Water Free Cleaning Solution: Environmental Durability of Electrodynamic Screen (EDS) Films in Water-Free Cleaning of Solar Collectors

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Abstract — **The energy output of photovoltaic power plants is greatly diminished by soiling. The current methods available to clean the solar panels require copious amount of deionized water, trained manual labor and/or robotic parts and thus are not practical for scaling up, not cost effective and are unfeasible especially in areas that have scarce water resources. The Electrodynamic Screen (EDS) film is a novel, anti-soiling, self-cleaning technology that charges the dust particles electrostatically, repels them off the surface by Coulomb force and removes them by a sweeping motion of the travelling electric field generated by the three phase design. The environmental durability, stability and operational efficiency of the EDS films made with either reflective silver electrodes or silver nanowire electrodes protected by zinc oxide is discussed. Development of a screen printable hybrid ink using silver nanowires and zinc oxide is discussed. Results from environmental durability tests including complete water immersion, high temperatures and UV exposure are discussed.**

Index Terms — **water conservation, silver, nanowires photovoltaic cells.**

I. Introduction

Solar power plants are chiefly located in semi-arid and desert regions, as they receive the highest amount of solar irradiance and have least interruption by clouds. These regions are also characterized by frequent dust storms, which result in the formation of a dust layer on top of the solar collectors. This dust build-up commonly referred to as 'soiling' serves as a major impediment to the photovoltaic modules in absorbing the solar irradiance and converting it to electrical energy. Studies have reported that in under an hour's time, a desert sand storm can leave solar panels with a thick layer of residue, which is capable of reducing their efficiency by upwards of 70–80%. These panels hence would require regular cleaning, even a daily cleaning routine, else they can be considered as futile.

The areas where the solar power plants are located are very often subjected to drought or chronic shortage of water therefore cleaning the solar panels becomes impractical and quite expensive. The Council on Energy, Environment and Water (CEEW) estimates the water requirements for operation and maintenance of the growing solar power plants in countries like India to lie between 7,000 and 20,000 liters per MW per wash. These panels are set to be cleaned once a week, although this may vary with the scale and location of plants.

The water free cleaning solutions that are available now include robots with brushes and air pumps that aim to either vacuum or blow away dust. These robots are powered chiefly by detachable batteries, which are replaced when the power runs out. This solution is infeasible as the batteries and moving parts often become malfunctioning when the temperature of the solar collector surface and environment are high during the day. The desert regions also face erratic temperature fluctuations which further serve as a hindrance to the moving parts and cause the batteries to become defective.

High pressure water jets with detergents which are the standard cleaning solution to soiling problems have also shown to form a haze on the glass over a period of time. They can also cause the glass to crack when exposed to repetitive cleaning. Additionally, the current cleaning solutions all require the power plant to be nonoperational during cleaning cycles. Hence the solution to solar panel cleaning technology needs to be scalable, viable in extreme environmental conditions and must ideally require no water or manual labor for operation in order to increase the efficiency of the power plants and work towards a sustainable solution in a cost-effective manner.

II. Electrodynamic Screen (EDS) Film Technology

The Electrodynamic Screen (EDS) film is a novel, anti-soiling, self-cleaning technology. The EDS film does not require water to operate, no manual labor and has no mechanical parts involved. The operation power consumption is 0.2 Wh/m 2 /cleaning cycle and can be harvested from the photovoltaic module itself. The EDS film can be integrated onto the photovoltaic modules and can be activated as frequently as required [1].

The EDS film comprises of interdigitated sets of parallel, conducting electrodes that can be activated by a three phase voltage sequence. Three phase voltage pulses of 1.2kV at 5Hz frequency is used for activation. Fig.1 shows the pictorial representation of an EDS film.

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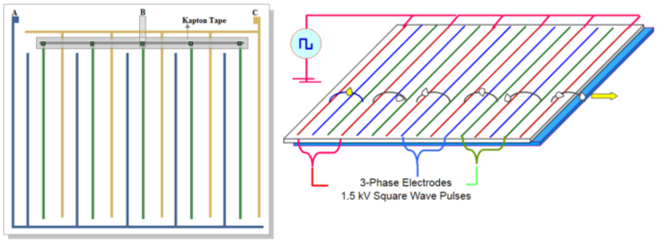

Fig. 1. Schematic diagram of electrode geometry of an EDS film showing three phase design

The electrodes are of width of 80 micrometer and have an inter electrode spacing of 700 micrometer. An ultrathin glass sheet (Corning® Willow® Glass) is applied on top of the electrodes using an optically clear adhesive to provide a dielectric medium for the non-uniform, time-variant electric field generated by the electrodes. The electrodes can be rendered either reflective or transparent by using a reflective silver ink or silver nanowire ink respectively as shown in Fig.2.

Fig. 2. Reflective EDS film integrated on solar cell (left) and transparent EDS film on borosilicate glass (right)

When activated, the electrodes are seen to charge the dust particles electrostatically in the presence of an electric field, repel them off the surface by Coulomb force and remove them by a sweeping motion of the travelling electric field generated by the three phase design. The efficiency of the EDS film to act as a self-cleaning surface when integrated on a solar cell is monitored by tests that measure the Dust Removal Efficiency (DRE) which gives the ratio of mass of dust on the film before and after EDS film activation and the Output Power Restoration (OPR) which denotes the ratio of the short circuit current read from a solar cell before and after activation of the electrodes.

III. Environmental Durability of Reflective EDS Film

The reflective EDS film is fabricated by screen printing the electrode design using Loctite 1011 from Henkel. The reflective ink can be screen printed on both borosilicate glass and FEP film in order to function as a self-cleaning surface. An edge sealant tape is used to seal the device once it is retrofitted onto a solar cell in order to render it as weather proof.

In addition to the cleaning efficiency tests, the reflective EDS film has been subjected to a complete water immersion test to simulate a heavy rainfall situation. Abrasion tests have also been performed to simulate a heavy dust storm. The EDS film has also been subjected to a range of temperature and humidity conditions to evaluate cleaning efficiency. In all these tests, the EDS has proved to be an effective and viable dust cleaning solution.

Field test setup units consisting of EDS films and control panels had been installed in test sites in Chile and at Sandia National Labs (SNL) Albuquerque. Test results for a three month trial period have demonstrated that the EDS films continue to perform consistently as self-cleaning surfaces with high DRE and OPR measurements. Fig.3 shows the field test setup unit deployed at both sites.

Fig. 3. Field test setup units for EDS film working and efficiency tests in Chile (left) and SNL field (right)

IV. Environmental Durability of Transparent EDS Film

Transparent EDS film is fabricated by screen printing the electrode design using silver nanowire (AgNW) ink from Novarials. Silver nanowire electrodes have the disadvantage of becoming unstable over time have not proven to be durable upon exposure to high heat and extreme environmental conditions. In order to make transparent EDS films durable and viable in a desert condition, we have used zinc oxide (ZnO) as a protective layer. Studies have shown that the use of ZnO can be effective to enhance the stability of silver nanowire (AgNW) [2]. An in-lab formulation of ZnO was carried out by mixing diethylzinc (DEZ) and tetrahydrofuran (THF) [3] and this solution was spin coated onto screen printed AgNW sheets. This structure is subjected to photolithography to obtain the desired electrode pattern of the EDS film. The process can be modified so as to produce either a sandwich structure, where the layer of AgNW is in between two ZnO layers or a stacked structure with ZnO-AgNW-ZnO combination. Fig.4 shows a pictorial representation of the completed EDS film.

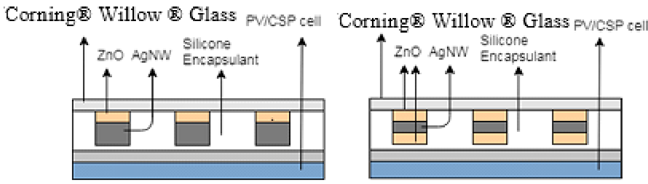

Fig. 4. Layered structure of the AgNW EDS film with ZnO protective film in stacked pattern (left) and sandwiched structure (right) when retrofitted onto PV cell / CSP mirror surface.

Four main tests were performed in order to assess the protective function of the ZnO layer rendered on the AgNW sheet layer.

- •Accelerated UV Exposure
- •High Voltage Test
- •High Heat/ Annealing
- •Water Immersion

For the accelerated UV test, the samples were subjected to ultraviolet radiation exposure for 100 hours in lab setup, simulating a desert environment's UV standards. The measurements recorded after the UV exposure show that resistance of the plain AgNW sample was increased by 2 times the resistance value recorded before the sample was subjected to UV exposure test whereas the ZnO/AgNW samples showed a marginal change in resistance readings. Fig.5 shows the SEM pictures that show degradation of plain AgNW samples and intact ZnO incorporated samples.

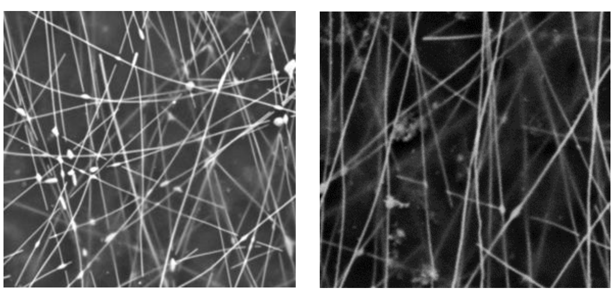

Fig 5. SEM images (15KX) show beading of AgNW (left) and intact ZnO-AgNW (right) after accelerated UV exposure for 100 hours

In the high voltage test, the samples were connected to a two phase power supply and a voltage of 1.2kV was passed through the busbars of the samples continuously for 10 minutes each. On recording the resistance readings after the test we see that the resistance of the plain AgNW sample was increased by 6 times the 'before' value whereas the ZnO/AgNW samples showed absolutely no change in resistance readings. Figure 6 shows a visual representation of these results along with the change in structural integrity of the silver nanowires when they are not covered by layer(s) of zinc oxide.

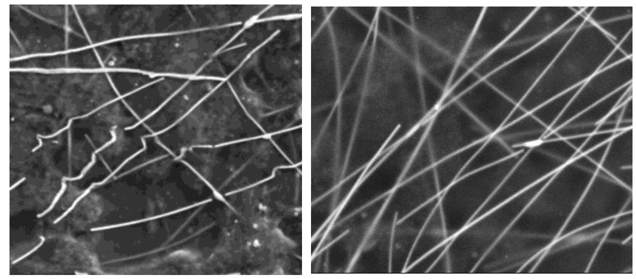

Fig 6. SEM images (14KX) show withering of AgNW (left) and intact ZnO-AgNW (right) after passing 1.2kV voltage for 10minutes

In the high heat test, the samples were introduced to a standard laboratory oven maintained at a temperature of 200°C for 30 minutes. Measurements taken after the test show that the resistance of the plain AgNW samples increased tremendously by 55 times than original. The ZnO/AgNW samples showed resistance readings of almost 50% decrease after annealing than before due to zinc nanoparticles fusing with the AgNW. Fig.7 shows the results.

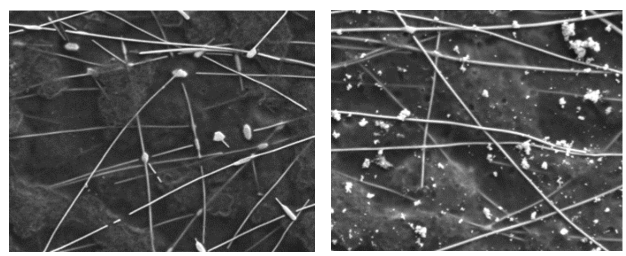

Fig 7. SEM images (15KX) show beading of AgNW (left) and undisturbed ZnO-AgNW (right) after annealing at 200°C

In the water immersion test, the samples were immersed in individual baths containing distilled water, for 5 minutes to mimic very heavy rainfall. Post test measurements showed a 4 times increase in resistance in the case of plain AgNW samples, whereas the ZnO/AgNW samples showed negligible or no change at all as demonstrated by Fig.8.

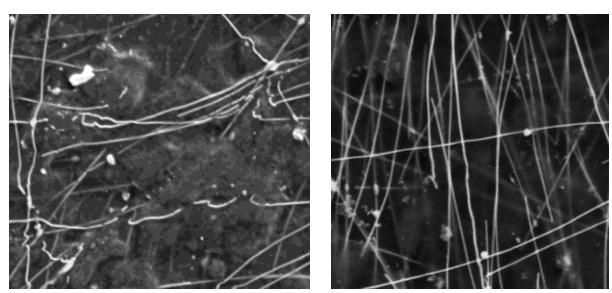

Fig 8. SEM images (15KX) showing breakage and island formation of AgNW (left) and stable ZnO-AgNW (right) after water

immersion test for 5 minutes, simulating heavy rainfall in desert regions

Hence the stability, durability and viability of silver nanowire electrodes of EDS film can be improved by the addition of zinc oxide layers. Future work involves patterning structures into favourable EDS films with different geometries.

V. Development of Hybrid Ink for Screen Printing

While spin coating the layer(s) of ZnO on AgNW layer has proven to enhance environmental stability and durability of the transparent conductive electrodes, the process involves using photolithography to realize the geometry required to make an EDS film. Photolithography is not a scalable option to make the EDS film for outdoor applications, when retrofitting onto PV modules or CSP mirror surfaces. The size or area needed to be covered by the EDS film becomes larger than the capacity of the mask writer and hence samples that need to be larger than 5 inches are harder to realize. In order to make the EDS films with AgNW and ZnO as electrode material to fit the commercially available photovoltaic modules or CSP mirror surfaces, the EDS film would have to be printed either by screen printing or a roll to roll process like flexographic printing.

We have developed a hybrid screen printable ink that has ZnO produced in lab mixed in the silver nanowire solution. Experiments to determine the ratio of zinc oxide to be mixed with the silver nanowire have yielded different combinations that could serve as reliable, durable transparent conducting electrodes. The current experiments aim at evaluating the performance of the different combinations to determine the best fit.

We have noticed that silver nanowires tend to form clumps or show higher cohesion characteristics when the amount of ZnO added is higher than 3 parts, when compared to the AgNW. Such clusters offer stronger conduction properties, but they do not necessarily maintain a continuous network, which leads to partially connected electrodes. Such structures hence cannot serve as ideal transparent conducting electrodes. Figure 9 shows the SEM images of the AgNW forming clumps when the ration of AgNW : ZnO was 6:4.

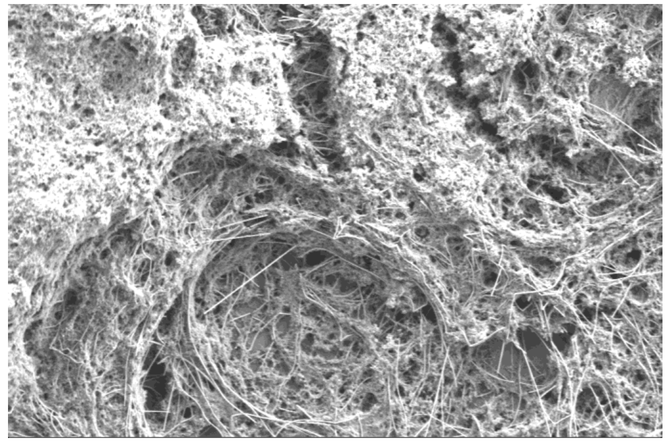

Fig 9. SEM images (4.26KX) showing clusters formed by silver nanowires when zinc oxide was mixed in the ratio AgNW : ZnO as 6:4.

We also noted that the nanowires tend to become more flexible when zinc oxide is added. Processing steps that usually cause breakage or damage to the nanowires have a lesser impact on structural integrity and behavior of the silver nanowires when ZnO is added to the screen printing ink.

The hybrid ink that is developed and is currently being tested for durability and performance are of two ratios,

- AgNW:ZnO as 3:1
- AgNW:ZnO as 3:1.5

We are also conducting experiments to determine the curing rate, curing temperature and duration required for the hybrid ink to function as desired electrode material. Figure10 shows the hardening or dense crystal formation of the ZnO when cured at 185°C for 30 minutes. This behavior of the ZnO has proved to be unfavorable, as it causes the electrodes to lose the desired transmission efficiency.

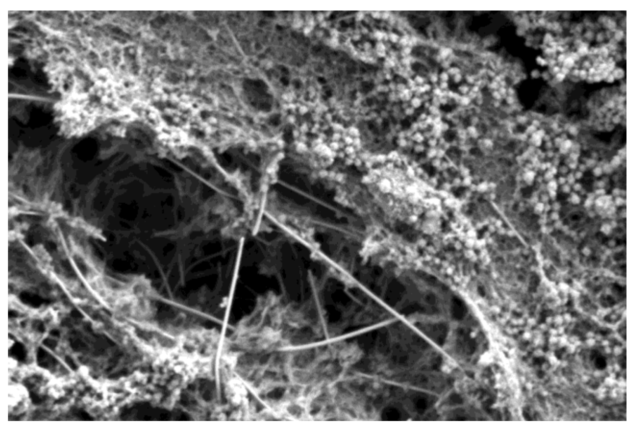

Fig 10. SEM images (16.5KX) showing zinc oxide crystal formation on top of silver nanowires when cured in unfavorable conditions. The hybrid ink was mixed in the ratio AgNW : ZnO as 3:1.

VI. EVALUATION OF AGNW-ZNO STRUCTURE AS ELECTRODES OF THE EDS FILM

The performance or functionality of and EDS film is evaluated based on the following metrics,

- Specular Reflectance Restoration (SRR)
- Output Power Restoration (OPR)
- Dust Removal Efficiency (DRE)

Specular Reflectance Restoration (SRR): percent of the specular reflectance restored by EDS film

SRR = SR after EDS film activation/SR clean

where SR is the Specular Reflectivity

Output Power Restoration (OPR): percent of the power restored in a solar cell by the EDS film

OPR = I_{SC} after EDS film activation/I_{SC} clean

Dust Removal Efficiency (DRE): percentage of the overall mass of dust removed by the EDS film

$$DRE = 100*[(m_{initial}-m_{removed})/m_{initial}]$$

These tests have been held as standard evaluation parameters for testing the performance of the EDS films which have predetermined electrode material (silver, copper, chrome). The hybrid ink material and the hybrid electrode structures discussed earlier will be tested with the same parameters to evaluate their performance as stable, viable electrode material.

VII. CONCLUSION

The Electrodynamic Screen (EDS) film has been proven to serve as a self cleaning surface technology that negates the usage of water, manual labor or robotic parts for the cleaning operation. Various inks and materials have been experimented with to establish a standard robust material that is environmentally stable, viable and cost effective. The fabrication process to make the EDS film as a scalable product and laminate it onto photovoltaic modules and CSP mirror surfaces has also been established. This paper elaborates on the new electrode structures and hybrid ink material that can be used as electrode material in order to render the EDS film as a highly transparent self cleaning surface technology.

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