Aluminum nitride coatings optimize thermal performance of light-emitting diode arrays

By Shou-jin Zeng, Zhi-feng Liu, Ji-bin Jiang, Ming-der Jean, and Su Yang

Aluminum nitride coatings deposited via electrostatic spraying may help lower production cost and optimize thermal performance of LEDs.

A new technological revolution in heat management technology uses ceramic-coated substrates to achieve better heat dissipation and improve reliability of light-emitting diodes (LEDs).1-3 About 80% of the heat generated in LEDs must be rapidly removed to extend device lifetime.

For thermal performance, thermal management materials are most critical in the LED’s die material, heat sink slug, and solder, because these are closest to the heat source and have the greatest impact on heat dissipation from the p-n junction in the LED array.4-7 Junction temperature (T) is affected by many factors, including the cooling system, environment, and interface material. Therefore, cost-effective thermal management solutions are necessary.

To achieve such heat dissipation, various solutions have been proposed.8-11 Because of its high thermal conductance, effective insulation, high optical transparency, and thermal and chemical stability,12,13 aluminum nitride is one of the most widely used thermal interface materials in LED packages. Previous studies have reported improved LED performance using aluminum nitride- and boron nitride-coated substrates.4-7,14,15

A current barrier to cost-effective production of LED modules is the need for highly conductive materials with reasonable production costs. Many studies have reported the thermal properties of aluminum nitride coatings fabricated via plasma nitriding treatment. However, electrostatic spraying also allows coating of aluminum nitride ceramics on LED array substrates. Electrostatic spraying is an economical technique. However, few studies report using electrostatic-
sprayed aluminum nitride coatings as a thermal interface material.

Therefore, we optimally deposited aluminum nitride films on copper substrates using electrostatic spraying. We determined the thermal performance of a 1.2-W LED fixed on an aluminum nitride thin-film-coated copper substrate. We also compared the thermal performance of aluminum nitride-coated and commercial heat sinks connected in series with a 7-W LED on an aluminum nitride-coated copper substrate.

**Surface morphology and microstructure of aluminum nitride coatings**

We deposited aluminum nitride coatings on copper substrates (55 mm in diameter and 5 mm thick) using an electrostatic spraying system (Model DISK-1600-D, R.I. Chen Machinery Co., Taichug City, Taiwan) and analyzed coating surface morphology using field emission scanning electron microscopy. We used energy-dispersive X-ray spectroscopy to measure the chemical composition of the sprayed aluminum nitride powders, which had a composition of 27.7 wt%/49.22 at.% nitrogen, 52.31 wt%/48.25 at.% aluminum, and 19.98 wt%/2.53 at.% gold. Table 1 shows the applied baking temperatures, substrate thicknesses, and powder flow rates. Additional parameters remained constant.

High surface roughness, microscopic hills, voids, valleys, and poor surface flatness in solid–air interfaces significantly affect heat flux of the thermal interface material and produce the greatest barrier for heat conductance. The electrosprayed coatings consisted of aluminum and aluminum nitride, which are not evenly distributed in the nitride layer and are incompletely nitrided. Figure 1 shows surface morphologies of samples 1 and 2. Sample 1 had an average volume of voids of 0.47% on its surface, whereas sample 2 had an average volume of 0.68%. This indicates that considerable defects grew in the coating layer’s crystal structure, which decreases thermal conductance.

We determined the composition of deposited thin films using Al2p, N1s, and O1s peaks from X-ray spectroscopy spectra of the aluminum nitride coatings. Sample 1 had Al2p and N1s peaks indicating an atomic composition of 52.3% and 47.7%, respectively. Sample 2 had Al2p and N1s peaks indicating an atomic composition of 56.4% and 43.6%, respectively.

**Thermal properties of aluminum nitride coatings**

Efficiency of heat dissipation in LEDs is measured in terms of thermal resistance, which determines the Tj value for LEDs under various operating conditions. Resistance also represents the temperature difference between the junction and surface of the chip.

To test thermal performance, we used the electrosprayed aluminum nitride coating as a heat sink for a 1.2-W LED package connected in a parallel circuit.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Control factor 1</th>
<th>Control factor 2</th>
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</thead>
<tbody>
<tr>
<td>Substrate</td>
<td>Cu</td>
<td>Cu</td>
</tr>
<tr>
<td>Baking temperature (°C)</td>
<td>180</td>
<td>100</td>
</tr>
<tr>
<td>Substrate thickness (mm)</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>Spray time (s)</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Speed (mm/s)</td>
<td>55</td>
<td>55</td>
</tr>
<tr>
<td>Powder flow rate (cm³/s)</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Ratio (resin:aluminum nitride)</td>
<td>1:3</td>
<td>1:3</td>
</tr>
<tr>
<td>Bake time (min)</td>
<td>30</td>
<td>30</td>
</tr>
</tbody>
</table>

**Capsule summary**

**BACKGROUND**
A current barrier to cost-effective production of LED modules is the need for highly conductive materials with reasonable production costs.

**APPROACH**
Electrostatic spraying is a lower-cost production technique that can be used to deposit aluminum nitride coatings on copper substrates, which may enhance the thermal performance of LEDs.

**OUTCOME**
Aluminum nitride coatings can enhance thermal performance of LED packages if the ceramics have appropriate surface roughness. Overall, such coatings can reduce junction temperatures and improve heat resistance and dissipation.
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Figure 2. Junction temperature (blue) and luminous flux (red) curves for nine LEDs tested at 700 mA.

board. During thermal testing, we drove the LED at 700 mA when it reached a steady state. Figure 2 shows the distribution of $T_j$ values (40°C–50°C), measured using an infrared camera (Model IRI-4010, Integrated Infrared Systems Inc., Towcester, U.K.), and luminous flux curves (50–42 lm), measured using an integrating sphere with a drive current of 700 mA, for tests with nine LED arrays.

Overall, aluminum nitride-coated substrates significantly reduced $T_j$ values for LED packages at 700 mA. However, it is important to consider luminous flux caused by the heat source, because luminous flux opposes $T_j$. Contact resistance for aluminum nitride-coated substrates decreases as $T_j$ value decreases, which leads to increased luminous flux for LED modules.

Comparison of thermal performance of aluminum nitride-coated and commercial heat sinks

We also compared the thermal performance of aluminum nitride-coated copper substrates and a commercial alternative (Model E27 Series E4 LED) as heat sinks for 7-W LED arrays consisting of seven 1-W modules (Figure 3(a)). During the thermal test, we again drove the LED at 700 mA when it reached a steady state.

We measured $T_j$ values at 60 min into the thermal test. Aluminum nitride-coated substrates had significantly reduced $T_j$.

Figure 3. (a) An experimental 7-W LED module consisting of seven 1-W LEDs. (b-c) 3-D contoured surface curves of $T_j$ values for (b) aluminum nitride-coated substrate and (c) commercial heat sinks. (d) Luminous flux of aluminum nitride-coated substrate and commercial heat sinks at various drive currents.
values, which indicate the distribution of heat dissipation. Values ranged 38°C–68°C for aluminum nitride and 40°C–90°C for the commercial heat sink. Aluminum nitride-coated copper substrates had an average $T_j$ of 66°C (Figure 3(b)), compared with a value of 82°C for the commercial heat sink (Figure 3(c)). This may be caused by high thermal conductance of the aluminum nitride crystal structure and wide heat scattering. We attributed increased $T_j$ values to heat flux clustering around the heat sink. Therefore, heat generated at the LED junction is not removed. This increases total thermal resistance of the LED array and does not allow efficient heat dissipation.

We measured slightly lower luminous flux for the aluminum nitride-coated LED array than for the commercial heat sink below 1,000 ma (Figure 3(d)). This may be caused by the application of a barium sulfate coating on the commercial substrate. Barium sulfate is a radiopaque substance, which increases light. However, the aluminum nitride-coated LED displayed higher luminous flux at 2,000 mA, measuring 1,499 lm with a peak strength of 15,021 au at 2,000 mA. By comparison, the commercial heat sink exhibited luminous flux of 1,250 lm with a peak strength of 1,126 au at 2,000 mA.

### LED thermal performance improved

Aluminum nitride coatings can enhance the thermal performance of LED packages if the ceramics have appropriate surface roughness. Overall, such coatings can reduce junction temperatures and improve heat resistance and dissipation. These results show that aluminum nitride ceramics applied via electrostatic spraying can produce an effective thermal interface material for LEDs. In addition, copper substrates with such aluminum nitride coatings can improve the thermal performance of LED modules.

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### References


