

Research Article

Elevated Temperature - Humidity Tests and Electrical Analysis for the Assessment of Sheet Resistance and Power Loss in Photovoltaic Cells

Suresh Kumar^{a*} and Bijan Sarkar^a

^aProduction Engineering Department Jadavpur University, Kolkata- 700 032 India

Accepted 2 Feb. 2013, Available online 1March 2013, Vol.3, No.1 (March 2013)

Abstract

The life data analysis is an important piece of the pie, but performing just the analysis is not enough to achieve reliable products. Rather, there are a variety of activities involved in an effective reliability program and in arriving at reliable products. As part of this overall reliability effort, accelerated life tests were performed on PV modules to determine the effects of humidity on sheet resistance over time and its impact on the loss of power. This paper compares the sheet resistance and visible transmission of three materials Indium Tin Oxide (ITO), Gallium Zinc Oxide (GZO) and Aluminum Zinc Oxide (AZO). The paper gives an insight into the variation in sheet resistance at different environmental parameters like humidity and temperature. The results from accelerated ageing test were used for the analysis. An electrical analysis were made to study the improvement in power loss with sheet resistance.

Keywords: Indium Tin Oxide (ITO), Gallium Zinc Oxide (GZO) and Aluminum Zinc Oxide (AZO, Sheet resistance, Finger length, Finer spacing.

1. Introduction

Photovoltaic panel electrical performance depends on environmental conditions such as the temperature, solar irradiance, angle-of-incidence, solar spectral(air mass), and the types of PV cells. Each PV panel is rated under industrial Standard Test Conditions (STC) of solar irradiance of 1,000 W/m² with zero angle of incidence, solar spectrum of 1.5 air mass and 25°C cell temperature. Electrical characteristics (M. Petkov et al,2011) from manufacturers include maximum rated power, open circuit voltage, short circuit current, maximum power voltage, maximum power current, and temperature coefficients. Fill Factor (%) is the ratio of actual rated maximum power P_m to the theoretical (not actually obtainable) maximum power ($I_{sc} \times V_{oc}$). This is a key parameter in evaluating the performance of solar panels. Typical commercial solar panels have a fill factor > 0.70, while grade B solar panels have a fill factor range from 0.4 to 0.7. Transparent conducting oxides (TCOs) are a special class of materials that can simultaneously be both optically transparent and electrically conducting and, as such, are a critical component in most thin-film photovoltaics. TCOs (Julia E et al,2011) are generally based on a limited class of metal oxide semiconductors such In₂O₃, ZnO (S Tewari et al_{2011} and SnO_2 , which are transparent due to their large band gap energy and can also tolerate very high electronic doping concentrations to yield conductivities of 1000S/cm or higher. However, these three basic TCOs alone do not meet the TCO performance needs of emerging PV and other applications.



Figure 1: Various environmental stresses on PV module

Transparent conductive oxides (TCO) are doped metal oxides used in optoelectronic devices such as flat panel displays and photovoltaics (including inorganic devices, organic devices, and dye-sensitized solar cell). Most of these films are fabricated with polycrystalline or amorphous microstructures. On average, these applications use electrode materials that have greater than 80% transmittance of incident light as well as conductivities higher than 10³ S/cm for efficient carrier transport. The transmittance of these films, just as in any transparent material, is limited by light scattering at defects and grain boundaries. In general, TCOs for use as thin-film electrodes in solar cells should have a minimum carrier concentration on the order of 10^{20} cm⁻³ for low resistivity and a bandgap greater than 380 nm to avoid absorption of light over most of the solar spectra. Mobility in these films

^{*}Correponding author: Suresh Kumar

is limited by ionized impurity scattering and is on the order of 40 cm²/(V·s). Current transparent conducting oxides used in industry are primarily n-type conductors, meaning their primary conduction is as donors of electrons. Suitable p-type transparent conducting oxides are still being researched.

To date, the industry standard in TCO is ITO, or tindoped indium-oxide. This material boasts a low resistivity of $\sim 10^{-4} \ \Omega \cdot cm$ and a transmittance of greater than 80% .However ITO has the drawback of being expensive. Indium, the film's primary metal, is rare (6000 metric tons worldwide in 2006), and its price fluctuates due to market demand (over \$800 per kg in 2006). For this reason, doped binary compounds such as aluminum-doped zinc-oxide (AZO) and indium-doped cadmium-oxide have been proposed as alternative materials. AZO is composed of aluminum and zinc, two common and inexpensive materials, while indium-doped cadmium oxide only uses indium in low concentrations.

Binary compounds of metal oxides without any intentional impurity doping have also been developed for use as TCOs. These systems are typically n-type with a carrier concentration on the order of 10^{20} cm⁻³, provided by interstitial metal ions and oxygen vacancies which both act as donors. However, these simple TCOs have not found practical use due to their electrical properties' high temperature and oxygen partial pressure dependence.

The Zinc oxide transparent conductive film can be coated on the top surface of photovoltaic cell. A film thickness of 300nm or more is sufficient for the cell and the requirements are as follows. The sheet resistance (Rs) (Mohamed et al,2011) should be 10Ω /Square or less with a visible transmission (T) (M.D. Benoy et al,2011) of 85% or more and the coating should have sufficient resistance to humidity and heat(http://www.ulvacuc.co.jp).

Knowledge of long term durability and reliability will play an important role in the successful emergence of thin film photovoltaic systems as a viable, cost effective alternative to traditional silicon based systems currently in the marketplace. As part of this overall reliability effort, accelerated life tests were performed on aluminium doped zinc oxide (AZO) transparent conducting oxides (M. Petkov et al,2011) to determine the effects of humidity, temperature and irradiation on sheet resistance over time (Melissa A. et al).

Table 1 : Comparison of Indium Tin Oxide (ITO), Gallium Zinc Oxide (GZO) and Aluminum Zinc Oxide (AZO).

Material	Sheet Resistance Rs Ω/Square	Visible Transmission T	Resistivity p
ITO	6.56	89.40%	$2.07 \text{ x } 10^{-4} \Omega$ -cm
GZO	6.21	85%	1.98 x 10 ⁻⁴ Ω-cm
ITO/AZO	6.07	90%	1.78 x 10 ⁻⁴ Ω-cm

Aluminum doped zinc oxide is used heavily by thin film PV manufacturers for its high conductivity, optical

transparency, manufacturing compatibility and cost. However the conductivity of AZO is known to degrade rapidly upon exposure to water at higher temperatures. Research is continuing to improve the stability of AZO through different deposition techniques and conditions. However, most degradation and performance studies of AZO and its variants have been performed under damp heat conditions (85°C and 85% relative humidity (RH) for 1000 h) as related to International Electrotechnical Commission (IEC) test 61646. The aggressive conditions used in IEC 61646 may not adequately describe or be representative of TCO performance at lower temperatures and humidities.

2. Accelerated aging tests

The impact of humidity and temperature on a zinc oxide based transparent conducting oxide (TCO) was assessed under accelerated aging conditions. An in situ electro analytical method was used to monitor the electrical properties for a conducting zinc oxide under controlled atmospheric (humidity, temperature and irradiation) conditions. A review of thin film photovoltaic (PV) literature has shown one major failure mode of cells/modules is associated with the ingress of water into modules in the field. Water contamination has been shown to degrade the performance of the TCO in addition corroding interconnects and other conductive to metals/materials associated with the module. Water ingress is particularly problematic in flexible thin film PV modules since traditional encapsulates such as poly(ethyl vinyl acetate) (EVA) (A.W. Czanderna et al, 1996) have high water vapor transmission rates. The accelerated aging studies (Tyoskin, et al, 1996) of the zinc oxide based TCOs will allow acceleration factors and kinetic parameters to be determined for reliability purposes.

The initial series of aging studies examined the effects of humidity on the sheet resistance of AZO at 79°C. Figure 2 shows increases in sheet resistance over time for all AZO samples held isothermally at various humidities. The resistance changes for the first 5 hours and are attributed to effects associated with the stabilization of temperature and humidity in the environmental chamber. For the first 24 h of accelerated aging, samples show a nonlinear increase in resistance over time, with higher humidity exposures amplifying non-linear effects. This could be attributed to water reacting with easily accessible oxygen vacancies at the surface of the AZO film followed by a slowdown in reactivity due to less reactive(inaccessible) oxygen vacancies in the AZO film or another mechanism Further investigation is of degradation is at play. warranted. After 24 h, resistances increase linearly over time with coefficients of determination (R2) greater the 0.99. Sheet resistances (A.W. Czanderna et al, 1996) increased at a higher rate when samples were exposed to higher humidities (Table 2). Rates of increase in resistances after 24 h were 0.38 /sq/h for an AZO filmheld at 79 °C and 97% RH compared to 0.01 /sq/h held at a similar temperature, but 0.4% RH. In another set of aging experiments, the effect of temperature

on sheet resistance at a constant relative humidity was examined. Table 3 shows the impact degradation rate on the sheet resistance of AZO over time at different temperatures under a constant 85% RH. As expected, an increase in temperature increased the rate of degradation (Figure 3). Samples held at 30°C and 44°C did not show any nonlinear degradation of sheet resistance upon exposure. However, the sample held at 85 °C and 85% RH showed a nonlinear rate of degradation during the first 24 h of exposure characteristic to that discussed earlier (Figure 1, 97% RH and 50% RH lines). This indicates a combination of high humidity and high temperature are required to promote the nonlinear degradation phenomena.



Figure 2 : Linear model for high stress and use stress for life

Accelerated Life Testing Data					
i	Failure time (h) at	Failure time (h)			
	373°K	at 393°K			
1	18816	14112			
2	26880	20160			
3	32760	24696			
4	37968	28560			
5	42840	32088			
6	47712	35784			
7	52752	39648			
8	58464	43848			
9	65352	49056			
10	76272	57288			

Table 2 : Accelerated Life Testing Data of same set of PV modules at two different temperatures.

The linear portion of the degradation for AZO at 85% RH can be related to temperature by the Arrhenius equation (11). Figure 4 shows a plot of 1/T versus the natural log of the sheet resistance. Table 2 presents the simulated failure times at $100^{\circ}C$ (373°K) and $120^{\circ}C$ (393°K).

Collision theory supposes that the rate of reaction depends on the rate collision of particles that are reacting. The rate of reaction directly depends on the rate constant k

which can be expressed as $k=A^*exp^{(-E_a/R^*T)}$, known as the Arrhenius equation, where, A is a constant, E_a is the activation energy, R is the universal gas constant, and T is the temperature (in kelvin).



Figure 3 : Linear model for high stress and use stress for life

Table 3 : The sheet resistance changes of AZO associated with accelerated aging tests in the environmental chamber for various humidity for a fixed temperature (79° C).

Sl.	Time in	Sheet Resistance (Ω /Sq.mm)		
No.	Hours	RH	RH	RH
		25%	50%	97%
1	0	75	82	82
2	25	80	104	107
3	50	84	118	123
4	75	87	125	132
5	100	90	132	139
6	125	93	138	147
7	150	95	144	155
8	175	98	150	163
9	200	100	155	*
10	225	102	160	*
11	250	104	164	*
12	275	107	169	*
13	300	109	173	*

The lifetime follows a Weibull distribution with $\beta = 2.6$, $\eta_{373K} = 52006$ h and $\eta_{393K} = 39151$ h. This permits obtaining the two parameters of the Arrhenius model. The slope and intercept of the line suggest an activation energy E_a of 0.91eV and pre-exponential factor (A) of 2.341012. The Arrhenius values are only valid at the lower temperatures where degradation occurs at a constant rate throughout the temperature exposure at 85% RH. These values are chosen to accelerate the degradation because a PV module has a high temperature operating limit of 90°C and a high temperature destruct limit of 120°C.



Figure 4 : Time versus sheet resistance of Aluminum doped Zinc Oxide (AZO) films under varied humidity conditions at a temperature 79° C.

Time	Sheet Resistance (Ω /Sq.mm)			
(Hours)	At 85°C	At 44°C	At 30°C	
0	64	63	61	
10	84	63	61	
20	97	63	61	
30	107	63	61	
40	115	64	61	
50	122	64	61	
75	130	64	61	
100	137	64	61.5	
125	144	64	61.5	
150	150	65	61.5	
200	*	65	61.5	
250	*	65	61.5	
300	*	65	62	
350	*	66	62	
400	*	66	62	





Figure 5 : Time versus sheet resistance of Aluminum doped Zinc Oxide (AZO) films under various temperatures.

3. Electrical analysis

Generated current typically flows perpendicular to the cell surface from the bulk of the cell and then laterally through the top doped layer until it is collected at a top surface contact. The resistance and current of the base is assumed to be constant. The resistance to the current of the bulk component of the cell, or the "bulk resistance", R_b , is defined as:

$$R_b = \frac{\rho l}{A} = \frac{\rho_b W}{A}$$

taking into account the thickness of the material. Where: l = length of conducting (resistive) path. $\rho_b =$ "bulk resistivity" (inverse of conductivity) of the bulk cell material (0.5 - 5.0 Ω cm for a typical silicon solar cell), A = cell area, and w = width of bulk region of cell.

For the emitter layer, the resistivity(http://www.pveducation.org) as well as the thickness of the layer will often be unknown, making the resistance of the top layer difficult to calculate from the resistivity and thickness. However, a value known as the "sheet resistivity"(http://www.pveducation.org), which depends on both the resistivity and the thickness, can be readily measured for the top surface *n*-type layer. For a uniformly doped layer, the sheet resistivity is defined as:

$$\rho_{\Box} = \frac{\rho}{t}$$

where ρ is the resistivity of the layer and t is the thickness of the layer. The sheet resistivity is normally expressed as ohms/square or Ω/\Box .



Figure 6 : The resistance of a square conductive sheet is the same no matter what size it is so long as it remains a square.

The resistance of a square conductive sheet is the same no matter what size it is so long as it remains a square. For non-uniformly doped *n*-type layers, i.e., if ρ is non-uniform:

$$\rho_{\Box} = \frac{1}{\int_0^t \frac{1}{\rho(x)} dx}$$

Based on the sheet resistivity, the power loss due to the emitter resistance can be calculated as a function of finger spacing in the top contact. However, the distance that current flows in the emitter is not constant. Current can be collected from the base close to the finger and therefore has only a short distance to flow to the finger or, alternatively, if the current enters the emitter between the fingers, then the length of the resistive path seen by such a carrier is half the grid spacing.

Current density at max. power Jmp A/cm ²	Finger Length b cm	Emitter Sheet Resistivity ρ (Ω/Square)	Finger Spacing S cm	Power Loss P _{Loss} mW
0.030	10	40	0.2	0.1200
0.035	10	40	0.2	0.1633
0.040	10	40	0.2	0.2133
0.050	10	40	0.2	0.3333

Table 5 : Change in current density versus power loss.

Table 6 : Change in current density versus fractional power loss.

Current density at max. power Jmp A/cm ²	Voltage at max power Vmp V	Emitter Sheet Resistivity ρ (Ω/Square)	Finger Spacing S cm	% Power Loss P%
0.030	0.45	40	0.2	0.89
0.035	0.45	40	0.2	1.04
0.040	0.45	40	0.2	1.19
0.050	0.45	40	0.2	1.48

The incremental power loss in the section dy is given by: $dP_{loss} = I^2 dR$

The differential resistance is given by:

$$dR = \frac{p}{b} dy$$

ρ is the sheet resistivity where in Ω/sqr distance along the b is the finger; and y the distance between two grid fingers as shown below. The current also depends on y and I(y) is the lateral current flow, which is zero at the midpoint between grating lines and increases linearly to its maximum at the grating line, under uniform illumination. The equation for the current is:

$$I(y) = Jby$$

where J is the current density; b is the distance along the finger; and y the distance between two grid fingers as shown above.

The total power loss is therefore:

$$P_{loss} = \int I(y)^2 dR = \int_0^{S/2} \frac{J^2 b^2 y^2 \rho_{\Box} dy}{b} = \frac{J^2 b \rho_{\Box} S^3}{24}$$
Where S is the appendix between grid lines

Where *S* is the spacing between grid lines.

Table 7 : Change in sheet resistivity versus variation power loss

Current density at max. power Jmp A/cm ²	Finger Length b cm	Emitter Sheet Resistivity ρ (Ω/Square)	Finger Spacing S cm	Power Loss P _{Loss} mW
0.030	10	40	0.2	0.120
0.030	10	35	0.2	0.105
0.030	10	30	0.2	0.090
0.030	10	25	0.2	0.075
0.030	10	20	0.2	0.060

Table 8 : Change in sheet resistivity versus variation fractional power loss.

Current	Voltage	Emitter	Finger	%
density	at max	Sheet	Spacing	Power
at max.	power	Resistivity	S cm	Loss
power	Vmp	ρ		P%
Jmp	V	$(\Omega/Square)$		
A/cm ²				
0.030	0.45	40	0.2	0.890
0.030	0.45	35	0.2	0.779
0.030	0.45	30	0.2	0.670
0.030	0.45	25	0.2	0.559
0.030	0.45	20	0.2	0.440

At the maximum power point, *Pgen*, the generated power is:

$$P_{gen} = J_{MP} b \frac{5}{2} V_{MP}$$

The fractional power loss is given by:

$$P_{\%lost} = \frac{P_{loss}}{P_{gen}} = \frac{\rho_{\Box} S^2 J_{MP}}{12 V_{MP}}$$

Hence, the minimum spacing for the top contact grid can be calculated. For example, for a typical silicon solar cell where $\rho = 40 \ \Omega/\text{sq}$, $J_{mp} = 30 \text{ mA/cm}^2$, $V_{mp} = 450 \text{ mV}$, to have a power loss in the emitter of less than 4% the finger spacing should be less than 4 mm.

4. Interpretation of result

Based on the sheet resistivity, the power loss due to the emitter resistance can be calculated as a function of finger spacing in the top contact. However, the distance that current flows in the emitter is not constant. Current can be collected from the base close to the finger and therefore has only a short distance to flow to the finger or, alternatively, if the current enters the emitter between the fingers, then the length of the resistive path seen by such a carrier is half the grid spacing. Various mechanism of losses occurring in the Si solar cells are briey discussed. Recombination, Resistive, Thermal are the major losses occurring in the solar cells at 1 sun solar concentration. At higher concentration levels the resistive losses become dominant. Various schemes for reduction of losses such as surface passivation using Si3N4, SiO2 for reduction at the front and back contacts.

5. Conclusion and future research scope

Combining the equations for resistive losses allows use to deteremine the total power loss in the top contact grid. The design of the top contact involves not only the minimisation of the finger and bus bar resistance, but the overall reduction of losses associated with the top contact. These include resistive losses in the emitter, resistive losses in the metal top contact and shading losses. The critical features of the top contact design which determine how the magnitude of these losses are the finger and bus bar spacing, the metal height-to-width aspect ratio, the minimum metal line width and the resistivity of the metal.

The energy conversion efficiency of a solar cell is degraded by an energy loss associated with the voltage drop along the surface sheet resistance of the cell. To minimize this loss, a dense grid of highly conducting line contacts, so called "fingers", is used on large area solar cells. However these fingers reduce the active area exposed to radiation. While the finger density must be sufficient to preclude the excessive sheet

resistance loss, the finger spacing should not be such that the energy loss due to shading becomes prohibitive. So the finger density and the finger spacing arises the issue of optimum finger density and optimum spacing which is wide research area for further improvement of performance and conversion efficiency of photovoltaic cells.

References

M. Petkov, D. Markova, St. Platikanov(2011) -Modelling of electrical characteristics of photovoltaic power supply sources, *Contemporary Materials (Renewable energy sources)*, II 2, Page 171 of 177. doi: 10.5767/anurs.cmat.110202.en.171P.

Julia E. Medvedeva (2010) - Combining Optical Transparency with Electrical Conductivity: Challenges and Prospects- Transparent Electronics: From Synthesis to Applications Edited by Antonio Facchetti and *Tobin J. Marks* _ 2010 John Wiley.

S Tewari and A Bhattachajee (2011) - Structural, electrical and optical studies on spray-deposited aluminium-doped ZnO thin films PRAMANA — Indian Academy of Sciences , *Journal of Physics*, Vol. 76, No. 1, January 2011 pp. 153–163.

Mohamed Mokhtar Atteg, Eng. Marai Ali Khalifa (2010) –Photovoltaic Materials and Solar Cell Design, International Renewable Energy Congress *November 5-7, 2010* – *Sousse, Tunisia.*

M.D. Benoy, E.M. Mohammed, Suresh Babu M., and Binu P.J, B. Pradeep (Dec.2009) - Thickness dependence of the properties of indium tin oxide (ITO) FILMS prepared by activated reactive evaporation, *Brazilian Journal of Physics*, vol. 39, no. 4.

Melissa A. Yaklin, Duane A. Schneider, Kirsten Norman, Jennifer E. Granata , Chad L. Staiger, Microscale Science & Technology Dept, CINT Science Dept, Materials, Devices & Energy Technology Dept, Photovoltaic and Grid Integration Department, Impacts of Humidity and Temperature on the Performance of Transparent Conducting Zinc Oxide -Sandia National Laboratories, MS0734, Albuquerque, NM 87185.

http://www.ulvac-uc.co.jp/pdf/prm_arc/056e/No56E-

04.pdf

http://www.pveducation.org/pvcdrom/design/sheet-resistivity.

A.W. Czanderna, F.J. Pern (Sept. 1996)- Encapsulation of PV modules using ethylene vinylacetate copolymer as a pottant: A critical review – *Elsevier Solar Energy Materials and Solar Cells*, Volume 43, Issue 2, 1 Pages 101–181.

Tyoskin, O.I. Krivolapov, S.Y.(June 1996) -Nonparametric model for step-stress accelerated life testing, *IEEE Transactions on Reliability*, Volume: 45 Issue: 2 On page(s): 346 - 350 ISSN: 0018-9529.

Olivier Haillant, David Dumbleton Allen Zielnik (July 2011) – An Arrhenius approach to estimating organic photovoltaic module weathering acceleration factors, *Solar Energy Materials and Solar Cells*, Volume 95, Issue 7, pages 1889 -1895.

http://www.pveducation.org/pvcdrom/design/sheet-resistivity.

Authors profile





E Suresh Kumar is a Research Scholar at Jadavpur University Kolkata and an Assistant Professor at College of Engineering, Trivandrum, India. His field of interest includes microelectronics, quality and reliability, renewable energy and photovoltaics.

Dr. Bijan Sarkar is a Professor and the former Head of the Department of Production Engineering at the Jadvapur University, Kolkata. He is a specialist in reliability, terotechnology, tribology and operations management. He supervised many M.Tech and Ph.D thesis and published papers in many internationally reputed journals.