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List of Publications

Related to this thesis

1. B. Ehrler, E. Alarcón-Lladó, S.W. Tabernig, T. Veeken, E.C. Garnett, and A. Polman, *Photovoltaics reaching for the Shockley–Queisser limit*, ACS Energy Letters **5**, pp. 3029–3033, 2020. (**Chapter 1**)
2. T. Veeken, B. Daiber, H. Agrawal, M. Aarts, E. Alarcón-Lladó, E.C. Garnett, B. Ehrler, J. van de Groep, and A. Polman, *Directional quantum dot emission by soft-stamping on silicon Mie resonators*, Nanoscale Advances **4**, pp. 1088-1097, 2020. (**Chapter 2**)
3. J.S. van der Burgt*, D.R. Needell*, T. Veeken*, A. Polman, E.C. Garnett, and H.A. Atwater, *Unlocking higher power efficiencies in luminescent solar concentrators through anisotropic luminophore emission*, ACS Applied Materials and Interfaces **13**, pp. 40742–40753, 2021. (**Chapter 3**)
4. T. Veeken, K. Orbons, N. de Gaay Fortman, A.A. Rossinelli, D.J. Norris, A.F. Koenderink, and A. Polman, *Anisotropic luminophore emission for enhanced light trapping in luminescent solar concentrators*, in preparation. (**Chapter 4**)
5. E. Akerboom*, T. Veeken*, C. Hecker, J. van de Groep, and A. Polman, *Passive radiative cooling of silicon solar modules with silica microcylinder arrays*, in preparation. (**Chapter 5**)
6. T.H. Fung, T. Veeken, D. Payne, B. Veettil, A. Polman, and M. Abbott, *Application and validity of the effective medium approximation to the optical properties of nano-textured silicon coated with a dielectric layer*, Optics Express **27**, pp. 38645–38660, 2019. (**Chapter 6**)
7. Y. Zhang, T. Veeken, S. Wang, G. Scardera, M. Abbott, D. Payne, A. Polman, and B. Hoex, *Plasma focused ion beam tomography for accurate characterization of black silicon validated by full-wave optical simulation*, under review by Advanced Materials Technologies, 2022. (**Chapter 7**)

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Other

8. L. Polak, T. Veeken, J. Houtkamp, M.J. Slaman, S.M. Kars, J.H. Rector, and R.J. Wijngaarden, *Two-step sputter-hydrothermal synthesis of* $NaTaO_3$ *thin films*, Thin Solid Films, **603**, pp. 413-417, 2016.
9. N. Tavakoli, W. Kim, T. Veeken, D. Poorten, L. Guniat, A. Rudra, A. Fontcuberta i Morral, E. Alarcon-Llado, *Coloured and semi-transparent nanowire-based solar cells for building integrated photovoltaics*, Preprint at http://arxiv.org/abs/2107.09465, 2021.

Summary

Light is an amazing phenomenon. It plays a central role in our modern society, ranging from electrical lighting to fiber-optic communication systems and mobile/computer displays to lasers. We use light to see the world around us, to study the smallest organisms with microscopes and the largest objects in the universe with telescopes. In addition, light can be a source of energy. Light from the sun provides more than 9000 times the amount of global primary energy supply our modern society generates. In the transition towards a world powered by renewable energy, photovoltaic energy conversion will play a key role, harvesting the nearly inexhaustible power that the sun provides. Photovoltaics (PV) is a mature technology that has seen decades of research and technological advances, which resulted in exponential growth of the installed capacity and exponential decline of the price of solar power generation. Two key challenges remain to be overcome to enable large-scale energy supply by PV: i) the further cost-reduction of solar electricity and ii) the integration of PV into our buildings, landscapes, and infrastructure.

In Chapter 1, we outline these two challenges in more detail. We start by investigating the potential of solar energy generation. We continue by quantifying the limits of photovoltaic energy conversion and comparing them to the current record-efficiency solar cells. Then, we discuss the role that photonics can play in PV. We conclude with a motivation to the thesis, discussing the two key challenges listed above.

In the remainder of this thesis, we investigate the photonic control over absorption and emission of light in photovoltaic systems to address these two challenges. In the first part (Chapters 2-4), we provide a fundamental description of nanophotonic structures to control the angular distribution of emission by dipole-like emitters. This has applications in, for example, up- and down-conversion schemes for photovoltaics and luminescent solar concentrators. In the second part (Chapters 5-7), we investigate photonic structures to enhance infrared emission for radiative cooling and surface textures for anti-reflection in silicon solar cells.

Up- and down-conversion schemes are designed to improve the conversion efficiency of photovoltaic systems. The absorption efficiency of the converted light in the solar cell is determined by the angular emission profile. Thus, controlling the direction of emission is of great importance to the efficiency. In Chapter 2, we introduce the use of Si nanocylinders to control the angular emission of CdSeTe/ZnS core–shell quantum dots (QDs). The Mie-like multipolar resonances in the cylinders can be tuned by changing their size, which influences the local density of optical states (LDOS) for the QDs placed on top of the cylinders. We treat the QDs as dipole-like emitters and use finite-difference time-domain (FDTD) simulations to optimize the cylinder dimensions for enhanced upward- or downward emission. QDs centered on a 400 nm diameter nanocylinder surface show 98% emission directionality into the Si substrate. Alternatively, for homogeneous ensembles placed over the nanocylinder top-surface, the upward emission is enhanced 10-fold for 150 nm diameter cylinders. Then, we demonstrate a novel soft-stamping method to selectively print a homogeneous layer of QDs on top of an array of Si nanocylinders. Experimental PL intensity measurements corroborate the simulated trends with cylinder diameter. PL lifetime measurements reflect well the variations of the LDOS at the QD position due to coupling to the resonant cylinders. These results demonstrate that the soft imprint technique provides a unique manner to directly integrate optical emitters with nanostructures. This can enable the application of nanophotonic structures in up- and down-conversion schemes for improved photovoltaics, or other optoelectronic devices such a light-emitting diodes (LEDs) or displays. This chapter also serves as the introduction to the next two chapters, where we study anisotropic emission for photovoltaic luminescent solar concentrators.

Building-integrated photovoltaic (BIPV) technologies integrate photovoltaic energy generation into the design of semi-transparent and opaque building envelopes. The photovoltaic luminescent solar concentrator (LSC) is an example of such a technology and offers the potential for low-cost, passive concentration of direct and diffuse light. Despite decades of research, the conversion efficiency for luminescent concentrator modules has fallen far short of that achievable by geometric concentrators. Recent advances in the photoluminescence quantum yield (PLQY) of semiconductor luminophores could significantly reduce parasitic losses, but efficient light trapping remains elusive to achieve high conversion efficiency LSCs. Anisotropically-emitting nanophotonic structures could enable a significant step forward in efficiency. In Chapter 3, we employ Monte Carlo ray-trace modeling to evaluate the conversion efficiency of LSCs using anisotropic luminophore emission, as a function of PLQY, luminophore concentration, and geometric gain. By spanning the full LSC parameter space, we define a roadmap towards high LSC conversion efficiency. To calculate the conversion efficiency from ray-tracing results, we derive an analytical function for the dark radiative current of an LSC. Design parameters are provided for optimized LSCs with practical geometrical gains of 10. We conclude that conversion efficiencies beyond 28% are achievable if strong anisotropic luminophore emission is combined with high PLQY. This analysis reveals that for high luminescent solar concentrator performance, light trapping is equally important to the luminophore PLQY.

After investigating the potential of light trapping for LSCs, now we demonstrate anisotropic luminophore emission to enhance light trapping in the LSC waveguide in Chapter 4. By embedding semiconductor nanoplatelet emitters into high-index TiO_2 nanocylinders, we alter their angular emission profile to increase emission into the angular range for total internal reflection (TIR). We explain the control over emission directionality by a combination of Mie-like multipolar resonances in the individual nanocylinders and the interaction with the lattice. We model the TiO_2 nanocylinder array as a photonic crystal (PhC) and identify the PhC waveguide modes as a function of the lattice pitch and wavelength. By increasing the pitch, we move the dominant PhC waveguide modes into the TIR angular range at the luminophore emission wavelength (650 nm). Angle-resolved photoluminescence measurements were performed on fabricated nanocylinders arrays to capture the angular emission profiles. By optimizing the cylinder shape and lattice spacing, we show an increase in light trapping from 75% (isotropic emission) to 83.5%. These results complement the results shown in Chapter 2, demonstrating nanophotonic emission control for photovoltaics and optoelectronic devices in general.

In the second part of the thesis, we study photonic structures for radiative cooling and anti-reflection of (silicon) solar cells. In Chapter 5, we investigate the use of passive radiative cooling (PRC) to dissipate excess heat from a silicon solar cell into or through the earth's atmosphere. To achieve a lower operating temperature, which is beneficial for both the efficiency and operating lifetime of a silicon solar cell, we make use of its spontaneous emission of infrared (IR) thermal radiation. The main challenge is to enhance PRC while simultaneously retaining transparency for sunlight above the silicon bandgap. We design and fabricate a hexagonal array of microcylinders that can be integrated into the top surface of the solar cell module glass. We use FDTD simulations to optimize the geometry to enhance emission in the IR wavelength range. Multipolar Mie-like resonances in the cylinders are shown to reduce reflection in the IR, which results in enhanced IR emissivity. Using integrating sphere spectroscopy, we measure the reflection of the silica cylinder array for IR as a well as visible to near-infrared wavelengths. The results in the IR compare very well to the simulated results, while we retain transparency for light with energy above the silicon bandgap. The fabricated microstructure increased the average emissivity between $\lambda = 7.5$ - 16 µm from 84.3% to 97.7%. With this design procedure, a PRC structure can be obtained for any photovoltaic device, with or without module glass encapsulation, or any other outdoor device that benefits from a lower operating temperature.

Complementary to light management of IR light, we investigate nanotextures for improved anti-reflection of light with energy above the bandgap. The emergence of these nanotextures in silicon solar cells has resulted in challenges associated with optical modeling. Whilst rigorous methods exist to accurately model black silicon (BSi) textures, the computational effort required limits the scope of modeling applications. In Chapter 6, we model three BSi nanotextures, each with a distinct random geometry, with an effective medium approximation (EMA). We validate the use of the EMA with full-wave optical simulations. We propose criteria for the validity of different optical simulation techniques based on a set of industrial photovoltaic textures. This analysis reveals a region within which neither geometric optics nor the EMA are adequate for calculating the reflectivity of a textured surface, and hence full-wave optical simulations are required. Even though we studied specific BSi textures for visible to near-infrared wavelengths, the proposed criteria are broadly applicable. We based the limits only on the root-mean-square roughness and correlation length, both normalized to the wavelength of the incident light, making them applicable to any surface texture.

Modeling and simulation of surface textures are commonly used in the PV industry to better understand the material properties, predict the device performance, and provide guidelines for optimizing fabrication parameters. Obtaining an accurate and reliable surface morphology of the BSi texture is one of the key challenges to achieving accurate models. In Chapter 7, we investigate the reliability and consistency of BSi texture characterization. We compare 3D models of complex BSi textures obtained by atomic force microscopy (AFM) and plasma focused ion beam (PFIB) tomography techniques. Hemispherical reflection measurement results are compared to full-wave optical simulated results to test the reliability and consistency of the tomography models. Our results provide evidence that PFIB tomography is more reliable and consistent at characterizing highly roughened BSi textures than AFM tomography.

Overall, this thesis provides new insights into several light management strategies to improve photovoltaic systems. Based on a fundamental understanding of the interaction between resonant photonic nanostructures and luminophores, we demonstrate control over the direction of emission. These insights and results pave the way for more efficient up- and down-conversion schemes and luminescent solar concentrators, specifically for photovoltaic applications. Similarly, we study the interaction of light with silicon solar cells to improve the emission of excess thermal energy and reduce reflection losses. We employ full-wave simulations to accurately predict this interaction at the scale of the wavelength of light to enable optimization of the surface textures. Many of these insights are also applicable to other optoelectronic devices such as photodetectors, light-emitting diodes, and displays.

Samenvatting

Fotonische controle over licht absorptie en straling in fotovoltaïsche systemen

Licht is een wonderlijk fenomeen. Het speelt een centrale rol in onze moderne samenleving, variërend van elektrische verlichting tot glasvezelcommunicatiesystemen en mobiele/computer schermen tot lasers. We gebruiken licht om de wereld om ons heen te zien, om de kleinste organismen te bestuderen met microscopen en de grootste objecten in het heelal waar te nemen met telescopen. Daarnaast kan licht een bron van energie zijn. Licht van de zon levert meer dan 9000 keer de hoeveelheid primaire energie die onze moderne samenleving opwekt. Bij de overgang naar een wereld die wordt aangedreven door hernieuwbare energie, zal fotovoltaïsche energieopwekking een sleutelrol spelen, waarbij de bijna onuitputtelijke energie die de zon levert wordt geoogst door fotovoltaïsche systemen zoals zonnepanelen. Fotovoltaïsche energieopwekking, Photovoltaics (PV) in het Engels, is een volwassen technologie die tientallen jaren van onderzoek en technologische vooruitgang heeft doorgemaakt, wat heeft geleid tot een exponentiële groei van de geïnstalleerde capaciteit en een exponentiële daling van de prijs van zonne-energie. Er moeten nog twee belangrijke uitdagingen worden overwonnen om grootschalige energievoorziening door PV mogelijk te maken: i) de verdere kostenverlaging van zonne-elektriciteit en ii) de integratie van PV in onze gebouwen, landschappen en infrastructuur.

In Hoofdstuk 1 schetsen we deze twee uitdagingen in meer detail. We beginnen met het onderzoeken van het potentieel van zonne-energieopwekking. We gaan verder met het kwantificeren van de limieten van photovoltaics en vergelijken deze met de huidige record-rendement zonnecellen. Vervolgens bespreken we de rol die fotonica kan spelen bij PV. We sluiten af met een motivatie voor het proefschrift en bespreken de twee belangrijkste uitdagingen die hierboven zijn opgesomd.

In de rest van dit proefschrift onderzoeken we de fotonische controle over absorptie en straling van licht in fotovoltaïsche systemen om deze twee uitdagingen aan te pakken. In het eerste deel (Hoofdstukken 2-4) geven we een fundamentele beschrijving van nanofotonische structuren om de hoekverdeling van straling door dipoolachtige emitters te controleren. Dit heeft toepassingen in bijvoorbeeld foton-conversieschema's voor fotovoltaïsche systemen, en voor luminescente zonneconcentratoren. In het tweede deel (Hoofdstukken 5-7), onderzoeken we fotonische structuren ter verbetering van de infraroodstraling voor stralingskoeling en oppervlaktestructuren voor antireflectie in siliciumzonnecellen.

Deel één

Het spectrum van de zon bevat licht met veel verschillende golflengtes, variërend van ultra-violet (hogere energie) naar zichtbaar tot infrarood (lagere energie). Figuur 1.1a *op blz. 5* laat de intensiteit van het zonnespectrum zien als functie van de golflengte (zwart) en hoeveel daarvan maximaal benut kan worden door een enkele zonnecel (oranje). Een enkele zonnecel kan theoretisch maximaal 33,7% van het zonlicht omzetten in elektriciteit, hoewel het record in de praktijk op 29.2% ligt. Het rendement wordt voornamelijk gelimiteerd doordat infrarood licht te weinig energie heeft (hoge golflengtes, rechts van het oranje oppervlak) en dus geen elektriciteit kan opwekken, en doordat ultra-violet en zichtbaar licht meer energie heeft dan de zonnecel kan gebruiken (boven het oranje oppervlak). De positie van de oranje lijn markeert de 'bandgap' van de zonnecel, de minimale energie (maximale golflengte) die licht nodig heeft om omgezet te kunnen worden in elektrische stroom. De bandgap verschilt per materiaal en bepaalt het maximale rendement — Figuur 1.2a *op blz. 7* laat het theoretische rendement per bandgap zien, en de behaalde records voor zonnecellen van verschillende materialen.

Om het rendement te verhogen van zonnecellen te verhogen, kunnen twee of meer zonnecellen op elkaar gelegd worden. Figuur 1.1b *op blz. 5* laat zien dat drie zonnecellen met verschillende bandgaps (blauw, groen en rood) ieder een ander gedeelte van het zonnespectrum omzetten. Tezamen verhoogt dit het maximum rendement naar 51,6%, maar maakt het tot nu toe altijd moeilijker en veel duurder om te fabriceren.

Foton-conversieschema's zijn een alternatieve manier om het theoretisch rendement van een zonnecel te verhogen; zie Figuur 1.3d ter illustratie *op blz. 11*. Hierin worden bijvoorbeeld twee lage-energie fotonen (minder energie dan de bandgap) omgezet in één hoge-energie foton (rood naar blauw), zodat die wel omgezet kan worden in elektriciteit. Andersom kan een hoge-energie foton gesplitst worden (blauw naar rood) in twee of meer lage-energie fotonen (met minstens de energie van de bandgap), zodat er meer elektriciteit opgewekt wordt.

Een materiaal waarin foton-conversie plaatsvindt moet eerst zonlicht absorberen, en daarna het geconverteerde licht weer uitzenden. Dat zal echter niet automatisch alleen richting de zonnecel uitgezonden worden. Daarom is het van belang om de richting te kunnen controleren waarin licht wordt uitgezonden. In Hoofdstukken 2, 3 en 4 demonstreren we hoe we nanofotonica gebruiken om de stralingsrichting te controleren van lichtgevende deeltjes.

Foton-conversieschema's zijn ontworpen om het rendement van fotovoltaïsche systemen te verbeteren. Het absorptierendement van het omgezette licht in de zonnecel wordt bepaald door het hoek-afhankelijke stralingsprofiel. Het beheersen van de stralingsrichting is dus van groot belang voor het rendement. In Hoofdstuk 2 introduceren we het gebruik van silicium (Si) nanocilinders om de hoekafhankelijke straling van CdSeTe/ZnS kwantumdeeltjes (KD's) te regelen. De Mie-achtige multipolaire resonanties in de cilinders kunnen worden afgestemd door hun grootte te veranderen, wat de lokale dichtheid van optische toestanden (LDOS) beïnvloedt voor de KD's die bovenop de cilinders zijn geplaatst. We modelleren de KD's als dipoolachtige emitters en gebruiken FDTD-simulaties (finite-difference time-domain) om de cilinderdimensies te optimaliseren voor verbeterde opwaartse of neerwaartse straling. KD's gecentreerd op een oppervlak van een nanocilinder met een diameter van 400 nm stralen 98%

neerwaards het Si-substraat in. Daarentegen, homogene ensembles die over het bovenoppervlak van de nanocilinder zijn geplaatst met een diameter van 150 nm, vertonen 10 keer meer opwaardse straling. Vervolgens demonstreren we een nieuwe zachte stempelmethode om selectief een homogene laag KD's op een reeks Si-nanocilinders te stempelen. Experimentele fotoluminescentie (PL) intensiteitsmetingen bevestigen de gesimuleerde trends als functie van de cilinderdiameter. PL-levensduurmetingen weerspiegelen goed de variaties van de LDOS op de KD-positie als gevolg van koppeling aan de resonanties. Deze resultaten tonen aan dat de zachte stempeltechniek een unieke manier biedt om lichtgevende deeltjes zoals kwantumdeeltjes direct te integreren met nanostructuren. Dit kan de toepassing van nanofotonische structuren mogelijk maken in foton-conversieschema's voor fotovoltaïsche systemen of andere opto-elektronische apparaten zoals light-emitting diodes (LED's) of displays. Dit hoofdstuk dient ook als inleiding op de volgende twee hoofdstukken, waar we anisotrope straling bestuderen voor fotovoltaïsche luminescente zonneconcentratoren.

Gebouwgeïntegreerde fotovoltaïsche (BIPV) technologieën integreren fotovoltaïsche energieopwekking in het ontwerp van semi-transparante en ondoorzichtige componenten van de gebouwde omgeving. De fotovoltaïsche luminescente zonneconcentrator (LSC) is een voorbeeld van een dergelijke technologie en biedt de mogelijkheid voor goedkope, passieve concentratie van direct en diffuus licht. Ondanks tientallen jaren van onderzoek, is het rendement van LSC's ver achtergebleven bij dat van geometrische concentrators. Recente ontwikkelingen in het fotoluminescentie-rendement (PLQY) van halfgeleider luminoforen (lichtgevende deeltjes) zouden de verliezen aanzienlijk kunnen verminderen, maar evengoed is efficiënte lichtopsluiting in het systeem nodig voor LSC's met een hoog rendement. Anisotroop stralende nanofotonische structuren zouden een belangrijke stap voorwaarts in rendement kunnen betekenen. In Hoofdstuk 3 gebruiken we Monte Carlo ray-trace modellering om het rendement van LSC's te evalueren met behulp van anisotrope luminofoorstraling, als een functie van PLQY, luminofoorconcentratie en geometrische versterking. Door alle LSC parameters te beschouwen, definiëren we een routekaart naar hoge-rendement LSC's. Om het rendement uit raytracing-resultaten te berekenen, leiden we een analytische functie af voor de donkerstroom van een LSC. Ontwerpparameters worden bepaald voor geoptimaliseerde LSC's met praktische geometrische concentratie van 10. We concluderen dat rendementen van meer dan 28% haalbaar zijn als sterke anisotrope luminofoorstraling wordt gecombineerd met hoge PLQY. Deze analyse laat zien dat voor hoge LSC rendementen, lichtopsluiting even belangrijk is als de PLQY.

Nadat we het potentieel van lichtopsluiting voor LSC's hebben onderzocht, demonstreren we nu anisotrope luminofoorstraling om de lichtopsluiting in de LSC-golfgeleider te verbeteren in Hoofdstuk 4. Door halfgeleider kwantumdeeltjes in te bedden in TiO_2 nanocilinders met een hoge brekingsindex, veranderen we hun hoekafhankelijke stralingsprofiel om de straling in het hoekbereik voor totale interne reflectie (TIR) te vergroten. We verklaren de controle over stralingsrichting door een combinatie van Mie-achtige multipolaire resonanties in de individuele nanocilinders en de interactie met het rooster. We modelleren het TiO_2 nanocilinder-rooster als een fotonisch kristal (FC) en identificeren de FC-golfgeleidermodi als een functie van de roosterafstand en golflengte. Door de roosterafstand te vergroten, verplaatsen we de dominante FC-golfgeleidermodi naar het TIR-hoekbereik bij de luminofoorstralingsgolflengte (650 nm). Hoek-opgeloste fotoluminescentiemetingen werden uitgevoerd op gefabriceerde nanocilinders-arrays om de hoekafhankelijke stralingsprofielen te meten. Door de cilindervorm en de roosterafstand te optimaliseren, laten we een toename in lichtopsluiting zien van 75% (isotrope stralingsverdeling) naar 83,5%. Deze resultaten zijn een aanvulling op de resultaten die worden getoond in Hoofdstuk 2.

Deel twee

De zonnepanelen die we op de Nederlandse daken zien zijn voornamelijk gemaakt van silicium (Si). Silicium kennen we vooral als bestandsdeel in zand en glas in de vorm van siliciumoxide (SiO_2). In de typische zonnecel wordt juist kristallijn Si gebruikt om zonlicht om te zetten naar elektriciteit. Naast elektriciteit wordt een groot gedeelte van het inkomende zonlicht omgezet in warmte, waardoor de temperatuur op kan lopen tot boven de 60 graden Celsius. Het rendement van een silicium zonnecel wordt minder met oplopende temperatuur, en ook de levensduur verslechtert. In Hoofdstuk 5 kijken we daarom naar een manier om een zonnecel passief te koelen (zonder dat dat energie kost) met fotonische structuren.
Om zonlicht om te kunnen zetten naar elektriciteit, moet het licht wel in de zonnecel terecht komen. Om de absorptie van licht in de zonnecel te maximaliseren, moet de reflectie minimaal worden (hier beschouwen we een zonnecel met een metalen achterkant die geen licht doorlaat). Oppervlaktetexturen kunnen de reflectie verminderen en ook de lichtopsluiting in de zonnecel verbeteren. In Hoofdstukken 6 en 7 onderzoeken we hoe oppervlaktetexturen beter en/of sneller gemodelleerd en gekarakteriseerd kunnen worden. Dit draagt bij aan het ontwerp en de fabricage van (silicium) zonnecellen met lagere reflectie en betere consistentie van de gefabriceerde (nano)structuren.

In het tweede deel van het proefschrift bestuderen we fotonische structuren voor stralingskoeling en antireflectie van (silicium) zonnecellen. In Hoofdstuk 5 onderzoeken we het gebruik van passieve stralingskoeling (PSK) om overtollige warmte van een silicium zonnecel van de aarde naar of door de atmosfeer af te voeren. Om een lagere temperatuur te bereiken, wat gunstig is voor zowel het rendement als de levensduur van een silicium zonnecel, maken we gebruik van de spontane straling van infrarood (IR) warmtestraling. De belangrijkste uitdaging is om PSK te verbeteren en tegelijkertijd de transparantie voor zonlicht boven de silicium bandgap te behouden. We ontwerpen en fabriceren een zeshoekig rooster van microcilinders die kunnen worden geïntegreerd in het bovenoppervlak van het glas van een zonnepaneel. We gebruiken FDTD-simulaties om de geometrie te optimaliseren om de straling in het IR-golflengtebereik te verbeteren. Van multipolaire Mie-achtige resonanties in de cilinders is aangetoond dat ze reflectie in het IR verminderen, wat resulteert in een verbeterde IR-straling. Met behulp van integrerende bolspectroscopie meten we de reflectie van het silica cilinderrooster voor IR en voor zichtbare tot nabij-infrarode golflengten. De resultaten in het IR komen goed overeen met de gesimuleerde resultaten, terwijl we transparantie behouden voor licht met energie boven de silicium bandgap. De gefabriceerde microstructuur verhoogt de gemiddelde straling tussen λ = 7,5 - 16 µm van 84,3% tot 97,7%. Met deze ontwerpprocedure kan een PSK-structuur worden verkregen voor elk fotovoltaïsch systeem, met of zonder een omsluiting van glas, of elk ander apparaat dat in de open lucht staat en profiteert van een lagere temperatuur.

Als aanvulling op het management van IR-licht, onderzoeken we nanotexturen voor verbeterde antireflectie van licht met energie boven de bandgap. De opkomst van deze nanotexturen in silicium zonnecellen heeft geleid tot uitdagingen in verband met optische modellering. Hoewel er rigoureuze methoden bestaan om de texturen van zwart silicium (zSi) nauwkeurig te modelleren, beperkt de vereiste rekenkracht de modelleringstoepassingen. In Hoofdstuk 6 modelleren we drie zSi-nanotexturen, elk met een aparte willekeurige geometrie, met een effectieve-stof benadering. We valideren het gebruik van de effectieve-stof benadering met lichtgolf simulaties. We stellen criteria voor de validiteit van verschillende optische simulatietechnieken voor op basis van een reeks industriële fotovoltaïsche texturen. Deze analyse onthult een gebied waarbinnen noch geometrische optica noch de effectieve-stof benadering geschikt zijn voor het berekenen van de reflectiviteit van een gestructureerd oppervlak, en daarom zijn lichtgolf simulaties vereist. Hoewel we specifieke zSi-texturen hebben bestudeerd voor zichtbare tot nabij-infrarode golflengten, zijn de voorgestelde criteria breed toepasbaar. We hebben de limieten alleen gebaseerd op de ruwheid en correlatielengte van de textuur, beide genormaliseerd naar de golflengte van het invallende licht, waardoor ze toepasbaar zijn op elke oppervlaktetextuur.

Modellering en simulatie van oppervlaktestructuren worden vaak gebruikt in de zonnecelindustrie om de materiaaleigenschappen beter te begrijpen, de prestaties van het apparaat te voorspellen en richtlijnen te geven voor het optimaliseren van fabricageparameters. Het verkrijgen van een nauwkeurige en betrouwbare oppervlaktestructuur van de zSi-textuur is een van de belangrijkste uitdagingen voor het verkrijgen van nauwkeurige modellen. In Hoofdstuk 7 onderzoeken we de betrouwbaarheid en consistentie van zSi-textuurkarakterisering. We vergelijken 3D-modellen van complexe zSi-texturen verkregen door atoomkrachtmicroscopie (AFM) en plasmagerichte ionenstraal (PFIB) technieken. Hemisferische-reflectie meetresultaten worden vergeleken met lichtgolf gesimuleerde resultaten om de betrouwbaarheid en consistentie van de textuurmodellen te testen. Onze resultaten leveren bewijs dat PFIB betrouwbaarder en consistenter is in het karakteriseren van sterk opgeruwde zSi-texturen dan AFM.

Als geheel biedt dit proefschrift nieuwe inzichten om fotovoltaïsche systemen te verbeteren door middel van verschillende fotonische controle over licht. Op basis van een fundamenteel begrip van de interactie tussen resonante fotonische nanostructuren en luminoforen, demonstreren we controle over de richting van straling. Deze inzichten en resultaten dragen bij aan de ontwikkeling van efficiëntere foton-conversieschema's en luminescente zonneconcentratoren, specifiek voor fotovoltaïsche toepassingen. Verder bestuderen we de interactie van licht met silicium zonnecellen om de straling van overtollige thermische energie te verbeteren en reflectieverliezen te verminderen. We gebruiken lichtgolf simulaties om deze interactie nauwkeurig te voorspellen op de schaal van de golflengte van het licht om optimalisatie van de oppervlaktetexturen mogelijk te maken. Veel van deze inzichten zijn ook toepasbaar op andere opto-elektronische apparaten zoals fotodetectoren, lichtgevende dioden en displays.

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"Fall in love with some activity, and do it! Nobody ever figures out what life is all about, and it doesn't matter. Explore the world. Nearly everything is really interesting if you go into it deeply enough. Work as hard and as much as you want to on the things you like to do the best. Don't think about what you want to be, but what you want to do. Keep up some kind of a minimum with other things so that society doesn't stop you from doing anything at all."

— Richard P. Feynman

"Remember to look up at the stars and not down at your feet. Try to make sense of what you see and wonder about what makes the universe exist. Be curious. And however difficult life may seem, there is always something you can do and succeed at.
It matters that you don't just give up."

— Stephen Hawking

"The measure of intelligence is the ability to change."

— Albert Einstein

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