SHORE

1. How is an LED fixture constructed or fabricated, and how does it work?

To best understand how an LED fixture is made, it might be best to first touch on how other types of light fixtures work. The traditional incandescent light works by electrical current flowing through a resistive metal filament (e.g. Tungsten), causing it to heat up and glow. Fluorescent lamps work in a similar vein – but instead of a filament, a sealed tube is filled with a mixture of gasses (typically mercury vapor and argon). As electricity flows through the gas mixture, the gasses are sent into a higher energy state. As they relax to their ground state, ultraviolet photons are emitted. These photons then strike a phosphor coating on the inside of the lamp, are absorbed and cause the phosphor to glow.

The Light Emitting Diode (LED) borrows from these two different technologies, with electrical current flowing across a very narrow gap between two dissimilar semiconductor metals. As electrical current flows, the metals are raised into a high energy state and then relax, emitting photons of a wavelength dependent on the materials they are made of. This is called electroluminescence and due to the multiple excitation levels in the semiconductors used in most LEDs, they luminesce in many colors simultaneously – creating what we interpret as white light. We are now seeing LED fixtures surrounded by phosphors that absorb the blue spectrum and convert it to a warmer color through phosphorescence. An LED fixture is comprised of five subsystems:

The light sources are the LED chips themselves – comprised of a metal semiconductor. Common metal sandwiches that are in use in most "white light" fixtures today are Indium Gallium Nitride (InGaN) whereas "amber" fixtures are typically made of Aluminum Indium Galium Phosphide (AlInGaP). A single fixture can contain up to 200 individual LEDs.

The optical system is comprised of a glass cover at a minimum, but beam-forming optics made of glass or acrylic are often included to shape the emitted light for a specific function – i.e. roadway, sport court, flood and spot illumination.

The LED Driver is a set of electronics that converts line power (120/240/277 VAC) into a regulated constant-current voltage source for the LED chips. The driver electronics often include the capabilies to dim the LEDs with a 0-10VDC source and to control the fixture with external devices such as photocells so that they do not have to be switched on at night and off in the morning.

Even though LEDs are much more efficient than their aforementioned counterparts, they will fail if they get too hot. Thus, thermal management is a very important subsystem. The most common thermal management system is an aluminum heatsink – fins that transfer heat to surrounding ambient air.

Lastly, the mechanical housing for the fixture is typically a powder-coated aluminum housing with gasket seals to keep moisture out.

Short Answer: An LED fixture is made of multiple semi-conductor chips, powered by a regulated DC driver, enclosed in a weather-sealed housing with glass and/or acrylic optics that help with beam-forming. LEDs work by converting electricity into photons (electroluminescence). The fixture shapes the light, sheds heat and protects the electronics.

2. **How would an LED fixture that could comply with the 2% blue light content restriction in Maui County's Outdoor Lighting Ordinance be fabricated and made?**

White light is comprised of every color in the visible color spectrum – red, orange, yellow, green, blue, indigo and violet. As most LED fixtures use materials that generate a large percentage of blue light (>20%), the 2% restriction requires some engineering. Early approaches were to use an "Amber LED" in which the semiconductor is made of AlInGaP. The downside of these devices is that their Color Rendering Index (CRI) is quite poor, and not suitable for roadway applications. The current approach is to make a phosphor-converted LED fixture, where blue LEDs (InGaN) are used, but the devices are subsequently coated with a phosphor that absorbs a large portion of the blue and converts the energy to warmer wavelengths through electroluminescence. The optics are then typically coated with a blue-blocking filter as some of the blue light is not fully absorbed by the phosphor. Some fixtures utilize purely filtered InGaN LEDs where a bandpass filter is placed in front of the LEDs such that only wavelengths longer than 500nm can pass, but this is very inefficient and is seldom done in commercial fixtures.

3. **What is the effect on an LED fixture that is fabricated and made to filter out blue spectral light content?**

Aside from Amber LEDs, the blue spectral content is still the predominant band produced by the fixture but is blocked from exiting the fixture with a long-pass filter. As a result, the overall efficacy of the fixture is reduced, and heat is retained which can cause premature failure of the LED driver electronics. In addition, luminous efficacy (lumens/watt) drops significantly, as filters throw away part of the emitted spectrum. Lights with less than 2% blue (400-500nm) have generally poor CRI, which leads to potential safety and security issues when used for roadway applications.

4. **What is the effect on an LED fixture that is fabricated and phosphor-coated to reduce blue spectral light content?**

Again, the blue spectral content is still the predominant band produced by the fixture but is mostly converted to longer wavelengths by a phosphor coating. The overall efficacy of the fixture is reduced somewhat, and some heat is retained which eventually could cause premature failure of the LED driver electronics, but the thermal issues with phosphor conversion are much less pronounced than with filtered LEDs. The phosphor is easily quenched, so not all the blue spectral content is converted in the current state of the art. As a result, long-pass filters are often employed to eliminate the 440-470nm residual spike. In addition, luminous efficacy (lumens/watt) drops moderately, as the conversion is only moderately efficient. As stated previously, lights with less than 2% blue (400-500nm) have generally poor CRI, which leads to potential safety and security issues when used for roadway applications.

5. What is the approximate percentage of light emission from streetlighting on the island of Maui within the overall skyglow of artificial light at night? How did you derive this approximation?

The dominant source for monitoring light pollution / skyglow from Artificial Light at Night (ALAN) is the Visible Infrared Imaging Radiometer Suite (VIIRS) on board the Suomi NPP and JPSS satellites. Excellent geolocated data sets are available from these instruments since 2014. To determine the contribution from streetlights on Maui, we employed the following process:

- Measured streetlight output with scientific-grade spectrophotometer
- Measured streetlight illuminance on asphalt
- Modeled reflection from asphalt
- Modeled resulting radiance towards VIIRS with atmospheric radiative transfer model
- Simulated VIIRS sensor response
- Factored in number of streetlights in five geo-located boxes
- Compared calculated data to VIIRS data for same geo-located areas

In this type of statistical modeling effort, a factor of two is a reasonable error allowance. Precision is not possible, given the sheer number of variables and the potential variance of each variable. Nonetheless, we reached some reasonable estimates for each of the study areas, yielding an estimate that County of Maui Streetlights comprise approximately 5.6-11.2% of the skyglow over the island of Maui.

6. **Given the approximate percentage of streetlight emissions within the entire artificial light topography, what would be the impact to overall skyglow by exempting streetlight fixtures from the 2% blue light content restriction contained in Maui County's Outdoor Lighting Code and allowing streetlights that have a color correlated temperature of up to 3000K? Why?**

To thoroughly answer this question, we must first look at the makeup of current streetlights (status quo), then analyze the skyglow impact of converting all 5,240 County of Maui streetlights to meet the 2% restriction and then look at the case of all the streetlights meeting a Color Corrected Temperature (CCT) of 3000K.

Status Quo

With approximately 1240 GE ERL-1 2700K LED fixtures in place on Maui, and most of the rest High Pressure Sodium (HPS) at 1900K, one might ask – what is their blue content? The 2700K LED in use has been measured at 11.7% blue as defined in the County of Maui Ordinance. The 1900K HPS fixture in use has been measured at 6.0% blue. This results in an average of 2052K when considering all of Maui County as a whole. As it has been calculated that 5.6-11.2% of the skyglow over Maui is directly derived from streetlights, that would be the baseline that we can compare two other scenarios with.

Replace All to Meet 2% Blue Restriction

While it is true that the biggest impact on skyglow is from the blue end of the visible spectrum, it is not a linear function – meaning that one has to consider how a streetlight fixture interacts with it's environment: shielding, pointing angle, height of fixture, beam spread, reflection of some surface, scattering and blocking sources, etc. Precisely calculating skyglow from many fixtures requires spectral distribution profiles (SDPs), ground albedo and advanced atmospheric propagation models. If we are assuming the same lumen output for all streetlights under consideration, we can simply use standard SDPs to compare the relative blue light content of different fixtures – called the scotopic/photopic (S/P) ratio. Assuming all the fixtures under consideration are fully-shielded and have no uplight leakage, we then apply a factor considering the spectral ground albedo (reflectance+scatter) such that we are comparing the amount of light that actually contributes to skyglow. With low-albedo asphalt ~0.10, that's ~5% of downward lumens heading skyward. Since this is the same for all scenarios, it cancels in comparisons.

Since we want to compare scenarios to the current baseline configuration of mixed LED and HPS fixtures, we normalize S/P ratios such that the current fixtures have a weighted S/P ratio ~ 1.0.

The Cree 19K5 Guideway which meets the 2% blue restriction would then have a weighted S/P of 0.45. This results in a relative skyglow vs baseline of 0.445 and therefore

$$\boldsymbol{sg\ contribution(2\%) = (5.6 - 11.2\%) * \ 0.445}$$

$$\boldsymbol{sg\ contribution(2\%) = \ 2.5 - 5.0\%}$$

Converting all the streetlights on Maui to a 1900K PC/Amber LED would decrease the streetlight relative contribution to skyglow considerably, but in absolute terms it would be less than a 5%

change. Overall skyglow would decrease, but by a slim degree, which is de minimus and a non-significant change in airglow – primarily because Maui's streetlights are not a major contributor to skyglow. The effect of restricting all the other fixtures on Maui would have a far larger impact.

Replace All with GE ERL-1 2700K LEDs

If all 5240 streetlights were converted to the GE ERL-1 2700K LED, the scenario would be marginally different from the baseline. These lamps have 11.7% blue and as a result will contribute more to skyglow. These lamps have a weighted S/P of 1.19. This results in a relative skyglow vs baseline of 1.187 and therefore:

$$sg\ contribution(2700K) = (5.6 - 11.2\%) * 1.187$$

$$sg\ contribution(2700K) = 6.6 - 13.3\%$$

Replace All to Meet 3000K Restriction

If all 5240 streetlights were converted to 3000K LEDs, the skyglow would increase a little more. 3000K LED fixtures typically emit between 18-25% blue, and would have a weighted S/P around 1.40. This results in a relative skyglow vs baseline of 1.385 and therefore:

$$sg\ contribution(3000K) = (5.6 - 11.2\%) * 1.385$$

$$sg\ contribution(3000K) = 7.8 - 15.5\%$$

This table summarizes the relative skyglow changes that would occur given a few street lighting scenarios:

Streetlight Scenario	Weighted S/P Ratio	Relative Skyglow vs Baseline	Maui Skyglow Share
Baseline - Current Mix	1	1	5.6 - 11.2%
CREE 19K5 Guideway 1900K LED (<2% blue)	0.45	0.445	2.5 - 5.0%
GE ERL-1 2700K LED	1.2	1.187	6.6 - 13.3%
Generic 3000K LED	1.4	1.385	7.8 - 15.5%

In summary, with full shielding and low-albedo asphalt, ground reflection dominates; the upward fraction is constant across these scenarios, so blue light content is the main lever. The S/P ratio is a practical, single-number proxy for "skyglow efficacy per photopic lumen" at night. It bakes in the stronger blue-light contribution without needing full spectral integrals, but this model could be more accurate if manufacturer's Spectral Power Distribution (SPD) curves were used.

7. Are there any implications for the safety of motorists, pedestrians, cyclists, and visitors under the 2% blue light content restriction in Maui County's Outdoor Lighting Ordinance as related to streetlighting?

At night our vision is naturally impaired. In low-light conditions, vision relies predominantly on the retina's rods instead of the cones. Rods are sensitive to dim light – most sensitive to blue and green wavelengths, but lack color vision, have low acuity (spatial resolution), and have a slow recovery time. Without blue light at night, roadways appear dim and small or low-contrast objects are more difficult to detect.

Streetlights that meet the 2% blue light restriction have at best a CRI of 60. At this level of color rendering (or worse) color cues such as clothing, facial expressions, signals are less distinct and require more time and concentration to notice and recognize. Likewise, pedestrians and cyclists are much harder to detect at a distance.

8. What are the comparative distinctions that can be drawn as between the Cree manufactured Guideaway LED light at 1900K at 50% CRI and the G.E. manufactured ERL1 LED fixture at 2700K at 70% CRI related to motorist, pedestrian, cyclist, and visitor safety on Maui County's roadways?

Both fixtures have glare-minimizing optics, similar lumen-output packages, NEMA 7-pin DALI controls for dimming/photocell control and zero uplight, so they both technically meet basic requirements for streetlights. The Cree 19K5 will feel dimmer at night for the same measured lux. The ERL1 will deliver better small-target visibility and earlier detection, but the Cree 19K5 will produce less glare and driver comfort in very dark areas. The Cree 19K5 has a warmer tone, less intrusive and moderately preserves night adaptation.

The CRI difference is the most impactful in terms of color recognition and resolution acuity. A low CRI (50 is low) makes it quite difficult not only to determine colors, but to see dark colors in particular. Depth perception and rate of speed estimation are significantly compromised at a CRI of 50.

The Cree 19K5 might excel in very dark areas – meeting environmental objectives and producing less glare in more remote locations where a driver's eyes are more dark-adapted (rods only), but in busier areas with more pedestrians and traffic, the ERL1 meets more of the Federal Highway Administration guidelines for roadway luminaires. If all streetlights on Maui are converted to the 2% standard, there will likely be a demonstrated need for a moderate increase in the number of streetlights required to provide adequate lighting levels at crosswalks and intersections.

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PROGRAM MANAGEMENT and SYSTEMS ENGINEERING

Requirements-driven program manager and systems engineer adept at creative, sustainable solutions for a variety of Government construction, O&M, and R&D projects, technical integration activities and computer networking installations. Possesses practical knowledge in program management of Government Operations & Maintenance (O&M) and Research & Development (R&D) programs and commercial alternative energy market development. Applies tailored system engineering principles to multi-disciplinary projects and communicates well to management and field crews. Core competencies include:

Program Management • Systems Engineering • Facility/Construction Management • Optical Systems
Data Modeling, Collection and Analysis • Network Installation • Programmable Controls • Acoustics

PROFESSIONAL EXPERIENCE

North Shore Systems Engineering, LLC • Paia, HI • 2015 - Present

Systems Engineering firm specializing in integration, data networking and analysis for alternative energy and space-object tracking installations.

Owner of Hawaii Court Tech
Sports Engineering Consultant for Clubs, Hotels and Private Residences on Maui and Hawaii. Renovated and built tennis, pickleball and basketball courts.

Consultant to Numerica Corporation
Systems Engineering Consultant for the MRT Space Tracking System in Kihei, HI. Deployment systems engineer for planned systems in Western Australia, South Africs, Oman and Canada.

Consultant to US Fish and Wildlife Service
Project Manager / Government Representative for facility and mechanical systems upgrades at Kealia Pond National Wildlife Refuge, overseeing installation and programming of HVAC reheat units, Variable Frequency Drives (VFD) and 30kW photovoltaic system.

Consultant to ASRC Federal Services
Systems Engineering Consultant for the Maui High Performance Computing Center (MHPCC) and Air Force Research Laboratory (AFRL) in network configuration and combined data analysis of multiple disparate and geographically dispersed alternative energy systems for supercomputer chilled water and air conditioning facility.

Schafer Corporation • Kihei, HI • 2010 - 2016

Leader in advanced concept development, system design, analysis and prototyping of aerospace capabilities for the military and civilian communities.

Chief Systems Engineer
Science and Engineering Technical Advisor (SETA) for NASA Johnson Space Center, Orbital Debris Program Office in design, development, construction, integration and test of a 1.3m optical telescope facility – the Meter-Class Autonomous Telescope (MCAT) on Ascension Island, South Atlantic Ocean. Was the sole engineer on-site during construction, integration and testing.

- Verified geodetic alignment of all concrete forming, electrical and data routing, Trane HVAC installation, dome and telescope integration

Technical Advisor
SETA in support of several AFRL/RDSM and NASA-JSFC worldwide small telescope facilities. Program support included HANDS, Raven, MCAT and TAKO. Role focused on site surveying, permitting, system engineering, upgrades, on-site maintenance and engineering at Exmouth/Learmonth (Western Australia), Morón (Southern Spain) and Roi-Namur (Marshall Islands) sites.

Technical Director
Responsible for successful execution of the Maui Energy Improvement Initiative (MEII), an operational solar field for the Air Force Research Laboratory (AFRL) and the DoD High Performance Computing Modernization Office (HPCM). Responsible for defining, permitting and constructing both a research and development facility for solar insolation studies and construction and integration of a novel 100kW Concentrating PhotoVoltaic solar power field for use by the Maui High Performance Computing Center (MHPCC). Program value was $3.9M.

Raytheon / Photon Research Associates • Kihei, HI • 2007 – 2010
Leading pioneer in the development and application of physics-based modeling, simulation and analysis products and services for both government and commercial markets.

Senior Technical Director
Technical program management and business development in support of MDA, USAF and US Navy customers in the Pacific. Customers included the Air Force Maui Optical and Supercomputing Site, the Aegis BMD Program, NAVAIR, Space and Missile Command, the USA/SMDC THAAD Program and others. Role specifically included EVMS program management, technical oversight and team leadership, financial reporting, briefing preparation and delivery, mission planning, rehearsal and execution and data simulation, collection and analysis.

Boeing / Rocketdyne Technical Services • Kihei, HI • 1993 – 2007
Work centered on the Maui Space Surveillance Site (MSSS) – eleven telescopes designed for tracking satellites and missiles with visible and infrared sensors to collect data on near-Earth and deep-space objects.

Senior Program Manager
Technical program management of a multi-faceted $26M task to support development, integration, observations and data analysis for the laser and missile defense programs executed at MSSS.

- Customers included the Aegis BMD Program, the MDA/SMDC Critical Measurements of Counter Measures (CMCM-2) Program, the USA/SMDC THAAD Program and others.
- EVMS program management, technical oversight and team leadership, financial reporting, briefing preparation and delivery, mission planning, rehearsal and data simulation, collection and analysis.

Site Director
Integrated oversight of Operations and Maintenance (O&M) and Research and Development (R&D) activities at the Maui Space Surveillance System. Technical program management of $20M/year task order to operate and maintain the primary observatory on Haleakala.

- Oversight functions included electro-optics, electronics, facilities, civil engineering, communications, safety and environmental, security, software, information technology and operations.
- Position required cognizance of numerous Air Force Instructions (AFI's), US Space Command Requirements, safety standards, security classification guides, etc.
- Demonstrated ability to manage to these requirements, led the site to a perfect score on the May 2003 Inspector General Unit Compliance Inspection (IG/UCI), had no catastrophic safety incidents and managed the budget to less than 3% variance from plan for the entire period.
- Managed 75-85 direct and indirect reports.

NASA Goddard Space Flight Center • Greenbelt, MD • 1988 - 1993
Work centered on the development, integration, testing and deployment of airborne and spaceborne solid-state lasers for platform-based atmospheric and planetary LiDAR, star-sensing and range-finding.

Section Head
Technical lead of NASA Code 723, Solid-State Laser Development Branch. Performed laboratory research on lamp-pumped Alexandrite lasers, diode-pumped LiCaAlF (LICAF) and LiSrAlF (LISAF) lasers, integration engineer on LAGEOS-II, Gamma-Ray Explorer (GRO) and Mars Observer Laser Altimeter (MOLA) programs.

EDUCATION

PhD Program Study in Intense Field Solid State Physics • American University • Washington, DC • 1991-1993

MS Program Study in Engineering Physics • University of Virginia • Charlottesville, VA • 1987-1988

1983 - 1987, Bachelor of Science in Physics • Guilford College • Greensboro, NC • 1983-1987