

# THREE EFFICIENCY BENEFITS FROM THIN FILM PLASMONIC SOLAR CELLS

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## ABSTRACT

In a race to reduce the cost per Watt of solar generated power, there is generally a tradeoff between high efficiency and low cost. By going to thinner devices, less material can be used; however, clever light management designs must be utilized to avoid the loss in current caused by reduced absorption in a thin active layer. Here we discuss such design schemes incorporating either dielectric or metallic structures to approach the bulk absorption limit in optically thin layers. As a specific example, a plasmonic back grating can result in absorption of 80% of the incident above bandgap light in a GaAs layer of only 200 nm. If the reduction in current upon thinning of the cell is limited, an improvement in the open circuit voltage can be obtained through a reduction of the bulk recombination current. Under the condition that the open circuit voltage increases more rapidly than the short circuit current decreases, thinner layers will produce more efficient cells. Finally, the incorporation of metallic scatterers can potentially improve the fill factor by reducing the sheet resistance of a top surface-passivating layer. We show experiments that suggest that the sheet resistance decreases for a metal particle decorated GaAs structure, which can be modeled using a simple circuit diagram. By combining all three effects, we consider the possibility of high efficiency solar cells that are an order of magnitude thinner than their bulk counterparts and consider their role for future photovoltaic device architectures.

## INTRODUCTION

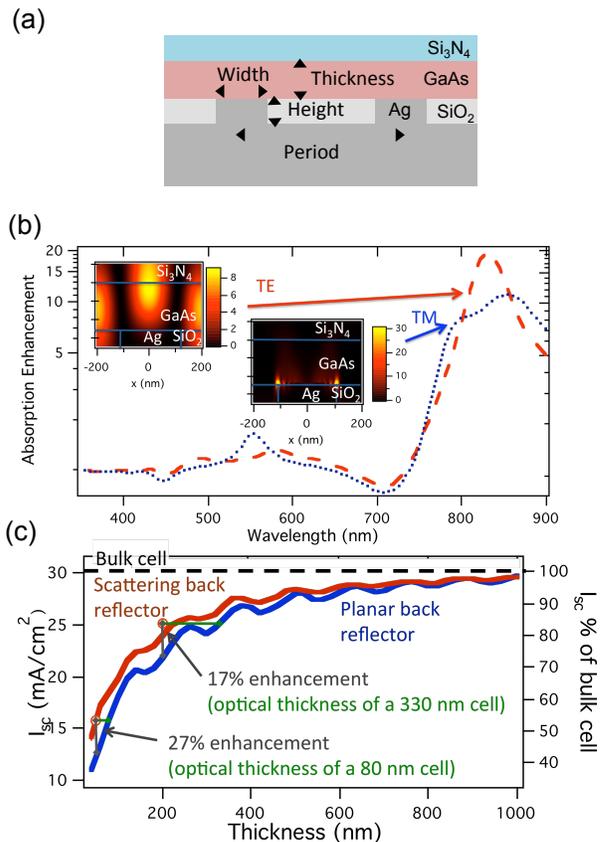
In recent years, much attention has been given to the coupling of light to solar cells with the intent of increasing absorption and hence photogeneration within the cell [1,2]. In particular, metal particles are attractive because of their relatively large scattering cross-sections [3]; however, the increased scattering must be weighed against the increased loss due to absorption within the metal itself. With proper design, this limitation can be overcome, and cells based on scatterers can outperform traditionally designed cells.

While the use of metallic scattering objects may improve semiconductor absorption, one must ensure that other relevant efficiency factors (e.g.  $V_{oc}$  and FF) are not detrimentally affected. Further, if the overall efficiency is improved, one must avoid cost enhancements that would increase the cost per Watt of such a cell, which would counter the positive effects of the efficiency

improvement. Here we describe design concepts that in principle could lead to low cost, high efficiency solar cells based on both photonic and optoelectronic design considerations.

## INCREASED OPTICAL ABSORPTION

Plasmonic particles are known to improve absorption by three mechanisms. First, if particles are placed on top of the solar cell, light will be preferentially forward scattered into the semiconductor due to its higher refractive index. The net effect is less reflection, i.e. it works as an anti-reflection coating. Second, the particles can scatter light



**Figure 1. Absorption enhancements. (a) Optimization parameters for a 50 nm thick GaAs structure, (b) absorption enhancement from a photonic waveguide mode (shown here for TE) and a surface plasmon polariton mode (TM), and (c) calculated photocurrent as a function of thickness.**

into waveguide modes of the structures. This results in an increased path length by making the propagation direction normal to the incoming light. Third, light can be trapped locally in resonances that lead to extremely high field intensities over a small volume of the cell. By changing the size of the scattering objects, the relevance of each of these effects can be modified in order to determine which structure has the maximum absorption.

As an example, we consider the absorption enhancement of a GaAs solar cell with a metallic grating on the back through Finite Difference Time Domain (FDTD) simulations (see Fig. 1). GaAs was chosen because of its high internal quantum efficiency, which results in collection of nearly all photogenerated carriers. This allows for a simplified device model. We also in-fill the metallic grating with SiO<sub>2</sub> so that the GaAs wafer retains its original form (i.e. it is not etched into or damaged in any way), which means that it can remain in its planar, high quality optoelectronic state.

Optical simulations of the electromagnetic fields are performed, and the field profiles are used to calculate the absorption within the semiconductor [2]. The electron generation rate per unit volume within the semiconductor is given by:

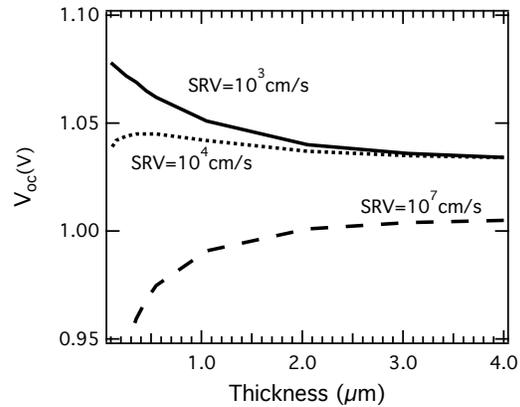
$$GR = \int_{\text{solar spectrum}} \left( \frac{\epsilon'' |\bar{E}(\omega)|^2}{2\hbar} \right) d\omega \quad (1)$$

where  $|\bar{E}(\omega)|^2$  is the magnitude of the electric field squared within the structure resulting from solar illumination and  $\epsilon''$  is the imaginary part of the dielectric function of the semiconductor. Assuming a high quality material like GaAs, we can integrate the generation rate over the thickness of the cell to obtain the average current per unit area, which corresponds to the short circuit current density,  $J_{sc}$ , of the device.

The grating structure was optimized for a 50 nm thick layer of GaAs, and a plot of the wavelength resolved absorption enhancement shows that the optimized structure results from increasing absorption near the bandedge (~870 nm) of GaAs (Fig. 1b). The TE polarization leads to enhancements associated with a photonic waveguide mode of the structure, while the TM enhancement results from surface plasmon polaritons (SPPs) localized on the grating. For the 50 nm thick GaAs structure, the enhancement of the photocurrent is 27%, which is equivalent to the absorption of an 80 nm planar cell (Fig. 1c). With proper design, a 200 nm thick cell can absorb over 80% as much as an optically thick cell (>1 μm). Using similar design concepts, it should be possible to design other thin cells that absorb nearly the entire available incident spectrum.

## INCREASED OPEN CIRCUIT VOLTAGE

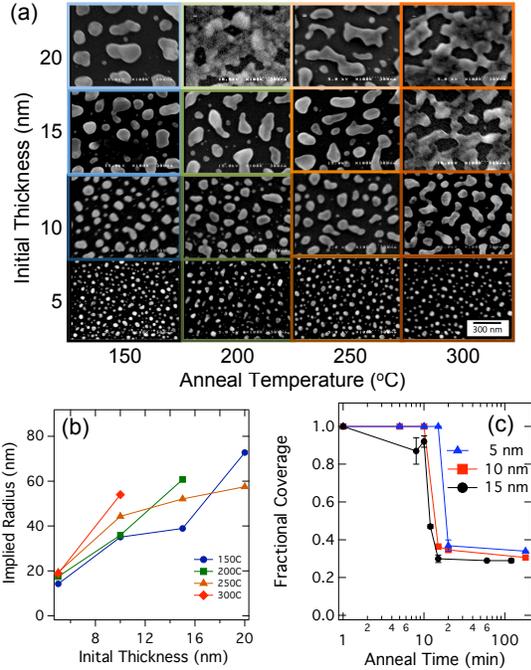
Using the above-mentioned light trapping techniques, one can now consider the benefits of using significantly less material, and hence design a much thinner solar cell. The first advantage is reduced material consumption. This can help mediate material abundance concerns [2] and can also result in cheaper cells by consuming less raw material and speeding up the deposition process by using less reactor time. The second advantage of a thin cell is the possibility of improved device performance. The improved performance can come in the form of (i) better carrier collection and (ii) an improvement in the open circuit voltage as a result of decreased recombination current. To demonstrate this effect, a GaAs solar cell was modeled using AFORS-HET, and the cell's performance was determined for a range of thicknesses and surface recombination velocities (SRV). For unpassivated structures, the SRV is large and causes a significant decrease in the  $V_{oc}$  as the cell is thinned. For well-passivated cells (e.g. using AlGaAs or InGaP window layers for a GaAs cell), the SRV can be greatly reduced. For a SRV of 10<sup>3</sup> cm/s, recombination is mainly from the bulk, rather than the surface, even down to thicknesses below 100 nm. Thus, for such a cell, the short diode limit yields  $V_{oc} \propto \ln(1/w)$ , where  $w$  is the thickness. This increased  $V_{oc}$  for decreased cell thickness is shown for a typical device model (Fig. 2).



**Figure 2. Increase in the  $V_{oc}$  of a GaAs cell upon thinning of the active layer. The effect is most pronounced for well-passivated surfaces with low surface recombination velocities.**

## INCREASED SHEET CONDUCTIVITY

The addition of metallic scattering objects to the top of a solar cell may also improve the sheet conductivity, which leads to an improvement of the fill factor (FF). Such a result was hypothesized after observing an improvement of the FF upon placing small metallic particles on top of a GaAs solar cell [4]. To test this hypothesis, we measured the sheet resistance for a number of particle-decorated

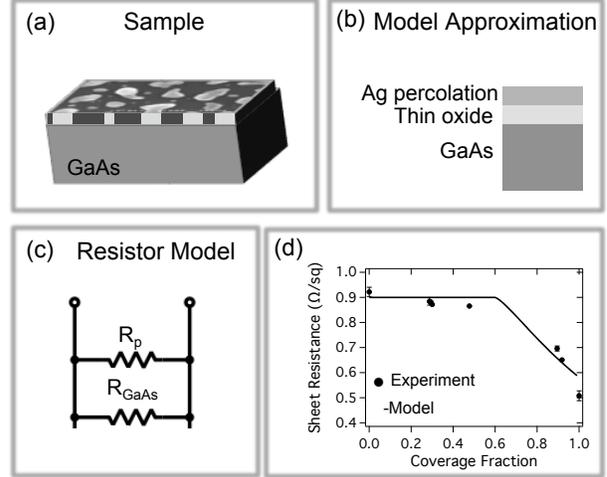


**Figure 3. Particle formation conditions. (a) Particle size and shape depend on initial film thickness and anneal temperature. (b) Thicker films lead to larger particles. (c) Films typically break into particles after 10 to 20 min regardless of initial film thickness given the experimental conditions used in this work.**

GaAs surfaces and found a strong correlation with fractional coverage.

To deposit particles on the surface of the semiconductor, we thermally evaporated Ag and annealed the samples under forming gas (95% N, 5% H). Depending on the processing conditions (initial thickness, anneal temperature, and anneal time), a variety of particle sizes and surface coverages were obtained (Fig. 3). The implied radii of particles were calculated from the SEM images of the surface and varied from approximately 20 nm to 80 nm and depended mostly on the initial film thickness rather than the anneal temperature. Under the conditions used here, the breakup of the film into particles typically occurred after 10 to 20 min of annealing.

4-point probe measurements were conducted on the samples to determine the effect of the particles on the sheet resistance (Fig. 4). For low fractional coverages (<40%), the resistance was dominated by the GaAs substrate, while for larger fractional coverages the resistance dramatically decreased. We believe that this behavior is a result of a thin oxide layer that had formed on top of the GaAs substrate and insulated it from the Ag film (Fig. 4b). The probes were able to break through the oxide to contact the GaAs; however, very little conduction occurred through the Ag at small fractional coverages. For large fractional coverages, the Ag particles form a



**Figure 4. Simple resistor model for improved sheet resistance. (a) 3D schematic and (b) cross section of the Ag particle coated GaAs sample. (c) Circuit diagram of the parallel resistor model of the system. (d) Resistor model used to describe the experimental 4-probe data.**

percolating network, which then allowed for conduction in the Ag layer as well.

We constructed a two resistor model to describe this effect, which produces reasonable agreement with the experimental data (Fig. 4d). In this model, the Ag film is treated as a percolating network,  $R_p$ , connected in parallel with GaAs,  $R_{GaAs}$ . The equivalent resistance is given by:

$$R_{eq} = \frac{R_p R_{GaAs}}{(R_p + R_{GaAs})} \quad (2)$$

While this work shows that the metal improves the surface conductance for these structures, a more practical enhancement could be achieved by removing the oxide prior to metal coating.

## CONCLUSIONS

We have shown that thin film plasmonic solar cells can have efficiency benefits from three independent effects: increased semiconductor absorption (improved  $J_{sc}$ ), decreased nonradiative recombination (improved  $V_{oc}$ ), and decreased sheet resistance (improved FF). In addition to these efficiency benefits, cost benefits can be achieved through less material use. To avoid increased fabrication costs, simple templating methods and cheaper metals like Cu and Al should be considered for large scale adoption of these concepts.

## ACKNOWLEDGEMENTS

We thank M. Deceglie for helpful conversations and acknowledge financial support from the Department of Energy, Office of Basic Energy Sciences under Contract No. DE-FG02-07ER46405.

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