PERFORMANCE OF HIGH POWER LIGHT EMITTING DIODE FOR VARIOUS ZINC OXIDE FILM THICKNESS AS THERMAL INTERFACE MATERIAL

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Abstract

Oxide ceramic materials have attractive features either as filler or substrate materials in electronic packaging. Consequently, ZnO thin film for various thicknesses was prepared over Al substrates by RF sputtering and used as heat sink for high power LED. The thermal transient curve of device under test (DUT) was recorded for five boundary conditions. Rise in junction temperature (T_J) was measured and observed low value (54.4°C) for 200 nm ZnO thin films at 350 mA. The difference in junction temperature rise (ΔT_J) was observed as 7.46 °C at 700 mA when compared to bare Al substrates. The total thermal resistance ($R_{th\text{-}tot}$) of the DUT was low for 200 nm ZnO thin film coated Al substrates. AFM images were used to evaluate the surface roughness factors and their influence on thermal resistance. As expected, the surface roughness, grain size and peak-valley distance were strongly influenced the heat flow.

Index Terms: *ZnO thin film, thermal interface material, LED, thermal resistance, surface roughness*

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1. INTRODUCTION

Surface irregularities play a controlling part in the behavior of the interface and may create thermal contact resistance as a result of air gaps occupied at irregular surface. This could be avoided and achieved good thermal contact conductance by means of filling the air gap using thermally conductive materials. As predicted, in all cases, the thermal resistance follows a straight line as a function of bond line thickness (BLT). Thermal conductivity of the bulk material is well determined by this method [1].

Nitride and oxide based materials have been suggested for thermal interface materials and thermal paste (TP) type TIM has been mostly used for all electronic packaging applications for ease of use. Though they have been employed extensively as dielectric materials in printed circuit board technology for effective heat dissipation, the synthesis processes of these nitride and oxide based ceramic coated substrates are a significant drawback as these raw materials are costly [2]. Zinc oxide is a II–VI compound semiconductor with wide band gap (~ 3:37 eV), by which it has been recognized as a promising photonic material in the ultraviolet (UV) region. ZnO is very abundant in nature, has high thermal and chemical stability [3].

Xu et al., also reported that out of all the commercial thermal interface materials studied, the ZnO filled silicone of Dow Corning gives the highest thermal contact conductance [4]. ZnO is also considered as a promising candidate for GaN epitaxy as substrate mainly due to the fact that the lattice mismatch between GaN and ZnO is very small compared to that with the most commonly used substrate, sapphire. The convincing thermal conductivity (1-1.2W/mK) and low thermal expansion coefficient of wurzite ZnO [5] increases the avenues of this material to be engineered into interesting hints at new electronic applications down the road. The surface quality plays a crucial role on thermal contact resistance and defines the thermal conductivity considerably. Surface roughness (finish) is defined as the average deviation from the mean surface height. In general for very low thermal resistance, a surface finish in the range of 1.27–1.5 µm is recommended [6].

A research demonstrated that the surface roughness between 0.4 µm and 1.63µm in the presence of TIM resulted in less than a 2.5% difference in interface thermal resistance [7]. In our knowledge, thin film has not been reported as thermal interface material especially ZnO. We have also prepared AlN thin film as thermal interface materials in another work [8] and achieved good results in contact conductance. In another study, two different thickness of ZnO were tested as thermal interface material and achieved good results where the influence of surface parameters has not been addressed [9].

Accurate measurement of bond line thickness is necessary in order to achieve precise bond line thickness control. A conventional bond line thickness measurement method is cross-sectioning, which requires a cured die to be cut open along a line. Generally, a thin bond line is preferred over a thick one, since the stress concentration at the corners of the joint is lesser in a thinner bond line. Also, the air cavity concentration is lesser in a thin bond line as compared to a thick one. Consequently, three different thicknesses of ZnO thin film are used as thermal interface material and the influence of their thickness and surface parameters on the thermal resistance of given LED are tested.

1.1 Theoretical Background

The device junction temperature in the test condition can be determined by

$$T_J = T_{J0} + \Delta T_J \qquad (1)$$

Where T_{J0} = initial device junction temperature (ºC), ΔT_J = change in junction temperature due to heater power application (ºC). Static mode was applied using still air box for all measurement, which applies heating power to the DUT on a continuous basis while the T_J was monitored through measurement of temperature-sensitive parameter. The thermal contact conductance for joint between contacting solids is defined as

$$h_c = \frac{Q/A}{\Delta T} = \frac{Q/A}{T_1 - T_2} = \frac{Q}{A(T_1 - T_{2)}} \qquad (2)$$

Where T_1 and T_2 are the temperatures of the bounding surfaces of the contact, and *Q/A* is the heat flow per unit area [10]. The effective total thermal resistance at the interface between two materials is a sum of the resistance due to the thermal conductivity of the TIM and contact resistance between the TIM and the two contacting surfaces (see fig.1). This is generally expressed as [11].

$$R_{\text{effective}} = (BLT/k_{\text{TIM}}\,\text{A}) + R_{c1} + R_{c2} \qquad (3)$$

Where, *BLT* and k_{TIM} are the bond line thickness and thermal Conductivity of the interface material respectively and *A* is the area. R_{c1} and R_{c2} are contact resistances of the TIM at the boundary with the two surfaces and illustrated schematically in Fig. 1a. In this study, the prepared thin film thickness is considered as bond line thickness.

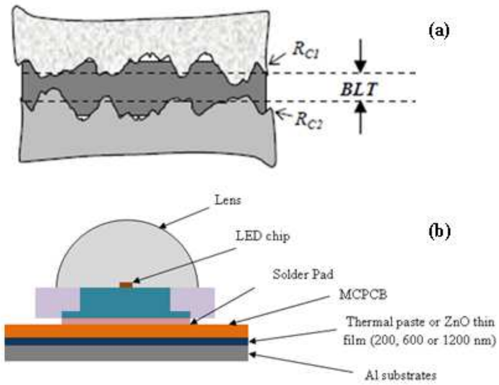

Fig-1 (a) Thermal interface material inserted between the two contacting bodies where R_{c1} and R_{c2} are contact resistances of the TIM at the boundary with the two surfaces and (b) Schematic illustration of LED employed thermal paste or ZnO thin film as thermal interface material

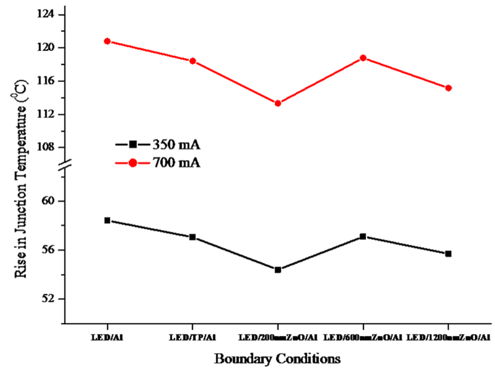

Fig2. Rise in junction temperature of 3W green LED for five different boundary conditions measured at 350 and 700 mA.

2. EXPERIMENTAL WORK

2.1 ZnO Thin Film Synthesis

The synthesis of ZnO thin film has already been reported in another work by the same author [9]. Briefly, ZnO (99.99% purity) target was used in RF sputtering for ZnO thin film coating on Al substrates (23 cm x 25 cm x 1.5 cm) which were used as heat sink. High pure Ar (99.999%) was used as sputtering gas. Initially, the chamber pressure was pumped down to 8.5 x 10^{-6} mbar after loading the ultrasonically cleaned substrates into the chamber. Pre-sputtering was carried out to remove the surface oxidation of the target without opening the source shutter. All coatings were made in 150W RF power at chamber pressure of 6.61 x 10^{-3}. The ZnO thin film was prepared in three different film thicknesses (200, 600 and 1200 nm). The surface morphology of the prepared ZnO thin film was also tested using atomic force spectroscopy

(AFM) (model: ULTRA Objective, Surface Imaging Systems, GmbH) in the non-contact mode.

2.2 Thermal Transient Analysis

The thermal performance of prepared ZnO thin film as interface material was tested and thermal transient curve was captured for the given LED based on the electrical test method JEDEC JESD-51. The high power (3W green) LED package attached with Metal Core Printed Circuit Board (MCPCB) was fixed on bare Al substrate (without and with thermal paste) and ZnO thin film (200, 600 and 1200 nm) coated Al substrates (see fig.1b) and carried out the experiment using Thermal Transient Tester (T3Ster) in still air box. For comparison, the thermal behavior of given LED with thermal paste condition was also tested where cooler master thermal paste kit was used as thermal interface material. The thermal transient analysis was carried out for the given LED at three different currents 100 mA, 350mA and 700 mA at room temperature. The current densities were calculated as 0.961 A/mm^2, 3.37 A/mm^2 and 6.75 A/ mm^2 respectively. After the LED was forward biased for 900s, the transient cooling curve of heat flow was captured for another 900s. To confirm the repeatability/ reproducibility, the experiment was repeated for 3 times. The obtained cooling profile of the LED for uncoated and different thicknesses of ZnO thin film coated Al substrates was processed for structure functions using T3ster Master Software.

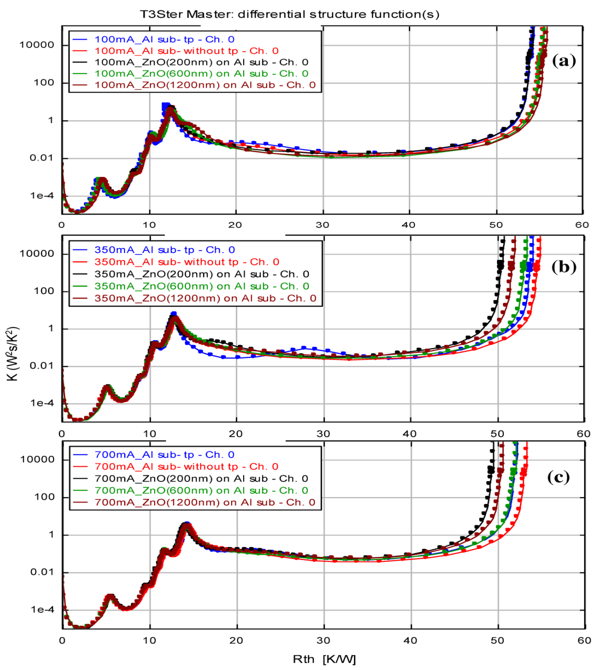

Fig3. Differential structure function of 3W green LED for five different boundary conditions recorded at (a) 100, (b) 350 and (c) 700 mA

3. RESULTS AND DISCUSSION

3.1 Thermal Resistance Analysis

The transient cooling curve for all samples is recorded and the observed raise in junction temperature is given in Fig. 2. Since the ΔT_J for 100 mA, we didn't discuss the results here. But a noticeable decrease in T_J could be observed at and above 350 mA driving currents for ZnO thin film interface. It reveals that the rise in T_J shows very low for 200 nm ZnO thin film coated substrates and the ΔT_J between bare and 200 nm ZnO thin film samples show low value (ΔT_J =7.46 °C at 700 mA) than other thicknesses.

Table1: Total thermal resistance of 3W green LED at five boundary conditions

Total Thermal resistance (K/W)			
Boundary conditions	100 mA	350 mA	700 mA
LED/Al	55.43	54.90	53.31
LED/TP/Al	54.32	54.08	52.16
LED/ZnO(200nm)/Al	54.20	50.67	49.46
LED/ZnO(600nm)/Al	55.51	53.31	52.09
LED/ZnO(1200nm)/Al	55.86	51.96	50.62

Moreover, rise in T_J for both TP and 600 nm ZnO thin film interfaces shows almost similar results for ≥350 mA. An increase in T_J from 200 nm to 600 nm may be due to either higher thermal resistance of ZnO or surface roughness parameters at higher thickness. The cumulative structure function of 3W green LED for five different boundary conditions was recorded as given in Fig. 3. The $R_{th\text{-}tot}$ of the given LED was measured from the cumulative structure function and the observed values are given in Table – 1. From table -1, the results measured at 100 mA reveals the influence of ZnO interface thickness on $R_{th\text{-}tot}$ as increases with thickness. It also shows high value for ZnO thickness ≥ 600 nm. It obeys the conditions of equation 3 where the $R_{effective}$ increases with BLT increases. The $R_{th\text{-}tot}$ values measured at driving current ≥ 350 mA shows the behavior of the thermal conductivity of ZnO thin film with temperature generated as a result of rise in junction temperature. It is attributed to the efficient lateral heat spread of thick ZnO thin film (>600 nm) than thin ZnO (200 nm) at high current density.

Table 1 exhibits that the observed $R_{th\text{-}tot}$ is low (49.46 K/W) for 200 nm ZnO coated at 700 mA than other boundary conditions. It is also observed that the $R_{th\text{-}tot}$ is low for ZnO coated Al substrates compared with TP applied boundary condition. In addition, a small increase in $R_{th\text{-}tot}$ is noticed with increase of ZnO thickness from 200 nm to 600 nm. This may be due to the influence of thermal mismatch between Al substrate and ZnO at increased temperature. The thermal mismatch is directly proportional to coefficient of thermal expansions (CTE) and temperature difference since Al have high CTE (22.2 x 10^{-6} / K) than ZnO (2.43 x 10^{-6}/K). At high current density, the temperature difference between Al and ZnO is high as a result of high T_J and hence thermal mismatch stress developed at high current density (≥350 mA). It is evidently proved by observed the difference in R_{th} (ΔR_{th}) was low for 100 mA (1.31 K/W) than higher driving current (≥350 mA). It is also observed that 100 % increment in ΔR_{th} could be noticed for high driving current for 600 nm ZnO thin film coated samples. Normally, the thermal conductivity of polycrystalline material is determined by the grain size and microstructure effects, such as impurity and defect [12,13].

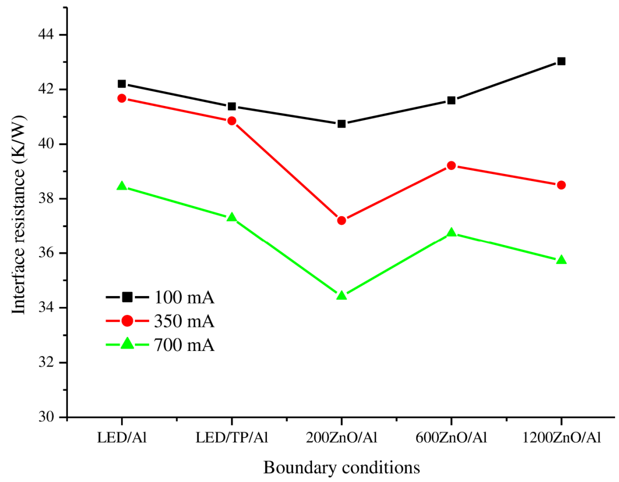

Fig4. Interface thermal resistance of 3W green LED for five different boundary conditions measured at various driving currents

Overall, 200 nm ZnO coated Al substrates shows low $R_{th\text{-}tot}$ values for all driving currents. It attributes the influence of BLT on the thermal resistance of the interface material. In order to study the thermal resistance of interface material, the interface resistance is derived from the cumulative structure function analysis (Fig. 3) and the observed interface resistances for different thickness of ZnO at various driving current are shown Fig. 4. It explains that the interface resistance is low for 200 nm ZnO thin film than other thicknesses. Fig.4 also reveals the influence of driving current on the interface resistance and shows low values for all boundary conditions measured at 700 mA. It clearly indicates that the interface resistance value increase for the film thickness increases from 200 to 600 nm. This may be due to the influence of surface roughness parameters such as step profile of the surface or peak valley distance range. A detailed discussion on this surface roughness parameters are discussed in the consecutive section.

Moreover, a small decrease in resistance could be observed for TP applied boundary condition than bare Al substrate condition. This may be due to the thermal conductivity of interface material (air - 0.024 W/m.K and thermal paste - 0.8 W/m.C). A decrease in interface resistance of ZnO thin film is attributed to low thermal conductivity of thermal paste than ZnO interface (1-1.2W/mK) used in this study. During the burning of LED at high driving current, the temperature of the interface is increased which induces the thermal conductivity and hence the resistance decreases. But the quality of the thin film also influences the thermal conductivity. In our study, the interface resistance is observed as high for thicker film (≥600 nm) than 200 nm. It may be due to the volume of micropore increases with increase in thickness [14] and hence the interface resistance increases.

3.2 Surface Analysis by AFM

In order to measure the surface topography, AFM was used to capture the surface images of the bare Al and ZnO coated Al substrates and presented in Fig. 5 (a-d). Fig. 5 a shows the surface image of bare Al substrate and reveals the rough nature and Fig. 5 (b-d) depicts the surface topography of ZnO thin film coated Al substrates for various thickness and also show smooth surface when compared to bare Al one. From fig. 5, it is easy to understand that the film thickness plays an important role on surface modification. Each fig. parts in Fig.5 have distinct surface which is mainly due to substrate and film thickness variations.

Table2. Surface roughness parameters of ZnO thin film coated on Al substrates

Samples	Bare Al	200nm ZnO/Al	600nm ZnO/Al	1200nm ZnO/Al
Roughness (nm)	34.2	5.3	13.5	11
Grain size (µm)	1.43	0.25	0.49	0.32
Peak – valley range (nm)	200-500	25-55	60-145	35-125
Max. peak-valley range (nm)	320	40	100	80

It has been reported that roughness plays an important part in determining the thermal resistance of a contact interface. The influence is positive, i.e., increases the resistance. A twofold increase in roughness can result in a four to fivefold increase in the thermal resistance [15].

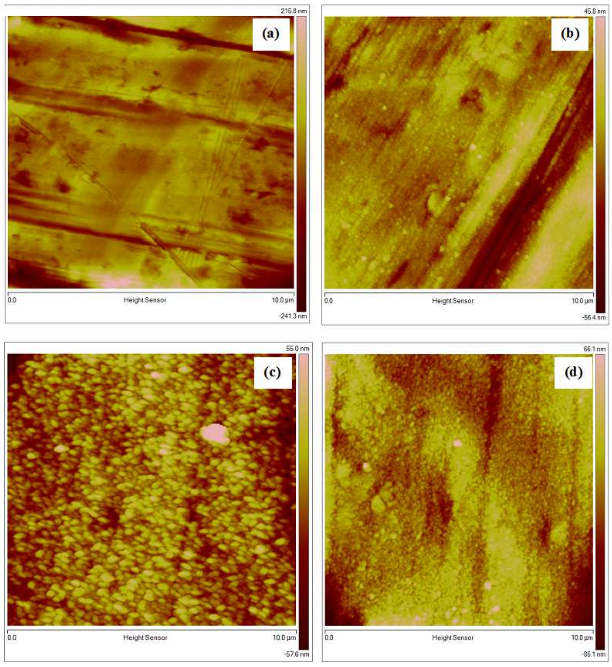

Fig5. AFM images of (a) bare and ZnO thin film coated Al substrates at (b) 200 nm, (c) 600 nm and (d) 1200 nm thickness

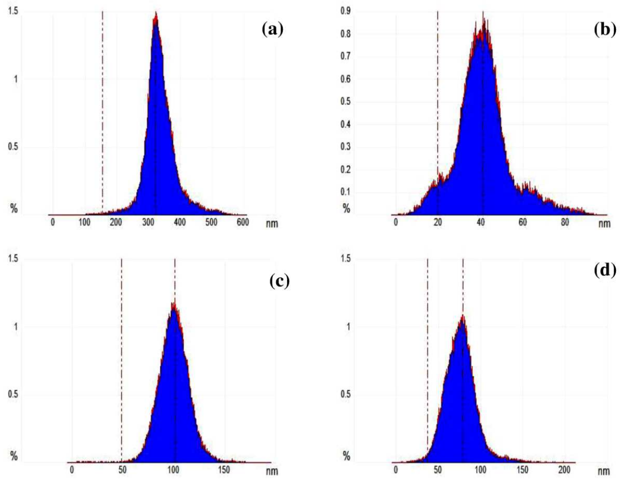

Fig6. Step profile of (a) bare and ZnO thin film coated Al substrates at (b) 200 nm, (c) 600 nm and (d) 1200 nm thickness.

Consequently, the surface roughness of the all our samples are also measured using software and the observed values are presented in Table – 2. It clearly indicates that the roughness value increases with thickness increases. Among the ZnO thin film samples, low value in surface roughness could be observed with 200 nm ZnO on Al and hence the LED samples with 200 nm ZnO coated Al substrates show low value in R_{th-tot} than other thicknesses. Moreover, thin film coating gives surface smoothness when it is coated over rough or unpolished surfaces and evidenced by observing low surface roughness values than bare substrate (see fig.5). A noticeable increment in surface roughness could be observed from 200 nm to 600 nm ZnO thin film samples. This could be one of the reasons for huge difference in R_{th-tot} between 200 and 600 nm ZnO thin film samples as stated by Yovanovich et al work [15].

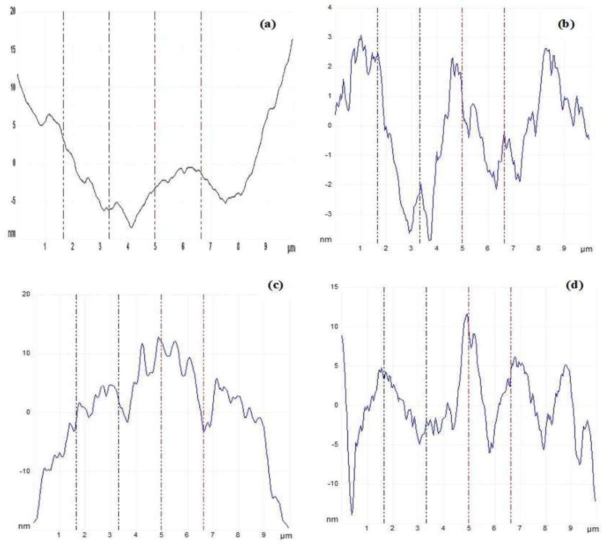

Fig7. Peak-valley distance of (a) bare and ZnO thin film coated Al substrates at (b) 200 nm, (c) 600 nm and (d) 1200 nm thickness

In addition, the grain size of ZnO thin film is also evaluated from AFM images and also given in table – 2. It shows that the grain size increases with thickness increases. According to the ref. [13], the grain size is one of the leading factors which affect the thermal transport which is evidently proved in our studies by observing low R_{th-tot} and $R_{th-b-hs}$ for 200 nm ZnO thin film than other thickness. Moreover, the thermal contact resistance of ZnO thin film with large grain size is high compared to thin film with small grain size and hence the 200 nm ZnO thin film shows low resistance value than other thickness [14]. It can be seen that the 200 nm ZnO thin film show smaller grain size than other two thicknesses (600 and 1200 nm).

The surface step profile study is a scientific approach for the surface analysis in electronic industries. It will give the surface waviness profile of the specified surface under study. It is the measure of the highest peak and deepest valley across the surface profile from the baseline. It clearly represents the contact points on the surface for thermal conductivity [16]. To analyze the surface step profile of the bare and ZnO thin film coated surface, the AFM images were processed using software and observed the surface step profile as given in Fig. 6. It also clearly indicates that the area under the curve indicates the distribution of highest peak and deepest valley across the bare Al and ZnO thin film surface. The X axis shows the percentage of step profile distribution on the surface and shows maximum height of the surface step profile for bare Al substrate and the range is also between 200 and 500 nm. Fig. 6 also clearly depicts that the peak height and depth valley distribution is low for 200 nm ZnO coated Al substrates than all other ZnO thicknesses (see table - 2).

From the AFM analysis, it could also be observed that the roughness profile of the surface of bare and ZnO thin film coated substrates are given in Fig. 7 (a-d). In order to understand the increase of $R_{th\text{-}tot}$ for 600 nm ZnO thin film coated Al substrate in detail, the peak-valley distance analysis is also carried out using the roughness profile of all bare and ZnO thin film surfaces and the observed results are presented in Table – 2. It clearly indicates that the maximum peak-valley distance is high for 600 nm ZnO thin film (100 nm) than other thicknesses and hence the contact conductance of MCPCB on 600 nm ZnO thin films coated Al substrate is low compared to other thicknesses.

CONCLUSIONS

RF sputtered ZnO thin film was used as TIM for high power LED and tested the thermal resistance of 3W green LED at three different ZnO thicknesses. 200 nm ZnO thin film coated Al substrates showed high ΔTJ vale of 7.46 °C at 700 mA when compared with bare substrate. Low Rth-tot and TJ was evidently proved due to low BLT (200 nm of ZnO thin film) at interface between MCPCB and heat sink. In addition, heat transport at high rate was also achieved with low surface roughness of ZnO thin film with smaller particles.

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Shanmugan Subramani has received his bachelor degree (1997) in chemistry, diploma in (1998) chemical process instrumentation and Master degree (2000) in Energy Science. He has received his Ph.D in the field of thin film solar cells during 2009. He has published more than 65 research papers in the refereed International journals and conferences. He also has a research experience of more than 7 years. Now he is working as a Post Doctoral Research Fellow in School of Physics, University Sains Malaysia upto date. His research is focused on identifying best thermal interface material in solid state devises in semiconductor industries.

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