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Dr. Alan Mills reporting from San Diego where the high brightness LED was the leading feature at Intertech's LED 2002 techno-business meeting. This conference provided a good overview of the opportunities and technological challenges that are inherent in future HBLED markets. A record attendance of about 270 under depressed economic conditions is probably a good indication of the importance of this class of LEDs and solid state lighting applications in the world economy of the future.

Solid state lighting – a world of expanding opportunities at LED 2002

Vibrant markets

In spite of the current worldwide economic conditions, solid state lighting is creating a vibrant industry led by new and expanding markets based on high-brightness light emitting diodes (HBLEDs). Since the mid-1990s these LEDs have provided a semiconductor growth market in which year on year growth has exceeded 40% leading to 2001 sales values of over $600 million. In the future, this growth industry aims to compete with incandescent lamps at 15 lumens per Watt (l/W) by 2007 and most fluorescent lamps (at 80 to 100 l/W) by 2012. (See Figure 1.). Because most LEDs are manufactured by the MOCVD process, they have also been the main support of the related production equipment industry for some time and LED deposition equipment now accounts for over 50% of the industry value.

Although some new applications achieved commercial status this year, only single digit market growth was recorded. Market value was not able to maintain significant (double digit) year on year growth because declines in unit prices consumed most of the increases generated in unit volumes for both the AlInGaP and gallium nitride segments. However, high brightness LEDs were again the *highlight* of the total LED market and power efficiencies continued to improve. Red LEDs achieved 55 lumens per Watt, blue moved up to 10 l/W and white to 25 l/W. Historical and future cost-performances are reproduced in Figure 2.

AlInGaP based LEDs were the volume and value leader during the nineties, but gallium nitride based device markets have been growing more rapidly during the last few years and according to Pierre Maccagno from Needham & Co Inc., they attained a 60% market share in 2001 (out of a $1.2 billion high brightness market) to become the largest technology segment. The market leader in this segment is still Nichia with its volume production of blue, green and white LEDs, although strong competition is anticipated as competitors such as AXT, Cree, Lumileds and Toyoda Gossei, rapidly add capacity to meet a shortfall in III-nitride LED requirements.

The main application segments in 2001 for high brightness LEDs are listed below with their estimated respective market shares enclosed in brackets. They comprise a diverse group of unrelated markets with LED penetration levels that are low for most end uses, a factor that should add stability in the future to these and other developing HBLED markets.

a) back lighting for cell phones and other LCD displays (31%)

b) interior and exterior automotive lighting (27%)

Design Goal	2002	2007 Replace Incandescent	2012 Replace Fluorescent	2020
Performance (Lumens/Watt)	25	50	150	200
Lifetime (Hrs)	>1000	10 000	>10 000	>10 000
Color Rendering Index (CRI)	60	80	>80	>80
Lamp Output (Lumens/Watt)	20	200	1000	1500
Cost Target ($/K lumens)	500	50	<15	<5

Figure 1: HBLED Road-Map (Optoelectronics Industry Assoc)

c) large signs and displays (25%)

d) signals & illumination (at less that 5% each)

Progress and growth in the cell phone LED market have improved as the displays have changed from green to yellow to full colour and additional growth is forecast to come from the increased use of colour screens. This use is expected to grow to 50% of the market in 2003 and to 75% by 2007. Supporting these estimates is the historical colour backlight market shares that have been reported as 28/400 in 2000, 46/384 in 2001 (all in millions of cellphone units) with the market share estimated to be 430/600 in 2006.

Steady growth in the automotive market is anticipated in all application areas as more and more car models receive the LED treatment and as the number of LEDs per vehicle continues to increase (over 300 LEDs for some high-end models). The LED advantages sound similar; improved safety, power savings, styling opportunities, reduced dimensions, multi-colour interior lighting options, brand definition and system cost savings. Concept vehicles have demonstrated low beam, fog lamp and marker lighting. However, annual market growth rates in this segment are expected to remain in the 10 to 15% range.

In the large sign segment, LEDs are mostly replacing mini-cathode ray and light-bulb based systems where typical energy savings in the 75% range have been reported. Of the installed base, about 65% of the installations have been for outdoor video signs, such as sports stadia and advertising plus mono-colour terminal and traffic signs. The remainder (35%) were used indoors for arenas, other video displays and exit signs. Advertising requirements are expected to drive this market segment in the future because of slowing demand for the large video displays.

Since power requirements are much lower for LED based lighting and displays units, solar power becomes a realistic alternative solution under suitable climatic conditions. One small

LED Cost/Performance

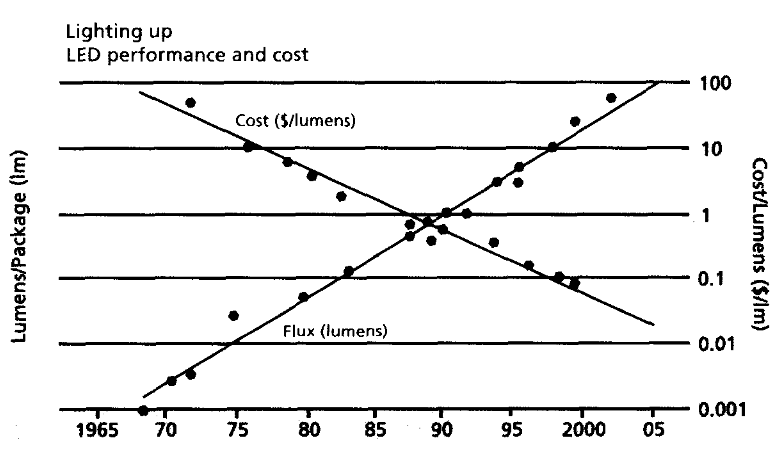

Figure 2. Source: R. Heitz, Agilent.

market segment that has been completely revolutionized by the solar/LED synergy is that of marine navigational lighting, where microprocessor control can now be used to provide remote control and permanently sealed units. According to David Green, the Research Manager from Carmanah Technologies Inc., the LED advantages over incandescent systems are; LED beacons weigh 1/10th as much, last up to 10 times as long, cost 1/10th as much, reduce the buoy sizes, reduce the size of the service vessel required and eliminate the need for regular ship servicing. Other potential solar supported applications for LEDs include shelter illumination, road and railway hazard lighting, taxiway and runway lighting and outdoor signage.

Thus the developing markets for solid state lighting (coloured & white) include aviation, (beacons, reading, runway and cockpit lights), neon replacements and maritime safety. White LEDs are already providing benefits for zonal, proximity and other specialty lighting uses. The Navy has many shipboard and dockyard applications where the low voltage and longer lifetimes are very desirable on the basis of lower power use, improved safety and less maintenance. The total high brightness LED market is forecast by Strategies Unlimited to exceed $3 billion by 2005 (see Figure 3.).

The LED solution to general white lighting is still 10 to 15 years away. However, coloured lighting and beacon uses and some functional white applications have turned into developing markets. The potential for LED sources from the point of view of conformal, power, temperature, design utility and lifetime benefits have finally come to the attention of many architects and according to Kathryn Conway from LED Consulting, the related LED sessions at the 2002 Light Fair Conference sold out.

Production issues

In spite of their current successes, the HBLEDs still have a long way to go to attain their full potential. Process and packaging yields, lifetimes and power efficiencies can all be improved leading to more light output per chip at a lower cost. For example, in some of the initial applications insufficient attention was paid to heat removal, which led to overheating and 'unexpected' shortening of the LED and product lifetimes. LEDs operate at relatively low temperatures (compared to incandescent lamps), but as light output per unit area and duty cycles increase, the thermal management and heat removal from the package becomes more and more important in order to keep junction temperatures at acceptable levels.

To meet the growing market needs, work is on going worldwide to improve light extraction from the chip, improve optics, develop new substrates, minimize existing substrate short comings, substrate thinning, die separation, alloy segregation (for indium nitride), layer growth, emission wavelength variations, use of larger substrates, chip testing and heat removal. Blue, violet and UV LEDs have additional requirements because the higher energy of their light can affect the lifetime of their encapsulant materials. On a systems basis, the driver electronics also need to be optimized due to the low voltages required, efficient, stable and long lived power conversion systems (AC to DC) are needed that can withstand the minus 40 to 80°C temperature ranges that can be encountered in outdoor service. As the answers to these problems are obtained and the overall production technology continues to advance, additional markets will open up and increased market penetration will occur.

White LEDs

Although a serious incursion into the world lighting market by white LEDs may be more than a decade away, the annual market size ($12 billion) and the wide range of advantages offered by the LED (high efficiency, lower operating temperatures, the non-use of mercury, extended lifetime, global power savings) continue to drive the long term development of this lighting source. At this stage, the best competing technology (or technologies) have yet to be proven from a range of gallium nitride device possibilities for white light that include

a) RGB LEDs (red, green, blue) to form white

b) blue LEDs + phosphor

c) UV LEDs plus multiple (RGB) phosphors (full phosphor conversion)

d) double or multiple quantum well LEDs

Even though most of today's white LEDs are made by partial phosphor conversion (see b above), each of the listed alternatives have advantages and disadvantages that may eventually provide the final solution(s). These multiple solutions further complicate the end result for the perfect white LED because in addition, chip engineering processes such as wafer bonding and die shaping techniques similar to those developed for the most efficient yellow high brightness LEDs also need to be developed in the different materials, substrates and process used for gallium nitride emitters.

Political support

In the USA and in keeping with other semiconductors, LEDs now have a technology road map. This initiative has been generated by the potential advantages that can be derived from solid state lighting. It was realized that to achieve the orders of magnitude improvements in cost and performance, significant advances in the understanding of the fundamentals of solid state lighting, materials and devices would be required. Sandia National Laboratories will have a key role in this long term research program toward energy efficiency goals. The main research topics are the solid state physics of gallium nitride materials, related MOCVD processes, low defect substrates and advanced device structures.

The background information provided by this programme is the basis for the Next Generation Lighting Initiative (NGLI) with federal financial support included in a Senate Energy Bill. Money to support the development of advanced solid state lighting systems by 2012. Its technical goals are 160 lumen per Watt LEDs with a ten year life and 100 l/W organic LEDs with a five year life. The programmes will be administered by a private consortium funded by Department of Energy grants with an initial funding level for solid state lighting (SSL) estimated to be in the $10 million range.

The Canadian government is also backing SSL development as part of planned energy savings and its efforts to meet the Kyoto Protocol. It has allocated $20 million with an initial grant of $6.6 million to TIR Systems Ltd. in 2001. The programme goal is commercially viable white SSL systems by the year 2010.

An organic challenge?

Perhaps of limited awareness to many to and not usually widely reported has been the

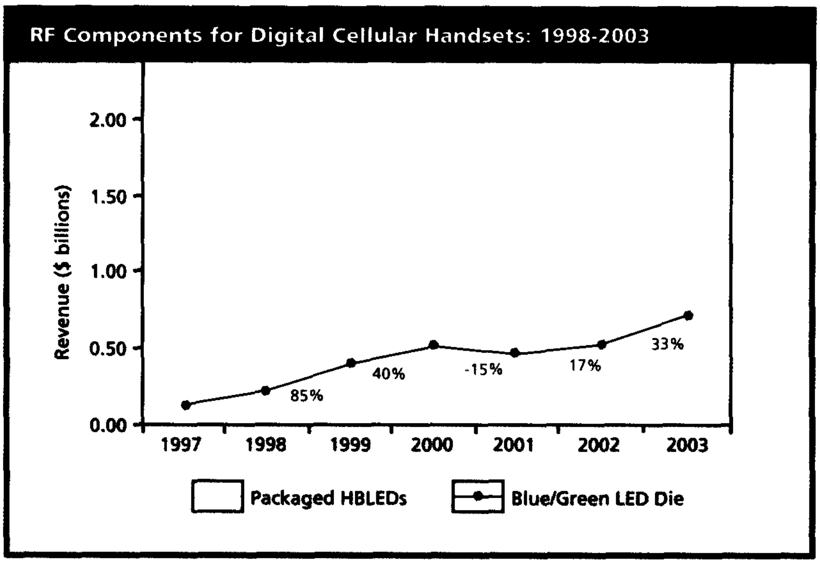

Figure 3

parallel development of organic light emitting diodes or OLEDs. In the last decade this technology has made significant advances and the state of the art in this field appears to be about five years behind gallium nitride technology. In advancing this technology, thousands of organic compound and polymer materials have been made and evaluated in OLED test devices and a range of manufacturing processes are available that produce working OLEDs. Based on these results, limited capacity production lines have been installed for such applications as cellphone, MP3 and camera displays where limited volumes of OLEDs have already been manufactured and installed in high-end models. Toshiba recently provided and example of advanced OLED technology with the demonstration of a 17" developmental display.

OLED devices are very efficient in material use, requiring very thin layers of active material (in the 50 to 200nm range). To enable the production of today's organic displays peak light emission efficiencies have increased from the 2% range in 1999 to 7% in 2002 and many of the lifetime materials problems associated with electrodes and the light emitting molecules and/or polymers have been reduced to acceptable levels. OLEDs are close to volume production and may soon compete with LEDs for flat screen displays, for some low level lighting applications and especially for conformal or curved displays, both static and video. For these applications, an OLED may be the final answer.