DALLAS SEMICONDUCTOR MAXIM

AUTOMOTIVE DISPLAY DRIVERS

Feb 10, 2003

LEDs Are Still Popular (and Improving) After All These Years

This article discusses a 35-year-old display technology that itself has rapidly changed — the LED. This overview covers the origins of LEDs, the traditional applications, and how improvements in the technology have stimulated new applications.

Introduction

In recent years, articles have focused on new display technologies. Articles have covered the explosion of TFT color LCD panels of ever-increasing size into laptops and flat screen monitors; PDP (plasma display panels) for high definition TV CRT replacement; polymer LED (PLED) or organic LED (OLED) displays for the small color displays in games, cellphones, and PDAs.

This article discusses a 35-year-old display technology that itself has rapidly changed - the LED. This overview covers the origins of LEDs, the traditional applications, and how improvements in the technology have stimulated new applications.

A Brief History of LEDs

Commercial research into LED technology started in the early 1962s, notably at Bell Labs, Hewlett-Packard, IBM, Monsanto, and RCA. Work on gallium arsenide phosphide (GaAsP) led to the introduction of the first commercial 655nm red LEDs in 1968, by H-P and Monsanto. In 1971 H-P released the 5300A 500MHz portable frequency counter using a GaAsP LED display. LED displays flourished in the early 1970s as numeric displays in pocket calculators by H-P, Texas Instruments, Sinclair and others. For a short time, LEDs appeared in digital watches, but were soon replaced by LCDs. Meanwhile, LEDs replaced incandescent and neon lamps as status indicators and became the standard numeric and alphanumeric display choice for instrumentation.

The LED's hottest competition in the 1970s and 1980s for consumer goods came from vacuum fluorescent displays (VFDs), whose bright blue-green display offered high intensity and high contrast when viewed through a green or blue filter. VFDs were first developed by ISE Electronic Corporation in 1967. ISE, often known by the division name of Noritake, together with Futaba and NEC, offered display tubes from the late 1960s and early 1970s, starting with simple single digit displays used in rapidly growing desktop calculator market. Multi-digit display tubes appeared soon, reducing manufacturing cost, and these are possibly best remembered for their appearance in the popular Casio pocket calculators. Later, Samsung started making tubes for their own consumption for use in consumer goods. In 1993, NEC sold their complete manufacturing line to ZEC in China, and between them Futaba, ISE, Samsung, and ZEC produce around 95% of the world's VFD tubes production.

In the 1980s and onward, monochrome LCDs competed strongly with LEDs and VFDs for consumer devices, instrumentation, and automotive panels. LCDs have the advantage of lowest power and easily customization, and became the obvious choice for battery operated applications. Although LCDs don't emit light, there are many applications where ambient light can be guaranteed. Alternatively, the light from a couple of green, orange, or yellow LEDs can be diffused and spread behind a small (10 square centimeter) LCD with an opaque plastic molding, to provide a cheap and pleasant backlight.

Who Manufactures LEDs?

The worldwide production of LEDs is now around 4 billion units a month. According to ITIS (Industrial Technology Information Service) of Taiwan, Taiwan now produces around half the world's demand from its over 30 LED manufacturers, with Japan and USA being the next most productive. Ten years ago, Japan was the lead producer, and Taiwan's output was a little over 10% of the world's demand. Most LED manufacturers are actually assemblers and packagers, buying wafers or dice from foundries in Japan, USA, and (more recently) Taiwan.

The C.I.E., Lumens and Candelas

It's probably helpful to include in a discussion of display technology a short tutorial of radiometric and photometric theory. Radiometry is the measurement of radiant energy at all wavelengths (visible and invisible), while photometry is the measurement of apparent brightness to the human eye. The human eye "sees" the range of light wavelengths from 380nm to 740nm as the familiar color spectrum (Figure 1).

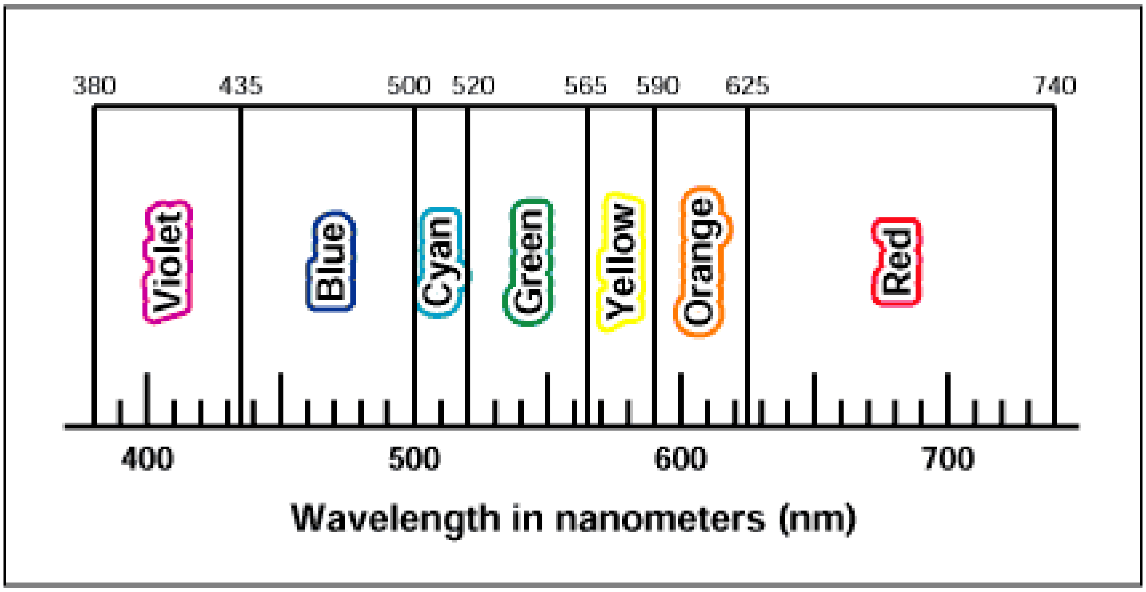

Figure 1. Wavelength of color

The Commission Internationale de l' Eclairage (CIE) formalized standards for the measurement of light, and the response of the human eye or "standard observer", back in the 1930s. These standards characterized the variation in eye response over the entire visible range under a variety of lighting conditions, such as daylight and night. The CIE also defined the primary colors (Table 1).

Table 1. CIE Definition of Colors

Color Name	Wavelength
Red	700nm
Green	546.1nm
Blue	435.8nm

These standards and definitions have been controversial, and other standards exist. The points of interest for displays are that the human eye response peaks roughly at green 555nm, is sensitive to yellow, falls off sharply towards blue at 400nm, and also towards red at 700nm. This can be seen in the 1931 photopic (daylight) chromaticity diagram, which is shown in a simplified form in Figure 2. The curve for scotopic (night-adapted) is quite different, peaking at about 512nm.

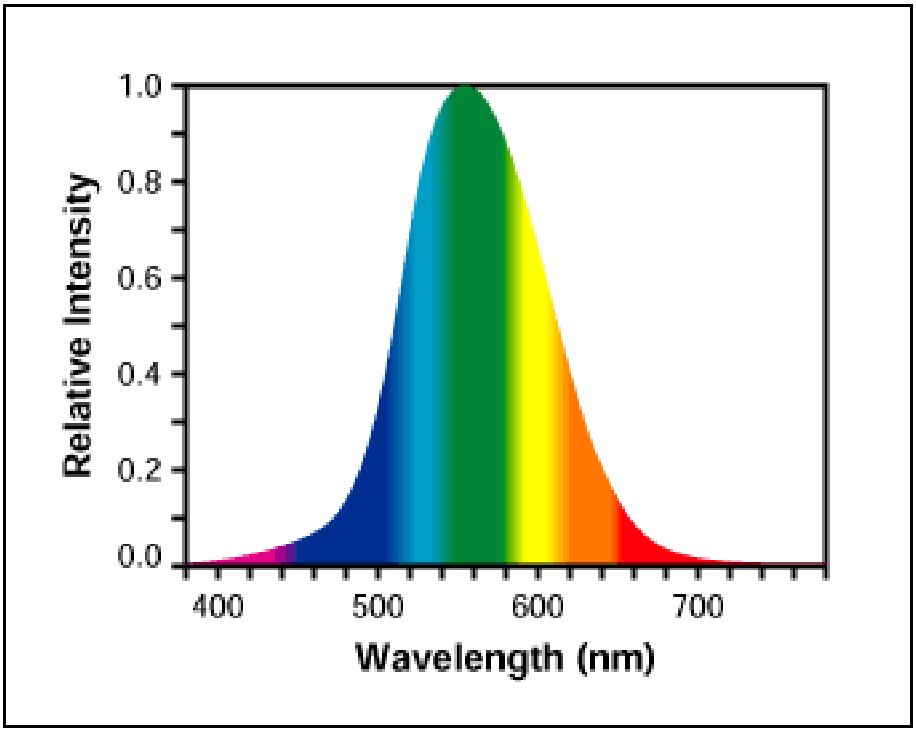

Figure 2. Human eye daylight color response

Radiant light intensity (all wavelengths) is measured in lumens. The lumen is defined such that 683 lumens of light is provided by 1 watt of monochromatic radiation at a wavelength of 555nm. Luminous intensity, in candelas (cd), results from the application of the CIE color response to the radiant flux and provides the measurement for the visible portion of a light source. Display intensity, therefore, is described in cd or mcd to indicate the light output useful to the observer.

What are LEDs?

A light emitting diode (LED) is a PN junction semiconductor diode that emits photons when forward biased. The light emitting effect is called injection electroluminescence, and it occurs when minority carriers recombine with carriers of the opposite type in a diode's band gap. The wavelength of the emitted light varies primarily due to the choice of semiconductor materials used, because the band gap energy varies with the semiconductor. Not all injected minority carriers recombine in a radiative manner in even a perfect crystal; non-radiative recombination occurring at defects and dislocations in the semiconductor can give rise to wide variations in useful emissions in seemingly identical diodes. This means in practice that manufactured batches of LEDs are sorted and graded for intensity matching.

LEDs are processed in wafer form similar to silicon integrated circuits, and broken out into dice. Chip size for visible signal LEDs generally fall in the range 0.18mm square to 0.36mm square (Figure 3). InfraRed (IR) LEDs can be larger to handle peak powers, and LEDs for lighting are larger again.

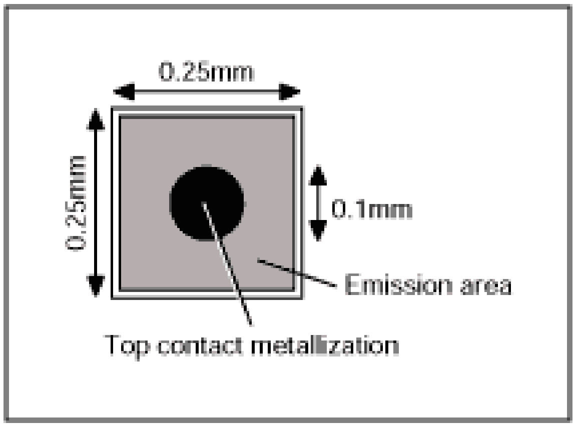

Figure 3. Typical GaP LED die

The simplest packaged LED product is the lamp, or indicator. The basic structure of an LED indicator consists of the die, a lead frame where the die is actually placed, and the encapsulation epoxy which surrounds and protects the die, and also disperses the light (Figure 4). The die is bonded with conductive epoxy into a recess in one half of the lead frame, called the anvil due to it's shape. The recess in the anvil is shaped to throw the light radiation forward. The die's top contact is wire bonded to the other lead frame terminal, the post.

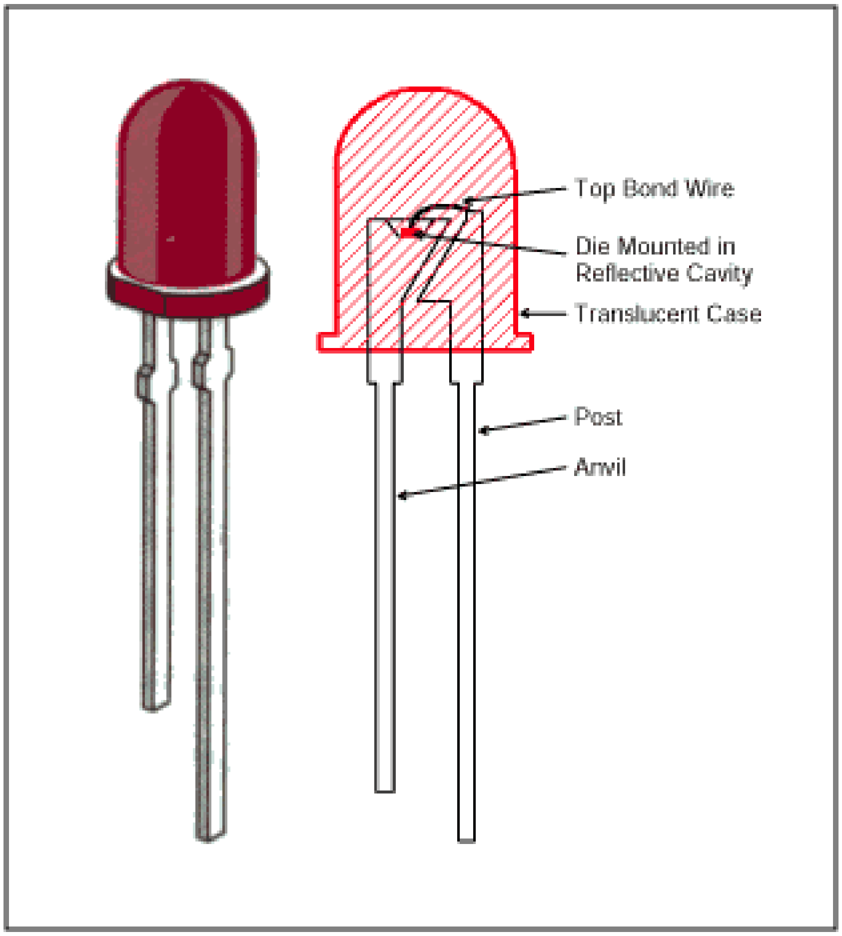

Figure 4. Typical LED indicator and cutaway showing construction

The mechanical construction of the LED lamp determines the dispersion or radiation pattern of the light. A narrow radiation pattern (Figure 5) will appear very bright when viewed on-axis, but the viewing angle will not be very wide.

The same LED die could be mounted to give a wider viewing angle, but the on-axis intensity will be reduced. This tradeoff is inherent in all LED indicators, and can be easily overlooked. High brightness LEDs with a 15° to 30° viewing angle are a good choice for an information panel directly in front of an operator, but a wide direction indicator or automotive dashboard might require as wide an angle as 120°.

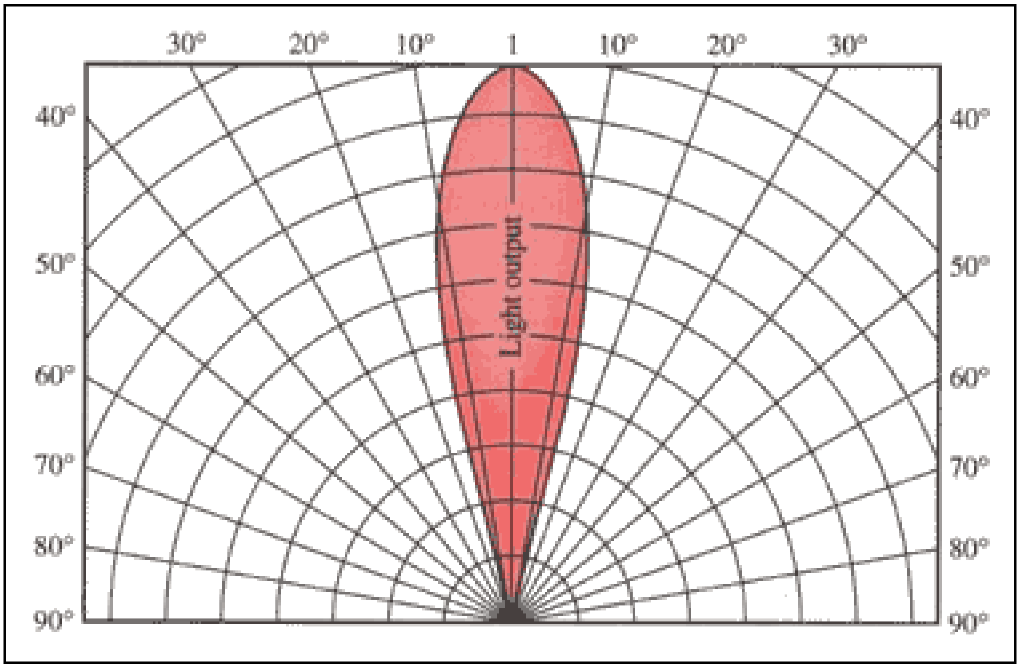

Figure 5. Narrow LED indicator radiation pattern

LED Numeric and Alphanumeric Display Construction

The familiar 7-segment numeric display digit actually suffers from a misnomer, as there's nearly always an 8th segment for the decimal point (DP). The less familiar "starburst" alphanumeric displays are similarly referred to as 14-segment and 16-segment digits, ignoring the DP again. Starburst displays provide an economical way of showing the full 26 characters of the roman alphabet, in upper case, as well as the numerals 0-9. The difference between the 14-segment and the 16-segment digit types is that the top and bottom bar is split on the 16-segment digit, improving the appearance of some characters (Figure 6).

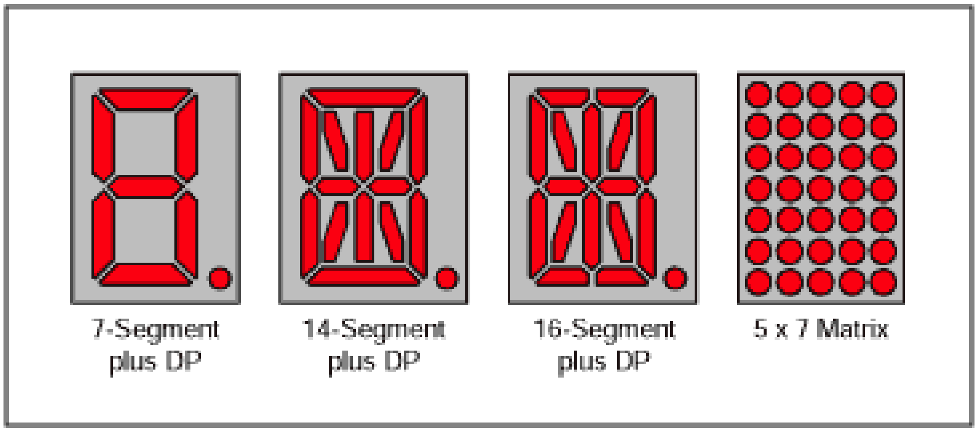

Figure 6. 7-segment, 14-segment, 16-segment, and 5 x 7 matrix digit types

The 5 x 7 matrix is even more versatile, capable of displaying the roman alphabet in both upper and lower case as well as a wide variety of symbols. The difference in the display quality is shown in Figure 7, which compares the characters displayed using the 5 x 7 matrix font map of the Maxim MAX6952/3 display driver with the characters displayed using the identical font map of the Maxim MAX6954/5 starburst display driver. The 5 x 7 matrix is inadequate for CJK (Chinese-Japanese-Korean) characters, and a font granularity of 12 x 12 is often cited as a minimum resolution.

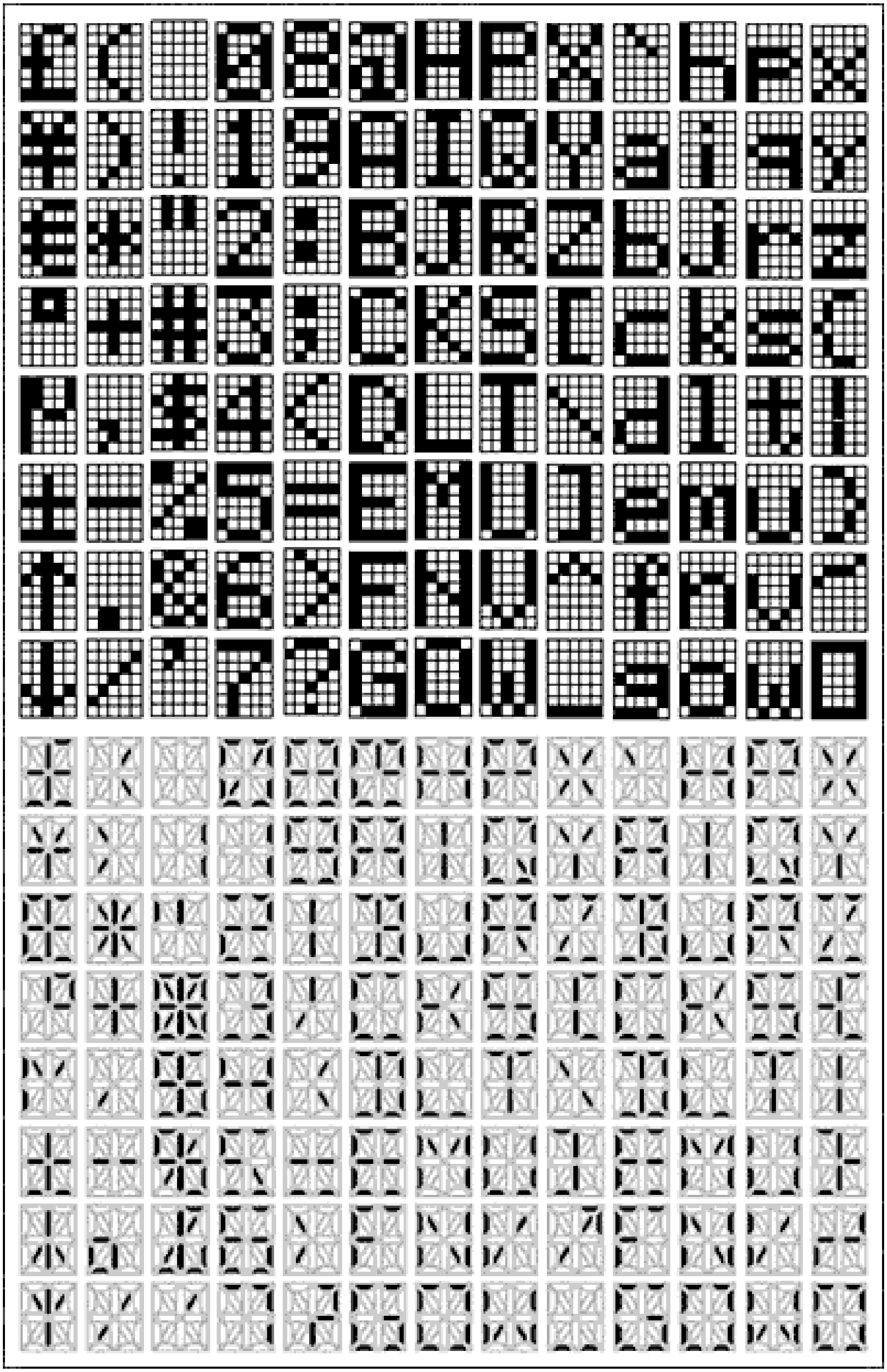

Figure 7. Comparing 5 x 7 matrix and starburst characters

Most LED numeric and alphanumeric display digits are actually hybrids, mounting multiple LED chips in a package. Some very small display digits (for example the "bubble-top" calculator displays popular in the 1970s) are monolithic. Either way, the shape of each segment is defined by a reflector and light pipe mounted around the LED die, not by the die itself. Small displays use one die per display segment, while large displays may use 2 or more dice per segment to spread the light effectively and show reasonably uniform intensity across the segment.

In the manufacturing process, the chips are mounted on either a lead frame or a PCB, and wire bonded to an interconnection pattern. The dice are mounted using conductive paste, because the die substrate forms one of the two diode connections (Figure 8). The interconnection pattern usually connects either the anode or the cathode LED chip connections together to reduce the number of pins required for the digit. As a result, displays are referred to as CA (common anode) or CC (common cathode) types, and integrated circuit display drivers will specify one type or the other (Figure 9).

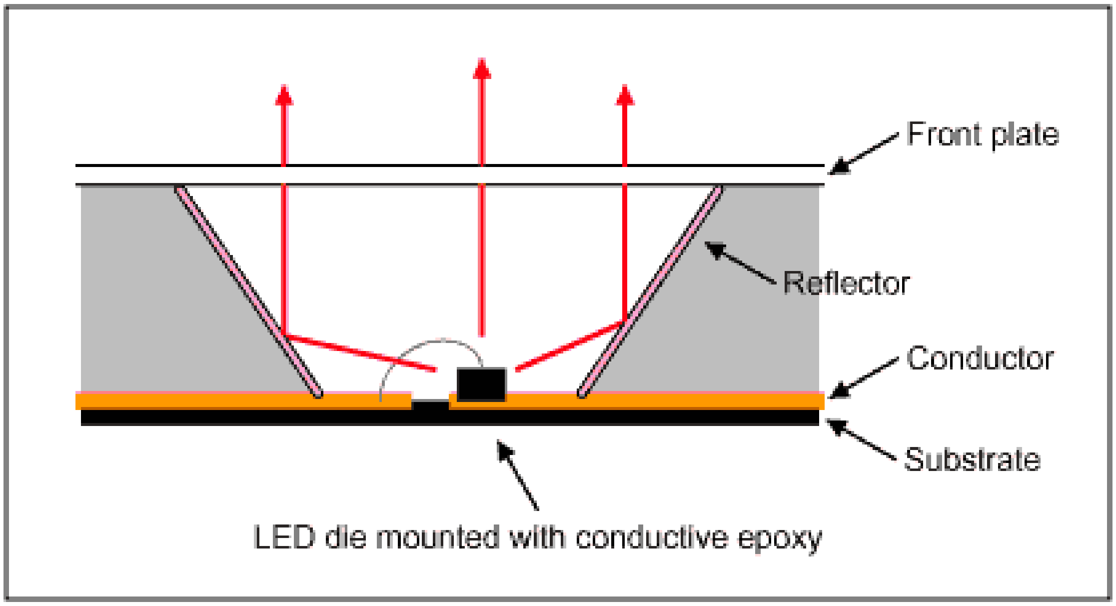

Figure 8. Mounting an LED die to form a digit segment

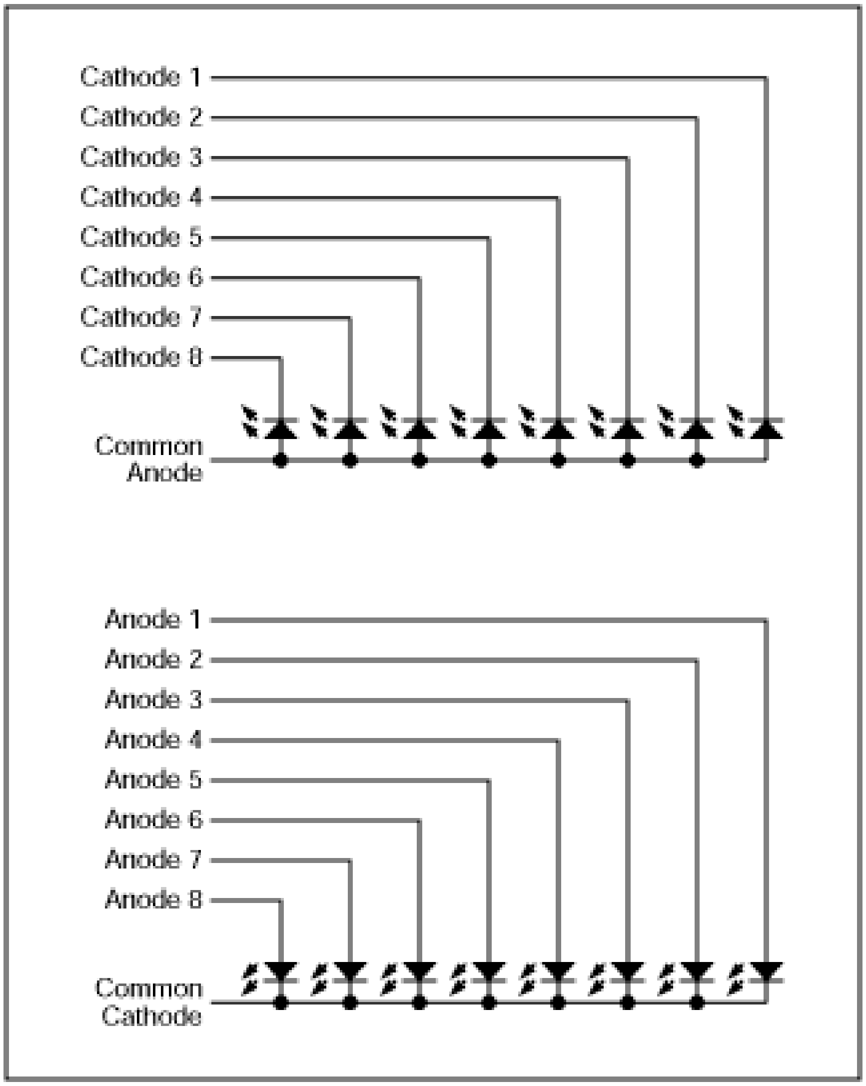

Figure 9. Common anode and common cathode LED digit types

The lead frame method of construction is similar to that used for integrated circuit manufacturing. The frame is normally etched silver plated steel, providing good heat conduction and light reflection. The reflector channel forming the light pipe for each segment is epoxy filled during construction, and the epoxy provides the mechanical strength and the environmental protection to the display.

A cheaper construction method uses a PCB type substrate instead of a lead frame. Displays built this way are often referred to as "stick" types, because the method is commonly used to build multi-digit displays, for example 4-digit clock LEDs. Stick construction allows the display to be built without epoxy fill, which saves cost but leaves the display susceptible to degradation from contaminants.

LED Electrical and Optical Characteristics

The electrical behavior of LEDs is similar to other semiconductor diodes. The forward voltage is higher, and is different for the different materials used for different colors (Figure 10). The forward voltage rises with current, and falls with temperature by about 2mV/°C. And, like all semiconductors, the LED must be derated at higher operating temperatures.

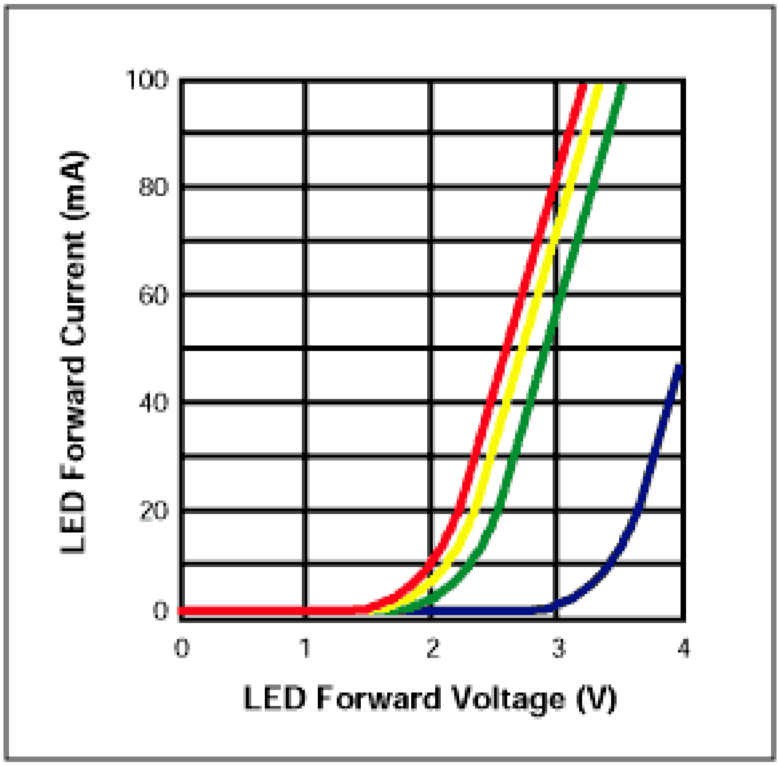

Figure 10. LED forward voltage varies with color and current

The optical behavior of the LED varies significantly with temperature. First, the amount of light emitted by the LED lamp falls as junction temperature rises. This is because of an increase in the recombination of holes and electrons that make no contribution to light emission. Also, the emitted wavelength also changes with temperature, mainly due to the semiconductor energy gap changing with temperature.

Driving LEDs – Static Drive and Multiplex Drive

The easiest way to drive multiple LEDs, such as display digit segments, is to drive each LED separately, each with a resistor or current source setting the forward current. This technique is called static drive because the LED current is continuous. Static drive is useful when relatively few LEDs are driven, with the sensible limit being about two 7-segment digits. High efficiency LEDs can be driven to high brightness with 2mA, which is available from the output ports of most microcontrollers.

When a lot of segments are to be driven, static drive demands an uneconomic number of drive outputs, 1 per LED. Multiplex, or pulse drive reduces the drive connections by strobing only a small number of segments (typically a complete digit) at a time. The strobing is done at a high enough repetition rate that the eye perceives continuous illumination. However, the LEDS must be driven at a higher current to compensate for the reduced duty cycle.

An advantage of pulse drive is that the human eye behaves as a partially integrating and partially peak reading photometer. As a result, the eye perceives rapidly pulsed light somewhere between the peak and the average brightness. This means that a low duty cycle high intensity pulse of light looks brighter than a DC signal equal to the average of the pulsed signal. Therefore one advantage of multiplexed operation is an improvement in display intensity for a given average power consumption.

The efficiency of an LED typically rises with forward current, presuming constant junction temperature. This is not always the case however, and LED data sheets should be examined (and compared) carefully when choose the optimum peak current (Figure 11). However, multiplying can often provide 1.5 times the light output from the average drive current of the cycle, compared to the equivalent DC level.

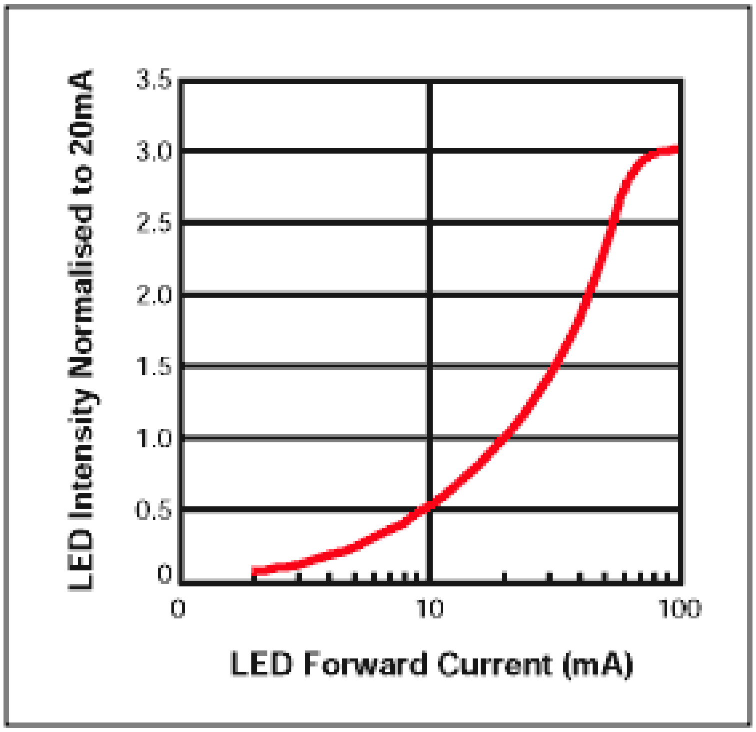

Figure 11. LED light output vs. current

As LED drive currents increase for multiplexing, internal temperatures within the chip also increase. There is a point where the effect of the temperature increase is such that the drop in photon conversion efficiency, due to the higher temperature, negates the effect of the increased current density through the junction. At this point increasing drive currents can result in little, no change, or even decreases in light outputs from the LED chip.

The standard connection for multiplexing LED digits uses a separate pin for each digit' common cathode connection, while the anode segment connections are commoned across all the digits (Figure 12). The number of connections required can be calculated as being 1 for every digit used, plus 1 for every segment within a digit. A more pin-efficient scheme relies on the fact that during the multiplex operation, only one digit drive output is actually in use. By making the LED drive pins alternate duty between driving digits and segments, n drive pins can be used to drive n digits each with n-1 segments. This technique is used in the Maxim MAX6951 LED driver to drive 8 numeric digits with only 9 pins (Figure 13).

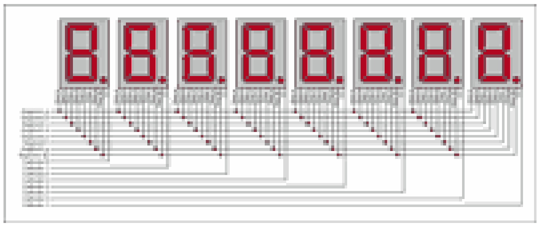

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Figure 12. Standard connections for multiplexing

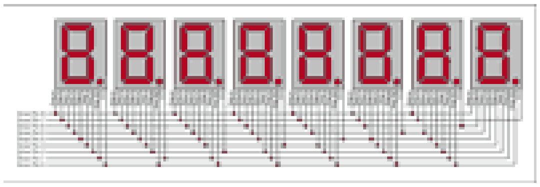

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Figure 13. Reduced pin-count multiplexing - MAX6951 connections

LED Life Expectancy

LEDs have a MTBF (mean time between failures) usually in the range of 100,000 to over 1,000,000 hours. This is a long time for continuous operation, considering a year is 8760 or 8784 hours. In practice, the useful measure of LED lifetime is its half-life, that is an LED is deemed to have reached the end of its life when the light output falls off to half the original.

When current flows through an LED junction the current flow is not uniform, resulting in small temperature differentials within the chip. These temperature differentials exert stress on the lattice, causing minute cracks to occur. These lattice defects accumulate with use, and reduce the photon conversion efficiency of the chip, so reducing light output. The attrition rate varies according to the LED material, temperature, humidity, and the forward current.

Blue and White LEDs

There are essentially two technologies for generating white light from LEDs. One way is to mount a red die, a green die, and a blue die very close together within a package, and mix the light outputs in the correct proportions to achieve white light. The problem with this approach, ignoring the technical issues of setting the correct LED drive levels, is the cost of 3 dice. Nonetheless, tricolor LEDs are popular for LCD backlights in consumer applications because the user can set the backlight color to any hue desired.

The cheaper approach, pioneered notably by Nichia, involves including a phosphor with the blue LED that absorbs some of the blue light and fluoresces in a second color to achieve a near-white. Some early white LEDs using this technique showed a noticable blue tinge, but the most recent developments are excellent and can be seen in the emerging full color PDAs and cell phones.

Recent Applications for LEDs

LED processes changed rapidly in the 1980s with the emergence of high efficiency GaAlAs and ultra efficiency InGaAlP LEDs (Table 2). In a short space of time, the quantum efficiency of LEDs was approaching several percent, all primary colors (RGB) were available, and reliability was at least as good as the other display technologies. Surface mount LEDs are available in single color (including white), bi-color (usually red and green), and tri-color (Figure 15) and these have proliferated in backlights for smaller LCD panels, equipment panels, and indoor message boards. Outdoor message boards using LEDs instead of filtered incandescent lamps use clusters of LEDs grouped together close enough so that the light outputs merge to create a typically 25mm square pixel (Figure 14). These message boards (or variable message signs) are used for advertising displays and traffic signs. Another rapidly growing market is traffic lamp replacement. Incandescent traffic lamps draw somewhere between 75W and 150W, depending on size (20cm or 30cm) and color (due to differences in the transmissivity of the red, green, and orange filters used). LED traffic lamps draw around 7W – 15W, and can be replaced every 5 years instead of every year for incandescents.

Table 2. LED Processes

Light Emitting Layer	Timeline	Comments
GaAsP (Gallium arsenide phosphide)	1960s	Original low efficiency red using liquid phase epitaxy
GaP (Gallium phosphide)	1970s	High efficiency red
GaA|As (Gallium aluminum arsenide)	1980s	Single and double heterostructure processed using vapor phase epitaxy increase efficiency
InGaA|P (Indium gallium aluminum phosphide)	1990s	Metal organic vapor phase epitaxy
InGaN (Indium gallium nitride)	2000s	Ultrabright green and blue

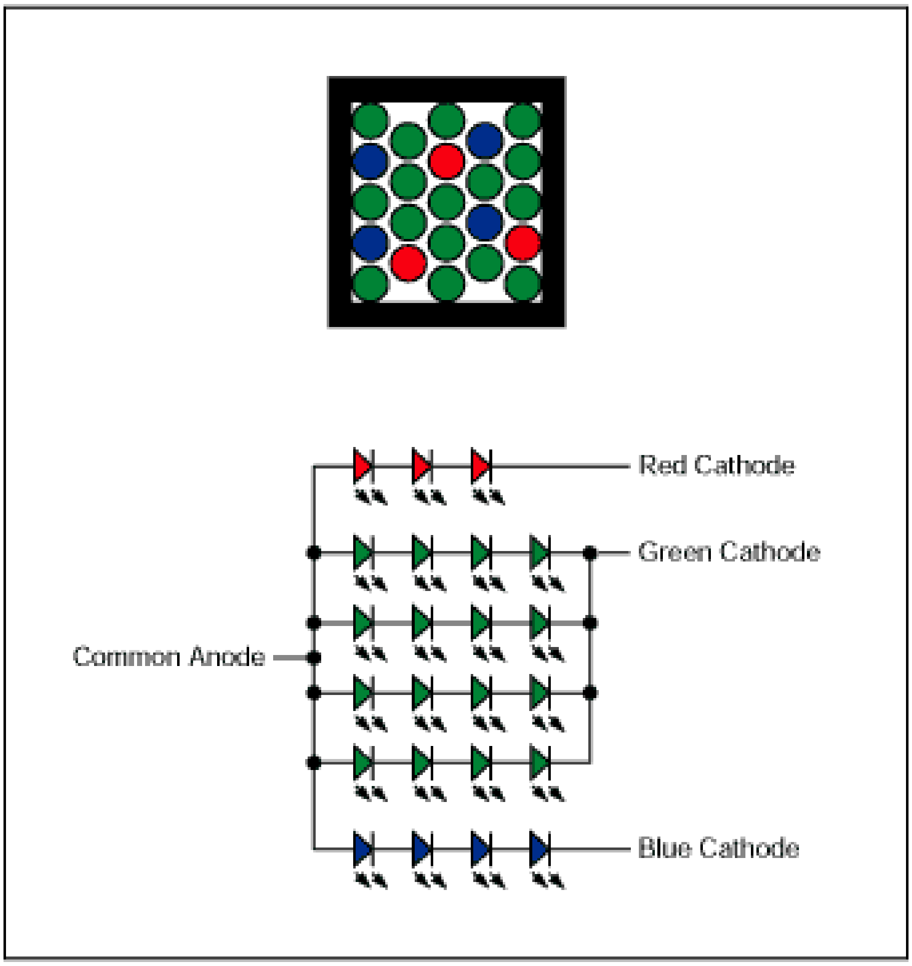

Figure 14. LED cluster pixel for outdoor message boards

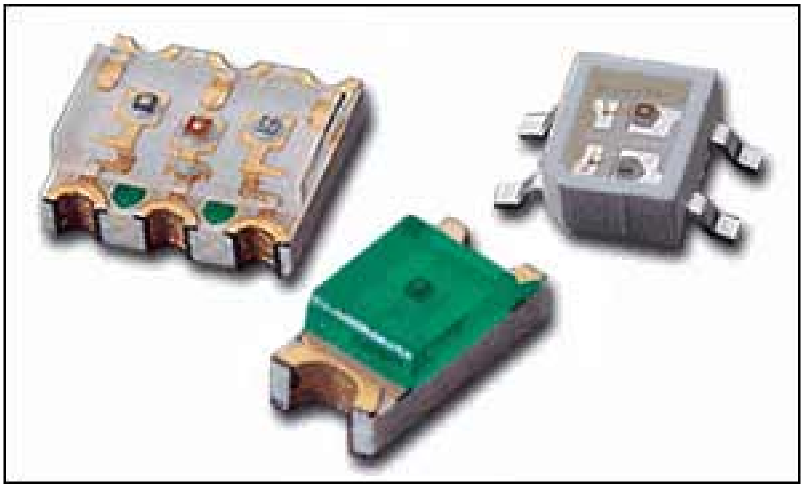

Figure 15. Surface mount LEDs from everlight

Future Applications for LEDs

Current ultra brightness LEDs exceed the light output of incandescent and halogen lamps and are not subject to the maintenance requirements (a life of a few thousand hours at best) associated with filament lamps. Also, LEDs are easily dimmed using PWM an other techniques. So the goal of the LED process developers is to build a very high brightness white LED which is economic enough to be used for domestic lighting. Right now, there is interest in high efficiency, long-life lamps by hotels and factories because not only is electricity for lighting a significant expense, but there is also the labor cost in actually replacing bulbs to consider also.

Comparison of Display Technologies

Display Type	Emissive or Reflective	Technology	Advantages	Disadvantages
Liquid Crystal Display	Reflective	An LCD uses the properties of liquid crystals in an electric field to guide light from oppositely polarized front and back display plates. The liquid crystal works as a helical director (when the driver presents the correct electric field) to guide the light through 90° from one plate through the other plate.	- Small, static, mono panels can be very low cost - Both mono and color panels widely available - Static panels offer lowest power/voltage display - Reflective panels in general are low power - Very easy custom segment shapes, sizes - Reverse backlit mono panels are attractive	- Backlight adds cost, and often limits the useful life - Requires AC drive waveform - Fragile unless protection added - Can have narrow temp range (0°C - 50° C) - Temperature compensation usually required - Can have narrow viewing angle - Low yields raise cost for larger (17"+) displays

Light Emitting Diode	Emissive	LEDs are photon emitting semiconductors which emit light due to the injection electroluminescence effect. The wavelength of the emitted light varies primarily due to the choice of semiconductor materials used, and is commonly in visible spectrum or infra-red.	- Lowest cost red or green emissive indicator - Available in very small sizes - Very bright versions available (higher cost) - Red and green types work from 3V supply	- LED is point source, so light shaping required to make segment shapes - White and blue LEDs expensive, need >3.6V supply - Can have narrow viewing angle - Color and efficiency vary with temperature and current - Care required to achieve 50khrs+ life
Organic LED Polymer LED	Emissive	These displays use organic electroluminescent materials deposited on a glass or flexible substrate. Devices based on small molecules are usually referred to as OLEDs. Those based on large organic "polymer" molecules are usually called PLEDs. Light is generated by injection electroluminescence, like LEDs. The choice of organic material sets the emission color. OLED pixels are capacitive (10s to 100s of picofarads) leading to significant switching losses for large displays with high multiplex ratios.	- Moderate cost for small (<4") color panels - Wider viewing angle than LCD - Faster element response than LCD - Emissive, unlike LCD color panels RGB and mono displays - Can be built on a flexible substrate	- 6V to 16V operating voltages - Differential aging effects limit life - Power consumption high for matrix panels >128 x 64

Vacuum Fluorescent Display	Emissive	The VFD is a vacuum tube using hot filaments to generate thermoelectrons, A grid (static display type) or multiple grids (multiplexed display type) control and diffuse the thermoelectrons, which are attracted to one or more high voltage phosphor coated anodes, which then emit light. The anodes are at the back of the display, so the emitted light passes through the grid(s) and filaments and the display front to be seen by the user. The filaments are not run hot enough to be usually visible.	- Wide operating temperature range - Long (40khrs+) life - Wide viewing angle - Very bright, attractive, typically green display - Very easy custom segment shapes, sizes - Different colored segments easy - 12V grid/anode voltage versions available	- Filament supply (±8% typ. tolerance) required - 10V to 60V grid/anode operating voltages - RGB displays available, but expensive - Phosphors other than green limit display life

A similar version of this article appeared in the October 2002 issue of *Elektronik Industrie* magazine.

A347, February 2003

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