A Critical Advance In MR16 Lamps

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Abstract

The Holy Grail of lighting is a man-made light source that has superior energy efficiency, long life, good lumen maintenance, wide temperature starting and operating range, instant starting without life degradation, full range dimming, excellent color, low- to-moderate cost, and is capable of being a “point source.” All conventional lamps fail substantially in one or more of these fundamental criteria.

As it has evolved, solid-state lighting (SSL or LED) has succeeded in meeting many of these criteria. Various current products demonstrate energy efficiency, long life, good lumen maintenance, wide temperature range, instant starting, and full range dimming. Most recently, superior color has also been achieved. However, while individual LED sources are reasonably close to a point source, they have low lumen density per point, forcing lamp engineers to use multiple point sources to create a highly directional lamp. The multiple sources create multiple shadows and in some cases colored shadows that are considered undesirable in display applications.

The recent commercialization of GaN on GaN technology is a significant breakthrough in energy density, allowing 5-10 times more lumens to be generated per unit volume. The primary benefit is smaller LED emitter size, which in turn reduces the size of directional lamps and results in point source-like behavior. Another important benefit is greater heat tolerance, enabling the dense lumen package to operate more readily in a compact package and in enclosed fixtures.

A commercial product using GaN on GaN technology has been developed as a family of MR16, 12-volt AC lamps. Depending on the version, the lamp family’s performance approaches that of generic 50-Watt MR16 halogen lamps and is comparable to 30-35 watt premium or IR halogen lamps. The products include integral drivers that operate well on a number of combinations of transformers and dimmers, which are delineated in product literature. Common applications include track and recessed lighting (provided that the normal glass lens is removed) and one version is specifically for enclosed luminaires such as used in landscape lighting.

Lamp color rendering is available in standard and high CRI versions. The standard version is offered at either 2700K or 3000K and 80 CRI. The high CRI version is offered at either 2700K or 3000K and 95 CRI. To achieve high color rendering with deep red (R_9>90), this product employs "violet pumped" triphosphor, achieving a closer match to the blackbody than conventional two phosphor "blue pumped" LED. As a side effect, the lamps' violet emission around 410 nm reacts with optical brightening agents to have a unique whitening effect for display uses.

The resulting product appears to be a significant leap in LED technology for the huge worldwide MR marketplace, with performance that, within practical wattage and lumen limits, rivals common halogen MR16 and the best LED light engines with remote drivers.

Introduction

While most of the world's politicians and environmentalists are focused on the demise of the common incandescent lamp and the rise of the A-lamp LED for existing lamp sockets worldwide, designers are anxious for the LED MR16 lamp. In a wide range of applications in homes, hotels, stores, offices, and outdoor locations, the MR16 halogen lamp remains in high demand due to its small size, style, crisp-warm tone and highly directional light quality. For over 30 years, the MR16 has been synonymous with "lighting design" more than any other light source.

The lighting community is frustrated that an LED replacement for the MR16 halogen lamp has been too long in coming. Common knowledge about LED lamps, particularly their preference for low voltage power, seems to suggest that MR16 LED lamps should be easy to develop and would be among the most important products for early adopters. But despite a number of product attempts, (even including a lamp with an internal fan), until recently none have posed a reasonable challenge to the performance of the halogen lamps they might replace.

With a fundamental technical breakthrough, a product has been developed that can meet or exceed the expectations of the marketplace. This review indicates that the first MR16 lamp family with performance comparable to generic MR16 halogen lamps appears to have been achieved.

This paper has been developed to critically review the new technology and to assess the accuracy of product claims. While the intended primary audience is the professional engineer or lighting designer, this paper will be useful to many in architecture, interior design, product design, engineering, manufacturing, and others directly engaged in the design, construction, and management of facilities, as well as those particularly concerned with light, lighting and color.

Understanding GaN on GaN

Basic Science

Light emitting diodes (LEDs) are a special type of diode, which is a common electronic circuit component used in all electronic devices. Like all diodes, an LED passes electric current in one direction only. All diodes dissipate some energy when the electric current passes through; common diodes convert this energy to heat, but LEDs convert the energy substantially to light. The color of light emitted is determined by the type of semiconductor material that is used in the active region of the device, and by the thickness of the individual layers within the active region. All LEDs that generate white light for architectural lighting use Gallium Nitride (GaN) as the semiconductor material. The forward voltage drop (measured in volts) and the current through the diode, (measured in amps or milliamps) measure the wattage of the diode. These are typically regulated by a driver, an electronic circuit between the LED and mains power, that maintains stable voltage and current in order to prevent the LED from fluctuating or burning up.

Practical Differences Between GaN on GaN and Other Technologies

To make an LED, crystal layers of GaN are grown on a substrate material. The substrate material must have certain qualities, and the most commonly used for LEDs today are sapphire and silicon carbide. Due to differences in material properties between GaN and these materials, the GaN crystal grows imperfectly on such foreign substrates, and produces a high incidence of imperfections which reduce the light generation efficiency of the LED.

The primary scientific breakthrough of this product is the ability to grow GaN crystals on its native GaN substrate (“GaN on GaN”). The crystal grows much more perfectly, can accommodate much higher power densities, and allows the LED emit 5-10 times more light from the same crystal area. This is called “light density”- it’s the reason that GaN on GaN devices exhibit far more point-source-like qualities. As an added benefit, the GaN on GaN technology is more heat tolerant than other substrate types and allows higher energy conversion in small form factors.

To further increase efficiency compared to other diode types, this family of products uses a design that mitigates LED “droop”, a phenomenon observed in GaN-based LEDs wherein efficiency drops as power density is increased. This design allows the LEDs to maintain high efficiency at high operating power densities, and produces a very bright, point-source-like light source.

Color

Common Colorimetry and Color Metrics

Introduction

MR16 lamps are often selected for their ability to render objects vividly and make colors appear natural. Part of the original appeal of the MR16 was its higher Correlated Color Temperature (CCT) in comparison to common incandescent lamps. Objects with higher color temperature than the ambient environment appear brighter and call attention to themselves- hence the old theater lighting axiom of “fill warm and key cool”. The halogen MR16 lamp is the perfect addition to regular tungsten lighting, and adds highlights and sparkle to a conventional design in an energy efficient and economical product. No wonder that the MR16 epitomizes ***lighting design***- the lamp enabled the artistic and dramatic potential of lighting in everyday projects.

But the MR16 has other important qualities. It is small, attractive, and adds sparkle and drama to ordinary spaces. It is often used for the general lighting of sophisticated spaces because of its size and the interesting contrast it creates. This legitimizes the concept of 2700K MR16’s for fill lighting as well as 3000K MR16’s for key lighting. In fact, a commonly applied professional accessory for the MR16 lamp is a 2700K filter, used for precisely this purpose.

Importance of Color

MR16 lamps are often used in art display and other situations were color rendering is quite important. From the experience of lighting designers worldwide, however, there are applications where color matters somewhat, and applications where color ***really*** matters. These tend to include:

- Museums
- Galleries
- Retail clothing
- Jewelry
- Food sales and service

LED lamps produce light differently than halogen lamps. Halogen MR16 lamps tend to emit light almost perfectly relative to the reference standard “blackbody”. But LED lighting is more like fluorescent lighting, using blended phosphors to fluoresce and emit light of various wavelengths that, working together, synthesize white light. The relative accuracy of this synthesis among different MR16 LEDs is a crucial criteria when specifying sources for lighting design.

Review of Spectral Power Density (SPD)

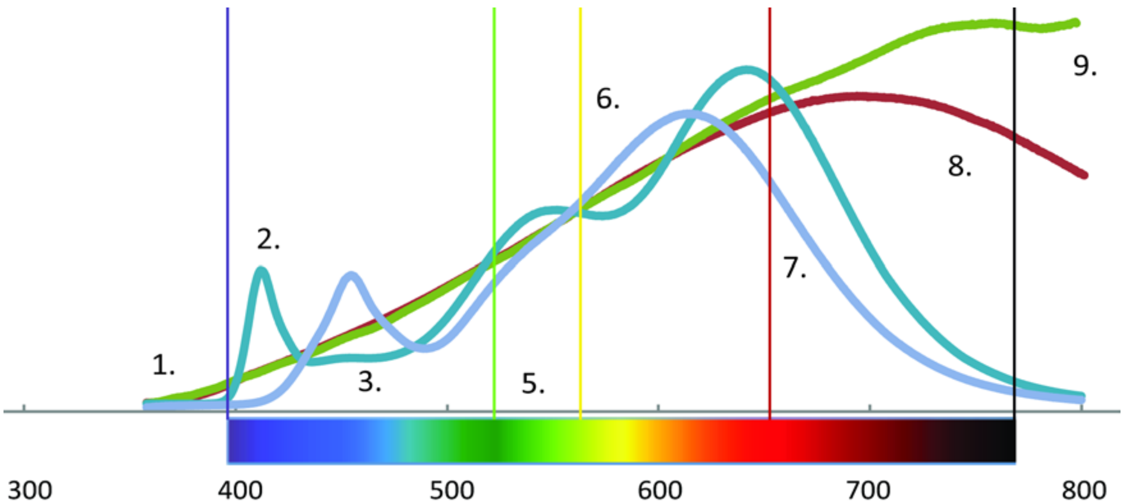

Figure 1-1 Spectral Power Density of MR16 Sources

Professional evaluation of a light source often begins by reviewing its color spectrum. Especially as light sources become more complex and use quantum physics to create light (rather than heat), a spectral power density diagram is an intuitive way to better understand what to expect of the light source.

In figure 1-1, the spectra of several lamps are demonstrated:

A conventional halogen MR16 lamp with premium dichroic coating

A halogen IR MR16 (narrow flood)

A first generation LED (BP2P), blue pump, 3000K at 80 CRI

An LED using GaN on GaN (VP3P), violet pump, 2700K at 95 CRI

The conventional halogen MR16 lamp emits light very closely matching the blackbody curve, as expected. But note several key observations (keyed to the figure):

1. In the UV region, all LED sources have no emission, but halogen lamps do. While it seems small, UV from most light sources is the principal cause of photodegradation and must be controlled.

2. Violet pumped LED lamps overshoot violet and other near-UV wavelengths, which can improve whiteness rendering (see below). But even short wave visible light is a source of concern with respect to museum lighting. See discussion in the last part of this report.
3. Violet pumped lamps undershoot the blackbody in blue, but not by much.
4. Blue pumped LED lamps strongly overshoot blue at approximately the human circadian response peak, with both positive and negative potential in health and light situations.
5. Blue pumped LED lamps undershoot cyan, reducing color rendering throughout the green-blue range.
6. Most sources are about the same in the green-yellow-orange range.
7. The lower CRI LED products roll-off in medium and long wave red, hence the poor R9 numbers (see below)
8. Pure red is centered at about 687 nm. The high CRI LED lamps approach the response of the halogen IR lamps. While the LED lamps then roll off fairly quickly towards long wave red, the halogen IR lamps roll off more gently.
9. Only the conventional halogen lamp follows the blackbody curve into the IR region.

It is generally recommended that analyzing the SPD of any candidate light source should be the first step in color review. Because human color vision varies due to chromatic adaptation, cognition and other factors, it often helps to identify potential issues from the SPD chart before relying on other metrics or visual inspection.

Color Rendering Index (CRI)

The best-known metric for color quality, CRI, is a quantitative measure of the ability of a light source to reproduce objects faithfully relative to an ideal light source. CRI has been criticized and replacement systems proposed (see below), but none has yet managed to replace this well-established system.

CRI is determined by comparing the color of sample color swatches under a test light source versus under a reference light source of the same correlated color temperature. The CRI value is computed using eight colors (R_1 through R_8) that are unsaturated, pastel-like colors. Six supplementary colors are also tested to provide additional information. R_9 through R_{12}, for instance, are saturated colors (red, yellow, green and blue). For LED sources, high CRI values are often presented with their R_9 value (red), as red is typically the weakest color typically rendered by LED sources but well rendered by the halogen lamps they are intended to replace. For instance, most common 3000K LED MR16 lamps have CRI 80, which is considered good, but R_9=0, which means that reds and warm tones will be slightly sallow.

Perhaps the toughest criticism of CRI is that the system was developed primarily for halophosphor fluorescent lamps, whose SPD's exhibit very little peak-and-valley behavior. With sources like LED showing potential for exaggerated peaks and valleys throughout the spectrum, critics claim CRI is not well suited to explain in a single number the quality of state-of-the-art light sources.

Color Quality Scale (CQS)

CQS, developed by scientists at the US National Institute of Standards and Technology (NIST), was designed to replace CRI and compensates for most of CRI's shortcomings. However, CQS is one of a number of competing systems being considered by the International Commission on Illumination (CIE). Six other candidate systems from around the world are also in the running. CQS is a leading contender, but for now, CRI is still the recognized system.

Creating White Light with LED

Red Green Blue (RGB) LED

LEDs are available in all three colors, and mixed together, can generate white light at virtually any color temperature, or for that matter, any color of light at all. The principle of RGB color mixing is the underlying technology behind television, digital cameras, theatrical lighting, and a multitude of other uses. Using three LED chips in close proximity, LED color changing systems have been popular since the invention and practical dissemination of the blue LED in the late 1990's.

However, there are practical problems with using RGB for a white light source, especially for architectural lighting where the light source is expected to remain stable for 25,000 hours or longer. The three types of LED – red, green, and blue – age and degrade at different rates. This method was long abandoned for use in architectural lighting, and for theatrical lighting, the system was expanded to include more colors of LED.

Blue Pump Two Phosphor (BP2P) LED

LEDs are not naturally white – GaN-based LEDs for architectural lighting can be designed to emit any one color in the range of UV-A (380 nanometers) through green (550 nanometers). Most of the LED industry has chosen royal blue (around 450 nanometers) because blue light excites "R" (red) and "G" (green) phosphors, and letting some blue through completes the spectrum. Depending on the color temperature of the LED, the direct amount of narrow band blue radiation (called the "blue spike") is pronounced. Conversely, physical limitations prevent light emission near this blue spike and especially in the cyan range, so most BP2P LEDs exhibit a “valley of cyan” and render those colors poorly (see "Spectral undershoot and overshoot" below).

The “blue spike” in most white LEDs is both a potential benefit and a potential problem. It coincides with the response of the human iPRG cells that cause circadian responses normally associated with daylight, which could be used positively by day but might present a photobiological problem at night.

Similar to fluorescent lamps, white LEDs can employ phosphor engineering to create higher CRI lamps that minimize the peaks and valleys of mainstream white LEDs. Some products also increase the deep red output (R_9), which reduces lumens and luminous efficacy but also results in a better display lamp.

Violet Pump Three Phosphor (VP3P)

In VP3P technology, violet light at 415 nanometers is used to excite phosphor material containing blue, green and red phosphors, very much like most modern fluorescent lamps. The source exhibits a “violet” spike and a valley of blue, although not as exaggerated as the “valley of cyan” in BP2P diodes. The resulting color spectrum has the potential of higher CRI and luminous efficacy. Besides, the added violet can excite fluorescent materials commonly used as brighteners in fabrics, detergents, and other products, a benefit to the display of certain retail products.

The “violet spike” has its own potential concerns. For display lighting purposes, the amount of visible radiation near UV may possibly create photodegradation damage similar to UV from halogen lamps- this is a potential issue for museum applications. On the other hand the violet spike causes few concerns when it comes to human health, because known detrimental health effects are confined to the ultra-violet range where VP3P LEDs do not emit light.

Unique Color Issues of LED

Blackbody matching

The practical reference of “good” color rendering is the blackbody, a theoretical object that can be heated to any temperature without oxidizing or burning. When sufficiently heated, the object glows, and the color of light emitted is referenced to the thermal temperature of the blackbody. Incandescent lamps (including halogen) are essentially blackbody sources, as the filament is heated to produce light. Natural daylight is also essentially a blackbody. The obvious difference between the two reflects the color temperature difference.

To a certain extent, the human eye can adapt to color deficiencies. It is not necessary for a light source to perfectly match the blackbody to adequately render colors. But for product concept and design, lamp manufacturers make every effort to match the blackbody spectrum, as the closest match will produce higher CRI.

Spectral undershoot and overshoot

The peaks and valleys of either LED pump method (BP2P or VP3P) are caused by physical principles that are unavoidable. Fluorescent lamps, in comparison, use mostly ultraviolet light to excite phosphors, and are capable of generating an almost perfect spectrum at any color temperature. But for LEDs, the prospect of an ultraviolet source poses too many possible application risks and problems. Phosphors absorb light at one wavelength and re-emit light at another, longer wavelength. Therefore, there is a “valley” of wavelength between the exciting light and the emitted light. For instance, if a blue LED excites a green phosphor, a valley of emission exists in the cyan range- this is the origin of the detrimental "cyan valley" in BP2P LEDs.

Deep red

Critical color rendering evaluations often focus on the deepest reds, as this is where most manmade light sources don’t do well. For the true burgundy of fine wine or the deep blood red of certain paints and fabrics, lack of emissions at 700 nanometers will be revealed quickly in comparative visual testing, and these colors will appear more orange with low CRI and low R_9 lamps. Lamps with CRI>90 and R_9>80 are most likely to appear natural when rendering these colors.

While it is possible to improve R_9 with good phosphor engineering, it is important to remember that lumens will be reduced as energy is moved from the green yellow region, to which the eye is most sensitive, to produce long wave red instead. As it was true with fluorescent lamps, it is also true with LED lamps: superior color rendering, especially in red, will result in lamps of lower lumens and lower luminous efficacy.

Whitening

In fabrics, printed materials, detergents, and toothpaste, artificial brighteners are used that capture violet and ultraviolet light and then fluoresce blue light, making whites appear "brighter." The VP3P system can potentially produce a far more pronounced effect than the BP2P system, where little fluorescence is excited.

Metamerism

Metamerism is a complicated effect that describes the ability for a particular set of objects to appear the same color under two different illuminants. A common complaint among retailers is that materials in two products, such as a sweater and a skirt, match under their display lighting system but clash when seen in daylight - a manifestation of what's called ***illuminant metameric failure***.

As a general rule, a light source that carefully follows the blackbody curve will avoid such practical problems of color shift.

Light Quantity

Luminous flux

The lumens emitted by a source are a historically significant measure of its output and efficacy, measured in lumens per watt. But luminous flux is less valuable when evaluating a directional light source, because the principal interest in the source is the candlepower (see below). Moreover, the lumens of the source contained within the assembly of lamp, reflector and/or lens cannot be used for conventional calculations. For these reasons, many directional light sources do not have published lumen ratings, and for those that do the information is of little practical value.

Candlepower

Basics

For most accent and display lighting, the Center Beam Candle Power (CBCP) and beam angle are used to make source selections. Being directional light sources, MR16 lamps are specified by their CBCP and beam angle in degrees. CBCP is the measure peak intensity also referred and is measured in Candela (Cd). Beam angle is defined by the angle at which the intensity is half of the peak intensity.

Less commonly, directional lighting is also described by field angle. Field angle is defined as the angles at which the intensity is 1/10 of peak intensity. Wider angles are called "spill light" and aren't usually described.

Candlepower "standards"

Over time, popular names were adopted to describe the beam of common lamps and luminaires. This system was more-or-less officially adopted by the industry and is used by hands-on practitioners, especially in theater, retail and museum applications.

Common name	*Nominal Beamspread*	*Common Variations*	*Use*
Pinspot	5°	1-6°	Extreme highlights or extremely long throws
Very Narrow Spot (VNSP)	8°	7-9°	Intense highlights of small objects or very long throws
Narrow Spot (NSP)	10°	10-15°	Highlights or long throws
Spot (SP)	15°	15-20°	Highlights or long throws
Narrow Flood (NFL)	25°	20-30°	Small area illumination
Flood (FL)	35°	30-40°	Area illumination and washes
Wide Flood (WFL)	55°	50-60°	Washes
Very Wide Flood	>60°		Broad area washes

Table 1 Generic Directional Lamp Beamspreads

Note that there are no specific standards of candlepower values. When lighting energy codes are not significant, users are accustomed to favorite lamps and specifiers are not overly exacting. But with the increased emphasis on energy efficiency, even relatively minor differences could weigh heavily on a purchasing decision.

Lamp design and candlepower value reporting

Taking advantage of the indefinite nature of beamspread "classes", in the 1990's lamp manufacturers began to make minor changes in beam angle in order to increase CBCP. For a given light source, every degree the beam narrows, there will be an increase in the CBCP. Likewise, for every degree the field narrows, there can also be an increase.

Consider the many types of MR16 halogen technology variants (see later). The various technologies make a difference, with some having significant impact. Take for instance the "flood" halogen lamps in Table 2. Manufacturers try to maintain a competitive standard candlepower of about 1500 at, which is the more-or-less standard 40-degree ANSI code "EXN" lamp developed in the 1970's. To achieve this, the ultra long life lamp, the premium smooth reflector lamp, and the 30-watt IR lamp are all narrowed to 36 degrees, and the "saver" lamp is narrowed to 32 degrees.

	Lamp Type	Beam Angle	CBCP
Lamp 1	50 watt premium with cover glass[1]	40	1500
Lamp 2	50 watt premium	40	1700
Lamp 3	50 watt generic cover glass[1]	40	1350
Lamp 4	50 watt generic	40	1500
Lamp 5	37 watt IR	40	2200
Lamp 6	50 watt aluminized	36	2000
Lamp 7	50 watt ultra long life	36	1500
Lamp 8	24 watt saver lamp	32	1300
Lamp 9	50 watt premium lamp, smooth reflector	36	1580
Lamp 10	30 watt IR	35	1600

Table 2- Common MR16 "Flood" Halogen Lamp Types

[1] Note that cover glass reduces CPCP by about 10%. This occurs in every halogen fixture with a lens, so actual candlepower of a lamp in use should be reduced by 10%. An LED is often not used with a lens, hence the actual output is as reported.

Practical Considerations

About the MR16 lamp

MR16 Halogen Lamps

The MR16 lamp made its first appearance in 1965 when it was introduced as a slide and film projector lamp by General Electric. “MR” stands for “multifaceted reflector” and 16 stands for the approximate diameter in 1/8 ths of inches. Over the years, MR16 lamps have become widely used in architectural lighting applications such as museums, retail stores, landscapes, and residential settings for accent, task, and display illumination. They are typically used in track lighting or recessed downlights for interior lighting and in landscape luminaires in outdoor settings.

The conventional halogen MR16 lamp employs a compact halogen lamp (“burner”) and a reflector made of coated glass. The burner is a quartz glass envelope compact lamp that must be protected from explosion. The coating is dichroic, which is used to reflect visible light but not infrared light, letting the IR heat out of the back of the lamp to be absorbed and dissipated by the housing. The common reflector style is faceted, although smooth reflectors are also used.

The advantages of MR16 lamps over other lamp types are related to their small size, color properties and beam control. These qualities have been harvested in hundreds of thousands of applications, especially when space is constrained or when aesthetics are of primary interest. Recessed luminaires with trims as small as 3” (76 mm) in diameter and track and landscape luminaires as small as 2.25” (57 mm) in diameter are extremely popular due to their size. Lamps are offered over a very wide range of power, from 10 watts to 75 watts. There are a number of major different beamspreads (see Table 1, above) and versions of varying technologies (Table 2). The differing technology in lamps resulted from demands of the marketplace as well as technical advances; for example, the premium dichroic and aluminized lamps provide stable color over life, and the long life lamps allow the appealing MR16 to serve as a downlight in elevators and other demanding service locations where relamping is inconvenient and expensive over the long term.

Lamp Type	***Characteristic***	***Discussion***
Generic	Original dichroic coating and conventional halogen burner	Coating degenerates over time, reducing performance and shifting lamp towards green
Premium	Titanium dioxide dichroic reflector, conventional halogen burner	Coating remains stable, lamp color remains consistent
Premium UV stop	Burner coated to absorb UV	Reduces UV emissions
Aluminized	Aluminized, not dichroic reflector, with conventional halogen burner	Full halogen spectrum in beam
GU10	Line voltage variation of generic lamp, halogen burner	Line voltage, relatively poor performance
Twist and Lock	GE's unique version, halogen burner	Premium lamp, special base
Colored	Dichroic coating used to alter lamp color temperature or to create a specifically colored lamp	Many niche products ranging from 3500-5500K lamps to tuned lamps (e.g. minus green jewelry display) and saturated colors
IR	Special "IR" burner is coated to pass light and reflect IR back onto filament to regenerate heat	Known as IR, HIR and IRC, most lamps are also premium and UV stop

Table 3 Common Types of MR-16 Halogen Lamps

The key disadvantages of halogen MR16s are short life, relatively low energy efficiency and the heat that they generate. Because of their high operating temperature, direct contact to skin or flammable materials should be avoided. Luminaires can suffer long term degradation of transformer life, socket life and wiring due to heat. Also, heat degradation in sockets is exacerbated by the frequent relamping required by halogen's short life.

Lamp life of halogen MR16 ranges from 2000 hours for generic lamps to 5000-6000 hours for most premium lamps. There are a few long life products rated 10,000 hours or more. Like other halogen lamps, dimming may extend lamp life but there will be considerable reduction in performance.

MR16 LED Lamps

LED MR16 halogen lamps have generally been designed for direct replacement in MR16 luminaires. This means that the lamp contains a driver suitable for 12 volt AC operation of the lamp. Most LED MR16 lamps work on existing transformers and dimmers, and in general, the MR16 will use less energy and create less heat than the halogen lamp it replaces, with benefits that include lower energy costs and longer equipment life.

The dimension of MR16 halogen lamps has been reasonably standardized throughout the industry, but the design of some LED sources has resulted in compromises in form factor. For instance, most LED lamps require convection cooling, and the use of any glass lens (normally needed for safety with halogen lamps) will damage most LED lamps. Some LED lamps even have protruding lenses to prevent the glass lens from being used. Others require internal fans that extend the height of the lamp beyond standard dimensions, and also can draw extra power when dimmed to 0%. Therefore, even though LED lamps are referred to as “MR16”, they may have dimensions that deviate from the standardized size envelope in a non-standard manner.

Lamp Family

Based on the same GaN on GaN design, the first products have been developed for commercial sale. The manufacturer wisely sought to limit the power to a value that could be warranted for at least 25,000 hours in common applications. The first group of products include four product lines, each offered in three beamspreads and two color temperatures,that capture the most commonly used lamps for professional accent lighting applications. At the time of this paper, only the narrow flood lamps were ready for evaluation.

Standard

The standard lamp, called “Essential,” is a 10-watt NFL, 80CRI, offered at both 2700K and 3000K. CBCP is roughly equal to that of a comparable generic 35 watt FMV. It is rated for use in recessed luminaires and track heads.

Premium

The premium lamp, called “Premium”, is a 12-watt NFL, 80CRI, offered at both 2700K and 3000K. CBCP is roughly equal to that of a comparable generic 50 watt EXZ. It is rated for use in recessed luminaires and track heads.

High CRI

The high CRI lamps, called "Vivid" are 12-watt lamps also rated for recessed luminaires and track heads. CRI is 95 with R9 of greater than 90. Performance is roughly equal to a 35 watt generic FMV.

Standard Outdoor

This lamp, which is rated for use in an enclosed and gasketed luminaire, is a 9.5 watt, 80 CRI source with performance roughly equal to a 35 watt generic FMV.

Light Quality

Beam quality and management

The optics of this LED product are not unusual, but are unique in 35W+ LED MR16 lamps; because of the single small high-intensity source, the optical system performs exceptionally well. While this LED is fundamentally a directional source, a lens is added to redirect the light energy. This lens is particularly effective at controlling beam, field and spill, essentially eliminating spill. See Figures 1-1 and 1-2, below. The LED is all but free of spill light, making glare shielding easier and more effective.

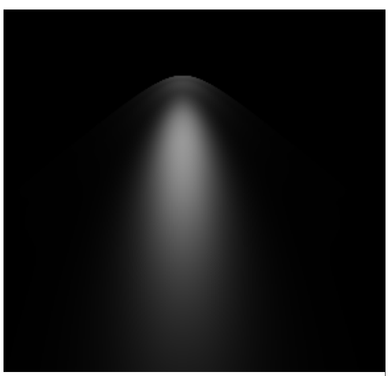

Figure 1-1 GaN on GaN LED

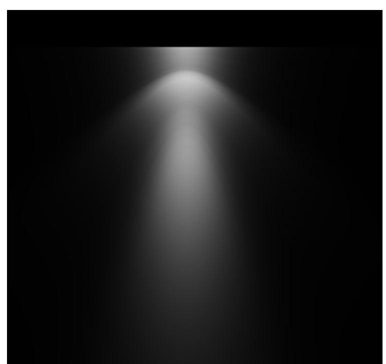

Figure 1-2 Halogen

Shadowing

Shadows play an important role in creating a dramatic and effect-rich lighting scene, and in interpreting textures. Especially if the texture structure is fine, small differences in shadow definition can have a big impact on the visual impression.

An infinitesimally small source or (a true "point") source creates a shadow with a crisp, immediate transition between light and dark. All practical light sources have some size and will have some transition between the dark of the full shadow and the unobscured illuminated area. This is illustrated in figure 1-0-2. The larger the source, the larger the transition area. The transition area also increases as the light source moves closer to the object. The transition zone is further increased with the introduction of multiple sources.

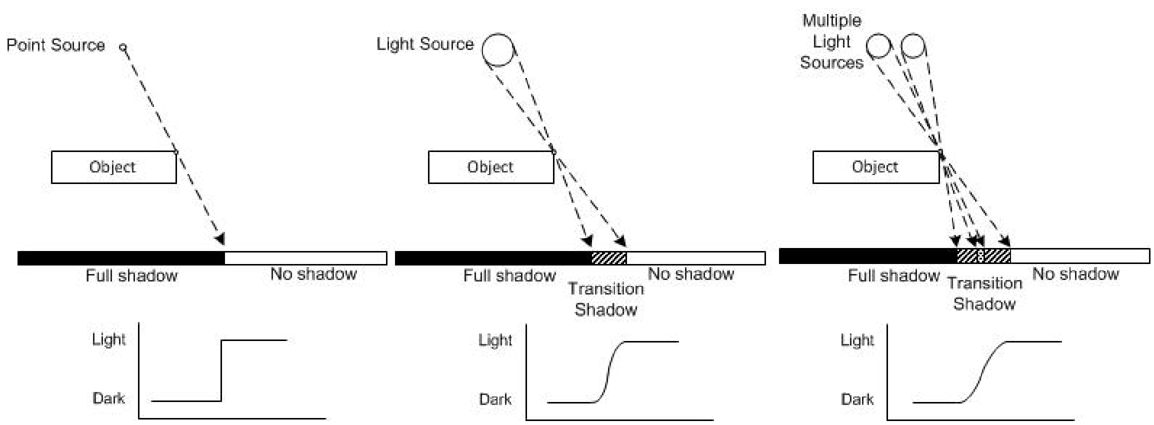

Figure 1-0-2 Shadows from Light Sources

Another advantage of a single source is that duplicate or mushy shadows are avoided (Figure 1-3)

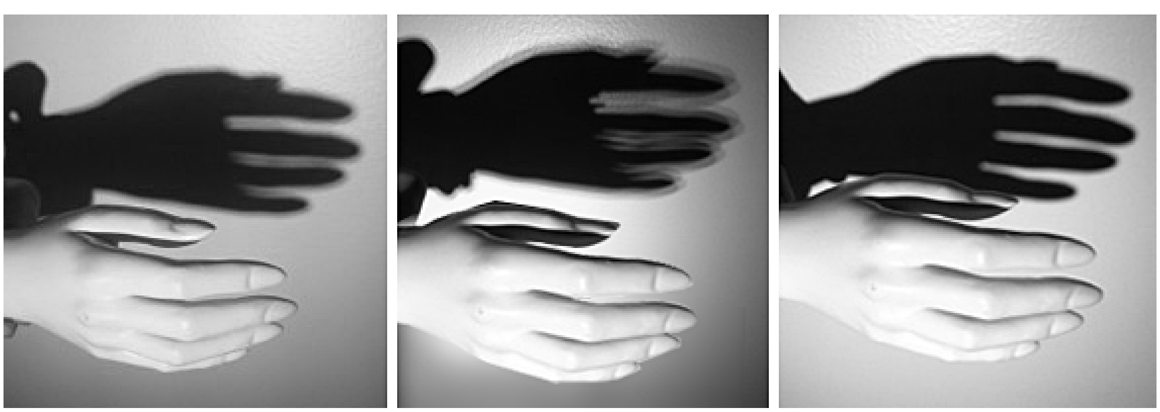

Figure 1-3 Shadows from (left) a large source (Halogen MR16), (center) multiple point sources (first generation LED MR 16 with 4 LEDs) and (right) single point source (GaN on GaN LED MR16) source

Beam Management Accessories

The artistry of using MR16s has historically involved external light quality management, notably the use of lenses to alter the beam pattern, and baffles and louvers to shield the spill light from sight. With this generation of products, new methods will need to evolve because:

- The source is relatively spill light free, making the shielding accessories less important
- The beam is relatively halation and striation free, making smoothing lenses mostly unnecessary.
- The beam of this LED is “flat”, meaning that the angle of equal intensity is greater than with most halogen lamps, resulting in a steeper run-back near beam edge. Beam edge modification may be needed for some art display and cannot be performed using the standard borosilicate lenses such as solite.

These issues are not generic. Compared to other LED MR16 products, this GaN on GaN family will probably require an accessory holder that maintains free airflow around the lamp (except for the totally enclosed version), and a unique set of accessories, in order to realize its full potential as a high performance display lighting system. This has been discussed with the manufacturer, but at this time, there are no special products.

Lamps were installed and tested relative to other current LED products in open backed arm lights used to light artwork. Because of the ventilation, a conventional accessory holder, solite lens and tube baffle (“snoot”) were successfully tested and have operated successfully for months without problems. Although far better than a halogen lamp, the LED lamp has enough spill light to necessitate a snoot and for art display, a softening lens remains important. However, for direct accenting, the beam is very good and a smoothing lens is not needed, as beam imperfections are negligible.

Many MR16 applications require the use of IR and UV filters that alter the color of the light and reduce light output. The violet peak of the GaN on GaN lamp may be of some concern, but compared to halogen lamps, both this family and conventional LED exhibit complete attenuation of UV and short wave indigo, whereas halogen lamps still emit measureable light well in the UV-A region.

Color Quality

Halogen lamps

The halogen lamp, especially without filters, is virtually a reference standard blackbody. However, most MR16 halogen lamps have some type of filtering, either in the UV and deep violet and/or in the IR and deep red. Nonetheless, they remain the reference standard against which LED will be judged.

A visual principle called the "Hunt Effect" describes a phenomena in which color quality becomes more important as colors are more brightly illuminated. This supports the notion that LED MR16s of lower CRI (which generate more lumens per watt) might be used for general and ambient lighting, and that less efficacious high CRI LED MR16s might be reserved for more brightly lighted accents. With current technology, the 10- to 12-watt 80 CRI MR16 LED might be used in many situations where full advantage can be taken of the superior efficacy of the LED, while the critical rendering applications would demand the 95 CRI LED and benefit from the long life of the LED source and energy savings.

Visual Acceptance

The challenge of the MR16 LED is to be visually acceptable in comparison to halogen MR16s. Taking into account the Hunt Effect and chromatic adaptation, the majority of existing MR16 applications will look best when using either 2700K or 3000K lamps, which will closely match an existing halogen installation. After all, halogen lamps can be dimmed to change color temperature, and the so-called "dim warm" behavior remains a challenge for LED systems. But in a space where the lights are usually dimmed, the 2700K LED can be used to approximate the typical dimmed color temperature.

But even among halogen MR16 lamps, it is common for the designer to seek a warmer color temperature. Often, color temperature warming lenses such as "cosmetic peach" are installed on halogen MR16 lamps to diminish the harsh cool edge of a halogen lamp operating at 3000-3100K. The use of UV filtering lenses for museum lighting applications has a more or less similar effect. In both cases, a 2700K LED would likely be best accepted.

Metameric behavior

Metameric pairs are two different colors or materials that match under different illuminants. There do not appear to be any significant differences among lamps, but designers should be forewarned that any two different light sources run the risk of causing different relationships between two different colors or materials, and care should be a consideration in any design.

Future testing is planned to determine whether BP2P and VP3P LED’s have any practical differences.

Whitening effect

The VP3P system is relatively unique in generating a violet peak. Like UV-A, violet can cause certain whitening agents to fluoresce, and produce the so-called “whiter-than-white” effect. This effect may be of practical benefit in retail lighting and some other applications, with the caveat that it might have other side effects. See the discussion about UV and IR below.

Deep Red

Whether to render deep red is a design decision that should be made carefully. Any LED with R9>50 will have lower lumens per watt, lower lumen output, and lower CBCP. When needed, the high CRI lamps do an excellent job, visually rivaling the color and halogen IR and sometimes performing better because of the whitening effect.

UV and IR

Infrared Light (IR)

Infrared light (IR) is radiant heat. It can be felt in the beam of an incandescent lamp. In fact, more than 90% of the energy consumed by an incandescent lamp becomes heat. Occasionally, IR has a beneficial effect, as in heat lamps that focus radiant heat for comfort or hot food holding. But most of the time the heat is wasted and often increases cooling loads in buildings.

Ultraviolet Light (UV)

Ultraviolet light (UV) consists of UV-A (blacklight), UV-B (which causes vitamin D synthesis, skin damage, skin cancer) and UV-C (which causes eye damage and is used as a germicidal). UV-A can be used for special effects, and a little UV-B causes Vitamin D2 synthesis in the skin. But UV-B and UV-C should be generally avoided in lighting because of their potential for damage. UV corresponds to wavelengths shorter than 400nm.

LED Considerations

Some LED emitters are specifically designed to emit UV, and others to emit IR, but these emitters are not used for architectural lighting. Architectural lighting LEDs emit neither UV nor IR.

However, one of the principal considerations involving MR16 LED is their use in the display of fine art and collectibles. Photodegradation occurs when paintings, drawings, apparel, and furnishings are exposed to light or UV, causing colors fade and fabrics to fall apart. Curators have developed methods for mitigating damage, and in particular, reducing exposure to light and eliminating exposure to UV and IR light are among the most important measures.

As a rule, LED MR16's are free of UV, but cannot be considered to be absolutely safe. In both the VP3P and BP2P systems, short wave visible light peaks are reason for concern. Filtering to reduce the peaks may be required for critical applications.

Powering and Dimming Behavior

The MR16 LED is generally intended as a replacement lamp to be used in existing MR16 halogen sockets. In addition to some type of transformer, a dimmer also controls many MR16 applications.

Since the combination of LED, driver, transformer and dimmer were never designed to operate together, unpredictable interactions can occur. In almost all cases, the low end of the dimming range is still fairly bright compared to a halogen lamp, which can fade to black. In addition, some combinations of lamp and other electrical components will cause the LED to flicker, drop out, or sometimes, not operate at all.

The design of the driver inside the LED is the key to how the device will operate. Without any real standardization, each LED product will most likely operate differently. In the case of this product, like those of other responsible manufacturers, a list of known compatibilities is listed on the product cut sheet and company website.

Applications Details

At present, MR16 LED developers have recognized the market potential of literally millions of existing lamps. Each replacement lamp offers economic benefits (see below) as well as reducing maintenance and being "greener."

However, the MR16 halogen lamp became popular for more than just small size. The ability to accessorize and use the product in an artful manner was important in its initial acceptance and popularity among designers. With this product, the use of conventional MR16 accessories (other than a snoot) is not recommended, as conventional lenses block the airflow around the heat sink of the lamp.

There are a number of other considerations including:

- Rated life in a recessed luminaire or in a track luminaire, provided that the original lens for the halogen lamp is removed
- A special version suited for outdoor lighting in an enclosed fixture
- Proper fit in most MR16 lamp holders (not all of MR16 LEDs fit)

Energy Efficiency and Economics

The basis of this calculation is the original halogen lamp. If replacing a 50-watt generic MR16 with a 12-watt LED, the approximate savings (including reduced transformer loss) will be about 40 watts per luminaire. At 10 cents per kilowatt-hour, the energy savings in a year of typical commercial use (4000 hours) will be about $16.00. This simple payback alone may be adequate justification for use of the lamp.

Dramatically reduced relamping costs are another advantage of the LED. A quality brand generic MR16 lasting 2000 hours costs about $4.00. By warrantying the LED to three years, these LEDs will outlast generic lamps 6 times over, saving $24.00 in lamp costs as well as the cost of relamping.

Summary

Sample GaN on GaN products were received with little fanfare, and immediately upon being placed into comparative testing, demonstrated visibly superior performance to other MR16 LED lamps. Detailed investigation followed, and the manufacturer's explanations were surprisingly complete, sensible and impressive. This is genuinely different and better technology, especially for the first application of GaN on GaN in architectural lighting as an MR16 lamp alternative. For a wide variety of current MR16 applications, these lamps are respectable alternatives to and perhaps even improvements upon halogen, and provide benefits of lower energy use and longer lamp life without sacrificing color or candlepower performance.

However, lighting design professionals will quickly realize that while this first generation GaN on GaN MR16 LED lamp is a worthy replacement of generic 50W lamps, their output is still less than some state-of-the-art halogen lamps, especially the 30-50 watt IR lamps. Further improvements in the technology will overcome the heat challenges and will provide higher output product in the future. Those designers needing performance and accessories for professional applications will find these LED MR16 products quite useful, but will probably need to continue to rely on light engine technology for a complete product family of more powerful products and proven accessories.