Lighting the way to a greener future

LEDs are revolutionizing lighting technology. They are more sustainable than traditional lighting sources because they use much less energy and last much longer. At the same time, lighting can be used in completely new ways. Molybdenum plays a key role in making the sapphire substrate of LED devices and is also important as a heat sink in these lights.

In Stockholm, Sweden on December 10, 2014, Isamu Akasaki and Hiroshi Amano of Japan, and Shuji Nakamura of the United States each received a share of the 2015 Nobel Prize in Physics from King Carl XVI Gustav of Sweden. Their accomplishment: the first high-brightness blue light-emitting diode (LED). Akasaki and Amano, working together, and Nakamura, working independently, produced blue LEDs in 1992 using different approaches. Their achievement, the culmination of years of research by many scientists around the world, made possible a bright future in energy-efficient lighting devices. Green and red LEDs have been available for many years, but only the advent of the blue LED enabled the blending of the three colors to produce white light. The researchers' work solved the problem and opened the door to the future.

Reflecting upon the Nobel award in an email statement, Frances Saunders, president of the Institute of Physics, a worldwide scientific organization based in London, said, "This is physics research that is having a direct impact on the grandest of scales, helping protect our environment, as well as turning up in our everyday electronic gadgets."

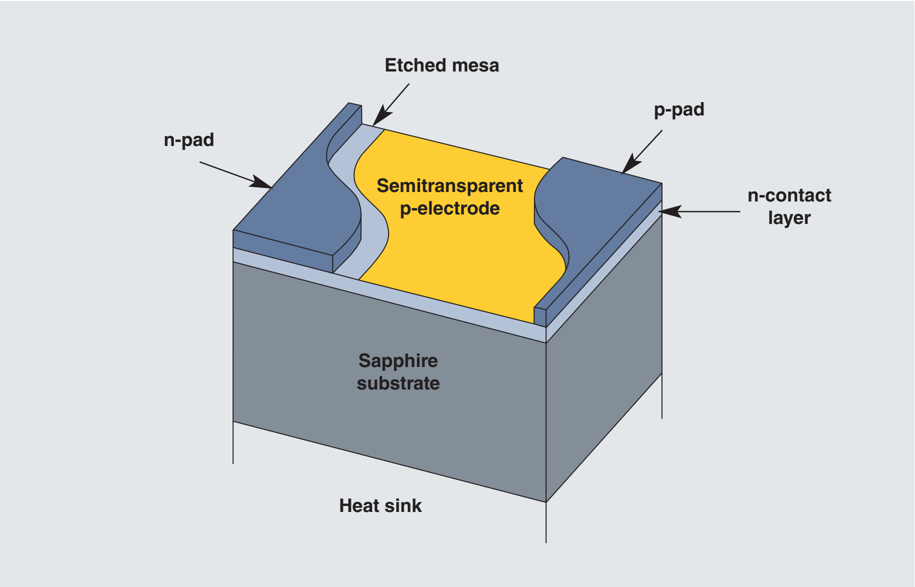
LED light and society

LED lighting is an extraordinary advance over current illumination technologies because it is much more eco-friendly. For a given amount of electrical power, LED bulbs produce four times the light of fluorescent lamps and nearly 20 times the light of an incandescent lamp. This energy efficiency is important because lighting is estimated to be responsible for 20%–30% of the world's electrical power consumption. Moreover, LED lights do not have the problem of mercury disposal associated with fluorescent lamps.

The high efficiency of LEDs and their ability to operate at low voltages has led to the miniature flashlights, key fob lights, and mobile phone lights that we are all so familiar with. Perhaps more importantly, they have fostered creative solutions for lighting areas that lack traditional electrical generation and distribution systems. For example, programs in Africa to replace polluting oil lamps have distributed millions of solar-powered LED lamps in remote areas. Durability is another great advantage of LED lamps. Their operating life is ten times that of fluorescent lamps and 100 times that of incandescent lamps.

Manufacturing the LED

The science of LED lamps is not the only revolutionary thing about them. They require manufacturing technology that is entirely different from traditional lamps. While the traditional incandescent lamp relies on heating a tungsten wire filament and the fluorescent lamp requires excitation of a gas-filled tube to activate fluorescent coatings on the tube, LED lighting is a semiconductor-based technology. A new way of making lights was needed and molybdenum plays an important role in that technology.



Schematic of a planar LED chip, illustrating the active region (yellow) and sapphire substrate (gray). Light is emitted through the semitransparent electrode of the active region. Source: STR Group: Modeling Solutions for Crystal Growth and Devices (www.str-soft.com)

Molybdenum metal crucibles for sapphire production. © Plansee

LEDs require a substrate on which to build the device. Substrates are made from high-purity single-crystal sapphire (Al_2O_3), because of its excellent thermal conductivity and thermal expansion match with the semiconductor layers to be built on it. To manufacture the required single-crystal material, sapphire is melted at temperatures above 2,000°C in molybdenum crucibles and allowed to solidify over a period of 15–20 days under carefully controlled conditions to form a solid single-crystal "boule." Boules are produced in a number of sizes, with a recently announced furnace claiming a capability of 500-mm diameter, 300-kg boules. Molybdenum's excellent high-temperature strength and its resistance to attack by molten sapphire are the primary reasons it finds use in this application. The high purity of molybdenum metal (99.97% is typical) assures contaminant-free sapphire with the best properties.

Growing the sapphire substrate

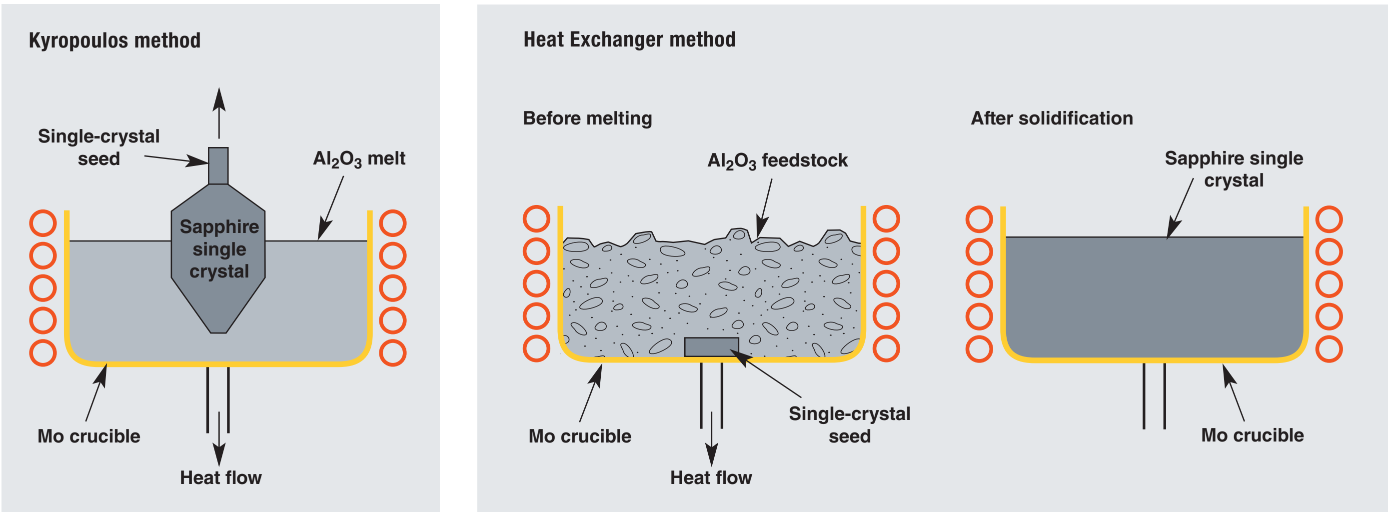
Most LED substrates are grown using one of two methods: the Kyropoulos method and the Heat Exchanger method. In the Kyropoulos method, a molybdenum crucible is filled with pure alumina (Al_2O_3) powder and melted. A cooled single-crystal sapphire seed with a desired orientation is brought into contact with the melt surface. By careful control of the melt temperature distribution a large sapphire single crystal grows from that seed. The crystal is slowly rotated and withdrawn from the melt as it grows.

The Heat Exchanger method places the seed, instead, at the bottom of the molybdenum crucible where it is cooled to prevent melting. The raw material is a mixture of alumina powder and 'crackle' (chunks of high-purity alumina recycled from previous runs). The furnace charge of raw material is then melted and allowed to cool under carefully controlled conditions. Eventually, all the melt solidifies as a sapphire single crystal grown from the original seed. In this method, the crucible is used only once, and is broken away from the finished boule.

In addition to the molybdenum crucibles used in these two processes, molybdenum heat shield assemblies help control the temperature distribution within the furnace. This critical function is necessary to manufacture single crystals of the required uniformity, since the growth process is dependent on temperature changes during the furnace run.

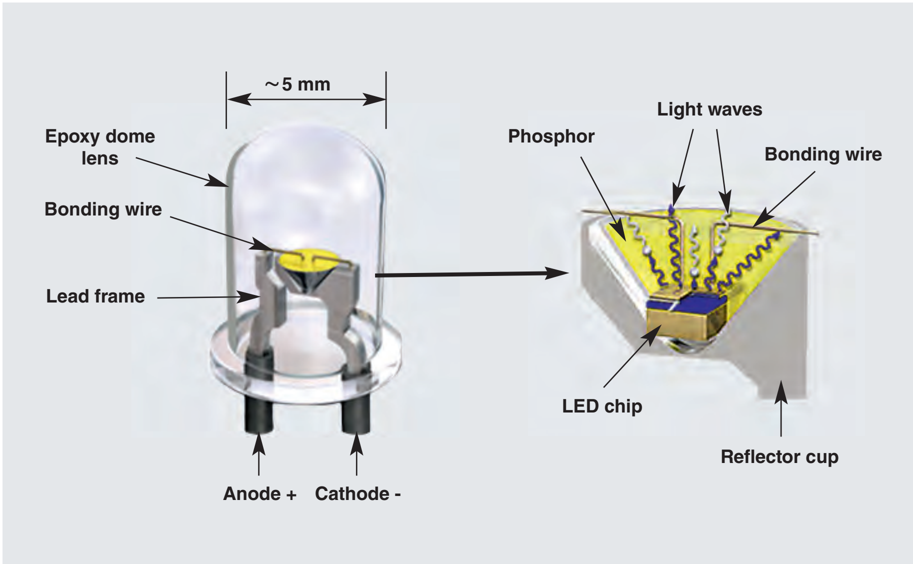
Producing the 'device' also requires molybdenum

After solidification, cylinders are core-drilled from the boule and individual wafers are sliced and polished from the cylinders. The wafers are less than 0.5 mm thick, and have diameters compatible with standard semiconductor processing equipment, where thousands of individual LEDs are produced on each wafer. The LED devices are built on the sapphire substrate, layer by layer, using processes like Metal Organic Chemical Vapor Deposition (MOCVD) or Molecular Beam Epitaxy (MBE). Such processes employ high temperatures ›



Schematic drawings of the Kyropoulos (left) and Heat Exchanger (center and right) techniques of crystal growth. Source: SubsTech (www.SubsTech.com)

Individual LED lamps with epoxy dome dyed to indicate the color of light produced. © iStockphoto.com/JamersonG



Individual LED light bulbs are only about 5 mm in diameter, but the LED chip is even smaller, measuring a fraction of a millimeter in length and width. Source: Molecular Expressions (www.micro.magnet.fsu.edu), National High Magnetic Field Laboratory (www.nationalmaglab.org).

and reactive materials, so molybdenum components are used in the deposition equipment.

Additional metal coatings may be needed for the LEDs to perform properly. Traditional physical vapor deposition (PVD) processes like evaporation are used to metalize the devices. Molybdenum heating coils and boats, which hold the evaporant, are common components used in these processes. Molybdenum's high-temperature strength and stability and its compatibility with evaporants make it a natural choice.

LED devices built on sapphire substrate need a structural base with compatible thermal expansion characteristics and high thermal conductivity to remove heat produced during operation. Here again molybdenum fills the bill, either as pure molybdenum metal or engineered composites of molybdenum and copper. Molybdenum-copper composites also appear in the heat sinks and base plates used for high-power LED lamps.

After the devices are manufactured on the sapphire substrate, the wafer is sectioned to obtain the individual LEDs, which are then assembled into lamps. The figure above emphasizes the size of a typical finished LED bulb. The LED chip, typically a fraction of a mm in planar dimensions, is embedded in a clear epoxy envelope that is only about 5 mm in diameter. Individual bulbs can be used alone (e.g. holiday lighting strings) or in groups (e.g. traffic signals, strip lighting, automotive lights or interior lighting fixtures as seen on the right).

The future

LED lamps have made great inroads in the automotive, commercial, and residential marketplaces worldwide. They have given designers new and creative ways to illuminate buildings and spaces e.g. the "Indemann" on the cover of this issue. The annual growth rate for LED lamps is estimated to be a phenomenal 45%. The U.S. Department of Energy has forecast that 74% of lighting sold will be LED by 2030, and that LEDs have the potential to reduce U.S. lighting energy consumption by almost one-half [1]. The global LED market has been predicted to grow from $4.8 billion in 2012 to $42 billion by 2019. With manufacturing costs continuing to drop thanks to ongoing research, development, and engineering advances, LED lighting will contribute even more to much-needed energy conservation efforts. As markets continue to grow, molybdenum will support that growth at nearly every step in the manufacturing process.
(John Shields)

Commercial LED lamps employ multiple individual bulbs. Semiconductor technology permits great latitude in the way individual devices are arrayed in the lamp. © iStockphoto.com/ludinko

1 www.ssl.energy.gov/tech_reports.html