Thermal Performance of High Power LED on Boron Doped Aluminium Nitride Thin Film Coated Copper Substrates

Zeng Yin Ong[1*], Subramani Shanmugan[1] and Devarajan Mutharasu[1]

[1]*Nano Optoelectronic Research Laboratory, School of Physics, University Sains Malaysia, Penang 11800, Malaysia.*

Authors' contributions

This work was carried out in collaboration between all authors. Author ZYO designed the study, performed the synthesis, conducted the measurement, and wrote the first draft of the manuscript. Author SS managed the analyses of the study, and improved the manuscript. Author DM proposed and designed the study, and managed the literature searches. All authors read and approved the final manuscript.

Original Research Article

ABSTRACT

Aims: The paper is aim to study the thermal performance of Boron doped Aluminium Nitride (B-AlN) thin film coated over Copper (Cu) substrate to improve surface configuration of the interface between two materials with different synthesis parameters.
Study Design: Synthesis of Boron doped AlN thin film by sputtering and post processed for various temperatures. The processed samples were characterized to study the behavior of B doping as well as the annealing temperature in changing the properties of B doped AlN thin film. The structural and surface properties were studied and reported.
Place and Duration of Study: Nano Optoelectronic Research Laboratory, School of Physics, University Sains Malaysia, Penang 11800, Malaysia, between December 2013 and July 2014.
Methodology: B-AlN thin films were prepared with five different gas ratios over Cu substrates by DC-RF coupled sputtering method and suggested for thin film based thermal interface material

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Corresponding author: Email: ongzengyin@gmail.com;

(TIM). 3W green LED package was tested with B-AlN thin films coated Cu substrates through thermal transient and surface analysis. The results are compared with the performance of bare Cu substrates.

Results: The thin film prepared with gas ratio of *Ar 7: N₂ 13* coated at 200°C showed the lowest thermal resistance R_{th} (53.27 K/W), board to ambient thermal resistance R_{thB-A} (36.03 K/W) and the lowest junction temperature T_j(120.98°C) at higher driving current (700 mA). Surface analysis results show that the thin film mentioned above exhibits low in surface roughness (8 nm) and range of valley depth (30-80 nm), which contribute in thermal performance of LED.

Conclusion: Overall, B-AlN films coated with gas ratio of *Ar 7: N₂ 13* are more favorable in reducing both total thermal resistance and junction temperature (T_j) of LED.

1. INTRODUCTION

In the advancement of the luminescence technology, evolution of Light Emitting Diodes (LEDs) have significant impact on lighting solutions which provides better optical performance than incandescent/halogen lighting technology, with its efficiency of about 10-20%. However, the efficiency of LEDs strongly depends on the junction temperature and improper thermal management would cause excessive rise in junction temperature that eventually compromising the overall performance [1,2]. Junction temperature of the LEDs need to be maintained below 120°C, if it exceeds which may lead towards device failure or damage [3]. Around 80% of the heat generated at the LED junction when forward biased must be removed to the ambient [4]. In order to extend the life of the LED device, a proper heat path from the junction to ambient must be established and addressed.

In recent PCB technology, Fire Retardant 4 (FR4) has been commonly used as electrical circuit board for LEDs. Recently high thermal conductive ceramics such as Alumina (Al_2O_3) and Beryllia (BeO) are being employed as dielectric materials in circuit board. Alumina is popular employed as insulating base, but it has its own drawbacks such as incapability of radiating heat emitted by LED chip. The beryllia type ceramic exhibits an excellent heat-radiating property, butit is classified as toxic and expensive [5]. To meet out the demands in electronic industry, highly conductive materials with reasonable production cost are preferred.

Group III nitrides are good in thermal conductivity, high thermal stability, high mechanical strength, excellent in electrical insulation, and highly recommended for electronic applications. Theoretically, thermal conductivity of AlN is reported to be about 280 $Wm^{-1}K^{-1}$ [6], however the typical value of AlN thin film is significantly lower at the range of 0.4 – 26 $Wm^{-1}K^{-1}$ and vary depending upon the deposition process conditions and their properties such as crystallite structure, film thickness, and impurities [7]. Although bulk BN has relatively high thermal conductivity (1300 $Wm^{-1}K^{-1}$) but it is commercially difficult to produce [8]. Very few works on combination of group III elements such as boron and aluminum in nitride thin film were reported and found that the boron doping can shrink the lattice of AlN and thus improves the thermal conductivity [9,10]. Several works had been reported on LED performance of AlN and BN coated substrates and noticeable improvement was achieved at high driving currents [11-12]. Though many papers have been reported on thermal properties of AlN and BN separately, B-AlN has not been reported so far.

In this study, B-AlN thin film were deposited for about one hour at different process conditions by DC-RF coupled sputtering method on copper (Cu) substrates. The thermal performance of 3W LED fixed on B-AlN thin film coated Cu substrates were conducted using thermal transient analysis method and the results based on cumulative structural function are presented here.

2. THEORITICAL 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). It should be noted

that the relationship between ΔT_J and power dissipation is usually linear under some specific conditions, and it may vary considerably at the extremes of device operation. The method itself is independent of the environment of the device under test (DUT), thus it is required to pay careful attention on environmental conditions in order to assure the significant test results. 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 efficiency of heat dissipation in LEDs is measured in terms of thermal resistance (R_{th}) which serves to the determination of junction temperature that arises in the LEDs under various operating conditions. It also helps to determine the maximum allowable external reference temperature for a given internal temperature and power dissipation. According to JEDEC standard 51-1 [13], the R_{th} of heat flow from the junction to ambient (total thermal resistance) of the LED is generally defined as in Eq.2:

$$R_{th} = \frac{T_J - T_A}{P_H} \qquad (2)$$

Where R_{th} is the thermal resistance from device junction to the ambient, T_J is the device junction temperature under steady state condition, T_A is an ambient temperature and P_H is the heat power dissipated in the device. By reducing the R_{th}, the device can be protected from overheating and led to operate for a longer lifetime.

3. EXPERIMENTAL WORK

3.1 B-AlN Thin Film Synthesis

B-AlN thin films were deposited on Cu substrates (23 cm (l) x 25 cm (b) x 1.5 cm (h)) by sputtering method using DC-RF coupled sputtering machine (Edwards make, Model-Auto 500). The sputtering process was conducted using pure Al (99.99% purity) target (3 inch in diameter and 4 mm in thickness) and Boron (B) (99.99% purity) target (3 inch in diameter and 4 mm in thickness). DC power source and RF power source were used to sputter Al and B target respectively. High pure Ar (99.999%) and N_2 (99.999%) were used as sputtering gas and reactive gas (nitrogen source) respectively. The Cu substrates were initially cleaned by rinsing in ultrasonic bath of acetone and isopropyl alcohol for 10 minutes.

The deposition chamber was initially pumped down to high vacuum of 3.56 x 10^{-5} mbar by using a turbo molecular pump backed by a rotary pump and fixed as base pressure for coating. In order to clean the surface oxidation of the targets, pre-sputtering process was carried out for about 5-10 minutes prior to film deposition. The discharge power of DC and RF were kept constant at 100W and 50 W respectively under the pressure of 9.54 x 10^{-3} mbar. A rotary drive assembly was used (25 RPM) to ensure the uniform film thickness. The B-AlN films were prepared on Cu substrates for about 1 hr at three different Ar and N_2 gas mixture ratios. The selective thin film samples were sputtered at two different temperatures for comparison.

The sputtering parameters used and the thicknesses obtained are summarized in Table 1. The surface morphology of all thin film samples was also analyzed using Bruker AXS make dimension edge atomic force microscope (AFM) system and the results were analyzed by using Nanoscope analysis software. In order to understand easily, the sample name (Sample 1 to 5) will be used for the discussion of our results in this paper.

3.2 Thermal Transient Analysis

In order to test and compare the performance of the thin film as thermal interface material on Cu substrates, 3W green LED package with starboard MCPCB were used and fixed on the B-AlN thin film coated substrates for thermal transient analysis. The measurement was carried out by Thermal Transient Tester (T3Ster) in a still air chamber (300 x 300 x 300 mm) at room temperature of 25±1°C according to JEDEC JESD 51-2A standards on natural air convection measuring method [14]. The schematic diagram of boundary conditions for LED testing is given in Fig. 1.

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 device junction temperature rise:

$$K = \frac{\Delta T_j}{\Delta V_F} \qquad (3)$$

During the calibration process, the LED was driven with lower operating current at 1mA to prevent self-heating effect at the junction. The

ambient temperature of the LED was fixed 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 25°C to 85°C at 10°C step (35°C, 45°C, 55°C, 65°C, 75°C and 85°C) and the voltage drop across the junction was noted at each ambient temperature. From the calibration process, the K-factor of the LED was determined $(2.289 \times 10^{-3}$ V/°C) from the graph of junction voltage (voltage drop) against ambient temperature as shown in Fig. 2.

During the thermal measurement, the LED was forward biased at three different driving currents (100 mA, 350 mA and 700 mA) for 900 s until it reached the steady state. Once the steady state was achieved, the transient cooling curve of heat flow was captured for additional 900 s. The thermal transient curve under different measurement conditions is captured based on the electrical test method JEDEC JESD51-51 [15]. The recorded cooling profiles of the measurement were processed for structure functions using T3Ster Master Software.

4. RESULTS AND DISCUSSION

4.1 Thermal Transient Measurement

Fig. 3(a-c) represents the complete heat transfer profile in the form of cumulative structural function from junction to ambient which is captured for the given LED fixed on B-AlN thin film coated Cu substrates at (a) 100 mA, (b) 350 mA, (c) 700 mA. From the Fig. 3(c), the curve region between point A and B is the thermal resistance of junction to board which is the

substrate, (R_{thJ-B}) of LED package at 700mA. The R_{thJ-B} value was recorded as 17.88 K/W based on JEDEC JESD51-14 standard [16]. According to the product datasheet, the R_{thJ-B} of the given LED at 700 mA is 17 K/W [17], this may due to different measurement method and conditions practiced by the industry. The region between the point B and C widely covered the profile and it explains the heat path from substrate to ambient.

From the analysis of cumulative structural function, the thermal resistance (R_{th}) is recorded and presented in Table 2. From the measurement of R_{th} shown in Fig. 3, it is found that Sample 1 shows the highest R_{th} value in all driving currents (100 mA, 350 mA, 700 mA). This may due to defects in crystal structure grows with gas ratio of *Ar 6: N$_2$ 14* and hence influences the heat conductance. At 100 mA, Sample 2 shows the lowest R_{th} value at 53.87 K/W. While Sample 5 achieved the lowest thermal resistance at high driving currents (350 mA and 700 mA).

Thermal resistances of board to ambient (R_{thB-A}) from the cumulative structural function are also analysed and the values are summarized in Table 2. From the measured results, it is observed that the R_{thB-A} value decreases as the driving current increases. It obeys the approach of Debye-Model, where the rise in driving current increases the thermal conductivity as the inverse proportionality between thermal resistance and conductivity shifts the transient towards lower resistance [18]. From Table 2, the lowest thermal resistance of R_{thB-A} (36.03 K/W) is also observed with Sample 5.
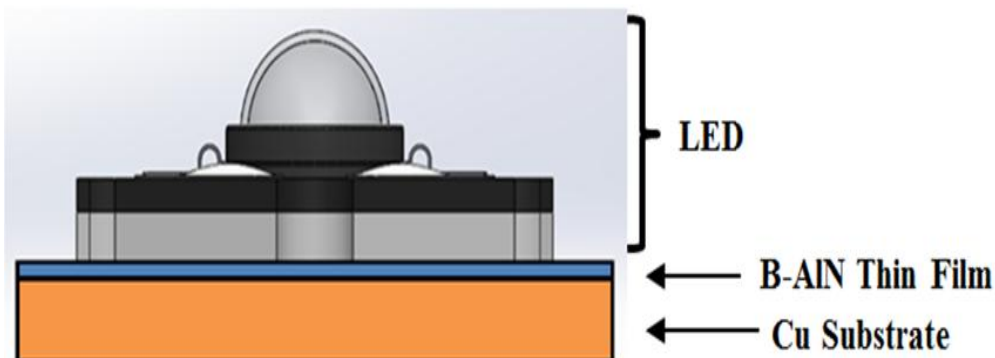

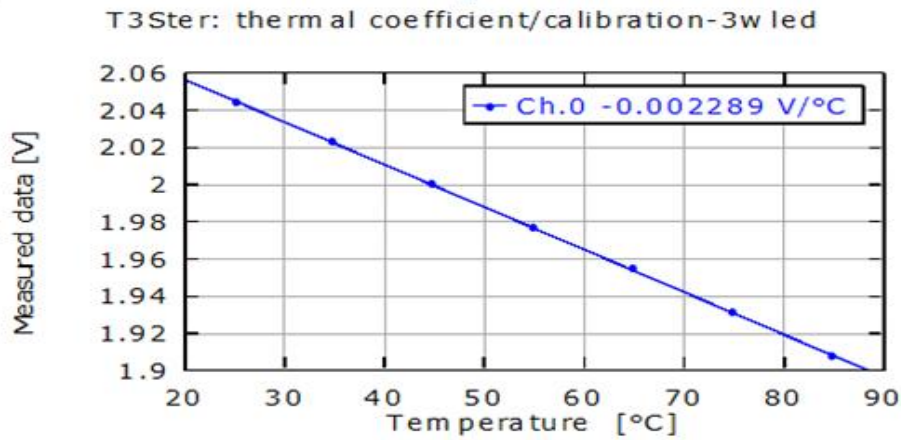**Fig. 1. Schematic diagram of LED mounted on B-AlN coated Cu Substrate**

Fig. 2. K factor calibration curve for given 3W green LED

Table 1. Deposition parameters

Sample name	Gas ratio (Ar:N$_2$)	Deposition temperature (°C)	Thickness (nm)
Sample 1	6 : 14	R.T.	201.1
Sample 2	7 : 13	R.T.	108.7
Sample 3	8 : 12	R.T.	303.1
Sample 4	7 : 13	100	126.8
Sample 5	7 : 13	200	99.8

Table 2. Thermal resistance of 3W green LED fixed on substrates prepared at various process conditions

Driving current (mA)	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Bare Cu
Junction to ambient thermal resistance, R_{th}(K/W)						
100	56.76	53.87	54.44	54.30	55.19	55.87
350	55.99	54.69	53.43	53.58	52.99	53.90
700	55.98	54.98	54.08	53.95	53.27	54.70
Board to ambient thermal resistance, R_{thB-A} (K/W)						
100	43.08	40.32	40.12	40.62	41.00	40.20
350	41.61	40.31	38.64	39.04	38.18	37.70
700	38.57	37.82	36.84	36.82	36.03	36.21

From the above results, the samples with lower thermal R_{th} were achieved by gas ratio of *Ar 7: N$_2$ 13*, at room temperature to higher substrate temperatures (200°C). It is observed that the B-AlN film coated using sputtering gas ratio of *Ar 7: N$_2$ 13* is more favorable in reducing the total thermal resistance of the given LED and hence supports for efficient heat dissipation. Films deposited at higher temperature may be useful to enhancing the thermal conductance of coated substrates due to the improved film quality [19]. Even though higher thickness was achieved for Sample 1 and 3 compared to samples prepared using gas ratio of *Ar 7: N$_2$ 13*, both samples reflects high R_{th}, and this may be due to film internal stress and strain developed under the influence of change in gas ratio during the synthesis that leads to poor adhesion on substrate [20], it is believed that by increasing the thickness of B-AlN film prepared on Cu substrate at higher temperature using gas ratio of *Ar 7: N$_2$ 13* may help to reduce thermal resistance further, as it was reported in previous work on the performance of ZnO coated substrates [21] which thicker film exhibited better thermal performance.

Fig. 4 shows the plot of measured R_{thB-A} for various boundary conditions with respect to driving currents. From Fig. 4, R_{thB-A} of LED for bare Cu decreases as the driving current increases. Moreover, the R_{th-B-A} for bare Cu

becomes lower than for Sample 1 to Sample 4 as input current increases. It may be due to the decrease of thermal conductance of B-AlN film on Sample 1 to Sample 4 as driving current increases. Moreover the lattice mismatch between thin film and substrate on Sample 1 to Sample 4 is possible which contribute in formation of thermal barrier that restricts heat flow from LED to substrate. In contrary, it clearly indicates that Sample 5 still has the lowest R_{thB-A} when compare with bare Cu substrate boundary condition at higher driving current.
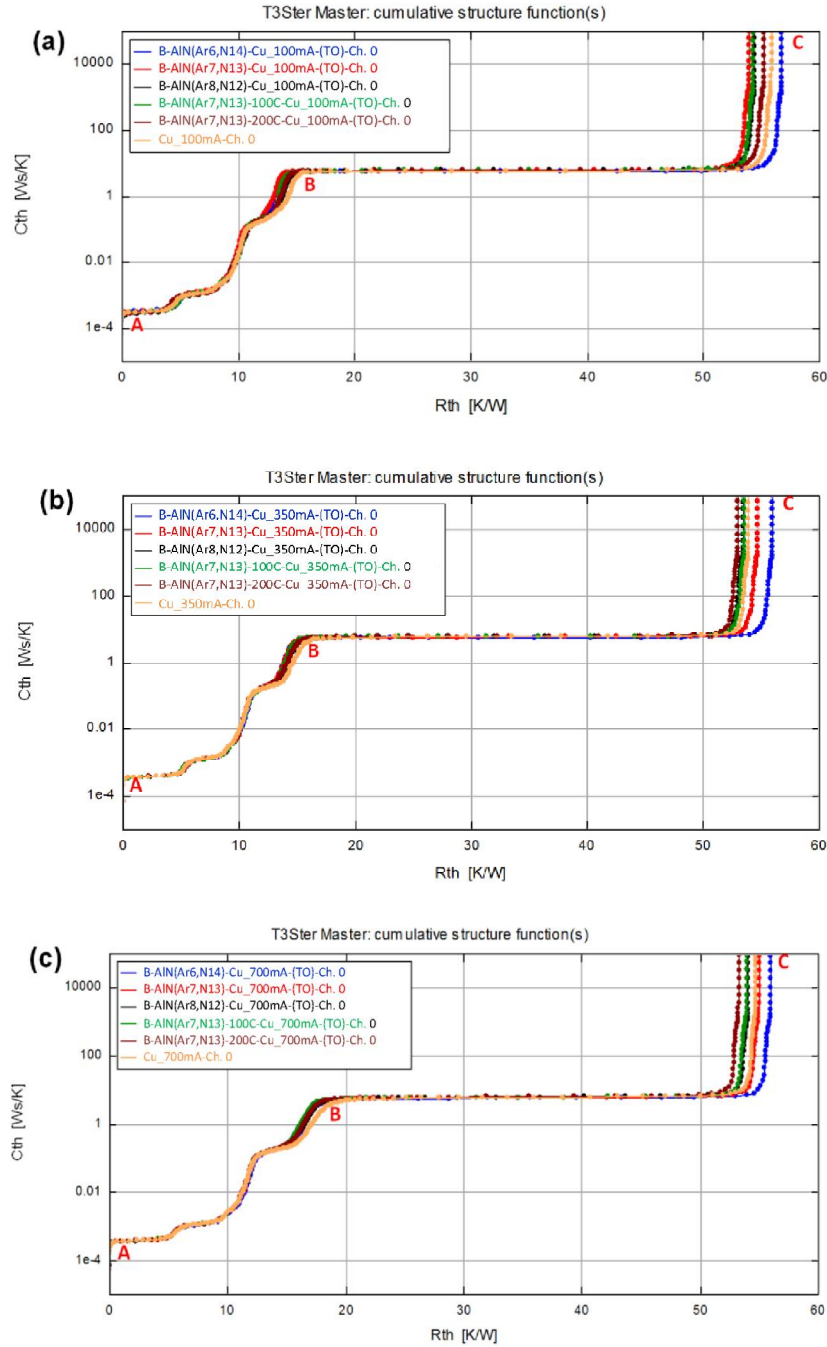

Fig. 3. Cumulative structural function of LED fixed on B-AlN coated Cu substrates measured at (a) 100 mA, (b) 350 mA, (c) 700 mA

Table 3 shows the rise in junction temperature of LED on thin film coated and bare substrates. Overall, Sample 5 performs well on reducing Tj of LED at higher driving currents. As observed from the measured results, Sample 1 exhibits highest Tj for all three driving currents, which agrees well with the result of thermal resistance. There is a difference in junction temperature (ΔTj) of 5.77°C between Sample 5 and Sample 1 when LED is driven at 700 mA. As the current increase from 350 mA to 700 mA, there is an increment on measured ΔT_j between Sample 1 and Sample 5. This may attribute to the effect of temperature on changing the thermal conductivity of thin films [22]. In addition, there is a noticeable difference in T_j variation pattern between100mA and higher driving currents (≥350 mA). This may due to the greater effect of molecular agitation of free electrons within the material at higher T_j when LED operates at higher driving current [23].

4.2 Surface Analysis

In order to analyze the contact resistance of B-AlN/Cu with MCPCB board (check which LED used), the surface morphology was recorded by using AFM with tapping mode at scan range of 10μm and analyzed the surface parameters. The captured surface morphology of B-AlN/Cu is

presented in 3D images as shown in Fig. 5. According to the surface roughness (R_a) of B-AlN thin films plotted in Fig. 6, the surface roughness of bare Cu substrate is 11nm. Sample 1 exhibits the highest value in surface roughness (14 nm) and this shows that the B-AlN coating with gas ratio of *Ar 6: N₂ 14* increase the surface roughness of Cu substrate, which leads to increase of the R_{th} and T_j of the given LED. This may due to disordered crystal structure at interface region contributed by stress and strain developed during synthesis, hence formed rougher surface and resulted in highest R_{th} at all current. According to Yovanovich et al. [24], contact conductance is high for the surface with low surface roughness. Even though the lowest surface roughness is achieved by Sample 2 (7 nm), it does not support in reducing both R_{th} and T_j of given LED at higher input current (350 mA and 700 mA), though its R_{th} is the lowest at 100 mA. It may attribute to the defects formed in thin film structure and hence reduced the thermal conductance for coated B-AlN on Cu. A relatively low value in roughness (8 nm) is also achieved with Sample 5. It shows that the coating prepared with gas ratio of *Ar 7: N₂ 13* at 200 °C reduces surface roughness of metal substrate and conducts more heat than the coatings prepared at other parameters.
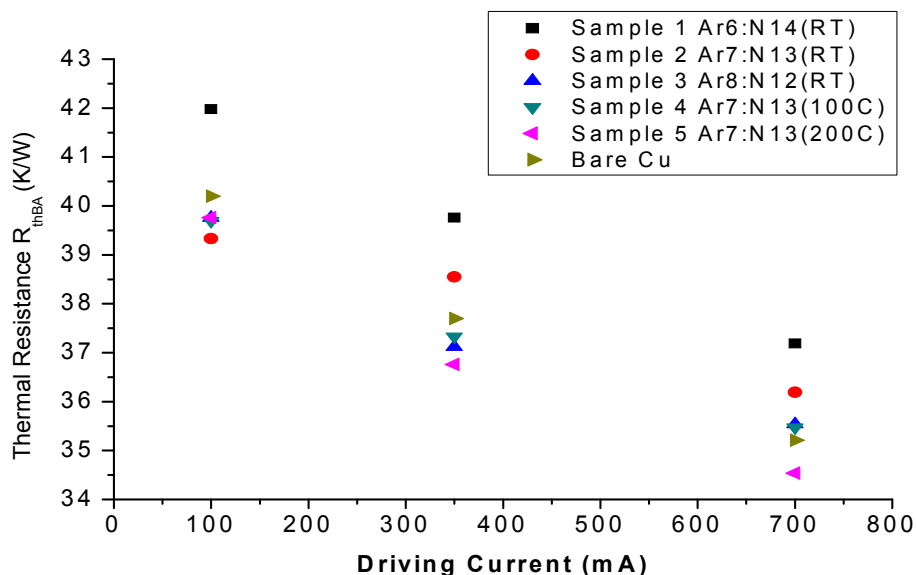

Fig. 4. Variation of R_thB-A of high power LED fixed on B-AlN thin film coated Cu substrates for different boundary condition at various driving currents
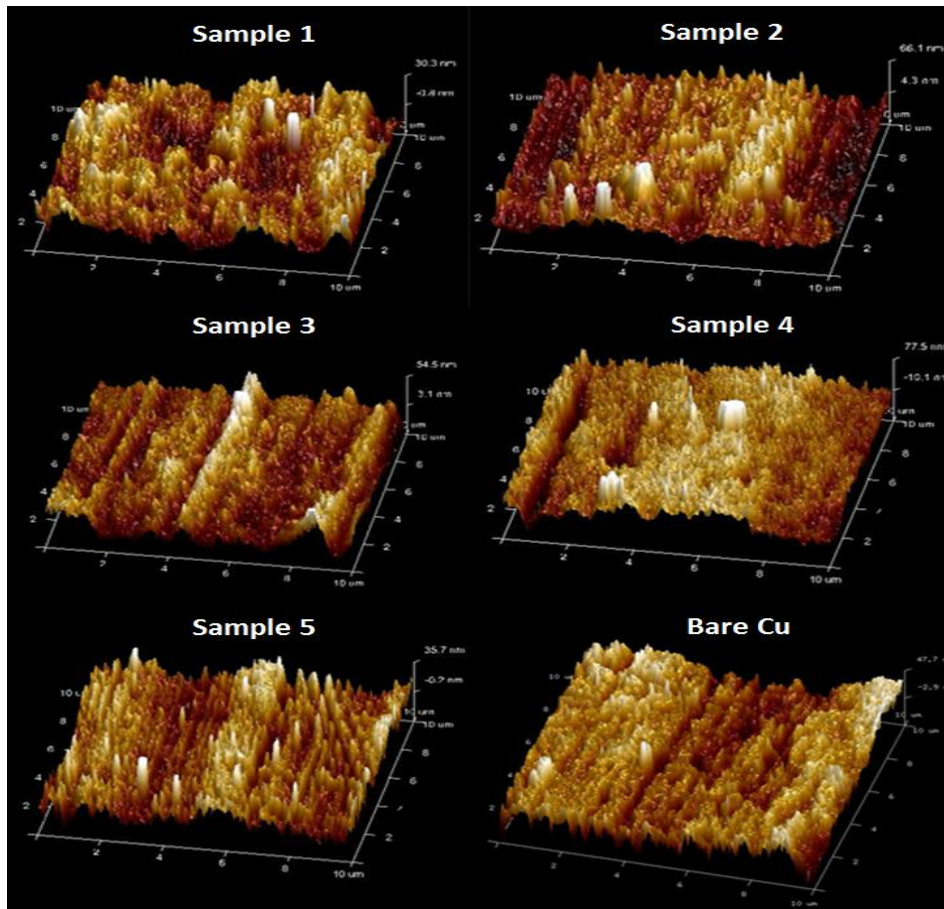
Fig. 5. AFM 3D images of surface morphology of B-AIN thin films prepared at various process parameters
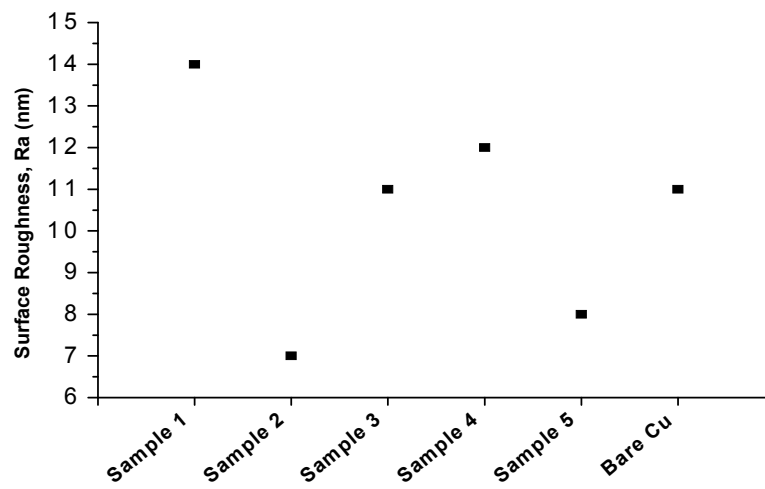

Fig. 6. Variation of surface roughness of B-AIN thin film prepared at various process parameters

The AFM images of all samples were processed for depth-valley analysis using AFM software and the observed results are shown in Fig. 7. The thermal conductance is related to the no. of points made contact with the surface of the material, if the no. of contact points is higher, these will result in increased contact resistance. From Fig. 7 it reveals that the range of valley depth on surface of Sample 5 is the lowest (30-80 nm) as compared with bare substrate (30-90 nm), this indicates that low no, of contact points is achieved on film surface of Sample 5. Sample 1-4 are exhibiting wider distribution range of valley depth than the bare substrate, these show large no. of contact points which result in increased contact resistance, hence leading to higher R_{th}. The overall result is evidenced for high thermal conductance with low surface roughness and range of valley depth [24].
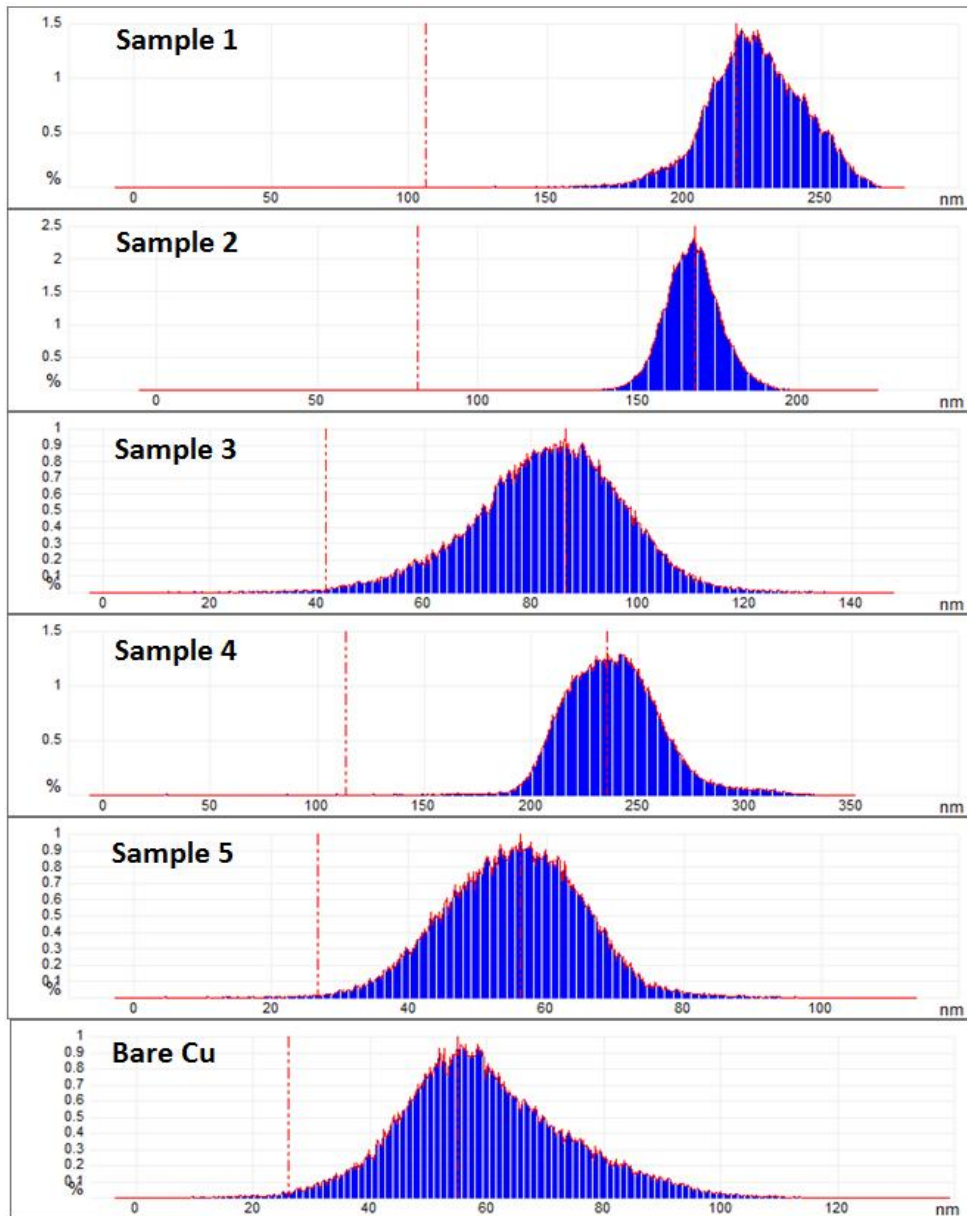

Fig. 7. Depth profile of surface of B-AlN coated Cu substrates

Table 3. Rise in junction temperature T_j of 3W green LED on coated substrates

Driving current (mA)	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Bare Cu
Junction temperature, T_j (°C)						
100	15.70	15.02	15.12	15.07	15.29	15.51
350	59.65	58.39	57.10	57.26	56.60	57.66
700	126.75	124.63	122.79	122.59	120.98	124.35

5. CONCLUSION

B-AlN thin film was prepared on Cu substrate by DC and RF coupled sputtering at different gas ratios and processed at various temperatures. B-AlN thin films were used as thermal interface material for high power LED. The R_{th} derived from the thermal transient curve was lower for B-AlN coated Cu substrates synthesized with gas ratio *Ar 7: N_2 13* at 200°C than for bare Cu substrate measured at 700 mA. Consequently, noticeable reduction in T_j of the given LED was also achieved by the same boundary condition. Surface analysis showed the influence of synthesis and processing parameters on the surface of B-AlN thin film which was affected the thermal performance of high power LED. Overall, it is suggested that the introduction of temperature (200°C) on preparation of B-AlN coating using gas ratio of *Ar 7: N_2 13* over Cu substrate as an effective thermal interface material for enhanced solid state lighting performance.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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