Accelerating the growth of the HB-LED industry

Jim Jenson of Veeco's MOCVD business explains how improving MOCVD process uniformity can boost yields and capital efficiency, hence lowering LED manufacturing costs and speeding adoption of LEDs for display backlighting and solid-state lighting.

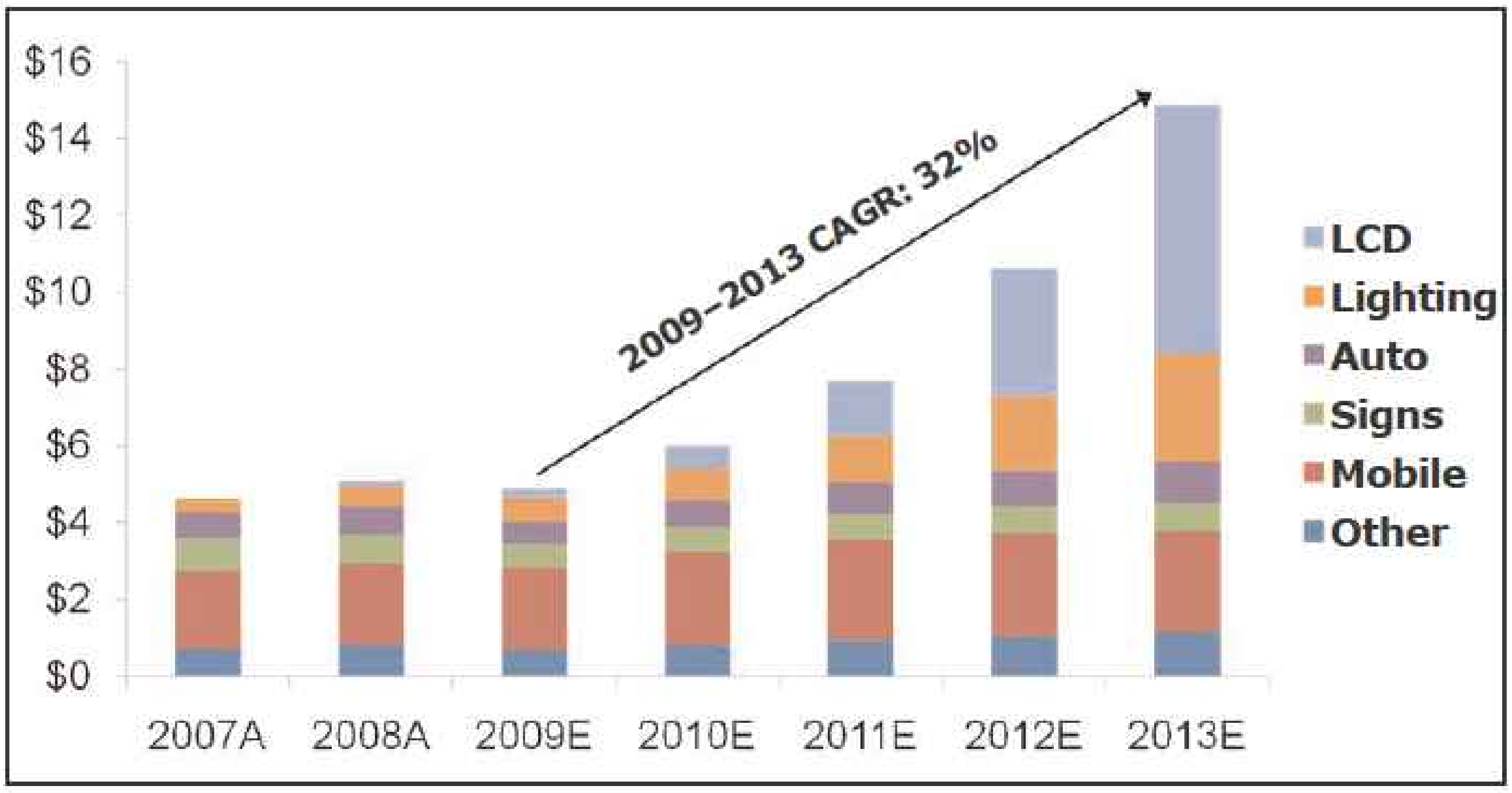

Figure 1: HB-LED market ($bn): Strategies Unlimited, August 2009.

The high-brightness light-emitting diode (HB-LED) market is poised for another period of explosive growth. This time it's driven by rapid adoption into LCD display backlighting and penetration into general lighting as advances in cost and performance are enabling them to compete with traditional light sources in these applications.

Metal-organic chemical vapor deposition (MOCVD) systems used to manufacture HB-LEDs perform the most critical process step in determining their brightness, yield, and total cost. The entire HB-LED device is created in this manufacturing step and the investment in MOCVD equipment can make up more than 50% of an LED fab's total capital expenditure. Therefore, it's critical that these systems are highly productive and produce high-quality LEDs.

MOCVD system suppliers must make rapid advances in yield and productivity in order for HB-LED manufacturers to execute their efficiency and cost improvement roadmaps. Veeco Instruments has fully embraced this challenge. To enable broad adoption of LEDs in display backlighting and solid-state lighting, Veeco is developing and introducing new MOCVD technologies to improve capital efficiency, including the recently announced TurboDisc® K465i™ GaN MOCVD system.

LED market growth in its infancy

Almost every illumination function in mobile devices such as cell phones and handheld music players is performed by HB-LEDs today. This mass adoption in mobile devices produced a $4bn HB-LED industry (see Figure 1). And that was just the opening act.

According to Strategies Unlimited in their August 2009 forecast update, the HB-LED market is forecasted to grow more than 30% per year between now and 2013. Although mobile device applications will still make up a large part of the HB-LED market, it is the rapid adoption for LCD display backlighting and general-lighting applications that are driving growth this time around.

The declining costs and improving performance of HB-LEDs has made them a viable competitor to conventional cold-cathode fluorescents (CCFLs) for backlighting LCD televisions. When compared to CCFL technology, HB-LED backlights require less power, enable thinner form-factors, are mercury-free, and can deliver superior display color and contrast. Most major manufacturers including Samsung, Sharp, and LG have introduced HB-LED backlit LCD televisions, with more models, from companies like Visio, Sony and others, being introduced every day. There is nothing subtle about this shift to HB-LED-backlit LCD panels.
The market research firm DisplaySearch is forecasting that, over the next five years, HB-LEDs are expected to become the prevailing LCD backlighting technology and by 2011 achieve a 56% market share.

The potential for HB-LEDs in general illumination applications represents the largest overall market. Until recently, most uses for HB-LEDs in general lighting have been in niche applications such as architectural and decorative lighting. However, recently white LEDs have begun to penetrate mainstream lighting applications such as retail display, outdoor, and residential

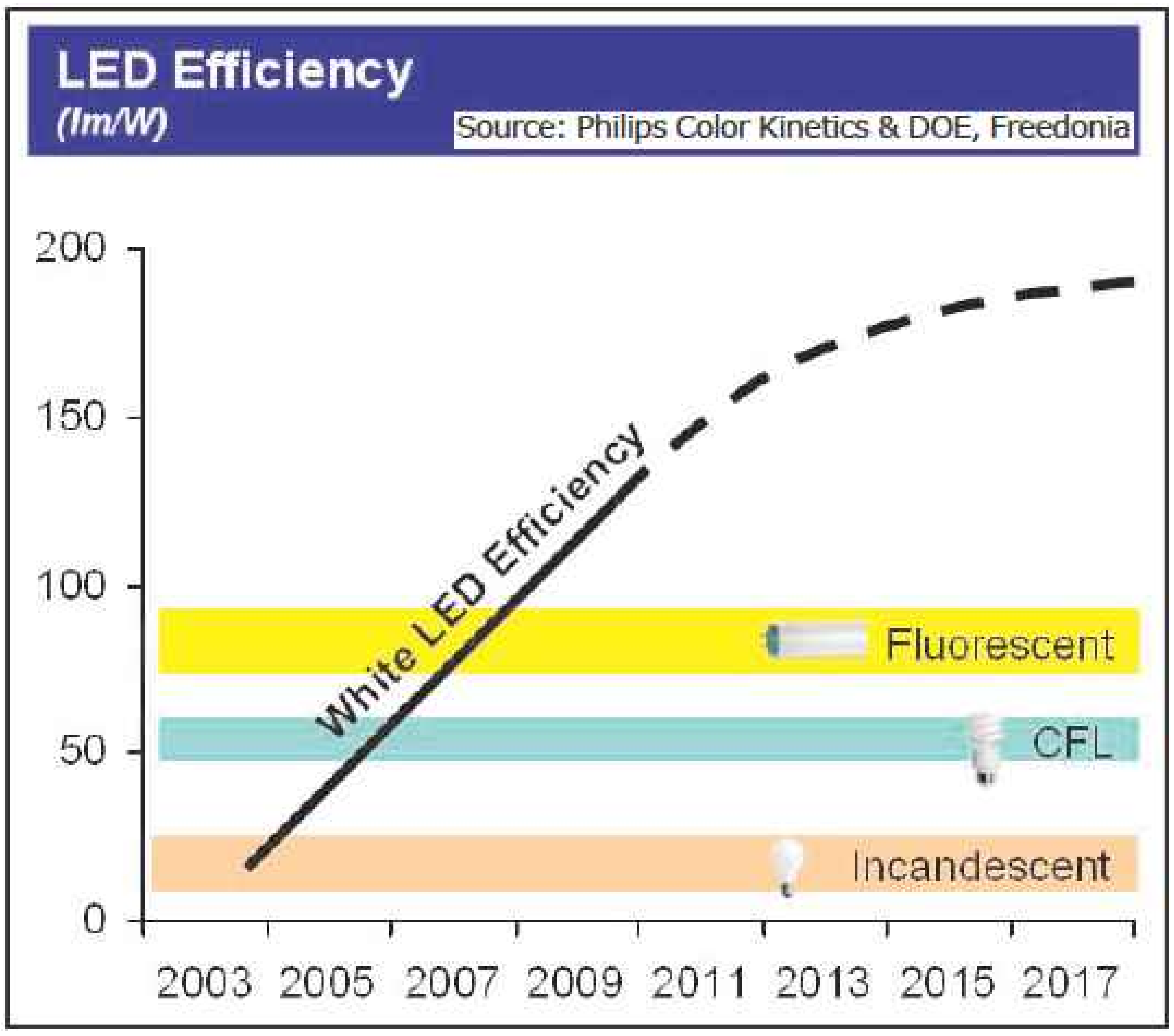

Figure 2: LED efficiency improvement roadmap.

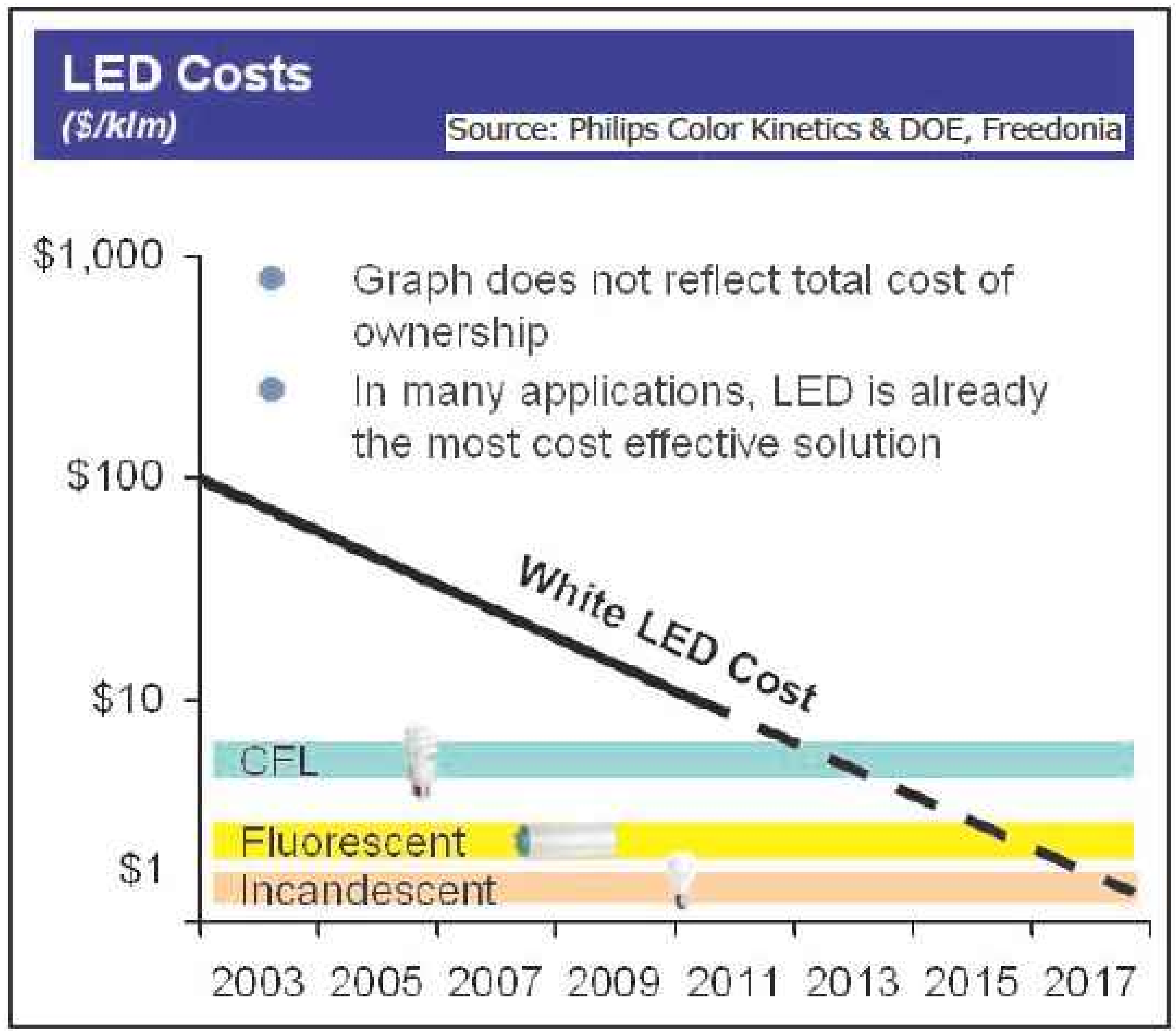

Figure 3: LED cost-reduction roadmap.

lighting. This penetration into general lighting applications is expected to accelerate as costs come down and performance improves. For example, HB-LEDs are becoming mainstream for general lighting in China, with government incentives accelerating the pace of adoption. Just recently there have been meaningful solid-state lighting announcements, such as Samsung partnering with Acuity Brands for LED lighting products and Philips reporting that 10% of its lighting business today is from LED products.

The success of HB-LEDs in mobile devices was just the beginning. Rapid adoption of HB-LEDs for LCD display backlighting and general illumination signals several years of double-digit growth for the industry.

Lowering costs and improving performance drive LED success

Today, in many applications, HB-LEDs are already the most cost-effective solution, especially when their long life is considered. However, to fully capitalize on the display and general-lighting markets, HB-LEDs must continue to drive down the cost of each lumen of light that they produce. This cost per lumen is a function of an HB-LED's luminous efficiency (amount light produced from electricity supplied) and its manufacturing costs.

LED efficiency is measured in lumens per watt (lm/w). Most of the research and development in the HB-LED industry is focused on improving this measure for the white HB-LEDs used in display and general lighting applications. As the chart in Figure 2 shows, HB-LEDs have already surpassed the efficiency of traditional incandescent and fluorescent light sources. This improvement is expected to continue as researchers and manufacturers make further advances in chip design, light extraction technology, packaging methods, and driver performance.

LED efficiency improvements translate directly into lower costs. As the efficiency of an HB-LED increases, the quantity of HB-LEDs needed to produce a target total lumens of output decreases. Fewer HB-LEDs results in lower total cost. But the cost reduction challenge does not end there. The industry must also focus on improving manufacturing yield and cost.

Currently the largest factor — about 42% of the total cost associated with HB-LED manufacture — is attributed to yield loss. Yield losses occur when emission wavelength, electrical properties, and efficiency fail to meet target specifications. Variations in any of these three parameters can produce 'off-spec' devices that are either unsalable or only adequate for commodity applications.

For example, achieving very tight distributions around target specifications is necessary to penetrate the fast-growing LCD television backlighting application. The backlight unit in an HB-LED backlit LCD TV is typically made from an array of 400–1500 individual HB-LEDs. Even small variations in individual HB-LED wavelength emission or efficiency will appear to the TV owner as non-uniformities in color and brightness across the display and would be unacceptable.

In addition to yield, manufacturers are also focused on reducing manufacturing costs. These costs include all the materials, equipment, facilities, labor, and other operating costs that go into manufacturing HB-LEDs. One of the biggest determinants of total cost of manufacturing HB-LEDs is the efficiency of the equipment employed. Manufacturing equipment performance affects overall factory productivity, materials usage, and yield. It follows then that the industry's manufacturing equipment suppliers must rapidly innovate in lock step with HB-LED manufactures to ensure that they stay on their steep cost-reduction curve (see Figure 3).

MOCVD advances key to LED cost and performance improvements

In the fabrication of the fundamental device in CMOS memory and logic chips (the transistor) dozens of equipment types and a multitude of manufacturing steps are required. In sharp contrast to the CMOS semiconductor process, the entire fundamental device in an HB-LED, as mentioned above, is fabricated in a single piece of equipment — the MOCVD system. MOCVD is the most critical process step when it comes to determining HB-LED brightness, yield, and total cost. Therefore, it is critical that these systems are highly productive and produce high-quality LEDs.

High-performance LEDs like those used in display backlights and general lighting are complicated layered structures using different compositions of AlInGaN alloys layered one on top of the other. Today's high-performance LEDs can have more than 100 separate layers. Each of these layers needs to have just the right thickness, crystalline quality, purity and composition to produce high-performance HB-LEDs.

All of these layers are 'grown' in an epitaxial deposition process using MOCVD equipment to form the HB-LED. The heart of the MOCVD system is the growth chamber where gaseous compounds flow over heated substrates where they decompose into their constituent elements and then recombine to form thin epitaxial layers. Following the MOCVD step, these epitaxial wafers are patterned with electrical contacts, singulated into individual die, and packaged. See Figure 4 for a high-level summary of the HB-LED manufacturing process.

In the MOCVD step, the maximum available light out is determined by the HB-LED structure grown in it. All subsequent steps are focused on getting as much of that light out as possible. A key factor in an MOCVD system's ability to enable brighter devices is its process window. An MOCVD system process window is the range of process gas flows, pressures, and temperatures with which uniform epitaxial material can be grown. A wide process window gives HB-LED manufacturers the freedom and flexibility to create advanced epitaxial growth structures.

Improvements in the MOCVD process can have a dramatic effect on overall LED manufacturing costs. The majority of manufacturing yield losses occurs in epitaxial growth and chip fabrication steps. Yield losses are due to structural variations attributable to variations in layer thickness, stoichiometry, and crystal defect densities induced during the MOCVD process. These yield losses typically come in the form of emission wavelength or brightness non-uniformities.

In the case of wavelength non-uniformities, process gas flow and temperature control in the MOCVD process are critical. One atomic percent difference in the indium content of an InGaN layer will result in a 12nm difference in wavelength. Similarly, 1 angstrom of

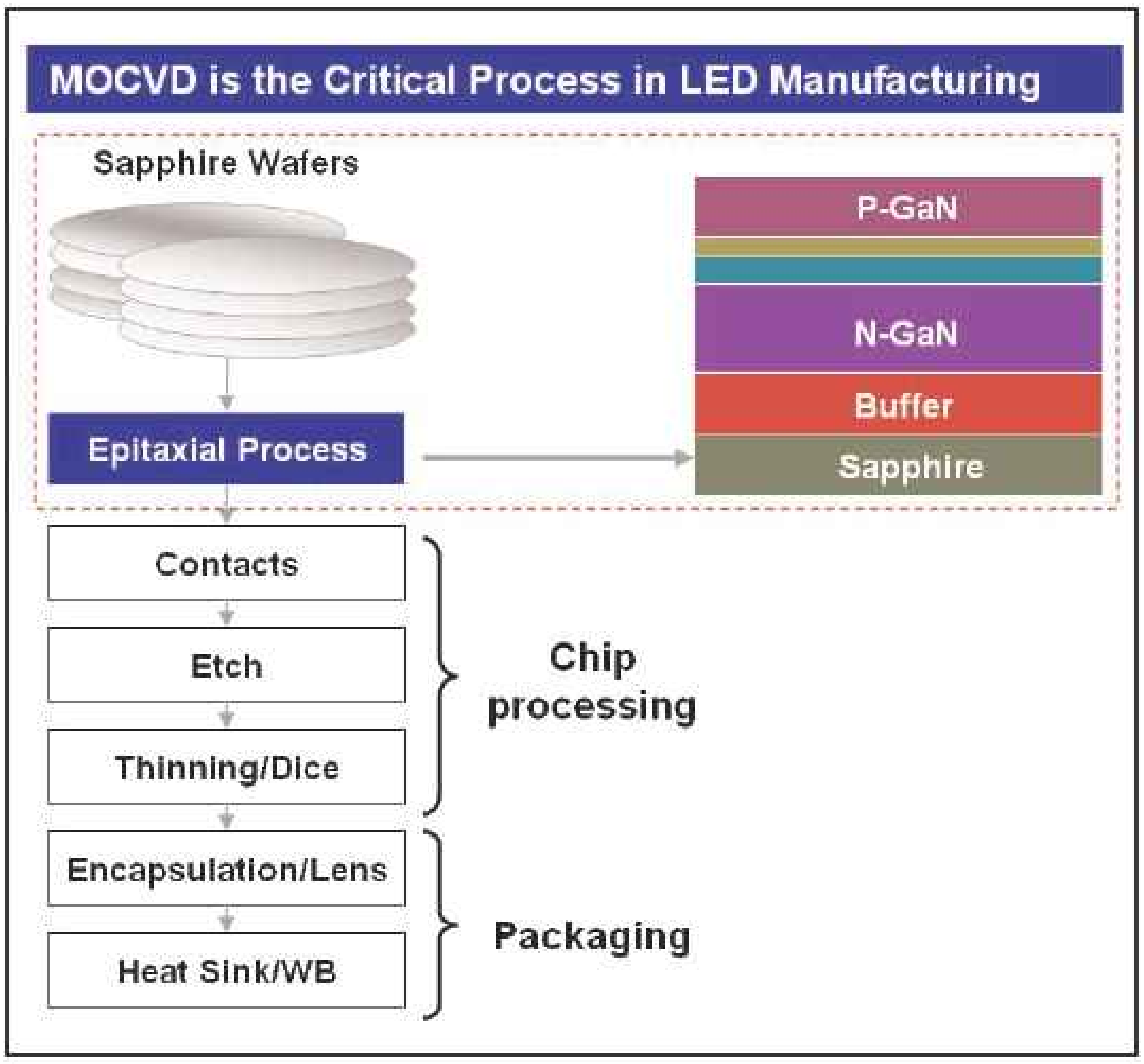

Figure 4: High-level HB-LED manufacturing process.

thickness variation will result in a 3nm variation, and a 1°C variation will result in up to 1.8nm shift. To reduce these variations, MOCVD system suppliers must focus on achieving uniform process gas flow to the substrates and substrate heating.

Reducing yield loss associated with brightness variations will also reduce the overall cost of HB-LED manufacturing. The brightness non-uniformity and overall HB-LED light output are tied to the quality of the crystalline layers in the LED structure. This quality is degraded by defects in the crystal structure caused by residual strain at the substrate-layer interface, parasitic gas phase reactions, and impurities or contaminants. All of these are influenced by MOCVD system design.

Epitaxial growth is an inherently slow process that can take from five to nine hours, or more, including setup times, depending on the device design and manufacturing process. So, on the productivity front, improvements in the MOCVD process can pay large dividends in HB-LED cost reduction. Throughput for MOCVD systems is driven by the system setup time, process time and overall system uptime.

Setup times can be minimized through the use of automated MOCVD reactor loading and unloading. Non-automated systems must be cooled down sufficiently for a human operator to handle the substrates and must be completely unloaded before a new batch is loaded. Automatic load and unload systems enable processed wafers to be removed from the reactor at much higher temperatures and, as a result, eliminate a significant portion of the process time allotted to system cool-down. Also, automation schemes that employ multiple carriers allow the next batch of wafers to be pre-loaded onto a carrier while another batch is running.

By placing the next-batch wafer loading step in parallel with the current-batch processing step, total process time is reduced.

Process time is largely dependent on deposition rates. However, increasing the deposition rate is difficult and can present trade-offs with crystal quality. If deposition is too fast, crystal defects increase and, as a result, LED efficiency deteriorates. Fast deposition technologies such as hydride vapor phase epitaxy (HVPE) are being explored due their higher deposition rates. However, HVPE has not been proven to be a cost-effective and manufacturable process for large-area substrates.

The most important factor in system uptime is the number of runs before maintenance events. During the MOCVD process, materials build up on the reactor walls. Eventually that material builds to such a level that it must be removed to avoid compromising the epitaxial growth process. The longer an MOCVD reactor can operate without having to remove material from the reactor walls, the higher its overall throughput will be.

The MOCVD system is the heart of the HB-LED fabrication process. This single piece of equipment manufactures the entire fundamental device — literally substrate in, HB-LED out. Therefore, it is imperative that MOCVD system suppliers rapidly advance the capability of their systems to enable HB-LED makers to achieve their brightness, yield, and total cost objectives.

How Veeco is driving LED industry success

Veeco has a history of collaborating with LED makers to create MOCVD process cost and performance improvements. Today, more than 80% of key LED makers use Veeco MOCVD equipment.

Veeco has fully embraced the challenge of improving MOCVD process yields and lowering its costs, combining these two challenges into the single concept of capital efficiency which is simply defined as the number of good wafers produced by the system for each capital dollar invested. To enable broad adoption of LEDs in display backlighting and solid-state lighting, Veeco is developing and introducing new MOCVD technologies with a goal to ultimately quadruple capital efficiency.

Veeco has secured an 'R&D matching' grant from the US Department of Energy to accelerate its development of next-generation, high-volume MOCVD systems to lower epitaxial growth cost for HB LEDs

In support of this goal, Veeco has increased 2010 R&D spending 100% compared to 2009 to support a multi-generational product roadmap. In addition, Veeco has secured an 'R&D matching' grant from the US Department of Energy to accelerate its development of next-generation, high-volume MOCVD systems to lower epitaxial growth cost for HB-LEDs.

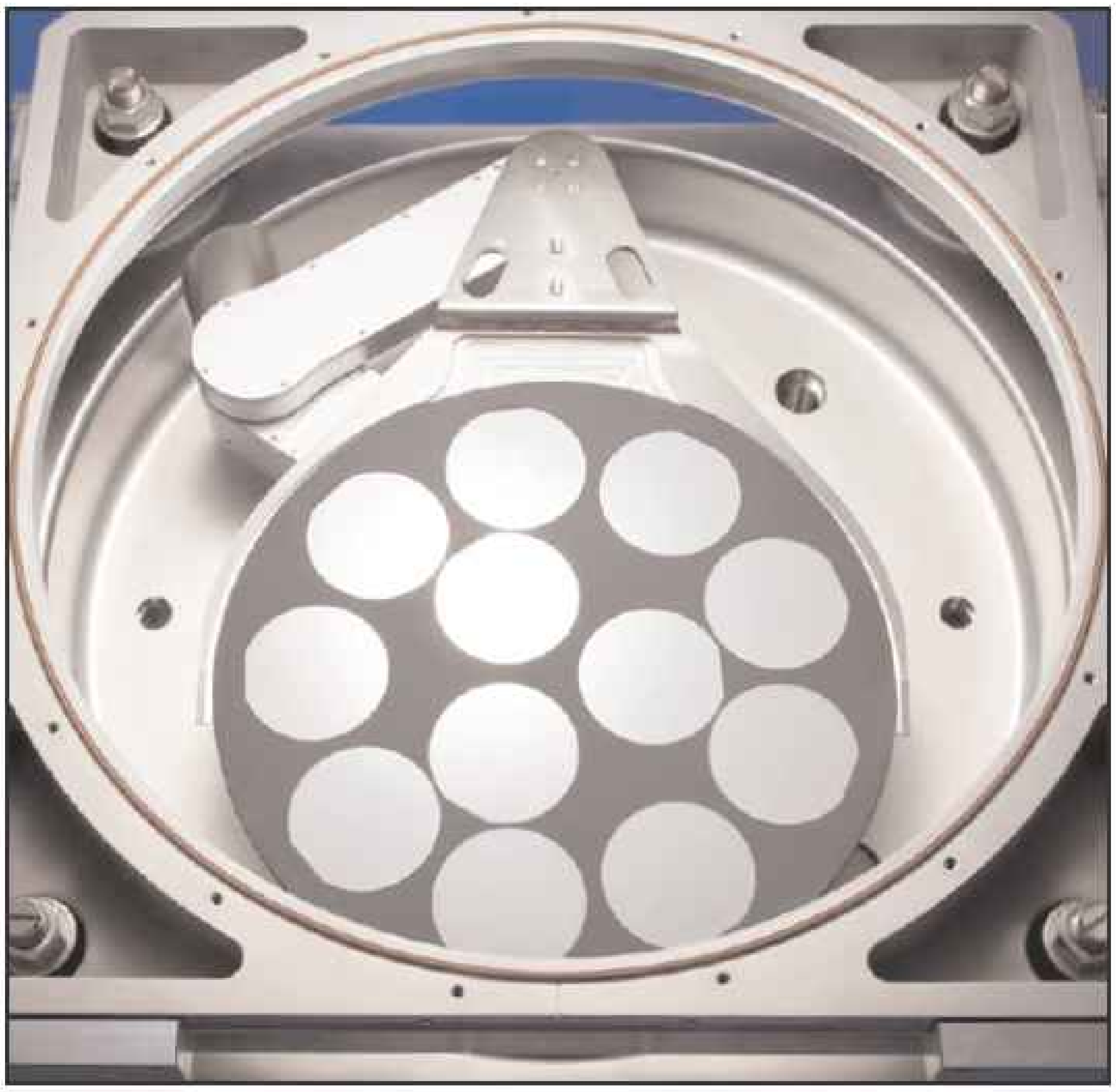

Figure 5: K465i, showing 4" sapphire wafers, removable carrier, and automated loading.

The most recent evidence of our progress is the introduction of the TurboDisc K465i GaN MOCVD system, Veeco's latest-generation production MOCVD tool. At the heart of the system is Veeco's Uniform FlowFlange® technology, which creates a uniform alkyl and hydride flow pattern across all wafers. As a result, the K465i delivers superior uniformity and repeatability with the industry's lowest particle generation. The K465i can enable customers to achieve world-class results: 90% yield in a 5nm bin size. That's the result of a 25% improvement in both wavelength uniformity and run-to-run wavelength repeatability. Also, the FlowFlange's simplified design provides ease-of-tuning for fast process optimization on wafer sizes up to 8 inches and fast tool recovery time after maintenance.

The K465i has completed its beta phase, where HB-LED manufacturers quickly qualified it for high-volume production. Veeco has already received orders for the system from multiple HB-LED customers throughout the Asia Pacific region and, as of this writing, interest for the tool from world-leading LED makers is strong.

Demand for HB-LEDs is high and expected to increase in the coming years. By increasing R&D investment, introducing innovative new technologies, and ramping MOCVD production capacity, Veeco is ready to help enable lower-cost and higher-performing HB-LEDs and accelerate their adoption into display backlighting and general illumination applications. ■

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