

DEVELOPMENT OF PHYSICAL MODELS FOR THE SIMULATION OF OPTICAL PROPERTIES OF SOLAR CELL MODULES

Von der Fakultät für Mathematik und Physik
der Gottfried Wilhelm Leibniz Universität Hannover
zur Erlangung des Grades

Doktor der Naturwissenschaften
Dr. rer. nat.

genehmigte Dissertation

von
M. Sc. Malte Ruben Vogt
geboren am 07.11.1986, in Langenhagen

2015

Contents

| | | |
|---|--|-----------|
| 1 | Introduction | 1 |
| 1.1 | Components of a typical solar cell module | 2 |
| I | Optical Measurements | 5 |
| 2 | Measurement theory and methods | 7 |
| 2.1 | Spectroscopic ellipsometry | 8 |
| 2.1.1 | The spectroscopic ellipsometer | 9 |
| 2.1.2 | Data analysis | 10 |
| Wavelength by wavelength fit | 11 | |
| Function fit | 11 | |
| Monte Carlo based data analysis | 12 | |
| 2.2 | Reflection and Transmission measurements | 13 |
| 2.2.1 | Reflection measurement | 14 |
| 2.2.2 | Transmission measurement | 15 |
| 2.2.3 | Extracting the refraction index from reflection and transmission measurements | 16 |
| 2.2.4 | Reflection and transmission of one planar slab | 16 |
| 2.2.5 | Calculating diffuse reflectance between two media | 17 |
| 2.3 | Conclusion | 20 |
| 3 | Measurement results: Determining the optical parameters of all solar cell module components | 21 |
| 3.1 | Optical properties of glass | 21 |
| 3.2 | Optical properties of antireflective coatings for glass | 28 |
| 3.3 | Optical properties of encapsulant materials | 30 |
| 3.3.1 | Reflectivity of colored silicone back encapsulation materials | 32 |
| 3.4 | Optical properties of silicon | 34 |
| 3.5 | Optical properties of silicon-nitride | 36 |
| 3.6 | Optical properties of aluminum-silicon-eutectic as rear reflector in solar cells | 38 |
| 3.7 | Optical properties of back sheets | 40 |
| 3.8 | Conclusion | 41 |

| | |
|--|------------|
| II Simulations of complete solar cell modules | 43 |
| 4 Ray tracing of entire solar cell modules and optical loss analysis | 45 |
| 4.1 Influence of the glass ARC | 49 |
| 4.2 Loss in the glass | 50 |
| 4.3 Influence of the encapsulation | 52 |
| 4.4 Influence of the cell ARC | 53 |
| 4.5 Colored PV modules | 54 |
| 4.6 Influence of the back sheet | 55 |
| 4.7 Discussion of potential for future improvements | 56 |
| 4.8 Conclusion | 57 |
| 5 Simulation of plasmonic nanoparticles | 59 |
| 5.1 Simulation model | 60 |
| 5.2 Results | 63 |
| 5.2.1 Normal incidence | 63 |
| 5.2.2 Oblique angle of incidence | 66 |
| 5.2.3 Shells | 70 |
| 5.3 Conclusion | 71 |
| 6 Numerical Modeling of c-Si PV Modules by Coupling the Semiconductor with the Thermal Conduction, Convection and Radiation Equations | 73 |
| 6.1 Simulation model | 74 |
| 6.1.1 Semiconductor and cell properties | 76 |
| 6.1.2 Heat transfer and module properties | 76 |
| 6.1.3 Calculation of heat sources using ray tracing | 79 |
| 6.1.4 Calculation of module power with SPICE | 80 |
| 6.2 Heat sources | 81 |
| 6.3 Field measurements | 82 |
| 6.3.1 Model validation via field measurements | 84 |
| 6.4 Results and discussion | 86 |
| 6.5 Conclusion | 88 |
| 7 Conclusion | 89 |
| Bibliography | 93 |
| List of Figures | 101 |
| List of Tables | 107 |

| | |
|--|------------|
| Appendix | 109 |
| A Characterizing the encapsulation material between two glass slabs | 109 |
| A.1 Theory | 109 |
| Reflection and transmission of two planar slabs | 109 |
| Reflection and transmission of three planar slabs | 111 |
| Fitting reflection and transmission to determine optical properties . . | 113 |
| A.2 Measurements | 114 |
| A.2.1 Refractive index data and comparison with literature | 116 |
| A.2.2 Extinction coefficient of measured materials | 117 |
| B Tables of the optical constants determined | 119 |
| B.1 Glass ARC | 120 |
| B.2 Soda-lime glass | 121 |
| B.3 Encapsulatant materials | 124 |
| B.4 Cell front side metalization (Ag) | 131 |
| B.5 Cell ARC (SiN) | 134 |
| B.6 Silicon | 139 |
| B.7 Cell rear side metalization (Al-Si) | 141 |
| B.8 Module frame (Al) | 144 |
| B.9 Back sheet | 147 |
| Publications | 149 |
| Curriculum Vitae | 151 |