THERMAL TRANSIENT ANALYSIS OF HIGH POWER LED EMPLOYING SPIN COATED SILVER DOPED ZnO THIN FILM ON Al SUBSTRATES AS HEAT SINK

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Silver doped Zinc Oxide (AZO) thin films were synthesized on Al substrates by sol gel spin coating method and annealed at various temperatures from 300 to 450°C. The as prepared and annealed samples (AZO/Al) were used as thermal substrates for high power LED performance. Thermal transient analysis was carried out for the given LED at various driving currents. Annealed AZO thin film (300°C) interfaced LED showed lower total thermal resistance for lower driving currents when compared with bare ZnO. All annealed samples other than 300°C showed increased thermal resistance for all driving currents. Consequently, rises in junction temperatures were low for AZO thin film (300°C) interfaced LED at lower driving currents. Improved reduction in junction temperature was noticed with AZO as compared with ZnO (ΔT_J = 4.34°C). The interface resistance was also showed lower value for 300°C annealed AZO thin film at all driving currents. The surface analysis was also evidenced the observed results. Overall, 300°C annealed AZO thin film was performed well on reducing both thermal resistance and junction temperatures for high power LEDs.

(Received November 26, 2014; Accepted January 21, 2015)

Keywords: ZnO thin film, spin coating, LED, Thermal analysis, interface resistance

1. Introduction

It is important to consider in thermal management when designing LED-based products since LED light output is directly related to its temperature. Much attention has been given to the development of materials with high thermal conductivity for electronic devices and heat sinks for the purpose of alleviating the heat dissipation problem [1]. Though the various thermal pastes are available to solve this issue, the paste like materials faces paste pump out problems and the conductivity range is also not suitable for high power electronic devices like LEDs. To overcome this issue, metals such as tin, aluminum, silver and copper [2,3] are often used as coating materials because of their low hardness, which increases the total contact area of the joint, and their high thermal conductivity, which enhances the heat transfer from heat source to heat sink.

Zinc oxide (ZnO), a direct wide bandgap (3.4 eV at Room temperature) II-VI compound n-type semiconductor, has a stable wurtzite structure with lattice spacing a = 0.325 nm and c = 0.521 nm. In order to obtain better crystallization quality and other properties such as optical, electrical, and thermal, researchers have tried on doping using various elements to ZnO. Transition metal doped nanostructure is an effective method to adjust the energy level surface states of ZnO, which can further improve by the changes in doping concentrations of doped materials and hence its physical and especially optical properties can be modified [2].

To improve the conductivity, ZnO thin films are usually thermally treated in a reducing atmosphere and doped with various dopants, e.g. B, Al, Ga, In, Zr, F, etc. The use of dopants not only enhances the conductivity of ZnO thin films by extrinsic defects but also improves the thermal stability [3-7]. The thermal treatment and doping process can also lead to the modification

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of surface morphology [3,6, 8–12]. The doped thin film can be prepared by various deposition techniques such as RF magnetron sputtering, chemical vapour deposition, pulsed-laser deposition, spray pyrolysis, and sol–gel process. Among them, the sol–gel process is simpler and offers the possibility of preparing a small and large-area coating at relatively low temperature and low cost [13].

In this research work, the Ag doped ZnO thin film was deposited on Al substrates and post processed at different annealing temperatures. The bare and annealed samples were used as heat sink for high power LED and tested their thermal performance using thermal transient analysis method. The surface image of post processed thin film was also recorded using AFM and the results are discussed here. The observed data were processed and discussed for various driving currents.

2. Experimental methodology

2.1 Synthesis of Ag doped ZnO thin film

Bare and Ag doped ZnO (AZO) thin films were deposited onto Al substrates by sol–gel spin coating method. For sol-gel preparation, Zinc acetate dehydrate (ZnAc), 2-butanol and diethanolamine (DEA) were used as Zn source material, solvent and stabilizer respectively. For bare ZnO thin film coating, 0.4 M ZnAc was dissolved in 2-butanol and prepared the ZnAc solution with the aid of DEA solution and the molar ratio of DEA to ZnAc was fixed at 1.0. In order to get clear and homogeneous solution, the mixture was stirred at 70°C using a magnetic stirrer for 6 hrs.

For Ag doping, $AgNO_3$ were selected as a source material and ZnAc was dissolved in 15 ml of isopropanol and added DEA solution under continuous stirring by magnetic stirrer at room temperature (solution A). 10 ml isopropanol mixed $AgNO_3$ solution was added to the clear solution of ZnAc (solution A). 7 % weight ratio of Ag/Zn was used for Ag doping. The prepared solutions were used to coat bare and AZO thin film by spin coating unit. Before coating, the Al substrates were cut into several pieces with 2 cm x 2 cm dimensions and cleaned with soap solutions followed by rinsing using distilled water. Later, the substrates were dipped in ethanol solution for 10 min in an ultrasonic bath followed by acetone cleaning and hot air drying. The cleaned and dried substrates were fixed on the center of the spin coater using a double sided tape. 5 drops of the prepared solution was put at the center of the Al substrate by plastic dropper and switched on the spinning motor. The rotating disc speed was controlled and maintained as 3000 rpm and 2000 rpm for bare ZnO and AZO thin film respectively. The spinning time for all coating was fixed as 30 seconds. The coating cycles for bare ZnO and AZO thin film was fixed as 20 and 15 respectively. Depending on the wet quality of the film, the drying time was varied from 1 min to 10mins and temperature was changed from 100°C to 150°C respectively. Finally, annealing process was also employed in air using tube furnace for about 1 hr at various temperatures from 300°C to 450°C at 50°C step size.

2.2 Thermal transient analysis

In order to test the effect of Ag doping on thermal transport behavior of spin coated ZnO thin film as TIM, bare ZnO and AZO thin film (200 nm) coated Al substrate was used as heat sink for 1W yellow LED package. The thermal transient analysis of the given LED for different boundary conditions (see in fig. 1) is conducted based on the electrical test method JEDEC JESD-51. The thermal transient cooling curve of the LED is captured by the Thermal Transient Tester (T3Ster) in still air box for various driving currents. Figure 1 illustrates the schematic diagram of LED testing configuration using bare ZnO and AZO coated Al substrate as a heat sink.

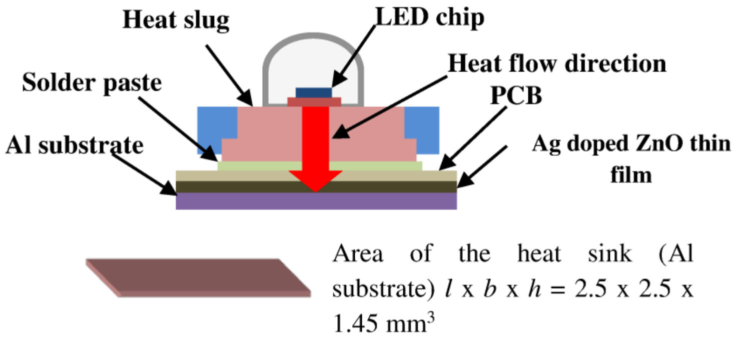

Fig. 1. Schematic diagram of LED testing configuration using Ag doped ZnO interface

During the thermal test, three different currents (100 mA, 350mA and 700 mA) were used to drive the LED in a still-air chamber at room temperature of 25°C ± 1 °C. The LED was forward biased for 900s. Once it reaches steady state, the LED was switched off and the transient cooling curve of heat flow from the LED package was captured for another 900s. The obtained cooling profile of the LED was processed using Trister Master Software for structure functions and evaluated the cumulative structure function for the given boundary conditions. From the transient cooling curve, the rise in junction temperature (T_J) was measured. From the cumulative structure function analysis, the $R_{th\text{-}tot}$ (total thermal resistance of the LED measured from junction to atmosphere) and $R_{th\text{-}b\text{-}hs}$ (thermal resistance of the interface layer (thin film) placed between MCPCB board and Al substrates) were measured.

In order to confirm the repeatability and accuracy, the experiment has been repeated for 3 times with same experimental conditions and parameters. The deviation of the observed results for each measurement was low ie < 0.1 °C for junction temperature measurement. Similarly, the deviation of the R_{th} of the LED observed for each measurement was low ie < 0.1 K/W. To ensure the reliability of the equipment, the T3Ster equipment is calibrated before we start the measurement.

2.3 K-factor calibration

Before the real measurement, the LED was thermally calibrated using dry thermostat and T3Ster as the power supply. The product of K and the difference in temperature sensing voltage (referred to as ΔV_F) produces the rise in device junction temperature:

$$\Delta T_J = \Delta V_F \, K \quad \rightarrow K = \Delta T_J \,/\, \Delta V_F \tag{1}$$

During the calibration process, the LED was driven with lower operating current at 1mA to prevent self-heating effect at the junction. The calibration was carried at 25°C and the voltage drop across the junction was recorded once the LED reaches thermal equilibrium with the temperature of the thermostat. Later, the ambient temperature of the LED was varied from 35°C to 85°C at 5°C step size and the voltage drop across the junction was noted at each temperature. From the calibration process, the K-factor of the LED was calculated from the graph of junction voltage (voltage drop) against ambient temperature. The K-factor of the LED was determined as 1.254 V/°C from the graph of junction voltage (voltage drop) against ambient temperature.

3. Results and discussion

3.1 Cumulative Structure Function analysis

The thermal transient curves of high power LED fixed on AZO thin film coated Al substrates (AZO/Al) were recorded for three different driving currents (100 mA, 500 mA and 700 mA) and the cumulative structure function curve was derived from the structure function analysis as shown in fig.2 (a-c). In fig.2, the variation of cumulative structure function with respect to the annealing temperature of AZO thin film samples is also included for discussion. The annealing process of thin film samples will demonstrate the effect of annealing temperature on heat conducting behavior of AZO thin film. Figure 2 clearly depicts that the driving currents also influence on total thermal resistance (R_{th}) and increased R_{th} is achieved with the LED measured at higher driving current (700 mA). This may be due to the heating effect during the measurement as a result of junction temperature increases with driving currents. It is mainly attributed to the current crowding phenomenon. From the literatures, the current crowding takes place at high current densities in semiconductor devises [14,15]. Additionally, the energy is propagated through the lattice by these phonon waves [16].

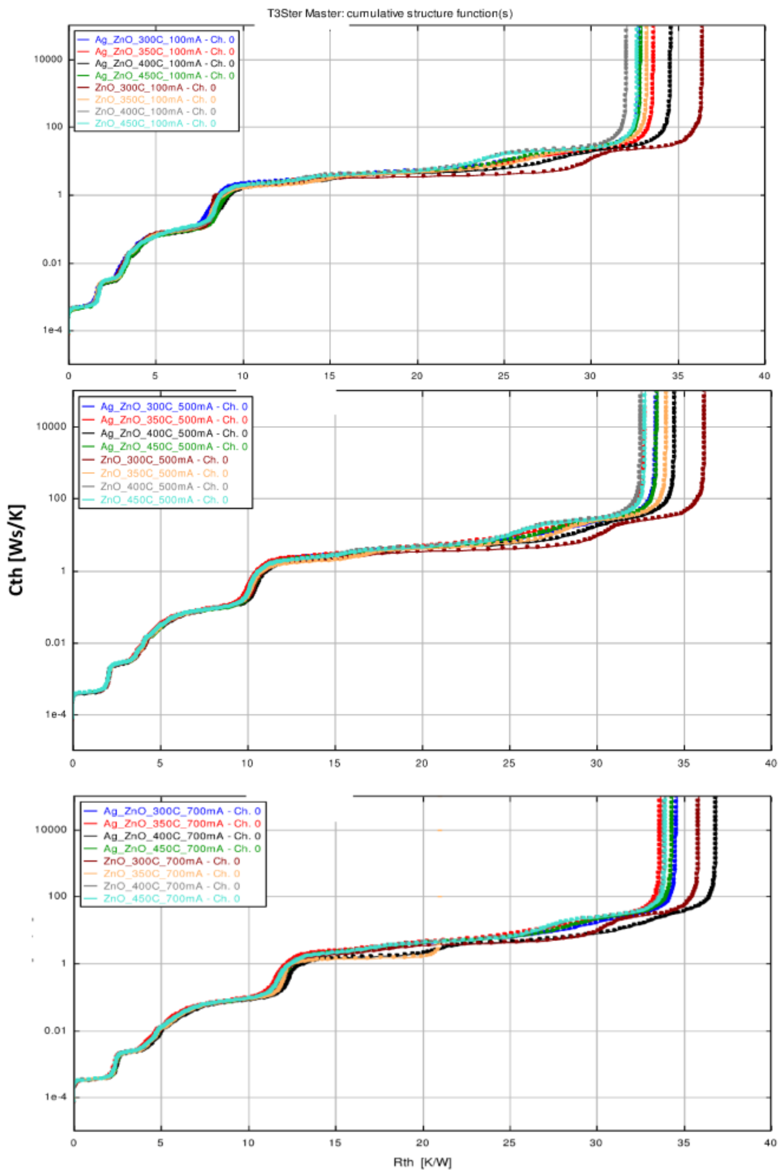

Fig. 2. Cumulative structure function of the LED using bare and Ag doped ZnO thin film as interface material recorded for three different driving currents.

In order to understand in detail, the R_{th} of the given LED was derived from the cumulative structure function curve (from fig. 2) and the observed data are summarized in Table – 1. It clearly explains the influence of annealing temperature as well as Ag doping on changing the R_{th} value of LED measured at various driving currents. From the table -1, low value in R_{th} is noticed with bare ZnO thin film annealed at 350°C for which the measured driving current is 700 mA. AZO thin film also helps to reduce the R_{th} of LED considerably with respect to annealing temperature of thin film samples especially the R_{th} value at 100 mA is low for AZO thin film annealed at 300°C than compared with bare ZnO thin film.

Table 1 Total Thermal resistance (R_{th}) of annealed ZnO and AZO interfaced LED measured at various driving currents

	AZO				**ZnO**			
	300°C	350°C	400°C	450°C	300°C	350°C	400°C	450°C
100 mA	32.80	33.62	34.58	32.88	36.38	33.26	32.01	32.69
500 mA	33.39	32.75	34.48	33.46	36.18	34.00	32.53	32.79
700 mA	34.52	33.61	36.81	34.33	35.80	34.03	33.88	33.96

The difference in R_{th} (ΔR_{th}) is about 3.5 K/W. At low driving current, the self-heating effect will be avoided and the observed results show the behavior of Ag doping on reducing the thermal resistance of the LED. No other annealed samples showed this much difference in R_{th}. As compared for 300°C, the ΔR_{th} observed between bare and AZO value decreases as the driving current increases ie low value in R_{th} is noticed with AZO. For all other annealing temperatures, increased R_{th} values are measured from the AZO as compared with bare ZnO.

Overall, higher annealing temperature for AZO does not help to reduce the R_{th} and better R_{th} is possible with bare ZnO. At higher temperature, AZO thin film show a conversion of n-type from p-type conductivity with the electron concentration being increased to 10^{20} cm^{-3} [17] and hence the current crowding effects occurs [14]. As a result of change in R_{th} of the LED, we can expect the considerable change in raise in junction temperature of the given LED. It is necessary to study the change in junction temperature for various boundary conditions. To support this study, the cooling transient curve of the given LED was recorded for three different driving current at various boundary conditions. The rise in junction temperature (T_J) was measured from the curve and the observed values are plotted in fig. 3.

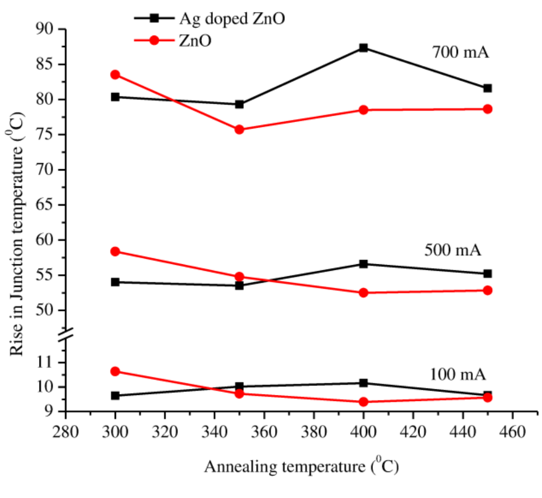

Fig. 3. Variation in junction temperature rise of the LED for various boundary conditions measured at different driving currents

Fig. 3 reveals that the AZO thin film interfaced LED shows low junction temperature with respect to driving currents. But very low value in T_J is noticed with bare ZnO thin film interfaced LED. From the fig.3, it also depicts that the T_J value decreases as the annealing temperature increases. Contrarily, increased T_J is observed with AZO thin film interfaced LED as the annealing temperature increases. Especially, 400°C annealed AZO film interfaced LED shows high value in T_J for all driving currents. As compared with bare ZnO interfaced LED, low value in T_J (54.02°C) is observed with AZO interfaced LED and the difference in T_J is 4.34°C (ΔT_J = 4.34°C) when measured at 500 mA. At 700 mA driving current, AZO interfaced LED shows high value in T_J and increases as the annealing temperature increases until 400°C as compared with bare ZnO interfaced LED. This may be due to the change in the lattice value as a result of the position of Ag on ZnO lattice [18]. The observed ΔT_J is 8.82°C which is high value and evidenced the influence of annealing temperature (400 °C) on increasing the T_J values of the given LED. Overall, On considering AZO interfaced LED, the ΔT_J is decreasing as the annealing temperature increasing and increased T_J is also noticed for AZO interfaced LED.

Based on the observation made by using AZO as thermal interface material, it is necessary to understand the heat transport property of the AZO thin film for various driving currents. In order to support this, the thermal resistance of the interface material is indirectly measured from the overall thermal resistance of the LED package. The cumulative structure function curve provides the thermal resistance network of the package from which the R_{th} of the interface (AZO) can be eliminated. The measured thermal resistances of AZO and bare ZnO interface ie thermal resistance between board and heat sink ($R_{th\text{-}b\text{-}hs}$) are plotted against the annealing temperature for various driving currents as shown in fig. 4.

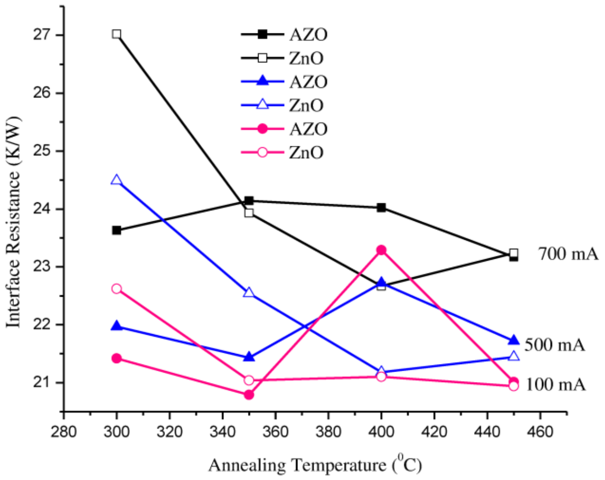

Fig. 4. Change in interface resistance between heat sink and LED package measured at various driving currents for different boundary conditions

From the fig. 4, it clearly shows that AZO thin film interface shows low value in thermal resistance when compared to bare ZnO for the annealed temperature of 300°C. A small decrease in R_{th} is noticed with AZO thin film interface as the annealing temperature increases upto 350°C for the driving current reaches until 500 mA. At 300°C, the difference in R_{th} ($\Delta R_{th\text{-}b\text{-}hs}$) of AZO thin film interface is high (3.39 K/W) as compared with bare ZnO when measured at 700 mA. It reveals that the AZO thin film conducts more heat from the LED to heat sink (substrate) after annealed at 300°C. An another noticeable increment in $R_{th\text{-}b\text{-}hs}$ is observed with 400°C annealed AZO thin film interface for 100 mA driving current. Overall, the interface resistance increases for AZO thin film as the annealing temperatures until 400 °C after that a decrease in resistance is noticed for higher annealing temperature (450°C). Moreover, a noticeable decrease in $R_{th\text{-}b\text{-}hs}$ could be observed for all ZnO thin film interface as the annealing temperature increases upto 400°C with respect to the driving currents.

3.2 Surface analysis

In order to understand the surface influence, bare ZnO and Ag doped ZnO thin film samples were annealed at various temperatures and characterized by AFM. The recorded AFM 3D images are given as shown in fig.5.

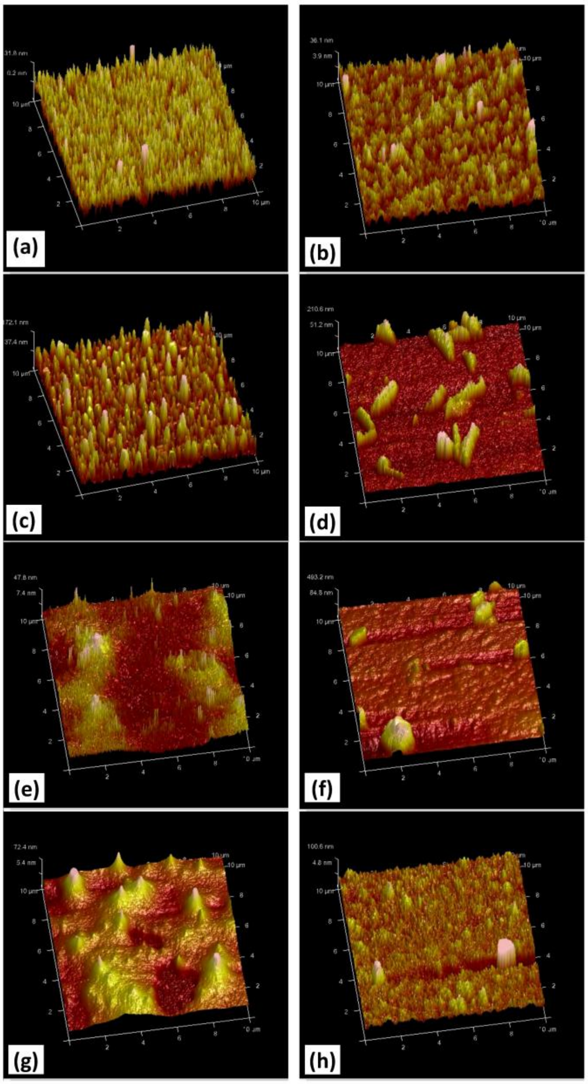

Figure 5 AFM surface morphology of bare and Ag doped ZnO thin film annealed at various temperatures

It clearly shows that the distinct surface morphology could be noticed with respect to annealing temperature as well as Ag doping. From the fig.5, the particle agglomeration could be observed for bare ZnO thin film as the annealing temperature increases (Fig.5 (a,c,e & g)). It shows clearly the influence of annealing temperature on surface morphology. As we look at the AZO thin film, distinct surface morphology was observed as the annealing temperature increased from 300 to 450°C. Moreover, the surface profile of the film was entirely changed with respect to the annealing temperature especially for 350°C. It has some plate type structure on the surface and does not show much influence on thermal resistance of the LED. When comparing the results of 450°C, the AZO sample surface shows uniform surface with large no. of contact points than bare ZnO.

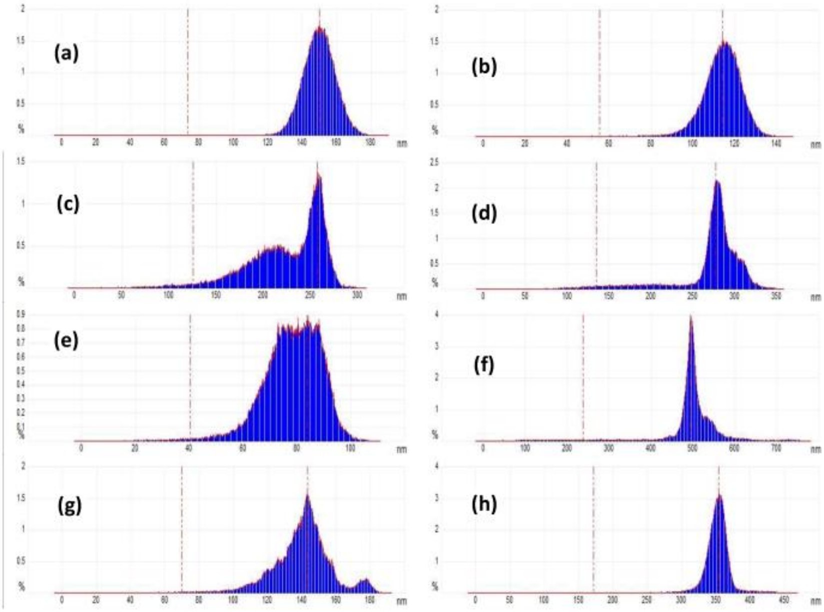

Fig. 6. Depth – valley histogram surface plot of bare and Ag doped ZnO thin film annealed at various temperatures

In order to study the surface profile, the depth-valley analysis on the surface of prepared thin film was also conducted for all samples using software and the processed histogram images are given as shown in fig.6 (a – h). The 'Y' axis gives the percentage of the depth available on the surface of the thin film which gives the ratio of depth-valley percentage in particular distance measured in nano meter scale (X axis). It explicitly shows that as grown samples shows wide histogram of depth - valley profile than annealed sample profile. Moreover, it is also observed that the more % of depth - valley profile is the evidence for high surface roughness. As seen in fig.6, the film annealed at above 300°C shows the high range in depth-valley and noticeable value is observed with 400°C annealed AZO samples.

From the fig. 6, the depth – valley distance is high for the thin film surface annealed at 400 °C and as a result, the increased resistance is possible on this surface. It was evidenced by observed high resistance value for AZO thin film surface than for bare ZnO surface. Fig. 6 also indicates clearly that the range in depth-valley % is low for AZO thin film surface and hence low thermal resistance is observed with AZO at 300°C (see table - 1).

4. Conclusion

Ag doped ZnO thin film was synthesized by spin coating method and annealed at various temperatures from 300 to 450°C. The bare and annealed AZO thin film was used as thermal interface material on Al substrates. Annealed AZO thin film interfaced LED shows good performance on reduced thermal resistance and also junction temperature for low driving current (100 mA). Spin coated bare ZnO thin film was also assisted to reduce total thermal resistance as well as the rise in junction temperatures. Overall, the bare and Ag doped ZnO thin film can be used as an alternative for thermal interface material in high power LEDs.

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