

Material Selection for Electrodes of Electrodynamic Screen (EDS): A Self Cleaning Technology for Solar Collectors

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Abstract

The Electrodynamic Screen (EDS) is a self cleaning surface technology that can be retrofitted or integrated onto the optical surface of solar collectors, which when activated, can charge dust and remove it off the surface without using water or robotic parts. The EDS film's electrodes enable the cleaning action and hence have to account for both conductivity and transparency to be included in the solar collectors. We present the different materials explored to serve this purpose, the reason for their selection, pros and cons of each material and results obtained upon testing their environmental durability and viability. The results from standardized accelerated weathering tests which validate the outdoor durability of the final electrode materials are also reported.

Keywords: Photovoltaic modules • High pressure water • Electrodynamic screen

Introduction

Frequent dust storms and chronic dust carrying winds are characteristics of the semi-arid and desert regions where solar power plants are typically installed, leading to the unavoidable situation wherein the surface of the harvesting systems gets covered by layers of dust deposits. Soiling, which refers to the accumulation of dust on solar collector surfaces, decreases the overall energy yield of solar power plants by about 0.2% daily, 3.5% monthly and up to 80% loss annually, depending on the region, if the solar panels are not cleaned frequently [1-3]. Hence to preserve economic viability and maintain required energy production, solar collector surfaces necessitate periodic cleaning once they show a significant decrease in energy output.

Large scale solar power installations rely on the usage of specialized water cleaning trucks that are used to periodically wash mirrors and photovoltaic modules. While this method has proven to be effective at restoring the output efficiency of the power plants, it is cost-demanding, energy-intensive and time-consuming in addition to being unsustainable in the localities where water is a scarce and expensive resource [4]. High pressure water jets with detergents used in this method, have been shown to form a haze on the top glass over a period of time. Water can also cause the glass to crack when exposed to repeated cleaning with a mismatched glass-water temperature.

The current cleaning market is fragmented. Water-free cleaning solutions currently available include robots with brushes and air pumps that aim to either vacuum or blow away dust with pressurized air, vibrations to mechanically dislodge dust, and wiper systems to physically brush the surface. 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 or when dust lodges in their individual parts [5]. This method of cleaning also abrades the surface over the 25 year lifetime of the solar panel or mirror. Anti-soiling coatings have not proved to withstand the environmental degradation factors such as high temperatures, erratic levels of relative humidity, UV exposure and scratching of the coating by dust.

These challenges surrounding water use, long term durability, manual labor and moving parts can be mitigated via the Electrodynamic Screen (EDS), a self-cleaning surface technology that can be retrofitted onto solar collector surfaces to actively eject dust. Our studies have shown that over 90% of the deposited dust can be removed within a minute or so of activation of the device, using a negligible amount of energy which can be harvested from the solar collector itself, thereby negating the need for an external energy source. Operation of the EDS film requires no water, no manual labor, no mechanical/moving parts or active wiping. The EDS film has proven to be environmentally stable and durable upon subjection to standard accelerated weathering tests [6].

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The Electrodynamic Screen (EDS)

The Electrodynamic Screen (EDS) is a self-cleaning surface technology that can be integrated or retrofitted onto the front cover-glass plates of solar panels and concentrating solar mirrors as shown in Figures 1 and 2 [7,8]. The EDS film consists of rows of interdigitated, parallel, conductive electrodes that are embedded within a transparent dielectric film which can serve as the optical surface of solar collectors [9]. When phased voltage pulses activate the electrodes, dust particles that are directly in contact with the film's top surface become electrostatically charged, suspended above the surface momentarily and are transported to the edge of the active area by the traveling-wave generated by the three-phase, alternating electric field.

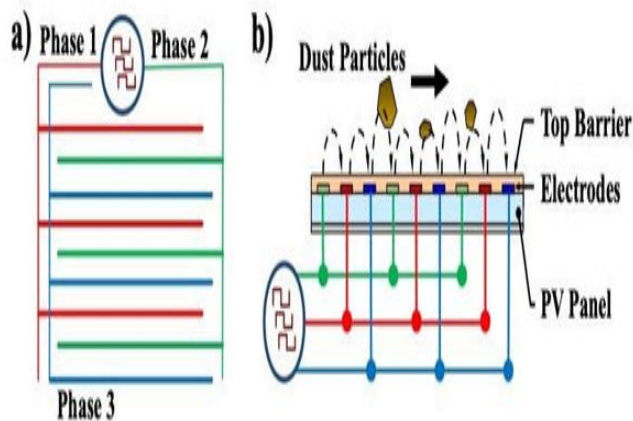


Figure 1. a) Schematic diagram of EDS film b) Dust movement on the top surface of the EDS film due to travelling electric wave.

Current prototypes of the EDS film are either produced in the lab where the electrodes are screen printed on borosilicate glass sheets of minimal thickness, or are flexographically printed on PET films by our industrial collaborators [10]. The top most layer of the EDS film acts as both the protecting layer for the underlying electrodes and the dielectric medium that supports and propagates the travelling wave and hence has to be highly transparent, robust, abrasion resistant and ideally of minimal thickness in addition to providing enough electrical insulation for the applied voltage and allow for triboelectric charging of sand particles [11]. This layer can be provided by either an ultrathin glass sheet or FEP/ETFE polymer films. The top layer is adhered to the supporting base structure by means of a suitable optically clear adhesive, which is also UV resistant and suitable for outdoor applications. The entire device is then sealed at the edges by using a compatible edge sealant tape to decrease the penetration of ambient moisture; this also ensures the durability of the device by minimizing the degradation of the adhesive and electrodes [12]. Our studies and tests have proved that efficient function of the EDS films is directly proportional to the environmental stability and performance of the electrodes, hence the choice of electrode material is of paramount importance (Figure 2).

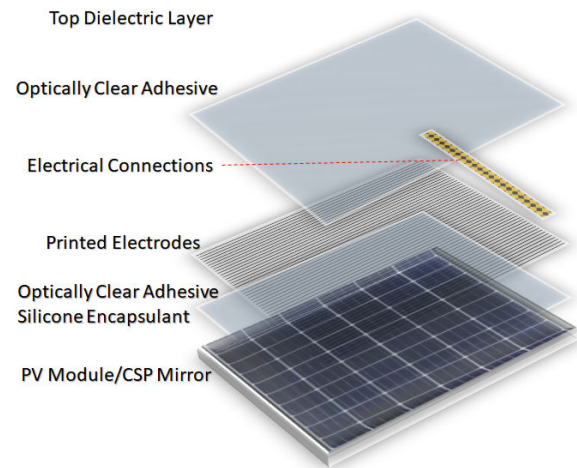


Figure 2. Schematic representation of EDS film integrated on the top surface of the solar collector.

Testing procedures

EDS films are evaluated for their self-cleaning functionality by measuring the Output Power Restoration (OPR%) when there are associated with PV modules, and also Specular Reflection Restoration (SRR%) when integrated with mirror surfaces and involved by also the standalone Dust Removal Efficiency (DRE%). There are Transmission Efficiency (TE%) measurement is done to measure the loss in the light transmission upon addition of the EDS film to a solar collector surface.

OPR is defined as,

$$OPR = \frac{(I_f - I_i)}{(I_o - I_i)} * 100\%$$

where I_f is the short circuit current measured after EDS activation, I_i is the short circuit current measured after dust deposition and before EDS activation, and I_o is the short circuit current measured on clean EDS film.

SRR is defined as,

$$SRR = \frac{(SR_r - SR_d)}{SR_0} * 100\%$$

where SR_r is Specular Reflectance after EDS activation, SR_d is the Specular Reflectance after dust deposition and before EDS activation, and SR_0 is the Specular Reflectance before dust deposition.

DRE for each trial is calculated by using the formula,

$$DRE = \frac{(m_0 - m_r)}{m_0} * 100\%$$

where m_0 is the original surface mass density of the dust on the panel, m_r is the remaining surface mass density of the dust on the panel after EDS activation.

Electrodes of the EDS Film

The charging of the dust particles is brought about when the electrodes of the EDS film are fed with pulsed voltage. It is evident that the electrodes serve as the main component of the device. Hence, obtaining a concrete electrode material in terms of conductivity, functionality, environmental durability and viability over a long term period is vital to establish the EDS film as a self-cleaning technology for solar fields. Transparent conductive electrodes are the ideal choice for EDS films that are integrated with photovoltaic modules whereas for concentrated solar power mirrors, the electrodes can be either reflective or transparent. The electrode material must also be easily available, cost efficient and printable via a repeatable or roll to roll method in order to be scalable in size and volume as required by the solar fields [13]. The materials that we isolated and experimented with, to serve as electrodes of the EDS film can be broadly classified into reflective and transparent materials and are listed below,

- Chromium
- Aluminum
- Silver
- Carbon nanotubes
- Aluminum doped zinc oxide
- Silver nanowires
- A hybrid ink material containing zinc oxide and silver nanowires

Reflective electrode materials

Concentrated Solar Power (CSP) also known as concentrated solar thermal systems generate solar power by using mirrors or lenses to concentrate a large area of sunlight onto a receiver. Electricity (sometimes called solar thermoelectricity) is generated when the concentrated light is converted to heat (solar thermal energy), which drives a heat engine or a steam turbine which is connected to an electrical power generator or powers a thermochemical reaction. CSP systems rely on reflecting the sunlight back to the receiver. When dust particles sit on the mirror surface, they contribute to scattering or deflection thereby reducing the output efficiency of the system. Reflecting electrodes are ideal for Concentrated Solar Power (CSP) mirror applications and can be used on curved or trough surfaces and planar or flat surfaces. To clean such a surface, the EDS film has to have electrodes that do not absorb the sunlight but rather reflect it to the receiver.

Table 1. Results of Tests on Reflective Electrodes.

Electrode Material	SR%	SRR%	OPR%	DRE%
HRC	92.52	89.7	93.9	82.1
Al	91	N/A	N/A	N/A
Ag	65.16	86.57	91.6	97.02

The choices of electrode material explored for reflective EDS films are,

- Highly Reflective Chrome (HRC)
- Aluminum
- Silver

Polished or unpassivated chromium (referred to as highly reflective chrome) has a high specular reflection when compared to other transition metals, and it has a maximum reflectance of about 72% in infrared at 425 μm and a minimum of 62% at 750 μm with almost 90% of infrared light being reflected [14]. Sputter coated HRC masks of lab scale size (5 inch x 5 inch) were procured from Nanofilm technologies and subjected to photolithography in order to realize them as functional EDS films. The HRC EDS films were then subjected to standard testing procedures defined for evaluating the self cleaning function of EDS films and were also tested for environmental durability.

Electrodes of the EDS film must be good conductors of electricity and ideally dissipate the heat that could be built by voltage transmission, environmental heating and heat from the underlying solar collector surface, and for these reasons Aluminum (Al) was explored as electrode material. The fabrication and testing procedures followed to make Al EDS films are similar to HRC EDS films.

HRC and Al EDS films were eliminated as a scalable option as the sputter coated masks have a size restriction both in terms of sputter coating and processing through photolithography. Al electrodes were nonfunctional when pulsed voltage was pumped through them; this was speculated to be a result of reduced electrode thickness ($\sim 1000 \text{ \AA}$) and faulty post processing for involved procedures. HRC and Al also showed decreased functionality over a period of time upon subjection to repeated testing .

Silver (Ag) is an ideal choice of electrode material for the EDS film as it satisfies the requirement for more current carrying capacity in smaller footprints and can also be screen printed or flexographically printed. The screen printed silver electrodes, upon curing in advocated temperatures, had rough top surfaces; the electrodes had craters and ridges on the top surface due to the evaporation of organics in the silver ink. Modification of curing temperatures and techniques resulted in improving the Specular Reflection (SR) of the electrodes, but the SR values are considered unsatisfactory as the SR of the mirror surface is 100%. Silver satisfies both conductivity and durability requirements for the EDS film; improving SR of the electrodes could lead to Ag being used as the primary electrode material. Table 1 gives the testing results for reflective electrodes.

Transparent Electrode Materials

EDS films with Transparent Conductive Electrodes (TCE) can be used in conjunction with PV modules and CSP mirrors. Transparent conducting materials have two features that are most important to evaluate their performance and efficiency as electrode material for the EDS film, namely sheet resistance (R_s) and optical transparency. These materials have intrinsically high conductivity in addition to high aspect ratio yields films with high transmittance, low sheet resistance, and high mechanical flexibility. They also have relatively inexpensive material and deposition costs. The following materials have been explored as transparent conductive electrodes,

- Carbon Nanotubes (CNTs)
- Aluminum doped Zinc Oxide (AZO)
- Silver Nanowire (AgNW)

Research has shown that CNTs can be effective as transparent conductive electrodes with long term functionality and viability [15,16] and thus were experimented with, as electrode material for the EDS films. CNTs were screen printed as electrodes on borosilicate glass substrates and subjected to evaluation procedures for conductivity, functionality and durability. A sharp decline in the OPR% and SRR% were observed on testing the samples over a period of 4 months and the samples had multiple dead electrodes indicating the presence of one or more 'dead spots' or discontinuity in each electrode. The failure of multiple electrodes could be a result of improper alignment of the CNTs resulting in arcing, thereby burning the electrodes at crowded nanotube junctions. They also showed degradation under UV exposure and moisture ingress. CNTs EDS films could be a promising, viable option if the aforementioned issues can be solved.

Sputter-coated AZO on soda lime glass samples were patterned into EDS films by using photolithography. A second procedure was to deposit AZO onto borosilicate glass in a clean room setting to produce laboratory made thin films which were then subjected to photolithography.

Table 2. Results of Tests on Transparent Conductive Electrodes

Electrode Material	SR%	SRR%	OPR%	DRE%
CNTs	96.23	89.79	95.51	97.19
AZO	96.6	92.2	97.7	94.2
AgNWs (screen-printed)	96.0	89.26	94.7	90.4
AgNWs (photolithography)	74.5	70.8	91.9	78.6

Both commercial procured and lab made AZO were then subjected to photolithography. Both commercially procured and lab made AZO films showed excellent functionality and durability. Testing revealed that failure of AZO EDS films is occurable when the AZO particles are unevenly distributed, leading to multiple breakpoints or dead spots in the electrodes. Deposition parameters have to be refined to ensure a uniform coating thickness. Use of solution-based AZO makes scaling up for roll-to-roll manufacturing of EDS films a possibility.

Silver nanowire (AgNWs) has gained attention as the metal nanowire electrodes bear the highest value of electrical conductivity and optical transmittance amongst the other options; the amount required in solution to fabricate silver nanowires is also considerably small [17,18]. EDS films were fabricated with AgNWs by both photolithography and screen printing; testing procedures confirmed that both methods can be used to produce functional electrodes.

The failure of AgNWs EDS films arises due to discontinuous nanowire networks, leading to dead electrodes; the nanowires are also prone to degradation when exposed to UV and high temperatures as they experience beading/melting due to the phenomenon of Joule heating [19]. The AgNWs also degrade when exposed to moisture over a period of time. AgNWs EDS films obtained by photolithography show underwhelming performance, as the films were spin coated prior to photolithography; spin coating results in films of minimal thickness, leading to electrodes of undesired thickness.

One approach to solve the aforementioned problems is to use a conductive filler material that can serve as an auxiliary enhancement; ZnO has been widely used for this purpose [20]. A concoction of Zinc Oxide (ZnO) and AgNWs was formulated in various produce a hybrid ink that resists degradation and exhibits enhanced conductivity and viability. The ZnO was made in the lab by mixing tetrahydrofuran and diethylzinc under controlled conditions and environment; the ZnO was then mixed with AgNWs in a customized ratio by weight. The test results were similar to the measurements obtained from screen printed AgNWs electrodes [21]. Testing results of transparent electrode materials is given in Table 2.

Discussion and Conclusion

Current demand in solar energy and the need for a renewable resource to replace the coal and fossil fuel burning depends on development of efficient and economical methods of removing dust from solar collectors' surfaces, in order to maintain high output efficiency of the solar power plants. Establishing the EDS film as a water-free, viable self-cleaning its

surface technology depends heavily on the performance of electrodes. This paper elaborates on the different materials explored to isolate a potential material for to serve as electrodes of the EDS film. We have tested the functionality, environmental durability and scalability options of the different materials; we have also formulated a hybrid ink that shows promising results when printed as electrodes of the EDS film.

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