Simulation of crystalline silicon solar cell top contact using ASPIN3 and COMSOL Multiphysics simulators

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***Abstract* – We present numerical simulations of conventional crystalline silicon solar cell using two numerical simulation tools - ASPIN3 and COMSOL Multiphysics. Mesh convergence and computation time analysis was carried out for both simulators using a test 1D model. A comparison of J-V curves calculated with both simulators shows excellent agreement. 2D simulations, where we varied the finger spacing of the top contact, were carried out at a constant finger width of 100 µm to find the maximum cell efficiency in three different simulation cases: *ideal, transparent* and *realistic*. In the *realistic* case, the maximum cell efficiency of 21.4% is found at 5.2 mm spacing.**

1 INTRODUCTION

Photovoltaics is a clean, environmentally friendly alternative to conventional electric power generation. Crystalline silicon (c-Si) solar cells dominate the photovoltaic market due to their low cost, long-term stability and large quantities of silicon in the earth's crust [1]. To achieve high cell efficiency many aspects of the cell design need to be optimized. Using device modeling and numerical simulation, the search for optimal parameters can be greatly simplified and accelerated.

The simulations in this paper were carried out with two simulators – ASPIN3 [2] and COMSOL Multiphysics [3]. ASPIN3 is an in-house developed 2D semiconductor device simulator based on the steady-state drift-diffusion model and can (in combination with optical simulators) be used to simulate the operation of various solar cells [4], [5]. Its numerical algorithm is based on 2D finite difference discretization of Poisson's equation, continuity equations and transport equations for electrons and holes. The optical generation rate profile is calculated using a built-in 1D optical simulator based on the transfer matrix method. COMSOL Multiphysics is a general-purpose software platform, based on advanced numerical methods, for modeling and simulating physics-based problems [6]. With the semiconductor module it is possible to solve the same set of equations as with ASPIN3, but using the finite elements method.

In this paper we first compare the results of both simulators for a test 1D P-N junction structure. Secondly, we perform a mesh convergence and computation time study. Finally, we focus on solving the optimization problem of top contact design [7], [8]. We use 2D simulations to determine the finger spacing that results in the highest efficiency of the modeled solar cell.

2 MODEL DESCRIPTION

The schematic diagram of the 2D model, which is based on the conventional crystalline silicon solar cell structure [9], is shown in Figure 1.

On the top side where light enters the structure, the top contacts' geometry is changed by varying the finger spacing. In the non-contacted region between the fingers there is a 60 nm thick SiN_x layer which serves as an anti-reflective coating and a front surface passivation layer where ideal passivation is assumed with a surface recombination velocity (SRV) of minority carriers of 0 cm/s. The emitter is a 1 µm thick n-type and the absorber a 148.5 µm thick p-type c-Si layer. There is a 0.5 µm heavily doped p-type c-Si back surface field layer on the bottom of the absorber. A 300 nm thick Ag layer serves as a metal contact and a back reflector and covers the entire rear side of the cell. Under the top and bottom contacts an SRV of minority carriers of 100 cm/s is assumed.

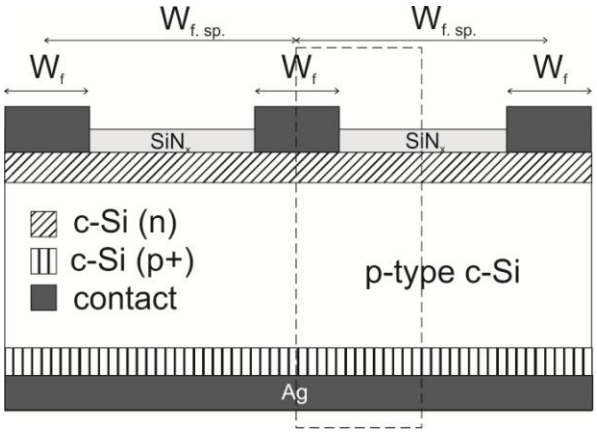

Figure 1: Schematic diagram of the simulated c-Si solar cell model (the simulation domain is inside the dashed box).

Parameter	c-Si(n)	c-Si(p)	c-Si(p+)
Layer thickness (μm)	1	148.5	0.5
Relative permittivity	11.7	11.7	11.7
Electron affinity (eV)	4.05	4.05	4.05
Band gap (eV)	1.12	1.12	1.12
Effective conduction band density (cm^{-3})	3×10^{19}	3×10^{19}	3×10^{19}
Effective valence band density (cm^{-3})	1×10^{19}	1×10^{19}	1×10^{19}
Electron mobility ($cm^2\ V^{-1}\ s^{-1}$)	1450	1450	1450
Hole mobility ($cm^2\ V^{-1}\ s^{-1}$)	500	500	500
Doping concentration of acceptors (cm^{-3})	0	4.9925×10^{15}	1×10^{19}
Doping concentration of donors (cm^{-3})	4.9925×10^{15}	0	0
Electron lifetime	10 ms	10 ms	10 ms
Hole lifetime	10 ms	10 ms	10 ms

Table 1: Material parameters used in the simulation.

To speed up the simulation we take advantage of the structure's symmetry which results in a smaller simulation domain (dashed box in Fig. 1). The material parameters used in the simulations are shown in Table 1. The optical generation rate profile, which is used in both simulators, is calculated with ASPIN3 by an optical simulation of the equivalent optical structure SiN_x(60 nm)/Si(150 μm)/Ag(300 nm) under AM1.5 spectrum for wavelengths ranging from 350 nm to 1200 nm.

3 RESULTS AND DISCUSSION

3.1 Preliminary results: 1D P-N junction J-V curve

We start with a simplified solar cell model, a 1D P-N junction, to compare the results given by each simulator independently. The modeled 1D structure is 4 μm thick, with both the p-type and n-type semiconductor layer equally thick at 2 μm and a doping of 1×10^{17} cm^{-3}. The contacts are ideal ohmic. Other material properties are the same as in Table 1. The generation rate has a constant value of 1×10^{21} $cm^{-3}s^{-1}$ throughout the whole structure. J-V curve was calculated by sweeping the applied voltage at the contacts of the structure. The simulated J-V curves calculated with both simulators and the relative difference are shown in Figure 2. The difference is very small for applied voltages below 0.5 V (flat region of the J-V curve) where it barely exceeds 0.01%. The relative difference increases around open-circuit voltage of 0.55 V, where the current density is low and the relative difference calculation includes division with values close to zero.

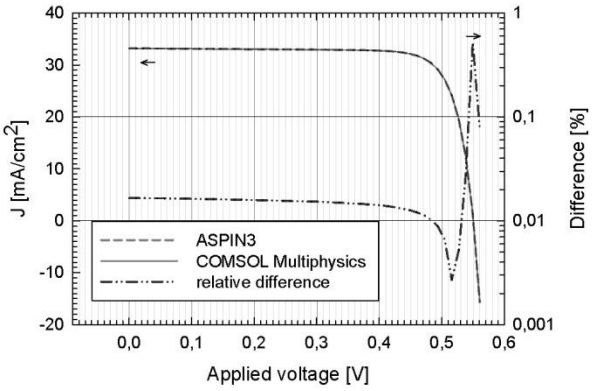

Figure 2: Comparison of J-V curves calculated with both simulators shows excellent agreement. The relative difference never exceeds 1%.

3.2 Mesh convergence and computing time analysis

Figure 3 shows how the accuracy of results and computing times change with respect to the number of mesh points used in our 1D test structure. To evaluate the accuracy of the results we evaluated the maximum electric field norm at the boundary between p-type and n-type semiconductor layers in the structure. As a reference to evaluate the accuracy we calculated the solution with each simulator using the mesh with most points (10^5).

As the number of mesh points increases, the maximum electric field norm values returned by the simulators converge to the reference value and the computation time increases. After 2×10^3 points the results of both simulators are almost the same as the reference value. The calculated values differentiate mostly when there is a small number of mesh points.

As the simulators use different numerical procedures, the results suggest that at low number of mesh points the finite elements method is more accurate than the finite differences method. However, further analysis shows that the distribution of points itself is a more important factor. COMSOL Multiphysics builds an optimum mesh automatically, whereas in ASPIN3 an equidistant mesh was used.

The computation times are shorter when using ASPIN3 for the number of points used in this study. The difference is relatively bigger at smaller number of points. At under 10^3 mesh points, ASPIN3 completes the simulation around three to four times faster than COMSOL Multiphysics. At 8×10^4 mesh points the difference is around 30%.

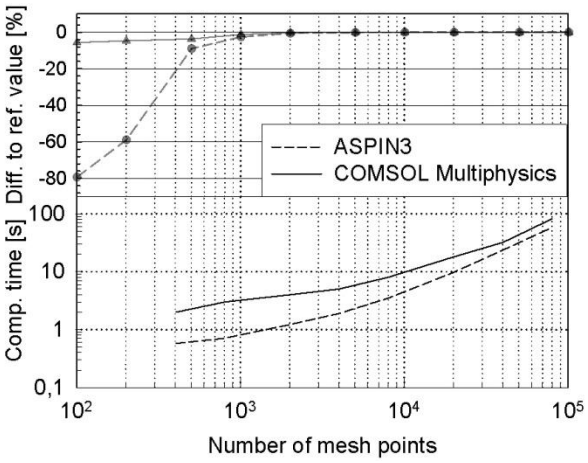

Figure 3: Mesh convergence and computation time results. The results converge to the reference value with an increasing number of mesh points as expected, with COMSOL Multiphysics being more accurate at lower number of points. Computation times increase with number of mesh points and are shorter in ASPIN3.

3.3 Top contact optimization

The 2D model is simulated under various conditions to find the optimal top contact design. The finger width has a constant value of 100 µm while the finger spacing (distance between two neighbouring fingers) is varied. The simulation is carried out under three different settings, approaching ever more realistic conditions. In the *ideal* case we assume contacts that are transparent to incident light and have ideal surface passivation (SRV of 0 cm/s). In the *transparent* case the contacts are still transparent, but the SRV has a value of 100 cm/s. In the *realistic* case we assume non-transparent contacts and an SRV value of 100 cm/s. The results are shown in Figure 5.

The highest efficiency result is obtained in the *ideal* case. Because of transparent contacts there are no shading losses and the current density does not decrease at narrower finger spacing, when the contact covers a relatively greater area of the cell. Due to ideal passivation there are no unwanted surface recombinations under the contacted area. As the series resistance, determined from the slope of J-V curve at $V_{OC,}$ increases from 1.437 Ω cm^2 to 1.754 Ω cm^2 with increasing spacing, the efficiency decreases. The highest efficiency of 24.4% would therefore be achieved at full contact coverage.

In the *transparent* case, the recombinations under the contacted area cause V_{OC} values to decrease at narrower spacing (the defective surface becomes relatively larger). The current is mostly not affected, as the contacts are still transparent. We observe an efficiency drop at narrower finger spacing, mostly due to a drop in V_{OC}. The optimal value of finger spacing at 4.2 mm results in 21.9% cell efficiency.

In the *realistic* case the non-transparent contacts block sunlight and the current decreases significantly at narrower finger spacing due to shading losses. Compared to the *transparent* case, the efficiency is lower, especially at small finger spacing values. At larger values the contacted area is relatively small and shading losses are almost negligible compared to other effects. The optimal finger spacing value is at 5.2 mm with 21.4 % cell efficiency.

As simulations for 1D show good agreement between both simulators, the results discussed in this section were calculated only using ASPIN3. Preliminary COMSOL Multiphysics simulations of the 2D structure also show agreement (grey circles in Fig. 5). In the *ideal* case there is some discrepancy, because the ideal contact passivation in COMSOL Multiphysics is defined using Schottky contacts, while in ASPIN3 selective contacts were used (same as Shottky, but without a barrier at the interface).

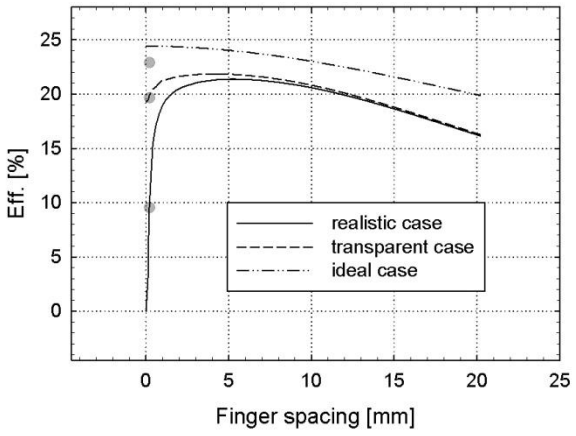

Figure 5: Cell efficiency in the *ideal*, *transparent* and *realistic* case calculated with ASPIN3. Grey circles show results obtained with COMSOL Multiphysics for comparison.

4 CONCLUSION

In this paper we present numerical simulations of conventional crystalline silicon solar cell using ASPIN3 and COMSOL Multiphysics simulators. A comparison of both simulators is carried out by J-V simulations of a test 1D P-N junction model. The agreement of results is excellent, suggesting that although they use different numerical procedures, both simulators produce the same results. A mesh convergence and computing time analysis shows that both simulators' output converge to the correct solution at high enough number of mesh points. COMSOL Multiphysics does a slightly better job at lower number of points mainly due to automatic optimal mesh generation as opposed to ASPIN3 where mesh has to be set up by the user. ASPIN3 calculates the solution faster than COMSOL Multiphysics, especially at lower numbers of mesh points. 2D simulations are carried out in three different cases (*ideal*, *transparent* and *realistic*) to find the optimal finger spacing at a constant finger width value of 100 μm. In the most realistic case which takes into account shading losses, series resistance and recombination effects due to passivation in the contacted area, the cell's efficiency reaches around 21.4 % at 5.2 mm finger spacing.

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