Abstract

Photovoltaic technologies are promising for sustainable energy generation, yet their performance is limited by thermal and optical losses. This thesis investigates radiative cooling and flat optics as photonic approaches to enhance efficiency and durability without altering the semiconductor device.

The first part of the thesis examines radiative cooling as a passive and scalable strategy for thermal management in photovoltaic systems. An extended detailed-balance model is developed to include nonradiative recombination mechanisms, specifically Auger and Shockley-Read-Hall processes, providing a more realistic description of heat generation in solar cells. The results show that radiative cooling can significantly reduce operating temperature and improve conversion efficiency, particularly under high thermal-load conditions. For single-junction silicon and gallium arsenide devices, temperature reductions on the order of 20 K and absolute efficiency gains approaching 1-2% are obtained. The analysis is then extended to multi-junction solar cells under unconcentrated and concentrated illumination, where the cooling effect remains effective and is amplified by the higher temperature sensitivity of multi-junction architectures. In concentrating systems, increasing the radiative cooler area relative to the solar cell is identified as a key design strategy, enabling temperature reductions exceeding 100 K at high concentration and maintaining cell temperatures below approximately 350 K.

To validate these results beyond the isothermal assumption, a three-dimensional finite-element thermal model was implemented in COMSOL Multiphysics. The simulations resolve heat conduction, thermal radiation, and interfacial resistances in multilayer PV-radiative-cooler assemblies, confirming the analytical trends and identifying key design requirements. Effective cooling requires high thermal conductivity ($k_{\mathrm{RC}} \geq 50$ $\mathrm{Wm^{-1}K^{-1}}$), strong thermal contact ($h_{\mathrm{c}}^{\mathrm{int}} \geq 10^3$ $\mathrm{Wm^{-2}K^{-1}}$), high reflectivity, and sufficiently large emitting areas to maintain solar cell temperatures below 350 K, even under concentrated illumination. These results establish radiative

cooling as an efficient and scalable passive solution for both conventional and concentrated photovoltaic systems.

The second part of the thesis investigates flat optical concentrators, specifically multilevel diffractive lenses (MDLs) and metalenses (MLs), as a route toward compact and scalable solar concentration. The key optical, geometrical, and technological requirements for deploying flat lenses in concentrating photovoltaic systems are identified, and a nonimaging theoretical framework is introduced to evaluate their performance. A comparative assessment of MDLs and MLs is then carried out in terms of spectral bandwidth, aperture diameter, numerical aperture, angular tolerance, materials, and fabrication maturity. The results show that MDLs, based on micrometer-scale thickness modulation, already enable millimeter- to centimeter-scale apertures with broadband achromatic performance over 400-1100 nm and moderate numerical apertures suitable for micro-CPV, making them the most viable near-term option. Metalenses offer exceptional phase and dispersion control, but their scalability is currently limited by group-delay constraints and nanofabrication complexity, restricting broadband achromatic designs to sub-millimeter apertures. Both technologies share the advantages of flat optics, including planarity, low profile, and compatibility with scalable fabrication, supporting integration with thermally managed and radiatively cooled photovoltaic platforms.

Overall, this thesis provides a unified framework for the optical and thermal optimisation of photovoltaic systems, showing that photonic engineering can passively enhance performance and reliability, paving the way for next-generation photovoltaic systems.