transition from fossil fuels to a sustainable and carbon-neutral energy system. This urgency has driven the renewable energy industry to accelerate the deployment of clean energy sources. Photovoltaic (PV) energy, particularly crystalline silicon (c-Si) and multicrystalline silicon (mc-Si) solar cells, has emerged as a critical component of this transition. These silicon-based solar cells have undergone significant technological advances, resulting in cost reductions and improved energy conversion efficiencies. However, while c-Si and mc-Si solar cells hold great promise for a cleaner energy future, they also face critical issues such as light-induced degradation (LID), which can lead to a decrease in efficiency [1-3].

This phenomenon is also related to the formation of metastable defects inherent in the solar cell substrate. [4, 5]. In addition, LID is activated by the injection of excess carriers through illumination of the solar cells above the bandgap. Further, solar cells based on p-type monocrystalline silicon (c-Si) with large amounts of both boron and interstitial oxygen ($O_i$) exhibit up to 10% power degradation under standard illumination conditions [6]. Furthermore, LID has been identified in p-type multicrystalline silicon (mc-Si) solar cells, with an efficiency loss approaching 6% [7]. Although intensive research has been conducted to explain the defect state transitions that occur in the LID process for c-Si and mc-Si solar cells, more studies are needed to ensure the sustainability of solar energy and effective management of these technologies.

In our work, a batch of c-Si and mc-Si solar cells undergoes an LID test. Moreover, we measured the open-circuit voltage $V_{OC}$ of theses solar cells at specific illumination and temperature conditions. Further, one of the determining factors in this work is the time interval of the measurements, the shorter the time, the greater the accuracy. In addition, in order to interpret the results of $V_{OC}$ variation as a function of illumination time, control of LID test parameters such as temperature and illumination intensity is critical. However, most of the studies on the LID phenomenon perform manual measurements at more or less regular time intervals of 5 minutes to 12 hours [2, 7–12]. This method can induce a wide margin of error. Furthermore, the introduction of the human factor adds more inaccuracy to the measurement, due to the handling of test equipment's ex: voltmeter and/or ammeter, thermometer, lux-meter…etc. Finally, these conventional approaches rely on expensive equipment and are labor-intensive, further increasing the overall cost of testing.

The proposed method, combining MATLAB/Simulink software with Arduino platform. This virtual data acquisition system (VDAS) offers significant cost benefits. By integrating readily available and affordable components such as Arduino boards, this method minimizes the need for expensive specialized equipment. Also, the real-time monitoring capability of the VDAS significantly reduces test time and human involvement, further lowering operating costs. Moreover, various configurations of the virtual data acquisition system have been proposed in the literature [13–15] to monitor the solar cell outputs. Nevertheless, the study of the LID on the solar cells by a VDAS has not yet been reported. In addition, the connectivity between MATLAB/Simulink and Arduino allowed us to simultaneously monitor three determining parameters during the LID experiment: the $V_{OC}$ output of the solar cells, the temperature and the light intensity, over a total illumination duration of 20 000 secs, with an acquisition time interval of one second (1 s) for all three parameters. The results obtained make it possible to clearly visualize the characteristic curve of the $V_{OC}$ variation as a function of illumination time. Furthermore, to obtain the desired results, our work was arranged into two parts: the first part was devoted to the establishment of the experimental setup, and the second one was to analyze the data acquired from the VDAS. Lastly, the obtained results will be discussed and a conclusion will be made.

## 2. Experimental Procedure

In this study, 200 µm thickness industrial solar-grade cells with an aluminum back surface field (Al-BSF) based on p-type mono- and multi-crystalline silicon substrates were used [16]. The substrate properties are regrouped in the Table 1.

**Table 1** *Solar cell substrate specification*

| Batch of cells | Substrate properties | | | | |
|---|---|---|---|---|---|
| | Silicon wafers | Elaboration technique | Dimension ($cm^2$) | Resistivity (Ω/cm) | Oxygen concentration ($cm^{-3}$) |
| N°1 | Pseudo-square mono-crystalline | Czochralsk method | 10 x 10 | 1-3 | $6 \times 10^{17}$ |
| N°2 | Multi-crystalline | Heat exchange method | | | |

The Arduino board simultaneously monitors by sensors the three parameters: the voltage $V_{OC}$ of the solar cell, the temperature T and the light intensity I (Fig .1). Moreover, to conduct an LID experience, a halogen lamp with a power of 500 W was used as a solar simulator (Fig .1) and illuminated the solar cells for ~ 6 hours at a distance of about 40 cm with an illumination of 0.055 W/m$^2$, the temperature was controlled by an air-cooling system. Further, the output data are collected and displayed (Fig .1) in real-time on MATLAB/Simulink using the support package for Arduino hardware [17].

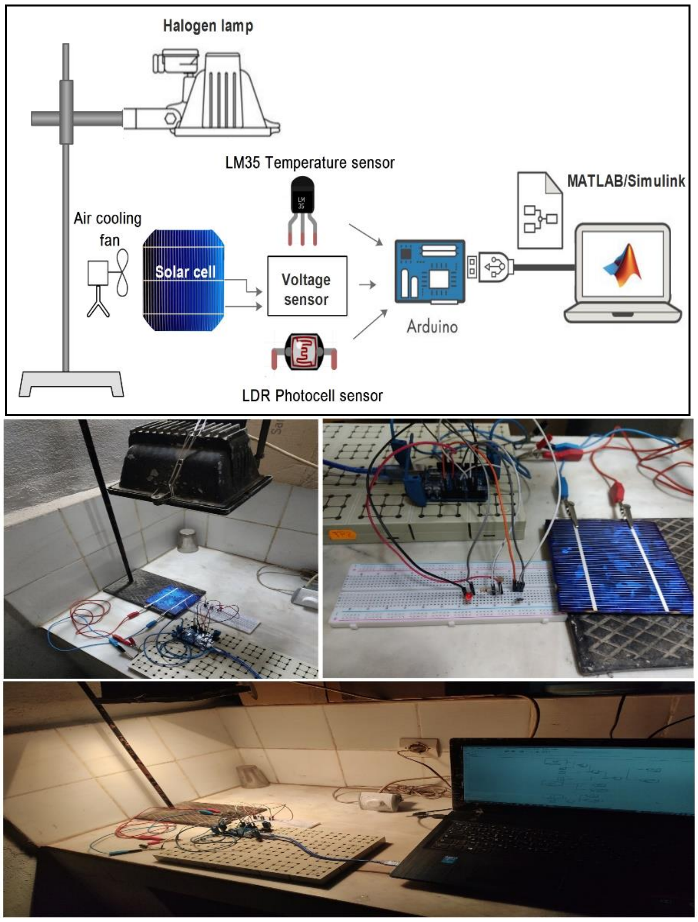


**Fig. 1** *A representation of (a) Schematic of virtual data acquisition system (VDAS); (b) Pictures of the experimental setup for LID test*

The Arduino board is programmed (Fig .2) to measure successively with an acquisition time interval of one second (1 s) for all three parameters: $V_{OC}$, T and I. During the solar cells light exposure, over 20 000 data points have been measured for each parameter.

## 3. Results and Discussion

### 3.1 Structure

The kinetics of defect formation responsible for the LID phenomenon is studied by monitoring the solar cells open circuit voltage as a function of the illumination time ($V_{OC}$ (t)). Moreover, a real-time virtual instrumentation system is used, allowing $V_{OC}$ (t) measurements with a temporal resolution of 1 s. Furthermore, during the measurements, the solar cells are illuminated by a halogen lamp at an intensity of 0.055 W/m$^2$. Fig. 3 shows the results of the variation with time of illumination of the three parameters: temperature, open circuit voltage and the intensity of light, for mono- and multi-crystalline solar cells, respectively. In addition, we observed that the temperature follows a rapidly increasing curve and then begins a more stable step for all tested samples. To keep the temperature in a range of values below 75°C, an air-cooling system was added in the experiment. A temperature below 75°C is required during illumination for a designation of LID light-induced degradation. Also, at experimental temperatures above 75°C a new form of degradation appears, named light and elevated temperature induced degradation (LeTID) [18–23]. Further, the light intensity I values (Fig. 3) presents a good stability with small fluctuations during the LID experiment. Furthermore, the decrementing of the $V_{OC}$ is illustrated in Fig. 3, the $V_{OC}$ values decrease inversely to the temperature [24,25]. Nevertheless, LID degradation is mainly based on the impact of light on the properties of the solar cell, more precisely the silicon absorbing layer. However, this phenomenon coexists with temperature-related degradation, and its impact is combined with the latter [26].

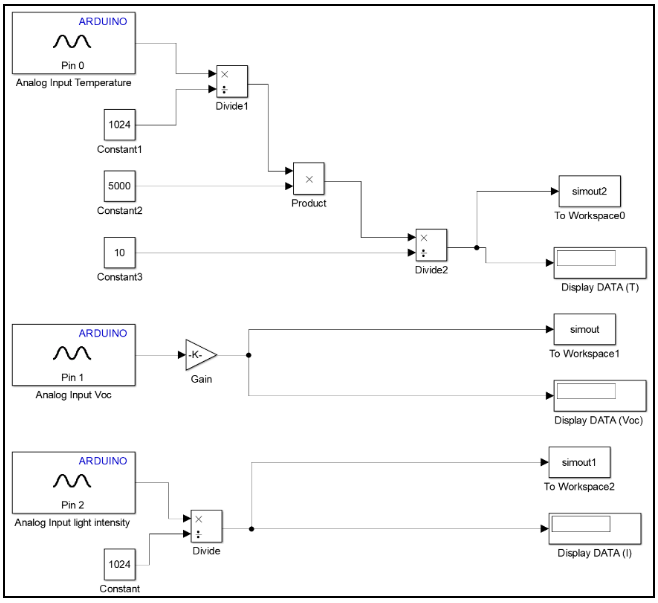


**Fig. 2** *MATLAB/Simulink model for real time implementation of an Arduino board*

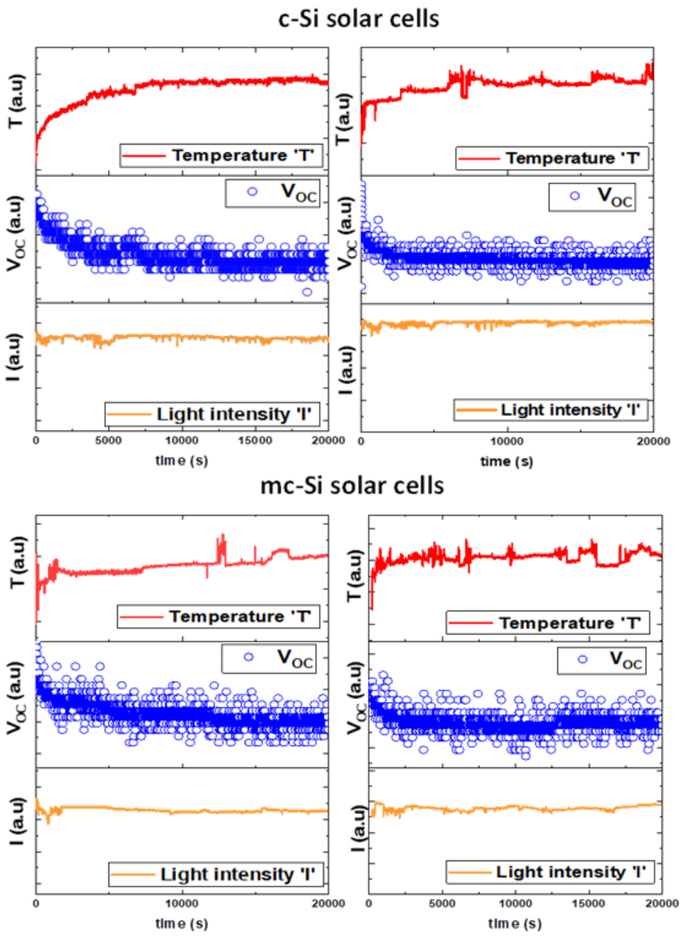


**Fig. 3** *Variations in temperature (T), open circuit voltage ($V_{OC}$), and light intensity (I) as a function of illumination duration, obtained from the VDAS measurements conducted on diverse mono- and multi-crystalline silicon solar cells*

Fig. 4 (a and b) represents an example of the $V_{OC}$ decay as a function of time for the same mc-Si solar cell under the identical measurement conditions. Moreover, manual monitoring of the $V_{OC}$ as a function of time is presented in Fig. 4(a), with a measurement number of 32 points over a duration of approximately six hours (~ 6 h) of illumination. Further, Fig. 4(b) depicts the $V_{OC}$ results as a function of time via the virtual measurement systems with several measurement runs of 20,000 points over the same duration of illumination. Furthermore, the rise in the value of $V_{OC}$ toward the last part presented in Fig. 4(a) can be interpreted as a possible regeneration of the $V_{OC}$ with time of illumination. However, the curve in Fig. 4(b) clearly decreases as a function of illumination time for the same solar cell under study. The large number of measurements obtained from the virtual measurement systems made it possible to follow with great precision the real trend of the variation of the $V_{OC}$ as a function of illumination time. Finally, this result could only be obtained by integrating an acquisition system (MATLAB/Simulink-Arduino) capable of performing several measurements in a very short time interval.

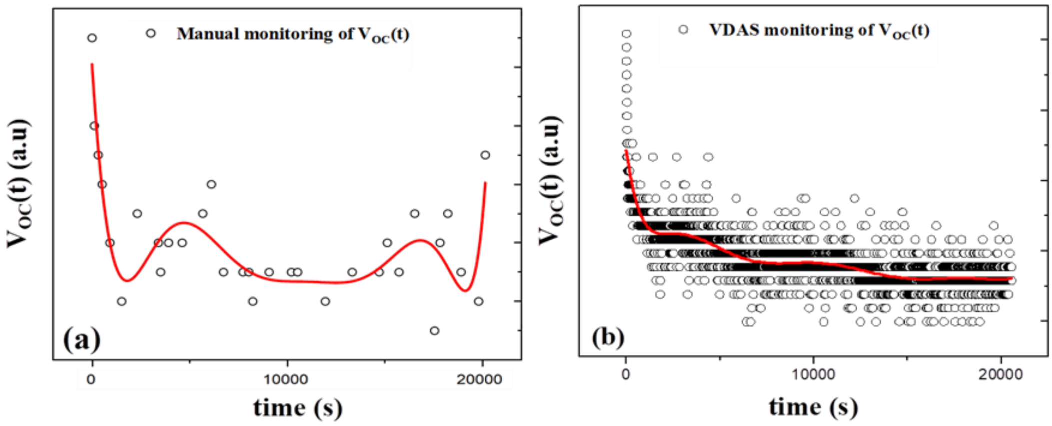


**Fig. 4** *Measure of $V_{OC}$ output for the same mc-Si solar cell vs. time (a) by manual monitoring and; (b) by the VDAS. Under illumination of 0.055 W/m² and for a duration of ~6 h at 35 °C, with red line as a guide to the eye*

## 3.2 Kinetic Modeling of the Solar Cell Output Variation as a Function of Light Soak Duration

The variation in the open circuit voltage $V_{OC}$ with time of illumination can be related to the concentration of defects [27]. We therefore chose this parameter to study the kinetics of degradation. The latter is simulated on the basis of chemical reaction models of the defects that form during the illumination step, following the open circuit voltage measured in situ during 6 h of illumination at 35°C.

We used the same approach as of Sporleder *et al.* [2] to analyze the degradation of the open circuit voltage $V_{OC}$ versus time in an LID test. A model based on a 2nd order reaction in the form of A+B→P is proposed to determine the types of reactions, including two impurities A and B with initial concentrations $A_0$ and $B_0$, respectively. The activated defects resulting in P concentrations are a function of time (t). A decrease in $V_{OC}$ (t) of the solar cells was observed with time of illumination. This reduction is due to an increase in the concentration of active defects P relative to the initial concentration of inactive defects $A_0$ and $B_0$ (Fig. 5). Note that in this model the ratio of the initial concentrations of impurities: $A_0$ and $B_0$ are two critical parameters. If we refer to the initial concentrations, three cases arise and are presented in Fig. 5.

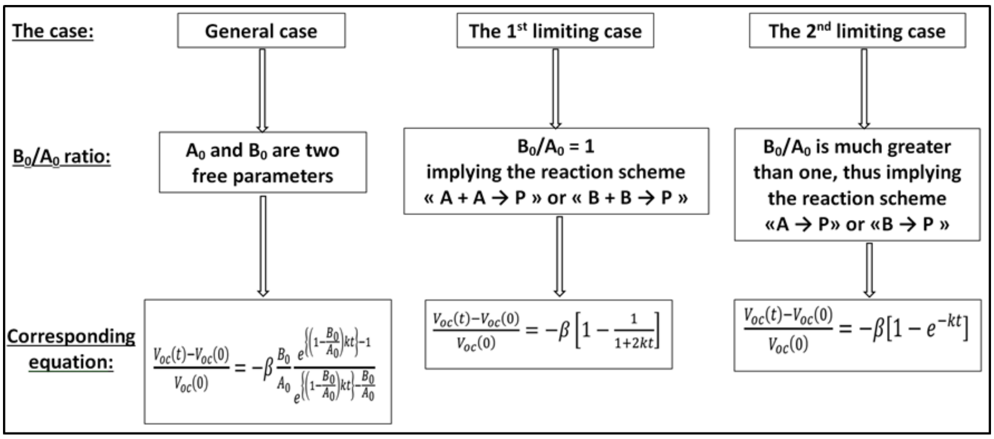


**Fig. 5** *The proposed kinetic model [2]*

The parameters β and k are the saturation of $V_{OC}$ and the degradation rate following a prolonged illumination time (t), respectively. As shown in figure .5, the reaction schema A + A → P or B + B → P model fits best with the kinetics of $V_{OC}$ degradation vs. time of illumination for the c-Si solar cells. Moreover, the c-Si solar cells behavior flow at first minutes of illumination, a rapid drop of the $V_{OC}$ followed by a much slower degeneration of the output, which clearly indicates two distinct forms of recombination center called fast recombination center (FRC) and slow recombination center (SRC). However, recent studies have shown that the FRC and SRC centers can be attributed to only one type of metastable defect [28].

For the mc-Si solar cells, the $V_{OC}$ (t) degradation kinetics flow the 2nd order reaction of type "A+B→P" including two impurities. Moreover, Sporleder *et al.* [2] have related the $V_{OC}$ degradation to tow mechanism, the dissociation of iron-boron pairs and the activation boron-oxygen-defect. Further, Ramspeck *et al.* [7] have reported that boron-oxygen complex formation is not primarily responsible for light induced degradation of mc-Si solar cells. Furthermore, a more recent study [10] demonstrates that the intra-grain regions dominate the mc-LID effect due to their large area fraction in mc-Si solar cell. Finally, the origin of the LID mechanism in mc-Si solar cells involves more than one defect and is more complex compared with the LID mechanism in the c-Si solar cells.

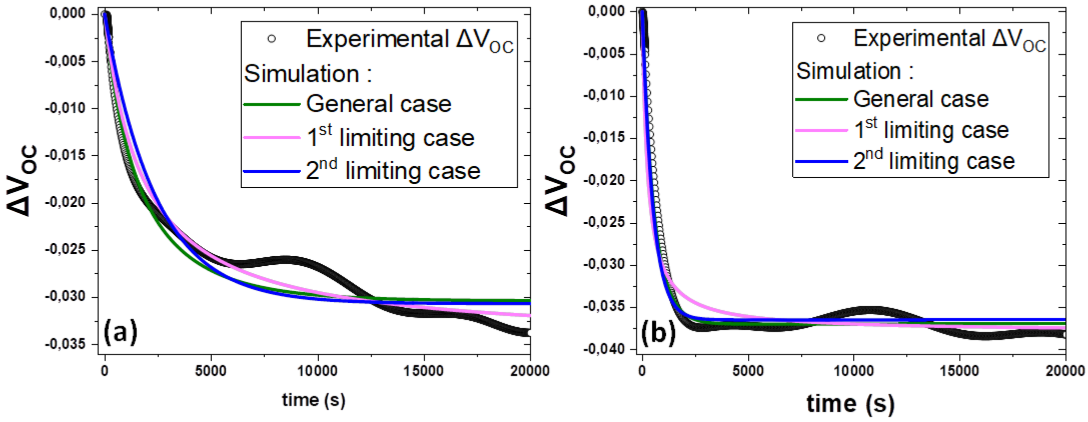


**Fig. 6** *Experimental and simulated curves of $\Delta V_{OC}$ as a function of light soak duration of 6 h at 35°C for (a) mono-crystalline solar cell; (b) multi-crystalline solar cell*

A comparison with other research is given in Table 2, the experimental data of $\Delta V_{OC}$ (t) found in the literature have been fitted with the different models. The obtained results (Table 2) show similarly reaction process for the same type of solar cell.

**Table 2** *Model results based on experimental $\Delta V_{OC}$ (t) for this work and reference dataset*

| Simulation results | c-Si solar cells | | mc-Si solar cells | |
|---|---|---|---|---|
| | This work | Ref [29] | This work | Ref [2] |
| The best fit model | A+A→P or B+B→P | A+A→P or B+B→P | A+B→P | A+B→P |
| The precursors with the initial ratio A0/B0 | 1 | 1 | 0.33 | 1.3 |
| β describes the saturation of $V_{OC}$ [%] | 0003477 | 0.01564 | 0.0365 | 1.46 |
| k the degradation rate [s-1] | 0.00028 | 0.00008 | 0.00078 | 0.000008 |

## 3.3 Temperature Dependence of the Defect Concentration ($N_{Voc}$)

To investigate the effect of temperature on the light induced degradation processes, c-Si and mc-Si solar cells where subjected to illumination intensity of 0.055 W/m$^2$ for ~6 h duration, while the solar cells temperatures were set to 35°C, 40°C, 44°C 58°C and 64°C, respectively. The resulting degradation of $V_{OC}$ as a function of illumination time is displayed in figure .7. We can observe that the temperature accelerated the $V_{OC}$ degradation to rich the complete saturation [26].

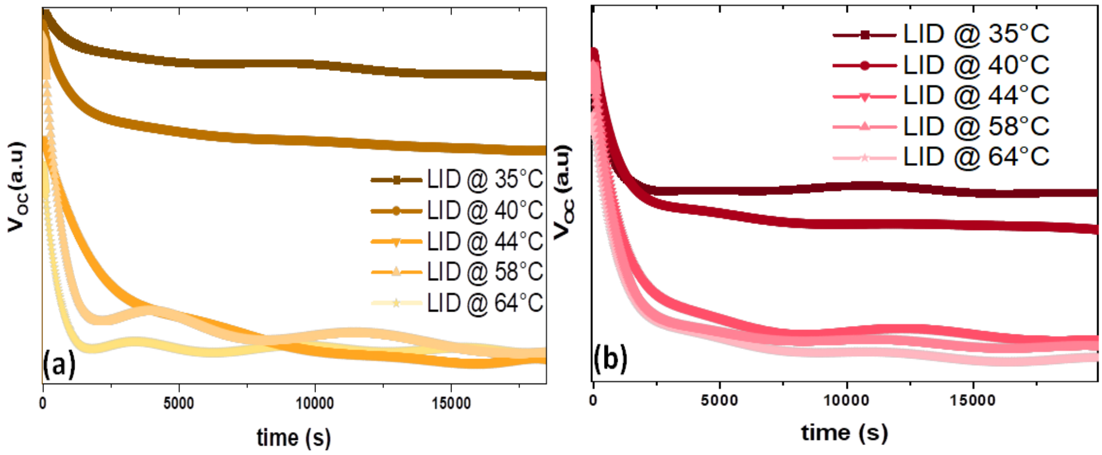


**Fig. 7** *Open-circuit voltage $V_{OC}$ degradation curves of (a) c-Si; (b) mc-solar cells at different temperatures, under illumination of 0.055 W/m² for ~6 h of duration*

The defect concentration $N_{Voc}$ is the most relevant quantity in the LID study [30]. Therefore, the time dependence of the defect concentration must be analyzed. Thus, the measured $V_{OC}$ (t) curves are converted into $N_{Voc}$ according to the following equation (Eq. 1) [27]:

$$N_{V_{OC}}(t) = e^{-qV_{OC}(t)/k_bT} - e^{-qV_{OC}(t=0)/k_bT} \tag{1}$$

To clarify if the formation of the defect is related to a thermally activated process, the $N_{Voc}$ (t) is calculated (Fig. 8) at different temperatures: 35°C, 40°C, 44°C, 58°C and 64°C and for the c-Si and mc-Si solar cells, respectively.

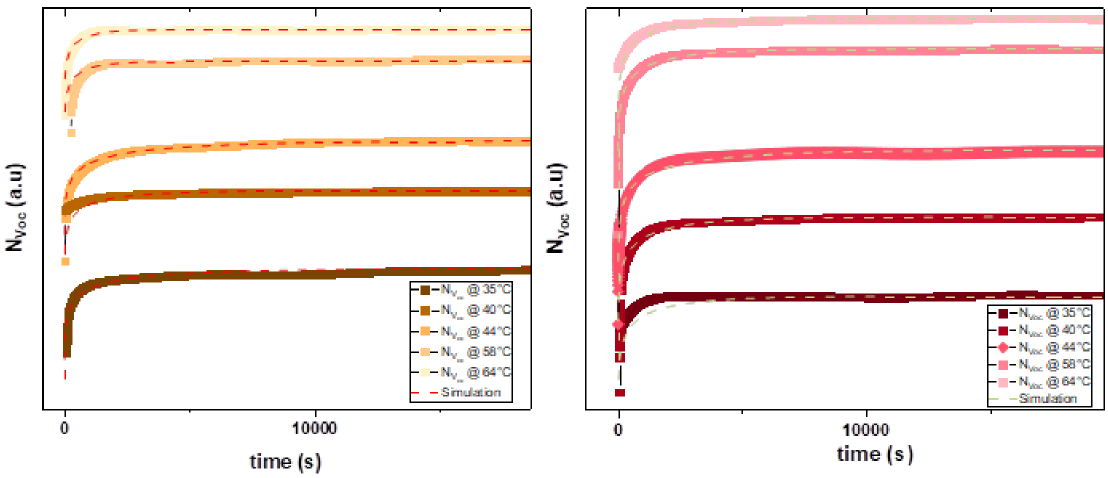


**Fig. 8** *Defect concentration $N_{Voc}$ as a function of light soak duration for the following (a) c-Si; (b) mc-solar cells, under different LID test temperatures*

Fig. 9 shows the variation of the defect concentration at saturation ($N_{max}$) vs. temperature, with measurements taken following an illumination time of 6 hours. Moreover, for both solar cells, we find an increase in the defect concentration at the saturation value with increasing the temperature. Further, the mc-Si solar cells are slightly more affected with temperature variation compared to the c-Si solar cells in the same experimental conditions. Finally, for temperatures superior to 50°C the formation of metastable defects starts to reach the complete saturation state for the two types of solar cells, these results are in good argument with the literature [7].

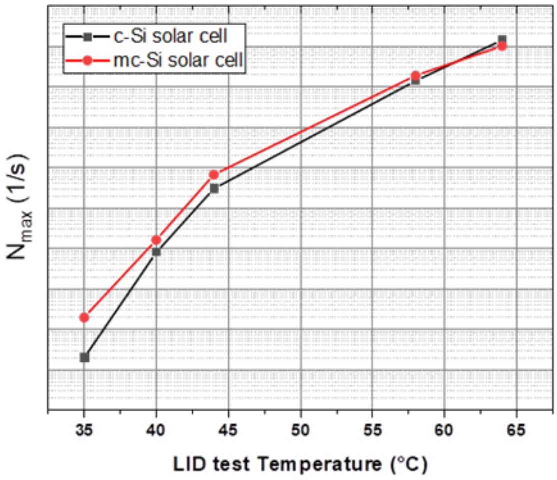


**Fig. 9** *Variation of the defect concentration at saturation $N_{max}$ vs. LID test temperatures*

## 3.4 Thermal Activation Energies of the Defects

The defect generation rate $R_{def}$ can be determined by fitting the following equation (Eq. 2) [30]. The measurement of $R_{def}$ at different temperatures allows the determination of the thermal activation energy $E_{act}$ of the defects using the expression (Eq. 3) [31].

$$N_{V_{OC}}(t) = N_{max}[1 - e^{-(R_{def}*t)}] \quad (2)$$

$$R_{def} = R_0 e^{-E_{act}/k_b * T} \quad (3)$$

Where:

$R_0$: is the characteristic factor of the physical mechanism of the defect formation, $k_b$ is Boltzmann's constant and T is the operating temperature.

Fig. 10 shows the Arrhenius plot of the defect generation rate $R_{def}$ as a function of temperature for c-Si and mc-Si based solar cells. Moreover, the measured data points lay on a straight line, which clearly proved that the formation process is thermally activated [32]. Further, from the slope of the linear curve illustrated in Fig. 9, we determined for the c-Si solar cells an activation energy of $E_{act,mono}$ ~0,42 eV. Previous studies have reported values in the range of 0.3 to 0.475 eV [27,33,34].

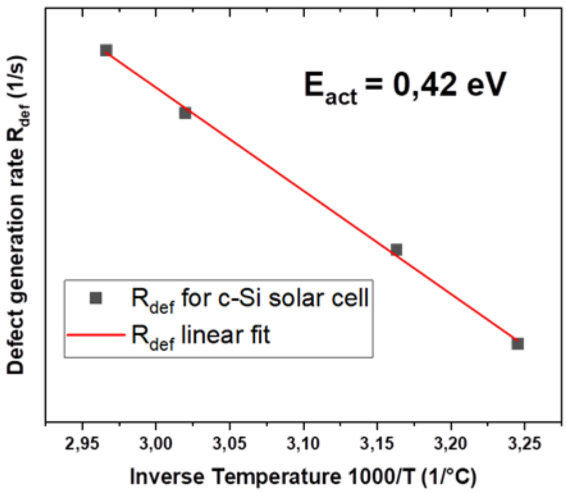


**Fig. 10** *Arrhenius plot of the defect generation rate $R_{def}$. Best fits to $E_{act}$*

## 4. Conclusion

In summary, the impact of LID test on industrial solar-grade cells with an aluminum back surface field (Al-BSF) based on p-type mono- and multi-crystalline silicon substrates, has been investigated. Moreover, the LID test was monitored using low-cost virtual data acquisition system (VDAS) based on an Arduino board coupled with

MATLAB/Simulink software. Further, the solar cell open-circuit voltage, temperature, and the light intensity data were measured and stored in real time. Furthermore, a comparison between the proposed VDAS and conventional data acquisition was made, the results show that VDAS solution is more accurate, less expensive and reduces the testing time. Also, the simulation of the $V_{OC}$ output degradation as a function of illumination time validated the predominance of one type metastable defect over the LID test of c-Si solar cells. Likewise, the interpretation of the $V_{OC}$ degradation mechanism model is implicit, that more than one metastable defect coin in the degradation of mc-Si solar cells. Additionally, the experimental $V_{OC}$ measurements obtained using VDAS allowed for the successful extraction of defect concentrations ($N_{Voc}$) and thermal activation energies ($E_{act}$) of the defects. The time required to reach the saturation points of the defect concentration $N_{max}$ was related to the temperature of the LID test. Finally, the proposed data acquisition system is expected to improve the testing and control of the solar cells, thus contributing to an increase in the efficiency of these last.

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## Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

## Author Contribution

*The authors confirm contribution to the paper as follows:* ***study conception and design:*** *Kouhlane, Y. & Bouhafs, D.;* ***data collection:*** *Chibane Y. & Zerguine, A.;* ***analysis and interpretation of results:*** *Kouhlane, Y. & Chibane, Y.;* ***draft manuscript preparation:*** *Kouhlane, Y. All authors reviewed the results and approved the final version of the manuscript.*

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