Color LEDs
Past, present and future

By **Dr Thomas Scherer** (Germany)

We have known for a hundred years how to get certain inorganic materials to emit light when a current is passed through them, and LEDs themselves have existed for some fifty years. These colorful indicator lamps that have no filament or gas filling have been gradually refined and have become available in more varied and vivid colors. In recent years their efficiency has improved to the point that LED technology is replacing even fluorescent lighting. The most recent developments include LEDs that can replace LCDs.

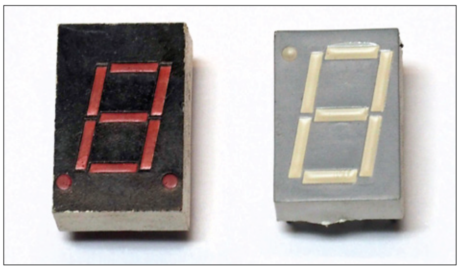

Figure 3. From the antiques collection: a red seven-segment LED display with a character height of 10 mm.

Figure 4. The first mass-market pocket calculators used tiny red seven-segment LED displays. (Source: Erhaka, *Wikimedia Commons*).

Figure 5. A LED miscellany. Top row, from left to right: red, yellow and four different green LEDs of 1970s vintage, compared to a modern blue LED which is so bright that its light saturates the camera sensor. Bottom row: modern green LEDs in 10 mm and 20 mm packages, and RGB, white and infrared LEDs.

After the invention of the crystal rectifier by Karl Ferdinand Braun in 1874 it was another 33 years before Henry Joseph Round discovered that the point of contact between the metal wire and the crystal could be made to emit light, yellow, red or even blue depending on the applied voltage. Round was therefore the original inventor of the LED and the electroluminescent effect in semiconductors that he discovered has been named the 'Round effect' in his honor. And so our story begins.

A slow evolution

The first modern-style LED was made at RCA. It produced invisible infrared light. That was in 1955, and the inventor was called Rubin Braunstein. Texas Instruments (TI) has the honor of being the first mass producer of LEDs, starting in 1962. TI's infrared LED had an efficiency of a mere 1.1 %! The first visible red LED was made by General Electric (GE), also in 1962; there was a surprisingly long gap of ten years before the first successful yellow LED was made, again at GE.

Through the 1970s red LEDs gradually improved. Efficiencies approached 5 % and they started to be used as indicator lights. Devices typically came in round 3 mm or 5 mm plastic packages and used only about 40 mW of power. They had many further advantages over bulbs with glowing tungsten filaments, including being insensitive to vibration and having a much longer life. Neon lamps, with their working voltages of 70 V to 100 V, also went the way of the vacuum tube: LEDs, operating from voltages of 1.2 V to 4 V (see the text box **Voltage and Color**) worked much better in transistor circuits. Also in the 1970s seven-segment displays began to appear using (red) LED technology: see **Figure 3**. Some readers will be able to remember the first pocket calculators like the one shown in **Figure 4**, which used tiny red displays that often consumed more power than the chip doing the actual calculating. My TI-59 from 1977, one of the first programmable calculators, had many more functions than that example, but still only had the same type of minuscule display. And it took such a long time for this schoolboy to save up for it!

Three different colors of LEDs were available in the 1970s: red, yellow and green. The upper row in **Figure 5** shows (ignoring the blue LED on the right for the moment) some antiques dating from this period. They were in general not particularly bright, the shades of red and yellow light emitted varied from device to device, and the green color was not exactly convincing. **Figure 6** shows the brightness and color variation in green LEDs from that time: all four LEDs are wired in series, with a current of 5 mA flowing through them. The LED at the

Voltage and Color

Inorganic LEDs are based on doped semiconductors, and often contain elements such as aluminum, arsenic, gallium, indium, phosphorus and nitrogen. More recently research has turned to LEDs employing carbon (in the form of diamond), silicon and zinc. The composition, concentrations and construction affect not just the efficiency of the LED, but also have a direct effect on the color of the emitted light. The energy of the photons emitted by a material depends on what is called the bandgap, which is the energy difference between the conduction band and the valence band of the semiconductor in question. The bigger the bandgap the higher the energy of the photon and the shorter the wavelength of the light. The bandgap has a big effect on the threshold voltage, which is the voltage that has to be exceeded before current will flow and before electrons will jump between the conduction and valence bands and so emit photons. The theoretical relationship is shown in **Figure 1**. It is now clear why the forward voltage of a blue LED is around twice as high as that of a red LED, as the frequency of the light is proportional to the photon energy.

Table 1 shows which semiconductor materials are used to produce which colors, along with the corresponding wavelength ranges and the forward voltage you can expect. Now, the actual voltage you might measure across the terminals of a real LED depends of course not just on the bandgap of the materials used but on many other details including the resistance of the materials and bonding wires and the semiconductor junctions. The voltage across the LED will also increase with increasing current. The reason that the transition between current not flowing and current flowing is not perfectly sharp is that in the transition region electrons behave statistically, having a certain probability of overcoming the bandgap which rises with increasing voltage. The spectrum of the light from an LED also moves slightly towards longer wavelengths ('warmer' colors) with increasing temperature: this is not a surprise, as the forward voltage drops with increasing temperature. If a particular application requires a stable color, the die temperature of the LED must be kept in mind.

The purity of color of the light from LEDs lies between that of (colored) incandescent bulbs and lasers. In other words, LEDs are not as narrowband as lasers, which emit light of practically a single wavelength, nor as wideband as incandescent bulbs. **Figure 2** shows that, particularly at longer wavelengths, LEDs are reasonably narrowband. The spectrum of blue LEDs, on the other hand, is somewhat broader. This characteristic is used in white LEDs that consist of blue LEDs plus a phosphor layer: the result is a more uniform spectrum and hence a more natural (that is, sunlight-like) light. The quality of light from a white LED is characterized by its 'color rendering index', or CRI, R_a. Values are specified relative to sunlight, which has a CRI of 100; white LEDs manage CRI values of between 75 and 95.

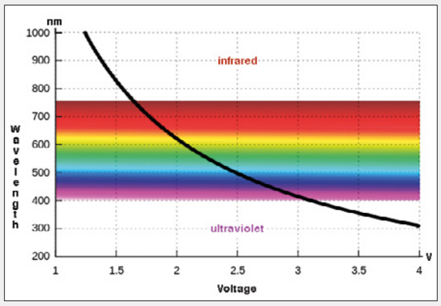

Figure 1. The relationship between an LED's forward voltage (bandgap) and light color. Voltage and wavelength are in inverse relation.

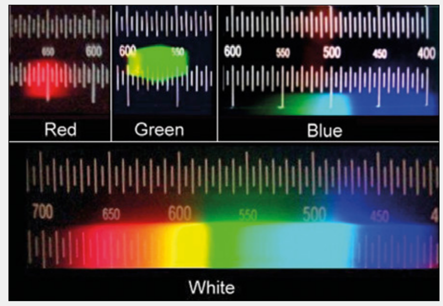

Figure 2. Spectra of various colors of LED. The shorter the wavelength, the more broadband the spectrum. Below, for comparison, the spectrum of sunlight. (Source: *Wikimedia Commons*).

Table 1

Color		Wavelength (nm)	Material		Voltage (v)
infrared		over 760	GaAs AlGaAs	gallium arsenide aluminum gallium arsenide	less than 1.6
red		610 to 760	AlGaAs GaAsP AlGaInP GaP	aluminum gallium arsenide gallium arsenide phosphide aluminum gallium indium phosphide gallium phosphide	1.6 to 1.9
orange		590 to 610	GaAsP AlGaInP GaP	gallium arsenide phosphide aluminum gallium indium phosphide gallium phosphide	1.8 to 2.2
yellow		570 to 590	GaAsP AlGaInP GaP	gallium arsenide phosphide aluminum gallium indium phosphide gallium phosphide	2.0 to 2.4
green		500 to 570	InGaN GaN GaP AlGaInP AlGaP	indium gallium nitride gallium nitride gallium phosphide aluminum gallium indium phosphide aluminum gallium phosphide	2.2 to 2.7
blue		450 to 500	ZnSe InGaN SiC	zinc selenide indium gallium nitride silicon carbide	2.6 to 3.3
violet		400 to 450	InGaN	indium gallium nitride	3.2 to 3.6
ultraviolet		230 to 400	AlN AlGaN AlGaInN	aluminum nitride aluminum gallium nitride aluminum gallium indium nitride	3.5 to 4.2

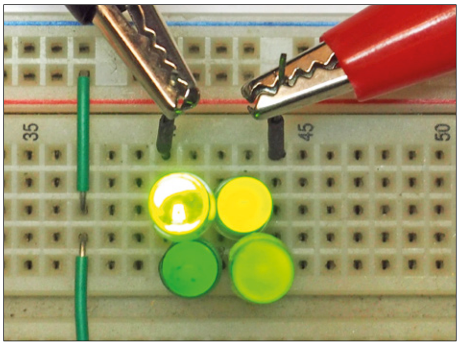

Figure 6. Four different green LEDs: each emits a different light. The LED at the top left is a modern 'superbright' device, which saturates the camera sensor. The other 5 mm LEDs are the samples from Figure 5.

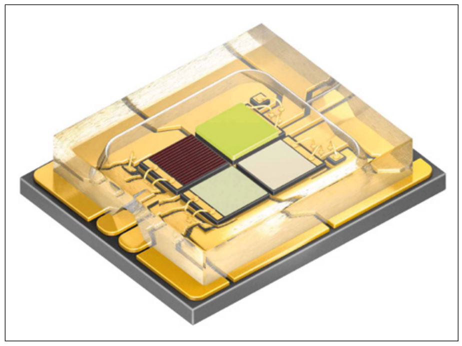

Figure 9. More than an RGB LED: this OSRAM OSTAR LED in an SMD package contains a white LED chip in addition to chips in the primary colors.

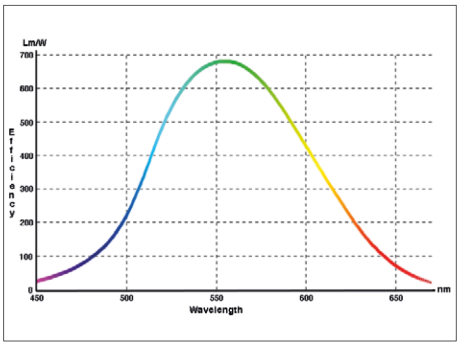

Figure 7. Maximum theoretically possible light output from an LED as a function of color. Note that the lumen is a unit which takes into account the sensitivity of the human eye to different colors.

Figure 8. An LED 'candle lamp'. The LED strips in this E14 bulb mimic traditional filaments. (Source: OSRAM).

upper left is a modern high-efficiency type for comparison purposes: it is so bright that it saturates the sensor on the camera. One of the old-school LEDs is more yellow-green than true green. Red and yellow LEDs suffered from similar weaknesses. Fortunately modern LEDs in 5 mm or SMD packages have beautifully deep colors and are so efficient that, when used as indicators, the current through them must be carefully limited to avoid dazzling the user.

Status quo

There was an even longer gap before LEDs in the previously missing blue color arrived. They first came on the market only in the 1990s, produced by Nichia. The development of the blue LED was judged worthy of a Nobel prize for its inventors Shuji Nakamura, Isamu Akasaki and Hiroshi Amano in 2014, a huge honor for such a small device. The award of the prize recognized the fact that high-efficiency blue LEDs are fundamental to making white LEDs, where a phosphor layer is added to the LED which absorbs a portion of the higher-frequency blue light and converts it into yellow light. The combination of this yellow light with the remaining blue light yields white light through additive mixing. This idea was developed by Jürgen Schneider at the Fraunhofer Institute and now forms the basis for almost all LEDs used in lighting applications. Today white LEDs have a slightly greater market share than color LEDs. You can read more about white LEDs in my article 'Let There Be LED' in the January/February 2016 issue of Elektor [1].

At the upper right of Figure 5 you can see a blue LED in a transparent plastic package, operating at 5 mA. It is so bright that it saturates the camera's sensor and so misleadingly appears bluish-white in color. At the bottom left are green LEDs in 10 mm- and 20 mm-diameter packages. The larger of these is a multi-chip LED containing four LED chips connected in series. Next to it on its right is a common-anode RGB LED which therefore has four leads. The three primary-color LED chips in this device can be driven in such a way as to create a mixture of practically any desired color. The transparent LED to its right is a modern white device, and on the far right is an infrared LED. The package of this device is transparent to infrared light.

From the meager levels of the seventies the light output of LEDs began to increase rapidly, especially at the beginning of this millennium, reaching efficiency levels of 100 lm/W. This puts white LEDs on a level where they can compete with fluorescent lamps, matching them for light output while offering the advantages of a longer service life and zero mercury content. In the laboratory, meanwhile, white LEDs have been made with output efficiencies exceeding 300 lm/W, just a few percent short of the theoretical limit of 350 lm/W at a color temperature of 6600 K. **Figure 7** shows how the maximum theoretically possible light output depends on the color of the LED. There is a nice paradox here: although the blue LEDs on which white LEDs are based have an efficiency of no more than 200 lm/W, the white LEDs offer a higher efficiency. The explanation for this is that the way the 'lumen' is defined takes into account the varying sensitivity of the human eye to different colors: green light at a given power looks brighter than other colors. And so, although when generating yellow light using the phosphor a little energy is lost (in fact, converted into heat), the white light looks brighter to us than the blue light directly from the chip under the phosphor would.

It is worth noting, then, that the potential for further refinements in the lab is almost exhausted as there is very little scope for further efficiency gains. There is still progress to be made, however, in converting these prototypes into real products. There is plenty of room for improvement in mass production processes to enable the manufacture of devices matching the performance achieved in the lab at reasonable prices. This will no doubt happen within the next decade, and then we will have at our disposal a wonderfully energy-efficient lighting technology based on modern semiconductors which, thanks to its excellent service life, will also have a relatively small carbon footprint.

Color LEDs

In recent years LEDs have reached such high efficiency and, thanks to mass production, low prices, that they have by and large completely superseded filament lamps. And LED lamps have moved on from the ungainly units seen in the past containing a large number of SMD chips: these days you can buy bulbs whose internal LED structures mimic the filaments of traditional slender candle-shaped filament bulbs (see **Figure 8**). So now it is possible to populate your chandelier with modern energy-efficient bulbs while still remaining faithful to its style. LED lighting is now available in practically any shape, size and color you can imagine: we shall return to this topic later.

Infrared LEDs have of course been used for many years in remote controls, as well as more recently in providing unobtrusive night-time lighting for security cameras or for military purposes. Another interesting application is the use in industry of infrared lamps consisting of hundreds of SMD LEDs with a total output power of over 100 W as a component in projectors to shine a grid of infrared illumination on one part of a production line or on an assembly station. The idea behind this is that, unlike a human operator's eyes, a robot's cameras can easily see the projected grid and hence orientate itself in space and better estimate the position of units on the production line. Humans working alongside the robots or monitoring their operation are not disturbed by the infrared light.

White LEDs are not the only way to generate white light: a more expensive, but equally good, if not better, alternative, is to use RGB LEDs. These consist of LED chips in (at least) the three primary colors mounted in a single package. By passing different currents through the different chips the outputs from the individual LEDs can be mixed at will to produce practically any desired color. **Figure 9** shows an example, an OSTAR SMD LED, which includes not only chips with red (625 nm), green (530 nm) and blue (453 nm) LEDs, but also a white LED. It is designed for use in specialist lighting applications such as providing precise illumination for surgical operations and other uses where color accuracy is critical. Despite its small size, this SMD device can output over 500 lm of light at its nominal current of 1.4 A.

Readers who like to strut their stuff occasionally will already be aware of the widespread usage of LEDs in discos and clubs. Stage spotlights, or 'PAR cans' as they are sometimes called, used to be incandescent lamps rated at several hundred watts equipped with colored filters. Nowadays they have been largely LEDified with all-electronic control (see **Figure 10**). Although the LED versions are not yet quite the equal of the old technology in all respects, the availability of ever brighter LEDs is closing the gap. Service life, robustness, much lower heat generation, reduced risk of injury (stage spotlights are prone to explosion) and instant electronic control all weigh in favor of the LED versions.

Colored LEDs don't have to be used in conjunction with music, of course. At an early stage Philips realized that even Joe and Janet Bloggs would be keen to have configurable mood lighting in their home. Under the 'LivingColors' brand the Dutch electronics giant has been marketing a range of table and wall lights for a few years now (see **Figure 11**). These remotely-controlled LED lamps can be adjusted over a wide range of colors. Each lamp contains a number of color and white LEDs that can produce static mixed colors or flashing patterns, and the lamps can also be dimmed. The success of this range led Philips to produce the 'Hue' range (**Figure 12**). This brand includes not only lamps, but also LED strips and 'normal' colored bulbs for E27 fittings, all remotely controlled using a 'bridge'. A range of lamps with built-in lithium batteries is also available under the 'Hue Go' brand. These lighting systems have been highly profitable for Philips and so doubtless further variants will also appear on the market. If you are looking for a more economical alternative, you will not be disappointed: the DIY sheds have spotted the opportunity and offer shelfloads of inexpensive color LED lighting of all kinds (**Figure 13**), costing just a fraction of the price of the big-brand products. For an even cheaper solution, you can import directly from China using eBay or Alibaba. In this case, of course, you have to reckon with the complications of dealing

Figure 10. Cameo type CLP56RGB05PS PAR stage effect light with 151 colored LEDs and a power rating of around 30 W at 230 V. Not only does the light sport a DMX interface for remote control, it also has a built-in microphone to enable 'light organ' effects.

Figure 11. Philips LivingColors: this lamp from the highly successful range contains remotely-controllable colored and white LEDs in a plastic enclosure.

Figure 12. The Hue series from Philips includes colored LED lamps with E27 fittings and a 'bridge' for remote control

Figure 13. These days you can find a huge selection of LEDs strips, bulbs and effect lamps with or without remote control in any DIY shed.

Figure 14. Google Nexus 6p: the OLED display on this reasonably-priced smartphone has a resolution of 2560x1440 pixels.

with possible customs charges, and of course always bear in mind that cheaper does not necessarily mean better value (see the text box **Feel the Quality**).
Naturally ultraviolet LEDs also have their uses. As well as specialist applications there are uses such as exposing the photosensitive lacquer on printed circuit boards or building 'black lights'. Another application for ultraviolet LEDs is illuminating the water flowing through a transparent pipe, with the aim of reducing the growth of algae in aquaria and swimming pools. Some varnishes can be cured using ultraviolet light, and the LEDs can also be used to test the resistance of products to exposure to ultraviolet light.

OLEDs

Organic LEDs (OLEDs) were discovered much later than inorganic LEDs, and so far cannot compete with them in terms of light output or long-term stability. However, their star is in the ascendant: the advantages of OLEDs are low-cost raw materials and, in principle, lower cost of manufacture, as they do not require such strict 'clean room' conditions. OLEDs can also be made in flat sheets: this is an advantage in many lighting applications, as the sheets do not have to be rigid. Flexible lamps are therefore a possibility. For a long time it has proved difficult to make OLED products outside a laboratory environment, but that is now changing. OLEDs can very easily be used, for example, to make displays, as printing technology allows the organic light-emitting pixels to be manufactured along with their interconnect wiring. RGB OLED displays are bright and contrasty. Similar approaches to manufacturing displays with semiconductors are much more complicated and decidedly more pricey. OLED displays are increasingly competing with LCD displays and in principle the OLED beats its liquid-crystal counterpart in virtually all departments. There is no backlight or any of its attendant problems, as the OLED pixels are themselves the source of light. Current consumption is also lower, as much of the light from an LCD's backlight is lost in the diffuser and in the polarization filters. Colors that change with viewing angle are a thing of the past with OLEDs. And last but not least the contrast ratio of an OLED display cannot be beaten: when an LED is off, it is off. Blacks really are black.
Given all these wondrous advantages you

Feel the Quality

LED lamps, containing a large number of individual LEDs to provide sufficient light output, have been available for some time. Since the mid-1990s car makers have routinely used a string of red LEDs for the 'third' brake light, even on mid-range vehicles: the red LEDs of the time were already bright enough and cheap enough. Customers were happy too, as the light did not need replacing as often over the life of the vehicle as an incandescent version. Brake lights are an important part of vehicle safety, and so not failing after a few hundred operating hours is a significant benefit. All very warm and fluffy, but cracks start to appear in the story when it comes face to face with reality.
More specifically, two phenomena come into play, which together make the situation far from ideal. The LED brake lights do indeed have a huge 'theoretical' service life of up to 50000 hours. But in the vehicle environment that does not represent much of a guarantee, what with vibration, bad weather and high humidity levels (which can lead to corrosion of printed circuit board tracks, for example), and extreme temperature variations. These lead to mechanical stress on the LED packages, chips and bond wires. As a result the quoted service life of 50000 hours is a pipe dream. The car's bodywork can get very hot in sunshine, and the heat dissipated by the LEDs adds to this to generate very high operating temperatures. The consequence is that LEDs in automotive applications do indeed last longer than incandescent bulbs, but not by the large factor that you might have hoped for. In addition to this there is the 'multiple LED effect': even under optimal conditions, when many LEDs are in use it is statistically inevitable that the time for which all LEDs will be working will be reduced. Correcting for this effect, a lamp consisting of ten LEDs might have a service life of only 15000 hours rather than the hoped-for 50000 hours. And, if in the real-world vehicle environment, the life of an individual LED falls to only 10000 hours, one LED in the ten-LED lamp might easily fail after only 3000 hours. But that is not the end of the story: in vehicle lights that use LEDs designed for a 12 V supply, the LEDs are often wired in series strings of two or three devices each, and so the failure of one LED leads to the loss of light from one or two more. Another problem is that the LEDs in vehicle lights are often hermetically sealed and so are not replaceable. Instead of just replacing a two-dollar bulb the whole lamp assembly has to be taken out and replaced.
These are not mere academic considerations, but reflect my own personal experience: the brake light on my 1996-model Fiat failed in just the way described above after only three years, and a replacement part plus labor was not a cheap proposition. And in case you are thinking 'well, that's Fiats for you' I should say that, despite the alleged reliability of Toyota vehicles I had an LED fail in exactly the same way on my Prius. In this case it was part of the left-hand rear light cluster, which contains a large number of integrated LEDs all firmly fixed in position. At eleven years (in fact, at the same time as the brake disks needed to be replaced) one of the lights failed. Fortunately a third-party replacement part was within my means, but still not cheap. If the LEDs in the headlight on a modern vehicle should fail, you are certainly looking at a tall bill from your garage. Modern technology comes at a price!
This disadvantage of multi-LED clusters becomes a significant problem when they are used for domestic lighting. Although humidity and temperature fluctuations play a lesser role in this environment, there is still the question of the quality of the com-

would be forgiven for asking whey OLED displays are not more widespread. The problem lies in the extremely demanding requirements of the manufacturing process. The many LEDs in a single display must all be equally bright (within rather narrow limits), and must stay that way over time. The consequence is that as little as two years ago even small-screen TVs were unrealistically expensive. However, towards the end of 2016 LG, the market leader in OLED TVs, introduced a model with a 55-inch diagonal for a reasonably affordable US$1500. Smartphones with OLED displays have been around for rather longer, and the price difference for small displays compared to LCDs is now relatively small: the moderately-priced Google Nexus 6p, produced by Huawei (**Figure 14**) contains a 2560x1440 pixel panel with some 11 million OLEDs. You might wonder why no iPhone has been produced using an OLED display: the answer is that, as of 2016, there is insufficient manufacturing capacity in the world. Capacity is steadily being increased, however, and the rumor mill has it that there may be sufficient capacity by the end of 2017 for an OLED panel to appear at least on the higher-end versions of the iPhone 8.

The future

Besides the rumors of an iPhone 8, OLED panels will shortly be found in all kinds of gadgets and appliances that need to display something. It is no exaggeration to say that pretty much every other kind of display technology will soon have had its day. OLEDs will also make inroads into lighting applications: when that starts to become economically feasible, many lighting manufacturers will jump on the bandwagon. Lamps for conventional fittings will remain the domain of semiconductor LEDs, since for the foreseeable future OLEDs do not offer the light density required to provide adequate illumination from a small bulb. Inorganic LEDs will also supersede practically all other lighting technologies except in niche applications with specialist requirements. This is because total operating costs are much lower than other technologies, not just because of their greater energy efficiency, but because they require less frequent maintenance as a result of their longer service life. Street lighting is one application where soon there will be no alternative to LEDs. LEDs could allow the construction of intelligent car headlights that automatically adjust the shape of the light cone away from oncoming vehicles to avoid dazzling their drivers; perhaps manually dipping and undipping the headlights will no longer be necessary. We should be so lucky!

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Web Links

[1] 'Let There Be LED': www.elektormagazine.com/150577

[2] www.youtube.com/watch?v=Oj8RIEQH7zA

ponents used. Low-cost LED strings from the Far East used for Christmas decorations or for fun are of course fine, but in many cases it is hardly possible to believe the price of a product on offer. A whole string can often be sold for less than the total cost of the LEDs it contains. How do they do it? The easiest reply to this question is usually 'at the expense of quality'. And aesthetic considerations are no determinant of when an LED becomes an ex-LED [2]; even my Christmas displays, which are of course done in the best possible taste, have on occasion suffered from LED strings (or at least parts of them) going to meet their maker.

Low-cost LED strips with a self-adhesive backing, which are powered indirectly from a low-voltage supply and which are often used for illumination in furniture and similar applications, suffer from the same problem. My personal tribulations involve two LED strips, each 2 m long, stuck to a length of aluminum section: a total of 120 LEDs. My estimate for the time to the first failure had been of the order of 4500 hours, but after just six months and perhaps 600 hours of operation eight LEDs had already kicked the bucket! I desoldered some replacement SMD LEDs of the same color from a spare strip and mended the original strips, but after another two months two more LEDs were pushing up the daisies (**Figure 15**), and no doubt this is not the end of my woes.

Figure 15. A failed LED strip. It is perhaps partly my fault that LED L30 has gone to join the choir invisible: because of the kink in the strip it was not being properly cooled, and it has failed to a short-circuit rather than an open-circuit. Other LEDs in the same strip, however, seem to have met their demise without such a good excuse.

Regular LED lighting can also often have shorter life than expected. LED bulbs have not been around for all that long, but nevertheless I have had four bulbs with E27 fittings and two GU10 spotlights bite the dust. In the case of the E27 bulbs it was the switching supply circuit whose coil proved all too mortal, whereas in the case of the GU10 spotlights the LEDs themselves became history after exposure to excessive temperature. In the case of two LED tubes bought as replacements for fluorescent lights the engineers at LG had put a fuse with too low a rating in the integrated switching power supply circuit: uprating the fuse fixed the problem and the tubes still work today. Also, my home-made LED lamp (**Figure 16**), which uses 13 high-quality LEDs, is still going strong after more than a decade.

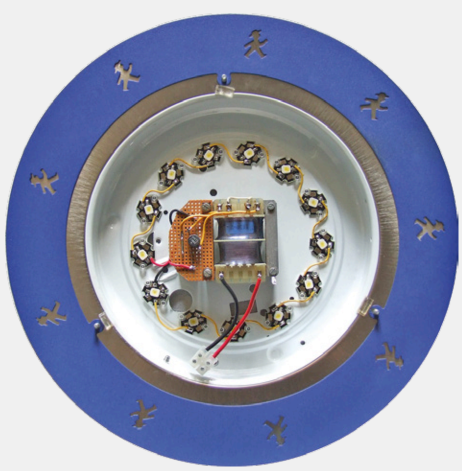

Figure 16. The first 'Scherer-brand' home-made LED lamp was made in 2005, and continues to run to this day, after over 10000 hours of operation.