ENGE2010 November 21-24, 2010

An Efficient Ray Tracing Algorithm for Simulation of Light Trapping Effects in Si Solar Cells with Textured Surface

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Introduction

Since the first implementation of pyramidal texturing into Si solar cell, three-dimensional (3-D) texturing of Si surface together with antireflection treatment of surface have been widely utilized to enhance the incoming light confinement in Si solar cells. Numerical modeling and analytical solution can provide an efficient and meaningful pathway in designing an optimized texture pattern, which would require cost-ineffective and time consuming works if investigated by experimental procedure solely. Ray-tracing is one of the most powerful techniques to fulfill the above purpose, but earlier numerical tools based on ray-tracing technique suffered from limitation in simulating real texture patterns because they could handle only the regular size of pyramidal pattern or regular array of regular pattern, and from long execution time. In later researches, two more advanced ray-tracing techniques, in which random size of pyramidal shapes and patterns could be handled to some extent, were developed. But one had restriction in positioning the adjacent unit cells in certain range around the target unit cell, by which finding of the adjacent unit cells would become feasible during ray tracing, resulting in failure in handling the truly random patterns. The other technique utilized a premeasured topological information of real surfaces obtained from the measurement of atomic force microscopy (AFM) in ray tracing simulation. But this technique also had difficulty in generating various patterns for simulation. Furthermore, both of the above methods used an asymptotic $O(N_r \times N_i \times N_o)$ time complexity, leading to limitations in increasing system size and number of rays. N_r, N_i and N_o are the number of rays, the average number of intersections and the number of objects respectively. In this work, we report a newly devised algorithm called "Slab-Outline" based on ray tracing technique, which can handle fully random texture in size and distribution of 3-D pattern. *Slab-Outline* algorithm can trace real object geometry with an asymptotic $O(N_r \times N_i \times \log_2 N_o)$ time complexity.

SLAB-OUTLINE Algorithm

◆***Slab-Outline algorithm uses K-Dimensional Tree (K-D Tree) data structure in order to attain the exact tracing of textured surface***

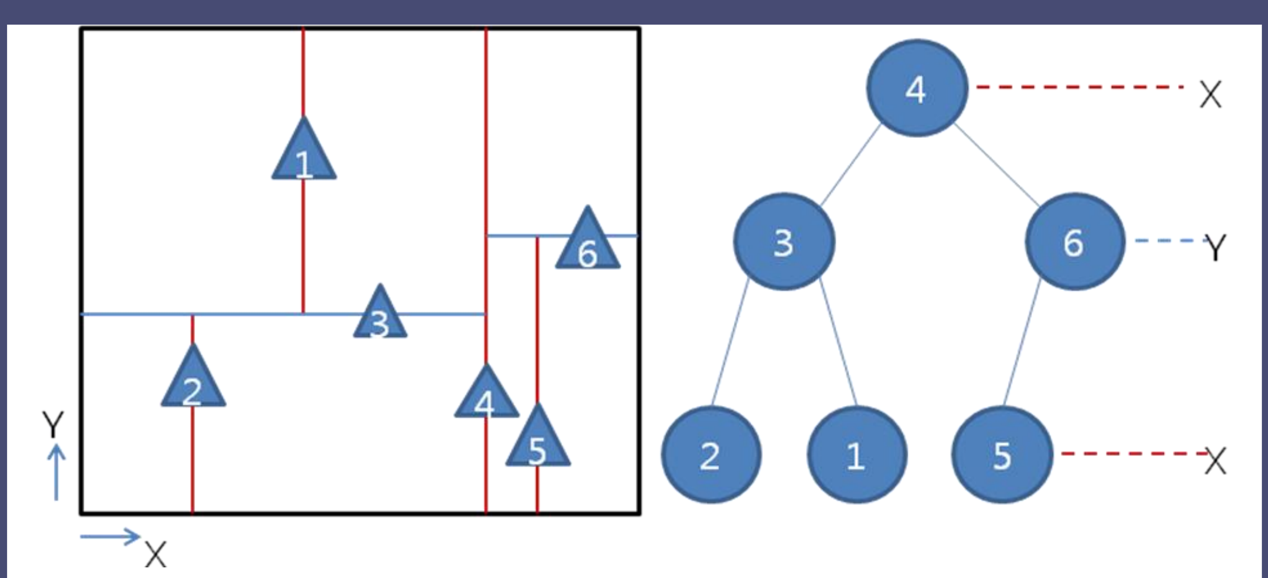

Fig. 1. Objects distribution in 2-D and related KD-Tree structure.

Step.1: Create geometrical information for texture.
Step.2: Create KD-Tree for texture.
Step.3: Start ray tracing procedure for number of rays Nr.
Step.3.1: Find intersection.
Step.3.2: Process optical property and calculate absorption value.
Step.3.3: Calculate next ray direction.
Step.3.4: Repeat steps 3.1, 3.2 and 3.3 until last ray's simulation is finished.

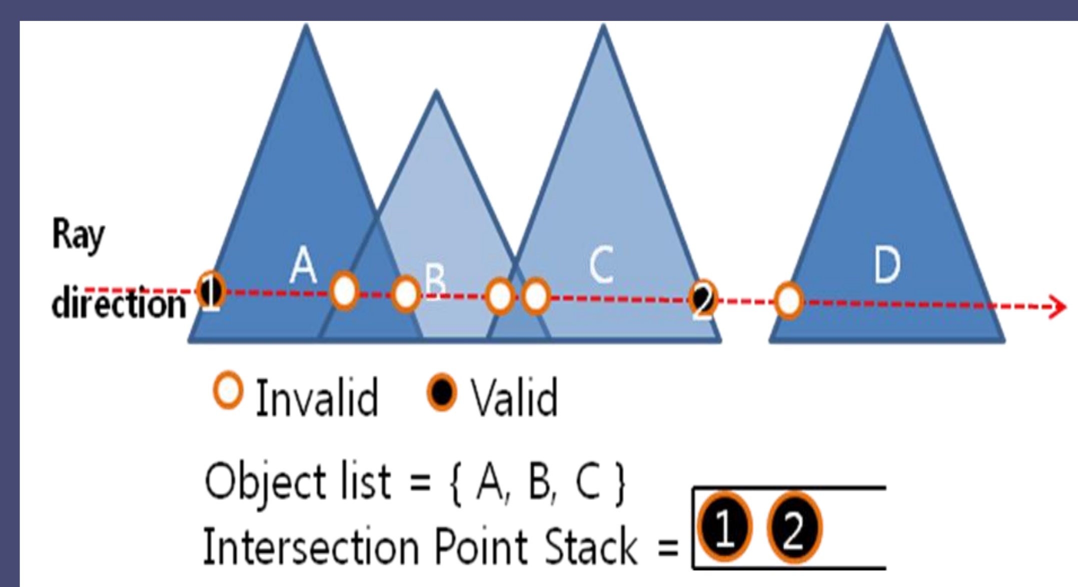

Fig. 2. Schematics of logic for finding intersection points between objects and ray.

Simulation & Experiment Results

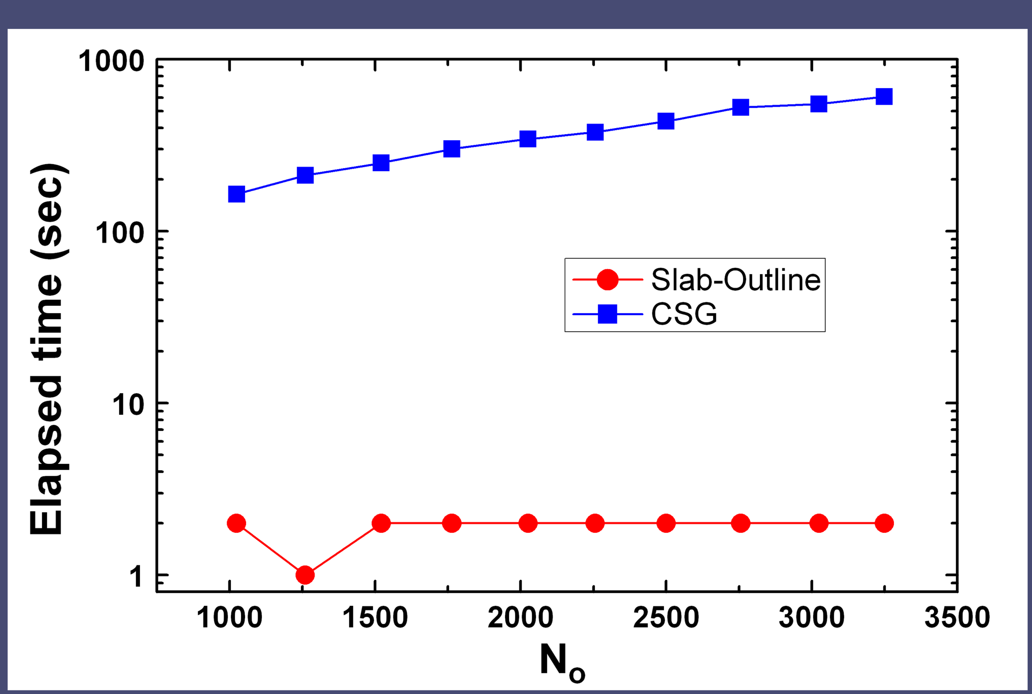

Fig. 3. Performance test result (Environment: 4CPU-2.96Ghz).

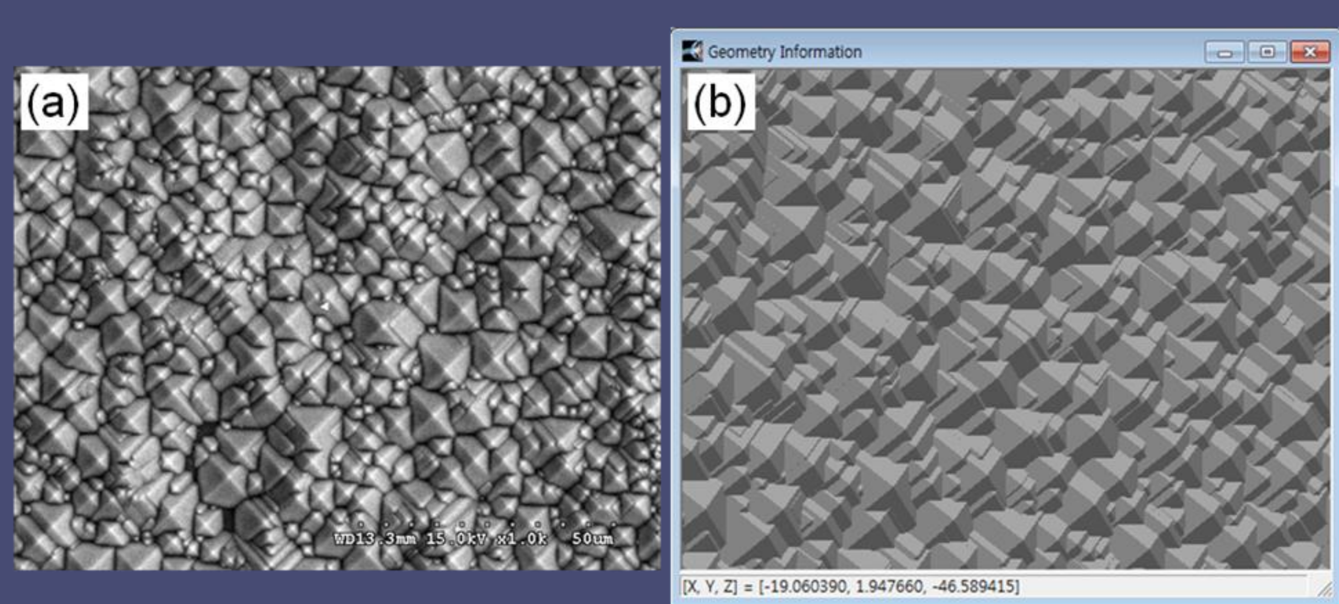

Fig. 4. (a) Surface morphology of textured Si sample.
(b) 3-D rendering image of the geometric information for simulation.

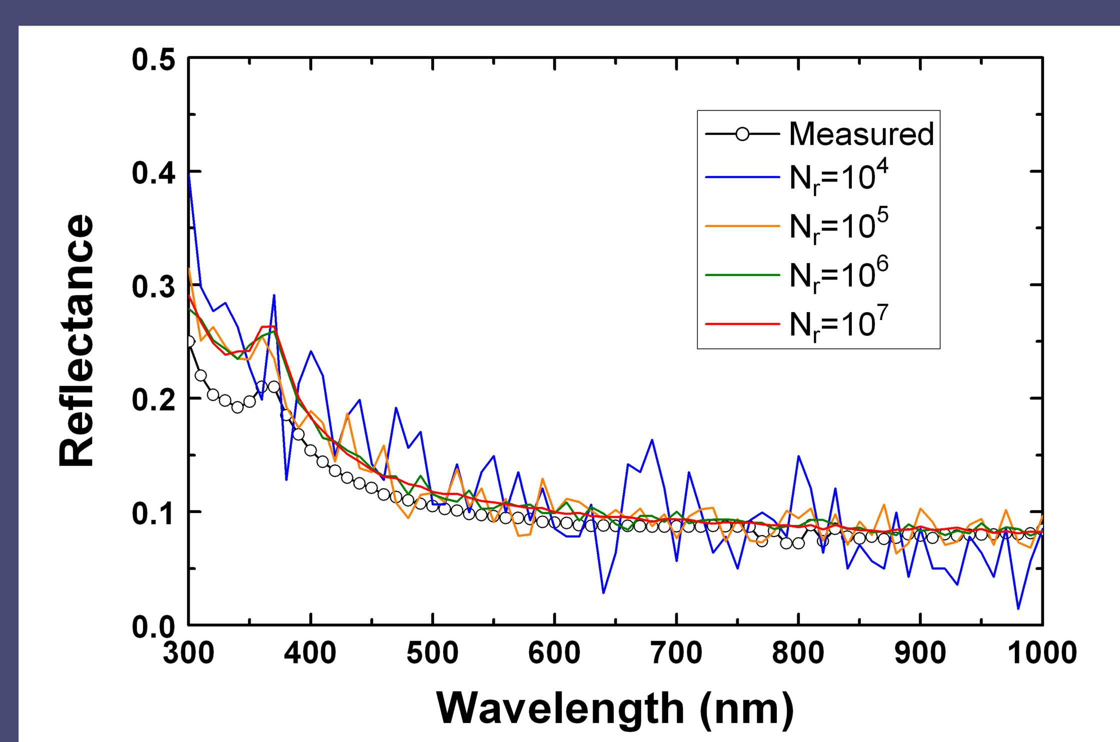

Fig. 5. Comparison of measured and simulated reflectance spectra.

The error calculated using L_2 norm was 0.208% at $N_r=10^4$. As N_r increased to 10^5 and 10^6 rays, the fluctuation in simulated spectrum became smaller, showing better agreement with the overall trend of the measured one to some extent. At $N_r=10^7$ rays, the overall shape of the simulated spectrum corresponded the measured one very well, and the calculated error by L_2 norm was significantly lowered to 0.04%.

Conclusions

- *New ray-tracing algorithm called **Slab-Outline** which can simulate the light trapping effects of a textured Si solar cells with superior efficiency.*
- *The validity of the Slab-Outline algorithm was verified by comparing the simulated reflectance spectra with the measured one from a textured Si surface.*
- *The superiority of computing time efficiency was proved by comparing the computing time between the current algorithm and CSG algorithm which is known to provide an exact tracing of real objects.*
- *In the course of verification of the Slab-Outline algorithm, it was shown that the number of rays and the input design of texture were crucial in decreasing the simulation error.*

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