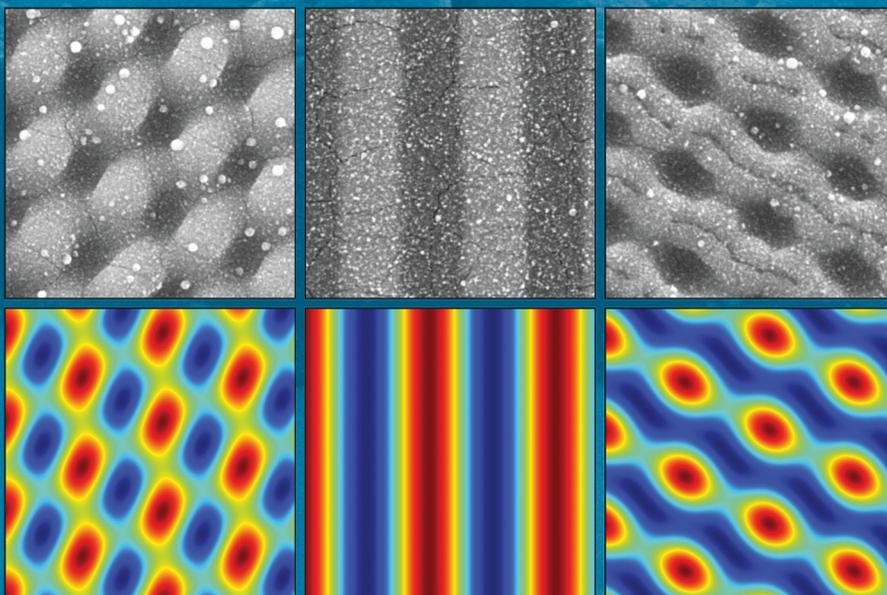


# Light Trapping by Light Treatment

Direct Laser Interference Patterning for the Texturing of Front Contacts in Thin-Film Silicon Solar Cells

Tobias Dyck



Energie & Umwelt /  
Energy & Environment  
Band / Volume 359  
ISBN 978-3-95806-208-5

Forschungszentrum Jülich GmbH  
Institute of Energy and Climate Research  
IEK-5 Photovoltaics

# **Light Trapping by Light Treatment**

## **Direct Laser Interference Patterning for the Texturing of Front Contacts in Thin-Film Silicon Solar Cells**

Tobias Dyck

Schriften des Forschungszentrums Jülich  
Reihe Energie & Umwelt / Energy & Environment

Band / Volume 359

---

ISSN 1866-1793

ISBN 978-3-95806-208-5

# Contents

<b>Abstract</b>	<b>i</b>
<b>1 Introduction</b>	<b>1</b>
<b>2 Fundamentals</b>	<b>5</b>
2.1 Solar Cells . . . . .	5
2.1.1 Thin-Film Silicon Solar Cells . . . . .	5
2.1.2 Light Management and Textured Interfaces . . . . .	9
2.1.3 Phase Model . . . . .	11
2.2 Lasers . . . . .	15
2.2.1 Properties of Laser Light and Beams . . . . .	15
2.2.2 Laser-Material Interaction . . . . .	26
<b>3 Devices and Methods</b>	<b>29</b>
3.1 Devices and Methods for Characterization . . . . .	29
3.1.1 Laser Characterization . . . . .	29
3.1.2 ZnO:Al Characterization . . . . .	32
Topography . . . . .	32
Electro-Optical Properties . . . . .	34
3.1.3 Solar Cell Characterization . . . . .	35
3.2 Devices and Methods for Laser Treatment . . . . .	35
3.2.1 Laser Sources . . . . .	36
Rofin1064 . . . . .	36
Rofin532 . . . . .	37
Rofin355 . . . . .	37
TruMicro5050 . . . . .	38
TruMicro5000 . . . . .	39
Powerlite8020 . . . . .	39
3.2.2 Beam Guiding . . . . .	44
Structuring System . . . . .	44
Scanner Lab Jack Setup . . . . .	45
Interference Setups . . . . .	46
3.3 Computational Devices . . . . .	46
Genetic Algorithm for Global Optimization . . . . .	47

<b>4</b>	<b>Process Comparison</b>	<b>51</b>
4.1	Direct Writing . . . . .	52
4.2	Laser-Induced Chemical Etching . . . . .	53
	4.2.1 Experimental Procedure . . . . .	53
	4.2.2 Results and Discussion . . . . .	54
4.3	Particle Lens Array . . . . .	57
	4.3.1 Experimental Procedure . . . . .	57
	4.3.2 Results and Discussion . . . . .	58
4.4	Laser-Induced Periodical Surface Structures . . . . .	60
	4.4.1 Experimental Procedure . . . . .	60
	4.4.2 Results and Discussion . . . . .	61
	Low Spacial Frequency LIPSS (LSFL) . . . . .	61
	High Spacial Frequency LIPSS (HSFL) . . . . .	62
	4.4.3 Speed Considerations . . . . .	64
4.5	Two-Beam Direct Laser Interference Patterning . . . . .	65
	4.5.1 Experimental Procedure . . . . .	65
	4.5.2 Results and Discussion . . . . .	66
4.6	Conclusion . . . . .	69
<b>5</b>	<b>Three-Beam Direct Laser Interference Patterning (DLIP)</b>	<b>73</b>
5.1	Experimental Setup . . . . .	73
	5.1.1 Layout of Experimental Setup . . . . .	75
	5.1.2 Adjustment and Calibration of Laser Beam Properties . . . . .	79
	5.1.3 Setup Parameters . . . . .	81
5.2	Interference Pattern . . . . .	82
	5.2.1 Simulate Interference Model ( <i>SINT</i> ) . . . . .	82
	5.2.2 Exemplary Pattern . . . . .	84
5.3	Surfaces Textures . . . . .	89
	5.3.1 General Features of DLIP Textures . . . . .	89
	5.3.2 Control of Texture . . . . .	92
	5.3.3 Ablation Process . . . . .	96
5.4	Modeling Ablation . . . . .	100
	5.4.1 Ablation Model . . . . .	100
	Ablation without Heat Diffusion . . . . .	100
	Ablation with Heat Diffusion . . . . .	102
	5.4.2 Determination of Material Properties . . . . .	105
	Optimization . . . . .	105
	Reliability of Optimization Results . . . . .	107
	Comparison of Model and Experiment . . . . .	109
	5.4.3 Virtual Laser Interference Patterning ( <i>VLIP</i> ) . . . . .	111
5.5	Summary . . . . .	113
<b>6</b>	<b>Application in Solar Cells</b>	<b>115</b>

6.1	Macroscopic Texturing . . . . .	115
6.1.1	Stitching of Laser Spots . . . . .	116
6.1.2	Electro-Optical Characterization . . . . .	120
6.2	Solar Cells . . . . .	123
6.2.1	Deposition of Tandem Solar Cells . . . . .	124
6.2.2	Characterization of Solar Cells . . . . .	125
6.3	Conclusion . . . . .	132
<b>7</b>	<b>DLIP Potential</b>	<b>135</b>
7.1	Light Trapping Efficiency . . . . .	135
7.1.1	Calculation of $LTE$ and $LTE_{\text{eff}}$ ( $PyLTE$ ) . . . . .	136
7.1.2	Comparison with Solar Cells . . . . .	137
7.1.3	Discussion . . . . .	139
7.1.4	Conclusion . . . . .	140
7.2	Influence of Setup Parameters on Light Trapping Efficiency . . . . .	141
7.2.1	Periodicity and Total Power . . . . .	142
7.2.2	Partial Beam Power . . . . .	144
7.2.3	Partial Beam Polarizations . . . . .	145
7.2.4	Angle of Incidence . . . . .	146
7.2.5	Conclusion . . . . .	147
7.3	Global Optimization of Setup Parameters . . . . .	148
7.4	Outlook . . . . .	151
7.4.1	Two Pulse Processing . . . . .	152
7.4.2	Short Laser Pulse Durations . . . . .	154
7.4.3	Conclusion . . . . .	156
7.5	Summary . . . . .	157
<b>8</b>	<b>Summary and Outlook</b>	<b>159</b>
	<b>Bibliography</b>	<b>163</b>
	<b>List of Tables</b>	<b>I</b>
	<b>List of Figures</b>	<b>III</b>
<b>A</b>	<b>Appendix</b>	<b>VII</b>

**Energie & Umwelt /  
Energy & Environment  
Band / Volume 359  
ISBN 978-3-95806-208-5**

