THIN AND SMALL FORM FACTOR CELLS: SIMULATED BEHAVIOR

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ABSTRACT

Thin and small form factor cells have been researched lately by several research groups around the world due to possible lower assembly costs and reduced material consumption with higher efficiencies. Given the popularity of these devices, it is important to have detailed information about the behavior of these devices. Simulation of fabrication processes and device performance reveals some of the advantages and behavior of solar cells that are thin and small. Three main effects were studied: the effect of surface recombination on the optimum thickness, efficiency, and current density, the effect of contact distance on the efficiency for thin cells, and lastly the effect of surface recombination on the grams per Watt-peak. Results show that high efficiency can be obtained in thin devices if they are well-passivated and the distance between contacts is short. Furthermore, the ratio of grams per Watt-peak is greatly reduced as the device is thinned.

INTRODUCTION

Microsystems enabled photovoltaics (MEPV) is a novel approach that relies on fabrication tools and techniques borrowed from the Mycrosystems arena. Recent MEPV experimental work has obtained relatively high efficiencies (around 15%) [1] while reducing the amount of silicon used by a factor of up to 30 (including Kerf loss) [2] in 250μm lateral sized back-contacted silicon solar cells. This approach uses scaling benefits observed in solar cells to produce small lateral dimensions, ultrathin and highly efficient solar cells. Reduction in material use, increased processing yields, increased carrier collection, elimination of shading, and increased Voc are some of the benefits observed as the scale of the cells is reduced. Further advantages of using MEPV technology have also been reported. [3] Given the advantages of these devices, other research groups have researched new ways to create thin and small size solar cells. [4,5,6]

Much work has been done to simulate the performance of macro-scale solar cells. In contrast, MEPV is a novel approach and much simulation work is needed to gain insight into critical device parameters. This paper presents simulation results of ultrathin solar cells. Commercially available simulations tools are used to create representative cross sectional models of the cells. The cells are then stimulated and parameters (processing and device) are systematically varied to gain insight into performance as a function of parameters.

SIMULATIONS

Two commercially available tools from Synopsys® were used to simulate the processes and the testing of the device. The processes that are simulated include implantation, diffusion, oxidation, etching, deposition, lithography, and epitaxy. All these processes are done in Tsuprem4 using a two-dimensional cross-sectional model of the device. The output of this software contains information about the strains in layers, boundaries of different materials, and impurity distribution. [7]

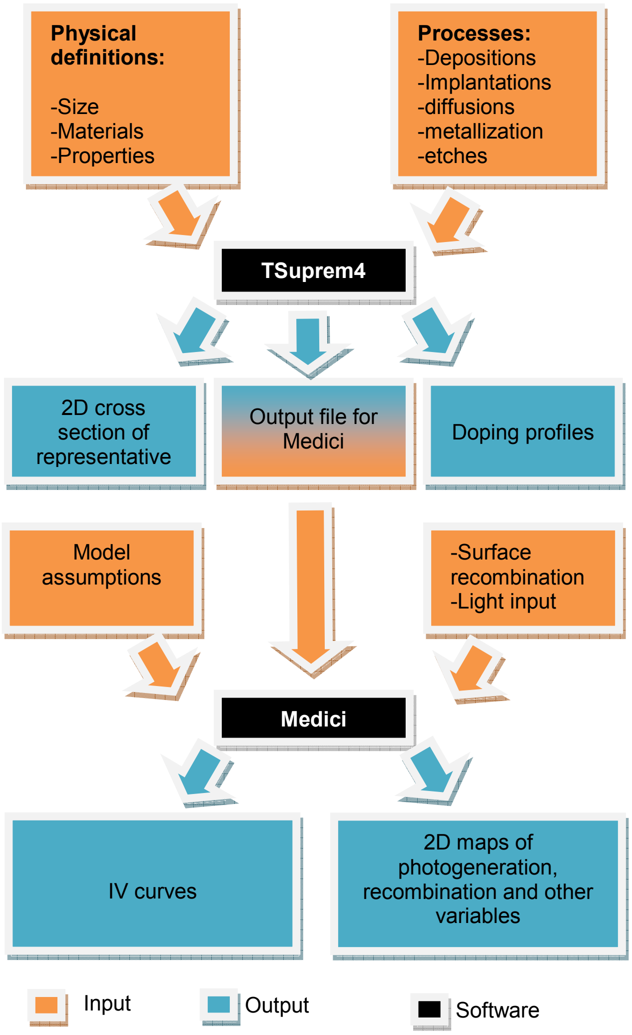

Figure 1. Flow chart of operations done by the simulation software.

Medici is then used to simulate the electronic performance of the devices. This software simulates the transient and steady state behavior of electrical, thermal, and optical characteristics of semiconductor devices created in Tsuprem4. [8] Figure 1 shows a diagram explaining the implementation of these tools.

Figure 2 shows the simulated two-dimensional, back-contacted solar cell. Light is incident from the front (bottom) and the carriers are collected at the back (top) through the n and p electrodes (green). In this example, the thickness of the cell is 14 μm (front to back) and the distance between the center of the electrodes is 24 μm. Silicon nitride layers (red) are deposited on front and back of the device to reduce surface recombination velocity and also as an antireflective coating on the front side. In this structure, carriers are generated near the front where most of the absorption occurs and then diffuse towards to the back where they are collected by the electrodes.

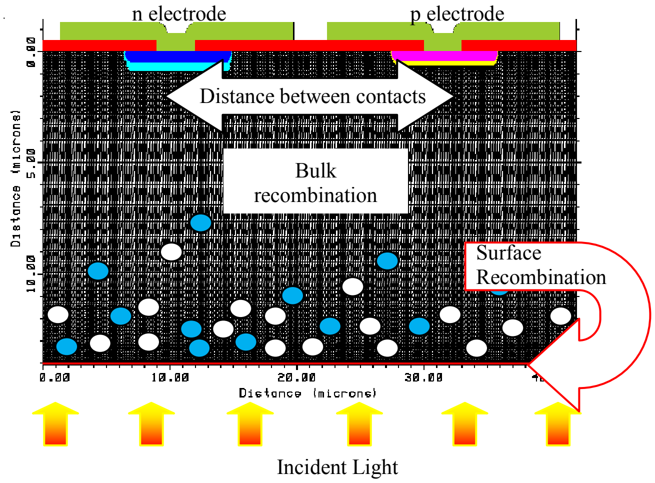

Figure 2. Structure of the 2 dimensional solar cell. Electrons and holes are represented as circles of different colors

From experience, three parameters that were found to strongly affect performance are the surface passivation, the thickness, and the distance between contacts. Surface passivation has a very strong effect on cell performance in micrometer sized cells due to the proximity of surfaces to active regions of the device. Un-passivated atoms at surfaces have incomplete bonds (dangling bonds) that act as carrier traps and degrade device performance. Surface recombination velocity (SRV) expresses the quality of the surface passivation where slower velocities indicate better passivation. Furthermore, given the back-contact nature of the cells, carriers generated near the surface have to diffuse (without the help of fields) through the thickness of the semiconductor. Therefore, device thickness is another important parameter that affects carrier collection.

In the simulations we tracked the conversion efficiency of the solar cell versus thickness for different surface recombination velocities. We varied the surface recombination from 10 to 10^6 cm/s and the thickness from 1 μm to 400 μm while keeping the lateral dimension constant at 42 μm. We also studied the effect of distance between contacts on efficiency. Finally, we analyzed the peak power produced as a function of material use.

The assumed material properties were a $7X10^{14}$ cm^{-3} p-type doping, (111) oriented silicon wafer, with lifetime of 1 ms. Implantations of boron (energy = 45 keV) and phosphorus (energy = 20 keV) were simulated, with a dose of $1X10^{15}$ cm^{-2}, tilt of 7°, and range of 0.15μm. A drive-in step at 900°C for 30 minutes was done in a N_2 atmosphere. IV curves were obtained through a truncated AM 1.5 solar spectrum (between 0.3 and 2.4 μm and divided into 100 points). The simulations assume the Shockley-Read-Hall recombination model, with concentration dependant lifetimes and mobilities, as well as Auger recombination models. The software solves the continuity and the Poisson equation simultaneously to obtain the current and voltage characteristics.

RESULTS

Effect of thickness and recombination velocity

Figure 3 plots an optimized efficiency (and corresponding thickness) as a function of surface recombination velocity. The optimized efficiency was obtained by selecting the thickness at which the efficiency is maximized for a given SRV. It is important to note that the optimized thickness drops rapidly from 400 μm to 25 μm as the SRV increases from 10 to 1000 cm/s. In contrast, the efficiency is reduced only 6% from 20% to 14%. This graph shows a motivation for using thin solar cells: A large savings in material usage is afforded by a small reduction in efficiency. When the thickness is reduced below 10 μm at higher SRVs, the efficiency starts to drop more rapidly due to absorption and surface recombination losses.

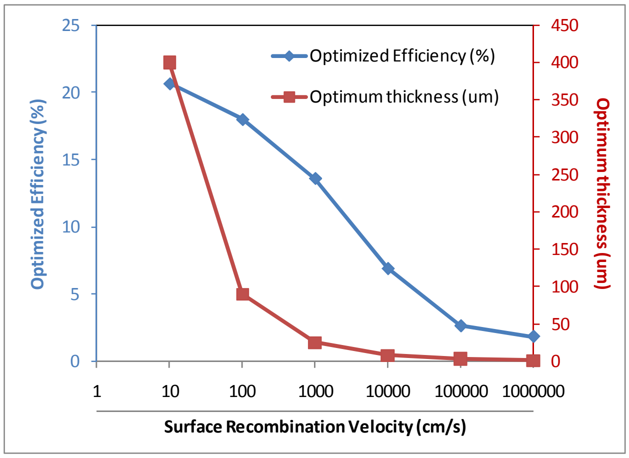

Figure 3. Optimum efficiency and thickness versus different surface recombination velocities.

This behavior is corroborated in Figure 4 which plots the effect of SRV on current density for various thicknesses. Again Figure 4 indicates that a thickness between 10 μm and 40 μm is needed to absorb and collect >95% of the carriers for SRVs below 1000 cm/s. Figure 4 gives insight into the operation of back-contacted solar cells. While material thickness is needed to absorb photons, if the cell is too thick for a given SRV, bulk recombination will dominate causing an overall loss of efficiency. This is clearly seen for the 400 μm trace which quickly falls as the SRV increases. In other words, a tradeoff exists between increasing photon absorption (through increased thickness) and reducing recombination loss (through decreased thickness).

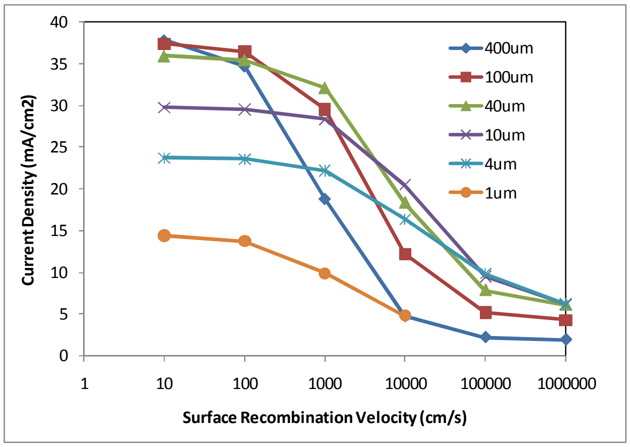

Figure 4. Current density versus surface recombination velocity for different thickness.

Effect of distance between contacts

Figure 5 plots the efficiency of a cell that is 14 μm thick as a function of the separation distance between the collection electrodes (contacts n and p). The graph shows the efficacy of using closely printed contacts. As the distance of the contacts is reduced, the efficiency increases by collecting carriers closer to where they were generated. As expected, lower quality materials (with a higher bulk recombination) yield lower efficiencies. However, it is interesting to see that for close contacts (below 40 μm), the need for quality material is mitigated as seen by the narrowing between the green and the red curves as the distance between contacts is shortened.

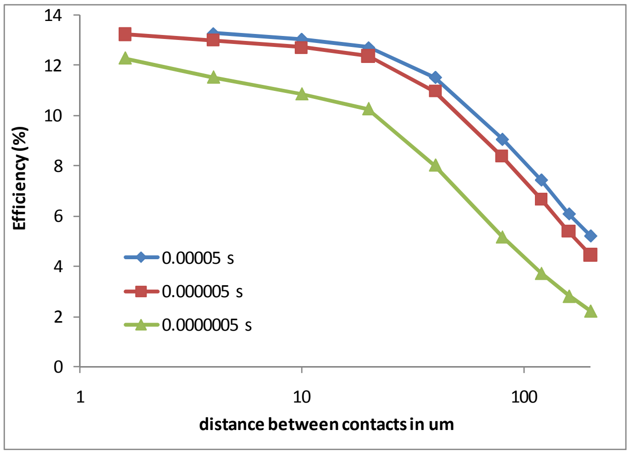

Figure 5. Efficiency vs. distance between contacts for a 14μm thick solar cell for different bulk lifetimes.

Effect of Material Use on Peak Power

The amount of material used to get a certain amount of power is often represented as grams per watt-peak. Figure 6 plots the grams per watt-peak as a function of the surface recombination velocity. For all thicknesses, the amount of material is reduced as the surface recombination is reduced. It can be seen that the amount of material needed to generate a watt-peak decreases drastically as the cells are made thinner. The efficiency does not diminish linearly with the thickness but the amount of material used does. Material costs are major portion of total module cost, therefore reducing material use while keeping efficiencies high is a key to achieving grid parity. Producing ultrathin cells is a means to reducing the amount of material used.

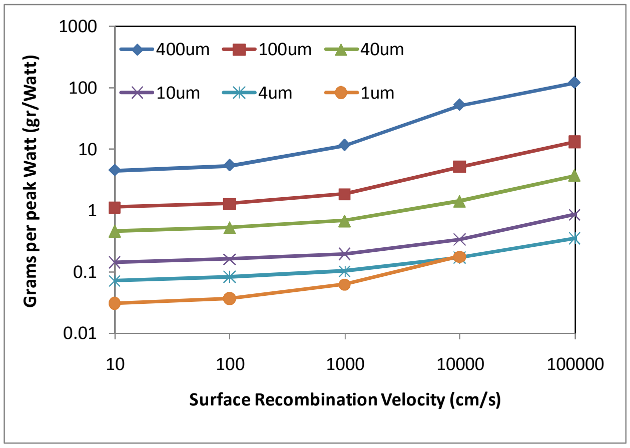

Figure 6. Grams per watt peak vs. surface recombination velocity for different thicknesses

SUMMARY

The understanding of the mechanisms that optimize and dominate ultrathin and small form factor solar cells is crucial for the deployment of MEPV based technology. Through this study we reveal some of the advantages and behavior of solar cells that are thin and small. Three main effects were studied: the effect of surface recombination on optimum thickness, efficiency, and current density, the effect of contact distance on efficiency, and the effect of surface recombination on grams per watt peak. The results reveal that it is vital that surface recombination velocity (SRV) on the front surface is minimized to reduce surface recombination. Moreover, the thickness of the device should be optimized based on the tradeoff between reducing recombination of the diffusing carriers (through decreased thickness) and increasing photon absorption (through increased thickness). The distance between contacts is also important since closer spacing is expected to enhance collection efficiency. Finally, we saw that using well passivated (low surface recombination) cells that are thin is an excellent way to reduce the amount of material needed to generate as much power as thick substrates.

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