Öko-Institut e.V.
Institut für angewandte Ökologie
Institute for Applied Ecology

Fraunhofer Institut
Zuverlässigkeit und
Mikrointegration

Adaption to scientific and technical progress under Directive 2002/95/EC

Exemption request No. 4

"Cadmium for use in solid-state illumination & display systems"

Email and checklist as submitted by 3M Center

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Dear Ms. Caprusu,

Please find attached an application for a new exemption to the RoHS Directive.

Please confirm receipt of this application and inform us whether additional or other formats (e.g. paper copies) are necessary.

Future correspondence regarding this application should be addressed to:

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(See attached file: Cd in Color-Converting Illumination or Display Systems.pdf)

Regards,
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Directive 2002/95/EC on the Restriction of Hazardous Substances in Electrical and Electronic Equipment (RoHS).

CHECK LIST FOR REQUEST FOR AN EXEMPTION
Cadmium For Use In Solid-State Illumination & Display Systems

Requested By 3M Company

	Question	**Response**
1	Please describe the material /component of the electrical and electronic equipment that contains the hazardous substance.	Semiconductor light emitting diodes (LEDs)
	Please indicate the type and quantity of the hazardous substance used in the homogenous material.	Cadmium is tightly bound within the crystal lattice of a thin layer hereafter referred to as the II-VI material (containing Group II elements such as Mg, Zn and Cd and Group VI elements such as Se) that is attached to a conventional LED. Each LED contains ~0.3 - 9 μg of Cd (depending upon the size of the LED). The homogeneous layer consists of ~25-35 mol % Cd.
	Please indicate the functionality of the substance in the material of the equipment.	The II-VI material converts light from a short-wavelength light source (for example a blue or UV LED) into that of a longer wavelength. The unique optical properties of the material allow the generation of wavelengths at a precise location anywhere within the visible spectrum. Up to 100% of the short-wavelength light can be converted into that of a different wavelength. More than one converted wavelength can be generated from a single II-VI material. At some wavelengths it is possible to enhance the power efficiency of the device with the II-VI material, compared to alternative approaches using other materials. More details about the design & use of II-VI color-converted LEDs are provided in the Appendix.
	Please also provide an estimate of the annual quantities of the hazardous substance used in this particular application.	This is a new technology. Based upon the small quantity of Cd contained within each LED (and tightly bound within the crystal lattice of the material) and our estimate of the total market for these LEDs, we estimate that the maximum Cd incorporation within II-VI color-converted LEDs distributed within the EU would be **less than 10 kg per year** by 2010. More details concerning the expected total quantity of Cd for the proposed applications are contained within the attached

		Appendix.
2	Please explain why the elimination or substitution of the hazardous substance via design changes or materials and components is currently technically or scientifically impracticable.	The II-VI material is the only material system capable of light emission across the entire visible spectrum. No other material or technology is capable of producing any arbitrary wavelength within the visible spectrum by itself. Elimination or substitution of the Cd in the semiconductor alloy would change the material properties and make it impossible to achieve the same performance attributes. Conventional LEDs can be made to emit light within certain different portions of the spectrum, but undesirable characteristics of these LEDs reduce their performance when combined together in systems. This detraction presents a barrier to the introduction of solid-state lighting. Also, the energy efficiency of standard green and yellow LEDs is far lower than that of standard blue and red LEDs. A wide variety of products such as displays, televisions, etc. could be produced using this technology that would otherwise be of inferior quality (if standard LEDs were used) and so would be impractical, would require more complicated electronics or would require mercury-containing fluorescent lamps. More detail is included below in the Appendix.
3	Please indicate if the negative environmental, health and/or consumer safety impacts caused by substitution are likely to outweigh the environmental, health and/or consumer safety benefits. If existing, please refer to relevant studies on negative impacts caused by substitution.	All of the alternative technologies will increase the risk of exposing the environment and people to a larger quantity of hazardous material, use more energy, and/or require more electronic components. The II-VI material, however, will decrease overall use and releases of RoHS restricted substances, decrease energy usage, and reduce WEEE. *1. Decreased use of RoHS materials* Applications that this technology could replace include projectors that use mercury lamps and LCD monitors and televisions that use mercury-containing fluorescent lamps. These mercury lamps would not be needed if these products used II-VI color-converted LEDs. Although small amounts of Cd would be put onto the EU market, this would replace much larger quantities of mercury which is also toxic but is more likely to be released into the environment during the product life cycle. Mercury in fluorescent lamps is relatively volatile and can easily escape into

the air when lamps are broken (see Section 5.2 in the Appendix). On the other hand, the Cd coating on II-VI color-converted LEDs is relatively inert (both as a result of being bound within the crystalline material and because it is contained within a passivating glassy encapsulation layer). In addition, the solubility of similar Cd compounds in water is very low (limiting the risk of environmental exposure throughout the product life cycle). Furthermore use of the II-VI color converted LEDs instead of conventional lamps could reduce the quantity of heavy metal compounds by more than 66 times. Table 1 shows the significantly smaller amount of Cd contained within the II-VI color-converted LED compared to the quantity of Hg contained in a conventional lamp having the same luminous output.

Conventional lamp	*II-VI converted LED*
5.0 μg Hg/lumen	0.075 μg Cd/lumen

Table 1. Quantity of mercury vs. cadmium heavy metals contained in equivalent projector display products.

2. Decreased energy usage

In addition to the potential release of Hg into the environment through broken fluorescent lamps, the energy efficiency of displays with Hg lamps is lower than that of displays using II-VI color-converted LEDs. The lower the energy efficiency of the device, the more electricity is required for its operation. The generation of this extra electricity requires the burning of more fossil fuels (which in turn releases more Hg and Cd and other heavy metals into the environment and also emits more CO_2 – contributing to increased global warming). The II-VI color-converted LEDs can decrease energy usage. In particular, where amber II – VI color-converted LEDs are used to replace standard amber LEDs, there is a saving in energy over the life of the LED such that the estimated reduction in Cd emissions (from energy generation) is 10X greater than the amount of Cd used in the LED.

3. Reduction in WEEE

Finally, it has been estimated that the present manufacturing process for green LEDs has a yield of

		only 10 – 15% for devices that have the desired properties (with the remainder being waste or lower-quality devices). II-VI color-converted LEDs can reduce the amount of waste associated with products through improvement of LED manufacturing yield and through higher performance than other light sources, which avoids the need for excess components (that other light sources need to include, in order to compensate for lower performance).
4	Please indicate if feasible substitutes currently exist in an industrial and/or commercial scale. Please indicate the possibilities and/or the status for the development of substitutes and indicate if these substitutes will be available by 1 July 2006 or at a later stage.	All of the potential substitutes have technical and environmental problems that render them unsuitable for the proposed applications. 1. Conventional LEDs have been on the market for many years but have not been adopted in many applications and suffer from several limitations that are overcome by II-VI color-converted LEDs. These limitations are: • Limited range of wavelengths commercially available • Large variation in color on individual wafers so that only a small fraction of LEDs emit light within an acceptable range for demanding applications. The rest are suitable only for low quality applications or are waste • Power efficiency for green and yellow LEDs is lower than for blue and red. 2. Phosphor-converted LEDs (which rely on a phosphor-containing coating to convert light from a blue LED to a longer wavelength) have been developed. These are widely used for the generation of white light, but relatively few single-color phosphor-converted LEDs exist. There is no single phosphor material system that spans the entire wavelength range of interest. In the case of yellow phosphor-converted LEDs the power efficiency is lower than that achievable by II-VI color-converted LEDs. 3. Many types of information displays (such as flat-panel televisions, computer monitors and laptop computer displays) are made using LCDs illuminated with mercury-containing fluorescent lamps. The main environmental disadvantage is the presence of mercury (discussed above and in more

		detail below in the Appendix). Fluorescent lamps also have color characteristics that are not optimal for this application. They also have lower energy efficiency and create more electronic waste in some display applications.
5	Please indicate if any current restrictions apply to such substitutes. If yes, please quote the exact title of the appropriate legislation / regulation.	Mercury is restricted by Directive 2002/95/EC although its use in special lamps for LCD displays is permitted by EU RoHS Annex Exemption No. 3 and in projector lamps by EU RoHS Annex Exemption No. 4. Conventional and phosphor-converted LEDs are not subject to restrictions.
6	Please indicate the costs and benefits and advantages and disadvantages of such substitutes. If existing, please refer to relevant studies on costs and benefits of such substitutes.	II-VI color-converted LEDs have attributes (described throughout this document) that can accelerate the adoption of solid-state lighting in a variety of applications and new display technology with characteristics that are not achievable by alternative approaches. In so doing, II-VI color-converted LEDs will: 1. reduce the quantity of heavy metals released into the environment (reducing releases resulting from breakage of fluorescent lamps and reducing releases associated with the generation of extra electricity in power plants) 2. reduce the amount of energy needed (through an improvement in the energy efficiency of devices) and 3. reduce the quantity of electronic waste (through improvement in manufacturing yields of LEDs and a reduction in volume and number of electronic components). All of this is accomplished by the introduction of a very small amount of Cd sealed within the crystalline II-VI material. There are other benefits which are described in the appendix (section 3).
7	Please provide any other relevant information that would support your application for an additional exemption.	See attached Appendix. This exemption request is to allow thin coatings containing Cd to be used on standard blue LEDs for a variety of novel applications. These new LEDs will have unique characteristics that cannot be achieved by any other existing technology. Therefore there are no direct substitutes. The use of these new LEDs will enable equipment manufacturers to produce products with superior performance characteristics than is possible with existing

		technology and which also (in some cases) use less energy than other light sources. These characteristics would have socio-economic benefits but also potentially benefit human health and the environment as is explained in the Appendix. Because this is a new technology that will spur innovation and has energy benefits and significant environmental benefits over other technologies, we ask for an expedited approval to help speed commercialization. Delays in granting this exemption could inhibit innovation in this area.

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Appendix:
Support for the Exemption of Cadmium in II-VI Color-Converting LEDs

1. Introduction & Executive Summary

Lighting comprises approximately 20% of the greater than 15 TW annual world energy consumption (1 TW = 10^{12} W). As a result of its significant role in energy consumption, lighting has been identified as an important area for efficiency improvements and has been given a high priority by the Eco-design of Energy-using Products Directive. The first step in the process is the large-scale replacement of incandescent bulbs with fluorescent lamps. This transition improves the energy efficiency of lighting, but at the cost of introducing large amounts of mercury into the consumer and commercial market. The next phase of this replacement will be the introduction of solid-state lighting (SSL) solutions into a large number of applications. SSL has the possibility to significantly improve the efficiency of lighting while at the same time removing the environmental impact (discussed below) of fluorescent lamps. At the present time some SSL solutions (mainly LEDs) are beginning to be adopted in a small number of applications. However, the most significant benefits will occur when SSL becomes wide-spread in the largest lighting applications (such as information displays and general illumination). There are at present technical limitations associated with current SSL technologies that are limiting the rate of adoption. As will be shown in this exemption request, the II-VI color-converted LED technology has a number of technical attributes that can accelerate the adoption of SSL by successfully addressing these issues. Alternative technologies can address some of these attributes, but no other approach is capable of achieving all of these advantages.

II-VI color-converted LEDs use a special material to improve the performance of LEDs. This innovative new technology takes advantage of the unique optical properties of a tiny amount of cadmium sealed within the II-VI material. The improved performance will foster the transition to solid state lighting systems, and will have the following significant benefits: overall reductions in use and release of RoHS restricted substances; increased energy efficiency; and reduced quantities of WEEE.

2. Overview of II-VI Color-Converted LEDs

The II-VI color-convertor material is an epitaxial multi-layer film consisting of elements from Groups II and VI of the Periodic Table (including Mg, Cd, Zn, Se) deposited by molecular beam epitaxy (MBE). The II-VI layer (having a total thickness of ~2 μm) contains approximately 25-35% Cd yielding a Cd weight of approximately 7 $\mu g/mm^2$ of light emitting area. The MBE growth process produces a single crystal material in which all of the constituent elements are covalently bonded. This characteristic is important because the lack of defects enables high efficiency color conversion (as defects present in a disordered crystal would decrease the operational efficiency of the material). The crystalline nature of the material also means that the components of the semiconductor alloy (including the Cd) are securely bound within the material and are thus very difficult to release to the environment. The II-VI layer is attached to the top of a short-wavelength light source (in this document a conventional blue or UV LED as shown in Figure 1). The light from this pump LED is absorbed by the II-VI layer and re-emitted at a different (longer) wavelength. As is commonly practiced with conventional LEDs, the II-VI layer is encapsulated within a glassy passivation layer (such as SiO_2, Si_3N_4, or TiO_2). This protective passivation layer provides improved performance and extended lifetime (as well as providing an additional layer of protection around the Cd-containing II-VI layer).

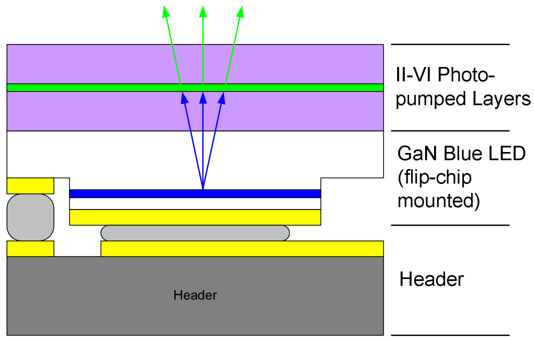


Figure 1. Schematic diagram of II-VI color-converted LED.

2.1 Controllable Color

The MBE growth process allows precise control over the material composition and layer structure (both of which are critical to controlling material properties that determine the final device performance). As a result, it is possible to design the II-VI layer to emit light *anywhere within the entire visible spectrum in a controllable manner*. This is a key distinction because the CdMgZnSe material system is the only material system capable of covering this entire emission wavelength range by itself. As will be discussed below, there are other approaches that emit light over portions of the visible spectrum. However, these other methods use materials that are quite different to II – VI color converters and have significant disadvantages that limit their use.

A demonstration of the wide range of colors available is shown in Figure 2 (in which the emission spectra of several different II-VI color-converted LEDs are shown along with the spectrum of the blue pump LED. Photographs of several of these color-converted LEDs (along with a blue pump LED) are shown in Figure 3.

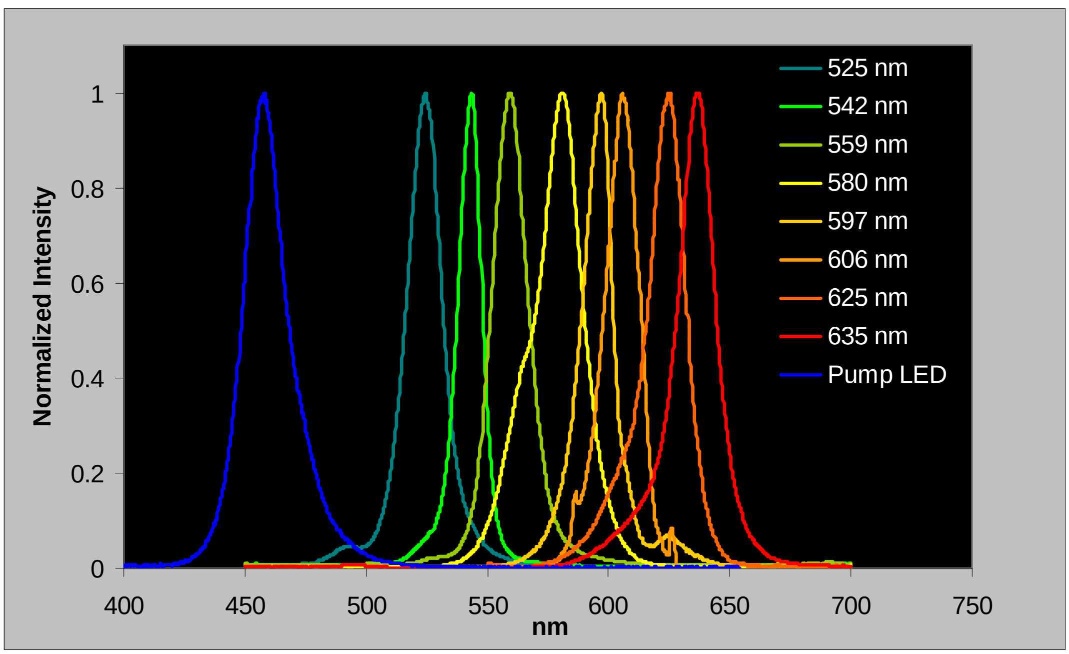


Figure 2. Output from several discrete color-converted LEDs

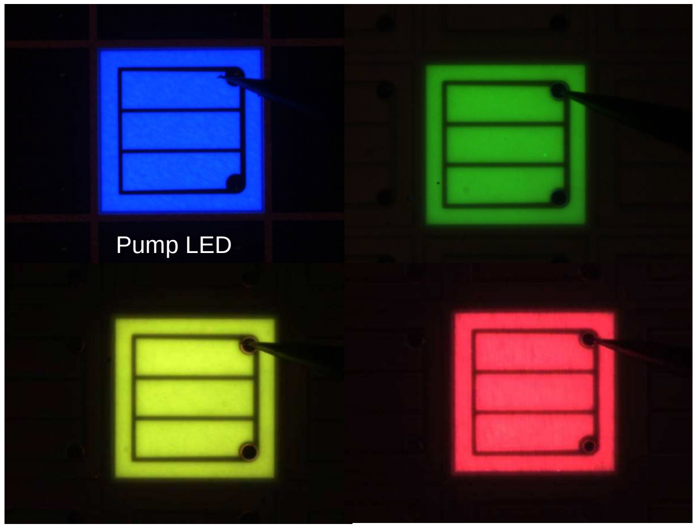


Figure 3. Photographs of blue pump LED and three different II-VI color-converted LEDs.

Any color can be created by mixing blue light that passes through the II-VI layer (or layers) with light of one or more other wavelengths that have been produced by one or more II-VI layers. The following examples show how it is possible to create a color-converted LED that emits light of more than one color. A simple example of this is shown in Figure 4 (which shows the spectrum of a magenta color-converted LED). A large proportion of the blue pump LED illumination is absorbed and converted into red light while the remainder of the blue light passes through the II-VI layer. The combination of the red and blue light creates the magenta color (in this case having CIE x, y chromaticity coordinates 0.59, 0.29). Appropriate design of the II-VI convertor layers and composition allows the adjustment of the relative amounts of light that are converted compared to the portion that passes through (allowing tuning of the color point anywhere between the two constituent colors).

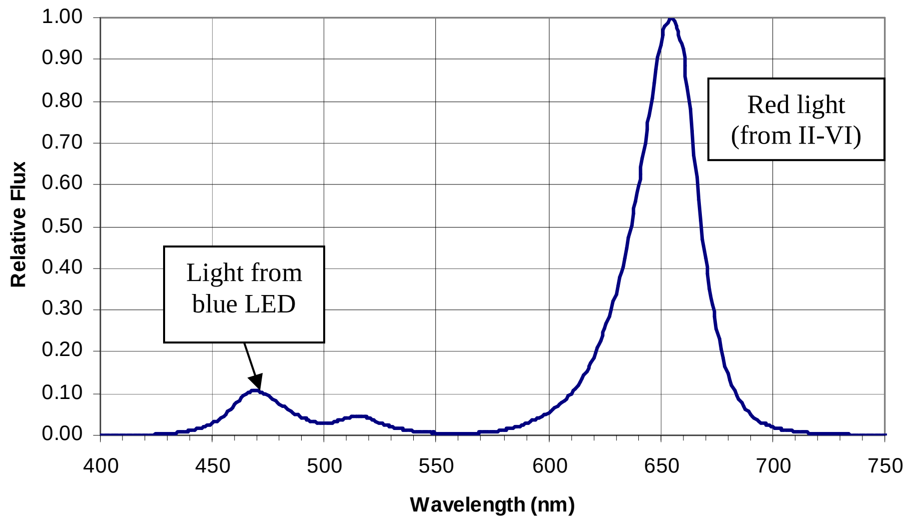


Figure 4. Spectrum of magenta color-converted LED.

A more complex example of a multi-wavelength color-converted LED is shown in Figure 5. Here both red and green light have been generated from a single blue pump LED with two different II-VI layers and the colors combined together to create a particular chosen white color point (CIE x, y coordinates = 0.32, 0.23 as shown in Figure 6).

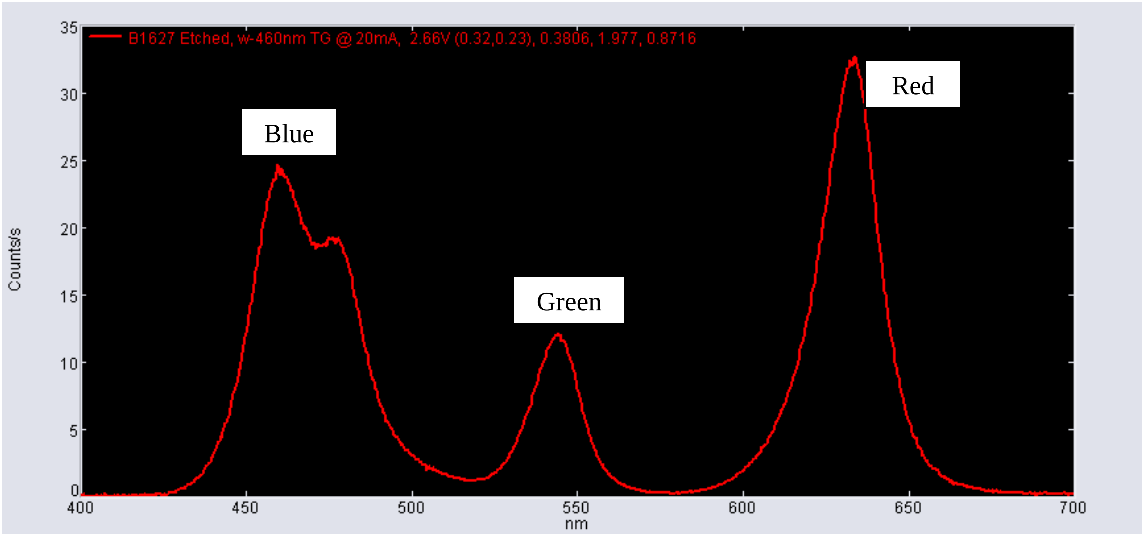


Figure 5. Custom-white color-converted LED emission spectrum

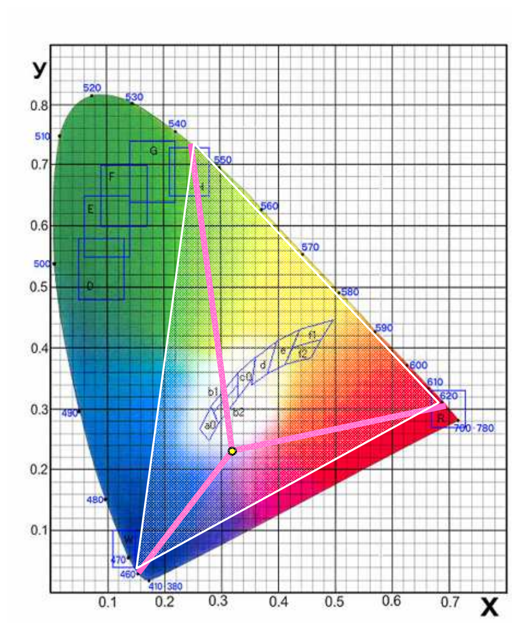


Figure 6. Chromaticity coordinates of the RGB (Red Green Blue) color-converted LED from Figure 5.

As with the two-color example described above, appropriate design of the II-VI convertor layers and composition allows the adjustment of the relative amounts of light that are converted in comparison to the portion that passes through (allowing tuning of the resulting color point anywhere within the white triangular color space in Figure 6 created by the constituent colors).

2.2 Wavelength Uniformity Improvement

In addition to the precise control of the emission spectrum from a single LED, II-VI color-convertors can improve the uniformity of devices across a wafer and therefore reduce electronic waste associated with unusable devices. Conventional InGaN LEDs are manufactured by the deposition of thin layers onto growth wafers using metal-organic chemical vapor deposition (MOCVD) techniques. MOCVD systems have faster deposition rates than MBE systems, but have reduced deposition control resulting in variable layer thickness and composition that, in turn, causes the LEDs to have variable emission wavelength. This has been compensated to a large extent in the growth of blue LEDs, but remains a significant problem for green LEDs. Finished LEDs are sorted into groups ("bins") on the basis of emission wavelength or output power through extensive testing. Variation in output wavelength is a significant cost not only to the LED manufacturers (who must test each device) but also to the final LED device users who must either design the final systems to be tolerant of variation in peak wavelength or pay a premium price for their LEDs and as a result many out-of-spec LEDs may become waste. On the other hand, II-VI color-convertors grown by MBE typically have very small emission wavelength variation across a wafer. In this way the II-VI color-convertor can be used to improve the yield of devices of a desired wavelength and so avoid waste while at the same time reducing the testing required on each LED.

The peak wavelength from a variety of locations on a commercial blue LED wafer was measured. This wafer was then used to construct a green II-VI color-converted LED wafer and the peak wavelength measurement repeated. The measured wavelength ranges of the original blue pump LED wafer and the green II-VI color-converted LED wafers are shown in Table 2. The wavelength variation across the blue pump LED wafer was 6 nm and is reduced to 2.5 nm by the addition of the II-VI layer.

Peak wavelength variation across wafer	
Blue InGaN wafer	Green II-VI LED wafer
6 nm	2.5 nm

Table 2. Improvement in wafer-level wavelength uniformity via II-VI color-conversion process.

This is a significant improvement, but becomes even more important when the small wavelength variation across a green color-converted LED wafer is compared to the variation across a conventional green InGaN LED wafer. Conventional single-color LEDs are sorted into a number of wavelength bins that each have a width of ~2.5 nm. LED manufacturers are very secretive about their yields so precise figures are not published but it has been estimated that only 10 – 15% of conventional green LEDs manufactured fall within the desired wavelength bin. On the other hand, it is possible that the green II-VI color-converted LEDs from an entire 2 inch (50 mm) wafer *would fall within a single wavelength bin (therefore improving the wavelength yield to 100%)*. This can be compared as described below to a typical conventional green InGaN LED wafer that contains devices lying within many wavelength bins.

Figure 7 below shows a representative plot of some of the wavelength bins (drawn as blue rectangles) associated with commercial LED products (from Nichia). The red arrow in Figure 7 points to a white box that represents the wavelength variation of II-VI color-converted LEDs from one wafer (having the wafer-level wavelength uniformity described above). It is important to note that the emitted light from LEDs originating from a single green InGaN wafer would span several of the wavelength bins shown in Figure 7, while the emission wavelength of the II-VI color-converted LED wafer would be constrained to fall within an area of color coordinate space many times smaller and would fit into the small boxed region indicated by the arrow in Figure 7.

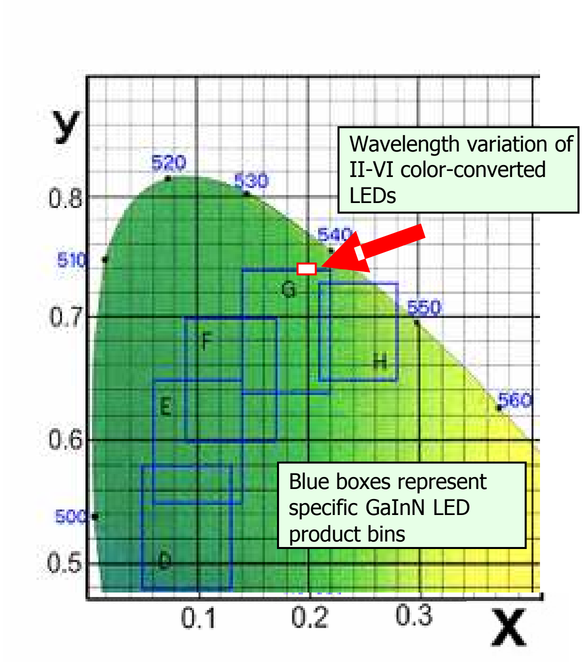


Figure 7. Comparison of wavelength variation of II-VI color-converted LEDs (which would all be within the small region indicated by the red arrow) to the wavelength variation of conventional LEDs (that lie within many "bins" indicated by the blue boxes).

3. Example Applications for II-VI Color-Converted LEDs

II-VI color-converted LEDs will find application wherever the precise control of the color or spectral characteristics are important. This includes the following application areas:

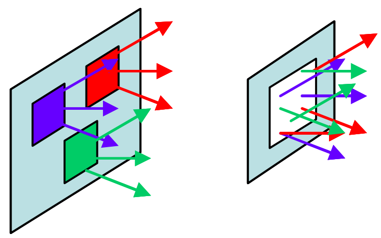
3.1 Backlights for Information Displays

Backlights are currently illuminated by cold-cathode fluorescent lamps (CCFLs) either via edge-lit light-guides or with banks of CCFLs directly behind the display. LEDs are used to illuminate small displays and some progress has been made on extending this to larger sizes.

This application requires a wide color gamut (to accurately display the widest possible range of colors). Fully-saturated colors (realized by narrow emission spectra of constituent colors) are key to a wide color gamut. Good mixing of the individual colors (if provided in separate light sources) within a small volume is also a requirement for this application. The ability to generate multiple wavelengths within a single device (which II-VI color-convertors can enable) would be an advantage. Finally, temperature stability (to preserve a desired color point across an operating temperature range) and energy efficiency are key attributes.

3.2 Projection Displays

The majority of projection information displays currently use mercury (alone, with phosphors, or with metal halides) in arc lamps as a light source to illuminate an image-forming device (typically either a liquid-crystal or micromirror array). As with all display applications, a wide color gamut constructed of fully-saturated colors is preferred. Temperature stability is also important for high performance in a variety of environments. Energy efficiency remains important in this application (especially for portable devices where battery lifetime is an issue). An additional concern for projection applications is the source "etendue" (the product of the source area and the solid angle into which it emits). Maximum system efficiency is achieved by small-etendue systems (which is possible with II – VI coated LEDs), so the generation of multiple narrow wavelengths from within a single source would improve system performance (compared to multiple sources combined together within a system) by minimizing the source etendue. Figure 8(a) shows a conventional LED Red/Green/Blue cluster in which the effective source size is large (due to space between the individual chips); Figure 8(b) shows a II-VI color-converted white LED in which the red, green and blue light is emitted from the same device. The colors or more easily mixed and the source is smaller and has greater symmetry (which leads to better collection and projection of the emitted light, thus improving the energy efficiency of the device).



(a) (b)

Figure 8. Examples of projection light sources: (a) conventional LED Red/Green/Blue cluster; (b) II-VI color-converted LED

3.3 Advertising Billboards

Conventional LEDs are currently used in this application. Re-calibration is typically used to adjust for differential aging of the different colors; temperature compensation is not used at present whereas temperature stability and a wide color gamut are primary requirements for this application. II-VI color-converted LEDs would be able to provide better color point control than conventional LEDs across typical operating temperature ranges and over the lifetime of the device.

3.4 Brand Identity lighting

The consistent presentation of a brand or corporate image is an important concern for many corporations. Some of the largest multi-national companies derive a significant portion of their market capitalization from brands that have been developed over the course of decades. These companies have a strong interest in guaranteeing that their brands are presented in the same manner around the world. Therefore, II-VI color-converted LEDs could be used to provide lighting having a guaranteed spectrum in any location and under most environmental conditions unlike conventional LEDs or other types of lighting.

Brand identity lighting at present is provided by a couple of different approaches but all of these have disadvantages. Neon tubing can be formed into desired shapes (though with a relatively small range of colors and significant limitations on the number of colors included on a single sign). The remainder of signage generally uses broad wavelength sources (either fluorescent or incandescent lamps) to backlight translucent signs or graphics with the desired image and have higher energy consumption than II – VI color-converted LEDs.

3.5 General Illumination

At present there is a shift from incandescent lamps to compact fluorescents for general illumination. Although public awareness education efforts and government policy decisions have been effective at influencing adoption, many consumers are still unhappy with the aesthetic quality of light from fluorescent lamps (as well as from some LED lamps currently available). Rapid consumer acceptance of more-efficient lighting solutions requires light that has a pleasing appearance (as measured by its correlated-color temperature).

A controllable white point/color temperature is a desirable feature. In particular, higher-color temperature light (having a larger blue spectral component) is desired for task lighting, while lower-color-temperature light (containing more yellow light) is preferred for illuminating living spaces. There are also differences in preference for color temperature in different countries and cultures. This is easily achievable with II-VI color converter LEDs (also, see section 4.2). Operating energy efficiency is important to policymakers and governing bodies.

4. Alternative Technologies: Comparing Properties and Performance

There are no other commercially-available alternative technologies that achieve the same overall system performance or spectral range as that demonstrated by II-VI color-converted LEDs. To better understand this it is useful to examine the characteristics of other light sources.

4.1 Fluorescent Lamps

One of the primary light sources used in a variety of lighting applications is the fluorescent lamp. The spectral emission of fluorescent lamps is characterized by a broad distribution with peaks controlled by the addition of various phosphors. The fluorescent lamp is used in conjunction with color filters deposited on the liquid crystal display (LCD) when incorporated into electronic displays. These filters only allow ~33% of the light through each pixel (representing a significant efficiency loss). In addition, the fluorescent lamp has a relatively small color gamut (which limits the range of colors that can be displayed). Wider-color-gamut fluorescent lamps have been developed, but these have approximately 20% lower energy efficiency.

In addition to the small color gamut and reduced efficiency when used in a display, fluorescent lamps contain significant quantities of Hg. In particular, a fluorescent lamp capable of generating 1000 lumens of light contains approximately 5000 μg of Hg (in a powdery form that is easily released into the environment if the lamp is broken). In contrast, a II-VI color-converted LED system capable of generating the same amount of light would contain approximately 75 μg of Cd. (This calculation assumes that 10 color-converted LEDs – each emitting 100 lumens – are used and each LED contains approximately 7 – 8 μg of Cd). Furthermore, the Cd contained in the II-VI material is a stable solid form that is less likely to be released into the environment unlike mercury in lamps which is liquid at room temperature and so forms a vapor very easily. See Section 5.2 for further discussion on the volatility of Hg in fluorescent lamps.

4.2 Conventional LEDs

Conventional LEDs utilize the InGaN and AlInGaP semiconductor material systems for the blue-green and amber-red portions of the visible spectrum, respectively. However, as can be seen in Figure 9, the power efficiency of conventional LEDs is very low in the green & amber region. Many LED applications (such as backlights for LCD displays) that utilize one or more clusters of red, green and blue LEDs to generate all colors currently use 2 green LEDs within each cluster to compensate for the low efficiency of the green LEDs (as shown in Figure 10).

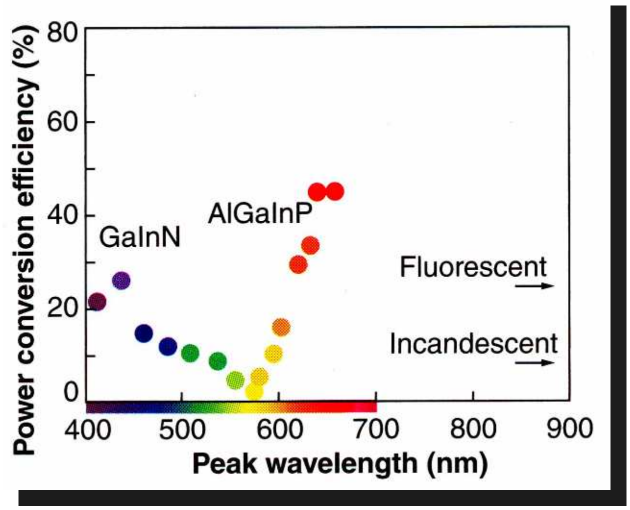


Figure 9. Efficiency of conventional LEDs (from D. Nicol et al. Laser Focus, March 2006).

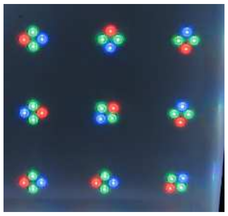


Figure 10. RGGB LED cluster used in a display backlight. RGB multi-chip package.

Another problem with conventional LEDs is their temperature stability (in which the amount of light emitted by an LED drops significantly as the device temperature increases). This is particularly noticeable for red and amber LEDs; green LEDs are somewhat more stable and blue LEDs have the greatest stability. Figure 11 shows the temperature performance of typical commercially-available InGaN and AlInGaP LEDs (taken from data sheets for LumiLeds, Osram and Epistar products).

Single-color LED applications can compensate for this to some extent by increasing the drive current when the device will be operated at elevated temperature. This can, however, be a self-limiting process: an increase in current will generally increase the junction temperature of the device, further lowering the output.

The temperature characteristics of conventional LEDs cause even greater problems when multiple single-color LEDs are combined together in a system. A notable example of this is an LCD TV display that uses RGGB clusters of LEDs (such as displayed in Figure 10 above). When power is first applied to the unit there is usually a reddish tint to the displayed images (as a result of the increased efficiency of the red AlInGaP LEDs at a lower temperature. The output flux of the red LEDs in the system decreases faster than that of the blue and green InGaN LEDs as a result of the warming of the LEDs during operation. The systems are usually designed to have best color balance at normal operating temperature (resulting in noticeably lower performance at other temperatures).

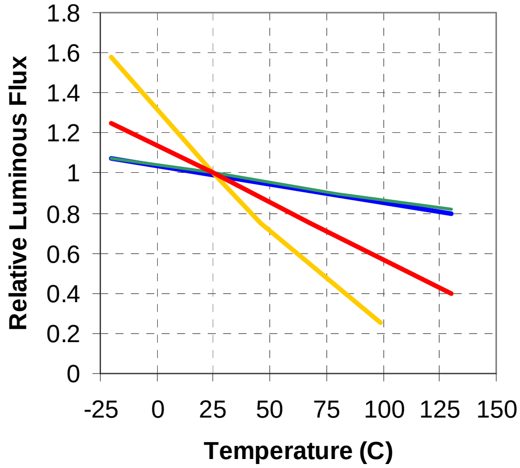


Figure 11. Temperature performance of conventional blue, green, amber and red LEDs.

The expected temperature performance of red and amber II-VI color-converted LEDs (as determined by photoluminescence measurements) is shown in Figure 12 along with the conventional blue InGaN LED performance data for comparison. As can be seen, the II-VI red and yellow material demonstrates temperature performance that is significantly better than that of corresponding yellow/amber AlInGaP LEDs. The reduced slope as a function of operating temperature will allow better performance of LED systems designed to operate across wide temperature ranges.

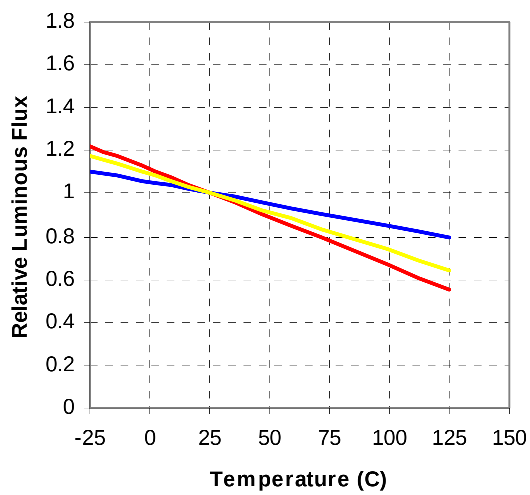


Figure 12. Expected temperature performance of II-VI color-converted red and amber LEDs.

4.3 Phosphor-Converted LEDs

Another conventional light source uses a short-wavelength pump LED to excite a phosphor that emits light of a desired wavelength. One characteristic of phosphors is a fairly broad emission spectrum. This is acceptable for the generation of white light, but often at the expense of color gamut or color-rendering (due to the lack of sufficient red content in the light). The phosphors which emit light with the narrowest wavelength range have a spectral full-width at half maximum (FWHM) of approximately 40 – 55 nm. By comparison, the spectral width of II-VI color-converted LEDs can be designed to be significantly narrower (approximately 25 nm). The narrow spectral width allows increased color saturation which in turn enlarges the color gamut (an important feature in display applications). The Ce^{3+}:YAG phosphor system has been widely used for the generation of white light (when combined with the blue pump LED light). A significant amount of effort has been expended to improve the robustness of this material system. However, many of the other proposed phosphors have failed to become commercially-viable products due to problems with material degradation that limited operational lifetime.

Table 3 shows the performance range of a variety of phosphor systems. It is important to note that (unlike the II-VI material system) no single phosphor material system emits light across the entire visible spectrum. This characteristic is important because materials- and processing compatibility issues make the combination of different phosphor materials together in a single system impractical. Furthermore, the spectral width as measured by the full width at half maximum (FWHM) for many of the materials is unacceptably broad for precise wavelength control (making combination of multiple phosphor materials to achieve a desired spectrum impractical). Finally, the robustness of a number of these phosphors has not been proven and only some have been commercialized. Ce^{3+}:YAG, oxi-nitrides, ortho-silicates and sulfo-selenides have appeared in commercial products; the data for other materials listed in Table 3 is derived from research results.

	Ce^{3+}:YAG	Gd:Garnets	Oxi-nitrides	Ortho-silicates	Chloro-silicates	Thio-gallates	Sulfo-selenides
Emission Range (nm)	560-570	570-580	554-567	505-575	525-560	510-560	530-650
FWHM (nm)	110-115	110-115	70-85	60-95	40-55	50-70	85-95

Table 3. Spectral characteristics of some phosphor material systems.

4.4 OLEDs

Organic LEDs (OLEDs) have been under development for many years (and have recently begun to appear in commercial products). OLED devices are extremely sensitive to degradation from moisture and oxygen and thus require sophisticated packaging and encapsulation. OLED device lifetimes have traditionally been limited to less than 5,000 hours, but recent advances have extended this. The primary disadvantage of OLEDs is the requirement to limit the current density to avoid material degradation as a result of heating. This is thought to limit the luminance (or brightness) of OLEDs to approximately 1000 candela/m^2 (too low to be useful for projection applications). For comparison, the luminance of a typical halogen automotive headlamp is 2.5×10^7 candela/m^2; conventional LEDs have demonstrated similar luminance (though at lower total luminous flux levels). The luminance of a source is related to the concept of etendue discussed above in Section 3.2: small-area sources emitting light into small angular regions have high luminance and are needed for high-efficiency low-etendue projection systems. Large-area sources emitting uniformly in all directions have very low luminance.

4.5 Quantum Dots

Quantum dots consist of II-VI materials (and thus also contain cadmium) in which the fabrication method creates small particles of controlled size. These particles act as down-convertors by absorbing short-wavelength light and re-emitting light of a longer wavelength. The emission characteristics are strongly-influenced by the particle size. This technology is in the early stages of development and has not yet been commercialized; it is not clear what the performance will be in final applications.

5. Environmental Benefits of II-VI Color-Converted LEDs

5.1 Accelerated Replacement of Incandescent & Fluorescent Lamps

There is presently a significant EU and world-wide trend to replace incandescent lighting with more efficient fluorescent lamps. Although this is a positive change (because it reduces energy consumption and reduces the emission of Hg and other hazardous substances through power generation) it does place large amounts of Hg onto the market in the form of fragile glass lamps. Furthermore, there is consumer resistance to fluorescent lamps in many applications due to the poor color rendering ability of fluorescent lamps. Conventional white LEDs (using a yellow phosphor in conjunction with a blue LED) typically lack enough long-wavelength light needed to generate the "warm-white" appearance desired in many applications. The technical attributes of II-VI color-converted LEDs (as described above) have the ability to accelerate the adoption of SSL by providing superior color control in a variety of important applications. This would eliminate the need to use lamps that contain mercury.

5.2 Decreased Overall Use of RoHS Restricted Substances

Mercury is present in fluorescent and other lamps used in a variety of lighting applications including projectors, LCD monitors and televisions. The presence of mercury in these lamps presents a variety of environmental and health risks that could be avoided through the use of alternative lighting solutions. In particular, these mercury lamps would not be needed if these products used II-VI color-converted LEDs. Although small amounts of cadmium would be put onto the EU market through the use of II-VI color-converted LEDs, this would replace much larger quantities of mercury which is also hazardous and is more likely to be released into the environment during the normal product life cycle.

II-VI color converted LEDs can provide a significant reduction in the quantity of heavy metal compounds used in a light source. Table 1 (used in the checklist and reproduced below) shows the significantly smaller amount of Cd contained within a II-VI color-converted LED compared to the quantity of Hg contained in a conventional lamp having the same luminous output (assumed to be approximately 1000 lumens in this analysis). This example shows a reduction in the weight of hazardous material of more than 66 times for the generation of the same amount of light.

Conventional lamp	*II-VI converted LED*
5.0 µg Hg/lumen	0.075 µg Cd/lumen

Table 1. Quantity of mercury and cadmium heavy metals contained in equivalent projector display products.

Mercury in fluorescent lamps is relatively volatile and can easily escape into the air when lamps are broken. Recent research has indicated that exposure to mercury vapor resulting from past spills of liquid mercury in the home may be an important pathway. A number of governmental agencies provide instructions and precautions for consumers to follow after breaking a fluorescent lamp (*e.g.* http://www.epa.gov/hg/spills/index.htm). These directions (particularly the suggestion to vacate the area and increase the air circulation) highlight the dangers associated with released Hg vapor from fluorescent lamps.

On the other hand, the cadmium coating on II-VI color-converted LEDs is relatively inert (both as a result of being bound within the crystalline material and from the addition of a passivating glassy encapsulation layer). In addition, the solubility of similar Cd compounds in water is very low (limiting the risk of environmental exposure throughout the product life cycle). II-VI color-converted LEDs therefore use significantly smaller quantities of hazardous materials to achieve the same luminous output while also substantially reducing the risk of personal and environmental exposure.

5.3 Improved Manufacturing Yield of LEDs

The manufacturing yield of conventional LEDs is closely-held information by LED manufacturers. However, it has been estimated that the peak wavelength across a single green InGaN LED wafer can vary by approximately 15 – 20 nm. Some applications (such as conventional information displays) can tolerate a wavelength variation of ~5 nm. Therefore, a significant fraction of LEDs on a single wafer will fall outside the range desired by a particular application. These LEDs must either be sold into another application, or (more likely) are considered waste and are discarded. II-VI color-converted LEDs, through their ability to significantly reduce the wavelength variation across a wafer (as described above), can dramatically decrease the amount of electronic waste associated with the fabrication of lighting systems/equipment. The manufacture of semiconductor wafers is a very energy-intensive process and also uses hazardous gases and chemicals. Improvements in yields will therefore have a direct environmental benefit through pollution prevention (by reducing the consumption of energy and chemicals used to make useful LEDs and by reducing the number of waste LEDs that are discarded immediately after manufacturing).

5.4 Reduced Volume (or Number) of Electronic Components

Large-format LCD information displays are presently illuminated primarily by backlights containing fluorescent lamps (as shown in Figure 13). The exact number and size of fluorescent lamps varies depending upon the display size and design, but typical backlights have 10 – 20 fluorescent lamps and associated electronics. LED backlights replace these dozens of fluorescent lamps with many LEDs (typically hundreds) that act as tiny point sources of light to illuminate the LCD panel. Elimination of large, fragile lamps (made possible by the performance improvements enabled by II-VI color-converted LEDs) would reduce the volume of electronic waste associated with these consumer market devices.

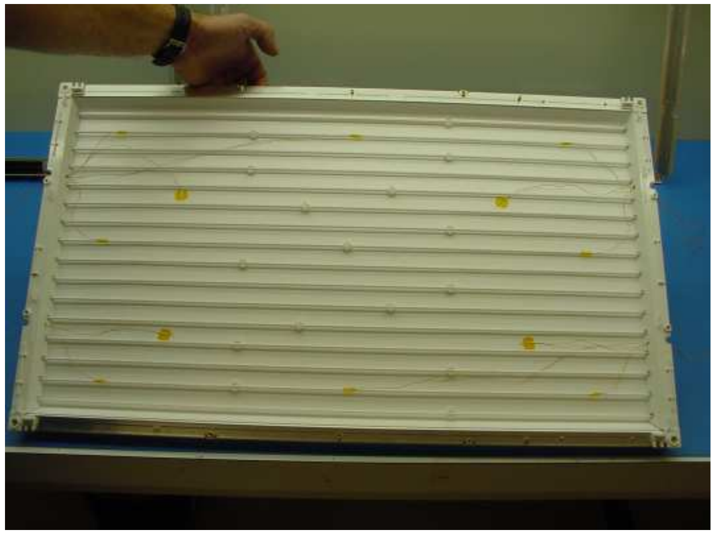


Figure 13. A partially disassembled LCD backlight (showing fluorescent lamps)

II-VI color-converted LEDs can also reduce the number of electronic components in an application (compared to the number of components required for conventional LEDs). A stable color LED device presently requires a compensation circuit (coupled with a look-up table) to actively adjust the relative fraction of light contributed by each LED to maintain the desired color point over the entire operating current range. II-VI color-converted LEDs would require reduced number of components (through the elimination of compensation circuits – including detectors with feedback) and also avoids the need to consume the energy that would be required to drive these circuits. Furthermore, LED devices presently often include more than one of a single color conventional LED (*e.g.* two green InGaN LEDs to compensate for the low green power efficiency and perhaps two red AlInGaP LEDs to compensate for the power decrease associated with operation at higher temperature are combined with one blue InGaN LED to create a RGB multi-chip cluster). II-VI color-converted LEDs would potentially eliminate the need for the additional LEDs. In large display applications (that require hundreds of such RGB LED clusters) this translates into a large reduction in the number of electronic components to achieve the desired performance.

5.5 Improved Energy Efficiency

The II-VI color-converted LED technology has the ability to improve the operating efficiency of LED devices. This is particularly important in the green-yellow region of the spectrum (in which the conventional InGaN and AlInGaP LED technologies have very low energy efficiency).

The external power efficiency of yellow (580 nm) II-VI color-convertor material has been measured (via photoluminescence) to be greater than 30%. In comparison, the best commercially-available amber LEDs (590 nm) have an energy efficiency of 10% or less. It is conservatively estimated that additional energy losses associated with the construction of a yellow or amber II-VI color-converted LED will reduce the total energy efficiency to no less than 15% (from the 30% measured on the II-VI material alone). Therefore II-VI color-converted LEDs are 50% more energy efficient yielding a 33% energy savings to generate the same amount of light as well as the ability to tune the emission wavelength to the exact color desired.

5.6 Additional Environmental Benefit From Using II-VI Color-Converted LEDs

Estimation of Potential Market Size

The total worldwide LED market for high-brightness (HB) LEDs in 2007 was approximately 39 billion units (and has been increasing at an annual rate of 26 – 29%/year during the past three years [Ref. 1]. Assuming that the unit growth rate is 20% during the next couple of years it is estimated that approximately 67 billion HB LEDs will be sold annually by 2010. Standard, high-current, high-power and multi-chip clusters comprised 81%, 10%, 2% and 7% of the HB LED market, respectively [Ref. 1]. During 2006, 48% of HB LEDs (by sales value) were white (blue pump LED + yellow phosphor); 28% were blue/green InGaN; 17% were red & amber AlInGaP; the remainder (7%) were RGB multi-chip devices [Ref. 2]. Finally, the EU accounts for approximately 20% of the worldwide lighting market [Ref. 3].

Commercially-available LEDs typically range in size from ~200 μm X 200 μm to ~1 mm X 1 mm; color-conversion of these LEDs with II-VI materials yields a Cd content of ~0.3 μg to 7 μg per LED. The total Cd content as a function of the number of II-VI color-converted LEDs is shown in Figure 14.

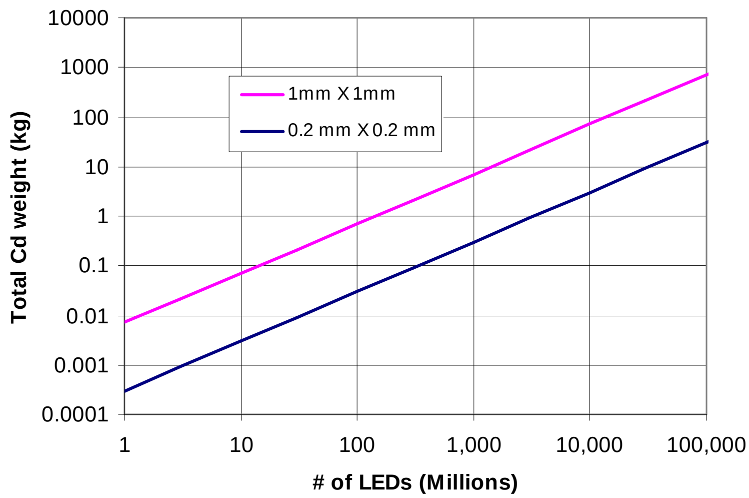


Figure 14. Total Cd content in II-VI color-converted LEDs for a range of die sizes.

It is possible to estimate the total quantity of Cd incorporated into II-VI color-converted LEDs sold within the EU to be **less than 10 kg per annum** by combining the above market segmentation numbers along with estimates of LED chip size by distributions of color & type and likely penetration rates of II-VI color-converted LEDs by application. For example, none of the blue InGaN LEDs currently sold (presently at least half of all blue & green InGaN LEDs) would use II-VI films. Furthermore, many of the white (blue + yellow phosphor) LEDs used in applications with low color-rendering requirements would also not require II-VI materials. The total annual content of Cd (in the form of products sold into Europe – and worldwide) would therefore be relatively small.

Estimated Overall Reductions in Cd Releases

The relatively small quantities of Cd incorporated within II-VI color-converted LEDs can be compared to the quantities of heavy metals that would be released through the production of electricity to run lower-efficiency devices. In particular, data for arsenic, cadmium, mercury and lead released from coal-fired electrical power plants in Japan [Ref. 4] and from all electrical power plants in Finland [Ref. 5] is available. Based on this data, the estimated reduction in lifetime emissions for a single II-VI color-converted amber LED as described in Section 5.5 (having 50% higher efficiency than a conventional amber LED and assuming 1W of operating power and 20,000 hour device lifetime) is shown in Table 4.

Estimated Reduction in Emissions over Device Lifetime (μg)				Quantity of cadmium in amber II - VI LED (μg)
As	Cd	Hg	Pb	Cd
80	10	50	30	1

Table 4. Estimated reduction in certain power plant emissions over lifetime of one amber II-VI LED

In particular, it should be noted that the estimated Cd emission reduction is 10X larger than the quantity of Cd contained in the II-VI color-converted LED (assumed to be ~1 μg for this analysis). Furthermore, this analysis assumes a relatively conservative Cd emission rate from power stations of 1 μg/kWhr for electricity generation (as listed in Ref. 4) whereas many power stations emit much more cadmium per kWhr. However, the Cd emission rate/kWhr is heavily dependent upon the mixture of fuel sources used to generate electricity [Ref. 6]. The use of large fractions of coal or oil to generate electricity will increase the Cd emission rate beyond that used in the above analysis and will further increase the net reduction in heavy metal emissions that would be achieved by the use of amber II-VI color-converted LEDs instead of standard amber LEDs.

Current market trends in information displays are also having an impact on device energy efficiency (which in turn affects heavy metal emission rates from electrical power generation). Wide-color-gamut (WCG) CCFLs are being adopted in an increasing number of LCD backlights to provide greater color saturation in response to consumer demands for more vibrant displays. Unfortunately, WCG-CCFLs are approximately 20% less efficient than conventional CCFLs (suggesting that market pressures are lowering the overall power efficiency of these consumer products). One example of a commercially-available display using WCG-CCFLs consumes 155 W of electricity [Ref. 7] of which approximately 75% of the power (115 W) is consumed in the backlight. LED backlights (an alternative approach) have power efficiency that is no higher than that of CCFL backlights when the LEDs are powered continuously. However, power savings can be achieved by dividing the LED backlight area into zones and dynamically controlling the brightness of these zones to match the brightness of the image to be shown. This technique of zonal adaptive illumination has been shown to yield a power savings of up to 80% compared to having the LEDs illuminated continuously [Ref. 8]. Zonal illumination is not possible with CCFLs (which must remain illuminated continuously). By taking into account these power savings it can be shown that this display using a zoned illumination backlight incorporating an amber II-VI color-converted LED and commercially-available conventional red, green and blue LEDs requires 65 W less than a backlight of the same brightness using WCG-CCFLs. An additional 650 kWhr of electricity is therefore required to power the WCG-CCFL device over its lifetime (assumed to be 10,000 hours). Table 5 shows the estimated heavy metal emissions associated with the generation of this additional electricity (using the same emission rates contained in the analysis for Table 4). It is clear that consumer demand for displays with a larger color gamut using existing technology has a significant environmental impact. II-VI color-converted LEDs have the ability to meet the market demand for a wide color gamut display while maintaining high power efficiency and reducing emissions from levels associated with standard CCFL backlights.

Estimated Reduction in Emissions over Display Lifetime (μg)			
As	Cd	Hg	Pb
5200	650	3250	1950

Table 5. Estimated reduction in certain power plant emissions over lifetime of one zonal adaptive illumination LED backlight (consuming 50 W) compared to the same display with a wide-color-gamut CCFL backlight (consuming 115 W).

Solubility data for related Cd compounds (including Cd, CdSe and ZnCdS) is available in Reference 9. All of these Cd compounds are insoluble in water at 20 ^oC. This is important when considering how II-VI color-convertor LED products may impact the environment throughout their product life cycle.

6. Conclusion

II-VI color-converted LEDs have a number of technical attributes that address many of the problems associated with current commercially available lighting solutions. Unlike alternative approaches, the emission wavelength from the II-VI film can be tuned anywhere within the visible spectrum. The ability to generate narrow emission peaks from a single material system enables better stability (through variations in temperature) than is possible with combinations of conventional LEDs made from different material systems. A much smaller amount of Cd is present in a lighting system than the amount of Hg contained within a fluorescent lighting system capable of generating the same amount of light. In addition, the Cd contained within the II-VI color-convertor material is covalently bound within the semiconductor lattice and encapsulated within a glassy protective coating, making it more stable and greatly reducing the possibility of release to the environment (unlike the Hg contained within a fragile fluorescent lamp). Where amber II – VI color-converted LEDs are used to replace standard amber LEDs, there is a saving in energy over the life of the LED such that the reduction in estimated cadmium emissions (from energy generation) is 10X (ten times) greater than the amount of cadmium used in the LED.

7. Suggested Definition of New Exemption

It is requested that Cadmium be exempt in the following application:

"Cadmium within a color converting single crystal semiconductor film for use in solid state illumination or display systems"

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