Visible Three-Dimensional Metallic Photonic Crystal

CNF Project Number: 1880-10
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Primary CNF Tools Used: CVD silicon deposition, reactive ion beam etcher, deep UV lithography

Abstract:
In this work, a novel Teepee-like photonic crystal (PC) structure on crystalline silicon (Si) is experimentally demonstrated. Our PC structure is shown to exhibit 98.5% solar absorption over $\lambda = 400$-1000 nm spectral range for 500 µm-thick silicon. By reducing the silicon solid content by 50 times to only 10 µm thick, we still achieve a 94.7% averaged solar absorption. This data represents, to the best of our knowledge, the best average absorption for such a super-thin Si.

Summary of Research:
In summary, we proposed and demonstrated a new Teepee-like PC design with broadband, wide-angle near-unity solar energy absorption, which is achieved by novel light trapping mechanisms: (1) Gaussian-type gradient-index interface profile and (2) near-orthogonal parallel-to-interface negative refraction. The Teepee-like PC structure is realized by a unique but simple photolithography patterning and RIE dry etching process, which is repeatable and IC-technology compatible for large-area, high-throughput wafer-scale fabrications. The funnel-like geometry of the PC structure with greater vertical depth and higher sidewall angle means it can achieve better light trapping than typical KOH-etched inverted pyramid structures.

Teepee-like PC on 500-µm crystalline silicon can already achieve broadband near-zero reflection and near-unity absorption ($A=98.5\%$) in $\lambda = 400$-1000 nm. For Teepee-like PC on much thinner c-Si ($t=10\mu$m), the average absorption is $\sim 94.7\%$. Even for near IR wavelengths ($\lambda=800$-1000nm), the average absorption is sustained at $\sim 90.5\%$. The main reason for enhanced light trapping and significantly improved near IR absorption in much thinner c-Si is the parallel-to-interface refraction effect, which creates near-90° optical refraction and vortex-like energy circulation patterns concentrated inside absorbing material. Therefore, the Teepee-like photonic crystal shows excellent promise for achieving greater efficiency improvement in both conventional and thin film crystalline silicon solar cells towards the Shockley-Queisser limit.

References:
Figure 1: (a) Schematic representation of the Teepee-like photonic crystal structure. (b) Optical reflection from polished, planar silicon wafer surface and from the Teepee-like photonic crystal structure surface. (c) SEM image of the Teepee-like photonic crystal structure at slanted view. (d) SEM image of the photonic crystal at front side view.

Figure 2: 3D contour plots of measured total absorption of (a) Teepee-like photonic crystal structure on 500 µm thick silicon with 60 nm SiO₂ AR coating, (b) Teepee-like photonic crystal on 10 µm thick silicon with 60 nm SiO₂ AR coating and 200 nm Ag back reflector, (c) planar 500 µm thick silicon, and (d) planar 10 µm thick silicon at different incident angles. (e) Measured integrated absorption of the four samples for λ = 400-1000 nm at different incident angles.