Cooling High-Power LED Packages with Thin-Film Thermoelectric Technology

By Edward Siivola, Advanced Development Engineer and Seri Lee, Chief Technology Officer, Nextreme Thermal Solutions, Inc.

The junction temperature of high-power LEDs can directly affect the performance and longevity of some LED devices. As the junction temperature rises, a significant loss of output (luminosity) can be expected. The forward voltage of an LED is also dependent on the junction temperature. As the temperature rises, the forward voltage decreases, which can cause excessive current drain on other LEDs in the array. This in-turn leads to thermal runaway conditions and ultimately to the failure of the device. High temperatures can also affect the wavelength of an LED fabricated using gallium arsenide, gallium nitride or silicon carbide.

Bulk thermoelectric (TEC) devices have been used to provide temperature control of LEDs. However, today a major trend in photonics has been the move to smaller form factor, higher power and more integrated, and cheaper packaging in order to enable a lower cost structure and concurrently opening the door for higher volume manufacturing. In the course of this transition, conventional TEC solutions have not kept pace with these needs due to their size and power density limitations.

Thin-film embedded thermoelectric coolers (eTECs) are smaller and thinner than conventional products and show promise for direct integration using industry standard manufacturing methods. In addition, thin-film eTECs have demonstrated a heat-flux pumping capacity that far exceeds that provided by traditional bulk TECs. This makes eTECs well suited for high heat density applications. The use of thin films allows for novel implementations of thermoelectric devices, particularly for cooling of high-power LEDs.

Thin-Film Thermoelectric Coolers

An enabling technology for thin-film thermoelectric coolers is the Thermal Copper Pillar Bump, which is also referred to as the “thermal bump.” The thermal bump is a thermoelectric structure made from a thin-film thermally active material embedded into flip-chip interconnects (in particular copper pillar solder bumps) for use in electronics packaging. The thermal bump shown in Figure 1 was developed by Nextreme as a method for integrating active thermal management functionality at the chip level in the same manner that transistors, resistors and capacitors are integrated into conventional circuit designs today. Unlike conventional solder bumps that provide an electrical path and a mechanical connection to the package, thermal bumps act as solid-state heat pumps and add thermal management functionality locally on the surface of a chip or to another electrical component. Thermal bumps are extremely small: 238 µm (microns) in diameter by 60 µm high. The size of the thermal bump enables the integration of thermal management capabilities at the wafer, die or package levels.

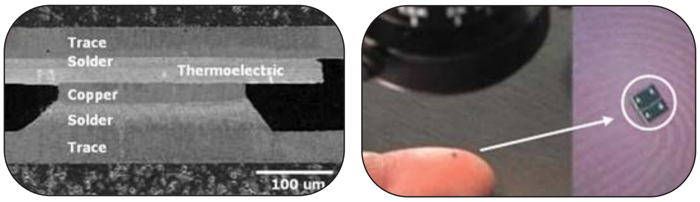

Figure 1. Cross-section SEM image of a thermal bump (left), and a module with four thermal bumps (right).

Thermal bumps make use of the thermoelectric effect, which is the direct conversion of a temperature difference to an electrical voltage and vice versa. Simply put, a thermoelectric device will create a current when there is a different temperature on either side of the device, or alternatively, when a voltage is applied to it, a temperature difference will be created. This effect can be used to generate electricity, to measure temperatures, to cool objects or to heat them.

Thermoelectric cooling of LEDs is available today through the use of discrete modules. Some modules are well suited for the cooling and temperature control of LEDs and enable the integration of thermal management capabilities directly into a package. For example, the OptoCooler UPF40 module shown below can pump a heat density of up to 72 W/cm^2 at 25°C, and as a result, it can move a maximum of 3.7 W of heat with an active footprint of 5.1 mm^2.

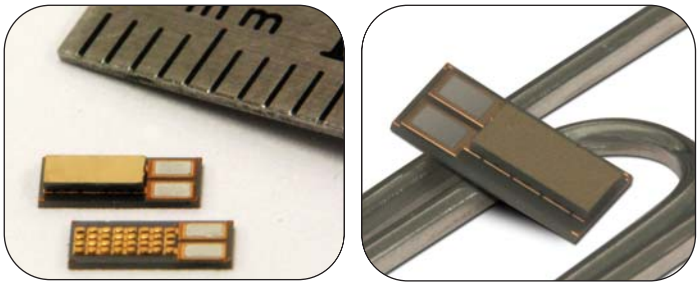

Figure 2. The OptoCooler UPF40 module shown with and without the top header.

Embedding eTECs into LED Packages

By taking advantage of the smaller; thinner eTECs form-factor a new approach is enabled for LED thermal management that focuses on providing appropriate cooling when and where it is needed within the opto-electronic system. This solution involves the integration of eTEC modules inside the packaging and as close to the heat-generating device as possible.

In the case presented here, two UPF40 modules were embedded into the package of a typical 3 W white LED (Seoul Semiconductor from the “Z-Power P4 series” product line) between the copper slug and the aluminum case. The LEDs were modified from their original form to accommodate thermocouple sensing. The lens was sectioned in half and removed to expose the die and top surface of the copper slug, as shown in both Figures 3 and 4. Care was taken to not disturb the portion of the lens containing the wire bonds so as to not alter the joule heating characteristics from the unmodified form.

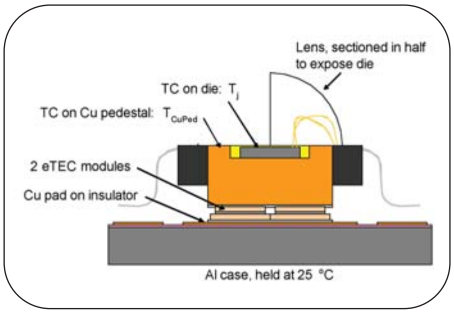

Figure 3. Schematic of the cross-section of the simple TEC integration.

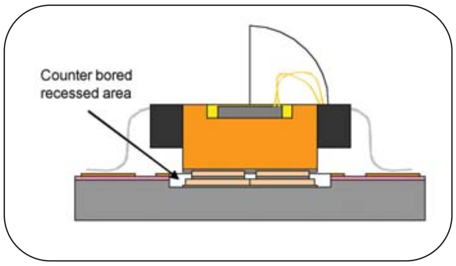

Figure 4. Schematic of the cross-section of the improved thermal TEC integration.

The lens modification was repeated and used in three overall package designs: the standard package, which was as received, and does not contain any TE device, the simple package, in which two UPF40 TE devices were inserted between the copper slug and the Al case with no addition changes, and the improved package where the Al case was modified to accommodate the volume of two UPF40 devices. Schematics of the latter two designs are shown in detail in Figures 3 and 4. Pictures of the actual devices are shown in Figures 5 and 6.

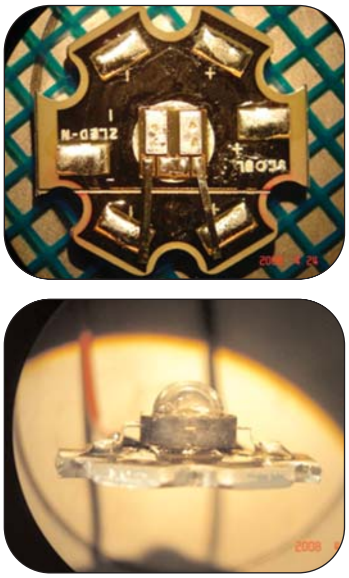

Figure 5. The Simple Design: in plane-view (top) showing the placement of two UPF40s on the case, and side-view (below) showing the pedestal attachment to the TE devices.

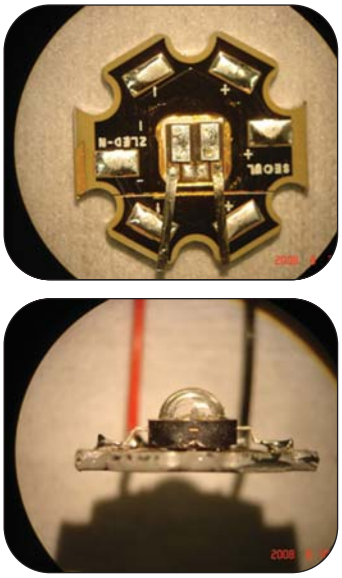

Figure 6. The Improved Design: in plane-view (top) showing the placement of two UPF40s in the case recess, and side-view (below) showing the pedestal attachment to the nearly hidden TE devices.

This simple package includes all of the same passive thermal resistances between the junction and case as the standard package but with the addition of the TE devices and one more interface. The improved package is referred to as such because of the addition of a recess in the Al case. This recess allows for two improvements. The first is that the pedestal is located at the same elevation as in the standard package so that the over-all dimensionality and appearance are unchanged. The second, and most important, is that the recess has removed the insulating layer from the thermal path allowing for a lower thermal resistance between the TE devices and the case. Discrete modules like the UPF40 are electrically insulating between the top and bottom surfaces which enables the removal of the case insulator without changing the electrical requirements of the overall package. In effect, this improved design replaces a thermally passive electrical insulation layer with a thermally active electrically insulating layer. The lower qHS for the improved package leads to an increased dT.

The three package designs, with the modified lens, were placed in a vacuum chamber with the Al star case attached to a heat-sink using thermal grease. During the course of the testing, the case was maintained at 25°C. Thermocouples were placed, similar to Figure 3, on both the top surface of the die and the copper slug adjacent to the die. In the case of the standard package, the LED current was swept from zero to 1 amp and the temperatures of the die and copper slug were recorded. In the simple and improved packages where TE devices were integrated, the current to the TE devices was set at the point that showed the lowest die temperature and then the LED current was swept up to 1 amp. The TE device current showing the maximum cooling effect is called Imax. A plot summarizing the results for the three packages is shown in Figure 7. The junction temperature curves for the simple and improved packages are shown for the respective Imax of each assembly. The standard package is also included for comparison.

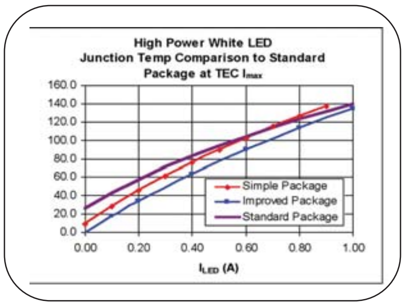

Figure 7. Plot of the junction temperature of the three package design with LED current.

If the standard, uncooled, package is considered as the baseline design, the cooling effect on the junction temperature by the TE devices can be shown by considering the temperature difference between the uncooled and TE cooled packages at the same LED current. Figure 8 plots this temperature difference, dT, as a function of LED current.

Note that both TE device packages show lower junction temperatures for lower LED currents. As the LED current increases, the load power on the TE devices increases and the cooling effect diminishes. The improved package shows a larger cooling effect over the entire LED current range when compared to the simple package. This demonstrates the realization of a reduced thermal resistance on the heat-rejection side of the TE devices. The removal of the case electrical insulation allows for an additional 12K of cooling when compared to the simple design. The reduction of qHS enables the improved design to show a lower junction temperature than the standard package. This dT improvement ranges from 25 K at small currents to 5 K at 1 amp. The data suggests that the LED can be over-driven to currents above 1 amp without any increase in junction temperature relative to the standard package.

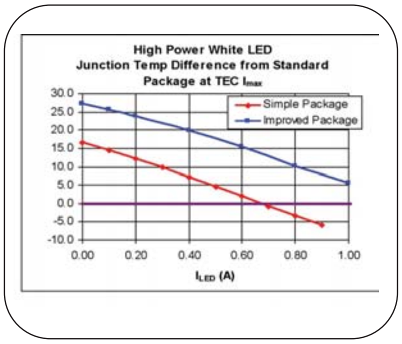

Figure 8. Plot of the cooling effect of the TE device packages relative to the standard package.

Two thin-film eTEC modules were embedded into an LED package using two designs; one where the eTEC device was simply inserted into the original interface between the slug and case, and a second design were the case was recessed allowing space for the module and removing the thermally insulating layer. A larger dT was achieved with the improved design and this was consistent with expectations based on an analysis of the series thermal resistances. The dT for the improved design ranged from 5K to 25K depending on the LED current. The observed cooling was significant enough to potentially allow for over-driving the LED to currents beyond specification, while maintaining a safe junction temperature.

Edward Siivola is an advanced development engineer for Nextreme Thermal Solutions. Before joining Nextreme, Ed was a research engineer and manager of the advanced processing and testing group at the Center for Thermoelectric Research at RTI International. He has published more than 14 technical papers and holds two patents. Ed has extensive experience in the development of advanced thermoelectric processing and device design. He can be reached at info@nextreme.com.

Dr. Seri Lee currently serves as the CTO at Nextreme, where he is responsible for directing thermal and power generation technology advancement projects. Dr. Lee is an active member of the ASME Heat Transfer Division K-16 Committee on Heat Transfer in Electronic Equipment and the IEEE/SemiTherm Executive Committee. He can be reached at info@nextreme.com.