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A Review of Solid State White Light Emitting Diode and Its Potentials for Replacing Conventional Lighting Technologies in Developing Countries

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Abstract

Lighting is an indispensable energy end use of man. A significant number people in developing countries live without electric lighting and depend on oil-based lamps. Globally, lighting consumes substantial amount of energy and is a major contributor to green house emissions. Conventional electric lighting systems such as incandescent lamps are highly inefficient and waste energy while the fluorescent/CFL lamps contain toxic chemicals like mercury. Incandescent lamps with short lifespan as well as the fluorescent/CFL lamps pose environmental waste disposal problems (e.g.). The use of renewable energy resource such as solar and wind power systems for example as sources of power for the most efficient and long life lighting source such as high-brightness light emitting diodes (LEDs) (also known as solid state lighting) would reduce global energy consumption for lighting by half, with corresponding reduction in green house emissions. In developing countries solar powered solid state lighting (SPSSL) would ensure access to electric lighting by the disperse population who may not be connected to the national grid in the near feature. In this article we elaborately review the upcoming solid state lighting technology. The physics and principles of operation of LEDs are also reviewed. The impact of this new lighting technology on developing countries in the areas of commerce, education, health and environmental impacts in comparison to conventional lighting technologies is the main thrust of this review.

Keywords: lighting, high-brightness LEDs, developing countries, renewable energy, solar power

1. Background

Lighting, artificial or natural, is one of the most important energy end use that man requires to carry out his day-to-day activities. Every task requires an appropriate lighting level, which to a greater extent depends on the habit of the user and the available lighting level. For example the general level of illumination recommended for household ranges between 50 lux to 150 lux (Buttler, 2001; Matei, 2003). But it is not everyone that has access to lighting sources with illumination within this range. In developing countries, a larger population of household use oil-based lamps (Mills, 2012). Most of the lamps provide illumination that is grossly inadequate to the end user. Lighting systems that provide better illumination such as... are particularly expensive to afford and maintain. Man's endless quest for efficient, reliable and affordable lighting sources has led to the transformation from the use of fire as a lighting source to oil lamps to the present day electric lighting. The need for efficient electric lighting has also led to the transformation from incandescent lamps to fluorescent lamps and now using solid state light emitting diodes.

It is reported that about 1.7 billion people living in developing countries (Table 1) do not have access to electric lightingand depends on oil lamps for home lighting (World Bank, 1996; Mills & Berkely, 2002). Oil lamps are expensive, inefficient (0.3 lm/W) (Dunlop, 1998), unhealthy and hazardous to its users. Globally, the lamp is a major source of green house gas and consumes significant amount of energy apart from many fire accidents/ hazards. The lanterns burns an estimated 470 million barrel of oil per year and release approximately 400 billion pounds of CO_2 equivalent gases into the atmosphere annually (Mills, 2005; Walsh, 2007). The soot from the oil lamp (specially the wick lamp) is not only a potential global warmer (Smith et al., 2000), but also a dangerous health hazard (Ritchie et al., 2001; Zhou et al., 2000). It is one of the most important absorbing aerosol species in the atmosphere with a global warming potential 680 times that of each equivalent mass of CO_2.

BLE 1: ESTIMATED UNELECTRIFIED RURAL POPULATION BY REGION, 1990

Table 1. Estimated Unelectrified Rural Population, 1990 (World Bank, 1996)

Region	*Estimated Unelectrified Rural Population (million)*
North Africa and the Middle East	**73**
Latin America and the Caribbean	**75**
Sub-Saharan Africa	**314**
South Asia	**632**
East Asia and the Pacific	**642**
Total	**1736**

Electric lighting is more efficient than oil based lighting. Common electric lighting lamps are incandescent lamp and fluorescent lamps. Incandescent lamp has luminous efficacy of 15 lumen/watt and fluorescent lamp a luminous efficacy of 80 lumen/watt. This corresponds to only about 5% and 25% respectively of electrical energy being converted to visible light; the remaining energy is wasted as heat. Studies have shown that about 30%, 20%, and 22% of all generated electric power is used for lighting in United State of America (USA), United Kingdom, and Nigeria/South Africa, respectively. Worldwide usage pattern are similar (OIDA, 2001; Oshokhine, 2003; MTP-Road Map, 2006). Consequently, significant improvement in lighting efficiency through energy savings technology and procedure would have a major impact on the worldwide energy consumption and economy.

Solid State lighting using light emitting diode (SSL-LED) is a new energy efficient option in the lighting industry. This technology promises superior attributes such as longer lifespan, and higher energy conversion efficiency of 95% (including driver losses) (Gordon, 2008) compared to incandescent and fluorescent lamps. Furthermore, SSL-LED is a very low pollution source; it is compact; rugged and has a higher colour rendition index.

Efficient and affordable lighting sources considerably reduce energy consumption and make energy available to extended number of users without posing any health risk to its users. On the economic stand point, it extends the number of commercial/productive hours in a day as part of the night is used for production and other commercial activities (e.g. buying and selling of goods and services). Longer commercial/productive hours in turn provide income to small scale businesses and by extension increases revenue to government.Increased government revenue could mean an improvement in the provision of social and infrastructural services to the people. Again, for the rest of the world, efficient lighting sources such as solid state lighting can dramatically reduce the global electricity energy consumption by nearly 50% (IP UtilityNET, 2011). Therefore, more energy would be available for other economic activities thereby improving the standard of living of the people especially in developing countries.

If SSL-LED are used in conjunction with solar panels as stand-alone solar powered systems, the impact will be felt most in poor rural villages of developing countries (Table 1) that may not be served by utility grid in the near future. This is because the growth rate of conventional electricity generation technologies is slow compared to population growth in most of these developing countries. In Africa for example, electricity generation growth was just 0.1% per annum from 1973 to 2006 (OECD/IEA, 2008).

The challenge of deploying stand-alone solar powered SSL-LED lighting systems is the initial cost (most of it is for solar panel); however, this cost is off-set by the long life-span of both the LED and the solar panels. Again, with improvement in the technologies and the understanding of the physics of LEDs and solar cell, their efficacies have been increasing while the cost is decreasing.

2. Some Physics Aspects of Light Emitting Diode

2.1 The Solid State Lighting (SSL)—Light Emitting Diode

Light Emitting diode (LED) is a semiconductor device that can be used to emit either visible or infrared light depending on the material used. The type of semiconductor material (direct or indirect band gap) used in the manufacture of LED determines the peak wavelength of emitted light. In direct band-gap materials the minimum of conduction band and maximum of valence band at the same occur at the same wave vector k, where as in indirect band gap materials they occur at different k-values. The generation of light in LED is classified as electroluminescence or injection luminescence. Under this process and for a forward biased LED junction, electrons occupying finite number of higher energy states in the conduction band jump to lower energy states (valence band) recombining with holes to produce light (photon). The emitted light has an energy which represents the difference between the higher and lower energy state of the electron's transition (i.e. the energy bandgap). The amount of energy carried by light depends on the wavelength and the shorter the wavelength the higher the energy (bandgap energy).

However, since the emitted light is at a specific wavelength and energy bandgap (narrowband), it appears coloured. Hence, to obtain white light the narrowband emission must be converted into semi-broadband emission that fills the entire visible spectrum. The advantage of SSL technology over fluorescent lamp is that the wavelength of the narrowband emission can be tuned with relative ease by altering the size of the energy bandgap of the semiconductor material. This can be done in such a manner as to either increase the quantum efficiency, or to minimize the Stokes-shift associated with its conversion to semi-broadband emission. This makes this technology potentially more efficient than fluorescent lamps (OIDA, 2001).

For LEDs to successfully replace conventional lighting sources such as incandescent and fluorescent lamps, they must be capable of producing higher luminous efficacy with high colour rendering index. The luminous efficacy (lumen per watt) of an LED is determined by three physical parameters: internal quantum efficiency, the extraction efficiency and white light conversion efficiency.

2.2 The Internal Quantum Efficiency of LED

The internal quantum efficiency is a measure of how many injected electrons and holes are converted to photons (light) and depends on the radiative and non- radiative carriers' lifetime.

The energy efficiency of any LED depends on the type of material and the amount of light it can generate.

2.2.1 Theory of Recombination

There are two competing processes that take place simultaneously and which determine the internal quantum efficiency of a LED. These processes are the radiative and non-radiative recombination of electrons and holes. The radiative process is accompanied by the emission of a photon and is the preferred process in LEDs, while the non-radiative recombination is accompanied by the emission of phonons. The latter process does not produce light.

A. Radiative Recombination:

The probability that an electron and a hole will recombine in a semiconductor material is given by (Schubert, 2010):

$$R \propto np$$

$$R = Bnp \tag{2.1}$$

and the recombination rate per unit volume is given by the bimolecular rate equation as

$$R = -\frac{dn}{dt} = -\frac{\mathrm{dp}}{dt} = Bnp \tag{2.2}$$

where B is the bimolecular recombination coefficient, n and p are the electron- and hole- concentrations respectively.

For low-level excitation, the recombination rate is given by Schubert (2010):

$$R = R_0 + R_{excess} = Bn_i^2 + B(n_0 + p_0)\Delta n(t) \tag{2.3}$$

and the time dependent carrier concentration is

$$\frac{dn(t)}{dt} = G - R = (G_0 + G_{excess}) - (R_0 + R_{excess}) \tag{2.4}$$

where G is the generation rate, G_0 is the intrinsic generation rate and G_{excess} is the excess carriers generated.

From equations (2.1) – (2.3), the carrier lifetime for an intrinsic semiconductor is calculated as:

$$\tau_r = \frac{1}{B(n_0+p_0)} \tag{2.5}$$

For high-level excitation, the photo-generated concentration is larger than the equilibrium carrier concentration i.e. $\Delta n \gg (n_0 + p_0)$ and the bimolecular equation is thus given as:

$$\frac{d\Delta n(t)}{dt} = -B\Delta n^2 \tag{2.6}$$

Equation (2.6) shows that unlike the low-level excitation, the carrier concentration in high-level excitation is non-exponential and is given in Equation (2.7) and the carrier lifetime given by Equation (2.8):

$$\Delta n(t) = \frac{1}{Bt + \Delta n_0^{-1}} \tag{2.7}$$

$$\tau(t)_r = t + \frac{1}{B\Delta n^2} \tag{2.8}$$

Equation (2.8) show that the minority carrier lifetime increases with time and for a sufficiently long time, low-level excitation condition is reached with t approaching the low-level value.

B. Non-Radiative Recombination

The different physical mechanisms that lead to non-radiativerecombinations in semiconductor LEDs are defects in crystal structure such as unwanted foreign atoms, native defects, and dislocations. Auger recombination and the surface effect. The probability of electron and hole recombining non-radiatively is given by the Schockley-Read equation for deep levels with trap energy E_T and concentration N_T as

$$R_{SR} = \frac{p_0\,\Delta n + n_0\,\Delta p + \Delta n\Delta p}{\left(N_T v_p \delta_p\right)^{-1}(n_0 + n_1 + \Delta n) + (N_T v_n \delta_n)^{-1}(p_0 + p_1 + \Delta p)} \tag{2.9}$$

For an intrinsic semiconductor material $p_0 = n_0 = n_i$, the recombination lifetime is calculated as

$$\tau_{nri} = \tau_{no}\left[1 + \frac{p_1 + n_1}{2n_i}\right] = \tau_{no}\left[1 + cosh\frac{E_T + E_{Fi}}{KT}\right] \tag{2.10}$$

Where T is the temperature, K is the Boltzmann constant and E_{Fi} is the energy at Fermi level.

Equation (2.10) shows that non-radiative lifetime can be minimized when the trap level is located close to the mid-gap energy, that is if $E_T + E_{Fi} = 0$. The result also demonstrates that deep levels are effective recombination centers if they are near the middle of the gap. Furthermore, as the temperature, T increases the non-recombination efficiency decreases.

The total probability of recombination is then given by the sum of the radiative and non-radiative probabilities

$$\tau^{-1} = \tau_r^{-1} + \tau_{nr}^{-1} \tag{2.11}$$

Thus, the internal quantum efficiency is defined as the ratio of the number of light quanta emitted inside the semiconductor to the number of charge quanta undergoing recombination, which is given by Equation (2.12)

$$\eta_{int} = \frac{\tau_r^{-1}}{\tau_r^{-1} + \tau_{nr}^{-1}} \tag{2.12}$$

Internal quantum efficiency is high in direct bandgap semiconductor material because of momentum conservation. The indirect bandgap semiconductor materials have low quantum efficiency because the lattice momentum in the conduction and valence bands are different and so, both photon and phonon emissions are equally likely. Internal quantum efficiency of over 50% has been achieved with the development of device structures such as double heterostructure, single quantum wells (SQW), multiple quantum wells (MQW) active layers that enhance radiative recombination over non-radiative recombinations (Kitai, 2010). Quantum well heterostructure are a key component of high-brightness LEDs because they can increase the strength of electro-optical interactions by confining charge carriers (electrons and holes) to a small region.

A quantum well is a thin layer of semiconductor that can confine carriers (electron/hole). Quantum wells are produced by fabricating a semiconductor heterostructure such that a narrow band gap material is sandwiched between two layers of wider ban dgap materials of InGaN/GaN QW. When the confined electron hole pairs recombine they emit a wavelength which is related to the well width.

For a quantum well, the recombination rate is given by the bimolecular formula as Kitai (2010),

$$R = B\frac{n^{2D}}{L_{QW}}\frac{p^{2D}}{L_{QW}} \tag{2.13}$$

Where L_{QW} is the thickness of the QW. n^{2D} and p^{2D} are the two-dimensional electron and hole densities respectively.

As the quantum well thickness (L_{QW}) is reduced to a size comparable to the de Broglie wavelength of the carriers, the energy within the well becomes quantized in discrete levels. Also, a thin quantum well active layer offers the potential of higher injected carrier densities since the carriers injected across the p-n junction become confined within the well, fill-up and cause an increase in the concentration of electrons and holes. The consequence is that more efficient radiative recombination occurs (the recombination rate is proportional to n^*p) leading to increased number of photons emitted (brightness). Another advantage of a thin quantum well is that it minimizes self-absorption. The main factors that affect energies of the quantized levels are the potential well height and the well width (Weisbuch & Vinter, 1991; Mullen, 2006).

As a possible solid state lighting source for general lighting, white light LED is particularly desirable. The breakthrough in the fabrication of p-type GaN-based materials in the 1990s by Amano et al. and Nakamura et al. enable white light LED sources to be realized. Amano et al. in 1989 obtained a p-type GaN film by successfully doping GaN with Mg as an acceptor impurity by post low electron energy beam irradiation (LEEBI) treatment. Amano and co-workers (1990) observed that under LEEBI, the Mg-doped GaN exhibit lower resistivity and that the photoluminescence properties improved considerably. Building upon this result, Nakamura et al. in 1992 obtained a much higher p-doping and uniform activation of Mg by using high temperature thermal annealing under nitrogen ambient (Amano et al., 1990; Denbaars, 2006; Nakamura, 1998). Further progress by Nakamura and Mukai between 1993 and 1995 led to the successful growing of high quality InGaN heterostructure quantum well active layer that emitted strong band-to-band emission from yellow to UV by only changing the indium (In) content of the InGaN. For example for a single quantum well structure that is composed of an InGaN active well layer sandwiched by n-type GaN and p-type AlGaN barrier layers, lowering the indium (In) content a UV LED is obtained while increasing In composition to 0.2 say, enables the production of blue LED (Nakamura, 1998). High-brightness LEDs are configured into two main orientations; that is using AlGaInP active layer with lattice matched to GaAs to generate amber to red colour and GaN/InGaN for blue to green colours. The disadvantage of AlGaInP active layer with lattice matched to GaAs is the non-transparency of the GaAs substrate to visible light which gives rise to photon absorption in the substrate. Currently two types of blue LEDs are commercially available; lateral contacted device with quantum well InGaN active layers on sapphire substrate from Nichia Chemical Industries, Ltd, Toyoda Gosei, Hewlett Packard Optoelectronics and the vertical contacted GaN/AlGaN double heterostructure device on conducting SiC substrate by Cree Research Inc. and Siemens (DenBaars, 2003).

3. LED Materials and Efficiency

3.1 External Quantum Efficiency

The luminous efficacy and hence the brightness of a LED can be low in spite of high internal quantum efficiencies if light is not extracted efficiently. The extraction efficiency is a measure of how efficiently internally generated photons are extracted from the device. At the moment, GaN crystal substrate are not available in sufficient large size and reasonable cost and so GaN family LEDs are epitaxially grown on poorly lattice matched substrates such as SiC and sapphire (Al_2O_3) (Denbaars, 2003; Suikhonen, 2008). The result is that crystal defect densities are high and most carriers are trapped thereby producing non-radiative transitions in the form of phonons in the lattice, which reduce the efficiency of the LED. Although the lattice mismatch of SiC substrate with GaN is only about 3.4%, and SiC have good electrical and thermal conductivity which might benefit high output power applications of GaN LEDs (Stokes et al., 2006) even at high temperature. However, the large difference in thermal expansion coefficient in SiC compared to that of GaN leads to increased tensile stress in the GaN film with temperature variation. The crystal structure of SiC has many forms (polymorphism or polytypism) which are called polytype. About 200 polytypes have been identified to date (Ferro & Soueidan, 2006) and the most common polytypes are: 4H, 6H and 3C polytype SiC substrate. However, the growing quality of 3C-SiC monocrystalline material is still an issue (Ferro & Soueidan, 2006) while on the other hand the cost of 4H- and 6H-SiC polytype substrates is high. Furthermore, though saphire (c-plane saphire) substrates have good thermal stability and are cost effective but, they have large lattice mismatch (16%) with InGaN active layer, which leads to large number of threading dislocations (TDs) and point defects (Stokes et al., 2006). The said TDs are thought to be caused by complex interactions of interface energy, nucleation density and island coalescence (Nakamura, 1998; Suikhonen, 2008). One good advantage of GaN based LED is that despite large defects caused by imperfectly matched substrate, the radiative lifetime of charge carriers is much smaller than the non-radiative life time, so most carriers can recombine to emit photons before encountering traps. Also, for the InGaN active quantum well layer LEDs, high indium fraction quantum dots form in the active layer during epitaxial growth. These quantum dots serve as radiative recombination centers and keep the electron-hole pairs away from the defects during device operation, resulting in high efficiency (Stokes et al., 2006).

Other defects that could lead to decrease internal efficiency of GaN based LED is the evolution of piezoelectric field as a result of bond stress between dissimilar materials with different lattice constants coming together. The presence of this electric field alters the optical properties of the InGaN LED and is called the quantum confined stark effect (QCSE). The QCSE creates band bending in quantum wells thus reducing the overlap between electron and hole wave functions with a corresponding reduction in absorption and luminescence as well as an increase in the threshold current. However, there is an inherent property of InGaN that tends to reduce the QCSE, it is the compositional fluctuation of InGaN in the presence of polarization effect. The presence of compositional fluctuation causes the spreading of the wavefunctions away from the corners of the well thereby increasing overlap and absorption. Furthermore, the variations in composition act as local centers of carrier confinement, thus increasing recombination rate. In order to ameliorate the QCSE, Nakamura et al. (2002) created a p-i-n junction that gave rise to an internal electric field in the intrinsic material. The reduction in the new field as a result of forward bias was able to counter the QCSE in the active region and thereby improving the efficiency of the LED.

The extraction efficiency of a compound semiconductor device is also severely limited by the total internal reflections (TIR) and Fresnel reflections (FR) at both LED chip/epoxy and LED chip/phosphor interface due to index mismatch. Semiconductor device materials have high index of refraction compared to air/epoxy and the resulting high degree of total internal reflection of light emitted from the active region ensure some of the light remains trapped thereby reducing the external efficiency of the device. Extraction efficiency has been improved dramatically by several techniques such as bridging the indices of refraction between the chip and air with optical material such as using a dome shape encapsulation; flip-chip design which allows emission through the substrate by reducing the effect of contact shadowing; chip shaping-which creates angle facets that reduce total internal reflection; surface roughening or patterning such as patterned sapphire substrate (PSS), which reduces reflections from the smooth, flat chip surface; and thin device structures, which minimizes emission from the sides of the device (Boroditsky & Yablonovitch, 1997; Report OM-31, 2005; Ibbetson, 2006).

3.2 White Light Conversion Efficiency

There are a variety of ways by which white light LEDs are fabricated, among which the colour mixing method and the phosphor down-conversion method are the most commercially viable (ODIA, 2001; IESN TM-16-05, 2005; Schubert & Kim, 2005; Wang et al., 2007; Zhu & Narendran, 2007). In the colour mixing approach to white light, three separate red, green and blue LEDs are combined to form white light. The efficiency of the colour mixing approach is high, but the problem associated with obtaining a consistent colour across an array is considerable since the drive voltages for different wavelength differs. This requires a complex drive circuitry with the consequent wastage of significant energy. Also, the maintenance of proper colour balance using this approach is complex as red, green and blue LEDs degrade at different rates over time and with variation in temperature. The appearance of white also changes with viewing angle (OIDA, 2001). In order to overcome these challenges several efforts have been made to produce white light without phosphors, the approach proposed by Yeh et al. (2008) involves stacking two or three InGaN/GaN quantum well structures of different indium content that emits in blue and yellow or blue, green and red. Using a pre-strained metallorganic chemical vapour deposition (MOCVD) growth technique, a low-indium InGaN/GaN QW is grown before the designated light-emitting high-indium InGaN/GaN QWs to create tensile strain in the GaN barrier layer right above the low-indium QW making the incorporation of indium during subsequent growth of QWs more effective. The increased indium content then leads to efficient emission of yellow, orange and red colours. By stacking the yellow- and blue-emitting QWs on a chip, Yeh et al., produced a white light LED with chromaticity coordinates of (0.334, 0.338) at injection current of 50 mA which is close to ideal condition. The colour temperature at the 50 mA injection current was 5600 K (value at sunlight at noon) (Yeh et al., 2008).

However, for general illumination the warm white colour temperature (2700 K to 4000 K) is preferred. Improvement in the crystal growth of green-red emitting quantum wells is also required for efficiency enhancement and high colour rendition index for general illumination purposes. Quantum dots white-light LEDs have also been fabricated. For example, the homoepitaxial growth of ZnSe on a ZnSe substrate resulted in a self-activated emission that produces white light (Chen et al., 2006). Such white light might be the result of combination of blue-green light from ZnSe active layer combined with yellow light from ZnSe substrate. At the moment CRI of this device is however poor for general illumination, the efficiency of the device is low and it has a shorter lifetime than InGaN white LEDs (Chen et al., 2006).

Furthermore, using magic size CdSe (1.5 nm), Weiss et al. (2006) were able to produce white light which covers the entire spectrum of 420 nm – 710 nm with chromaticity and color temperature of (0.33, 0.30) and 5400 K, respectively. This white light suffered from low CRI (79) and luminous efficiency (0.5 lm/W) due to lack of red emission.

The phosphor down-conversion approach is the most common approach. It involves over-coating a blue- LED or UV- LED with a phosphor or mixture of different colour phosphors to create white light (Li, 2008). This method produces white LED with high efficiency and long lifespan. It also produces relatively stable colour variation with temperature. Losses in extracted light efficiency in this approach is due to the physical shape of the phosphor, position of the phosphor, the refractive index mismatch which may lead to scattering of light back into the LED and the photoluminescence efficiency of the phosphors. Conventional phosphors are often encapsulated in an epoxy or silicon matrix (glass encapsulation have also been reported (Allen & Steckl, 2008; Kitai, 2008)). The large differences in the refractive indices of the phosphors and epoxy, together with small particle size and weak absorption of the phosphors give rise to diffuse scattering of incident and emitted light. This scattering caused by the phosphor reduces efficiency due to increased path length for light inside the phosphor, leading to re-absorption losses and decreasing the effective quantum efficiency the phosphor. The longer path lengths caused by randomization of light directionality as it passes through the phosphors increases light contact with high loss areas such as reflectors, phosphor layer, and LED chip which reabsorbs the light (Allen & Steckl, 2008). In order to minimize losses due to phosphors and enhance efficiency, the use of hemispherical optics and suspended phosphor on semi-transparent host (glass) have been demonstrated by Allen and Steckl (2008) to have satisfied the maximum efficiency requirements of low scattering compared to the conventional phosphor on chip method (Allen & Steckl, 2008). Again, there are optical backscattering associated with using conventional bulk phosphors. The losses account for about 50% reduction in the package efficiency of phosphor converted LEDs (Schubert & Kim, 2005).

Another approach to reducing losses due to backscattering is the use of quantum dots phosphors. Quantum dots have a much smaller size than the wavelength of visible light thereby reducing scattering and associated optical losses (Zhao, 2006). However, for large semiconductor quantum dots (QDs), in addition to scattering of light there is also an overlap between absorbance and emission bands which can lead to strong self-absorption of the emitted lights. The decoupling of this overlap by synthesizing small QDs allows the majority of their atoms to be located at the QD interface, the chemistry of these interface alone determines the emission colour, while the absorption is fixed by the dot size thereby eliminating the effect of self-absorption of emitted light (Wiscoxon et al., 2006).

High-brightness light emitting diodes (or high brightness light emitting diodes) are LEDs that combine the properties of high internal quantum efficiency, high extraction efficiency and high phosphor conversion efficiency to produce high luminous efficacy. At present the commercial high-brightness white LEDs have efficacy above 150 lumen/Watt (Durham, 2010). Given the challenges associated with developing very efficient white LEDs as enumerated above, it is imperative that developing countries should invest in the research towards the development of efficient white LEDs in their countries/continents rather than relying on the developed nations for breakthroughs. Investment in research and development of efficient high-brightness white LEDs and solar cells would drastically reduce cost of these materials and encourage their deployment in rural areas. In future, development of high-brightness white LEDs and low cost solar cells would eliminate darkness from the villages of developing countries while providing huge cost savings in city-lighting.

To explore the possibility of generating white light with high CRI, low CCT and high efficiency using LEDs, Ahemen and De (2012) have recently focused on the studies of synthesis and characterization of Eu-doped ZnS nanoparticle that could serve as a potential candidate for red-emitting phosphor. Their studies have revealed that pure and well-passivated ZnS:Eu^{3+} nano-particles can be synthesized with average nano-particles in the strong quantum confinement regime. The intensity of the red-light emitted from the synthesized ZnS:Eu nanophosphors was found to be size and site dependent. It is expected that further research will improve the intensity of the red-light emission and then ZnS:Eu nanophosphors can become potential candidates for white-light generation using a down conversion method involving pumping a combination of green, yellow and red phosphor with near ultraviolet (UV) LED to generate the white light.

Recently Narukawa et al. (2010) reported fabrication of three types of white LED with super-high luminous efficacy (η_L) and luminous flux (φ_v). The first type of white LED with a correlated colour temperature of 4600 K, had η_L of 249 lmW^{-1}, φ_v of 14.4 lm at a forward bias current of 20 mA. It was a phosphor conversion white LED lamp consisting of a blue LED die and a yellow phosphor of YAG (yttrium aluminum garnet). η_L for this white LED reached a maximum 265 lmW^{-1} at 5 mA and then decreased slightly with increasing injection current. However, the white LED was found to be deficient in red light component. To enhance the red component, a red phosphor, SrCaSiN:Eu was added to the YAG white LED. Well-passivated ZnS:Eu^{3+} red nano-phosphors (Ahemen & De, 2012) may also be potential candidate that can be added to above mentioned YAG white LED to improve the white light quality.

Narukawa et al. (2010) also fabricated a super high efficiency blue LED which was used in turn to fabricate a high power white LED with output power of 756 mW and luminous flux of 203 lm at 350 mA. They also fabricated another type of high power white LED using four high-power blue LED dies. φ_v and η_L were 1913 lm and 135 lmW^{-1} at 1 A respectively.

Tulkki and Santhanam (2013) discovered a light-emitting diode (LED) with 200% efficiency. When the LED is heated to 135 oC and biased by low voltage of 70 µV - the output light power was found to be 70 pW when the input power was 30 pW. It is considered that phonons (heat) assist the transitions of electrons from conduction band to valence band (recombination of electron and holes) and increase the emission of of photons more than expected from the input electrical energy. Energy conservation is however not violated. Thermally assisted enhanced photon emission has earlier been predicted in the case of picosecond Laser pulse Irradiated semiconductor thin films (De & Musongong, 2007). More research is underway on the newly discovered high efficiency LED which could have tremendous application in high efficiency solid state lighting system in future.

3.3 Energy Savings Potential of Solid State Lighting

About 30 billion electric lamps are used worldwide everyday consuming more than 2100 TWh electrical energy per year. This is about 34% of global electricity generation in 2006 (www.photonic521.org). Incandescent lamps have very poor energy savings potential with an efficiency of 15 lumen/Watt. Yet, highly inefficient incandescent lamp is the most common lamp used in developing countries. On the other hand, the fluorescent lamps are efficient lighting sources with average efficacy of 80 lumen/Watt (Table 2). Fluorescent lamps have received high acceptability globally particularly in developed countries with the European Union being the first to implement the ban on the use of incandescent lamps for the more efficient fluorescent lamps in September 2009 (Lee, Sr., 2010). A comparison of the various lighting sources is presented in Table 2.

Table 2. Efficiencies of Light Source Comparison (Dunlop, 1998; Gordon, 2008; Swoboda, 2010)

Light Source	**Lumens per Watt (Range depending on Wattage)**
Candle	1.4
Oil Lamp	0.3
Incandescent	10-18
Halogen	15-20
Compact Fluorescent Lamp (including Ballast) 5 – 26 W	35-60
Linear Fluorescent Lamp (including Ballast) 40 W – Full size and U-tube	80-100
Metal Halide Lamp	50-90
Cool White LED ≤5000 K	80-160*
Warm White LED 3300 K (Inc. Driver)	25-110*

* As of April, 2010.

Huge energy savings can be realized by replacing the current incandescent and fluorescent lamps with the most efficient SSL (Table 2). With the efficacy of SSL now at 208 lumen/Watt at 350 mA and 4579 K colour temperature (under laboratory test condition) and the commercial availability of cool white 160 lm/W (Cree XM-LED) or 132 lm/W (Cree XP-G LED) (Durham, 2009, 2010; Swoboda, 2010) over 50% of global electrical energy used for general lighting purposes could be saved per year. Such energy could be channeled to improve electricity supply to avert the current trend whereby regular power outages are experienced in most developing countries. If the white LED invented by Narukawa et al. (2010) as mentioned earlier become commercially available, such LEDs combined with low cost solar panels could now become the answer for removing darkness from many parts of the worl. Lighting with such technologies would be much more cost effective and environment-friendly than with incandescent and fluorescent lamps powered by usual electric supply systems.

Furthermore, the successful production of a white LED lamp known as “Acriche LED” with efficacy of 100 lm/W which is driven directly by alternating current (AC) without requiring an AC-D converter by Seoul Semiconductors would greatly ease the complexity associated with the current conversion process and losses therein (Lee, 2010). It is however discouraging as most of the available LED lamps fall far short of their much-admired lifespan of 100,000 hours. The efficacy of LEDs for lighting is not unknown to common people in developing countries. Future research on production of white LED with high lumen (>200) per watt and long life span and production of solar panels of reduced costs can go a long way in removing darkness from the developing countries, conserving energy in developed countries and reducing environmental pollution. Because of inadequate power supply and power rationing, some households in developing countries still celebrate when electricity supply resumes after days of outages.

3.4 Environmental Impact and Safety of SSL-LED

The green house gas (CO_2) emission for the above mentioned electrical energy used for lighting purposes is estimated in the order of 900 million tons. If SSL-LED is used to replace conventional lighting sources, at least a 30% (270 million tons) reduction in green house emission could be achieved. Besides green house gas emission, some lighting sources such fluorescent lamps contain an expensive and toxic chemical such as mercury. Mercury even in small amount is capable of contaminating ground water and soil in the environment where it is disposed. In developed countries there are efficient disposal systems such as recycling, landfills, incineration and crushing. All these disposal management options have different environmental impact and are capital intensive. An effective waste management system is lacking in most developing countries, so adopting fluorescent lighting nationally would be a great challenge. Although the amount of mercury content have been declining over the years, it is unlikely that energy efficient mercury-free fluorescent/CFL lamps will be in the market in the near feature (NEMA, 2005).

In spite of their high initial cost, SSL-LED lamps are environmentally friendly and as such are much easier to dispose of compared to other conventional lamps. Their long lifespan means less number of lamp replacement and therefore a considerable reduction in waste disposal problems.

Prolong exposure of fabrics to incandescent lamps weakens the fabric of clothes (Rihner & McGrath, 1992; Küller & Laike, 1998). On the other hand, fluorescent lamps are associated with certain health effect as headache and fatigue caused by harmonics generated by the lamp and induces disease activity among individuals with pathological sensitivity to ultraviolet light. In rare cases some persons can get rash from fluorescent lamps (Colman et al., 1976; Binnie, 1979; Rihner & McGrath, 1992; Küller & Laike, 1998; Beattie et al., 2003). It is also thought that patients with conditions such as xeroderma, pigmentosun, lupus migraine, epilepsy, myalgic and autism could be aggravated by flicker and /or UV/blue light (especially UVB and UVC) (Millard & Hawk, 2001; SCENIHR, 2008). The UV/blue has also been identified as a potential risk factor for aggravation of the light-sensitive symptoms in some patients with such diseases as chronic actinic dermatitis and solar urticaria. Some single envelope CFLs emits UVB (280–315 nm) and traces of UVC (100–280 nm) radiations (Millard & Hawk, 2001). Prolong exposure to these CFLs at closer range could lead to UV exposures approaching current workplace limits set to protect workers from skin and retinal damage (SCENIHR, 2008). The use of double-envelope energy saving bulbs would largely or entirely mitigate the risk of approaching this limit of exposure to UV emissions (SCENIHR, 2008). However, in developing countries accessing this double-envelope CFLs could be difficult owing to corruption on the path of business people who order for substandard goods unchecked. The LEDs particularly the surface emitting LEDs have no known health hazards yet. The limited brightness of LEDs has placed them on the safety circles by applying ICNIRP ELs for incoherent radiation as well as the recommendations of CIE TC 6–38 lamp safety for realistic viewing conditions (ICNIRP, 2000). In addition UVA (340–400 nm) have been found to be useful in the treatment of lupus. This is the likely wavelengths of UV- radiations used to excite phosphors for white light. There are also claims that UV (340–400 nm) photons may promote DNA repairs, cell-mediated immunity and apoptosis in a yet to be determined ways which may be responsible for any therapeutic applications (Millard & Hawk, 2001).

3.5 Education and Economic Impact of Solid State Lighting

The over 1.6 billion people in developing countries currently living without electricity depend on oil lamps to perform task. The low illumination and pollutants from oil lamps cause irritation to the eye of users especially when used at close range. For a student who must use the lamps at a closer length for reading this can reduce the length of reading hours. The consequence may be poor academic performance. Oil lamps are also responsible for the large number of respiratory track infections and sometimes early deaths thereby slowing down economic activities (SolarAid, 2008). Electric lighting using SSL would allow people to study for longer hours at night in schools as well as at homes. In most schools (tertiary or secondary) in some developing countries, electricity supply is regulated owing to high maintenance cost associated with running electricity generators; hence students are forced to read within limited time if they must not use oil lamps or candles.

To impact positively on the socioeconomic and educational development of developing countries, the use of renewable energy system to power SSL-LED lamps for lighting especially in rural villages is required. The advantage of this arrangement is that, both LEDs and solar PVs have long lifespan of between 11–22 years, and LEDS consumes less energy. There are other ranges of technology solutions which can meet energy needs in developing countries; wind power, and small-scale hydropower which exploit local resources, operate on small scale, and can meet needs of widely dispersed rural communities. The efficient use of electrical energy is an issue in the situation of low power production capacity from the aforementioned technologies and because of the associated costs. A cost analysis of LED-based lighting system driven with renewable sources in different parts of developing countries has shown them to be cost effective in comparison with existing options (Jones et al., 2005; Shailesh, 2006). For example, considering the present efficacy of white LED at 160 lm/W (Cree XM-1W LED), and the efficacy of 40 W fluorescent lamp which is currently at 100 lm/W. The size of a photovoltaic (PV) module required for lighting a house at 240,000 lumen (equivalent of six 40 W fluorescent lamps) in eight hours at one sun of five using 40 W fluorescent lamps (PV W_p = 384 Watts) would be almost two time the size of PV (W_p = 200 Watts) required to light the same house using white LEDs (equivalent of six 25 W LEDs) with the same amount of luminosity. The selection of a system (pedal generators, Pico-hydro and solar photovoltaic) however, should be based on the availability of local resources, local geographical situation, cost and the sustainability of the system. The use of SSL-LED lamps would greatly enhance the length of time that the small power generated (and/or stored) from the above sources are utilized thereby increasing the length of business activities and study hours far beyond daylight hours (IEA-PVPs T8-09, 2008).

3.6 Accessing Solar-Based Solid State Lighting in Developing Countries

Accessing solar lighting in rural areas of developing countries is quite difficult. The initial cost of acquiring the equipment (solar PV modules and super-radiant LEDs) could constitute a significant barrier to the adoption of this technology. For example, a single LED lamp that can fit to the current retrofits or “sockets” cost one thousand naira or more (~US$10). Hence there is a need for governmental and institutional support programme that would facilitate the use of this lighting system. Government could enact policies and laws that would support the use of solar lighting technologies using SSL-LEDs and at the same time show commitment that these laws are obeyed. Furthermore, such laws and policies must be geared towards reduction in the initial cost of the equipment and there accessibility. Subsidies, tax incentive and removal of duties on solar lighting products such as high-brightness LEDs, storage batteries and solar PV modules would greatly lower their cost and encourage their usage in developing countries. On the other hand, in urban centers that are grid connected, increasing tax on conventional lighting sources such as incandescent and fluorescent lamps would create competition in pricing. Competition in retail prices means that consumers have a choice to select whichever lighting source that they would like to buy and use, with the expectation that more consumers would go for the product that is more efficient and cost effective.

Performance and quality of solar lighting systems must be maintained at high standards, while keeping the prices at affordable rate. The charge controller and the LED drive circuitry should be made simple but efficient so that maintenance by trained local service providers would be easy for enhanced lifespan of usage after installation. The electronic components used in constructing the charge controllers and LED drive circuitry must also be assessable at affordable cost in retail market in the local communities.

3.6.1 Establishment of Credit Schemes

Since most of the people living in developing countries and without access to electric lighting are poor, for solar lighting using SSL-LED lamps to be successful, credit facilities must be available and accessible by them. Financial institutions such as microfinance banks, poverty alleviation programmes and non-governmental organizations could provide long term micro-credits to members of community cooperatives. However, the credit scheme should be such that it does not provide finance directly to the consumers but rather provide units of solar lighting products. This is to avoid the situation whereby monies given to this people are diverted to other socially unproductive uses.

The fear that such cooperatives might fail to payback may not suffice in this case, since loan refund would be at installment rate for a period of months or years depending on the size and cost of the unit purchased. Also, each household would be able to own a separate unit from the loans obtained from their contributions from the cooperatives. Informal community cooperatives called “bams” are common in developing countries like Nigeria. The community members contribute small monies (usually weekly) and obtain loans from these *bams* to pay back with interest over time usually within one year. The contributions (monies) are returned to members and the profits used to buy meat (cow) which is shared among members during Christmas, with the highest contributor taking the biggest share of the meat. These *bams* could be exploited as channels for solar lighting deployment in rural areas. Rather than share meat from the profits made, part of the profit could be used to provide efficient solar lighting units to members. The financial institutions on the other hand would benefit through profit made from these sales.

Another way to encourage the use of solar lighting using SSL-LEDs would be through donations from donor organizations or agencies. These donations could serve as pilot schemes to demonstrate to the rural people the advantages of adopting solar lighting. Non-governmental organizations (NGOs) and civil organizations on the other hand could act as facilitators through creation of awareness campaigns on the advantages of electric lighting using PVs over other technologies. Furthermore, they could provide technical training support on assembly and maintenance of the systems. They could also serve as a link between donor agencies and product consumers.

4. Conclusion

Developing countries are far from enjoying the benefit of electric lighting as a third of her population still leave in the dark with no hope of electric lighting in the near future. In urban centers of developing countries perennial power outage due to inadequate power generation has forced most of the people to use electricity as a secondary source of lighting with a larger population depending on kerosene lamps, which pose threat to health and environments, apart from causing deaths due to fire accidents. Moreover, inefficient lighting sources such as incandescent lamps are predominant lighting sources in developing countries and America, causing power wastage with little illumination. The gradual increase in the use of the efficient but highly toxic fluorescent lamps (e.g. CFL) posed danger to the developing world with poor waste management systems.

The option is the adoption of the most efficient solid state lighting using high-brightness light emitting diodes which provides good attributes such as high energy efficiency, long lifespan, ruggedness, high CRI and environmental friendliness among others. Long lifespan means less waste disposal problems and enhanced cost savings in the replacement of lamps. High energy efficiency means large energy savings for other productive activities or increased hours of electricity supply. For the local population, electric lighting can only be effective if SSL-LED lamps are powered by solar PVs. However, these products are expensive and so must be supported by government and other financial and donor institutions. These institutions could ensure that the high initial financial burden that would have been placed on consumers of these solar lighting using SSL-LED lamps are lessened to an affordable rate while at the same not compromising quality of the products. It is interesting to note that less than two decades when the first white LED was produced, the efficacy of white LEDs have now hit the target of 200 lm/W (under laboratory test condition) surpassing by far the efficacy of both incandescent and fluorescent lamps. Thus, there is a bright future for this emerging lighting technology.

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