LED-Based Lighting Reaching the end of the Tunnel

More than a century after the introduction of incandescent lighting and half a century after the introduction of fluorescent lighting, solid-state light source are revolutionizing an increasing number of applications. Whereas the efficiency of conventional incandescent and fluorescent light is limited by fundamental factors such as filament temperature, photon conversion efficiency etc that cannot be overcome, the efficiency of solid-state sources is limited only by human creativity and imagination. The first commercial technology for lighting was based on natural gas that lighted the streets and homes at the end of 19th century. As a result of the competition from Edison's incandescent lamp, gas lights were very much improved by the use of mantles soaked with thorium oxide, which converted the gas flame's heat energy and ultraviolet (UV) radiation into visible radiation. The incandescent light bulb first displayed in 1879 ultimately displaced gas lights. The efficiency of incandescent lamp is limited to about 17 lm/W by the filament temperature that has a maximum of about 3000K, which results in the utter dominance of invisible infrared emission. Fluorescent tubes and compact fluorescent lamps became widely available in the 1950s and early 1990s respectively. The efficiency of fluorescent lamp based on mercury vapour sources is limited to about 90 lm/W by a fundamental factor: the loss of energy incurred when converting a 250 – nm UV photon to a photon of the visible spectrum. Fluorescents are about five times as efficient as incandescent bulbs. They produce light by exciting vaporised mercury atoms in a glass tube, causing them to release UV light. That then strikes a phosphor coating inside the tube, which absorbs one wavelength of light and emits another, fluorescing white light. The solid state light sources offer huge potential benefits like reduced energy consumption, dependence on foreign oil and mercury pollution. Emission of green house gases (CO_2) and emission of acid rain causing SO_2 are also reduced due to decrease in energy demand. In a traffic light an ordinary bulb with a red filter uses about 150 watts, whereas the array of 12 red LEDS used in traffic lights consumes just 12 watts. Solid state lighting replacing power hungry incandescent bulbs in application such as traffic lights, railway signals, airport runway lights, brakelights, home and artistic lighting, display etc can cut the electricity demand in these areas in half from the present level of 22%. That is a tremendous saving. Also the low running temperature (150^0C) of LEDS means they can last for decades (20 years min) as there is hot filament to burn out. And they do not need to be housed in a delicate glass bulb.

Basic Working Principle

The LED coverts input electrical energy into output optical radiation in the visible or infrared portion of the spectrum, depending on the chemistry of the semiconductor material. If the semiconductor is doped with P- and n-type carriers can be increased by applying a forward bias to p-n junction. LED comprises a sandwich of n-type semiconductor that is rich in electrons and a p-type semiconductor that is depleted of them as shown in Fig 1. In other words, p-type has an excess of positively charged particles known as holes. At the junction of 'n' and 'p' layers is the active layer, where light is emitted. When a voltage is applied in the direction as shown in Fig 1 (forward bias) mobile electrons on the n-type side can easily cross the p-type side. On the p-type side, electrons have a high probability of holes in this region. Similarly mobile holes in the p-type region can cross to the n-type side and are likely to radiatively recombine with electrons, the majority charge carriers in this region. Radiative recombination of electrons and holes in the active layer leads to efficient emission of band-gap energy in the form of photons – the basic unit of light. With a voltage applied in the opposite direction (reverse bias), there is substantial barrier for electrons or holes to cross

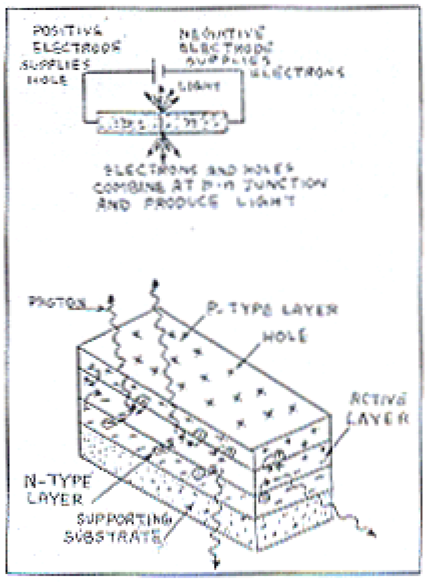

Fig 1 Semiconductor Chip

the interface, and little current flows and no light is emitted. Adjusting the diode's chemistry changes the size of the energy gap, and thus the colour of light emitted. In practice, not all the injected electrons recombine radiatively with holes. A part of the excess minority carrier recombines non-radiatively, and the excess energy of these carriers is dissipated as heat in the lattice. Some of the minority carriers diffuse away and hence recombination can occur in regions away from the junction. There are also losses due to internal reflection inside the chip. The emission efficiency of a LED active layer depends strongly on the density of dislocations, which act as nonradiative recombination centres and they degrade the radiative combination probability in the active layer. Defects and impurities in the semiconductor materials also reduce the generation of photons. All these factors have impact on the device efficiently. There has been tremendous improvement in luminous efficiency of LEDs, which increased from almost zero in 1960 to above 100 lumens/watt at present (Refer fig 2). The main reason for these improvements is the continued rise in material quality and the development of substances that allow efficient transformation at electrons and holes into photons in late 1990s engineers made a transparent gallium-phosphide wafer and sculpt at red LED into the shape of an inverted pyramid. This shape decreased the number of internal reflections and thus boosted the amount of light escaping from the chip to an astounding luminous efficiency of 110 lumens/W. this special geometry transformed more than 55% of the incoming electrons into photons at the red wavelength.

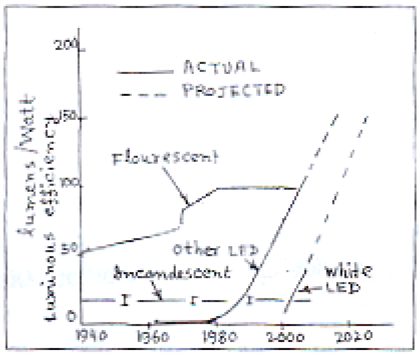

Fig 2 Luminous Efficiency Vs Year

Nitride Based Led

Recently tremendous progress has been achieved in GaN (Gallium nitride) based LEDs. This has resulted in a variety of applications such as traffic light, full color display and lighting. With a wide bandgap energy varying from 0.7 eV for InN to 6.3 ev for A1N, group III nitrides are highly promising for the LED applications from green to UV. These LEDs use GaN-based materials grown on sapphire substrates and InGaN – GaN multiple quantum well (MQW) structure as the active light emitting region. Conventional nitride based LEDs use an Mg-doped GaN as the p-contact layer. However the operational voltage of such LEDS is still high due to the low Mg ionization percentage. The low Mg ionization percentage will result in a highly resistive top p-GaN layer and large metal/p-GaN contact resistance. In order to achieve high performance nitride based LEDs, it is required to reduce p-GaN contact resistance. Mg-doped AlGaN / GaN strained layer super lattice (SLS) can be used to increase the Mg ionization %. By using such SLS p-contact layer contact resistance can be reduced and hence operation voltage also will be lower. It is also possible to use n^+ - InGaN / GaN short period superlattice (SPS) to reduce the contact resistance of nitride based LEDs. By growing such SPS structure on top of the p-GaN layer, one can achieve a good ohmic contact through tunneling when the n^+ (InGaN/GaN) – p (GaN) junction is properly reverse biased. Although these two methods reduce the operation voltage effectively, both methods require complex growth procedure. The other method to reduce p-contact resistance is to use p – in GaN as the capping layer on top of the p- GaN. On the other hand, transmittance of the p-metal layer at the top acting as p-contact of LED terminal is also important since photons generated in the active region will be partially absorbed by this layer. If the transmittance of p-metal layer is increased then it is possible to increase the LED output intensity. This can be done by using transparent indium tin oxide (ITO) to replace the conventional Ni/Au p-metal layer. It is known that ITO is a hard and chemically inert transparent material with a high electrical conductivity and a low optical absorption coefficient.

Therefore it is a good candidate for transparent contacts to many optoelectronic devices. Although it is possible to achieve good ohmic contacts by depositing ITO on n – GaN, ITO could only from Schottky contacts on p-GaN. As a result, the operation voltage of nitride – based LEDS with ITO p-contacts become too large for practical device applications. One possible way to solve this problem is to combine the transparent ITO p-contact with then – InGaN/GaN SPS tunneling contact structure. Since ITO could from good ohmic contacts on n-GaN, it is possible to simultaneously achieve a small specific contact resistance and a high upper contact transmittance by using such a combination. Metal organic chemical vapor deposition (MOCVD) method is used for growth of the crystal on sapphire substrate. Recently double-heterojunction LEDs and laser have been fabricated with an active layer as thin as 2 nm instead of the typical 0.1 to 0.3 μ m of conventional double-heterojunction structures. These devices are known as quantum – well LEDs/lasers. The carrier motion normal to the active layer in these devices is restricted, resulting a quantisation of the kinetic energy into discrete energy levels for the carriers moving in that direction. Due to this reason, the thin active layer cause drastic changes in the electronic and optical properties in comparison with a conventional double-heterojunction LED. Quantum – Well LEDs exhibit an inherent advantage over conventional double –heterojunction devices in that they allow high gain at low carrier density, thus providing significantly lower threshold currents. In mutiquantum-well (MQW) corresponding to multiple active layers, the layers separating the active regions are called barrier layers. MOW devices score over conventional double-heterojunction LEDs due to their lower threshold currents, narrower line – widths, higher – modulation speeds, lower frequency chirps and less temperature dependence. It has been established that a photoluminescence intensity from InGaN/GaN multiple – quantum – well (MQW) active region is strongly enhanced when the well width is narrower than 3 nm, which is used as the active layer of currently used LEDs. The reduction of dislocation density in the active layer is indispensable for achieving a long lived nitride based LEDs. GaN grown on sapphire substrate with nucleation layer reduces the dislocation density. The dislocations act as nonradiative recombination centers in GaN, and they degrade the radiative recombination probability in the active layer. The structure of high performance green LED is shown in Fig 3. It consists of a 30-nm-thick low temperature GaN nucleation layer grown at 550^{0}C on Sapphire substrate followed by a 2-μm thick si-doped n-type GaN cladding layer grown at 1050^{0}C, a mutiquantum well (MQW) active region, a 50-nm-thick Mg-doped Al 0.15 Ga 0.85 N p-cladding layer and a 0.25-μm – thick Mg-doped P-type GaN layer. On top of the p-GaN layer Si-doped n$^+$-In 0.23 Gα 77 N/GaN (thickness 5A^0 5A^0, 1A^0 m = 10^{-10}m) SPS structure is deposited. The MQW active region consists of five periods of 3-nm-thick In 0.45 Ga 0.55N well layers and 7-nm-Thick GaN barrier layer. the as-grown samples are then furnace annealed at 740^{0}C in N$_2$ ambient to activate Mg in p-type Al 0.15 Ga 0.85 N and p-type GaN layers. 260-nm-thick ITO contact layer is made by e-beam evaporation. For serving as n-type electrode Ti/A1/Ti/Au contact is deposited on n-type Gan layer. From the finished wafers 370 μm x 370 μm chips are cut and packaged into green LED lamps. LEDs emitting in the near ultraviolet (i.e., 410 nm) and blue (i.e. 470 nm) regions can be prepared by varying the indium composition. Using 5 period Si-doped 2.5-nm-thick. In 0.23 Ga 0.77 N Well layer and 12-nm-thick GaN barrier layer as MQW active layer bright blue LED (i.e. 470 nm) can be made.

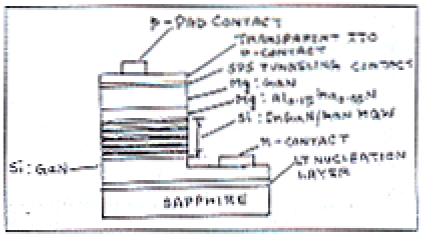

Fig 3 InGaN Green LED

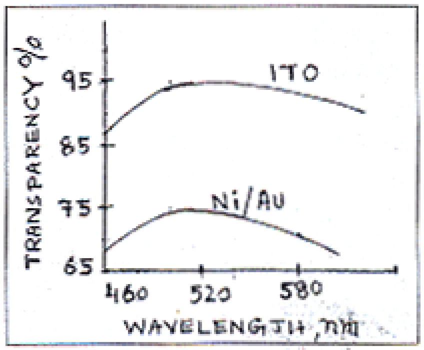

Fig 4 Transmission Spectra

Fig 4 shows that ITO is much more transparent when used as p-contacts instead of conventional Ni/Au p-contacts. At 520 nm, the transmittance of Ni/Au is only 74% while the same for ITO could reach 95%. Illumination intensity of LEDs with Ni/Au. From Fig 5 it can be seen that output power from

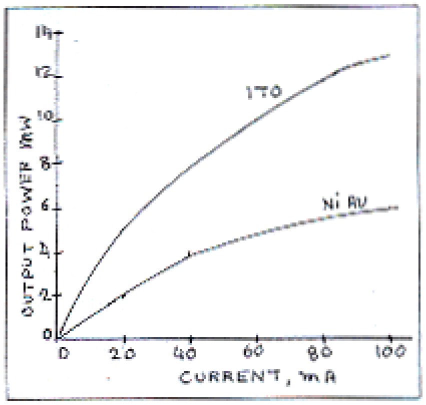

Fig 5 I-V Output Power

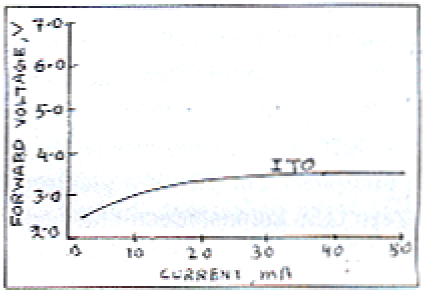

Fig 6 I-V Characteristic

LEDs with ITO is more than double of LEDs with Ni/Au p-contact. Fig 6 shows the I-V characteristics of nitride based green LEDs which can be operated at 3.0 volt. The contact resistance of ITO is only 1.03 x 10^{-3} ohm cm^2. These LEDs are also quite reliable. After 1,000 h of operation the luminous intensity decreases only by about 3%. With these technology improvement next, the external quantum efficiency (total number of output) photons/total number of injected electrons, of violet, blue and green LEDs in early 2,000 reached 32%, 22% and 10% respectively. The next of nitride based blue LEDs is ever increasing. From 1972 to 1982, next was stagnant at about 0.1%. At present blue LEDs having next of higher than 22%, which is much brighter than incandescent lamps are used.

White LED

LED-based lighting is sweeping away energy inefficient incandescent lighting in a host of applications. So, why are we still waiting LEDs to light our homes? Because, currently white LEDs available in the market is only 50% efficient compared to fluorescent light. LEDs won't light our homes until their efficiency beats fluorescent lamps. Progress towards making white LEDs began in earnest in 1993, when japanese firm Nichia used gallium nitride to make the first LED to emit visible blue light. This meant that for the first time, LED light of the right wavelength could be produced and used to bombard a phosphor to produce white light. Right now, the cheapest, most common way to produce a white light LED is to coat a blue LED in phosphor grains that absorb near – UV blue light and emit a combination of red, yellow and green wavelengths that together look white. LEDs such as these are used in pocket flashlights and bicycle lamps. But this two stage light production mechanism means some energy is wasted. The phosphor grains convert some of the energy to heat and for LEDs to beat the efficiency of domestic white fluorescent lighting, this waste has to be eliminated. So researchers are looking for a way to produce white light from LEDs by placing blue, green and red LEDs together on a chip, without using phosphors. But there's a problem a green LEDs are inefficient. Blue and green LEDs use the same semiconductor, indiumdoped gallium nitride, but green LEDs require more indium. The more indium is added, the slower the electrons fall into the holes, which lowers the light output. Researchers are trying to overcome these problems by finding new green emitters. While today's white LEDs use half as much power as incandescent bulbs to produce the same brightness, the new materials could slash that to one-tenth in about two years time. This will make white LEDs a compelling option for use in the home. Several promising strategies to create white light with higher efficiency are shown in Fig 7 using di, tri and tetrachromatic sources. These approaches differ in terms of their luminous efficiency (lm/W) i.e., visible light output power per unit electrical input power, colour stability and colour rendering capability i.e., the ability of a light source to show the true colours of an object. There is a fundamental tradeoff between colour rendering and luminous efficacy of radiation (1m per unit optical power). For optimized wavelength selection, dichromatic sources have the highest possible luminous efficacy of radiation, as high as 425 lm/W, but they

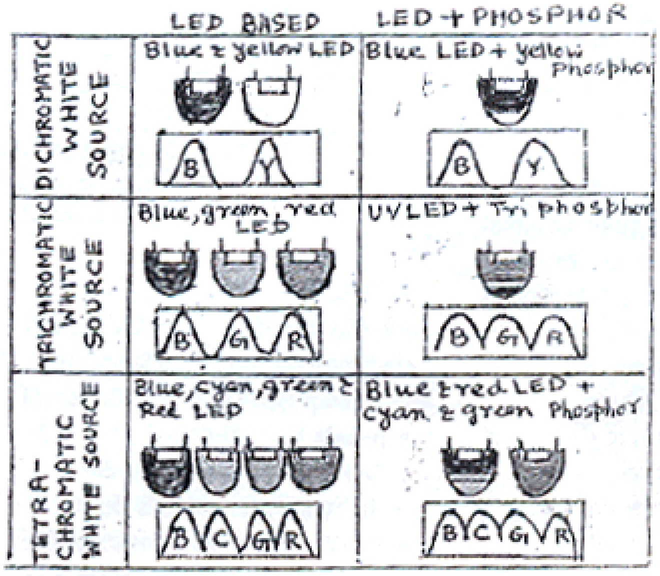

Fig 7 Strategies to Create White Light

poorly render the colours of the objects. Tetrachromatic sources have excellent colour rendering capabilities but have lower luminous efficacy than dichromatic or trichromatic sources. Trichromatic sources have both good color rendering properties and high luminous efficacies (300 lm/W) fig 7 also shows several phosphor based white light sources. Such sources use optically active rare-earth atoms embedded in an organic matrix. Cesium doped yittriumaluminium-garnet (YAG) is a common yellow phosphor. However, phosphor-based white light source suffer from an unavoidable stokes energy loss due to the conversion of short wavelength photons. This energy loss can reduce by 10 to 30% the overall efficiency of systems based on phosphors optically excited by LEDs. Such loss is not incurred by white light sources based exclusively on semiconductor LEDs and hence preferred. Furthermore phosphor-based sources do not allow for the extensive tunability afforded by LED-based sources. The luminous efficiency of a light source is a key for energy savings considerations. It gives the luminous flux in lumens (light power as perceived by the human eye) per unit of electric power. As can be seen from Fig 2, there has been continuous improvement in luminous efficiency of LEDs, which increased from almost zero in 1960 to above 100 lumens /watt in 2000. Luminous efficiencies of 425 lm/W and 320 lm/W could potentially be achieved with dichromatic and trichromatic sources respectively, if solid-state sources with perfect characteristics could be fabricated. Perfect materials and devices would allow a white LED to generate the optical flux of a 60 W incandescent bulb with an electrical input power of 3W. Further colour rendering index (CRI) is an essential figure of merit of illumination. A high CRI value indicates that a light source will accurately render the true colour of an object. Although trichromatic sources give good CRI values, tetrachromatic sources give excellent CRI (about 95) suitable for practically any application. LED emission powers decreases exponentially with temperature. As a result, the chromaticity point, CRI and efficiency of LED based light sources drift as the ambient temperature of the device increases. To avoid this change, corrective action must be taken by tunning the relative electrical input powers of the LED by energy efficient adaptive drive electronics with integrated temperature compensation. White sources that use phosphor have great colour stability because the intra rare-earth atomic transitions occuring in phosphor do not depend on temperature.

Strategies to increase the Efficiency

In order to increase the luminance and reliability of white LEDs certain strategies have been adopted which in general are;

Internal efficiency

The development of efficient UV 390 nm emitters, green (515 to 540 nm) emitters, yellow-green (540 to 570 nm) emitters and yellow (570 to 600 nm) emitters are a major challenge. The internal quantum efficiency i.e., photons created per electron injected of some of these emitters, particularly in the deep UV can below 1%, due to defects, dislocation and impurities in the semiconductor materials. Approaches like new type of epitaxial growth, growth on pseudomatched substrate and growth on nanostructured substrate overcome these bottlenecks.

Extraction Efficiency

The efficient extraction of light out of the LED chip and the package requires special care because this light tends to be generated near metallic ohmic contacts that have low reflectivity and are partially absorbing. Either totally reflective or totally transparent structures are desirable. The insight gives rise to replacement of absorbing GaAs substrate.

It has also spurred the development of new omnidirectional reflectors whose mirror loss is only 1% of those of metal reflectors. Sophisticated chip shapes and photonic crystal structures are becoming common place. Photonic crystals are periodic dielectric structures that have a band gap that stops the propagation of a ceretain range of light. Another fruitful strategy is to reduce deterministic optical modes trapped in LEDs by introducing indeterministic optical elements such as diffuse reflective and transmissive surfaces.

Phosphors

In solid-state lighting the excitation wavelength is much longer, typically in the range of 380 to 480 nm. Hundreds of phosphors are available for excitation at 250 nm, the dominant emission band of Hg lamps. Whereas high efficiency cesium doped YAG yellow (570 to 600 nm) phosphors are readily available, new high-efficiency phosphors in other spectrum are now being developed.

Chip and Lamp Power

Although substantial progress has been achieved in LED optical output power, but still no more increase in output power is required. Increase in chip area increases power, but it is frequently accompanied by a reduced efficiency due to absorption losses of waveguided modes propagating sideways within the semiconductor. New scalable geometries and high reflectivity omnidirectional reflectors will overcome this problem. Surface emitting devices are generally more scalable, as they do not suffer from waveguide losses. Surface emission can be accomplished by micro-raisrors that redirect waveguide modes towards the surface normal direction of the chip. The scaling of the current density requires strong confinement of carriers to the active region. Such confinement reduces carrier escape out of the active region and carrier overflow. Use of electron and hole blocking layers that prevent carriers from escaping from the active region will address this problem. Common epoxy encapsultants limit the maximum operating temperature to 120^0C. Use of silicone will increase this range to 190^0C and also offers mechanical stability.

Cooling

Common LED chips, driven at high currents quickly heat up as its thermal resistance is 200 K/W. Cooling with a fan or thermoelectric device is not acceptable as it reduces the power efficiency. Extraction of heat sink overcomes the bottleneck. Such packages have thermal resistances 5 K/W. in silicon technology scaling of ICs has reduced the cost of logic gates by more than six orders of magnitude. Similarly the scaling up of LED chip size and of the current density will enable substantial cost reductions that will bring white LEDs into offices and homes in about 2 years time.

Reference Book:

IEEMA Journal
September 2006