# Metal-black scattering centers to enhance light harvesting by thin-film solar cells

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## Abstract

Small metal particles are investigated as scattering centers to increase the effective optical thickness of thin-film solar cells. The particular type of particles used is known as "metal-black", well known as an IR absorber for bolometric infrared detectors. Gold-black was deposited on commercial thin-film solar cells using a thermal evaporator in nitrogen ambient at pressures of ~1 Torr. A broad range of length scales, as revealed by scanning electron microscope images gives rise to effective scattering over a range of wavelengths across the solar spectrum. The solar cell efficiency was determined both as a function of wavelength and for a solar spectrum produced by a Xe lamp and appropriate filters. Up to 20% increase in short-circuit photo-current, and a 5% increase in efficiency at the maximum power point, were observed.

## 1. Introduction

Thin film solar cells offer the advantages of lower materials and manufacturing costs, lighter weight, and durable flexibility over the conventional crystalline silicon solar cells that currently dominate solar cell applications. A disadvantage of optically-thin photovoltaic films is that they fail to harvest all of the incident solar flux. Many groups are pursuing investigation of increased effective path length within the absorber layers of such cells by deposition of small metal scattering centers. Lithographically produced self-assembled arrays of metal dots have been shown to increase solar cell efficiency, at least in part of the solar spectrum depending on geometry and size [1]. This work investigates the possibility of using sparse depositions of gold black, a nano-structured metal formed in a thermal evaporator at ~1 Torr inert ambient. The range of length scales inherent in such depositions produces spectrally-broad scattering that may provide efficiency enhancement across the entire solar spectrum.

Gold blacks are typically deposited using the method of Harris [2-6], in which different morphologies can be attained by changing parameters such as inert gas pressure, deposition rate, and the mass of gold in the boat. Particle size and packing fraction can be controlled by these parameters [7-10]. For thermal detectors, thick opaque films are required [11]. For solar cell coatings, sparse depositions are needed to allow scattered light to reach the semiconductor.

Surface plasmon polaritons are collective oscillations of electrons at the interface between metal and dielectric. Localized surface plasmons occur with metallic nano particles of size much smaller than metal's skin depth. Scattering cross sections are enhanced at resonance frequencies. Such scattering increases the effective optical path length in the thin films by diverting normally incident radiation to larger angles of incidence. The frequency of the surface plasmon resonance depends on the size and shape of the particle. Lithographically deposited or self-assembled metal dots have been shown to achieve efficiency enhancement within limited wavelength ranges determined by the dot morphology. For gold black, we intuitively expect a broad spectrum of enhanced scattering due to the broad particle-size distribution in gold black. Small metal-black particles may also improve efficiency via electric field enhancement at the plasmon resonance.

## 2. Experiment

Sparse metal black films were deposited by thermal evaporation in a chamber that was back-filled to ~1 Torr with nitrogen. At such pressures, the evaporated metal particles are able to combine into nano-scale agglomerates before reaching the substrate. The temperature of the receiving surface influences the characteristics of metal black thin films, and this is a parameter that is controlled in our customized deposition chamber. Generally, we cool the substrate below room temperature, for which samples are mounted on a copper plate that is cooled with a Peltier module.

Simultaneous depositions were made on thin film solar cells and a piece of silicon wafer of cm dimensions. The later was used for characterization by scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS). Parameters chosen to vary were the mass of gold, the $N_2$ pressure, and the evaporation current (proportional to the rate of deposition). A typical deposition run contained the following steps:

Figure 1 (left) is a schematic representation of the characterization scheme for the spectral response of the current. Fig. 1 (right) is a photograph of the set up. The Xe lamp illumination enters the monochromator which is scanned from 350 – 1100 nm while measuring the short-circuit current. Both control of the monochromator and recording of the short circuit current were handled by a Labview program.

For efficiency measurements the Xe lamp was set up to illuminate the solar cell uniformly with 350 mW incident power in a spot of 50 mm diameter. Filters were used to produce a sun-like spectrum. A Keithely source meter was used to obtain the IV curve. The experiment was carefully screened from stray light.

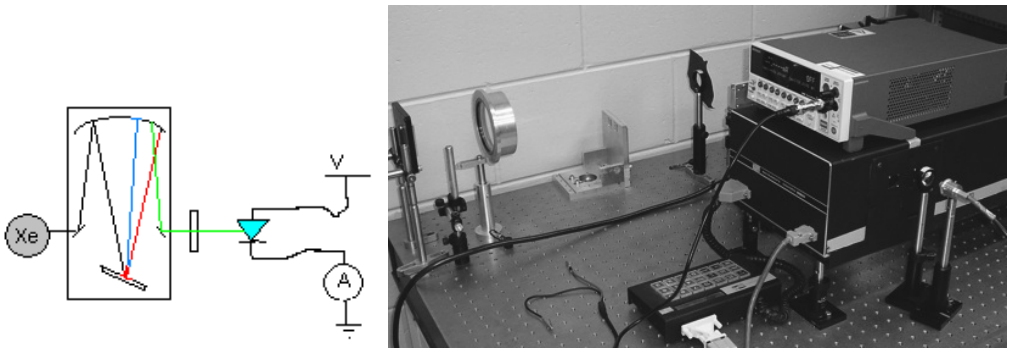


Figure 1 (left). Schematic diagram of solar cell characterization setup. The light from a Xe arc lamp is monochromated and passed through a filter is incident on solar cell whose spectral response is measured. (right) - Photograph of solar cell characterization facility.

Figure 2 presents the relevant characterization parameters that may be obtained from the IV curve. The intersection with the voltage axis at zero current gives the open circuit voltage ($V_{OC}$). The intersection with the current axis at zero applied voltage gives the short circuit current ($I_{SC}$). The optimum operating point is at the "knee" of the curve, where the power has its maximum value. The Maximum Power Point (MPP), $I_{SC}$, and $V_{OC}$ are indicated on the plot. The intersection of the dashed line with the IV curve gives the load resistance. Fill factor is defined as the ratio of the actual maximum obtainable power, ($V_m$ x $I_m$) to the theoretical (not actually obtainable) power, ($I_{sc}$ x $V_{oc}$). The efficiency is defined by $I_m V_m$/(optical power). Photocurrent enhancement factor is defined in terms of short circuit current by $E = I_{sc}^{(p)}/I_{sc}^{(ref)}$, where the numerator corresponds to the measurement with particles on the surface. IV characteristics and the spectral response of each solar cell were measured before and after the deposition of gold black in order to determine the effectiveness of the layer.

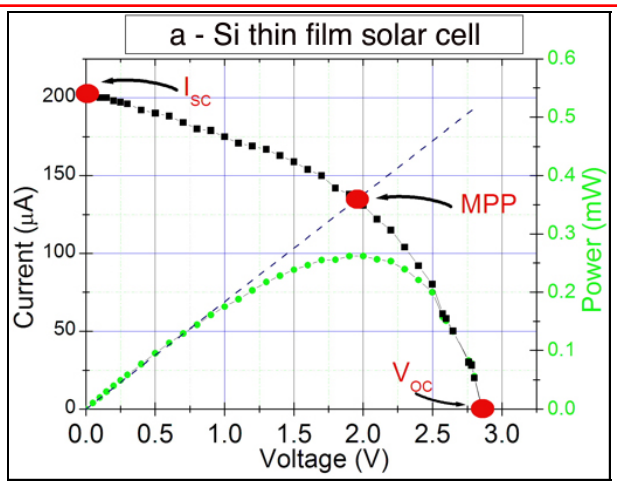


Figure 2. Thin film IV curve, plotted with power vs. voltage (circles), for the thin film solar cell. MPP (maximum power point) occurs at the knee.

## 3.Results

SEM images of samples are presented in Figures 3 and 4 (left). The percent coverage is defined as the ratio of the number of bright pixels to the total number pixels and was found from histograms of the SEM images (Figures 3 and 4, right). The dark peak of the histogram corresponds to substrate, while the bright shoulder is due to the gold black. To separate them for the area analysis, the dark peak was assumed to be symmetrical. Analysis of images such as these are used to correlate solar cell performance with deposition parameter values for purposes of optimization.

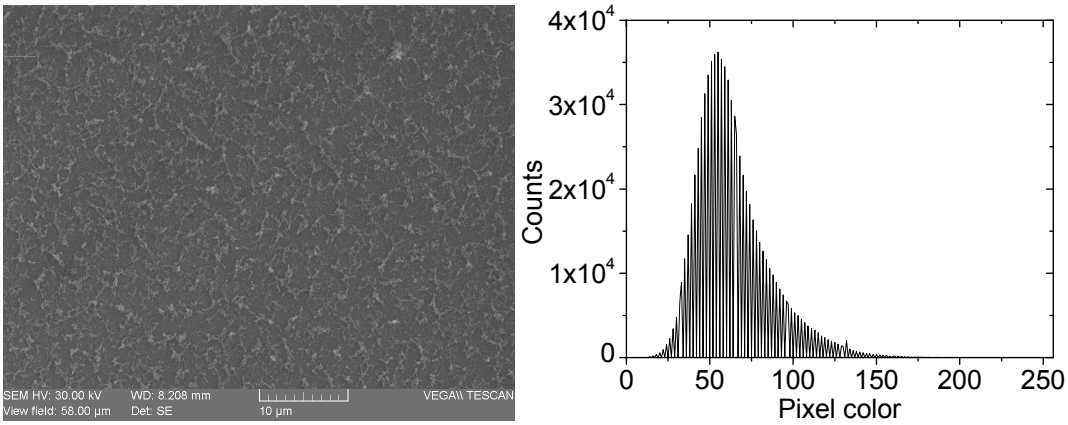


Figure 3 – (left) SEM image of light gold-black coating. (right) Histogram of image. The fraction of coverage by gold black was determined from the tail of the histogram that extends beyond ~100 on the brightness scale.

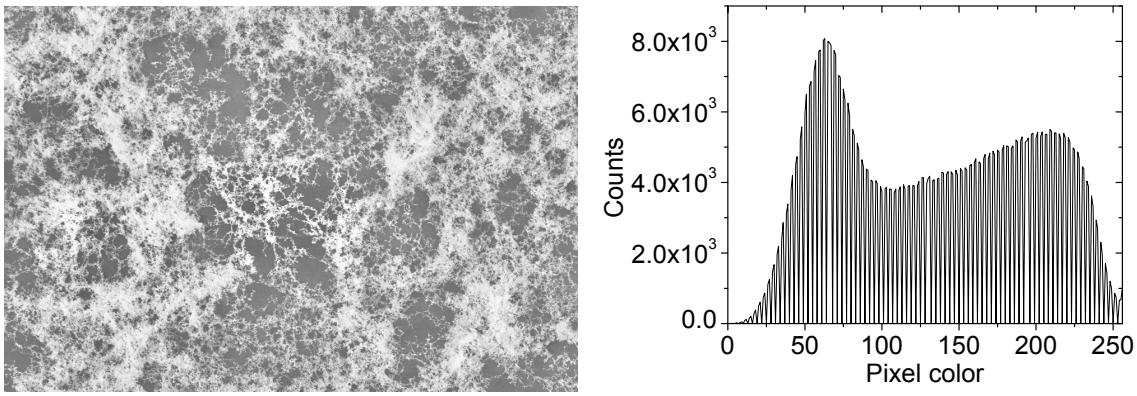


Figure 4 – SEM image and histogram of heavily coated sample.

Wavelet analysis for the image in Figure 4 is plotted in Figure 5. The peak shows that the mean particle size occurs at ~2.3 μm. The distribution of particle sizes ranges from 300 nm to 20 microns. Such data are used to correlate particle size, solar-cell efficiency, and deposition parameters for purposes of optimization.

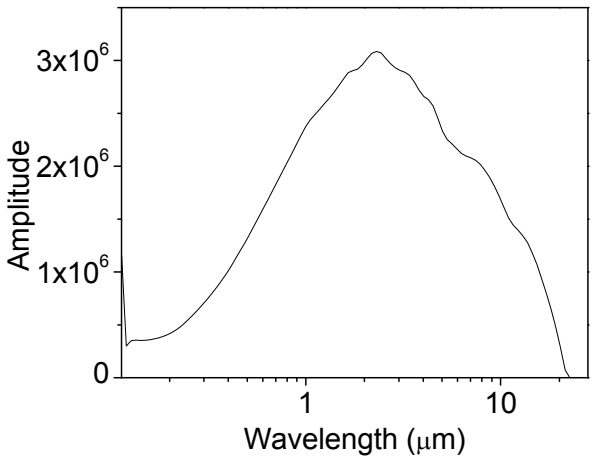


Figure 5 – Results of wavelet analysis for the image in Figure 4.

The thin film solar cell investigated was a commercial PowerFilm amorphous silicon cell, which is thin enough to be flexible. Fig. 6 (left) shows that after deposition of gold-black on the surface, the photocurrent increased by ~20% at most wavelengths, while the improvement was less (~10%) at the peak of the photo response at 580 nm. This was as expected; the improvement in photo response caused by scattering centers on the surface should be strongest at those wavelengths where the absorption by the film alone is weakest. The improvement disappeared when the deposited metal particles were wiped off.

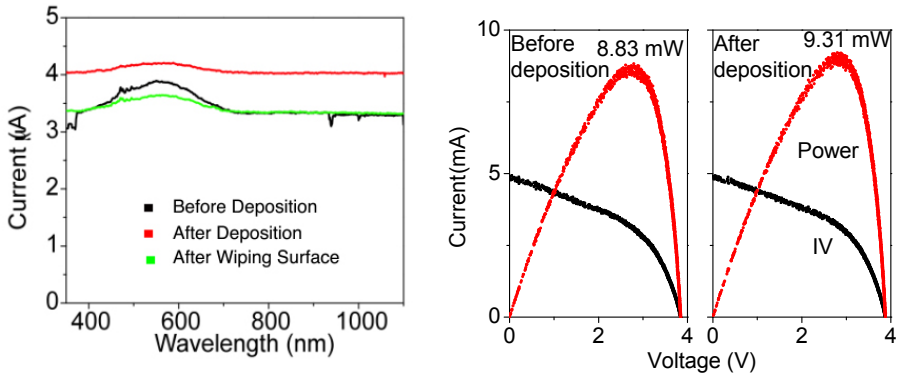


Figure 6 (left) Demonstration of short circuit photocurrent increase across the spectrum for thin film solar cell coated with gold-black particles. Photocurrent was measured under zero applied voltage. (right) IV and photo-power curves for amorphous silicon solar cell for solar spectrum irradiance. The value of the Maximum Power Point is given. After deposition, the maximum power point increased by 5%.

## Conclusion

Our hypothesis that gold-black coating gives spectrally broad enhancement in the efficiency of thin film solar cells is supported by the results. A dramatic 20% increase in the short circuit photocurrent at all relevant wavelengths was observed for a thin-film amorphous silicon solar cell that was treated with a metal-black surface coating. An efficiency enhancement of 5% was reported for a solar spectrum.

## Acknowledgments

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