

Table of Contents

1	Introduction	11
1.1	Thesis motivation and objectives	11
1.2	Thesis outline	13
2	Fundamentals	17
2.1	Basics of silicon solar cells	17
2.1.1	Device structure and working principle of front-junction nPERT silicon solar cells	17
2.1.2	Current-voltage characteristic of silicon solar cells	19
2.1.3	Carrier recombination in crystalline silicon	21
2.1.4	Impact of electrical and optical losses on current-voltage characteristic	24
2.2	Rear-side metallization of silicon solar cells	27
2.2.1	Review and state of the art	27
2.2.2	Novel cell design featuring screen-printed front side and physical vapor deposited rear-side metallization	29
2.2.3	Physical vapor deposition of metal layers	31
2.3	Rear-side metallization related losses	34
2.3.1	Ohmic losses due to lateral resistance of rear-side metallization	34
2.3.2	Ohmic losses due to contact resistance of rear-side metallization	40

2.3.3	Optical losses due to parasitic absorption in rear-side metallization.....	42
2.3.4	Rear-side metallization related recombination losses	45
2.4	Requirements of rear-side metallization for double-side contacted industrial silicon solar cells.....	46
2.5	Why aluminum-based PVD rear-side metallization for μ -type PERT solar cells?.....	47
3	Sputtering deposition processes of the investigated metal layers	51
3.1	Oerlikon SOLARIS 6 multi-layer sputtering deposition system....	51
3.2	Sputtering-deposition processes of the metal layers	53
3.2.1	Process parameters and deposition rate of aluminum sputtering deposition	54
3.2.2	Sputtering-deposition processes of the Al-Si (1 at% Si) layers..	55
3.2.3	Sputtering deposition processes of the silver layers.....	57
3.2.4	Sputtering deposition processes of the titanium layers	58
3.2.5	Maximum substrate temperature during aluminum sputtering deposition.....	59
3.3	Summary and conclusion.....	62
4	Contact formation process of aluminum-based metallization	63
4.1	Theoretical background on the contact-formation process of Al/Si-contacts	63
4.2	Characterization of contact formation process	69
4.3	Ti/Al stack against aluminum spiking	70
4.3.1	Theoretical background of titanium as a spiking barrier.....	70
4.3.2	SEM structural investigations of Ti/Al-stack.....	73

4.4	Novel Al-Si/Al-stack against Al-spiking.....	75
4.4.1	Process simulation of Al/Al-Si/Si system.....	76
4.4.2	SEM structural investigations of Al-Si/Al stack.....	79
4.5	Summary and conclusion.....	81
5	Specific contact resistance evaluation.....	83
5.1	Determination of specific contact resistance of point contacts on highly doped silicon.....	84
5.1.1	Sample structure and experimental setup.....	84
5.1.2	Analytical model to extract the contact resistance of the point contact from the measured data	88
5.1.3	Circular transmission line model to determine rear specific contact resistance $\rho_{c, rear}$	92
5.1.4	Verification of the analytical approximation with 3D numerical device simulations.....	95
5.1.5	Error contributions of wafer thickness and resistivity, BSF sheet resistance and contact radius.....	97
5.2	Specific contact resistance experimental results	99
5.2.1	Specific contact-resistance results on lowly doped n^+ -BSF.....	99
5.2.2	Specific contact-resistance results on highly doped n^+ -BSF	101
5.2.3	Comparison of the experimentally obtained $\rho_{c, rear}$ data with previously published ones	103
5.2.4	Summary and conclusion.....	103
6	Detailed optical study on rear-side reflectors for nPERT solar cells	107
6.1	Theoretical background	107
6.1.1	Optical properties of dielectric materials and metals	107

6.1.2	Light paths for PERT solar cell with regular upright pyramids and frustrated total reflection	114
6.1.3	Reflectance of silicon/passivation/metallization-system calculated with the matrix method.....	119
6.2	Numerical 3D-device-simulations and experiments on reflection samples	127
6.2.1	One-layer Al-metallization with various passivation configurations	129
6.2.2	Multi-layer Al-based metallization with first Al-Si layer as a spiking barrier	132
6.2.3	Multi-layer Al-based metallization with first Ti layer as a low resistance contacting metal	133
6.2.4	One-layer Ag-metallization on various passivation layers.....	140
6.2.5	Multi-layer Al-based metallization with first thin Ag layer as an IR reflector	142
6.2.6	Comparison of the optimized rear-side reflectors	146
6.3	Summary and conclusion.....	147
7	Plasma-induced damage of sputtering deposition of metal layers.....	149
7.1	Experimental approach.....	150
7.1.1	Microwave photoconductance decay (MWPCD)	151
7.1.2	Corona Oxide Characterization of Semiconductor (COCOS)	153
7.2	Experimental results.....	155
7.2.1	Impact of aluminum sputtering on the electrical properties of Si/SiO ₂ interface.....	155
7.2.2	Impact of Al sputtering on the electrical properties of Si/Al ₂ O ₃ interface	157

7.2.3	Impact of Al sputtering on the electrical properties of Si/SiN _x interface	158
7.3	Summary and conclusion.....	160
8	Cell results of front-junction nPERT solar cells	161
8.1	One-layer aluminum rear-side metallization (Batch-1 to Batch-4)	162
8.1.1	Batch-1: Influence of rear-side capping SiO ₂ on current generation	162
8.1.2	Batch-2: Influence of rear doping profile and thermal stress on cell performance	163
8.1.3	Batch-3: Influence of rear contact spacing on current-voltage characteristic.....	168
8.1.4	Batch-4: Influence of aluminum layer thickness on series ohmic losses	171
8.2	Multi-layer aluminum-based rear-side metallization (Batch 5)	175
8.3	Summary and conclusion.....	177
9	Thesis summary and outlook.....	179
10	Deutsche Zusammenfassung (German summary).....	185
	References	191
	Own publications	201
	Acknowledgments	203