Highly Efficient Light-trapping Structure for Thin-film Solar Cells using Topology Optimization

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Thin-film solar cell devices [1, 2] provide an economically viable sustainable energy source due to their potential in low-cost production. However, the limitation associated with the low optical absorption remains to be the main technical barrier that constrains the device efficiency in energy conversion. Effective light-trapping structure is thus critical to increase light absorption in thin-film cells [3]. Topological properties of light-trapping structures play vital roles in determining governing factors over light absorption in thin-film solar cells, such as effective mode coupling and surface reflection reduction [4]. In this work, a systematic method based on topology optimization is developed to design highly-efficient light-trapping structure for thin-film solar cells. The commonly adopted parametric approach relies on a prefixed design concept following physical intuition and engineering experience; it is incapable of handling topological variations during optimization. In contrast, our method built upon topology optimization allows a simultaneous consideration of multiple governing factors over absorption to achieve the most favorable light-trapping structure for various thin-film cells with substantial enhancement in absorbing performance. For the complicated physics involved in evaluating light absorption in thin-film solar cells, the rigorous coupled wave analysis (RCWA) [5] is adopted as the forward analysis model. Solving Maxwell's equations in Fourier space, it is efficient and accurate in calculating diffraction efficiencies of periodic optical gratings and multilayer stacks [6]. Resting upon RCWA, a sequential optimization model comprising nongradient-based and gradient-based topology optimization methods is constructed considering the severe nonlinearity owing to the resonant phenomena in thin-film cells light-trapping process. Applying the Genetic Algorithm (GA) based topology optimization first to identify promising structures, the gradient based topology optimization is then followed using the SIMP method (Solid Isotropic Material with Penalization) to fulfill further improvement. Functional gradient information required by the SIMP based topology optimization is derived on the basis of RCWA. Two testing cases of different thin-film solar cells are performed in our work, i.e. a less nonlinear cell structure (ITO/P3HT/bottom electrode) and a highly nonlinear cell structure (GaP/P3HT/bottom electrode). Our method is verified by comparing results with existing designs from intuitive approach. The effectiveness of our method has been confirmed from the satisfactory results for single-wavelength incidence as well as over solar spectrum. Nearly 100% absorption has been accomplished for a single incident wavelength and 50% average absorption achieved over solar spectrum without a back reflector, reaching a spectral enhancement factor more than 3 folds of the Yablonovitch limit [7]. By overcoming the challenges of complex physics and severe nonlinearity, this work extends topology optimization to a brand-new area of harvesting solar energy, showing its potential for achieving highly efficient innovative solar cell structures beyond the reach of intuition.

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