PV-TEC: RETROSPECTION TO THREE YEARS OF OPERATION OF A PRODUCTION ORIENTED RESEARCH PLATFORM

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ABSTRACT: At Fraunhofer ISE the PV-TEC (Photovoltaic Technology Evaluation Center) laboratory has been built up in 2005. Since then the center has been operated constantly and has been expanded by adding advanced technology and increased infrastructure capacity. Various databases have been introduced to track the work done in this large laboratory. In this paper we show data on e.g. roughly 120 thousand wafers have been processed during the last years in about 1300 individual experiments. Further we show the staff size needed for the conduction of this work. When setting up PV-TEC such data would have been helpful but was not available. A robust baseline process is constantly improved and serves as basis for the exploration of new technologies and cell structures. We show how a set of merely industrial processing systems can be combined with new technology components such that advanced solar cell concepts like LFC-PERC, MWT, EWT, and BJ can be developed and processed.
KEYWORDS: Silicon Solar Cell, Manufacturing and Processing, R&D and Demonstration Programmes

1 INTRODUCTION

By the end of 2004 the German PV-industry gave a favorable opinion with respect to the installation of a large technology evaluation platform to be built up at Fraunhofer ISE in Germany. This was the result of a workshop carried out at Fraunhofer ISE in October 2004 attended by several companies operating in the field of PV. In 2005 the BMU (German Ministry for Environment and nuclear safety) launched PV-TEC, a project with a volume of roughly 12 million € budget, in order to equip such a platform (PV-TEC: Photovoltaic - Technology Evaluation Center). Already by the end of 2005 the center became operable with 1200m² lab space and first solar cells being processed with efficiencies of about 15%. In the next years a large number of projects and various developments have been carried out at PV-TEC. The intention of this paper is to reveal observations and data gathered during the operation of the center throughout the last three years which could be of general interest for all institutes and companies which are dealing with expanding research needs. Various aspects are addressed in this paper e.g. statistical data on experiments in PV-TEC and R&D staff size, emerging technologies and solar cell concepts.

Various databases and planning instruments have been developed already in the beginning of the operation of PV-TEC to keep track of material and budget flow. General information was extracted from the databases to show the development of PV-TEC, e.g. the number of wafers processed during the last years. Furthermore the development of various innovative cell concepts on production oriented fabrication tools is detailed and the reached efficiency values are collected. To allow an estimation of the power needed to conduct such research, the development of employee numbers are given. With increasing demand for more research the lab infrastructure was extended. It will be shown what kind of infrastructure is required to operate such a platform. As infrastructure is very rarely addressed in the design of cell processes and R&D this contribution is considered to be relevant as well.

PV-TEC is the largest project the BMU has conducted in the field of PV so far. Monitoring such a project and the resulting R&D platform gives valuable insights into the structures needed to carry out efficient research which is close to industrial demands. R&D carried out on industrial machines represents an own class of research as such tools require relatively large experiments and bring in important industry related aspects like automation and inline testing. There is only little information available on how such environments influence the R&D work and the actual R&D targets. Finally the path of future development of the center will be shown, with respect to improved solar cell efficiencies using industrially applicable solar cell designs.

In [1] we describe the design and implementation of PV-TEC at Fraunhofer ISE and summarize the status of the center with respect to 2006.

Since then in the growing PV-marked the demand for R&D work is extremely high such that PV-TEC was constantly at a very high level of operation in order to comply with the requirements coming from the industrial partners. This demand has led to a constantly increasing number of batches which represent individual experiments conducted in PV-TEC. Each experiment represents several groups of wafers which are processed in the same way to analyze the impact of process variations. This development has lead to an increasing demand for wafers and linked to this development the PV-TEC staff was constantly expanded from year to year.

Developing, improving, and maintaining a robust baseline process is the basis for all developments which aim towards solar cells with high efficiencies while keeping close to the standard fabrication process.

PV-TEC began its operation by setting up the baseline process. Step by step innovative functions of the tools have been activated and the tool set has been supplemented by new systems serving special purposes in order to facilitate the fabrication of passivated solar cells and cell structures like MWT, EWT and BJ solar cells.

2 OPERATION PRINCIPLES

In PV-TEC automated tools are used to reach a reasonable throughput. For this purpose special I/O interfaces were developed to be able to use standardized cassettes (size: 100 wafers) for wafer transport inside of PV-TEC. Trolleys are used to transport the cassettes form one tool to the other. This allows an efficient and flexible interconnection of the various tools for new process sequences, maintaining a reasonable throughput within the systems.

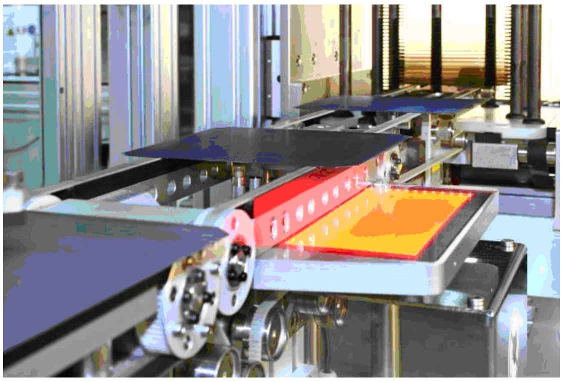

Figure 1 Automated handling and inline characterization in PV-TEC.

Figure 2 The use of industrial tools for R&D imposed many challenges for both researchers and equipment manufacturers.

However, the adaptation of the machine software to the needs of the R&D environment was very challenging since the tools are generally designed to conduct high volume production. Various software functions had to be added in order to adapt the tools to R&D requirements mostly related to precise tracking of wafers or groups of wafers which are supposed to be processed together.

3 STATISTICAL DATA

3.1 Number of individual experiments

During the years of operation the number of experiments which have been carried out in PV-TEC has significantly increased (s. Figure 3). Interestingly the average experiment size roughly was constant and close to 100 wafers (which is actually – but probably only by coincidence - the size of the cassettes used in PV-TEC) per experiment. However there is a significant spread in the size of experiments (not shown) between single wafer runs all the way up to experiments containing several thousands of wafers. Further the complexity of the experiments could be derived by the number of groups of wafer which are being processed identically within one batch. This data is for simplicity reasons not shown here. However, there is also a large spread between rather simple experiments up to batches containing very complex process variations. These experiments are planned with software which was written at Fraunhofer ISE for this purpose. The software not only allows the experiments to be designed within, it also contains a process database and does have an interface to the wafer database of PV-TEC. In this database the wafers are administrated. Both databases access tables which contain the running projects to which the experiments and the wafers are allocated.

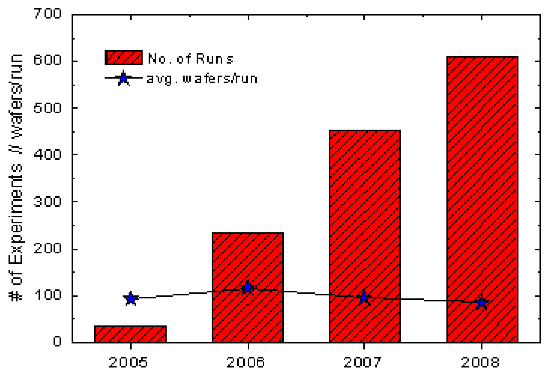

Figure 3 Experiments conducted in PV-TEC. Even though the size of individual experiments is varying considerably, the average size of an experiment is roughly one hundred wafers. This value remained essentially constant during the operation time of PV-TEC. In total roughly 1.300 experiments have been carried out in PV-TEC (by the end of 2008).

3.2 Number and type of wafers needed for the experiments

Beginning in November 2005 when PV-TEC started to ramp up large numbers of wafers have been processed (s. Figure 4). Already in the first year of operation (2006) more than 25 thousand wafers were processed and even exceeding 50 thousand in 2008. The ratio between mc and Cz wafers was balanced in first order over the years. When the innovative passivation processes (stack systems and thermal oxides in combination with advanced cleaning processes) became focus of the development in 2007 and 2008 significantly more FZ wafers have been used, as can be seen in the graph (numbers before where significantly lower and not yet included into the PV-TEC wide wafer database).

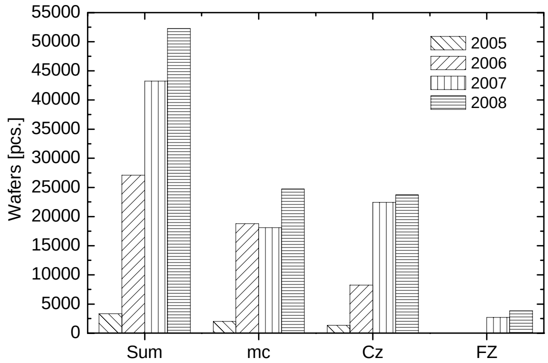

Figure 4 Number of wafers processed in PV-TEC during the three years of operation (in 2005 PV-TEC was only partly in operation). In total more than 120 thousand wafers have been processed in PV-TEC (by the end of 2008).

PV-TEC is equipped to process the formats 125x125, 156x156 and 210x210 mm². While most of the mc wafers have been 156x156 mm² type wafers, we have processed a considerable share of 125x125 mm² type mono wafers. The format 210x210 is rather rarely processed - in total roughly 1000 wafers of this size have been processed. Even though there has been increased interest in 2008 in this format no significant tendency is visible towards this format. However, this could change if new module technologies reach maturity allowing rear contacted cells e.g. MWT to be interconnected economically.

3.3 Personnel in PV-TEC

The conduction of such an amount of experiments was only possible by constantly increasing the number of employees (including research assistants) working in PV-TEC (Figure 5) and related labs.

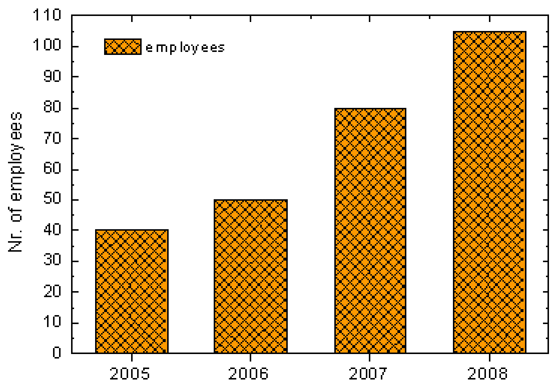

Figure 5 Even though growth is not an initial target of PV-TEC, considerable increase of the PV-TEC related staff size was needed to be able to meet the project volumes and related challenges. Currently more than hundred persons are working related to the PV-TEC lab.

3.4 Teaching for PV-companies

Amongst other service types one important example for a service which is provided by PV-TEC is the number of external trainings carried out at PV-TEC or externally by PV-TEC staff members. This reflects the growing need for skilled personnel in the growing industry where many employees have to be acquired from non-PV branches of business. In total more than 600 individuals have been trained to improve their PV-related skills (Figure 6).

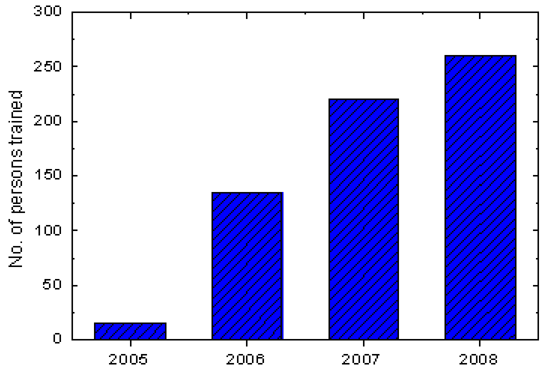

Figure 6 Training activity in PV-TEC. During the last years more than 600 persons have been trained to improve their PV-related knowledge and skills. The size of the trainings was usually limited to 12 persons per group.

4 ADVANCED TECHNOLOGIES

Part of the advanced cell processing technologies was already arranged for in the first set of equipment. Various examples are (for further details please see: [2-7]:

- Thermal oxidation tube in the four tube diffusion furnace
- Hot melt function of screen printer
- Single side etching capability in inline texturing tool
- PECVD passivation layer deposition in the AR-coating machine.
- Cleaning sequences in the batch wet processing tool mainly used for texturing and PSG etching.
- Laser drilling, Laser Fired Contact (LFC) formation and laser ablation capability in the laser systems for marking and laser edge isolation.

We have called this concept “state of the art +” meaning that the systems are capable of being used for baseline processing, but can also be used to execute advanced processes. These functions have been stepwise enforced meanwhile maintaining and improving the robust baseline process. This concept has proven to be very valuable. Besides the standard Al-BSF process sequences for mc and Cz silicon PV-TEC is capable of processing LFC-PERC, MWT, EWT and IBC cells (please see here: [8-12])

After installing PV-TEC constantly new equipment has been added in PV-TEC and additional laboratory areas which are now summarized in the PV-TEC complex e.g.:

- Disc laser for high speed drilling and other laser applications
- Inkjet printing system for masks and metal inks

- Inline diffusion and spray coating
- Inline light induced plating system
- PECVD system upgrade for Al_2O_3 deposition
- High volume inline PVD for metallization

From the beginning on PV-TEC was also equipped with high quality in-line and off-line characterization instruments. Also in this case significant extensions have been possible in the recent years, e.g. :

- High resolution luminescence (EL;PL)
- 3D topography systems for structure analysis
- Analysis systems for chromatography, titration, spectroscopy

The characterization systems are key to successful process and cell structure development. It is believed that the ongoing improvement of cells and cell structures will only be possible together with the development of improved characterization instruments and interpretation concepts.

5 ADVANCED CELL STRUCTURES

The PV-TEC reference process for Cz and mc silicon yields average efficiencies in the range of ~17% and ~16% respectively. Please note, that of course there are runs which considerably surpass this values but this is not considered to be relevant with respect to robustness.

The general process improvements seem to be of more relevance. By improving all aspects of the cell (texture, emitter, ARC, pastes+grid, firing and edge isolation) meanwhile maintaining the robustness of the process the standard cell process efficiency average was increased by >1% absolute within one year.

With respect to advanced cell structures the cells featuring passivated rear surfaces and contacts on both sides are of high interest, because they offer large efficiency potential, and are in general compatible with existing module technology. The LFC-technology allows processing such cells at moderate complexity increase. Recently we have suggested and demonstrated [8-10] various processing sequences from which such cells can emerge with minimal changes in the standard process. This principle is believed to be very helpful in terms of reducing market entry barriers and making use of existing knowledge as much as possible.

With respect to rear contacted solar cells there is a large variety of structures being developed. Currently MWT (Metal Wrap Through), EWT (Emitter Wrap Through) and BJ (Back Junction) cells are under investigation.

Of these cells the MWT cell is closest to the standard process and is considered to be implementable with least efforts. This cell concept has proven to surpass the standard cell process by ~0.4% in efficieny (abs.). Further it allows additional gain by avoiding FF loss, as occurs in standard module fabrication. In further research the MWT cells are supposed to be fabricated with passivated rear surfaces.

EWT solar cells are also under development. High speed laser drilling processes developed at PV-TEC allow to form the hole pattern in several seconds. A remarkable property of this cell structure is the capability of yielding high efficiencies for medium rather low bulk lifetimes. However this concept is not limited to this case. Excellent EWT cells exceeding 20% have been fabricated by Engelhart et al. with PVD processes [13] and on this conference we show efficiency values up to 18.8% for screen printed EWT solar cells [12].

PV-TEC has contributed to the development of the Quebec cells which represents the pure BJ cell concept [14].

It appears that the decision for the best suitable cell concept still cannot be made yet and it will probably turn out that based on the material or other circumstances different concepts are to be selected. Furthermore no consistent set of simulations exists in order to facilitate this decision. Such a set would also imply a rather broad knowledge on the set of existing and future technological limits in order to vary the relevant parameters.

6 INFRASTRUCTURE DATA

To be capable of increasing the research intensity, the infrastructure of PV-TEC has been expanded in 2008 to the full capacity. Initially the utility tools have been designed such that all system capacities could be increased in case the demand for more service would rise above the initial estimates. The design of the center in which the utility systems and the processing/characterization systems are spatially separated has allowed an efficient extension of the utility systems without disturbing the R&D activity for more than two weeks. The capacity of the utility systems is shown in Table 1.

Table 1 Utility systems of PV-TEC. The initial configuration was selected to operate PV-TEC during the first 2 years. The full capacity was already arranged for in the initial stage but realized in 2008 when the costs were justified by a demand for higher R&D capacity.

system type	sub system	initial configuration	full capacity
Ventilation	Air supply	22.500 m³/h	45.000 m³/h
	Process exhaust	7.400 m³/h	11.000 m³/h
	Chemical exhaust	15.200 m³/h	30.000 m³/h
DI-Water	Reservoir	10 m³	15 m³
	Production	1 m³/h	3 m³/h
Neutralisation	Reactor+buffertank	15 m³	29 m³
	Dosing unit	small	large

7 CONCLUSIONS

The launch and operation of PV-TEC is shown to have been very successful which was not clear from the beginning of the project, when only non binding letters of intent from the industry had to convince the BMU to launch PV-TEC. It can be seen that already in the first year of operation significant amount of R&D was carried out strongly increasing in the following years, e.g. more than 120 thousand wafers have been processed up to now. More than hundred persons are involved in PV-TEC related research. Within the “state of the art+” approach we have embedded various innovative components in the standard processing equipment. These components have been activated step by step and supplemented with new equipment.

Beginning with efficiencies close to 15% the development of improved processing sequences, technologies, characterization methods and materials, lead to efficiencies of in average at about ~16% and 17%

for mc and Cz respectively.

By developing advanced cell processes including passivated surfaces the efficiencies have shown to be further increasable without drastic modification in the state of the art standard process. This way industrial LFC solar cells with efficiencies exceeding 18% have been fabricated. Rear contacted solar cells like MWT and EWT are also being developed and remarkably high efficiencies exceeding 18% have also be achieved in this field.

The choice for the best cell concept still does not seem to be straight forward. Novel technologies and processes are expected to allow cost effective production of advanced devices. Further work in this technological area including simulation activity which accounts for shifted technological boundary conditions is considered to allow remarkable future improvement of the industrially produced silicon solar cells.

8 ACKNOWLEDGEMENTS

The authors acknowledge the BMU for funding this work in the projects PV-TEC (0329984) and MASSE (0329849B).

All companies that have supported the launch of PV-TEC and that have run projects with us in the last years are gratefully acknowledged.

We thank all equipment vendors that have provided PV-TEC with high quality equipment, and patiently have worked with us on the innovative functions and the software of the tools.

All PV-TEC staff members for their daily contribution to PV-TEC. Special thanks to the ISE utility staff for their essential work keeping the infrastructure of PV-TEC running day and night.

9 REFERENCES

1. D. Biro, et al., in Proceedings of the 21st European Photovoltaic Solar Energy Conference, (2006), Dresden, Germany, p. 621-4.
2. J. Rentsch, et al., in Proceedings of the 23rd European Photovoltaic Solar Energy Conference, (2008), Valencia, Spain, p. 1889-92.
3. R. Preu, et al., in Proceedings of the 4th World Conference on Photovoltaic Energy Conversion, (2006), Waikoloa, Hawaii, USA, p. 1040-3.
4. A. Grohe, et al., in Proceedings of the 22nd European Photovoltaic Solar Energy Conference, (2007), Milan, Italy, p. 1751-4.
5. N. Mingirulli, et al., in Proceedings of the 23rd European Photovoltaic Solar Energy Conference, (2008), Valencia, Spain, p. 996-9.
6. M. Zimmer, et al., in Proceedings of the 23rd European Photovoltaic Solar Energy Conference, (2008), Valencia, Spain, p. 1057-61.
7. M. Hofmann, in this conference.
8. L. Gautero, et al., in Proceedings of the 34th IEEE Photovoltaic Specialists Conference, (2009), Philadelphia, USA.
9. D. Biro, et al., in Proceedings of the 34th IEEE Photovoltaic Specialists Conference, (2009), Philadelphia, USA.
10. A. Wolf, et al., in Proceedings of the 34th IEEE Photovoltaic Specialists Conference, (2009), Philadelphia, USA.
11. F. Clement, et al., in Proceedings of the 23rd European Photovoltaic Solar Energy Conference, (2008), Valencia, Spain, p. 1871-74.
12. N. Mingirulli, et al., this conference
13. P. Engelhart, PhD-Thesis, University Hannover (2007), Universität Hannover
14. D. Huljic, et al., in 21st European Photovoltaic Solar Energy Conference, (2006), Dresden, Germany, p. 765-8.