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Status of GaN/SiC-based LEDs and their application in solid state lighting

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With the advances in light-emitting diodes (LED) efficiency over the last several years, solid-state lighting in the marketplace has grown significantly. This includes outdoor full colour displays, street and parking deck lighting, indoor lighting and hand held devices. In each application, there is an optimization between the LED chips, the components they are encapsulated into and the lighting systems made from these components. In this paper, the latest developments in GaN/SiC chip design, and the most recent white LED component efficacy will be discussed. Recent and predicted lighting system efficiency in the near future will also be presented.

1 Introduction LED technology has advanced dramatically in recent years. The efficiency of LED light bulbs and lighting fixtures has reached >100 LPW (lumens per watt), while that of white LED components has achieved 200 LPW in mass production [1]. In many cases, the payback of the initial cost of LED fixtures is less than two years. The payback less than one year has also been achieved for certain fixtures [2]. Long term reliability of LEDs has also progressed significantly. The lifetime warranty as long as 10 years is offered by Cree, Inc. for the most of its lighting fixtures. Together, these advances mean that the adoption of LED solid-state lighting (SSL) is now very economically viable. In this paper, the latest GaN/SiC chip designs, the efficiency of blue LED emission, and the efficacy of white LED components will be discussed. The paper will also include a discussion of current efficiency and the predicted future efficiency of LED lighting fixtures.

2 4H-SiC substrates While most LED chip manufacturers use sapphire or silicon as substrates for the growth of Group III-nitride epitaxial active layers, Cree uses 4H-SiC (0001) on-axis substrates because of their superior thermal conductivity, better coefficient of thermal expansion and lattice match to GaN. Furthermore, the absorption coefficient of 4H-SiC is below 1 cm^{-1} for lightly n-doped substrates (Fig. 1). The refractive index of SiC is also comparable to that of the GaN epilayers. These properties make very efficient light extraction possible for LED chips with SiC as a part of the devices. Today, III-nitride epitaxial layers grown on 150 mm diameter 4H-SiC (0001) wafers are in mass production. This further reduces the cost of LED chips.

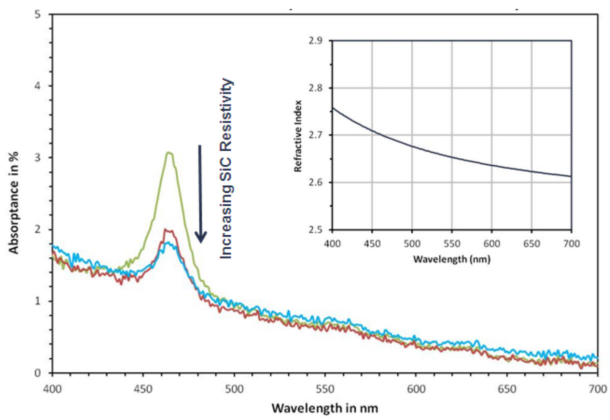


Figure 1 Plot of 4H-SiC absorption vs. wavelength. Data based on white light near-normal transmittance and reflectance measured on 500 μm thick double-side-polished SiC wafers. Inset shows refractive index data measured using variable angle spectroscopic ellipsometry. The data are in close agreement with Ref. [3].

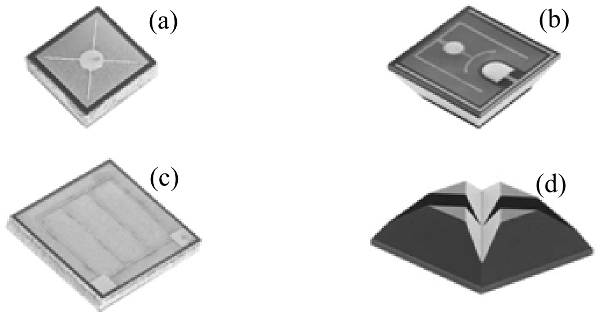


Figure 2 Scanning electron microscopy images of GaN/SiC based LED chip designs: (a) vertical with straight sidewalls, (b) lateral with beveled sides, (c) vertical with a surrogate (Si) substrate, and (d) lateral flip.

3 GaN/SiC based chip design and power efficiency SSL systems begin with the LED chip design. There are numerous chip configurations but this paper will only consider those incorporating a Group III-nitride epitaxial active layer on SiC substrates. Silicon carbide–based chips come in four major varieties. The simplest and earliest design is the vertical geometry configuration with p-type epi-up (Fig. 2a). This looks more like a "traditional" red or green LED where the chip is mounted in Ag-based epoxy and a wire bond is made on the device top surface in the component. The second design has both p- and n-contacts on the top surface and macroscopically shaped substrate (Fig. 2b). Sixty degree bevels are utilized for SiC substrate. This is necessary as SiC has much higher refractive index (n=2.7 [3]) than the index of typical package encapsulants (n=1.5). Another approach to chip design is to remove the growth SiC substrate. In this configuration, the epitaxial layers are structurally and electrically bonded to a highly conductive Si carrier substrate. A highly reflective mirror layer is placed between the Si carrier substrate and p-layer and the n-GaN epi-surface is microscopically textured to optimize light extraction (Fig. 2c). The result is a very efficient surface emitter with nearly Lambertian radiation pattern, which can be easily imaged using a secondary optic. The latest and most efficient SiC chip utilizes a beveled flip chip design (Fig. 2d) and employs a eutectic die attach process in place of wire bonds. Such chips are used in multiple small-chip power packages and single-chip power packages.

The most commonly employed emission wavelength of chips used in white LED components is 440-460 nm. In this wavelength range, the power efficiency (optical power divided by electrical power in) of Cree's power chip component products is typically 60-70% for top product bins. In a R & D laboratory prototype, power efficiency as high as 79% at 350 mA has been measured at room temperature for a wavelength of 447 nm (Fig. 3). Estimates for packaged light extraction efficiency based on ray-trace simulation of detailed chip models are in the 80-88% range depending on the chip type and size.

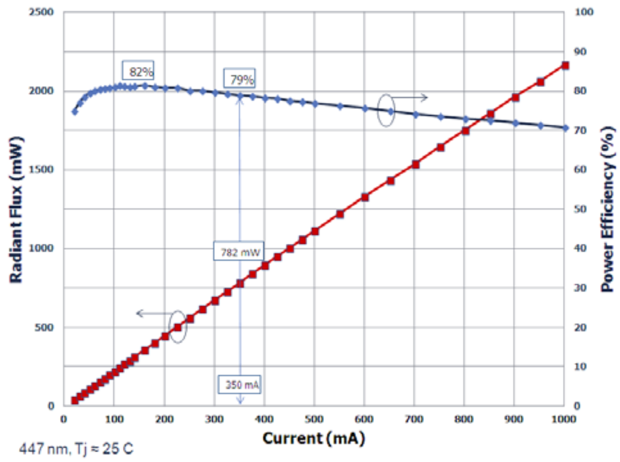
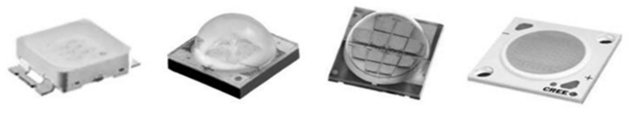


Figure 3 Plot of radiant flux (red squares) and power efficiency vs. current of an encapsulated GaN/SiC based LED chip with wavelength of 447 nm at room temperature.

4 White LED components with GaN/SiC based chips Cree makes a variety of LED components to meet the requirements of different lighting system designs. The chip(s) is (are) coupled in the component to a phosphor system usually containing yttrium or lutetium aluminum garnet for green/yellow down-conversion for cooler white, with the addition of a nitride-based red-emitting phosphor for warmer white. Incorporation of the phosphor is done using several different methodologies driven primarily by the design of the component itself. Some of the most common types of Cree LED components employed in solid-state lighting systems today are shown in Fig. 4. In Fig. 4a, an example of a plastic housing package is shown where typically between one and six chips are placed in a cavity with a reflective metallic base for heat conduction and electrical connections are made using wire bonds. A silicone and relatively dilute phosphor mixture is then dispensed into the cavity forming a slightly concave lens. This type of LED component is commonly utilized in flat panel display backlighting and diffuse lighting applications where the power input per component is typically less than one watt. In Fig. 4b an example of a eutectically attached flip chip on a ceramic substrate is shown. Here the chip (see Fig. 2d) is conformally coated with a relatively dense phosphor blend and a clear silicone lens is molded onto the ceramic/chip/phosphor system. This type of component is commonly utilized in either diffuse lighting or, with the addition of a secondary lens, spot lighting applications. The package size for these types of components is typically 2.5-5 mm on a side, and the power input per device is in the 1-5 W range.

Figure 4c shows an example of a high power (6-30 W) ceramic package using multiple 1 mm^2 chips (see Fig. 2c) and a molded hemispherical lens. In this case, the dies are eutectically attached, and the phosphor is coated on the planar surface and upper edges of each die. This design enables the use of imaging secondary optics with very low



(a) (b) (c) (d)

Figure 4 Common styles of white LED components made using (a) dies in a dispensed phosphor/lens in a plastic housing, (b,c) phosphor-coated die on a ceramic substrate with clear molded lens, and (d) a dam and fill phosphor/lens over dies on a MCPCB substrate.

etendue necessary for low angle spot lighting. Lastly, Fig. 4d shows an example of a high power (6-100 W) metal-core printed circuit board package (MCPCB) or ceramic PCB. In this case, an array of small to midsized chips (0.1-0.5 mm^2) is mechanically and electrically connected to the package. Various series/parallel arrangements of chips can be made to obtain select voltage ratings over a wide range (3-225 V). A dam (typically circular or square) is placed around the chips before a silicone and phosphor mixture is dispensed into the cavity defined by the dam. These components generally have a large source size (9-32 mm diameter) which limits their use to wider spot light applications and diffuse lighting applications. However, unlike the previous three examples which require solder attach to a separate PCB to thermally and electrically incorporate the part into the lighting system, this type of component simply requires two screws and soldering two wires to the surface anode and cathode.

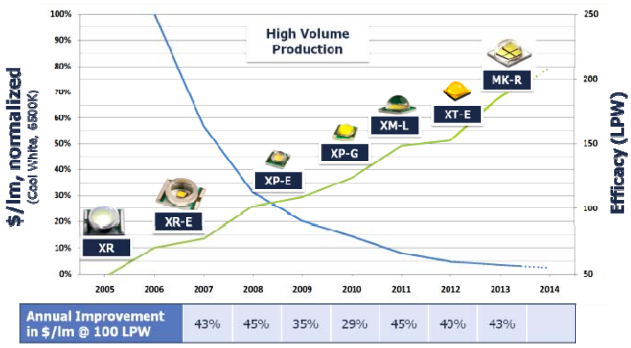


Figure 5 Technology improvements in chip and component designs over time have driven the affordability of LED lighting.

The LED technology advancement in recent years has driven the component efficacy up and the cost down. The recent history of Cree component efficacy and the component cost per lumen at an efficacy of 100 LPW are illustrated in Fig. 5. Most recently, a so-called MK-R component that emits white light at over 200 LPW at 1 Watt operation power is in high volume production. In the R/D lab, room temperature efficacy has reached as high as 276 LPW in February of 2013 [4]. In this case the CCT was 4401 K and the LED drive current was 350 mA. The rapid improvement of LPW performance makes LED lighting much more affordable as fewer LED chips/components are required to achieve a given system lumen output and efficacy. Overall, the cost in terms of $/lumen at 100 LPW has been reduced annually by 30 – 45% per year in the past several years.

5 LED lighting today and tomorrow A large variety of LED-based lighting systems incorporating the components discussed above are now available. Their output ranges from less than 100 lm flashlights to 80,000 lm high bay lights with system efficiencies up to 120 LPW. The payback on the initial cost compared to less efficient incumbent lighting technology is less than two years in many cases, which has led to mass adoption in many applications. For example, two types of Cree LED light bulbs (A19 type and BR30) with up to 75 LPW efficacy and 10-year warranty are sold at Home Depot for from less than $10 to $20. CRI (color rendering index) is over 80 for both bulbs, which provides a high quality white light that is acceptable for all but specialty applications.

Based on today's R&D results (and a track record of transitioning such results to commercial products in the past), we expect that by 2015 roadway lighting (4100 K) with system efficacy of more than 150 LPW and indoor fixtures at more than 125 LPW (wall-plug) will be commercially available. The assumptions for this prediction are listed in the Table 1.

Table 1 Projected LED lighting levels of performance in 2015.

	6000K	4100K	3500K	2700K
Data Sheet LPW	210	189	169	151
Typical * Thermal Loss	5%	5%	5%	5%
Typical * Optical Loss	5%	5%	5%	5%
Typical * Driver Loss	8%	8%	8%	8%
Achievable * LPW	174	157	140	125
CRI	~75	~80	~82	~83

* Typical with average/good design practices

In summary, the performance and cost of GaN/SiC-based LED lighting have improved tremendously in the past few years. This has given new tools to engineers and lighting designers in the rapidly evolving solid-state lighting industry. LED lighting is ready for many of today's applications and will soon be the most efficient mainstream light source available.

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