High-Brightness LEDs lighting up the future

According to Stan Bruderle of Dataquest (in "LEDs - The Future Couldn't Look Brighter"), sales of optoelectronic semiconductor devices should grow from about US$7bn in 1999 to over US$12bn in 2004 (Figure 1), a compound annual growth rate of about 14% (similar to the growth forecast for silicon-based microelectronics).

Annual growth in LED sales can be split into two segments:

• older, more mature LEDs (5-7%); and
• new LEDs such as the nitride-based blue and white LEDs and the red, orange and green aluminium indium gallium phosphide (AlInGaP) based high-brightness LEDs (15-40%).

Several factors are driving the growth of today's LED products: the more important ones are brightness, available colours, power efficiency, architectural form flexibility, rugged construction and low applied voltages. These are contributing to growth in markets such as traffic lights, automotive brake signals and instrument displays, video displays, airport runway and taxi lights, hazardous lighting, exit and decorative signs, and the many uses of the new white-LED-based products.

Future possibilities include, for example, simplified, single-fixture traffic signals where the three colours light up separately and different-shaped arrangements of the LEDs are used for each colour to allow recognition by those who are colour blind. There even appears to be an LED version of the silicon industry’s “Moore’s Law” (for IC functionality or performance) in which LED brightness doubles about every 18 months.

LED lamp/display market leaders are shown in Table 1 (based on estimated 1999 revenues), but this is expected to change due to rapid growth of new companies such as Mingstar, Kingbright, Ledtech, Everlight and Lite-On. High-brightness LEDs are potentially a disruptive influence on the existing lighting industry, because of the sudden arrival of upstart products that are superior in new areas of the performance envelope and because of recent pressure for lower power consumption to reduce peak demand loads.

However, to protect their share of future markets some major international lighting companies have been forming joint ventures with LED producers, e.g. between General Electric and EIMCORE to form GEFCO; Philips and Agilent (formerly HP) to form Lumileds; and OsramSylvania and Infineon Technologies to form Osram Optoelectronics.

Table 1. The market leaders in sales of LED lamps and displays (source, Gartner Group).
Two auto-related companies have also diversified into this arena. Uniroyal Technology Corp has bought the silicon carbide manufacturer Sterling Semiconductor and has a cooperative agreement between Uniroyal Optoelectronics and EMCORE (as well as spawning start-up NovaLux), while Toyota has for sometime held a 41% interest in nitride-based LED manufacturer Toyoda Gosei.

Because of their efficiency and potential energy savings on a national scale, the new generation of LEDs has not gone unnoticed by US government agencies (including the US Energy Department and the Environmental Pollution Agency) and power generation companies. Additionally, their long-life, low-power, low-voltage and cool operation have made white LEDs popular for space applications while the low power consumption of coloured LEDs has made the installation of traffic lights a priority to save on peak power demands for the electric utility companies.

According to Gary Fernstrom from Pacific Gas & Electric (California's biggest utility company), some of these replacements are supported by incentives from the Department of Energy and the power companies, with US$50m available in California for LED traffic signal installation. In the Northern California PG&E region alone, he estimates that 5 MW would be saved if 50% of the signals were changed to LED units; worldwide, hundreds of megawatts could be saved.

Fernstrom notes that energy saving has become very important in many states of the USA, including California where, since deregulation in 1996, electricity demand has grown by 30% but supply by only 6%, leaving an energy shortfall (including even winter power shortage alerts). This is anticipated to be almost 1000 MW in 2001, in part caused by recent hidden standby uses for everyday items such as computers and household appliances, plus a recent display mania for lighted soft-drink machines. This shortage is also causing some new rules to be proposed, such as limiting all exit signs sold in California to a rating of 5 W or less, eventually saving 10 MW - more if LEDs are used as well as reducing maintenance costs and improving safety, since they do not in general suffer catastrophic failures like a blown light bulb. Such a precedent would represent very significant savings if followed by the rest of the world.

According to Rachel Schmeltz from the US Environmental Pollution Agency, one aspect of their Energy Star efficiency programme to promote LED signs has been rated a resounding success. The paybacks are less than one year and provide a reduction in carbon emissions. A 75% energy reduction in new exit signs results in annual savings of 2bn kWh. The US Government has required Energy Star labelled products to be used since 1999, but many states in the USA still have to formally adopt the programme (which also includes specifications for other traffic signals).

Reviewing the lineage of the high-brightness LED, George Craford of LumiLeds reckons that the cost per lumen of the lowly red LED (which began life in 1960) has improved 10-fold for every decade - from less than 0.1 lumen/Watt to the best red and orange LEDs now providing about 100 lumen/Watt. The red LED has been a real success story, where per decade the light output has increased 30-fold per decade.

Significantly, the light generation efficiency of these single-source LED chips has improved to where today's quantum efficiencies are very high so that the main engineering challenge is now the extraction efficiency or the ability to get all the light out of the chip to where it is needed. This has led to novel changes in the shape of the LED chip and to the replacement of the gallium arsenide production wafer with transparent gallium phosphide (through wafer bonding after the LED has been produced, as in the case of the high-brightness orange LEDs). By using a "truncated-inverted-pyramid" design (see Figure 2), the external quantum efficiencies now exceed 50% for the orange LEDs so that more than 12 lumens can be extracted from one chip on a pulsed output basis.

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a road LED traffic light in 1994 to the current North American market penetration level of 10% of lights sold and a total installed base of 350,000 units at the end of 1999 (over 40% being red lights and green and crosswalk lights about 20% each - see Figure 3). It forecasts 60% market penetration in North America by 2005.

William Gartner of Traffic Technology Inc compares the 135 W power consumption of a standard traffic light versus 16 W for their Unilight LED version and, similarly, 155 W for the green turn arrow versus 8 W for the LED version. The LEDs 80-90% reduction in power use results in a US$60-80 annual cost reduction per light (except for amber due to its low duty cycle) and annual maintenance savings of about US$2500 per intersection. Gartner sees 24 million signals being replaced by the year 2020 with annual savings of US$2.5 billion (equivalent to one power station). He also quoted Jeff Nelson from Sandia National Laboratory as saying that if all the incandescent and fluorescent bulbs in the world were replaced with LEDs, it could save the equivalent of 38 nuclear power plants. This could start in about 25 years, based on the technology improvements anticipated for white-light LEDs.

Although traffic signals are currently the largest traffic application for LEDs, Nathaniel Behura of LEDpro highlights other applications which are growth market opportunities, both primary sources (Table 2 - mostly government regulated) and secondary sources (Table 3, e.g. pathway delineation and warning lights - currently not as regulated). Many of these applications make use of the ruggedness of LED lighting systems in conjunction with their low power demands, enabling some LED-based systems in remote locations to be powered by solar cells.

The case has been well documented for the traffic markets, but general lighting applications such as white-light production and display signs present equally large opportunities for LEDs. The market for large outdoor signs (2m x 3m and larger) has been growing for several years, especially since the advent of the blue LED in 1997 enabled the manufacture of white and full-colour signs (e.g. the new NASDAQ sign in Times Square New York, which uses 19 million LEDs and covers the end of a building). Other rapidly growing uses are for advanced white-lighting applications such as flashlights and indoor lighting and for coloured lighting, lighting strips and replacements for neon lights (e.g. AlInGaP orange and red high-brightness LEDs and InGaN violet, blue, green and white LEDs).

Apart from the USA, there is also significant activity in both Asia and Europe. Asian use of the large outdoor signs is ahead of Europe and North America, while Japan’s acceptance of traffic signals is ahead of everybody. Most European countries are installing LED traffic lights, but Sweden could be leading the pack in novel road applications for supplemental lighting. According to Nils Borg from Borg & Company and Lars Bylund from Polk Design Group KB in Stockholm, these include road and footpath markers, traffic information lights and 3 W white LED pilot markers for roads instead of conventional lighting, with the potential for 60-90% energy savings. There are now roadmaps in North America and Europe to improve LED production technology and to promote their wider use.

**Table 2. Primary light source applications of LEDs.**

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<thead>
<tr>
<th>Vehicle traffic signals</th>
<th>Pedestrian signals</th>
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<tr>
<td>Hazard identification beacon (flashing beacons)</td>
<td>Lane-use control signals</td>
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<td>Railroad signals</td>
<td>Airfield lighting</td>
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**Table 3. Supplementary (secondary) light source applications of LEDs.**

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<thead>
<tr>
<th>Pedestrian crosswalk lighting</th>
<th>Pavement indication at traffic signal stop</th>
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</thead>
<tbody>
<tr>
<td>Warning lights</td>
<td>Variable message signs</td>
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<tr>
<td>Highway barrier lighting</td>
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According to Gary Fernstrom from Pacific Gas & Electric (California’s biggest utility company), some of these replacements are supported by incentives from the Department of Energy and the power companies, with US$36m available in California for LED traffic signal installation. In the Northern California PG&E region alone, he estimates that 5 MW would be saved if 50% of the signals were changed to LED units; worldwide, hundreds of megawatts could be saved.

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According to Bernd Keller of GaN LED manufacturer Cree Lighting Company, only the traffic light and large-sign applications can currently be considered volume markets. Other applications may have large market potential but are at the stage of technology development and mostly restricted to specialty markets by the current high cost per lumen of the available light. However, as manufacturing technology advances and the costs per lumen are reduced, growth rates will increase. (A similar situation also holds for GaN-based high-temperature and high-power electronics.)

As Cree Inc is also a manufacturer of silicon carbide substrates, it is not surprising that their LEDs use this substrate, which is deemed to have advantages for electrical and heat conductivity. However, recent measurements of higher GaN thermal conductivity may nullify some of these advantages (see ISCS report, this issue, page 28).

The advantages of GaN-based LEDs are high efficiency, high light output and long life. Also, they can operate at high materials temperatures. New performance records are continually being reported for GaN devices, and most are a further step toward new applications. However, Keller reported a recent world record that is worthy of note: that the 28% quantum and 21% wall-plug efficiency is immediately accessible to LEDs. Currents of large-area pulsed LEDs illustrate the potential for practical applications (see Figure 4).

This is very significant because these LEDs are the foundation of the phosphor-converted white light emitters that are expected to challenge incandescent lighting in the distant future. For the time being, white LEDs have to be satisfied with smaller volume markets such as flashlights and back-lighting applications.

The creation of the blue LED and its growing list of applications (including the large, outdoor full-colour signs and white LED products) was enabled by the original commitment of Nichia, the world's leading supplier of blue LEDs, which now also offers green LEDs for traffic lights and phosphor-based white LEDs for general lighting. According to Naoki Yoshida of Nichia America Corp, their continuing development of GaN LEDs includes a large research programme for the development of other InGaN single quantum well LED products, including amber lights and the recently announced yellow LED based on their phosphor technology.

Nichia also leads the world in the field of blue and violet solid-state lasers (which are basically overdriven LEDs). These have the potential to revolutionise the DVD market by quadrupling the disc capacity and opening up markets for other optoelectronic products. Since the technology merits of GaN LEDs are now not in doubt, time is the controlling factor for their wider acceptance in many world markets.

Last but not least, some LED applications that do not receive as much publicity were highlighted by Manfred Hubert from Efos Inc, which deals mainly in the UV and infrared curing of inks and coatings on many surfaces and embryonic medical LED uses including laser therapy, photo-biostimulation and fluorescence diagnostics.

Wavelengths used for these processes range from 200-900 nm, most of which (except for short-wavelength UV) are immediately accessible to LEDs. Arrays of AlGaAs LEDs have been developed for skin radiation therapy, and biostimulation cures by wavelength-specific LED radiation are being evaluated for skin ailments, including some cancers. LEDs are ideal light sources for these treatments because of their small size and because it is normally not too difficult to match an LED output to the peak absorption wavelength of the drug being applied. As these treatments receive approval from the medical regulatory authorities, high unit volumes of these LEDs may be required.

With such a positive outlook in so many application fields, there must be no doubt in many minds that LED businesses are the place to be. This certainly seemed to be the outlook of the vendors present at the LED-2000 conference, and this sentiment was spread across the business spectrum, from the traffic signal manufacturers, to the white- and coloured-light fixture makers, to LED key-chain makers, to the LED manufacturing and test equipment suppliers, the wafer and process chemical suppliers and, of course, to the LED chip makers themselves.