Designing and Manufacturing Microelectronic Packages For High-Power Light-Emitting Diodes

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Abstract

A new microelectronic package was designed for a high-power light-emitting diode (LED). The objective was to build a package that enables the LED to operate with currents as high as 2 Amps. An innovative thin-film interface has been developed to electrically connect the cathode of the LED die to a 22AWG Cu wire. This thin-film interface is wirebondable and solderable, and consists of three layers: Au, Ni93/V7, and Si. Four 1 mil Au wirebonds, supporting 2A of maximum current, connect the Au thin-film to the LED die cathode. Sn96Ag4 solder is used for connecting the Ni93/V7 thin-film to the 22AWG Cu wire. To provide an electrical, mechanical and thermal platform for the anode of the LED die, a sub-assembly was developed. This sub-assembly utilizes a Cu substrate on which the anode of the LED die is attached with Au80Sn20 solder. The LED die, thin-film interface and Cu substrate integrate into the sub-assembly, which then solders onto a Cu heatsink. Electrical current flows into the heatsink, through the LED, across the thin-film interface, then out the Cu wire. All-metal interfaces from the LED anode to the heatsink provide a thermally conductive path. However, testing results show that the LED fails with currents of 815 mAmps or less. It appears that the failure was caused by thermal management within the die and is not due to the design of the package.

Keywords: High-Power Light-Emitting Diode, Thin-Film, Microelectronics Packaging, Metallization

1. Introduction

Increasing the current through a light-emitting diode (LED) increases brightness, but comes at the cost of producing more heat within the LED [1]. The heat must be efficiently dissipated to prevent the LED from overheating and failing. The objective of this project was to design a package that would efficiently dissipate the heat from a LED and thereby allow more current to be injected to yield a higher brightness.

Existing high-power LED packages use various designs to cool the LED die. Two primary classifications for cooling devices are active cooling packages and passive cooling packages. While active systems use additional electrical power to operate devices that draw heat away from the LED, passive systems do not use any additional electrical power.

Active systems are favored when an LED must operate at the highest brightness possible, regardless of the amount of electrical power needed to drive the cooling system. One type of active cooling design transfers heat away from the source by circulating coolant. The heat generated by the LED transfers to a stream of coolant, which then flows away from the LED and towards a heatsink. In an experiment to show the benefits of active cooling, LEDs were cooled with a microchannel array [2], which flows coolant through small tubes below the LED (Fig 1). Fabricated in silicon, the tube arrays cause the coolant to increase in pressure and velocity, then quickly dissipates the LED heat.

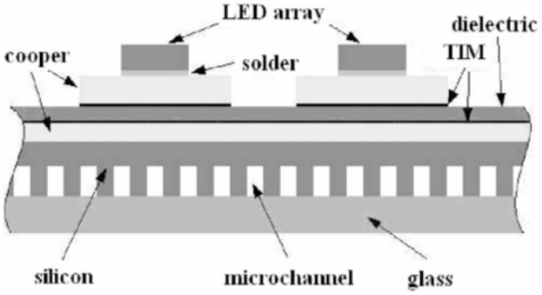


Figure 1: Microchannel cooling system [2]

A thermo-electric cooler (TEC) uses many alternating layers of n-type and p-type semiconductors to transfer heat. As current runs through the TEC, heat transfers from the LED die to the other side of the TEC. Researchers [3] have used TECs to effectively reduce the thermal resistance of

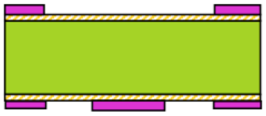
LEDs at high currents. There are no moving parts and no fluids to leak out.

Although various passive cooling methods exist, most ultimately transfer the LED heat to a heatsink. Heatsinks are usually made from a single bulk of metal and most have finned surfaces to allow air to flow in-between these fins, thus dissipating the heat. In fabricating LED packaging to combine with a heatsink, the LED is often connected in a sub-assembly, which then attaches to the sink.

One method of packaging LED dies in a passive cooling system is to mount them in cavities etched in Si wafers [4]. Metal interconnects are formed on the cavity bottom, then the LED is mounted inside the cavity (Fig 2). The base of the cavity transfers heat away from the LED. Fabrication becomes complex because holes are etched in the silicon cavities, then filled with solder to form the electrical interconnections. While this design is innovative, some steps present fabrication challenges. Thermal stress becomes an issue when reflective layers are used on the side walls. Adding metal layers to the side walls may increase the reflectivity of the surface, but this film can also produce harmful stresses on the Si. Other issues include anisotropic etching challenges and the need for backside-alignment lithography.

(a)Thermal oxidation

(b)Photolithography



(c) BOE etching

(d) KOH etching

(e) Solder balls implanted

(f) Solder balls reflow

Figure 2: Si wafer with etched cavity and solder connections [4]

Another passive cooling system design uses ceramics as a substrate instead of Si. Many ceramics do not provide high thermal conductivity; however, thermal vias can be used as conductive heat paths directly underneath the LED (Fig 3). Similar to the Si packages, a metal heatsink attaches to the backside of the substrate. While various arrangements have been attempted, studies show that a single large via dissipates heat better than many small vias [5]. The ceramic may serve as an insulator in other parts of the package, but the amount of ceramic material near the heat path should be minimized.

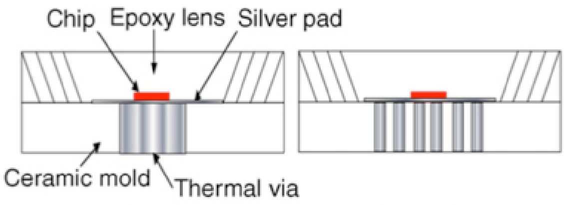


Figure 3: Metal thermal vias in ceramic substrate [5] Single large via on left, multiple small vias on right

2. Package Design and Process Development

2.1 LED Die Structure

The LED to be packaged is an XB900 LED die (Fig 4), made by Cree Incorporated [6]. The PN-junction of the LED die is comprised of InGaN and emits blue light at a wavelength of 470nm. Cree fabricates the InGaN PN-junction on a thermally conductive SiC substrate. When the LED die is integrated into its packaging, the SiC is positioned above the PN-junction on the cathode side. SiC is transparent at 470nm and allows the blue light to emit out the top of the LED. Directly above the SiC is a layer of Au that provides an electrical contact point for the cathode. The Au circle in the center is intended to be a wirebonding surface, while the arms extending from the center distribute current across the substrate.

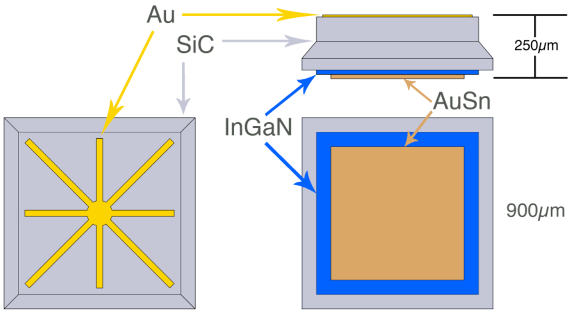


Figure 4: Three views of Cree XB900 LED die

Directly below the PN-junction is a smooth Al layer that reflects downward traveling light upward through the SiC (Fig 5). Below the metal reflector is an encapsulation layer that separates the reflector from a Au80Sn20 (wt%) metallization. This metallization is the anode for the LED.

A Cu heatsink was used as a passive cooling device. The anode of the LED was connected to the heatsink and the cathode was interfaced with a 22AWG copper wire. This wire was connected from

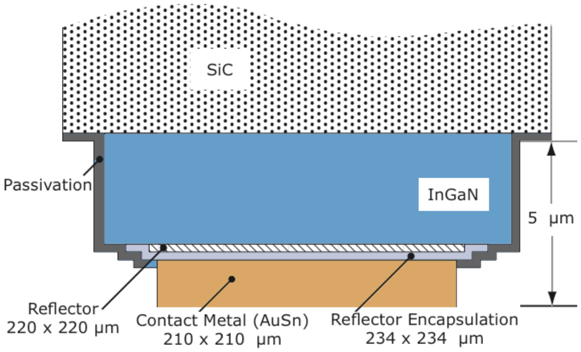


Figure 5: Cross-section of Cree XB900 LED die [6]

the LED cathode to a ground terminal. The heatsink was connected to a power supply through a current-limiting resistor. In addition to creating a good thermal bond between the LED die (anode) and the heatsink, the package requires a highly conductive electrical connection between the Au cathode and Cu wire. Therefore, the package design includes two interfaces: one interface connects the bottom of the LED to the Cu heatsink, and the other interface connects the top of the LED to the 22AWG Cu wire (Fig 6).

2.2 *Thin-Film Processes*

Figure 7 presents an innovative conductive thin film interface, which is wirebondable and solderable. This thin-film interface allows an electrical connection between the LED die cathode and the 22AWg Cu wire. Another important feature is the use of a sub-assembly to facilitate wirebonding. The LED die, thin-film interface and Cu substrate are combined into a low-profile assembly that can be easily fit in a wirebond machine. The sub-assembly is then soldered on top of a Cu heatsink to provide a highly conductive thermal dissipation path (Fig 8).

The metallization of the thin film interface consists of an Au layer over Ni93/V7 on top of a Si substrate. Ni acts as an adhesion layer between Si wafers and Au layer since Au does not adhere well to Si. However, pure Ni could not be sputtered since it is a ferromagnetic material. Pure Ni will react with the sputtering gun's magnetic field, which results in a damaged sputtering gun. The Delco process [7], was utilized to sputter deposit the Ni93/V7; adding vanadium to nickel drops the Currie temperature. An alloy of 7wt.% V and 93% Ni has a Currie temperature below room temperature. This paramagnetic alloy is easy to sputter deposit. Fortunately, the Ni93/V7 films did not delaminate from the Si wafers at any point in the manufacturing process.

An Au layer was then sputter deposited on top of the Ni93/V7. A profilometer was employed to measure the thickness of the films, obtaining 821nm of Ni93/V7 and 215nm of Au. The Au layer not only protects Ni93/V7 from oxidation, but also works as a wirebondable and solderable metallization. A thick Au layer is needed for wire bonding, but not good for soldering. In this design, 215nm of Au proved to be wirebondable and solderable.

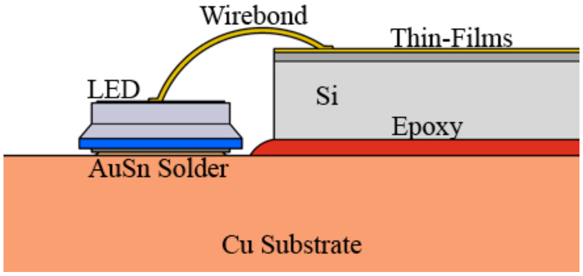


Figure 6: Two Interfaces of LED

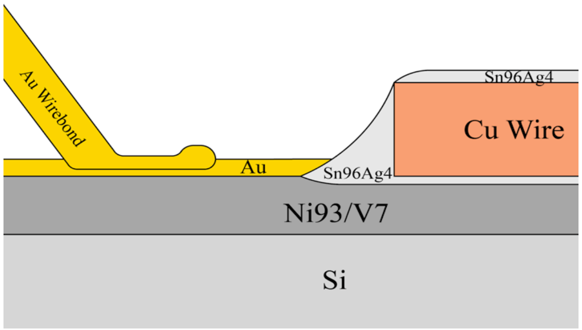


Figure 7: Cross-section of wirebond and solder joint

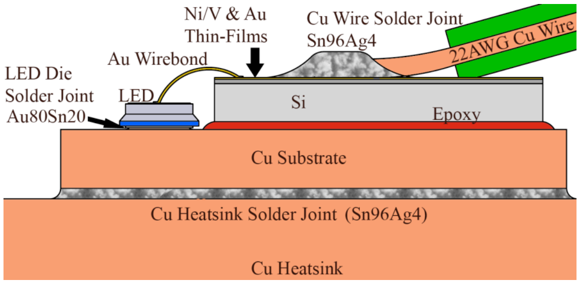


Figure 8: Sub-Assembly Soldered on Cu heatsink

2.3 *Package Assembly Process Development*

There are three solder joints in the package assembly:

1) LED die solder joint (Connected the Cu substrate with Au80Sn20)
2) Cu heatsink solder joint (Connected the Cu substrate with Sn96Ag4)
3) Cu wire solder joint (Connected the thin-films and the Cu wire with Sn96Ag4)

A 32mil thick Cu substrate was used for attaching both the LED die and Si thin film interface. After soldering the LED die and epoxying the Si thin-film interface to the Cu substrate, wirebonding was employed to connect the LED cathode to the Si thin film interface. This resulted in a sub-assembly ready for soldering to an external heatsink. Using Cu for the sub-assembly substrate allows for coefficient of thermal expansion (CTE) matching to the Cu heatsink.

The LED die contains an Au80/Sn20 bottom-side metallization, which melts at 282˚C. This is used to produce the first solder joint to the Cu substrate. Soldering the LED die to the Cu substrate requires flux to clean the Cu-oxide. AIM Solder's WS-715M flux, is a neutral alcohol based, organically activated, rosin-free water soluble liquid flux.

In addition to providing mechanical bonding, epoxy was used to electrically insulate the thin-films from the Cu substrate. The epoxy's thermal conductivity was not of importance since the Si was not a critical component in the thermal path. Si by itself would not adequately insulate the thin-films from the Cu substrate. The silicon's inability to provide insulation would cause current leakage and may result in a short across the LED. This problem is solved by adding a layer of epoxy between the Si and Cu substrate, providing electrical insulation.

The epoxy employed was Dimethacrylate Ester (Loctite part# 27131) which supports higher temperatures, partially cures after several minutes, and fully cures overnight. Even when the Loctite fully cures, it remained soft and flexible, yet sticky. Cu has a CTE of $16.8\text{x}10^{-6}$/˚K [8], while silicon has a CTE of $2.5\text{x}10^{-6}$/˚K [8], so having a flexible adhesive is desirable. After curing, the parts were ready for wirebonding.

2.4 Wirebonding LED Die to Cu Substrate

An F/K Delvotek wedge-wedge thermosonic wirebonder was used with 1mil Au to make bonds between the LED die cathode and the Si thin-film interface. To test the current limitations of the wirebonds, needle-probes were connected to a power supply and the current required to fuse the bonds was measured. Bond wires typically fused at 1000mA. For safety, each bond wire in the package was designed to experience no more than 50% of the fusing current: 500mA. Therefore, running 2 amps of current through the LED would require four 500mA rated wirebonds.

2.5 Cu Substrate to Heatsink Solder Joint

Connecting the sub-assembly to a heatsink allows heat to travel down through a solder joint and into a large mass of Cu. For soldering the sub-assembly to the heatsink, a lead-free solder alloy of 96% Sn and 4% Ag solder wire is used with a rosin-core flux. The lead-free solder has a melting temperature of 221˚C, which is lower than the AuSn (282˚C) alloy used to attach the LED die to the Cu substrate. The Sn96Ag4 solder alloy connects the sub-assembly to a Cu heatsink containing a 2cm diameter, 2cm tall cylinder of Cu embedded in a finned block of aluminum.

2.6 Cu Wire Solder Joint

Using a fine-tipped soldering iron, a 3in long 22AWG Cu wire was soldered to the Ni/V and Au films on the Si square, creating the Cu wire solder joint. When the iron is removed, heat at the joint transfers to the rest of the assembly and cools to a solid. The length of the 22AWG wire was chosen for being a reasonable length for attaching alligator clips to, yet keeping a few inches away from the package. For both joints, the Sn96Ag4 solder contained rosin flux, which was cleaned off after soldering using IPA, then DI H20.

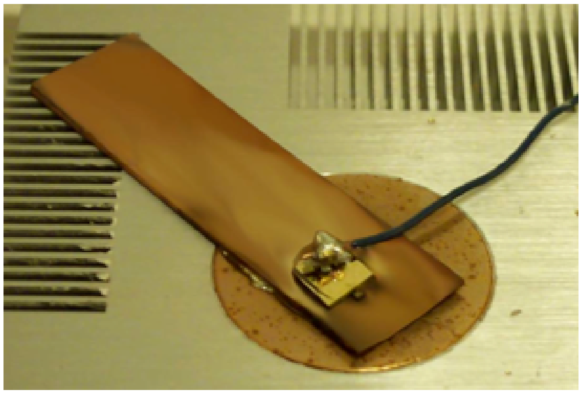


Figure 9: Completed Package Design

3. Testing Results

3.1 Electrical Results of Epoxy Layer

If the Si and epoxy layers do not insulate the thin-films from the Cu substrate, then the LED die will not turn on due to a short across the Si and epoxy. To check the resistance of the Si and epoxy layer, one needle probe contacted the Au film and another needle probe contacted the Cu substrate. When applying voltages across the probes, only a small amount of current passes though. This test was conducted before any wirebonds connections were made between the thin film interface and the cathode of the LED die. The test results show that a leakage of 240μA is found when applying 10V. This small amount of current (0.05%) passing through the Si and epoxy is unlikely to short the LED.

3.2 Electrical Results of Wirebonding

Some packages received 4 wirebonds, yet even in packages with fewer wirebonds, the LED burned out before the wirebonds fused. None of the LEDs exceeded 815mA of diode current, so no more than 2 wirebonds are necessary.

The multiple-wirebond connections are capable of supporting more current than was utilized by the LED. These connections may be over-built, but they work very well in the LED packages.

3.3 Electrical Input and Light Output of LED

The Cree XB900 LED die data sheet lists 400mA as the maximum recommended DC forward applied current. This value holds for dies without encapsulants and assumes a 25˚C ambient temperature. With typical diode voltages of 3.4V, the maximum DC input power becomes 1W. The goal for this package design was to obtain a diode current of 500mA and input power of 2W.

Table 1: LED output data

LED #1				
V supply	V res	V led	I led	P led
V	V	V	mA	mW
2.6	0.008	2.59	3.08	8
2.8	0.040	2.76	14.6	40
3.0	0.102	2.90	37.2	108
3.2	0.188	3.01	68.7	207
3.4	0.290	3.11	106	330
3.6	0.402	3.20	147	470
3.8	0.520	3.28	190	623
4.0	0.641	3.36	234	786
4.2	0.764	3.44	279	959
4.4	0.887	3.51	324	1138
4.6	1.01	3.59	368	1322
4.8	1.13	3.67	412	1513
5.0	1.24	3.76	454	1706
5.2	1.36	3.84	496	1906
5.4	1.46	3.94	534	2103

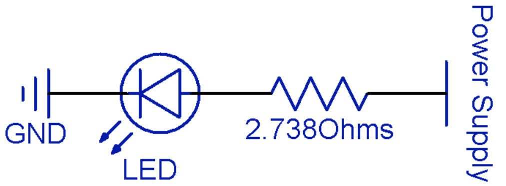


Figure 10: LED in series with limiting resistor

Connected in series with a 2.738Ω current limiting resistor, the LEDs packaged using the new design successfully operated at 2W of diode input power. The power supply voltage was increased in intervals of 0.2V until the diode input power reached 2W. A Keithly SourceMeter 2400 power supply provided output current measurements, which allowed for calculations of the voltage across the resistor, the voltage across the diode, and the diode input current.

Though the LED fails at high input powers, the electrical connections remained robust. All four LEDs failed at currents below 1A. Until a new LED die design allows for the support of higher input powers, the 1mil wirebonding process will not need to make more than two bonds.

Even though the LED is mounted on a highly conductive metal, it appears to overheat. One possible explanation is that at these high voltages, the heat generated inside the PN-junction does not transfer outside of the package fast enough. If this explanation is true, then it is likely that even with an excellent thermal path on outside of the LED, heat would remain trapped within the LED. Fortunately, an indirect method for measuring the temperature exists and can be used in future research. As an LED PN-junction heats up, the peak wavelength of emission shifts. The LED's PN-junction temperature can be determined without the need to probe or contact the device [9]. Using an optical spectrum analyzer, wavelength shifts as small as 0.1nm could be measured. A project for continuing study of the new LED package design would be to characterize the LED die's performance as a function of temperature. A comparison could be made between the heat dissipated by the Cu-substrate and the heat dissipated when the Cu-substrate is connected to the Cu heatsink. Using wavelength shift values to measure temperature, the new LED die package could be compared to existing LED packages.

4. Summary and Future Study

This project proposed a new package design for a high-power LED. The thin-film interface exhibited very good electrical connections. The wirebonds attached to the Au thin-films with ease. The solder joint easily wetted to the Ni93/V7 thin-films. The Ni93/V7 may provide a stronger mechanical connection if the adhesion to the Si thin-film interface improved, but this will need to be confirmed in future research. Overall, the ability to interface both wirebonds and solder joints went surprisingly well.

While the new package was assembled with a Cu heatsink, the sub-assembly is built on a Cu substrate, which permits bonding with a wide variety of other cooling devices. Passive and active cooling systems that have a Sn96Ag4 solderable surface can connect to the sub-assembly.

In applications where maximum high brightness is needed, an active cooling device can be attached to maintain very cool temperatures. Both TEC and mircochannel arrays offer low temperatures and will easily fit underneath the sub-assembly when space is an issue. While the active cooling devices may cool the LED more effectively, they consume power in doing so. When switching from less efficient light sources to LEDs, power is conserved. However, if the amount of conserved power is less than the amount consumed by an active cooling device, then the overall system may actually work less efficiently than before switching to the LEDs.

Using a passive cooling device, the LED can operate in applications that minimize power consumption. Since cooling devices, such as heatsinks, do not consume power, the lighting system supplies power to the LEDs, but not any other devices.

Cu has shown many benefits when used as the subassembly substrate. When bonded to another Cu surface, the CTEs are matched, which decreases the amount of thermal stress at a material interface. This allows the package to be exposed to lower temperatures because different materials contract at different rates. Maintaining cold package temperatures keeps the LED at lower temperatures and support higher currents.

Another benefit to making the substrate out of a metal, rather than ceramic, is the ability to use the heatsink as both an electrical and thermal connection. While some package designs separate the electrical connections from the heat path, the new package design, uses a Cu substrate as the anode and eliminates the need for a second wire in the package. The anode provides a conductive path for both electricity and heat.

Unfortunately, at high input power the LED die fails in this package. Further investigation is required to determine whether the problem resides in the design of the LED die, in the package, or both. When newer LED dies can more effectively use the new package design to transfer heat from inside the PN-junction to the outside of the die, the LED will be able to dissipate more of the heat away from the PN-junction and prevent device failure. Until then, existing LED dies will burn out when implemented in the new package design and connected to high power.

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