

Transfer of the Metal Wrap Through Solar Cell Concept to n-Type Silicon

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"Twenty years from now you will be more disappointed by the things you didn't do than by the ones you did do. So throw off the bowlines. Sail away from the safe harbor. Catch the trade winds in your sails. Explore. Dream. Discover."

Mark Twain (1835 – 1910)

Abstract

This thesis presents the transfer of the metal wrap through (MWT) solar cell concept from *p*-type to *n*-type crystalline Czochralski-grown silicon (Cz-Si) wafers with 156 mm edge length. An industrially-feasible MWT solar cell structure with screen-printed metallization is developed, which combines the advantages of *n*-doped silicon with those of a rear contact cell structure. The conversion efficiency of the fabricated solar cells increases continuously within various development cycles. The studies focus on reverse bias stability, emitter diffusion, and electrical contacting of highly boron-doped surfaces. Specific characterization of the reverse bias behavior of the solar cells point out the major challenge to be overcome for a reliable operation after module encapsulation. The vias and the rear *p*-type contacts represent the most important MWT specific structures. Detailed investigations result in optimizations and process simplifications with respect to the rear contact configuration. The maximum energy conversion efficiency achieved for large-area *n*-type Cz-Si MWT solar cells within this work is 20.4%. Analytical calculations yield a potential energy conversion efficiency of almost 22% for *n*-type Cz-Si MWT solar cells by integration of technological improvements.

New tube furnace diffusion processes are developed to form deep driven-in boron dopings with low surface concentration in a single process step. The emitters formed therewith feature low dark saturation current density of $(30 \pm 3) \text{ fA/cm}^2$ for passivated and textured surface with a sheet resistance of about $120 \text{ } \Omega/\text{sq}$. Despite low maximum dopant concentration of only $(1.8 \pm 0.2) \cdot 10^{19} \text{ cm}^{-3}$, low specific contact resistance of less than $4 \text{ m}\Omega\text{cm}^2$ is obtained for screen-printed and fired metal contacts. It is experimentally shown for the first time that the depth-dependent course of the dopant concentration contributes to a low-ohmic contact formation. This correlation is also demonstrated by means of an analytical model which is based on metal crystallites. Furthermore, it is shown that charge carrier recombination underneath the metal contacts correlates with both the metal crystallites and the junction depths of the boron dopings.

The progress in emitter formation and the improved understanding of metallization related issues are also of high interest for other solar cell types. Furthermore, findings from this thesis also contributed fundamentally to the ongoing development in *p*-type MWT solar cell technology.

Kurzfassung

Diese Arbeit beschäftigt sich damit, das „Metal Wrap Through“ (MWT) Solarzellenkonzept von p -dotierten auf n -dotierte Substrate zu übertragen, die aus kristallinem Czochralski-Silizium (Cz-Si) mit einer Kantenlänge von 156 mm bestehen. Es wird eine industriell umsetzbare MWT-Solarzellenstruktur mit siebgedruckter Metallisierung entwickelt, welche die Vorteile von n -dotiertem Silizium mit den Vorteilen einer rückseitig kontaktierten Zellstruktur vereint. Die Effizienz der hergestellten Solarzellen steigt über mehrere Entwicklungszyklen hinweg kontinuierlich an. Die Untersuchungen beschäftigen sich vor allem mit der Rückwärtsstabilität, der Emittendiffusion und der elektrischen Kontaktierung stark Bor-dotierter Oberflächen. Die Herausforderungen, die für einen zuverlässigen Betrieb nach Moduleinkapselung überwunden werden müssen, werden durch spezifische Untersuchungen des Verhaltens der Solarzellen unter Rückwärtsspannung aufgezeigt. Die Durchkontaktierungen (Vias) und die rückseitigen p -Kontakte bilden die wichtigsten MWT-spezifischen Strukturen. Die rückseitige Kontaktanordnung konnte im Zuge detaillierter Untersuchungen optimiert und deren Herstellung vereinfacht werden. Der erreichte Wirkungsgrad für großflächige MWT-Solarzellen aus n -dotiertem Cz-Si beträgt 20,4%. Analytische Berechnungen zeigen ein Effizienzpotenzial von nahezu 22% für MWT-Solarzellen aus n -dotiertem Cz-Si bei Integration technologischer Verbesserungen auf.

Neue Rohrofen-Diffusionsprozesse werden entwickelt, um tief eingetriebene Bordotierungen mit geringer Oberflächenkonzentration in einem einzigen Prozessschritt auszubilden. Die damit hergestellten Emittoren weisen eine geringe Dunkelsättigungsstromdichte von $(30 \pm 3) \text{ fA/cm}^2$ für eine passivierte und texturierte Oberfläche und einen Schichtwiderstand von ungefähr $120 \text{ } \Omega/\text{sq}$ auf. Trotz geringer maximaler Dotierkonzentration von nur $(1,8 \pm 0,2) \cdot 10^{19} \text{ cm}^{-3}$ ergeben sich geringe spezifische Kontaktwiderstände kleiner $4 \text{ m}\Omega\text{cm}^2$ für siebgedruckte und gefeuerte Metallkontakte. Erstmals wird experimentell gezeigt, dass der tiefenabhängige Verlauf der Dotierung zu einer niederohmigen Kontaktausbildung beiträgt. Diese Korrelation wird auch anhand eines analytischen Modells, welches auf Metallkristalliten beruht, demonstriert. Des Weiteren wird gezeigt, dass die Ladungsträgerrekombination unterhalb der Metallkontakte sowohl mit den Metallkristalliten als auch mit der Tiefe der Bor-Dotierprofile korreliert.

Die Fortschritte in der Emittorausbildung und das verbesserte Verständnis metallisierungsbedingter Fragestellungen sind auch für andere Solarzellentypen von besonderem Interesse. Erkenntnisse aus dieser Arbeit trugen auch grundlegend zur Weiterentwicklung der MWT-Solarzellentechnologie auf p -dotierten Substraten bei.

Table of Contents

1	Introduction	1
1.1	Motivation and objectives	1
1.2	Thesis outline.....	3
2	Fundamentals of Silicon Solar Cell Technology	5
2.1	Introduction	5
2.2	Solar cell characteristics	5
2.2.1	Two-diode model and dark saturation current densities	6
2.2.2	Determination of dark saturation current densities of passivated surfaces.....	8
2.2.3	Current-voltage characteristics and cell parameters.....	13
2.3	Fundamentals of diffusion and dopant properties in crystalline silicon	16
2.3.1	Fick’s law	17
2.3.2	Properties and diffusion of boron atoms in silicon	19
2.3.3	Properties and diffusion of phosphorus atoms in silicon.....	23
2.4	Metal-semiconductor contact	25
2.4.1	Schottky contact.....	26
2.4.2	Current transport mechanisms.....	28
3	MWT Solar Cells: State of the Art and Transfer to n-Type Silicon	29
3.1	Introduction	29
3.2	State of the art solar cell structures with front side emitter.....	29
3.2.1	H–pattern concept and others.....	30
3.2.2	Metal wrap through (MWT) concept	35
3.3	Ongoing development of p-type MWT technology	38
3.4	Processes for fabrication of n-type H–pattern solar cells	42
3.4.1	Basic process sequence	43
3.4.2	Challenges in the fabrication process and approaches	45
3.5	Transfer of the MWT concept to n-type silicon	50
3.6	Chapter summary	53

4	Boron Emitter Formation and Passivation	55
4.1	Introduction	55
4.2	Boron diffusion with liquid BBr_3 as dopant precursor	55
4.2.1	Principle, process sequence, and objectives	56
4.2.2	Samples for processes characterization	58
4.3	Characterization of basic diffusion processes	61
4.3.1	Process description and approach	61
4.3.2	Emitter sheet resistances	62
4.3.3	Doping profiles	65
4.3.4	Emitter dark saturation current densities	67
4.3.5	Impact of varied drive-in temperatures	69
4.4	Formation of custom-made doping profiles	70
4.4.1	Doping profiles with deeper junction	70
4.4.2	Doping profiles with lower surface dopant concentration	71
4.4.3	Doping profiles without surface depletion by wet-chemical etching	75
4.5	Identification of suitable diffusion barrier layers	77
4.5.1	Sample preparation	78
4.5.2	Results	79
4.6	Chapter summary	83
5	Contacting of Boron Emitters Using Ag-Al Screen-Printing Pastes	85
5.1	Introduction	85
5.2	Review on electrical contacting of boron-doped surfaces	85
5.3	Impact of junction depth on the specific contact resistance	87
5.3.1	Sample preparation	88
5.3.2	Specific contact resistance	90
5.3.3	Microstructure analysis	91
5.4	Analytical model for calculation of specific contact resistances	94
5.4.1	Approach	95
5.4.2	Calculation of specific contact resistances	97
5.4.3	Impact of the doping profile shape on the specific contact resistance	101
5.4.4	Discussion	102
5.5	Doping profiles with decreased maximum dopant concentration	104
5.5.1	Sample preparation	104
5.5.2	Specific contact resistance	106
5.6	Charge carrier recombination at metal crystallites	107
5.7	Chapter summary	112

6	Electrical Properties of the Backside Contacts of MWT Solar Cells	115
6.1	Introduction	115
6.2	Challenges for the MWT backside contact structure.....	115
6.3	Methodology for characterization of the electrical contact behavior	118
6.3.1	Approach and test structure fabrication	118
6.3.2	Procedure for current-voltage measurements	121
6.3.3	Leakage currents and their impact on forward current-voltage characteristics.....	121
6.3.4	Thermal power dissipation under reverse bias load.....	122
6.4	Results of the test structures for various MWT cell concepts	123
6.5	Study of impact factors on leakage current after reverse biasing.....	130
6.6	Detailed investigation of leakage current after reverse biasing	133
6.7	Chapter summary	136
7	Solar Cell Results and Loss Mechanisms	139
7.1	Introduction.....	139
7.2	Development of the energy conversion efficiency.....	139
7.3	Impact of reverse bias load on cell characteristics	143
7.3.1	Cell fabrication and measurement methods	144
7.3.2	Current-voltage characteristics	147
7.3.3	Dark reverse current-voltage characteristics and dark lock-in thermography measurements I.....	149
7.3.4	Dark lock-in thermography measurements II.....	152
7.3.5	Section summary	155
7.4	Decrease of metallization-losses and discussion of MWT-specific issues.....	156
7.4.1	Cell fabrication and basic process characterization	157
7.4.2	Current-voltage characteristics	160
7.4.3	Implied open-circuit voltages and metallization-related voltage losses	163
7.4.4	Series resistance contributions and MWT-specific losses.....	166
7.4.5	Section summary	171
7.5	Solar cells utilizing the latest BBr ₃ diffusion processes	172
7.5.1	Cell fabrication and process characterization	173
7.5.2	Current-voltage characteristics	175
7.5.3	Metallization-related voltage losses	180
7.5.4	Section summary	183
7.6	Simplified fabrication process for n-type MWT solar cells	185
7.6.1	Cell fabrication and process characterization	186

7.6.2	Current-voltage characteristics	188
7.6.3	Section summary and conclusion	192
7.7	Estimation of conversion efficiency potential	193
7.8	Chapter summary	195
8	Summary	199
9	Outlook	202
10	Deutsche Zusammenfassung	203
	Appendix	207
A	Current transport models and specific contact resistance.....	207
B	Measurement and characterization methods	211
B.1	Current-voltage measurements of bifacial n-type solar cells....	211
B.2	Electrochemical capacitance-voltage measurement.....	214
B.3	Inductive sheet resistance measurement.....	215
B.4	Transmission line model	217
C	Structuring methods for the rear phosphorus doping	218
C.1	Inkjet-assisted structuring of diffusion barrier layers	219
C.2	Redistribution of phosphorus doping by laser irradiation.....	220
D	Parameters for calculation of series resistance contributions	222
	Bibliography	223
	List of Symbols	249
	List of Abbreviations	257
	List of Publications	261
	Danksagung	267