Reliability Evaluation of Photovoltaic Modules Fabricated from Treated Solar Cells by Laser-Enhanced Contact Optimization Process

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According to the International Technology Roadmap for Photovoltaics, passivated emitter and rear solar cells dominate the market in 2021 of up to 80% and are forecast to remain state of the art at least for the next 5 years. Within the production process of solar cells, it is typical to have cells with lower efficiency grades due to variations in manufacturing processes or material defects. Reprocessing such solar cells could save cost due to increased production yield and simultaneously reduced cost for recycling of unusable/unsellable low-efficiency cells. Herein, the impact of the laser-enhanced contact optimization (LECO) process on the power output and reliability of solar modules using commercial off-spec cells of different manufacturers is analyzed. LECO is a downstream process for optimizing metal–semiconductor contacts on finished solar cells. The treatment leads to a significant economic gain due to enhanced cell efficiency (Wp↑, therefore manufacturing cost per Wp ↓) even of already good solar cells. Herein, the first evaluation of the impact of the LECO process on the cell output power on an industrial scale (>1000 cells) and on module reliability is presented. The results for common short-term effects like light-induced degradation and light- and elevated temperature-induced degradation are within expected limits and the durability against, for example, potential-induced degradation is not changed due to the LECO process. The results further show that cell sorting is crucial for a reliable module and to avoid outliers in terms of unexpected degradation and recovery phenomena of individual cells.

1. Introduction

According to the International Technology Roadmap for Photovoltaics,\cite{1} passivated emitter and rear solar cells (PERCs) dominate the current market (>80% share\cite{1}) and they will remain state of the art at least for the next five years. In the development of the PERC cell technology, a major focus is currently on metallization\cite{1–3} to optimize the efficiency of the cell, while in parallel a reduction in, for example, silver is required to lower consumable costs. Within this area, a novel helpful tool is the laser-enhanced contact optimization (LECO) process. LECO is a downstream treatment for solar cells, that can be used for the improvement of metal–semiconductor contacts. As the metallization quality of PERC cells is very sensitive to variations in the manufacturing process, a major share of low-efficiency/off-spec cells within a production occurs due to an imperfect contact between the metal and semiconductor. These very cells can be recovered from scrap to the benchmark level of the standard production by the LECO treatment. The process itself was introduced in 2019 as an application on...
several cell types.\cite{4} The effectiveness of improving the contact resistance of off-spec PERC cells has been shown on lab scale where a reduction from $>270$ to $3 \, \text{m}\Omega \, \text{cm}^2$ could demonstrated on an extremely low-doped emitter ($>200 \, \Omega \, \text{square}^{-1}$).\cite{14} Beyond just recovering scrap cells, LECO can be utilized to further optimize PERC cells if implemented in the cell production itself. In the latest publications, a clear efficiency gain could be shown, which was generated due to an adaption of the firing process\cite{6} and the additional usage of an adapted metallization paste.\cite{7} First investigations on the long-term stability of a small number of lab cells indicate that the LECO process does not significantly impact the degradation stability against boron—oxygen-related LID (BO-LID), light- and elevated temperature-induced degradation (LETID), and potential-induced degradation (PID),\cite{8} which are the most common degradation types for PERC cells and modules.\cite{9–14}

In this work, we present the effectiveness of LECO on cell level in an industrial scale using lower-grade solar cells from different manufacturers, as well as a comprehensive study on reliability on module level.

2. Experimental Section

2.1. Cell Treatment by LECO Approach

In the cell optimization process, in total, over 1000 solar cells from three different manufacturers and with different initial qualities (all standard process, standard pastes, but by manufacturer scrapped due to low power or optical properties) were treated by the LECO process. Table 1 shows the respective numbers and cell classes that were used to investigate the impact of LECO treatment on the PV module level.

The cells of producer 1 were provided in three monocrystalline off-spec cell classes, sorted by electrical and optical classification. In addition, the lowest available efficiency bin of monocrystalline PERC cells by manufacturer 2 and multicrystalline cells of manufacturer 3 were used. All those cells were treated with the LECO process. As a reference, a batch of 195 cells of the commercial efficiency class of 20% and optical B classification from manufacturer 1 was used.

The patented LECO treatment\cite{15} was performed on the commercially available LECO Labtool developed by Cell Engineering in Germany.\cite{16} In Figure 1a, the region of impact (ROI) of the LECO process was sketched. During treatment, a laser scanned over the cell surface inducing charge carriers. Simultaneously, a negative voltage was applied to the cell. This reverse bias accelerated the induced free carriers through the metal—semiconductor interface (Figure 1b). The LECO treatment of a full-size solar cell took at the moment about 1.6 s. The parameter recipe used was the standard setup for PERC cells (available on the LECO-Labtool software “LECO-Control”).

As a result of the LECO treatment, the contact resistance between the silver finger and the silicon emitter decreased. At the same time, the passivation quality was not influenced.\cite{5–7}

A first model of the microscale contact formation was recently presented by Großer et al.,\cite{17} introducing LECO-induced locally limited current-fired nanoscale silicide contacts.

The electrical characteristics of the solar cells were measured before and after the LECO process with a sun simulator and partly also with electroluminescence imaging.

2.2. Module Manufacturing

To study the reliability of the LECO-processed cells, several PV modules with different treated solar cells were manufactured. The module materials were standard production module materials, including standard rolled solar glass coated with an antireflection coating (ARC), UV-transparent, and UV cut-off ethylene vinyl acetate (EVA) as front- and rear-side encapsulants, respectively, and a white backsheet.

For the LECOed solar cell reliability study, modules were manufactured, where always 20 cells from each cell category, as defined in Table 1, were interconnected in series, and each pole was connected to an individual junction box for reliable $I–V$ curve measurements. The junction boxes were manufactured without any bypass diodes, and they were electrically and mechanically separated from each other. With the 20-cell approach, different types of solar cells mentioned in Table 1 can be studied simultaneously in a single module and easily compared.

The sample modules were divided into two groups. Group 1 consisted of LECO-treated solar cells from batches with different classes based on electrical and optical criteria manufactured by producer 1. Group 2 contained a string made from reference solar cells manufactured by producer 1 without the LECO process and two strings made from cells from producers 2 and 3 after the LECO process. The total amount of 17 60-cell modules including 9 modules according to the described setup for group 1 and 8 modules according to group 2 were fabricated at Fraunhofer CSP. A sketch and picture of the front and rear sides of the modules are shown in Figure 2.

Table 1. Numbers and initial classes of used solar cells for this investigation.

| Classification | Producer 1 | Producer 2 | Producer 1 | Producer 3 |
|----------------|-----------|-----------|-----------|-----------|
| Class 1<sup>a</sup> | Class 2<sup>a</sup> | Class 3<sup>a</sup> | Reference<sup>6</sup> |
| Initial label | Off-spec | Low eta | 20%, optical B | Low eta |
| No. of cells | 216 | 226 | 224 | 193 | 195 | 194 |

<sup>a</sup>Cells used for LECO treatment; <sup>6</sup>Not treated cells used as reference.
After manufacturing, all modules were measured by a flash test to determine the module power and with electroluminescence to check for cracks or other module manufacturing-induced defects that may influence reliability testing. Power loss and changes in the electro luminescence (EL) images of that group of cells will serve as reference.

### 2.3. Reliability Tests

To investigate the stability of the LECO-processed cells, the modules mentioned above were put through different reliability and durability tests. As LECO does not fundamentally change the semiconductor material itself, the first main focus was to verify...
the stability against short-term effects. The stability against LETID was tested for the first set of modules, following the draft version of IEC TS 63342.[18] A preconditioning for BOLID was performed utilizing the current-induced degradation (CID) method, where a current near $I_{SC}$ ($I = 10$ A) was applied to the modules at 25°C for 24 h. These test conditions assured activation of BOLID but did not activate LETID defects.[12,19]

Subsequent two modules were tested for LETID by applying a current of $2 \times (I_{SC} - I_{MPP})$ at 75°C for intervals of 168 h to a total test time of 3 weeks.

In the second test run, we concentrated on any kind of modification due to PID. Here mainly the focus was on manufacturer 1 as no direct reference existed for manufacturers 2 and 3. PID tests were performed following IEC TS 62804-1 procedure.[20] The modules were exposed to a potential of 1000 V, while being in a climate chamber set to 85°C and 85% relative humidity (rh) for intervals of 96 h.

The third group of modules was run through a set of long-term IEC-based tests and sequences. A damp heat (DH) test (IEC 61215[21] MQT 13, 85°C, 85%rh) and thermal cycling (TC) test (IEC 61215 MQT 11, temperature changes between −40 and 85°C, $I_{MPP}$ current injection during the heating phase), as well as outdoor exposure, were run. Those tests were planned to be test-to-fail; results will be compared with commercially available cells and modules and it is expected that those test-to-fail sequences will take several months to be completed. No final test-to-fail results are yet available from these extended reliability tests. However, the first results are presented in Figure 9 for the first 600 h of the DH test (60% of minimum IEC requirement) and the first 200 cycles of TC (100% of IEC requirement).

All modules were characterized by flash tests at standard test conditions (STC) and low-light conditions (200 W m⁻²), as well as EL imaging with a current near $I_{SC}$ and partly at 10% $I_{SC}$. Characterizations were performed pre-, intermediated, and post-testing. Furthermore, during some tests, online monitoring was applied to detect changes during applied stress.

Beyond the indoor tests, some modules were installed outdoors on the roof of Fraunhofer CSP to investigate the energy production of each LECO-treated cell type. Such modules got a CID preconditioning prior initial flash test and installation on the roof. $I-V$ curves will be taken regularly and between measurements the modules are kept at $P_{MPP}$ conditions to achieve real-outdoor module temperature conditions. Besides the online measurements, the modules will be taken of the roof from time to time for indoor characterization. The first outdoor results will available in autumn 2021. Results will be published elsewhere when available.

3. Results

The results will be split into two sections. First, the cell optimization results will be presented. Those show the potential of the LECO process. The second section displays the results of module testing.

3.1. Cell Results

The results from cell measurement before and after the LECO process for the three cell producers are shown in Figure 3. The cells of producer 1 originate from the same manufacturing process but are sorted into different quality classes. For producers 2 and 3, only one efficiency grade class is investigated.

The solar cells of producer 1 before the LECO process have a median power of 3.46, 4.52, and 4.98 Wp and all solar cells after the LECO process have a power of about 5.2 Wp. This shows a relative gain in power up to 34.3% after the LECO process. The solar cells from manufacturers 2 and 3 had initially already high-efficiency grades but still showed after the LECO process 1.6% and 2.0% gain in median power increase. In Figure 4, three

![Figure 3](image-url)  
*Figure 3.* Absolute power of solar cells before and after LECO treatment.
representative EL images of the same cells before and after LECO are depicted.

From Figure 4, the origin of the improvement in the power of the cell can be derived. Clearly visible series resistance ($R_s$)-related defects\(^{[22]}\) are removed after the LECO treatment. So, the gain in power arises via the reduction of $R_s$. The cells of producers 2 and 3 have been initially more homogeneous in terms of a quite narrow efficiency level and a hardly visible change in EL signals. From previous publications it is already known that the largest improvement due to LECO can be observed for the low-efficiency, low-fill factor (FF) cells\(^{[3,4]}\) leading to a lower spread of data. Therefore, the observed results underline the already known properties of the LECO treatment.

3.2. PV Module Results

3.2.1. Initial Characterization

After module manufacturing, 17 modules were initially characterized. The results of the flash tests are given in Figure 5.

As expected from the results on cell level in Figure 3, the modules from producer 1 and 2 (monocrystalline material) had similar output power, while the multicrystalline cells from producer 3 reached a lower, but expected, output power, representing similar cell-to-module (CTM) ratios for all cells under investigation.

The influence of LID, LETID, PID, and long-term durability will use the initial characterization results as a reference and next only normalized numbers will be presented due to better comparison.

![Figure 4. Electroluminescence image of one representative solar cell of a) class 1, b) class 2, and c) class 3 from producer 1 before and after LECO treatment.](image)

![Figure 5. Initial string power after LECO treatment and module manufacturing, before stability testing.](image)
reduction in \( J_{SC} \), as is common with BO degradation.\(^{[23]}\) The FF remains largely stable.

The test for LETID susceptibility was performed with one module from each of the two groups. Samples were randomly assigned to each test. Except for the conspicuous sample, producer 1, class 2, all other samples in the LETID test had a reduction in performance between 1% and 1.5% after the BO test. For the determination of degradation by LETID, the power loss is related to the power after BO preconditioning. As shown in Figure 7, there is only a small degradation of around 2% after 2 weeks and the string power remains at the same level after this point. The cells can be regarded as LETID stable according to the IEC 63342 standard.\(^{[18]}\) The result for producer 1, class 2 is an exception as this is a string with a BO degradation of 4.5%. In this case, the BO degradation regenerates under the LETID test conditions, so that an increase in performance is found (similar to results in the study by Pander et al.\(^{[24]}\)).

3.2.3. PID

Degradation due to PID has been investigated in four test cycles equals 4-times IEC TS 62804-1 requirement. After the first 96 h, the power degradation is very low at 1% at STC conditions for all modules. In the further course, the highest power losses are seen for producer 1, Ref and producer 2 (2.8% and 2.7%, respectively). Slightly higher power losses are seen in the low-light power (3.2% for producer 2, Figure 8). However, good stability regarding PID was observed for all cells. Actually, the degradation was comparable with the modules that were only subjected to DH conditions, as shown in Figure 9.

3.2.4. Long-Term Testing

The status of the DH test is shown in Figure 9, left. Short-term degradations of 1–2% are observed with respect to the results after CID. No significant differences are seen between the different groups. We also carried out interim measurements during the TC test. The status of the TC test can be seen in Figure 9 on the right side. The only abnormality found so far is the

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**Figure 6.** Power loss due to BOCID (24 h, 10 A, 25 °C).

**Figure 7.** Power loss due to LETID (2x(\( J_{SC} - J_{MPP} \)), 75 °C).

**Figure 8.** a) STC and b) low-light power changes due to PID (85 °C, 85%rh, 1000 V).
regeneration of the BO degradation of the string with producer 1, class 1 cells. In this special case, we observed an increase of $I_{SC}$ (+1.5%) and $V_{OC}$ (+2.5%), while these parameters are quite constant for the other strings, that show a slight degradation of 1–2.5%.

4. Summary and Discussion

To reduce costs by process optimizations, new and innovative processes for waste reductions will be essential in the future. The LECO process provides both: improved cell efficiencies and a reduced number of off-spec cells due to its capability to significantly improve low efficiency, not sellable ($P < 4$ Wp), solar cells. Within this contribution, the effectiveness of the LECO process was investigated and the stability of the resulting solar cells was studied in extensive accelerated aging tests and will be confirmed by outdoor energy yield measurements that are ongoing.

To evaluate the effectiveness, in total, over 1000 solar cells of different classes and manufactured by different producers were treated with the LECO process. A gain of up to 34.3% relative in cell power could be observed, while the largest boost was seen for the low-efficiency, low-FF cells. LECO leads to a sharpened efficiency distribution and this obviously in the end leads to a reduced share of off-spec cells. However, as the results show, cell sorting will be still essential for the production of reliable and predictable PV modules. Even individual cells within a string can significantly lower the output power and therefore will also negatively affect energy production.

The origin of the efficiency improvement by LECO treatment is an improved series resistance, which was also clearly shown within this work by electroluminescence images of cells before and after the LECO treatment.

To analyze the reliability of the optimization process and the final durability of the processed cells, a large batch of cells with initially different characteristic were LECO processed. Modules comprising string-wise-treated and nontreated cells have been used for extensive stability testing. The results show that the degradation stability against the typical degradation mechanisms, LID, LETID, and PID, seems not to be impacted by the LECO treatment. Preliminary results of ongoing DH and TC tests also showed no influence, which can be accounted to the LECO treatment. Nevertheless, some outliers can be observed, which originate from the properties of the used off-spec material itself and the cell sorting criteria as only a power sorting was done and no additional sorting, for example, for optical properties or current matching.

To cover all long-term effects, further testing of the modules, used within this work, is ongoing. The results will be published elsewhere as soon as long-term testing is finished. First, an extended TC > 600 cycles, DH > 2000 h, and a combined stress test sequence containing DH–UV–high frequency (HF) is in progress. Finally, we build 12 standard modules with LECO-treated and nontreated solar cells from the same batch from the three different classes of producer 1. We will measure the energy yield of the PV modules at the Fraunhofer CSP outdoor facility and compare the data after sufficient duration.

Acknowledgements

The authors thank the German Federal Ministry of Economics and Technology (BMWi) for funding this work under the contract of CTS1000plus with the reference number of 03EE1028A. The affiliations and a reference were updated on March 11th, 2022.

Open access funding enabled and organized by Projekt DEAL.

Conflict of Interest

The authors declare no conflict of interest.
Data Availability Statement

Data available on request from the authors.

Keywords

degradation, durability, efficiency optimizations, laser treatments, laser-enhanced contact optimization, photovoltaics, reliability

Received: July 15, 2021
Revised: September 10, 2021
Published online: November 5, 2021

[1] VDMA, https://itrpv.vdma.org/en/ (accessed: July 2021).
[2] R. Preu, E. Lohmüller, S. Lohmüller, P. Saint-Cast, J. M. Greulich, *Appl. Phys. Rev.* 2020, 7, 041315.
[3] A. Blakers, *IEEE J. Photovoltaics* 2019, 9, 629.
[4] R. Mayberry, K. Myers, V. Chandrasekaran, A. Henning, H. Zhao, E. Hofmüller, in 36th European Photovoltaic Solar Energy Conf. and Exhibition 2019, ISBN: 3-93633860-4.
[5] E. Krassowski, S. Großer, M. Turek, H. Höffler, in 37th European Photovoltaic Solar Energy Conference and Exhibition 2020, pp. 1–25, ISBN: 3-936338-73-600.
[6] H. Höfllner, T. Fellmeth, J. Greulich, E. Krassowski, A. Henning, in *Proc. of Silicon PV Conf.*, AIP Conference Proceedings 7645, 2021.
[7] E. Krassowski, S. Großer, M. Turek, A. Henning, H. Zhao, in *Proc. of the 9th Workshop on Metallization and Interconnection for Crystalline Silicon Solar Cells*, AIP Conference Proceedings 2367, 2021, p. 020005, https://doi.org/10.1063/5.0056380.
[8] E. Krassowski, T. Luka, V. Naumann, M. Turek, S. Großer, H. Zhao, in *Proc. of Silicon PV Conf.*, AIP Conference Proceedings 16683, 2021.
[9] K. Bothe, J. Schmidt, *J. Appl. Phys.* 2006, 99, 013701.
[10] T. Luka, F. Kersten, M. Pander, M. Köntopp, M. Turek, W. Bergholz, T. Pernau, *PV Power Plant Technol. Business* 2020, 23, 51.
[11] D. Chen, M. Vaqueiro Contreras, A. Ciesla, P. Harner, B. Hallam, M. Abbott, C. Chan, *Prog. Photovoltaics Res. Appl.* 2020, 29, 1180.
[12] F. Kersten, P. Engelhart, H. C. Ploigt, A. Stekolnikov, T. Lindner, F. Stenzel, M. Bartzsch, A. Szpeth, K. Petter, J. Heitmann, J. W. Müller, *Sol. Energy Mater. Sol. Cells* 2015, 142, 83.
[13] V. Naumann, D. Lausch, A. Hähnel, J. Bauer, O. Breitenstein, A. Graff, M. Werner, S. Swatek, S. Großer, J. Bagdahn, C. Hagendorf, *Sol. Energy Mater. Sol. Cells* 2014, 120, 383.
[14] P. Hacke, K. Terwilliger, R. Smith, S. Glick, J. Pankow, M. Kempe, S. K. I. Bennett, M. Kloos, in *Conf. Record of the IEEE Photovoltaic Specialists Conf.*, 2011, pp. 000814–000820.
[15] H. Zhao, Patent: WO 2018/024274, CE Cell Engineering GmbH, 2018.
[16] www.cell-engineering.de/product (accessed: June 2021).
[17] S. Großer, E. Krassowski, S. Swatek, H. Zhao, C. Hagendorf, *J. Photovoltaics* 2021, https://doi.org/10.1109/JPHOTOV.2021.3129362.
[18] IEC TS 63342—Light and elevated temperature induced degradation (LETID) test for c-Si Photovoltaic (PV) modules: Detection (Draft), 2021.
[19] J. M. Fritz, A. Zuschlag, D. Skorka, A. Schmid, G. Hahn, *Energy Procedia* 2017, 124, 718.
[20] DIN IEC/TS 62804-1 VDE V 0126-37-1:2017-05 Photovoltaik (PV) Module – Prüverfahren für die Erkennung von spannungsinduzierter Degradation, https://www.vde-verlag.de/normen/0100379/din-iec-ts-62804-1-vde-v-0126-37-1-2017-05.html (accessed: July 2021).
[21] DIN EN 61215-1 VDE 0126-31-1:2017-05 Terrestrische Photovoltaik(PV) Module – Bauartzulassung, https://www.vde-verlag.de/normen/0100380/din-en-61215-1-vde-0126-31-1-2017-05.html (accessed: July 2021).
[22] T. Trupke, E. Pink, R. A. Bardsor, M. D. Abbott, *Appl. Phys. Lett.* 2007, 90, 093506.
[23] C.-M. Lin, M. Gläser, E. Malguth, S. Uredat, N. Bernhard, D. Lausch, in *33rd European Photovoltaics Solar Energy Conf. and Exhibition*, 2017, pp. 978–982.
[24] M. Pander, T. Luka, B. Jäckel, J. Bauer, D. Daßler, M. Ebert, M. Turek, C. Hagendorf, in *36th European Photovoltaic Solar Energy Conf. and Exhibition*, 2019, p. 812.