# P-TYPE MWT SOLAR CELLS: CURRENT STATUS AND FUTURE EXPECTATIONS

B. Thaidigsmann, M. Hendrichs, S. Nold, E. Lohmüller, A. Wolf, F. Clement, D. Biro, R. Preu
Fraunhofer Institute for Solar Energy Systems ISE, Heidenhofstr. 2, 79110 Freiburg, Germany

ABSTRACT: This work gives a review on the present status of p-type metal wrap through (MWT) silicon solar cell development and presents future expectations. With novel materials and approaches, many critical issues that have been discussed as potential show stoppers in the past are now overcome. The MWT technology, especially when combined with rear surface passivation, has the potential to significantly decrease cost of ownership. According to our calculations, MWT-based modules show a cost advantage of 2 % against H-pattern approaches; cell conversion efficiency is expected to reach 21 to 22 % in the medium term.
Keywords: MWT, PERC, HIP-MWT, CoO, silicon, photovoltaics, PV

## 1 INTRODUCTION

### 1.1 Motivation

"Are MWT solar cells at a dead end or finally approaching breakthrough?" is a question that may arise after both research institutes and industry have promoted industrial fabrication of MWT solar cells [1] for a decade now [2–6], but still today MWT modules do not hold a significant market share. This work aims at finding an answer to this question. It presents an overview over the development of the MWT cell and module technology and discusses the advantages and disadvantages compared to conventional H-pattern approaches. Furthermore, this paper reviews the variety of different MWT structures and contact layouts that have been published over the last years.

### 1.2 MWT Structures

Figure 1 summarises the most popular MWT configurations. The main motivation behind the introduction of novel structures is the simplification of the process sequence in order to reduce fabrication costs.

Yin et al. proposed a simplified version of the conventional MWT-BSF structure that only exhibits an emitter on the front [7]. For MWT solar cells with rear surface passivation (MWT-PERC) [8], a simplification of the structure is also possible [9]. A simplified MWT structure with rear surface passivation but without rear emitter is called high-performance MWT (HIP-MWT). Improvements such as selective emitter structures [10] are compatible with all presented MWT approaches.

## 2 APPROACH

A review of recent publications from institutes and industrial manufacturers is carried out. This allows for an identification of trends and challenges. Despite the option to integrate rear surface passivation and to vary the contact layout, several configurations of the diffused areas have been developed (regarding the formation of an emitter in the vias or beneath the rear n-type contacts) [7, 9, 11]. The simplification of the process sequence as well as the module interconnection is the driving force behind these developments.

Since the selection of the MWT cell structure is independent from the geometric arrangement of the rear contacts, these two issues are evaluated individually within this work. The most promising external contact layout is identified by taking into account the expected

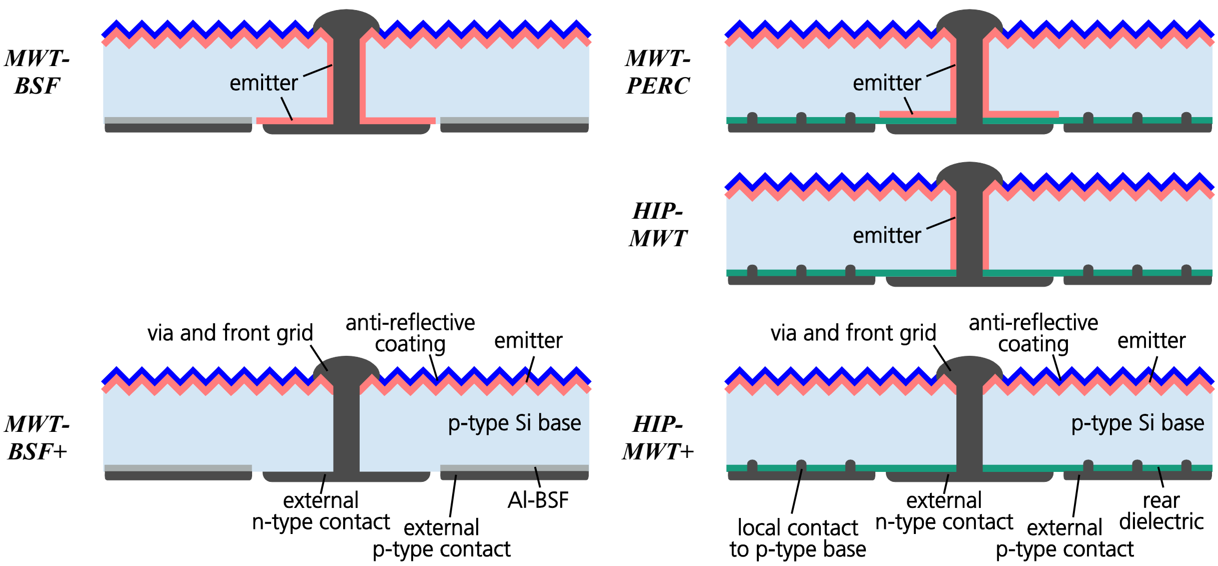


**Figure 1**: Overview over the various MWT structures for p-type silicon base material that have been evaluated so far. MWT-BSF+ denotes a simplified MWT-BSF structure without an emitter in the via and at the rear. This structure was first published by Yin et al. [7]. The high-performance MWT (HIP-MWT) approach [9] is a simplified version of the conventional MWT-PERC structure that omits the rear emitter. Within this paper, the further simplified structure even without an emitter in the via is referred to as HIP-MWT+.

conversion efficiency for each contact configuration as well as cost of ownership calculations.

## 3 RESULTS AND DISCUSSION

### 3.1 Efficiency Potential

The estimated efficiency potential of p-type MWT solar cells with printed contacts is calculated using analytical device modelling based on previously published experimental results for HIP-MWT solar cells with magnetically Cz-grown silicon (mCz-Si) base material, stencil printed front grid and three external contact rows [12]. Figure 2 shows the results of the calculation after considering the following improvements: reduction of the emitter dark saturation current density to $j_{0e}$ = 100 fA/cm$^2$, narrower front grid lines (50 % less shading), reduced rear surface recombination velocity $S_{pass}$ = 10 cm/s, optimised base resistivity and a reduced interstitial oxygen concentration of $[O_i]$ = 3·10$^{17}$/cm$^3$. Stable conversion efficiencies exceeding 21 % seem feasible in the medium term. The calculation does not account for the positive impact of an increased number of rear contact rows discussed in the following. This, as well as the integration of novel front contact approaches such as plated contacts [13] and an optimised formation of local rear contacts with reduced recombination might increase the maximum efficiency even further.

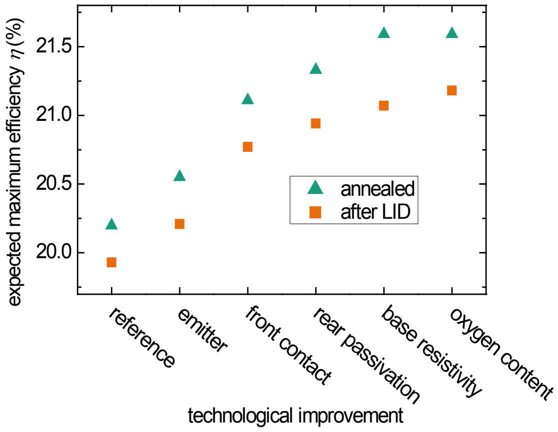


**Figure 2:** Expected development of the conversion efficiency of p-type MWT solar cells with passivated rear surface after integration of technological improvements.

### 3.2 Current status of the MWT technology

According to several publications, the MWT technology shows an efficiency gain of up to $\Delta\eta \approx 0.5$ % absolute compared to H-pattern solar cells [5, 9, 14]. Table 1 shows a selection of representative MWT results from industry and institutional research. Superior conversion efficiencies with maximum values of 20.6 % [15] have been reported. Nevertheless, several companies that had been working on MWT technology [16, 17] did not bring the concept to mass production yet. We attribute this to the lack of an economically feasible module interconnection technology in the past. Foil-based approaches [6] had been commercialised [18] but only now producers of appropriate structured backsheets announced competitive prices. Moreover, ribbon-based interconnection [19] is moving into the focus of equipment manufacturers [20] especially due to its reliability, cost effectiveness and the similarities to conventional module interconnection.

Recent progress in via paste design enables new and even more simplified MWT structures [7, 9]. Besides the drilling of the vias, these structures do not require MWT-specific process steps, thus retrofitting of production lines for conventional solar cells is getting more attractive – the front end process sequence is the same as for H-pattern solar cells.

### 3.3 Cost optimised metallisation layout

Analytical simulation with *Gridmaster* [25] and bottom-up cost calculations with *SCost* [26] are used to determine the most-cost effective metallisation layout for screen printed p-type Si HIP-MWT and H-pattern PERC solar cells (Cz-Si, 156 mm edge length, 1.1 Ωcm) and modules. Figure 3 shows the simulated conversion

**Table 1:** Published MWT solar cell results for p-type silicon base material. mCz denotes magnetic field assisted Cz growth.

| company/institute | cell type | comment | $\eta$ (%) | $j_{sc}$ (mA/cm$^2$) | $V_{oc}$ (mV) | $FF$ (%) | $j_{-12V}$ (mA/cm$^2$) |
|---|---|---|---|---|---|---|---|
| *Bosch* *(2011,* [2]*)* | MWT-BSF Cz-Si | selective emitter (SE) | 19.4 | | | | |
| *Canadian Solar* *(2013,* [7]*)* | MWT-BSF+ cast mono Si | SE | 19.6 | 39.0 | 639 | 78.7 | 2.45 |
| *ECN* *(2012,* [21]*)* | MWT-BSF mc-Si | | 17.9 | 36.4 | 632 | 77.8 | |
| *Fraunhofer ISE* *(2011,* [22]*)* | HIP-MWT mc-Si | | 18.2* | 36.9 | 637 | 77.3 | 2.55 |
| *Fraunhofer ISE* *(2011,* [15]*)* | MWT-PERC FZ-Si | dispensed front grid, SE | 20.6* | 39.9 | 661 | 78.3 | 4.65 |
| *Fraunhofer ISE* *(2012,* [12]*)* | HIP-MWT mCz-Si | stencil printed front grid, SE | 20.2* | 39.2 | 661 | 78.0 | 2.75 |
| *Fraunhofer ISE* *(2012,* [23]*)* | HIP-MWT+ FZ-Si | | 20.3* | 39.2 | 664 | 78.1 | 4.71 |
| *Kyocera* *(2008,* [24]*)* | MWT-BSF mc-Si | RIE texture | 18.3* | 37.2 | 626 | 78.5 | |

* independently confirmed

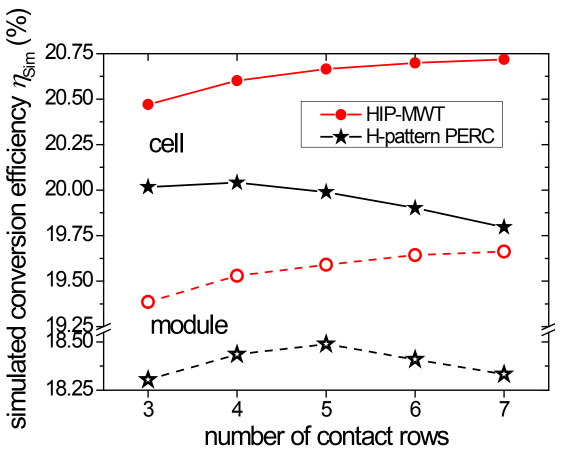


**Figure 3:** Simulated conversion efficiency of p-type Si HIP-MWT and H-pattern PERC solar cells and modules.

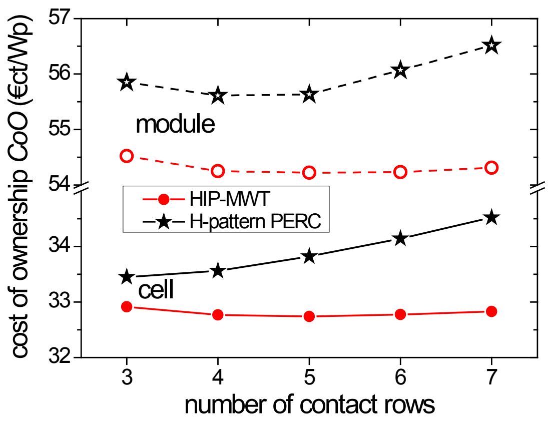


**Figure 4:** Calculated cost of ownership for p-type Si HIP-MWT and H-pattern PERC solar cells and modules.

efficiencies for both cell technologies on cell and module level. For all simulated cells the number of contact rows is varied methodically while the front finger width is constantly set to 60 µm. As a basis for the HIP-MWT metallisation layout an asymmetrical rear design with equal number of n- and p-type contact rows as typically used for ribbon-based cell interconnection [19, 20, 27] is assumed. On the rear 15 n-type and 5 p-type contact pads per contact row measuring 2 mm in diameter are applied. The front pseudo-busbar is tapered linearly and the width is conversion efficiency optimised according to analytical simulations for each simulation layout. The H-pattern PERC solar cells feature nonlinearly tapered front busbars with a maximum width of 1 mm. As for the HIP-MWT cells the number of p-type pads is 5 per contact row. The module conversion efficiency is aperture area related with an assumed cell and edge gap of 2 mm. For both cell technologies a ribbon-based module assembly process is presumed. Electrical cell-to-module losses $CTM_{electrical}$ are calculated using analytical simulation. In case of the HIP-MWT modules 4 mm wide copper ribbons are applied regardless of the metallisation layout. For the H-pattern modules the copper ribbon width is subsequently reduced from 1.5 mm for the three contact row layout to 1 mm for layouts with five and more contact rows. The sum of the optical losses and gains is assumed with $CTM_{optical} = -1$ % relative for all simulated module efficiencies. A more detailed cost calculation is presented by Hendrichs et al. [28].

The results clearly demonstrate an advantage for the MWT approach that allows for lowering the front grid series resistance by adding additional contact rows without decreasing the active cell area. In agreement with experimental results [5, 9, 14] the over-all conversion efficiency gain of the MWT technology is in the range of 0.5 % absolute on cell level. Due to reduced $CTM_{electrical}$ the conversion efficiency advantage of the MWT technology is doubled to about 1 % absolute on module level when comparing metallisation layouts with five contact rows.

Nevertheless the increased performance of the HIP-MWT solar cells and modules is accompanied by increased costs during cell production and module integration. The key question is whether the HIP-MWT approach can be cost competitive with the conventional H-pattern PERC technology. Figure 4 shows the calculated cost of ownership of p-type Si HIP-MWT and H-pattern PERC solar cells and modules. All material and processing costs are selected to the best of our knowledge and are representative for a 400 MWp production facility located in Europe. Copper ribbon costs are included with an expected price of 20 €/kg whereas a price of 670 €/kg is assumed for the silver paste. In case of the MWT modules the additional rear isolation layer for the rear contact pad insulation is included with 3 €/m². Furthermore the investment of the adapted back-contact tabber and stringer is supposed to be 125 % of a conventional tabber and stringer.

For the investigated module assembly process the HIP-MWT solar technology is found to be more cost effective on cell and module level when compared to the conventional H-pattern PERC approach. On module level the cost advantage sums up to 2 % when metallisation layouts with five contact rows are compared.

From a cost of ownership perspective, the optimum number of contact rows is in the range of 4 to 7 for HIP-MWT solar cells. However, since the complexity of the tabber stringer increases with increasing number of contact rows, a realistic number of contact rows for MWT is 4 or 5. For modules made from H-pattern solar cells, the calculation shows minimum cost of ownership with 4 or 5 busbars.

3.4 MWT specific issues

In principle, the MWT approach is easily integrated into existing p-type solar cell structures by adding a laser drilling process step for the formation of vias [9]. Nevertheless, a number of issues arise from the rear n-type contact. Table 2 summarises the current status of the relevant MWT related questions and presents the most promising solutions.

From our point of view, solutions to all issues exist. The most important topic for future investigations is the long-term reverse bias stability. First experiments show that via pastes exist which do not show increasing leakage current after reverse load [29, 30]. Regarding the reverse bias stability, MWT solar cells without rear emitter even offer the promising possibility for an integrated bypass diode functionality at no extra cost – its implementation solely demands for a specially adapted via paste composition [31].

**Table 2:** Status of MWT-specific questions and loss mechanisms.

| issue | comment | status | most promising solution(s) |
|---|---|---|---|
| *via drilling* [34] | only a few milliseconds per via are required with laser drilling | solved | laser processing |
| *via metallisation* [35–37] | series resistance is negligible when a sufficient amount of vias is used | solved | metallisation during printing of solder pads |
| *recombination (j02) due to inhomogeneous via emitter* [38] | does not occur when optimised process sequences are applied | solved | omit via emitter |
| *rear contact isolation* [2, 39, 40] | reduction of *pFF* by up to 1 % absolute observed | solved | omit rear emitter |
| *rear emitter shunting by Ag paste* [8, 41] | relevant for MWT-BSF, adapted via pastes solve this issue | solved | omit rear emitter |
| *leakage current from via metallisation to p-type base* [23] | relevant for MWT-BSF+ and HIP-MWT+; MWT-BSF+ most critical due to direct contact at the rear | solved | adapted via paste, rear dielectric |
| *reverse bias stability* [9, 22, 23, 29, 31] | relevant for MWT-BSF+ and HIP-MWT(+); MWT-BSF+ most critical due to direct contact at the rear | long term stability to be proven | adapted Ag paste, rear dielectric |
| *contact layout* [14, 42] | flexible design of front grid possible, low series resistance and reliable printability are most important | solved | 4 to 5 contact rows |
| *module integration* [6, 19, 20] | foil-based or ribbon-based interconnection possible | solutions exist | not yet clear |

3.5 Discussion

Our calculations and the review show clear advantages for the MWT approach compared to conventional H-pattern solar cells. The investigation confirms increased conversion efficiency and decreased cost of ownership for MWT-based modules.

Indeed, the introduction of novel technologies and approaches bears risks and uncertainties. This might be one of the key reasons why the market share of MWT-based modules is still negligible. A main advantage of the conventional H-pattern approach is the availability of well-proven and reliable equipment and production processes. On the other hand, however, the current crisis that affects a major part of the solar industry might be a motivation to introduce new technologies. With a production process closely related to conventional H-pattern solar cells, MWT offers the possibility to decrease cost of ownership of the module production and similarly to pave the way for module integration of other back-contact solar cell structures with even higher efficiency potential, e. g. back-contact-back-junction solar cells [32, 33].

## 4 CONCLUSION

This work summarises the current status of the MWT technology for p-type silicon base material. Detailed bottom-up cost calculations demonstrate the advantage of the MWT approach compared to modules based on H-pattern solar cells. Analytical device modelling reveals an efficiency potential of significantly above 21 % even after light-induced degradation. A review of the most important MWT-related questions shows that solutions to all issues exist. Recently, foil suppliers announced cost-effective prices for foil-based interconnection. At the same time, ribbon-based interconnection gained attraction since adapted tabber and stringer systems only cause a slight increase in investment costs compared to conventional equipment.

In conclusion, MWT solar cells and modules are ready for industrial fabrication and competitive production technology exists. Thus, the question “Are MWT solar cells at a dead end or finally approaching breakthrough?” cannot be answered by examining the current state of research but rather depends on the willingness of the industry to take the risk of implementing a new technology. From our point of view, this risk is manageable and offers the opportunity to resist the current crisis – not least because MWT-based modules have a more homogeneous optical appearance and thus form a premium segment product which are well suited for building integrated applications.

## REFERENCES

[1] E. van Kerschaver, R. Einhaus, J. Szlufcik et al. *A novel silicon solar cell structure with both external polarity contacts on the back surface*. In: Proceedings of the 2nd World Conference on Photovoltaic Energy Conversion; 1998, p. 1479–1482.

[2] K. Meyer, M. Menkoe, H.-J. Krokoszinski et al. *MWT Cells with Al-BSF on Cz Silicon with Efficiencies Up to 19.4 %.* In: Proceedings of the 26th European Photovoltaic Solar Energy Conference and Exhibition, EU PVSEC. München: WIP-Renewable Energies; 2011, p. 984–988, doi:10.4229/26thEUPVSEC2011-2BO.8.1.

[3] N. Nakatani, T. Sakamoto, K. Fukui et al. *High Efficiency Multicrystalline Silicon Back-Contact*

*Solar Cells*. In: Technical Digest of the 17th International Photovoltaic Science and Engineering Conference, PVSEC; 2007, p. 401–403.

[4] M. N. van den Donker, P. Wijnen, S. Krantz et al. *The Starfire Project: Towards In-Line Mass Production of Thin High Efficiency Back-Contacted Multicrystalline Silicon Solar Cells*. In: Proceedings of the 23th European Photovoltaic Solar Energy Conference and Exhibition, EU PVSEC. München: WIP-Renewable Energies; 2008, p. 1048–1050, doi:10.4229/23rdEUPVSEC2008-2AO.3.4.

[5] F. Clement, M. Menkoe, T. Kubera et al. *Industrially feasible multi-crystalline metal wrap through (MWT) silicon solar cells exceeding 16% efficiency*. Sol. Energ. Mat. Sol. Cells 2009;93(6-7):1051–5, doi:10.1016/j.solmat.2008.11.059.

[6] J. Bultman, D. Eikelboom, R. Kinderman et al. *Fast and easy single step module assembly for back-contacted c-Si solar cells with conductive adhesives*. In: Proceedings of the 3rd World Conference on Photovoltaic Energy Conversion; 2003, p. 979–982.

[7] W. Yin, X. Wang, F. Zhang et al. *19.6% Cast Mono-MWT Solar Cells and 268 W Modules*. IEEE J. Photovoltaics 2013:1–5, doi:10.1109/JPHOTOV.2013.2239357.

[8] F. Dross, E. van Kerschaver, C. Allebe et al. *Impact of Rear-Surface Passivation on MWT Performances*. In: Proceedings of the 4th World Conference on Photovoltaic Energy Conversion. Piscataway: IEEE; 2006, p. 1291–1294, doi:10.1109/WCPEC.2006.279650.

[9] B. Thaidigsmann, F. Clement, A. Wolf et al. *HIP-MWT: A simplified structure for metal wrap through solar cells with passivated rear surface*. In: Proceedings of the 1st International Conference on Crystalline Silicon Photovoltaics, SiliconPV: Elsevier; 2011, p. 498–502, doi:10.1016/j.egypro.2011.06.172.

[10] V. Lowe, A. Day. *High-temperature-stable contact metallization for silicon solar cells*. IEEE Trans. Electron Devices 1984;31(5):626–9, doi:10.1109/T-ED.1984.21580.

[11] B. Thaidigsmann, A. Drews, T. Fellmeth et al. *Synergistic Effects of Rear-Surface Passivation and the Metal Wrap Through Concept*. IEEE J. Photovoltaics 2012;2(2):109–13, doi:10.1109/JPHOTOV.2012.2183577.

[12] B. Thaidigsmann, M. Linse, A. Wolf et al. *The Path to Industrial Production of Highly Efficient Metal Wrap Through Silicon Solar Cells*. GREEN 2012;2(4):171–6, doi:10.1515/green-2012-0008.

[13] A. Mette, C. Schetter, D. Wissen et al. *Increasing the Efficiency of Screen-Printed Silicon Solar Cells by Light-Induced Silver Plating*. In: Proceedings of the 4th World Conference on Photovoltaic Energy Conversion. Piscataway: IEEE; 2006, p. 1056–1059, doi:10.1109/WCPEC.2006.279322.

[14] K. Meyer, H.-J. Krokoszinski, D. Lahmer et al. *Novel MWT Cell Design on Monocrystalline Silicon Wafers*. In: Proceedings of the 25th European Photovoltaic Solar Energy Conference and Exhibition, EU PVSEC. München: WIP-Renewable Energies; 2010, p. 1774–1777, doi:10.4229/25thEUPVSEC2010-2CV.2.18.

[15] E. Lohmüller, B. Thaidigsmann, M. Pospischil et al. *20% Efficient Passivated Large-Area Metal Wrap Through Solar Cells on Boron-Doped Cz Silicon*. IEEE Electron Device Lett. 2011;32(12):1719–21, doi:10.1109/LED.2011.2167709.

[16] A. van der Heide, D. Gribenski, J. Szlufcik. *Industrial Fabrication of Multi-Crystalline MWT Cells with Interconnection Flexibility of 16.5% Efficiency*. In: Proceedings of the 24th European Photovoltaic Solar Energy Conference and Exhibition, EU PVSEC. München: WIP-Renewable Energies; 2009, p. 942–945, doi:10.4229/24thEUPVSEC2009-2AO.2.3.

[17] L. M. Augustin, M. N. van den Donker, H. Scholten et al. *Mass Production and Field Performance of Durable Metal-Wrap-Through Integrated Back Contact Foil Based "Sunweb" Modules*. In: Proceedings of the 26th European Photovoltaic Solar Energy Conference and Exhibition, EU PVSEC. München: WIP-Renewable Energies; 2011, p. 3113–3116, doi:10.4229/26thEUPVSEC2011-4CO.6.1.

[18] M. Späth, P. C. de Jong, I. Bennett et al. *First Experiments on Module Assembly Line Using Back-Contact Solar Cells*. In: Proceedings of the 23th European Photovoltaic Solar Energy Conference and Exhibition, EU PVSEC. München: WIP-Renewable Energies; 2008, p. 2917–2921, doi:10.4229/23rdEUPVSEC2008-4AV.3.47.

[19] U. Eitner, D. Eberlein, M. Tranitz. *Interconnector-Based Module Technology for Thin MWT Cells*. In: Proceedings of the 27th European Photovoltaic Solar Energy Conference and Exhibition, EU PVSEC. München: WIP-Renewable Energies; 2012, p. 3461–3464, doi:10.4229/27thEUPVSEC2012-4BV.3.14.

[20] A. Spribille, M.-S. Hendrichs, B. Thaidigsmann et al. *HIP-MWT: Our Approach for High Performance Ribbon Based Back Contact MWT Modules with low CTM Losses*. In: SNEC 7th International Photovoltaic Power Generation Conference & Exhibition; 2013.

[21] M. W. P. E. Lamers, C. Tjengdrawira, M. Koppes et al. *17.9% Metal-wrap-through mc-Si cells resulting in module efficiency of 17.0%*. Prog. Photovolt: Res. Appl. 2012;20(1):62–73, doi:10.1002/pip.1110.

[22] B. Thaidigsmann, A. Spribille, H. Plagwitz et al. *HIP-MWT - A New Cell Concept for Industrial Processing of High-Performance Metal Wrap Through Silicon Solar Cells*. In: Proceedings of the 26th European Photovoltaic Solar Energy Conference and Exhibition, EU PVSEC. München: WIP-Renewable Energies; 2011, p. 817–820, doi:10.4229/26thEUPVSEC2011-2BP.1.5.

[23] E. Lohmüller, B. Thaidigsmann, S. Werner et al. *Evaluation of Via Pastes for p- and n-Type Metal Wrap Through (MWT) Solar Cells*. In: Proceedings of the 27th European Photovoltaic Solar Energy Conference and Exhibition, EU PVSEC. München: WIP-Renewable Energies; 2012, p. 590–595, doi:10.4229/27thEUPVSEC2012-2AO.2.6.

[24] N. Nakatani, T. Sakamoto, K. Fukui et al. *High Efficiency Multicrystalline Silicon Back-Contact Solar Cells*. In: Technical Digest of the 17th International Photovoltaic Science and Engineering Conference, PVSEC; 2007, p. 401–403.

[25] T. Fellmeth, F. Clement, D. Biro. *Analytical Modeling of Silicon Solar Cells*. in press. Journal of Photovoltaics 2013, doi:10.1109/JPHOTOV.2013.2281105.

[26] S. Nold, N. Voigt, L. Friedrich et al. *Cost Modeling of Silicon Solar Cell Production Innovation along the PV Value Chain*. In: Proceedings of the 27th European Photovoltaic Solar Energy Conference and Exhibition, EU PVSEC. München: WIP-Renewable Energies; 2012, p. 1084–1090, doi:10.4229/27thEUPVSEC2012-2AV.5.4.

[27] A. Drews, F. Clement, A. Spribille et al. *HIP-MWT Solar Cells – Pilot-Line Cell Processing and Module Integration*. In: Proceedings of the 27th European Photovoltaic Solar Energy Conference and Exhibition, EU PVSEC. München: WIP-Renewable Energies; 2012, p. 828–831, doi:10.4229/27thEUPVSEC2012-2DO.2.2.

[28] M. Hendrichs, B. Thaidigsmann, T. Fellmeth et al. *Cost-Optimized Metallization Layout for Metal Wrap Through (MWT) Solar Cells and Modules*: this conference, 2CV.3.6.

[29] E. Lohmüller, M. Thanasa, B. Thaidigsmann et al. *Via Pastes for MWT Silicon Solar Cells*. IEEE J. Photovoltaics submitted for publication.

[30] A. Spribille, E. Lohmüller, B. Thaidigsmann et al. *Wet Chemical Single-Side Emitter Etch Back for MWT Solar Cells with Al-BSF and Challenges for Via Paste Selection*: this conference, 2BV.1.14.

[31] B. Thaidigsmann, E. Lohmüller, F. Fertig et al. *Characterization and modeling of screen-printed metal insulator semiconductor tunnel junctions for integrated bypass functionality in crystalline silicon solar cells*. J. Appl. Phys. 2013;113(21):214502, doi:10.1063/1.4807931.

[32] W. P. Mulligan, M. A. Carandang, M. Dawson et al. *Reducing Silicon Consumption by Leveraging Cell Efficiency*. In: Proceedings of the 21st European Photovoltaic Solar Energy Conference, EU PVSEC. München: WIP-Renewable Energies; 2006, p. 1301–1302.

[33] R. Schwartz, M. Lammert. *Silicon solar cells for high concentration applications*. In: International Electron Devices Meeting; 1975, p. 350–352, doi:10.1109/IEDM.1975.188896.

[34] A. Knorz, S. Gutscher, A. Fell et al. *High Speed Laser Drilling: Parameter Evaluation and Characterisation*. In: Proceedings of the 25th European Photovoltaic Solar Energy Conference and Exhibition, EU PVSEC. München: WIP-Renewable Energies; 2010, p. 1410–1416, doi:10.4229/25thEUPVSEC2010-2CO.5.6.

[35] E. Lohmüller, B. Thaidigsmann, J. Bartsch et al. *Advanced metallization of rear surface passivated metal wrap through silicon solar cells*. In: Proceedings of the 1st International Conference on Crystalline Silicon Photovoltaics, SiliconPV: Elsevier; 2011, p. 546–551, doi:10.1016/j.egypro.2011.06.180.

[36] R. S. Watt, G. Laudisio, Y. Wang et al. *A Metallization System for Metal Wrap Through Solar Cells*. In: Proceedings of the 26th European Photovoltaic Solar Energy Conference and Exhibition, EU PVSEC. München: WIP-Renewable Energies; 2011, p. 2174–2176, doi:10.4229/26thEUPVSEC2011-2CV.4.11.

[37] F. Clement, M. Menkoe, D. Erath et al. *High throughput via-metallization technique for multi-crystalline metal wrap through (MWT) silicon solar cells exceeding 16% efficiency*. Sol. Energ. Mat. Sol. Cells 2010;94(1):51–6, doi:10.1016/j.solmat.2009.06.020.

[38] B. Thaidigsmann, E. Lohmüller, U. Jäger et al. *Large-area p-type HIP-MWT silicon solar cells with screen printed contacts exceeding 20% efficiency*. Phys. Status Solidi RRL 2011;5(8):286–8, doi:10.1002/pssr.201105311.

[39] A. Spribille, F. Clement, D. Erath et al. *Dispensing of Etching Paste and Inkjetting of Diffusion Barriers for MWT Solar Cell Processing*. In: Proceedings of the 25th European Photovoltaic Solar Energy Conference and Exhibition, EU PVSEC. München: WIP-Renewable Energies; 2010, p. 2654–2658, doi:10.4229/25thEUPVSEC2010-2DV.1.74.

[40] F. Clement, M. Lutsch, T. Kubera et al. *Processing and Comprehensive Characterisation of Screen-Printed mc-Si Metal Wrap Through (MWT) Solar Cells*. In: Proceedings of the 22nd European Photovoltaic Solar Energy Conference, EU PVSEC. München: WIP-Renewable Energies; 2007, p. 1399–1402.

[41] M. Neidert, F. Clement, M. Menkoe et al. *Development of Via Pastes for High Efficiency MWT Cells with a Low Shunting Behaviour*. In: Proceedings of the 24th European Photovoltaic Solar Energy Conference and Exhibition, EU PVSEC. München: WIP-Renewable Energies; 2009, p. 1424–1429, doi:10.4229/24thEUPVSEC2009-2CV.2.5.

[42] A. Burgers, J. Bultman, A. Tip et al. *Metallisation patterns for interconnection through holes*. Sol. Energ. Mat. Sol. Cells 2001;65(1-4):347–53, doi:10.1016/S0927-0248(00)00112-4.